Electronics System

(According to the Syllabus Prescribed by Director General of Civil Aviation, Govt. of India)

Volume : 1

FIRST EDITION

ELECTRONICS

Volume : 1

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Dedicated To

Shri. Laxmi Narain Verma

[Who Lived An Honest Life]

Preface

Aircraft Instrument System (IS) is one of the disciplines in Aircraft Maintenance Engineering curricula. For this reason, this course of study is given at the semifinal stage to students of AME. The approximate time required to cover the entire syllabus will be one semester. An elementary knowledge of Physics and Maths is sufficient to understand this book.

This book in it's present form is the result of several years of teaching experience to the students of AME. In the capacity of Student and Teacher the need has been felt of a book out lining the entire syllabus of Aircraft Instrument System (IS) of paper III in the form of book for those who join this adventurous line of Aeronautics. It is only when one ventures to supply such a need oneself than one realizes why others have failed to bridge the gap, thus it is with a feeling of huminity and uncertainty that one submits the attempt to the reader for his or her verdict. My thanks are due to those who have helped me with their valuable suggestions.

I would very much appreciate, criticisms, suggestions for improvement and detection of errors from my readers, which will be gratefully acknowledged.

Mr.
(Senior Instructor) ***Dated : July, 2009***

CONTENTS

CHAPTERS		PAGE NO.

■■■

CHAPTER - 1
KNOWLEDGE OF ELECTRICAL TERMINOLOGY AND COMPONENTS USED IN AC/DC CIRCUITRY, OHM'S LAW, KIRCHHOFF'S LAW AND THEIR APPLICATION

GENERAL

Anyone concerned with aircraft maintenance in aware of the increasing use of electricity in modern systems and recognizes the importance to the mechanic of a thorough understanding of electrical principles. While the use of electricity today is so common as to be taken for granted, its widespread use in aircraft electrical systems emphasizes the importance of a sound electrical background for the airframe and powerplant technician.

In the study of physics, the electron theory of the structure of matter was introduced to explain the fundamental nature of matter. A more detailed examination of this theory is necessary to explain the behaviour of the electron as it applies to the study of basic electricity.

MATTER

Matter can be defined as anything that has mass (weight) and occupies space. Thus, matter is everything that exists. It may exits in the form of solids, liquids, or gases. The smallest particle of matter in any state of form, that still posses its identity, is called a molecule.

Substances composed of only one type of atom are called elements. But most substances occur in nature as compounds, that is, combinations of two or more types of atoms. Water, for example is a compound of two atoms of hydrogen and one atom of oxygen. A molecule of water is illustrated in Fig. 1.1. It would no longer retain the characteristics of water if it was compounded of one atom of hydrogen and two atoms of oxygen.

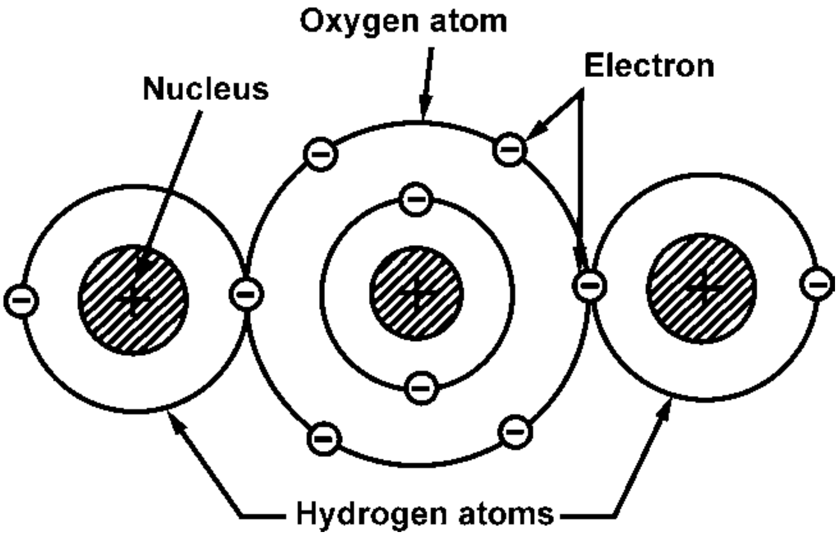


Fig. 1.1. A Water Molecule.

THE ATOM

The atom is considered the basic building block of all matter. It is the smallest possible particle that an element can be divided into and still retain its chemical properties. In its simplest form, it consists of one or more electrons obriting at a high rate of speed around a centre, or nucleus, made up of one or more protons, and, in most atoms, one or more neutrons as well. Since an atom is so small that some 200,000 could be placed side by side in a line 1 inch long, it cannot be seen, of course. Nevertheless, a great deal is known about its behaviour from various tests and experiments.

The simplest atom is that of hydrogen, which is one electron orbiting around one proton, which is one electron orbiting around one proton, as shown in Fig. 1.2. A more complex atom is that of oxygen (see Fig. 1.3), which consists of eight electrons rotating in two different orbits around a nucleus made up of eight protons and eight electrons rotating in two different orbits around a nucleus made up of eight protons and eight neutrons.

An electron is the basic negative charge of electricity and cannot be divided further. Some electrons are more tightly bound to the nucleus of their atom than others and rotate in an imaginary shell or sphere closer to the nucleus. While others are loosely bound and orbit at a greater distance from the nucleous. These latter electrons are called "free" electrons because they can be freed easily from the positive attraction of the protons in the nucleus to male up the flow of electrons in a practical electrical circuit.

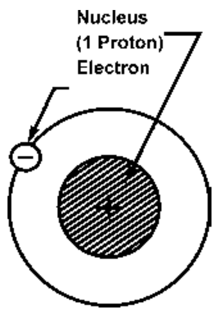


Fig. 1.2. Hydrogen Atom.

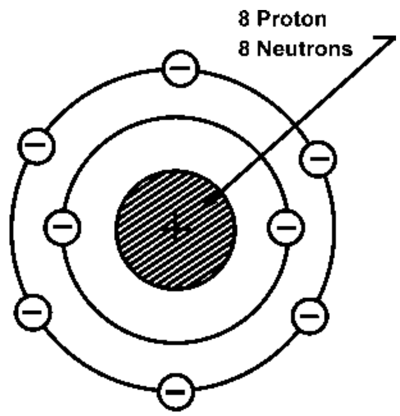


Fig. 1.3. Oxygen Atom.

The neutrons in a nucleus have no electrical charge. They are neither positive nor negative but are equal in size and weight to the proton. Since a proton weighs approximately 1,845 times as much as an electron, the overall weight of an atom is determined by the number of protons and neutrons in its nucleus. The weight of an electrons is not considered in determining the weight of an electron is not considered in determining the weight of an atom. Indeed, the nature of electricity cannot be defined clearly because it is not certain whether the electrons is a negative charge. With no mass (weight) or a particle of matter with a negative charge.

Electricity is best understood in terms of its behaviour, which is based in part on the charge an atom carries. When the total positive charge of the protons in the nucleus equals the total negative charge of electrons in orbit around the nucleus, the atom is said to have a neutral charge. If an atom has a shortage of electrons, or negative charges, it is positively charged and is called a positive ion. If it possesses an excess of electrons, it is said to be negatively charged and is called a negative ion.

CONDUCTORS AND INSULATORS

Some materials have an atomic structure that easily permits the movement of electrons. These materials are referred to as conductors. Materials are typically good conductors if they have fewer than five electrons in their outer shells. Four excellent conductors are silver, copper, gold and aluminium Materials which oppose the movement of electrons are called insulators. Insulators typically have between five and eight valence electrons and therefore do not easily accept additional electrons. To prevent the inadvertent flow of electricity, insulators are often placed around conductors. Some common insulating materials are plastic, rubber, glass, ceramics, air (or vacuum), and oil.

ELECTRON FLOW

Consider what happens when a conductor made of copper is connected across a source of electrons.

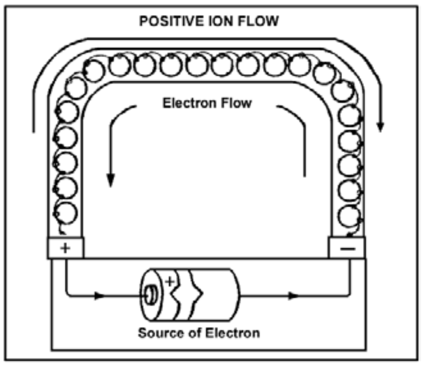


Fig. 1.4. When a positive source attracts an electron from a conductor, it leaves a positive ion. This on attracts an electron from an adjoining atom. This exchange continues through the conductor until an electron is furnished by the negative terminal to replace the one taken by the source.

The positive terminal of the source attracts an electron from an atom in the conductor and the atom leaves the conductor. The atom which lost the electron now becomes a positive ion and pulls an electron away from the next atom. This exchange continues until the electron that left the conductor initially is replaced by one from the source's negative terminal. (Fig. 1.4.)

Electron movement takes place within the conductor at about the speed of light, which is approximately 186,000 miles per second. However, this does not mean that a single electron moves from one end of a conductor to the other at his speed. Instead, an electron entering one end of the conductor almost immediately forces another electron out the other end. (Fig. 1.5.)

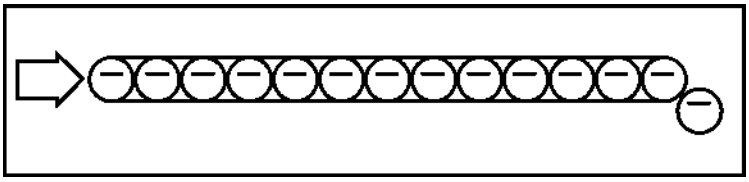


Fig. 1.5. When one electron enters a conductor, it immediately force another electron out of the opposite end.

EFFECTS OF ELECTRON FLOW

Although you cannot see the movement of electrons within a conductor, you can see and use the effect of this movement. For example, as electrons flow through a conductor they produce a magnetic field around the conductor. The greater the amount of flow, the stronger the field. Furthermore, as electrons flow, the opposition to their flow produces heat within the conductor.

DIRECTION OF FLOW

Since the flow of electricity could not be observed, it was only natural to assume that it flowed from a high level of energy to a lower level or, in electrical terms, from "positive" to "negative". This theory worked well for years. In fact, many textbooks were written calling the flow of electrons "current flow" and assumed a flow from the positive terminal of the source to the negative terminal.

As scientists gained knowledge of the atom, it became apparent that the negatively charged electron actually moved through a circuit. Therefore, most textbooks have been revised to explain electron flow as being from the negative terminal, through the load, and back into the positive terminal.

Because electricity was thought to flow from positive for so long, the theory is still discussed and is referred to as **conventional flow**. Although the conventional flow of electricity is technically incorrect, it does follow the arrow symbology used on semiconductors. The proper flow of electricity is termed **electron flow**. You may use either method for tracing flow, as long as you remain consistent. This chapter follows electron flow and uses the terms flow and current interchangeably. In chapters dealing with semiconductor devices and their symbols, the flow of conventional current is used. This is because the arrows used in semiconductor symbols point in the direction of conventional current flow. (Fig. 1.6.)

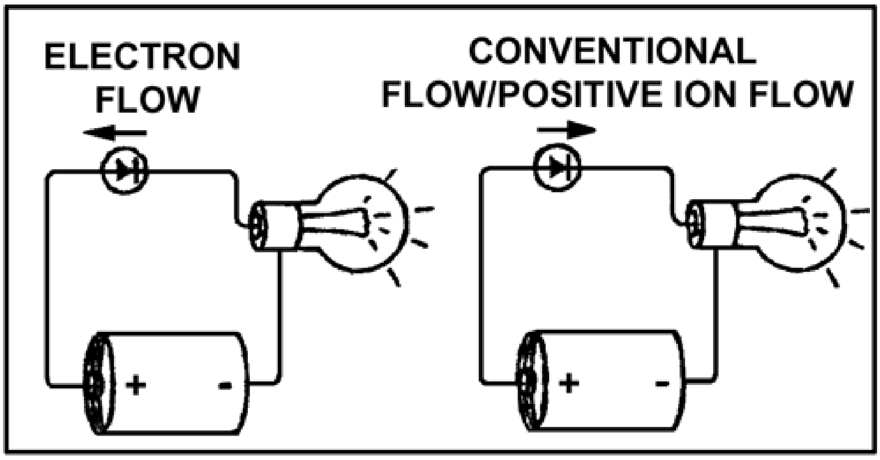


Fig. 1.6. Electron flow refers to the flow of electron from the negative terminal to the positive terminal. On the other hand, conventional current is said to travel from positive to negative. It is easier to think in terms of conventional current when working with semiconductor symbols.

UNITS OF ELECTRICAL MEASUREMENT

The electron is such a small particle that an enormous number of them are required to obtain a measurable unit. The **coulomb** is the basic unit of electrical quantity and is equivalent to 6.28 billion, billion electrons. This is typically written as 6.28×10^{18}. The symbol for quantity is **Q.**

When one coulomb of electrons flows past a point in one second, there is a flow of one **ampere**, or one **amp.** It makes no difference whether you think in electron flow or conventional flow, it is all generally called current. The symbol used to represent current is **I.**

The **ohm is** the standard unit of resistance, or opposition to current flow, and is represented by anΩ. One ohm is the resistance through which a force of one volt results in a flow of one ampere.

the force that causes electrons to flow is called the **electromotive force** or **EMF.** An electromotive force is measured in **volts**. One volt represents the amount of force required to cause one amp of flow through one ohm resistance. A number of terms are used to express electrical force. They are: voltage, voltage drop, potential, potential difference, EMF, and IR drop. These terms have slightly different meanings, but are often used interchangeably. The symbol used to represent the volt is **E**.

Typically, electricity is used to generate **power**. The standard unit of measure for electrical power is the **watt**. One watt is the amount of power dissipated when one amp of current flows under a force of one volt. The symbol for power is **P**. (Table 1.1.)

Table 1.1. This table illustrates a summary of electrical characteristics and their corresponding units

CHARACTERISTIC	SYMBOL	UNIT
Electrical Charge (Quantity)	Q	Coulomb
Electromotive Force	E or V	Volt
Current	I	Ampere or Amp
Resistance	R	Ohm
Power	P	Watt

STATIC ELECTRICITY

Electricity is often described as being either stick or dynamic. Since all electrons are alike, these words do not actually describe two different types of electricity; rather, they distinguish between electrons at rest and those in motion. the word static means "stationary" or "at rest," and refers to the deficiency or to the excess of electrons. Originally it was thought that static electricity was electricity at rest because electrical energy produced by friction did not move. A simple experiment, such as running a dry comb through hair, will produce cracking or popping sounds, indicating static discharge are taking place. The charges thus built up consist of electrons transferred to the comb as the results of friction. The discharge is caused by the rapid movement of electrons in the opposite direction from the comb to the hair as the charges neutralize each other. In the dark it is possible to see these discharges as tiny sparks.

Static electricity has little practical value, and often causes problems. It is difficult to control and discharge quickly. Conversely, dynamic, or current electricity, is generated and controlled easily and provides energy for useful work.

A summary of that part of the electron theory dealing with charges will help explain static electricity. All electrons are alike, but repel each other. Electron & Proton are not alike, but attract each other. Hence, the fundamental law of electricity is that like charges repel and unlike charges attract.

GENERATION OF STATIC ELECTRICITY

Static electricity can be produced by contact, friction, or induction. As an example of the friction method, a glass rod rubbed with fur becomes negatively charged, but if rubbed with silk, becomes positively charged. Some materials that built up static electricity easily are flannel, silk, rayon, amber, hard rubber, and glass.

When two materials are rubbed together, some electron orbits of atoms in one material may cross the orbits or shells of the other, and one material may give up electrons to the other. The transferred electrons are those in the outer shells or orbits and are called free electrons.

When a glass rod is rubbed with silk, the glass rod gives up electrons and becomes positively charged. The silk becomes negatively charges since it now have excess electrons. The source of these electric charges is friction. This charged glass rod may be used to charge other substances. For example, if two pith ball is touched with the charged glass rod, some of the charge from the rod is transferred to the balls. The balls now have similar charges and, consequently, suspended and each touched repel each other as shown in part B of (Fig.1.7). If a plastic rod is rubbed with fur, it becomes negatively charged and the fur is positively charged. By touching each ball with these differently charged sources, the balls obtain opposite charged and attract each other as shown in part C of (Fig.1.7).

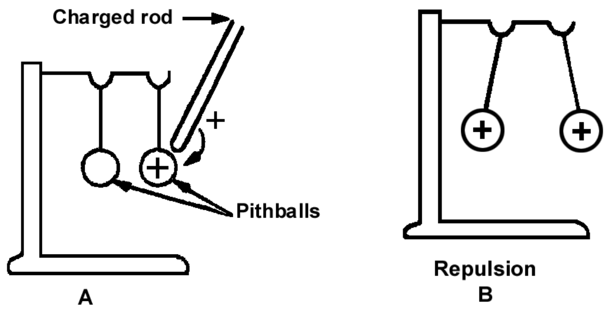


Fig. 1.7. Reaction of like and unlike charges.

Although most objects become charged with static electricity by means of friction, a charged substance can also influence objects near it by contact. This is illustrated in Fig. 1.8. If a positively charged rod touches an uncharged meter bar, it will draw electrons from the uncharged bar to the point of contact. Some electrons will enter the rod, leaving the metal bar with a deficiency of electrons (positively charged) and making the rod less positive than it was or, perhaps, even neutralizing its charge completely.

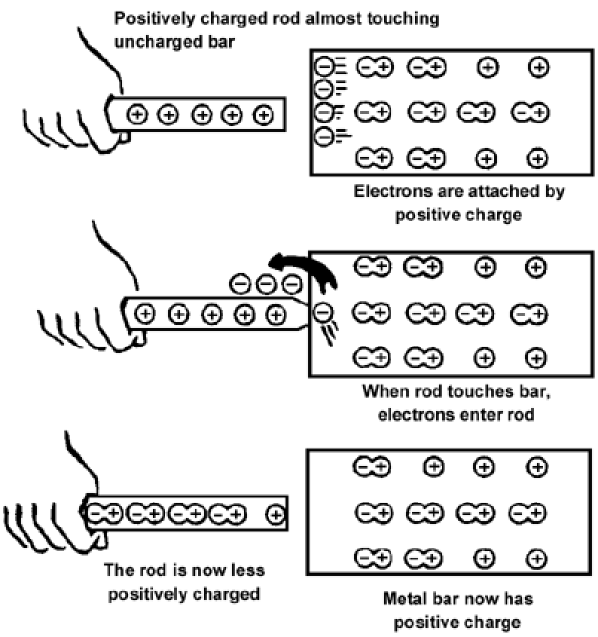


Fig. 1.8. Charging by contact.

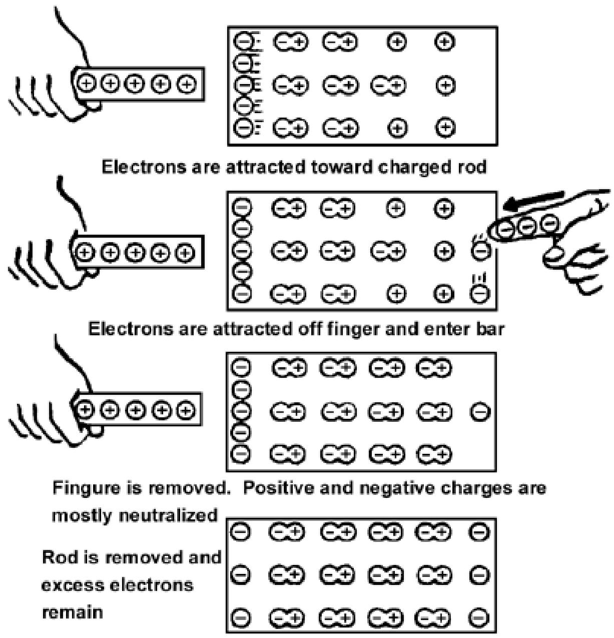


Fig. 1.9. Charging a bar by induction.

A method of charging a metal bar by induction is demonstrated in (Fig. 1.9). A positively charged rod is brought near, but does not touch, an uncharged metal bar. Electrons in the metal bar are attracted to the end of the bar nearest the positively charged rod, leaving a deficiency of electrons at the opposite end of the bar. If this positively charged end is touched by a neutral object, electrons will flow into the metal bar and neutralize the charge. The metal bar is left with an overall excess of electrons.

ELECTROSTATIC FIELD

A field of force exists around a charged body. This field is an electrostatic field (sometimes called a dielectric field) and is represented by lines extending in all direction from the charged body and terminating where there is an equal and opposite charge.

To explain the action of an electrostatic field, lines are used to represent the direction and intensity of the electric field of force. As illustrated in (Fig. 1.10), the intensity of the field is indicated by the number of lines per unit area, and the direction is shown by arrowheads on the lines pointing in the direction in which a small test charge would move or tend to move if acted upon by the field of force.

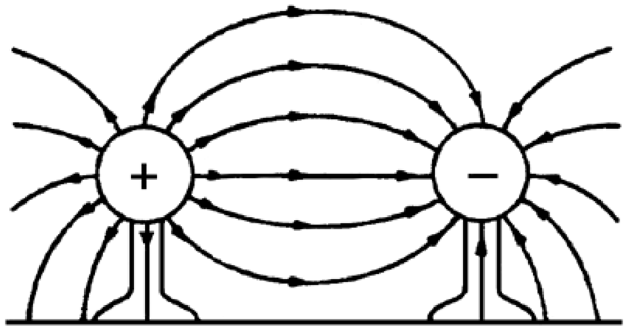


Fig. 1.10. Direction of electric field around positive and negative charges.

Either a positive or negative test charge can be used, but it has been arbitrarily agreed that a small positive charge will always be used in determining the direction of the field. Thus, the direction of the field around a positive charge is always away from the charge, as shown in (Fig.1.10), because a positive test charge would be repelled. On the other hand, the direction of the lines about a negative charge is toward the charge, since a positive test charge is attracted toward it.

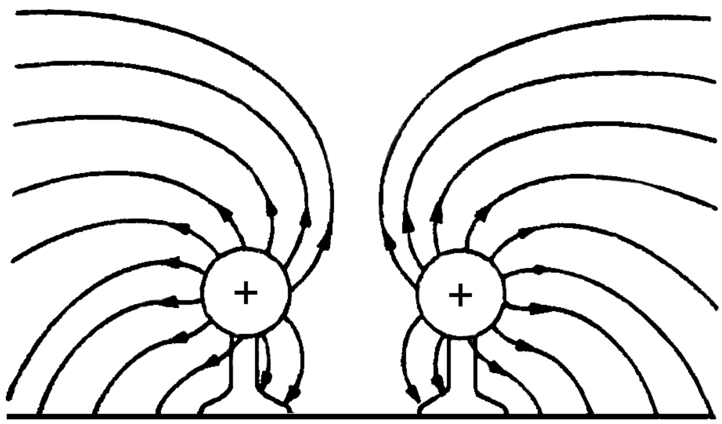


Fig. 1.11. Field around two positively charged bodies.

Fig.1.11 illustrate the field around bodies having like charges. Positive charges are shown, but regardless of the type of charge, the lines of force would repel each other if the charges were alike. The lines terminate on material objects and always extend from a positive charge to a negative charge. These lines are imaginary lines used to show the direction a real force takes.

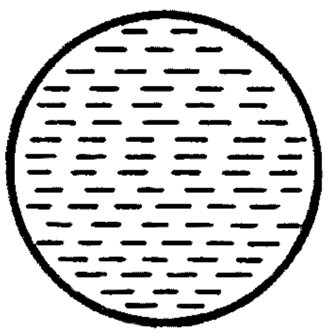


Fig. 1.12. Even distribution of charge on metal disk.

It is important to know how a charge is distributed on an object. (Fig.1.12) shows a small metal disk on which concentrated negative charge has been placed. By using an electrostatic detector, it can be shown that the charge is spread evenly over the entire surface of the disk. Since the metal disk provides uniform resistance everywhere will results in an even distribution over the entire surface.

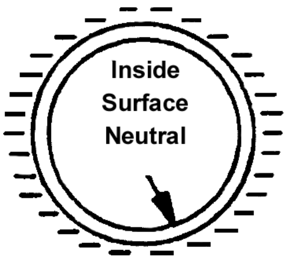


Fig. 1.13. Charge on a hollow sphere.

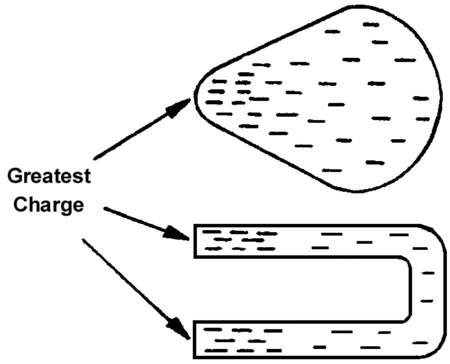


Fig. 1.14. Charge on irregularly shaper objects.

Another example, shown in (Fig.1.13), is the charge on a hollow sphere. Although the sphere is made of conducting material, the charge is evenly distributed over the outside surface. The inner surface is completely neutral. This phenomenon is used to safeguard operating personnel of the large Van de Graff static generators used for atom-smashing. The safest area for the operators is inside the large sphere, where millions of volts are being generated.

The distribution of the charge on an irregularly shaped object differs from that on a regularly shaped object. (Fig.1.14). shows that the charge on such objects is not evenly distributed. The greatest charge is at the points, or areas of sharpest curvature, of the objects.

The effects of static electricity must be considered in the operation and maintenance of aircraft. Static interference in the aircraft communication systems and the static charge created by the aircraft's movement through the air examples of problems created by static electricity. Parts of the aircraft must be "bonded" or joined together to provide a low-resistance (or easy) path for static discharge, and radio parts must be shielded. Static charges must be considered in the refuelling of the aircraft to prevent possible ignitating of the fuel, and provision must be made to ground the aircraft structure, either by static conducting tires or by a grounding wire.

OHM'S LAW

Definitions

In mathematical problems, emf is expressed in volts, and the symbol E is used to indicate the emf until the actual number of volts is determined. R is the symbol for resistance in ohms, and I is the symbol for current, or amperage. The letter I may be said to represent the intensity of current. The letter symbols E, R and I have an exact relationship in electricity given by Ohm's law. This law may be stated as follows : The current in an electric circuit is directly proportional to the emf (voltage) and inversely proportional to the resistance. Ohm's law is further expressed by the statement " 1 volt causes 1 ampere to flow through a resistance of 1 ohm. The equation for Ohm's law is

$$I = \frac{E}{R}$$

which indicates that the current in a given circuit is equal to the voltage divided by the resistance.

An equation is defined as a proposition expressing equality between two values. It may take as many forms as those shown for Ohm's law in (Fig.1.15). The different forms for the Ohm's law equation are derived by either multiplication or division. For example

$$R(I) = R\left(\frac{E}{R}\right)$$

becomes $$RI = \frac{RE}{R}$$

Then $$RI = E \quad \text{or} \quad E = IR$$

In a similar manner, if both sides of the equation E = IR are divided by I, we arrive at the form

$$R = \frac{E}{I}$$

OHM'S LAW	
CURRENT = $\frac{\text{ELECTROMOTIVE FORCE}}{\text{RESISTANCE}}$	
$I = \frac{E}{R}$	AMPERES = $\frac{\text{VOLTS}}{\text{OHMS}}$
RESISTANCE = $\frac{\text{ELECTROMOTIVE FORCE}}{\text{CURRENT}}$	
$R = \frac{E}{I}$	OHMS = $\frac{\text{VOLTS}}{\text{AMPERES}}$
ELECTROMOTIVE FORCE = CURRENT × RESISTANCE	
E = I R	VOLTS = AMPERES × OHMS

Fig. 1.15. Equation for Ohm's law.

Thus we find it simple to determine any one of the three values if the other two are known. Ohm's law may be used to solve any common dc circuit problem because any such circuit, when operating, has voltage, ampere, and resistance. To solve alternating-current (ac) circuit problems, other values must be taken into consideration. These will be discussed in the chapter on alternating current.

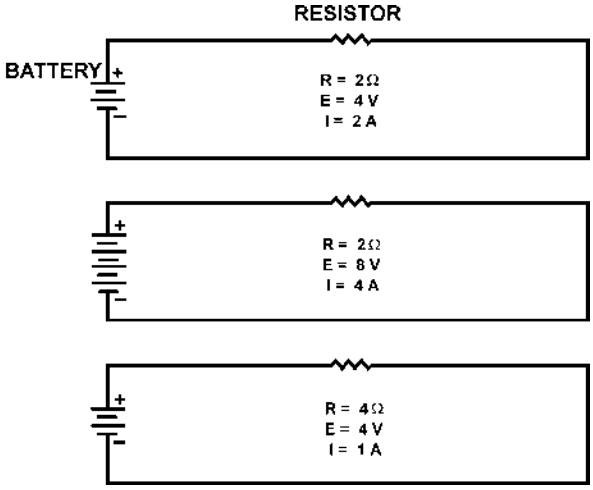


Fig. 1.16. Effects of current and voltage.

From the study of Ohm's law, it has been seen that the current flowing in a circuit is directly proportional to the voltage and inversely proportional to the resistance. If the voltage applied to a given circuit is doubled, the current will double. If the resistance is doubled and the voltage remains the same, the current will be reduced by one-half (see Fig.1.16). The circuit symbol for a battery that is the power source for these circuits and the circuit symbol for a resistor or resistance are indicated in the illustration.

The equation of Ohm's law are easily remembered by using the simple diagram shown in (Fig.1.17). By covering the symbol of the unknown quantity in the diagram with the hand or a piece of paper, the known quantities are found to be in their correct mathematical arrangement. For example, if it is desired to find the total resistance of a circuit in which the voltage is 10 and the amperage is 5, cover the letter R in the diagram. This leaves the letter E over the letter I; then

$$R = \frac{E}{I} = \frac{10}{5} \quad \text{or} \quad R = 2\Omega$$

if it is desired to find the voltage in a circuit when the resistance and the amperage are known, cover the E in the diagram. This leaves I and R adjacent to each other; they are therefore to be multiplied according to the equation E = IR.

One of the simplest description of the Ohm's law relationships is the water analogy. Water pressure and flow, along with the restrictions of a water valve, respond in a manner similar to the relationship of voltage, amperage, and resistance in an electric circuit. As illustrated in (Fig.1.18), an increase in voltage (electrical pressure) creates a proportional increase in current (electrical flow), just an increase in water pressure creates an increase in water flow. (Fig.1.19) shows the relationship between resistance and current. As the resistance of a circuit increases, the current decreases, assuming that the voltage remains constant. Water responds similarly. As the water valve is closed (increasing resistance), the water flow decreases.

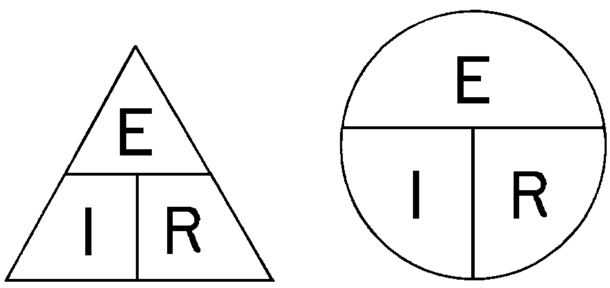


Fig. 1.17. Diagram for Ohm's law.

The water analogy of Ohm's law is simple comparison. Use the analogy to gain a better understanding of the relationship between voltage, amperage, and resistance.

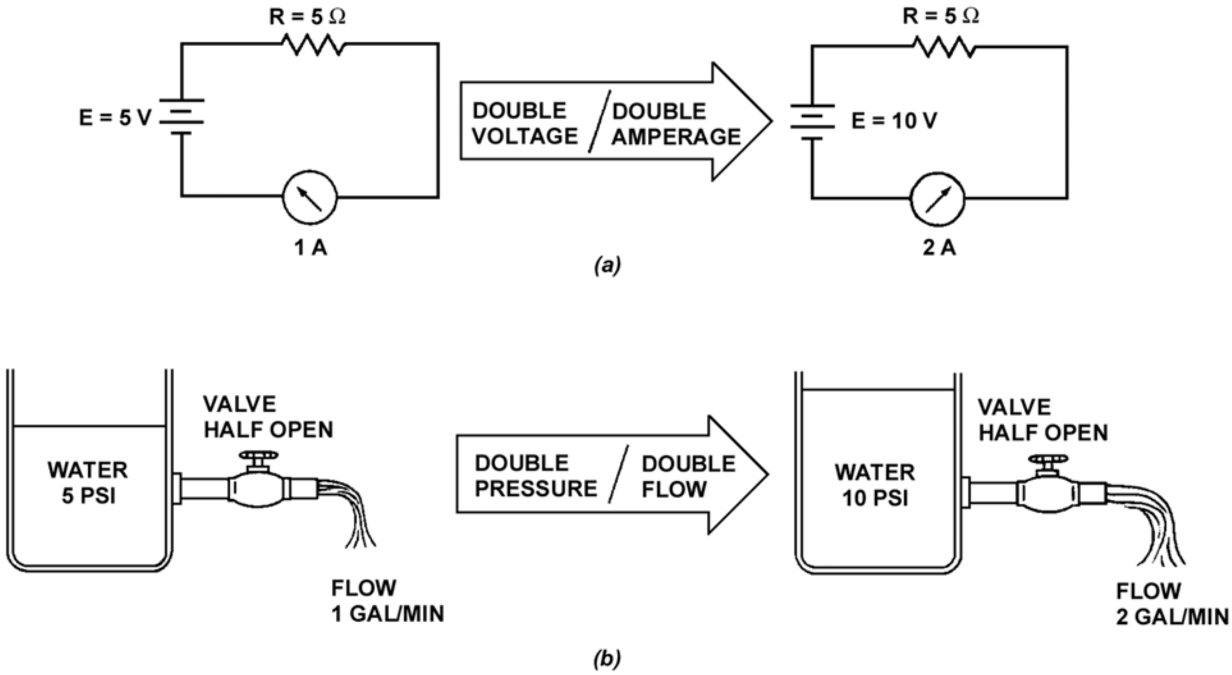


Fig. 1.18. Water analogy of changing voltage.

ELECTRIC POWER AND WORK

Power means the rate of doing work. One horsepower (hp) [746 watt (W)] is required to raise 550 pounds (Ib) [249.5 kilograms (kg)] a distance of 1 ft [30.48 cm] in 1 s. When 1 Ib [0.4536 kg] is moved through a distance of 1 ft, 1 foot-pound (ft.Ib) [13.82 cm.kg] of work has been performed; hence 1 hp is the power required to do 550 ft .Ib [7601 cm.kg] of work per work per second. The unit of power in electricity and in the SI metric system is the watt (W), which is equal to 0.00134 hp. Conversely, 1 hp is equal to 746 W. In electrical terms, 1 watt is the power expended when 1 volt moves 1 coulomb per second through a conductor; that is, 1 volt at 1 ampere produces 1 watt of power. The formula for electric power is

$P = EI$ or Power = voltage × amperage

The power equation can be combined with the Ohm's law equations to allow more flexibility when determining power in a circuit. The following are the three most common varieties of the power equations.

$$P = EI \qquad P = I^2R \qquad P = \frac{E^2}{R}$$

The derivatives of the basic power equations are found as follows :

If $P = EI$ and $E = IR$

then, substituting for E,

$P = (IR)I$ or $P = I^2 R$

Of course, these equations can be arranged to solve for E, I, or R :

$$E^2 = PR \qquad I^2 = \frac{P}{R} \text{ and } R = \frac{P}{I^2}$$

When power is lost in an electric circuit in the form of heat, it is called the I^2R loss because the heat produced is a function of a circuit's current and resistance. The equation $P = I^2 R$ best represents the heat energy loss of any dc circuit, where P equals the lost power, measured in watts.

Power in an electric circuit in the form of heat, it is called the IR loss because the heat produced is a function of a circuit's current and resistance. The equation $P = I^2 R$ best represents the heat energy loss of any dc circuit, where P equals the lost power, measured in watts.

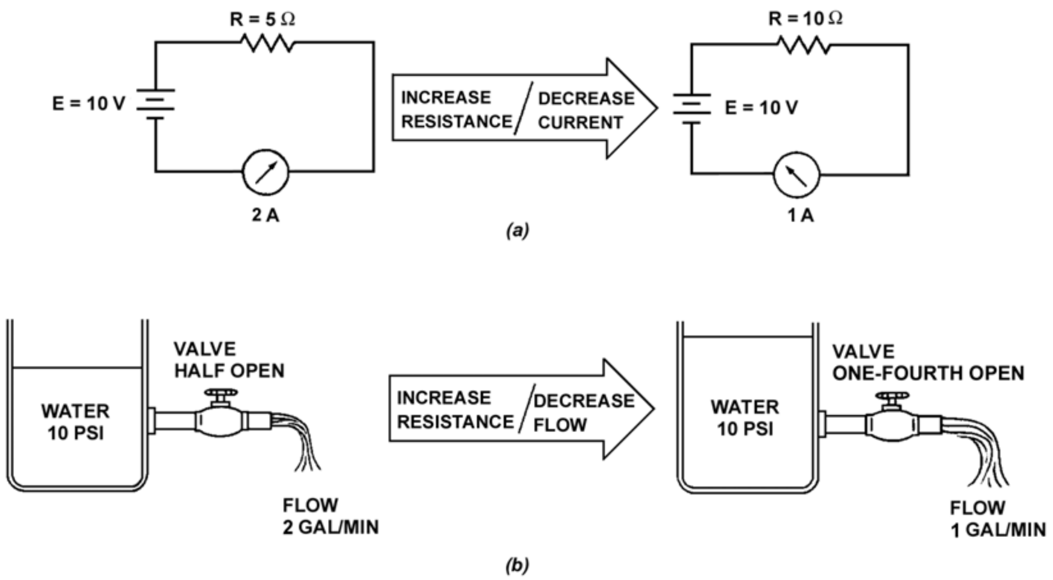


Fig. 1.19. Water analogy of changing resistance.

Power in an electric circuit is always additive. That is, total power equals the sum of the powers consumed by each individual unit. The power consumed by any individual load can be found using the equation

$$P = I^2 R \qquad \text{or} \qquad P = IE$$

While determining power of any portion of a circuit, be sure to apply the I, E or R (current, voltage, or resistance) that applies to the load being calculated.

Since we know the relationship between power and electrical units, it is simple to calculate the approximate amperage to operate a given motor when the efficiency and operating voltage of the motor are known. For example, if it is desired to install a 3-hp [2.238 kilowatt (kW)] motor in a 24-V systems and the efficiency of the motor is 75 percent, we proceed as follows:

$$1 \text{ hp} = 746 \text{ W}$$

$$P = 3 \times 746 = 2238 \text{ W}$$

$$I = \frac{2238}{24} = 93.25 \text{ A}$$

Since the motor is only 75 percent efficient, we must divide 93.25 by 0.75 to find the approximately 124.33 A is required to operate the motor at rated load. Thus, in a motor that is 75 percent efficient, 2984 W of power is required to produce 2238 W (3 hp) of power at the output.

Another unit used in connection with electrical work is the joule (**J**), named for James Prescott Joule (1818-1889), an English physicist. The joule is a unit of work, or energy, and represents the work done by 1 watt in 1 second. This is equal to approximately 0.7376 ft.Ib. To apply this principle, let us assume that we wish to determine how much work in joules is done when a weight of 1 ton is raised 50 ft. First we multiply 2000 by 50 and find that 100,000 ft.Ib of work is done. Then, when we divide 100,000 by 0.7376, we determine that approximately 135,575 J of work, or energy, was used to raise the weight.

It is wise for the technician to understand and have a good concept of the joule because this is the unit designated by the metric system for the measurement of work or energy. Other units convertible to joules are the British thermal unit (Btu), calorie (car), foot-pound, and watthour (Wh). All these units represent a specific amount of work performed.

THE IDEA OF ELECTRIC POTENTIAL

In (Fig.1.20) is shown a simple voltaic cell. It consists of copper plate (known as anode) and a zinc rod (i.e. cathode) immersed in dilute sulphuric acid (H_2SO_4) contained in a suitable vessel. The chemical action taking place within the cell causes the electrons to be removed from Cu plate and to be deposited on the zinc rod at the same time. This transfer of electrons is accomplished through the agency of the diluted H_2SO_4 which is known as the electrolyte. The result in that zinc rod becomes negative due to the deposition of electrons on it and the Cu plate becomes positive due to the removal of electrons from it. The large number of electrons collected on the zinc rod is being attracted by anode but is prevented from returning to it by the force set up by the chemical action within the cell.

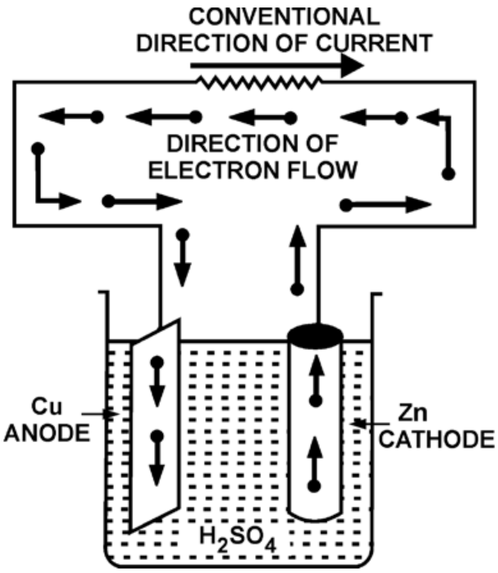


Fig. 1.20.

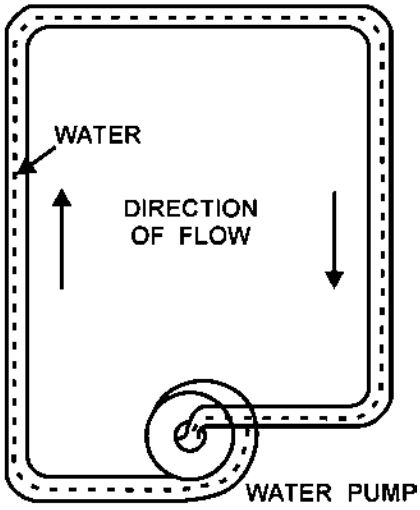


Fig. 1.21.

But is the two electrodes are joined by a wire externally, then electrons rush to the anode thereby equalizing the charges of the two electrodes. However, due to the continuity of chemical action, a continuous difference in the number of electrons on the two electrodes is maintained which keeps up a continuous flow of current through the external circuit. The action of an electric cell is similar to that of a water pump which, while working, maintains a continuous flow of water, i.e. water current through the pipe (Fig. 1.21).

It should be particularly noted that the direction of electronic current is from zinc to copper in the external circuit. However, the direction of conventional current (which is given by the direction of flow of positive charge) is from Cu to zinc. In the present case, there is no flow of positive charge as such from one electrode to another. But we can look upon the arrival of electrons on copper plate (with subsequent decrease in its positive charge) as equivalent to an actual departure of positive charge from it.

When zinc is negatively charged, it is said to be at negative potential with respect to the electrolyte, whereas anode is said to be at positive potential relative to the electrolyte. Between themselves, Cu plate is assumed to be at a higher potential than the zinc rod. The difference in potential is continuously maintained by the chemical action going on in the cell which supplies energy to establish this potential difference.

RESISTANCE

It may be defined as the property of a substance due to which it opposes (or restricts) the flow of electricity (i.e., electrons) through it.

Metals (as a class), acids and salts solutions are good conductors of electricity. Amongst pure metals, silver, copper and aluminium are very good conductors in the given order.*

*** However, for the same resistance per unit length, cross-sectional area of aluminium conductor has to be 1.6 times that of the copper conductor but it weighs only half as much. Hence, it is used where economy of weight is more important than economy of space.**

This, as discussed earlier, is due to the presence of a large number of free or loosely-attached electrons in their atoms. These vagrant electrons assume a directed motion on the application of an electric potential difference. These electrons while flowing pass through the molecules or the atoms of the conductor, collide and other atoms and electrons, thereby producing heat.

Those substances which offer relatively greater difficulty or hindrance to the passage of these electrons are said to be relatively poor conductors of electricity like bakelite, mica, glass, rubber, pv.c. (polyvinyl chloride) and dry wood etc. Amongst good insulators can be included fibrous susbtances such as paper and cotton when dry, mineral oils free acids and water, ceramics like hard porcelain and asbestos and many other plastics besides p.v.c. It is helpful to remember that electric friction is similar to friction in Mechanics.

THE UNIT OF RESISTANCE

The practical unit of resistance is ohm.** A conductor is said to have a resistance of one ohm if it permits one ampere current to flow through it when one volt is impressed across its terminals.

**** After George Simon Ohm (1787-1854), a German mathematician who in about 1827 formulated the law of known after his name as Ohm's Law.**

For insulators whose resistance are very high, a much bigger unit is used i.e. megaohm = 10^6 ohm (the prefix 'mega' or mego meaning a million) or kilohm = 10^3 ohm (kilo means thousand). In the case of very small resistance, smaller units like milli-ohm = 10^{-3} ohm or microhm = 10^{-6} ohm are used. The symbol for ohm is Ω.

TABLE 1.1 MULTIPLES AND SUB-MULTIPLES OF OHM

Prefix	Its meaning	Abbreviation	Equal to
Mega -	One million	MΩ	10^6 Ω
Kilo -	One thousand	kΩ	10^3 Ω
Centi -	One hundredth	----	-------
Milli -	One thousandth	mΩ	10^{-3} Ω
Micro -	One millionth	μΩ	10^{-6} Ω

LAWS OF RESISTANCE

The resistance R offered by a conductor depends on the following factors :

(i) It varies directly as its length ℓ.
(ii) It varies inversely as the cross-section A of the conductor.
(iii) It depends on the nature of the material.
(iv) It also depends on the temperature of the conductor.

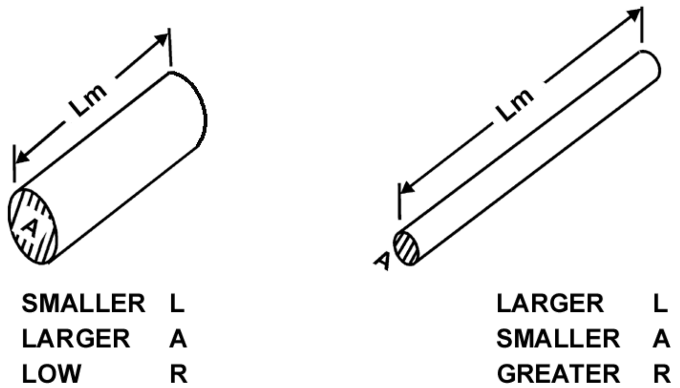


Fig. 1.22.

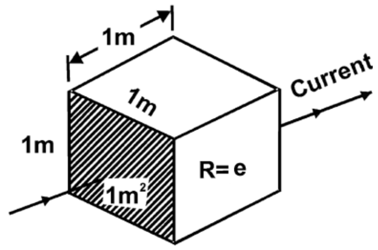


Fig. 1.23.

Neglecting the last factor for the time being, we can say that

$$R \ \alpha \ \frac{1}{A} \qquad \text{or} \qquad R = \rho \frac{\ell}{A} \qquad \text{.........................(1)}$$

where ρ is a constant depending on the nature of the material of the conductor and is known as it is specific resistance or resistivity.

If in Eq. (i), we put

$\ell = 1$ metre and A = 1 metre^2, then R = ρ

Hence, specific resistance of a material may be defined as the resistance between the opposite faces of a metre cube of the material.

UNITS OF RESISTIVITY

From Eq. (1), we have $\rho = \frac{AR}{\ell}$

In the S.I. system of units

$$\rho = \frac{A\ \text{metre}^2 \times R\ \text{ohm}}{\ell\ \text{metre}} = \frac{AR}{\ell}\ \text{ohm - metre}$$

Hence, the unit of resistivity is ohm-metre $(\Omega - m)$.

It may, however, be noted that resistivity is sometimes expressed as so many ohm per m^3. Although, it is incorrect to say so but it means the same thing as ohm-metre.

If ℓ is in centimetres and A in cm^2, then ρ is in ohm-centimetre $(\Omega - m)$.

Values of resistivity and temperature coefficients for various materials are given in table

EFFECT OF TEMPERATURE ON RESISTANCE

The effect of rise in temperature is :

(i) to increase the resistance of pure metals. The increase is large and fairly regular for normal ranges of temperature. The temperature/resistance graph is a straight line (Fig.1.24). As would be presently clarified , metals have a positive temperature co-efficient of resistance.

(ii) to increase the resistance of alloy, though in their case, the increase is relatively small and irregular. for some high-resistance alloys like Eureka (60% Cu and 40% Ni) and manganin, the increase in resistance is (or can be made) negligible over a considerable range of temperature.

(iii) to decrease the resistance of electrolytes, insulators (such as paper, rubber, glass, mica etc.) and partial conductors such as carbon. Hence, insulators are said to possess a negative temperature-coefficient of resistance.

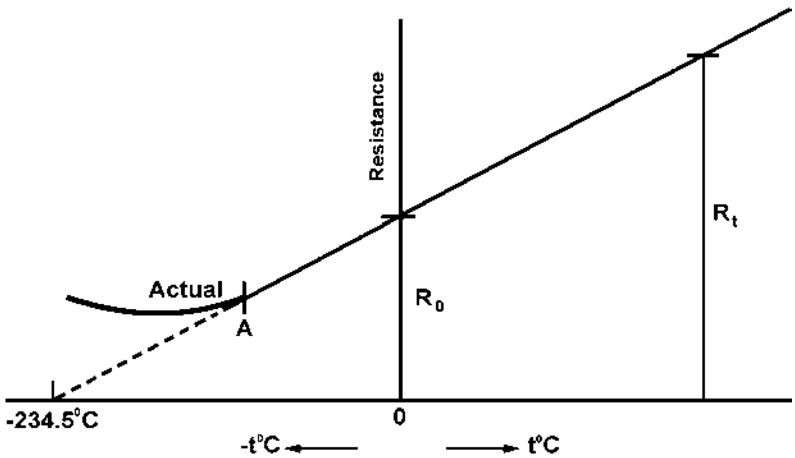


Fig. 1.24.

TEMPERATURE COEFFICIENT OF RESISTANCE

Let a metallic conductor having a resistance of R_0 at 0^0C be heated of t^0C and let its resistance at this temperature be R_t.

Then, considering normal ranges of temperature, it is found that the increase in resistance $\Delta R = R_t - R_0$ depends

(i) directly on its initial resistance

(ii) directly on the rise in temperature

(iii) on the nature of the material of the conductor.

or $\quad R_t - R_0 \propto R \times t \quad$ or $\quad R_t - R_0 = \alpha R_0 t$

where α (alpha) is a constant and is known as the temperature coefficient of resistance of the conductor.

Rearranging Eq. (i), we get $\alpha = \dfrac{R_t - R_0}{R_0 \times t} = \dfrac{\Delta R}{R_0 \times t}$

$$R_0 = 1\Omega,\ t = 1^0C,\ \text{then}\ \alpha = \Delta R = R_t = R_0$$

Hence, the temperature-coefficient of a material may be defined as :

the increase in resistance per ohm original resistance per ^0C rise in temperature.

TABLE 1.2. RESISTIVITIES AND TEMPERATURE COEFFICIENTS

Material	Resistivity in ohm-metre at 20^0C ($\times 10^{-8}$)	Temperature coefficient at 20^0C ($\times 10^{-4}$)
Aluminium, commercial	2.8	40.3
Brass	6 - 8	20
Carbon	3000 - 7000	- 5
Constantan or Eureka	49	+ 0.1 to - 0.4
German (annealed) (84% Cu; 12% Ni; 4% Zn)	1.72	39.3
Gold	2.44	36.5
Iron	9.8	65
Manganin (84% Cu; 12% Mn ; 4% Ni)	44 - 48	0.15
Mercury	95.8	8.9
Nichrome (60% Cu; 25% Fe ; 15% Cr)	108.5	1.5
Nickel	7.8	54
Plantinum	9 - 15.5	36.7
Silver	1.64	38
Tungsten	5.5	47
Amber	5×10^{14}	
Bakelite	10^{10}	
Glass	10^{10} - 10^{12}	
Mica	10^{15}	
Rubber	10^{16}	
Shellac	10^{14}	
Sulphur	10^{15}	

TYPES OF CIRCUIT

To cause a current to flow in a conductor, a difference of potential must be maintained between the ends of the conductor. In an electric circuit this difference of potential is normally produced by a battery or a generator; so it is obvious that both ends of the conductor must be connected to the terminals of the source of emf.

Fig.1.25 shows the components of a simple circuit with a battery as the source of power. One end of the circuit is connected to the positive terminal of the battery and the other to the negative terminal. A switch is incorporated in the circuit to connect the electric power to the load unit, which may be an electric lamp, bell, or relay or any other electric device that could be operated in such a circuit. When the switch in the circuit is closed, current from the battery flows through the switch and load and then back to the battery. Remember that the direction of current flow is from the negative terminal to the positive terminal of the battery. The circuit will operate only when there is a continuous path through which the current may flow from one terminal to the other. When the switch is opened (turned off), the path for the current is broken, and the operation of the circuit ceases.

Since aeroplanes are usually constructed of metal, the airplane structure may be used as an electric conductor. In the circuit in (Fig.1.25) if one terminal of the battery and one terminal of the load are connected to the metal structure of the airplane, the circuit will operate just as well as with two wire conductors. A diagram of such a circuit is shown in (Fig.1.26). When a system of this type is used in an airplane, it is called a **grounded** or **single-wire**. The ground circuit is that part of the complete circuit in which current passes through the airplane structure. Any unit connected electrically to the metal structure of the airplane is said to be grounded. When an airplane employs a single-wire electric system, it is important that all parts of the airplane be well bonded to provide a free and unrestricted flow of current throughout the structure. This is particularly important for aircraft in which sections are joined by adhesive bonding.

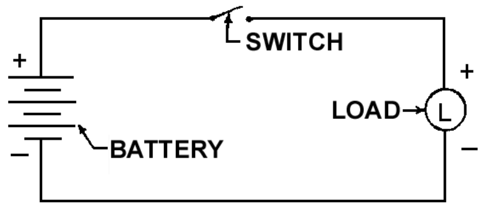


Fig. 1.25. Simple dc circuit.

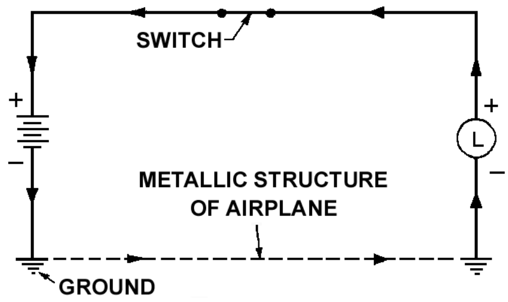
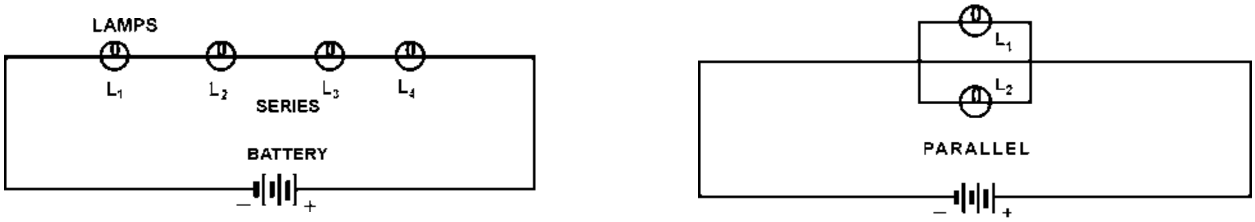


Fig. 1.26. A single-wire electrical system.

There are two general methods for connected units in an electric system. There are illustrated in (Fig.1.27). The first diagram shows four lamps connected in series. A **series circuit** contains only one electron path. In a series through each unit of that circuit. Therefore, if one unit of a series circuit should burn out, or open, the entire circuit will no longer receive current. For example, in Fig.1.27 (a), if lamp 1 should open, the other lamps of that circuit will also stop illuminating.



(a) (b)

Fig. 1.27. Two basic methods of connecting units in an electric circuit :
(a) Series - if one lamp opens, all lamps stop illuminating
(b) Parallel - if one lamp opens, the other is unaffected

In a **parallel circuit** there are two or more paths for the current, and if the path through one of the units is broken, the other units will continue to function. The units of an aircraft electric system are usually connected in parallel; hence the failure of one unit will not impair the operation of the remainder of the units in the system. A simple parallel circuit is illustrated in the diagram of Fig.1.27 (b).

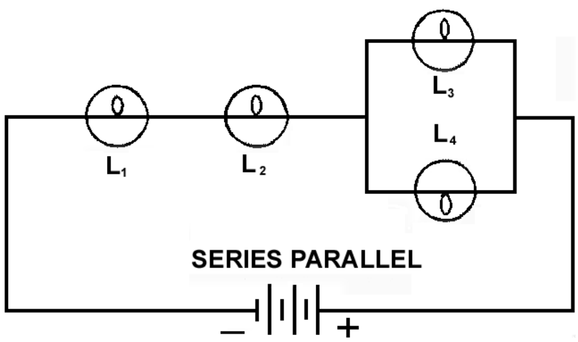


Fig. 1.28. A series-parallel circuit diagram.

A circuit that contains electrical units in both parallel and series is called a **series - parallel circuit** (see Fig.1.28) Most complex electrical systems, such as communication radios, flight computers, and navigational equipment, consist of several series-parallel circuits. Ohm's law can be used to determine the electrical values in any common circuit, even though it may contain a number of different load units. In offer to solve such a circuit, it is necessary to know whether the units are connected in series, in parallel, or in a combination of the two methods. When the type of circuit is determined, the proper formula may be applied.

VOLTAGE DROP

When a current flow through a resistance, a voltage or pressure drop is created. This loss of voltage, known as a **voltage drop** (V_x), is equal to the product of current and resistance. An individual voltage drop is expressed as $V_x = IR$, where V_x is measured in volts. I in amps, and R in ohms, Note: Thee subscript (x) is used here to represent a number that applies to a specific voltage drop, such as voltage drop # 1 (V_1) or voltage drop # 2 (V_2). In a series circuit, the sum of the individual voltage drop is equal to the applied voltage. This may be expressed as

$$E_t = V_1 + V_2 + V_3$$

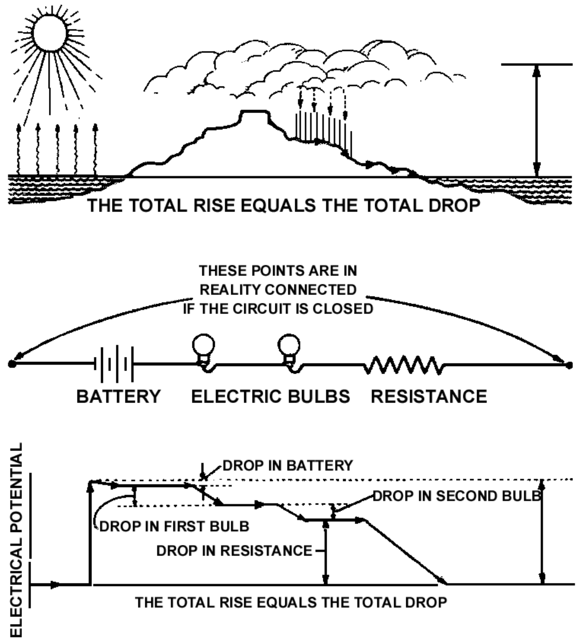


Fig. 1.29. Water analogy of voltage drops.

for a circuit containing three resistors. (Fig.1.29) shows this concept using the water analogy. Notice that with either the water of electrical circuit, the total pressure rise is equal to the total pressure drop; that is, the electrical pressure increase created by the battery is equal to the total pressure drop across both lamps and the resistor. This can be expressed mathematically as

$$E_t = V_{L1} + V_{L2} + V_R$$

SOLVING SERIES CIRCUITS

As explained previously, a series circuit consists of only one current path. When two or more units are connected in series, the entire quantity of moving electrons (current) must pass through each unit to complete the circuit. Therefore, each unit of a series circuit receives the same current flow, even though their individual voltage drops may vary.

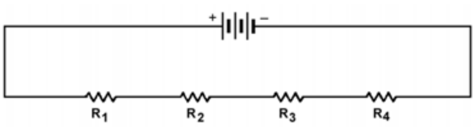


Fig. 1.30. A series circuit with four separate loads.

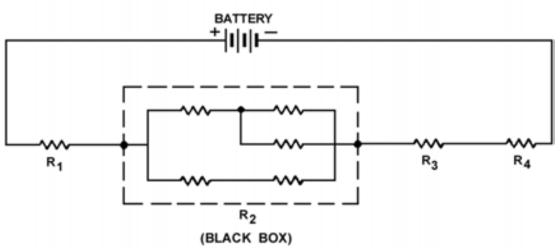


Fig. 1.31. A series circuit containing a series-parallel load.

Two ore more units do not have to be adjacent to each other in a circuit to be in series. In the circuit of (Fig.1.30), it can must be the same, regardless of the direction of current flow. If we replace the load resistor R_2 with an electronic system or device contained in a black box as shown in (Fig.1.31), the current flow in each resistor will still be the same, provided that the total resistance of the black-box as a single unit rather than concern ourselves with the separate components within the black box. Thus we see that there is only one path for current flow in a series circuit; however, an individual load unit may consist of more than one component within itself. Note that the black box in (Fig. 1.31) is shown with several resistance connected in a network within the box. In the series circuit under consideration, we are only concerned with the total resistance of the black-box unit.

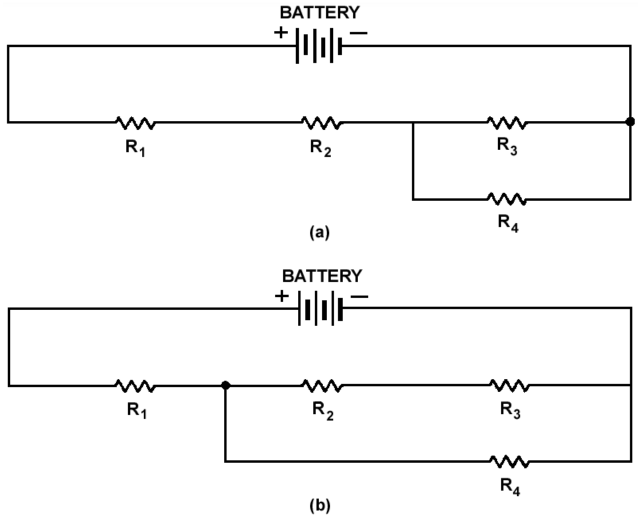


Fig. 1.32. A circuit diagram showing load units connected in both series and parallel.

The load units adjacent to each other in a circuit are connected in series if there are no electrical junctions between the two units. This is illustrated in (Fig.1.32). In circuit a, R_1 and R_2 are connected in series because there is no electrical junction between them to taken a part of the current, and all the current flowing through R_1, must also pass through R_2. In circuit b, R_1 and R_2 are not connected in series because the current that flows through R_1 is divided between R_2 and R_4. Note, however, that R_2 and R_3 are in series because the same current must pass through both of them.

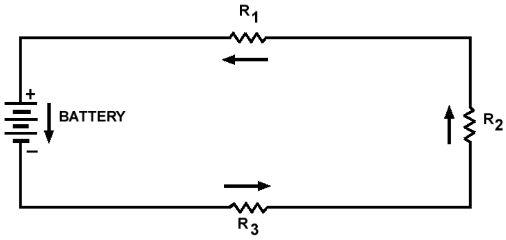


Fig. 1.33. Current flow in a series circuit. Each load receives equal current

Examine the circuit of (Fig.1.33) in which R_1, R_2, and R_3 are connected in series, not only to each other but also to the power source. The electrons flow from negative to positive in the circuit and from positive to negative in the power source. The same flow, however, exists in every part of the circuit, because there is only one path for current flow. since the current is the same in all parts of the circuit,

$$I_t = I_1 = I_2 = I_3$$

That is, the total current is equal to the current through R_1, R_2, or R_3.

RESISTANCE AND VOLTAGE IN A SERIES CIRCUIT

In a series circuit, the total resistance is equal to the sum of all the resistances in the circuit; hence

$$R_t = R_1 + R_2 + R_3 + ...$$

The voltage (potential difference) measured between any two points in a series circuit depends on the resistance between the points and the current flowing in the circuit. (Fig.1.34) shows a circuit with three resistances connected in series. The difference in potential maintained by the battery between the ends of the circuit is 24V.

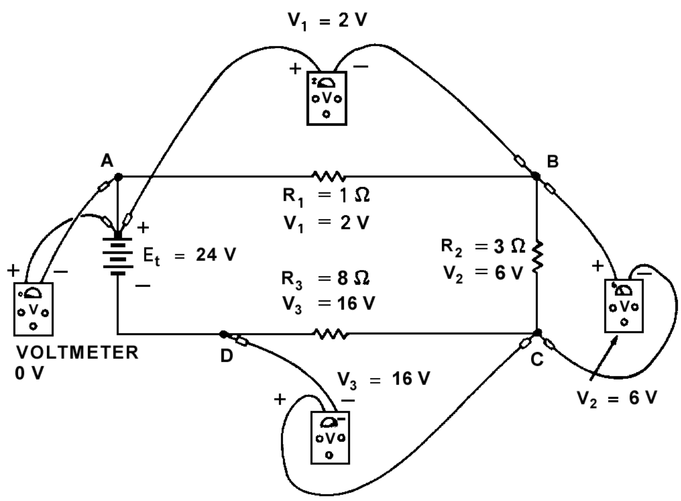


Fig. 1.34. The summation of voltage drops.

As previously explained in the discussion of Ohm's law, the voltage between any two points in a circuit can be determined by the equation.

$$E = IR$$

That is, the voltage is equal to the current multiplied by the resistance. In the circuit of Fig.1.34, we have given a value of 1 Ω to R_1, 3Ω to R_2, and 8Ω to R_3. According to our previous discussion, the total resistance of the circuit is expressed by

$$R_t = R_1 + R_2 + R_3$$

or $$R_t = 1+3+8 = 12\Omega$$

Since the total voltage E_t for the circuit is given as 24, we can determine the current in the circuit by Ohm's law, using the form

$$I = \frac{E}{R}$$

Then $$I_t = \frac{24V}{12\Omega}$$

Since we know that the current in the circuit is 2A, it is easy to determine the voltage across each load resistor. since $R_1 = 1\Omega$, we can substitute this value in Ohm's law to find the voltage difference across R_1.

$$V_1 = I_1R_1$$

$$= 2\times 1 = 2V$$

In like manner, $$V_2 = I_2R_2$$

$$= 2\times 3 = 6V$$

and $$V_3 = I_3R_3$$

$$= 2\times 8 = 16\,V$$

When we add the voltage in the circuit, we find

$$E_t = V_1 + V_2 + V_3$$

$$V_t = 2+6+16 = 24\,V$$

We have determined by Ohm's law that total of the voltages (voltage drops) across units in a series circuit is equal to the voltage applied by the power source, in this case the 24-V battery.

In a practical experiment, we can connect a **voltmeter** (voltage-measuring instrument) from the positive terminal of the battery in a circuit such as that shown in Fig.1.30 to point A, and the reading will be zero. This is because there is not appreciable resistance between these points. When we connect the voltmeter between these points. When we connect the voltmeter between the positive terminal of the battery and point B, the instrument will give a reading of 2V. By similar use of the voltmeter, we measure between points B and C and obtain a reading of 6V, and between points C and D for a reading of 16 V. In a circuit such as that shown, we can assume that the resistance of the wires connecting the resistors is negligible. If the wires were quite long, it would be necessary to consider their resistance in analysing the circuit.

As we have shown, in a series circuit, the voltage drop across each resistor (load unit) is directly proportional to the value of the resistor. Since the current through each unit of the circuit is the same, it is obvious that it will taken a higher electrical pressure (voltage) to push the current through a higher resistance, and it will require a lower pressure to push the same current through a lower resistance.

The voltage across a load resistor is a measure of the work required to move a unit charge (given quantity of electricity) through the resistor. Electric energy is consumed as current flows through a resistor, and the electric energy is converted to heat energy. As long as the power source produces electric energy as rapidly as it is consumed, the voltage across a given resistor will remain constant.

Students who have mastered Ohm's law and the three fundamental formulas for series circuits can apply their knowledge to the solution of any series circuit where sufficient information is given. The following examples are shown to illustrate the techniques for solutions:

Examples A : Fig. 1.35.

$$E_t = 12\,V$$

$$I_1 = 3A$$

$$R_2 = 2\Omega$$

$$R_3 = 1\Omega$$

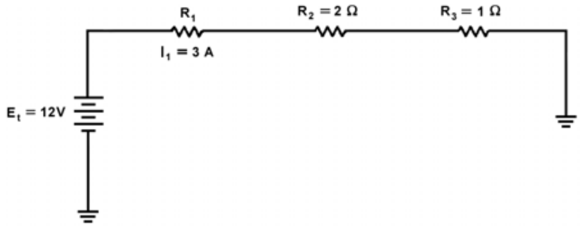


Fig. 1.35. Series circuit for Example A.

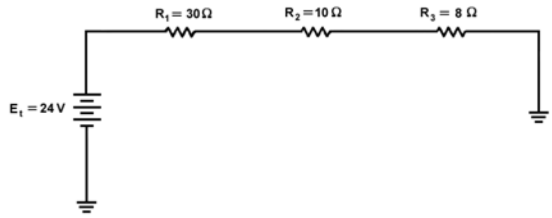


Fig. 1.36. Series circuit for Example B.

Since I_1 is given as 3 A, it follows that I_t, I_2, and I_3 are also equal to 3A, because current is constant in a series circuit. Then

$$R_t = \frac{E_t}{I_t}$$

$$= \frac{12}{3} = 4\Omega$$

$$V_2 = 2 \times 3 = 6V$$

$$V_3 = 1 \times 3 = 3V$$

Since $R_1 + R_2 + R_3 = R_t$, we can easily determine that $R_1 = 1\Omega$. By using the formula E= IR, we find that $V_1 = 3V$.

The solved problem may then be expressed as follows:

$E_t = 12V \quad I_t = 3A \quad R_t = 4\Omega$

$V_1 = 3V \quad I_1 = 3A \quad R_1 = 1\Omega$

$V_2 = 6V \quad I_2 = 3A \quad R_2 = 2\Omega$

$V_3 = 3V \quad I_3 = 3A \quad R_3 = 1\Omega$

Examples B : Fig. 1.36.

$V_t = 24V$

$R_1 = 30\Omega$

$R_2 = 10\Omega$

$R_3 = 8\Omega$

Then $R_t = 30 + 10 + 8 = 48\Omega$

$$I_t = \frac{E_t}{R_t}$$

$$= \frac{24}{48} = 0.5A$$

V_1, V_2, and V_3 are determined by multiplying each resistance value by 0.5 A, the current value of the circuit. The solved circuit is shown in (Fig. 1.37).

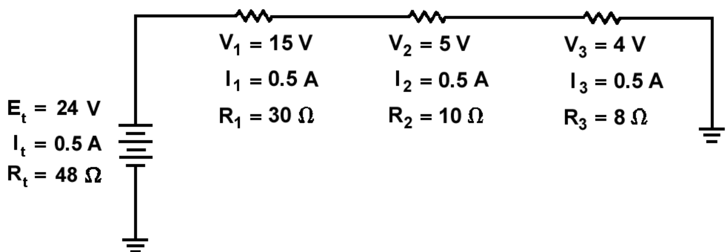


Fig. 1.37. Simplified circuit for Example B.

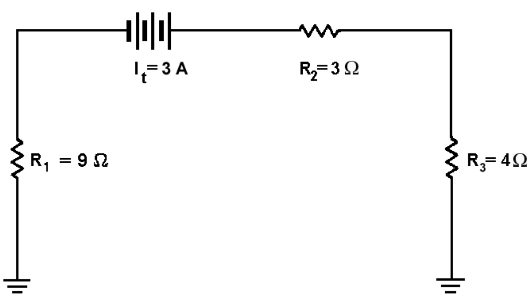


Fig. 1.38. Series circuit for Example C.

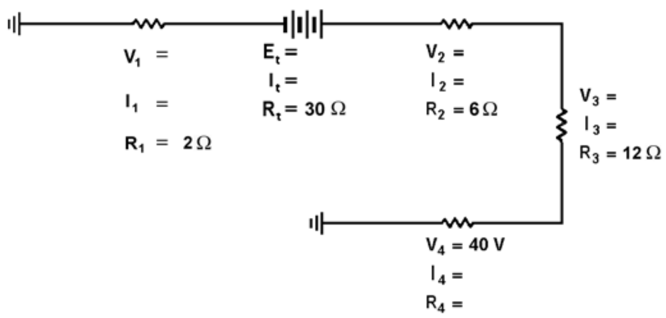


Fig. 1.39. Series circuit for Example D.

Example C : Fig. 1.38.

This circuit presents the case where current and resistance are known, and it is required to find the individual and total voltages. The known circuit values are as follows :

$I_t = 3A$

$R_1 = 9\Omega$

$R_2 = 3\Omega$

$R_3 = 4\Omega$

From the values given, we can easily determine that the total resistance is 16Ω . The voltages can then be determined by Ohm's law :

$E = IR$

$E_t = I_t \times R_t$

$= 3 \times 16 = 48\ V$

The values of the solved circuit are then as shown below :

$E_t = 48V$	$I_t = 3A$	$R_t = 16\Omega$
$V_1 = 27V$	$I_1 = 3A$	$R_1 = 9\Omega$
$V_2 = 9V$	$I_2 = 3A$	$R_2 = 3\Omega$
$V_3 = 12V$	$I_3 = 3A$	$R_3 = 4\Omega$

It will be noted in all the circuits presented thus far that the values are always in accordance with Ohm's law formulas. It is recommended that the students check the problems given to verify the results.

Example D : Fig. 1.39.

The values for the circuit shown are indicated in the illustration. It is left up to the student to work out the solution. Remember that the total resistance for a series circuit is equal to the sum of the individual resistance.

SOLVING PARALLEL CIRCUITS

A parallel circuit always contains two or more electric current paths. When two or more units are connected in parallel, each unit will receive a portion of the circuit's total current flow. That is, the circuit's total current divides at one or more points, and a portion travels through each resistance of the circuit (see Fig.1.40.)

Typically, when we analyse a circuit of this type, we assume that the resistance of a wire is negligible and the power source has no internal resistance. A parallel circuit always contains more than one path for current to flow; therefore, the current can "choose" which load unit to travel through. Current always tries to take the path of least resistance and will drive proportionately through a parallel circuit containing load units of different resistances. In a parallel circuit, each load unit will receive a portion of the total current flow. The unit with the highest resistance will receive the least current flow. The unit with the lowest resistance will receive the highest current flow. Equal resistors receive equal current flows.

Typically, load units of an aircraft are arranged in parallel with respect to the power source and to each other. This is done to allow a different current path through each unit; therefore, the resistance of each unit will determine the current flow through that unit. An example is a flap motor using 30 A, a navigation light using 2A, and the landing light, with the switch turned off, using 0A. This type of current flexibility is a necessity for almost every electrical system.

The resistors (load units) do not need to be arranged as in Fig.1.40 to be connected in parallel. The three circuits of Fig.1.41 shows loads connected in parallel. Circuits a and b are identical to the circuit of Fig.1.35 and circuit c has an additional load unit connected in parallel. A careful examination of the circuits will reveal that the connection are in common for each side of the power source. There is a direct connection (current path) without resistance from any one negative terminal of a load unit to the negative terminal of any other load unit and to the negative terminal of the power source. The same condition is true with respect to all positive terminals.

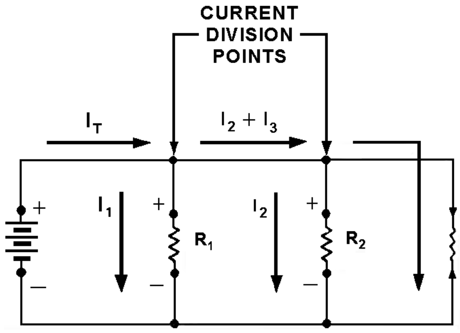


Fig. 1.40. Current flow through a parallel circuit.

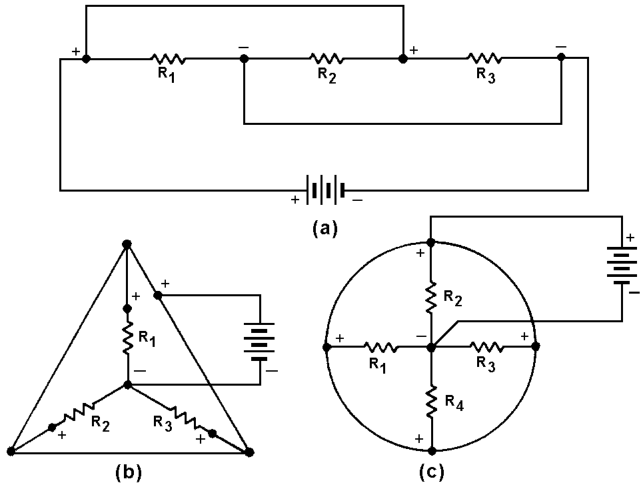


Fig. 1.41. Different arrangements of parallel circuits.

There may be some junctions between two or more resistors connected in parallel, but these junctions do not change the fact that the resistance are still connected in parallel. It will be noted in Fig. 1.42 that three of the resistance, R_1, R_2 and R_3 have common terminals with one another, even though there are other resistance connected between their common terminals and the power source. It will further be noted that R_4 and R_5 are connected in parallel because they have positive terminals connected together and negative terminals connected together. The resistance R_6 is in series, not with any other single resistance, but with the parallel groups.

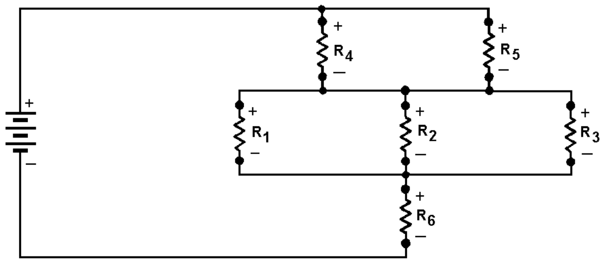


Fig. 1.42. Parallel grouping of resistors.

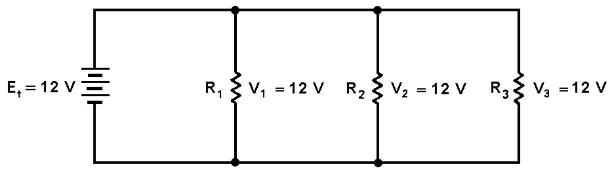


Fig. 1.43. Voltages in a parallel circuit.

The voltage across any resistance, but with the parallel groups is equal to the voltage across any other resistance in the group. Note in Fig. 1.43 that the voltage of the source is 12 V. Since the terminals of the source are connected directly to the each resistance is the same as that of the battery or source. By testing with a voltmeter, it would be found that the potential difference across each resistance in the circuit would be 12 V. There formula for voltage in a parallel circuit is

$$E_t = V_1 = V_2 = V_3 = V_4 ......$$

This formula states that a consistent voltage will be applied to each unit of a parallel circuit. The ability to apply an equal voltage to all power users is another important reason that the entire aircraft electrical system (not necessarily individual electrical components) is wires in parallel. As described earlier, the current in a parallel circuit divides proportionally among each resistance (load unit).

In the circuit of Fig.1.44, the current through R_1 is given as 4A, the current through R_2 is 2A and the current three resistance, the power source must supply 4+2+6, or a total of 12A to the circuit. It must be remembered that the power source does not actually manufacture electrons, but it does not apply the pressure to move them. All the electrons that leave the battery to flow through the circuit must return to the battery. The power source for a circuit can be compared to a pump that moves liquid through a pipe.

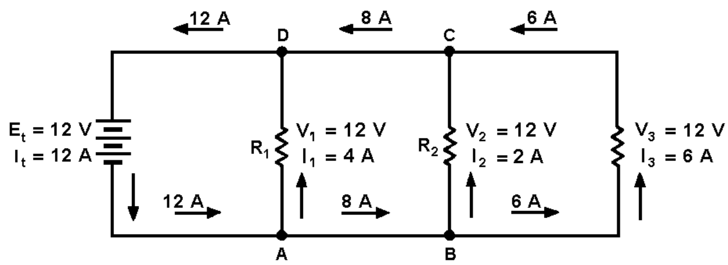


Fig. 1.44. Current flow in a parallel circuit.

An examination of the circuit in Fig. 1.44 reveals that a flow of 12 a comes from the negative terminal of the battery, and at point A the flow divides to supply 4A for R_1 and 8A for the other two resistors. At point B the 8A divides to provide 2A for R_2 and 6A for R_3. On the positive side of the circuit, 6A join 2A at point C, and the resulting 8A joins 4A at point D before returning to the battery. The formula for current in a parallel circuit is then seen to be

$$I_t = I_1 + I_2 + I_3 + ...$$

Since the current flow and voltage are given for each resistor in (Fig.1.44), it is easy to determine the value of each resistance by means of Ohm's law; that is,

$$R = \frac{E}{I}$$

Then $$R_1 = \frac{12}{4} = 3\Omega$$

$$R_2 = \frac{12}{2} = 6\Omega$$

$$R_3 = \frac{12}{6} = 2\Omega$$

$$R_t = \frac{12}{12} = 1\Omega$$

Remember when solving for R_t to be sure to use the voltage drop for resistor 1 and current through resistor 1 (V_1 and I_1). However, E_t can be substituted for V_1 because voltage is constant in a parallel circuit.

The formula for the total resistance in a parallel circuit can be derived by use of Ohm's law and the formulas for total voltage and total current. Since

$$I_t = I_1 + I_2 + I_3$$

and $$I = \frac{E}{R}$$

We can replace all the values in the preceding formula for total current with their equivalent values in terms of voltage and resistance. Thus we are arrive at the equation

$$\frac{E_t}{R_t} = \frac{V_t}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

In a parallel circuit, $E_t = V_1 = V_2 = V_3$. Therefore, we can divide all the terms in the previous equation by E_t and arrive at the formula

$$\frac{1}{R_t} = \frac{1}{R_t} + \frac{1}{R_2} + \frac{1}{R_3}$$

Solving for R_t, the equation becomes

$$R_t = \frac{1}{1/R_1 + 1/R_2 + 1/R_3}$$

This equation can be expressed verbally as follows : The total resistance in a parallel circuit is equal to the reciprocal of the sum of reciprocals of the resistance.

The **reciprocal** of a number is the quantity 1 divided by that number. For example, the reciprocal of 3 is $\frac{1}{3}$. When the reciprocal of a number is multiplied by that number, the product is always 1.

If the formula for total resistance in a parallel circuit is applied to the circuit problem of Fig. 1.39, we find

$$R_t = \frac{1}{1/3 + 1/6 + 1/2}$$

$$= \frac{1}{0.33 + 0.167 + 0.5} = \frac{1}{1} = 1\Omega$$

If some or all the resistances in a parallel circuit are of the same value, the resistance value of one can be divide by the number of equal-value resistances to obtain the total resistance value. For example, if a circuit has four $12 - \Omega$ resistors connected in parallel, the value 12 can be divided by the number 4 to obtain the total resistance value of 3Ω for the four resistances.

When two resistances are connected in parallel, we can use a formula derived from the general formula for R_t to determine the total resistance. The formula is as follows :

$$R = \frac{1}{1/R_1 + 1/R_2}$$

Inverting, $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$

Using a common denominator,

$$\frac{1}{R_t} = \frac{R_2}{R_t \times R_2} + \frac{R_t}{R_1 \times R_2}$$

Combinating, $\frac{1}{R_t} = \frac{R_1 + R_2}{R_1 \times R_2}$

Inverting $R_t = \frac{R_1 \times R_2}{R_1 + R_2}$

From the foregoing formula, we find that when two resistors are connected in parallel, the total resistance is equal to the product of the two resistance values divided by their sum. If a $5 - \Omega$ resistance is connected in parallel with a $6 - \Omega$ resistance, we apply the formula thus :

$$R_t = \frac{5 \times 6}{5 + 6}$$

$$= \frac{30}{11} = 2.73\,\Omega$$

Another fact of parallel resistor groups is that the total resistance of the group is always less than the smallest resistance of that groups. For example, if $R_1 = 3$, $R_2 = 6\Omega$ and $R_3 = 2\Omega$, then R_t will be less than 2Ω. As previously stated,

$$R_t = \frac{1}{1/R_1 + 1/R_2 + 1/R_3}$$

or $R_t = \frac{1}{1/3 + 1/6 + 1/2}$

$$= \frac{1}{0.33 + 0.167 + 0.5} = \frac{1}{1} = 1\Omega$$

The R_t of 1Ω is indeed less than 2Ω, the smallest resistance of the group.

The rules to determine voltage, current, and resistance for parallel circuits have numerous application. For example, a parallel circuit having some resistance values unknown, but at least one current value given with a known resistance value, can be solved through the use of Ohm's law and the formula for total resistance. (Fig.1.45).

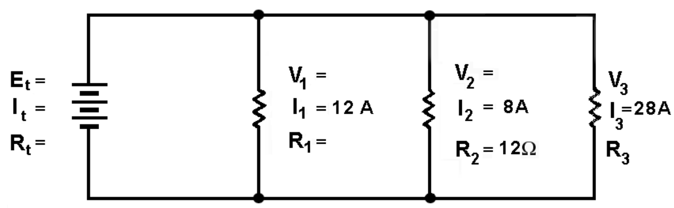


Fig. 1.45. Diagram of a parallel circuit.

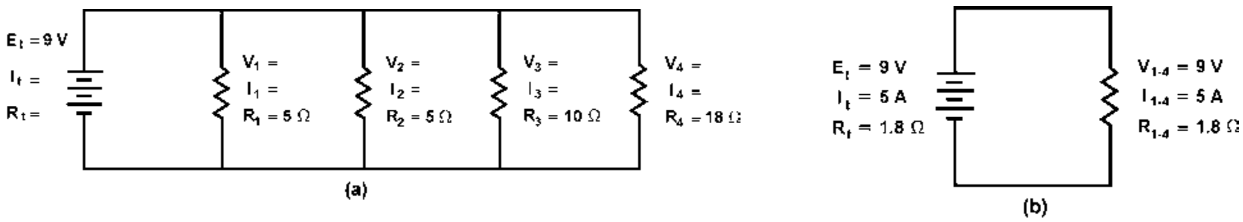


Fig. 1.46. A parallel circuit and its simplified equivalent.

An examination of this circuit reveals that $I_2 = 8\,A$ and $R_2 = 12\Omega$. With these values it is apparent that the voltage across R_2 is equal to 96 V. That is ,

$$V_2 = I_2 \times R_2$$
$$= 8 \times 12 = 96V$$

Since the same voltage exists across all the load resistors in a parallel circuit, we know that E_t, V_1, and V_3 are all equal to 96 V. We can then proceed to find that $R_1 = \frac{96}{12}$ or 8Ω and $R_3 = \frac{96}{28}$ or 3.43Ω. Since total current is equal to the sum of the current values, $I_t = 12 + 8 + 28$ or 48A. The total resistance is then $\frac{96}{48} = 2\Omega$, since $R_t = E_t/I_t$

In any circuit where a number of load units are connected in parallel or in series, it is usually possible to simplify the circuit or in series, it is usually possible to simplify the circuit in step and derive an equivalent circuit. A sample parallel circuit and its simplified equivalent are illustrated in (Fig. 1.46).

The first step used to solve this parallel problem is to combine all individual resistors using the formula

$$R_t = \frac{1}{1/R_1 + 1/R_2 / 1/R_3 + 1/R_4}$$

or $$R_t = \frac{1}{1/3 + 1/5 / 1/10 + 1/18}$$

or $$R_t = 1.8\Omega$$

The second step is to solve for I_t.

$$I_t = \frac{E_t}{R_t}$$

$$= \frac{9V}{1.8\Omega} = 5A$$

The third step is to find the individual current flows through each resistor. Since voltage is constant in a parallel circuit, E_t can be substituted for each individual voltage drop.

$$I_1 = \frac{E_1}{R_1} \qquad I_1 = \frac{9V}{5\Omega} \qquad I_1 = 1.8A$$

$$I_2 = \frac{E_2}{R_2} \qquad I_2 = \frac{9V}{5\Omega} \qquad I_2 = 1.8A$$

$$I_3 = \frac{E_3}{R_3} \qquad I_3 = \frac{9V}{10\Omega} \qquad I_3 = 0.9A$$

$$I_4 = \frac{E_4}{R_4} \qquad I_4 = \frac{9V}{18\Omega} \qquad I_4 = 0.5A$$

The fourth step should be to check the calculations. In a parallel circuit, current is additive to find total current. Therefore, if the sum of the individual current flows equals the total current, the calculations were done correctly. The check would be as follows :

$$I_t = I_1 + I_2 + I_3 + I_4$$
$$= 1.8 + 1.8 + 0.9 + 0.5 = 5.0\,A$$

Since 5A is the calculated total current flow, one can assume that the calculations are correct. Another quick check can be done by comparing the calculated total resistance with the smallest resistance value of the parallel group. As stated earlier, the total resistance of a parallel group must always be less than the lowest-value resistor. If this is not for your calculations, it must be assumed that a mistake was made.

SERIES-PARALLEL CIRCUITS

As the name implies, a series-parallel circuit is one in which some load units are connected in series and some are connected in parallel. Such a circuit is shown in (Fig. 1.47). In this circuit it is quickly apparent that the resistance R_1 and R_2 are connected in series and the resistance R_3 and R_4 are connected in parallel. When the two parallel resistance are combined according to the parallel formula, one resistance, $R_{3,4}$ is found, and this value is in series with R_1 and R_2 as shown in (Fig.1.48). The total resistance R_t is the then equal to the sum of R_1, R_2 and $R_{3,4}$.

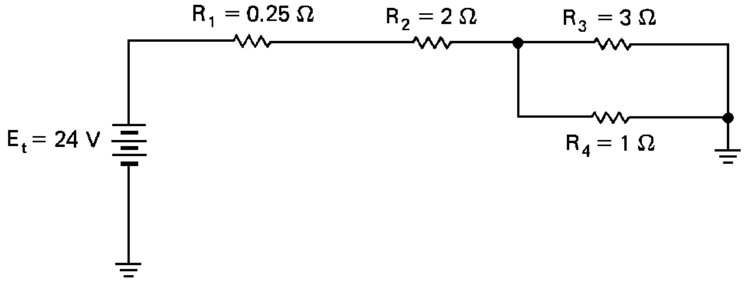


Fig. 1.47. A simple series-parallel circuit.

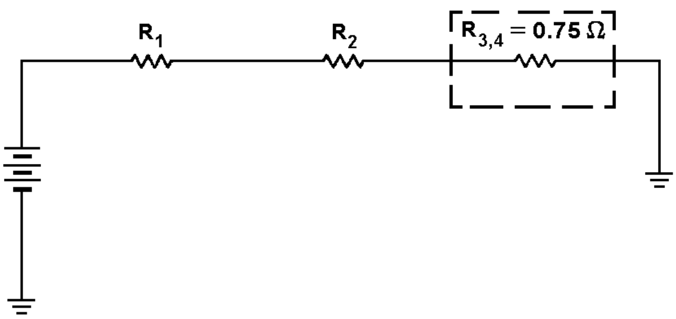


Fig. 1.48. A series equivalent of the series-parallel circuit of Figure 1.47.

If certain values are assigned to some of the load units in the circuit of (Fig. 1.42), we can solve for the unknown values and arrive at a complete solutions for the circuit. For the purposes of this problem, the following are known :

$E_t = 24V$

$R_1 = 0.25\Omega$

$R_2 = 2\Omega$

$R_3 = 3\Omega$

$R_4 = 1\Omega$

To solve for the unknown values, the following steps must be taken

The first step is to combine the parallel resistors R_3 and R_4, use the formula

$$R_{3,4} = \frac{1}{1/R_3 + 1/R_4}$$

$$= \frac{1}{I/3 + I/1} = 0.75\Omega$$

Second, combine all series resistors using the formula

$$R_t = R_1 + R_2 + R_{3,4}$$

$$= 0.25 + 2 + 0.75 = 3\Omega$$

In this case, the resistance total was found by using only two steps be performed in opposite order and /or several times to determine the value of R_t.

Third, compute total current using the formula

$$I_t = \frac{E_t}{R_t}$$

$$= \frac{24}{3} = 8A$$

Fourth, compute the voltage drop across the series resistors. the formula V_x = IR will be used twice in this case, one for R_1 and once for R_2. Note: Because I_1 and I_2 have not yet been calculated, I_t must be substituted for their values. This is possible because both R_1 and R_2 are in series.

$$V_1 = I_1R_1$$

$$= 8 \times 0.25 = 2V$$

$$V_2 = I_2R_2$$

$$= 8 \times 2 = 16V$$

Fifth, calculate the voltage drop across the parallel resistors using the formula V_x= IR. This can only be done for the entire group of parallel resistors ($R_{3,4}$) because the current flow through the individual resistors is yet unknown. since voltage is constant in parallel, the voltage drop across $R_{3,4}$ is equal to the voltage drop across R_3 and R_4 individually.

$$V_{3,4} = I_{3,4}R_{3,4}$$

$$= 8 \times 0.75 = 6V$$

Therefore,

$$V_3 = 6V \text{ and } V_4 = 6V$$

Note: I_t was substituted for the unknown value $I_{3,4}$ because the effective resistor $R_{3,4}$ is in series (see Fig. 1.43).

Sixth calculate current flow through the parallel resistors using I = V/R.

$$I_3 = \frac{V_3}{R_3}$$

$$= \frac{6}{3} = 2A$$

$$I_4 = \frac{V_4}{R_4}$$

$$= \frac{6}{1} = 6A$$

The entire circuit has now been analyzed using the basic elements of Ohm's law. The completed solution is listed below.

$E_t = 24V$	$I_t = 8A$	$R_t = 3\Omega$
$V_1 = 2V$	$I_1 = 8A$	$R_1 = 0.25\Omega$
$V_2 = 16V$	$I_2 = 8A$	$R_2 = 2\Omega$
$V_3 = 6V$	$I_3 = 2A$	$R_3 = 3\Omega$
$V_4 = 6V$	$I_4 = 6A$	$R_4 = 1\Omega$

It should be considered that the previous series - parallel circuit was relatively simple and the therefore easy to solve. In many cases where several groups of series and parallel resistance are combined, the calculations above must be repeated and / or performed in different order.

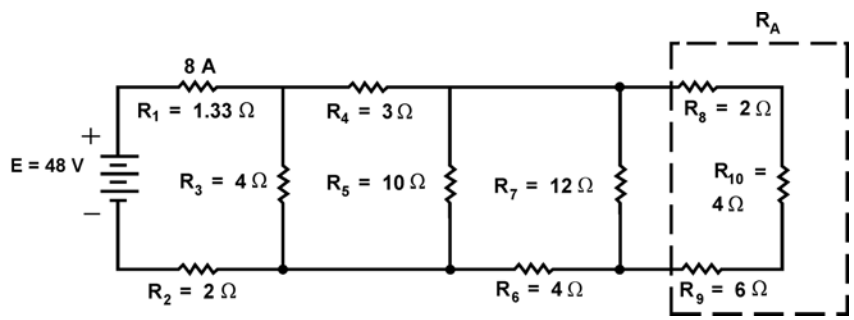


Fig. 1.49. Series-parallel circuit.

The solution of a series-parallel circuit such as that shown in (Fig. 1.49) is not difficult provided that the load-unit (resistance) values are kept in their correct relationships. To determine all the values for the circuit shown, we must start with R_8, R_9, and R_{10}. Since these resistance are connected in series with each other, their total value is $2+4+6=12\Omega$. We shall call this total R_A: that is, $R_A=12\Omega$. The circuit can then be drawn as in (Fig. 1.50) it can be seen that R_2 and R_A are connected in parallel. The formula for two parallel resistances can be used to determine the resistance of the combination. We shall call this combination R_B. Then

$$R_B=\frac{R_7\times R_A}{R_7+R_A}$$

$$=\frac{12\times 12}{12+12}=\frac{144}{24}=6\Omega$$

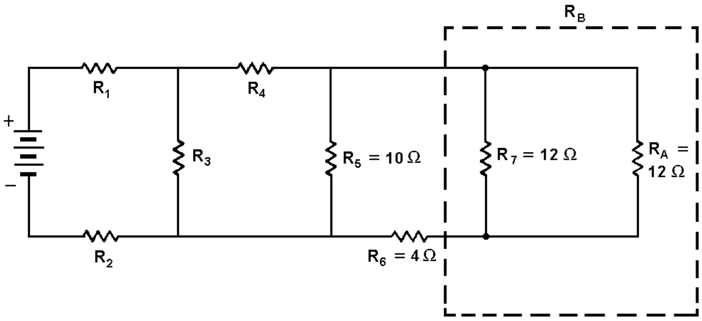


Fig. 1.50. First simplification step.

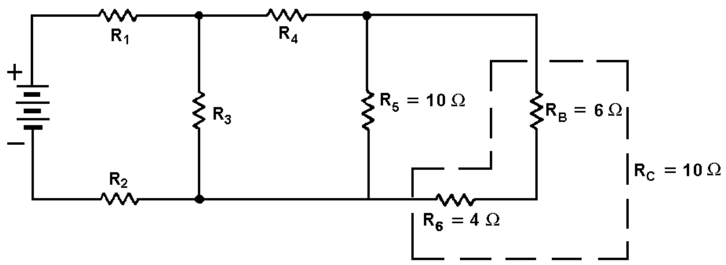


Fig. 1.51. Second simplification step.

Now an equivalent circuit can be shown in (Fig. 1.51) to further simplify the solution. in this circuit we combine the two series resistance, R_B and R_6, to obtain a value of 10Ω, for R_C. The equivalent circuit is then drawn as in (Fig. 1.52).

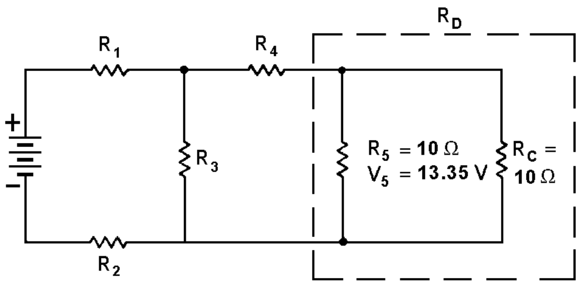


Fig. 1.52. Third simplification step.

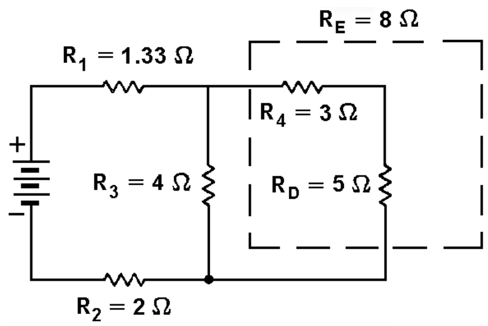


Fig. 1.53. Fourth simplification step.

Since the new equivalent circuit shown that R_5 and R_C are connected in parallel and that each has a value of $10\,\Omega$, we know all that the combined value is 5Ω. We designate this new value as R_D and draw the circuit as in (Fig. 1.53). R_D is connected in series with R_4; hence the total of the two resistances is 8Ω. This is designated as R_E for the equivalent circuit of (Fig. 1.54). In this circuit we solve the parallel combination of R_3 and R_E to obtain the value of 2.67Ω for R_F. The final equivalent circuit is shown in (Fig. 1.55) with R_1, R_F, and R_2 connected in series. These resistance values are added to find the total resistance for the circuit.

$$R_t=1.33+2.67+2=6\Omega\ 3$$

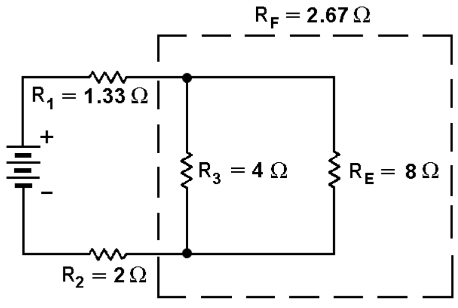


Fig. 1.54. Fifth simplification step.

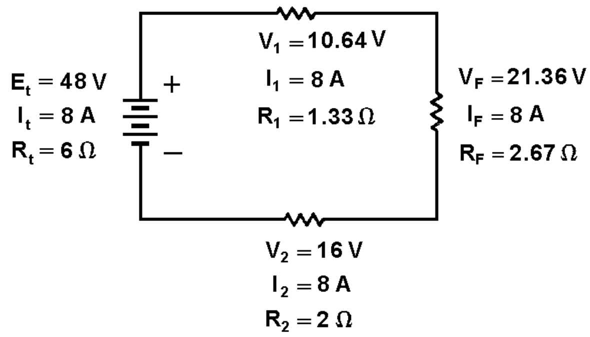


Fig. 1.55. Final simplified version of Figure 1.49.

With the total resistance known and E_t given as 48V, it is apparent that I_t=8A (I_t=E_t/R_t). The values for the entire circuit can be computed using Ohm's law and proceeding in a reverse sequence from that used in determining total resistance. First, since I_t=8A, I_1, I_F, and I_2 must each be 8A because the resistance are shown to be connected in series in (Fig.1.55). By Ohm's law (E=IR_ we find that V_t = 10.64 V, V_F=21.36 V, and V_2=16V. Referring to (Fig. 1.54.), it can be seen that 21.36 V exists across R_3 and R_E. This makes it possible to determine that I_3=5.33 A and I_E=2.67A. In (Fig. 1.53) we note that I_4 and I_D must both be 2.67 A because the two resistances are connected in series. Then V_4=8V and V_D=13.35V. Since V_D is the voltage across R_5 and R_C in the circuit of (Fig.1.52) it is easily found that I_5 = 1.33A and I_C = 1.33 A. In the circuit of (Fig. 1.51) it is apparent that 1.33 A must flow through both R_B and R_6 because they are connected in series and we have already noted that I_C= 1.33A. Then V_B = 8V and V_5=13.35V.

Since V_B = 8V, we can apply this voltage to the circuits as shown in (Fig. 1.49) and (Fig.1.50) and note that both V_7 and V_A are 8V. Then I_7 = 0.67 A and I_A = 0.67AA. Since R_8, R_9, and R_{10} are connected in series and the same current, 0.67 a, flows through each, V_8=1.33 V, V_9=4 V, and V_{10} = 2.67V.

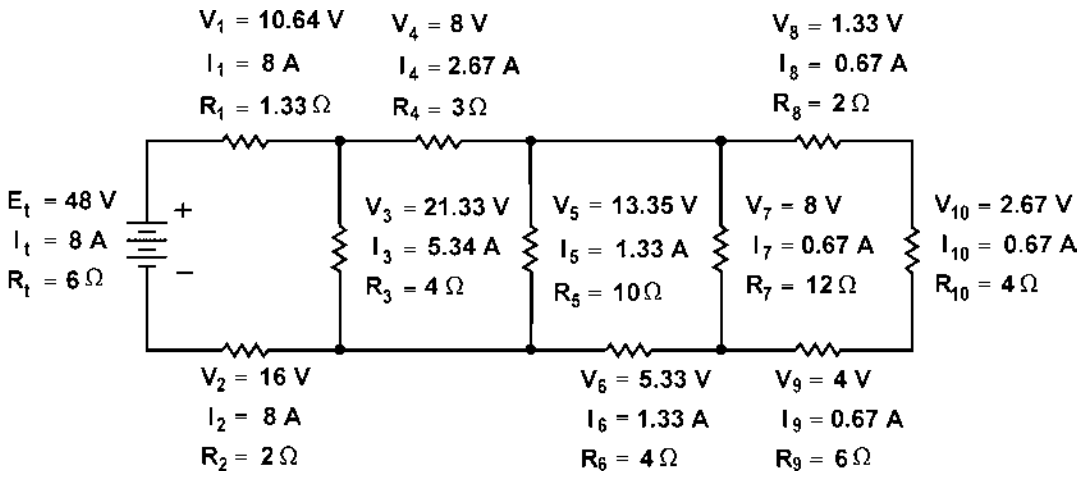


Fig. 1.56. The completely solved version of Figure 1.49.

The completely solved circuit is shown in (Fig.1.56). A check of all the values given will reveal that they comply with the requirement of Ohm's law. Note: some minor error may exist due to rounding of the numbers during calculation.

SHORT AND OPEN CIRCUITS

When two points of circuit are connected together by a thick metallic wire (Fig.1.57), they are said to be short-circuited. Since 'short' has practically zero resistance, it gives rise to two important facts :

(i) no voltage can exist across it because $V = IR = I \times 0 = 0$

(ii) current through it (called short-circuit current) is very large (theoretically, infinity)

Two points are said to be open-circuited when there is no direct connection between them (Fig.1.58). Obviously, an 'open' represents a break in the continuity of the circuit. Due to his break

(i) resistance between the two points is infinite.

(ii) there is no flow of current between the two points.

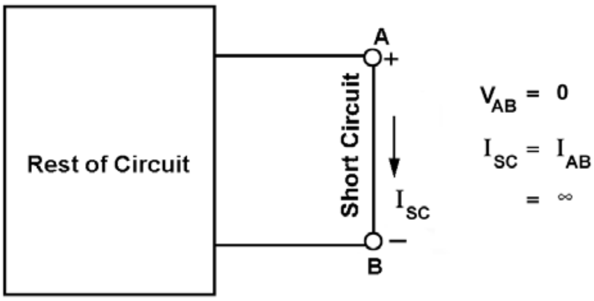


Fig. 1.57.

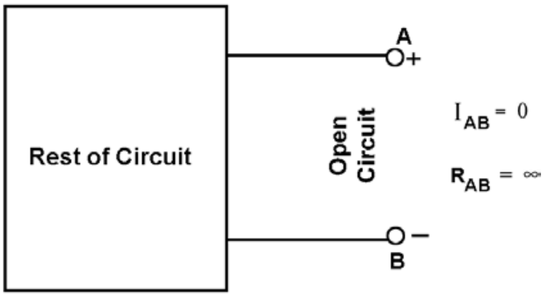


Fig. 1.58.

SHORT IN A SERIES CIRCUIT

Since a dead (or solid) short has almost zero resistance, it causes the problem of excessive current which, in turn, causes power dissipation to increase many times and circuit components to burn out.

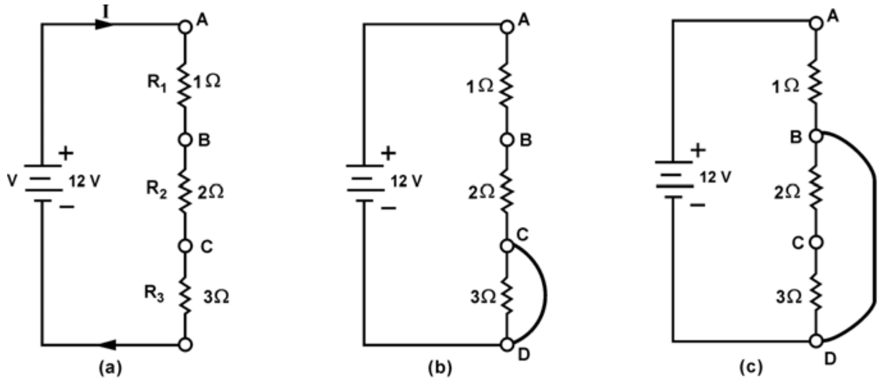


Fig. 1.59.

In Fig.1.59 (a) is shown a normal series circuit where

$$V = 12V, R = R_1 + R_2 + R_3 = 6\Omega$$

$$I = V/R = 12/6 = 2A,\ \ P = I^2R = 2^2 \times 6 = 24W$$

In Fig.1.53 (b), 3Ω resistor has been shorted out by a resistance copper wire so that R_{CD}=0. Now, total circuit resistance $R = 1 + 2 + 0 = 3\Omega.$ Hence, I = 12/3 = 4 A and P = $4^2 \times 3$ =48 W.

Fig.1.53 (c) shows the situation where both 2Ω and 3Ω resistors have been shorted out of the circuit. In this case,

$$R = 1\Omega, I = 12/1 = 12A \text{ and } P = 12^2 \times 1 = 144W$$

Because of this excessive current (6 times the normal value), connected wires and other components can become hot enough to ignite and burn out.

OPEN IN A SERIES CIRCUIT

In a normal series circuit like the one shown in Fig.1.60 (a), there exists a current flow and voltage drops across different resistors are proportional to their resistances. If the circuit become 'open ' anywhere, following two effects are produced:

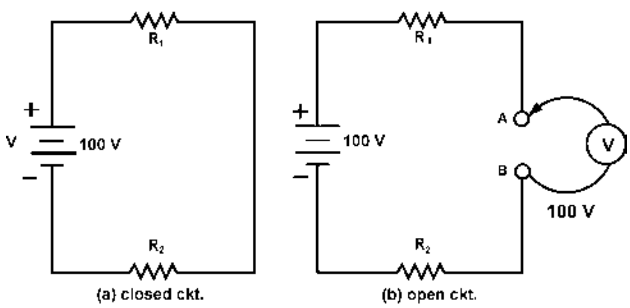


Fig. 1.60.

(i) since 'open' offers infinite resistance, circuit current becomes zero. Consequently, there is no voltage drop across R_1 and R_2.

(ii) whole of the applied voltage (i.e. 100 V in this case) is felt across the 'open' i.e. across terminals A and B Fig.1.60 (b).

The reason for this is that R_1 and R_2 become negligible as compared to the infinite resistance of the 'open' which has practically whole of the applied voltage Divide rule of art. 1.15. Hence, voltmeter in Fig.1.60 (b) will read nearly 100 V i.e. the supply voltage.

OPEN IN A PARALLEL CIRCUIT

Since an 'open' offers infinite resistance, there would be no current in that part of the circuit where it occurs. In a parallel circuit, an 'open' can occur either in the main line of in any parallel branch.

As shown in Fig. 1.61 (a), an open in the main line prevents flow of current to all branches. Hence, neither of the two bulbs glows. However, full applied voltage (i.e. 220 V in this case) is available across the open.

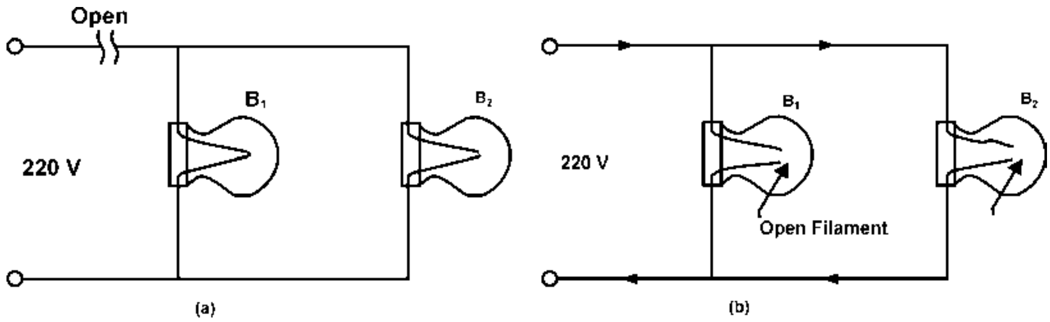


Fig. 1.61.

In this Fig.1.61 (b), 'open' has occurred in branch circuits of B_1. Since there is no current in this branch, B_1 will not glow. However, as the other bulb remains connected across the voltage supply, it would keep operating normality.

It may be noted that if a voltmeter is connected across the open bulb, it will read full supply voltage of 220 V.

SHORTS IN PARALLEL CIRCUITS

Suppose a 'short' is placed across R_3 (Fig.1.62). It becomes directly connected across the battery and draws almost infinite current because not only its own resistance but that of the connecting wires AC and BD is negligible. Due to this excessive current, the wires may get hot enough to burn out unless the circuit is protected by a fuse.

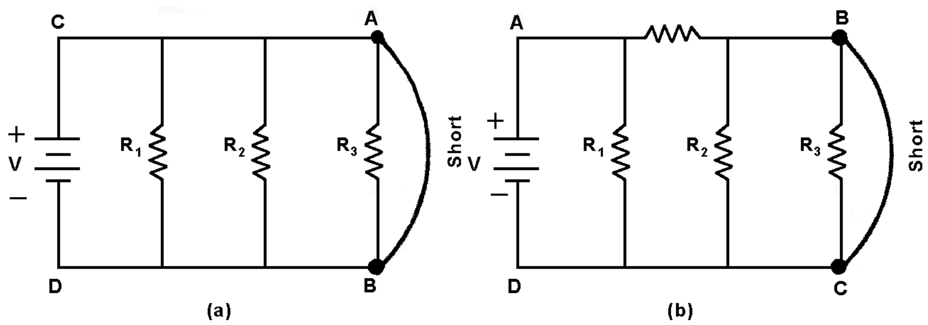


Fig. 1.62.

Following points about the circuit of Fig. 1.62 (a) are worth noting.

1. not only is R_3 short-circuited but both R_1 and R_2 are also shorted out i.e. short across one branch means short across all branches.
2. there is no current is shorted resistors. If these were three bulbs, they will not glow.
3. the shorted components are not damaged. for example, if we had three bulbs, they would glow again when circuit is restored to normal conditions by removing the short-circuited.

It may, however be noted from Fig.1.62 (b) that a short-circuit across R_3 may short out R_2 but not R_1 since it is protected by R_4.

PRACTICAL APPLICATIONS OF OHM'S LAW

For an aircraft technician, there are countless uses for the material contained in this chapter. Ohm's law can be used during the installation, repair, and inspection of various electrical units; in the acquisition of electrical components; in determining wire sizes for a given application; and in basic electric circuit design. Some examples of these applications are stated in the following problems. It should be noted that owing to the brevity of these examples, they may not fully illustrate the complexity of a given solution that might be encountered during actual aircraft maintenance.

Problem No. 1. During an annual inspection it was noticed that the bus bar (the main electrical distribution connection) had been replaced by the previous aircraft owner. One way for the technician to verify the airworthiness of this bus bar is to determine its actual load-carrying capability and compare it with the aircraft's actual total load. It was determined from the part number of the bus bar that the maximum amperage allowable to enter this part was 60 amps. Is the bus bar within its amperage limit ?

Sol:- By applying Kirchhoff's law for parallel circuits, it was determined that the current flowing from the bus bar was also the current flowing through the bus bar. The maximum allowable current through the bus is 60 amps; therefore, the total aircraft load could not exceed this value. Since all aircraft circuits are connected in parallel to the bus, the total current was determined using

$$I_t = I_1 + I_2 + I_3 + I_4 + I_5 + I_6 + I_7$$

If the loads on the aircraft are as follows, it is a simple process to determine if the bus bar is electrically overloaded.

Navigation	10 A
Navigation ratio	4 A
Communication ratio	3 A
Pitot heat	12 A
Flap Motor	8 A
Hydraulic pump motor	16 A
Fuel pump motor	6 A

Simply sum the individual current flows to find the total current flow.

$$I_t = 10A + 4A + 3A + 12A + 8A + 16A + 6A = 59A$$

Since the aircraft's total load is only 59 amps and the bus bar can handle 60 amps the bus illustration can be considered within its current limit.

Problem No. 2. What size generator must be placed on the aircraft used in Problem 1 ? The approved generators for that particular airplane are rated at 30, 60 and 90 A.

Sol:- Once again, since we know that the current to a point is equal to the current from that point, we can determine that the 59 A "pulled" from the aircraft's bus bar must be "pushed" into the bus by the generator. Therefore, the 60-A generator would be required as a minimum. However, the 59A calculated earlier does not include the current needed to charge the battery after starting the aircraft engine. (Note: On this aircraft, the battery current does not feed through the bus; it is received directly from the generator). Since battery charging current can often exceed 20 A for short periods, the 90-A generator should be installed.

Problem No. 3. While a new electric fuel pump is installed on an aircraft, the fuel flow adjustment must be made by changing the voltage to the pump motor, hence changing the fuel flow through the pump. To accomplish this voltage change, the aircraft system contains an adjustable resistor in series with the fuel pump motor. If the aircraft manual calls for 8 V to be applied to the pump motor and the aircraft system voltage is 14 V, at what resistance must be variable resistor be set ?

Sol:- Since voltage drops are additive in a series circuit, the voltage drop of the resistor plus the voltage drop of the fuel pump must equal 14V (system voltage); or, 14 V- 8V = resistor voltage drop. The voltage drop of the resistor is therefore 6V. The equation R = E/I can be used to determine the resistor's value. According to the data plate of the fuel pump, the motor draws 2 A at 8V. Since the motor and resistor are in series, 2 A must also flow through the variable resistor. Using

$$R_r = \frac{V_r}{I_r}$$

Where R_r = resistance of the resistor in ohms
V_r = the voltage drop over the resistor (6V)
I_r = the current flow through the resistor (2A)

$$R_r = \frac{6V}{2A} = 3\Omega$$

The variable resistor should be set for 3Ω in order to produce the correct fuel flow.

KIRCHHOFF'S LAWS *

These laws are more comprehensive than Ohm's law and are used for solving electrical networks which may not be readily solved by the latter. Kirchhoff's laws, two in number, are particularly useful (a) in determining the equivalent resistance of a complicated network of conductors and (b) for calculating the currents flowing in the various conductors. The two-laws are :

1. Kirchhoff's Point Law or Current Law (KCL)

It states as follows :

In any closed electrical network, the algebraic sum of the current meeting at a point (or junction) is zero.

Put in another way, it simply means that the total current leaving a junction is equal to the total currents entering that junction. It is obviously true because there is no accumulation of charge at the junction of the network.

consider the case of few conductors meeting at a point A as in Fig.1.63 (a). Some conductors have currents leading to point A, whereas some have currents leading away from point A. Assuming the incoming currents to be positive and the outgoing currents to be positive and the outgoing currents negative, we have

$$I_1 + (-I_2) + (-I_3) + (+I_4) + (-I_5) = 0$$

or $I_1 + I_4 - I_2 - I_3 - I_5 = 0$ or $I_1 + I_4 = I_2 + I_3 + I_5$

or **Incoming currents = outgoing currents**

similarly, in Fig. 1.63 (b) for node A

$+I + (-I_1) + (-I_2) + (-I_3) + (-I_4) = 0$ or $I = I_1 + I_2 + I_3 + I_4$

We can express the above conclusion thus : $\sum I = 0$ .... at a junction

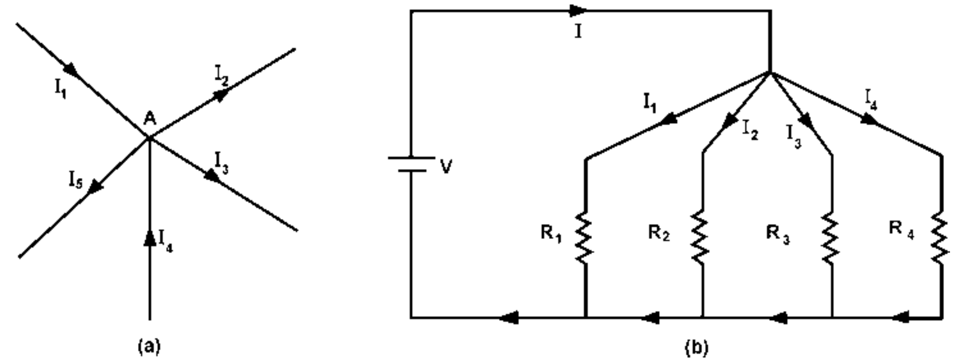


Fig. 1.63.

2. Kirchhoff's Mesh Law or Voltage Law (KVL)

In states as follows :

the algebraic sum of the products of currents and resistances in each of the conductors in any closed path (or mesh) in a network plus the algebraic sum of the e.m.fs. in that path is zero.

In other words, $\sum IR + \sum \text{e.m.f.} = 0$

It should be noted that algebraic sum is the sum which takes into account the polarities of the voltage drops.

The basis of this law is this : If we start from a particular junction and go round the mesh till we come back to the starting point, then we must be at the same potential with which we started. Hence, it means that all the sources of e.m.f. met on the way must necessarily be equal to the voltage drops in the resistances, every voltage being given its proper sign, plus or minus.

DETERMINATION OF VOLTAGE SIGN

In applying Kirchhoff's laws to specific problems, particular attention should be paid to the algebraic signs of voltage drops and e.m.fs., otherwise results will come out to be wrong. Following sign conventions is suggested.

a. Sign or Battery E.M.F.

A rise in voltage should be given a +ve sign and a fall in a voltage a -ve sign. Keeping this in mind, it is clear that as we go from the -ve terminal of a battery to its +ve terminal (Fig.1.64), there is a rise in potential, hence this voltage should be given a +ve sign. If, on the other hand, we go from +ve terminal to -ve terminal, then there is a fall in potential, hence this voltage should be preceded by a -ve sign. It is important to note that the sign of the battery e.m.f. is independent of the direction of the current through that branch.

b. Sign of IR Drop

Now, take the case of a resistor (Fig.1.65). If we go through a resistor in the same direction as the current, then there is a fall in potential because current flows from a higher to a lower potential. Hence, this voltage fall should be taken -ve. However, if we go in a direction opposite to that of the current, then there is a rise in voltage. Hence, this voltage rise should be given a positive sign.

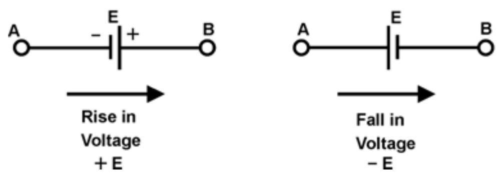


Fig. 1.64.

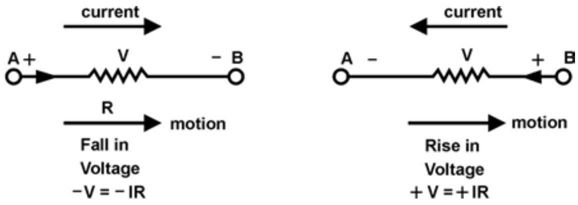


Fig. 1.65.

It is clear that the sign of voltage drop across a resistor depends on the direction of current through that resistor but is independent of the polarity of any other source of e.m.f. in the circuit under consideration.

Consider the closed path ABCDA in (Fig.1.66). As we travel around the mesh in the clockwise direction, different voltage drops will have the following signs :

I_1R_1 is -ve (fall in potential)
I_2R_2 is -ve (fall in potential)
I_3R_3 is +ve (fall in potential)
I_4R_4 is -ve (fall in potential)
E_2 is -ve (fall in potential)
E_1 is +ve (rise in potential)

Using Kirchhoff's voltage law, we get

$$-I_1R_1 - I_2R_2 - I_3R_4 - E_2 + E_1 = 0$$

or $$I_1R_1 + I_2R_2 - I_3R_3 + I_4R_4 = E_1 - E_2$$

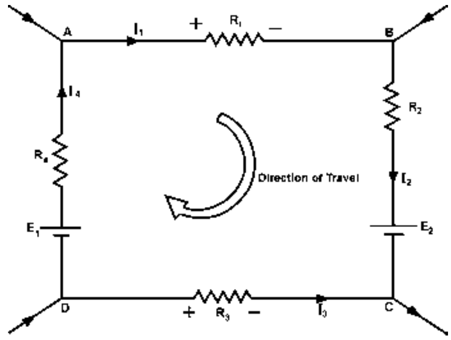


Fig. 1.66.

ASSUMED DIRECTION OF CURRENT

In applying Kirchhoff's laws to electrical networks, the question of assuming proper direction of current usually arises. The direction of current flow may be assumed either clockwise or anticlockwise. If the assumed direction of current is not the actual direction, then on solving the question, this current will be found to have a minus sign. If the answer is positive, then assumed direction is the same as actual direction. However, the important points is that once a particular direction has been assumed, the same should be used throughout the solution of the question.

Note. It should be noted that Kirchhoff's laws are applicable both to d.c. and a.c. voltage and currents. However, in the case of alternating currents and voltages. any e.m.f. of self-inductance or that existing across a capacitor should be also taken into account

Example 1. Determine the currents in the unbalanced bridge circuit of (Fig.1.67) below. Also, determine the p.d. across BD and the resistance from B to D.

Sol:- Assumed current directions are as shown in (Fig.1.67).

Applying Kirchhoff's Second Law to circuit DACD, we get

$$-x - 4z + 2y = 0 \text{ or } x - 2y + 4z = 0 \quad \text{.........................(1)}$$

Circuit ABCA gives

$$-2(x - z) + 3(y + z) + 4z = 0 \text{ or } 2x - 3y - 9z = 0 \quad \text{.........................(2)}$$

Circuit DABED gives

$$-x - 2(x - z) - 2(x + y) + 2 = 0 \text{ or } 5x + 2y - 2z = 2 \quad \text{.........................(3)}$$

Multiplying (1) by 2 and subtracting (2) from it, we get

$$-y + 17z = 0 \quad \text{.........................(4)}$$

Similarly, multiplying (1) by 5 and subtracting (3) from it, we have

$$-12y + 22z = -2 \text{ or } -6y + 11z = -1$$

Eliminating y from (4) and (5), we have 91z = 1 or z - 1/91 A

From (4); y = 17/91 A. Putting these values of y and z in (1), we get x = 30/91A

Current in DA = x = 30/91 A Current in DC = y = 17/91 A

Current in $AB = x - z = \frac{30}{91} - \frac{1}{91} = \frac{29}{19} A$

Current in $CB = y + z = \frac{17}{91} + \frac{1}{91} = \frac{18}{91} A$

Current in external circuit $= x + y = \frac{30}{91} + \frac{17}{91} = \frac{47}{91} A$

Current in AC = z = 1/91 A

Internal voltage drop in the cell = 2 (x + y) = 2 × 47/91=94/91 V

$\therefore$ P.D. across points D and B = $2 - \frac{94}{91} = \frac{88}{91} V$ *

Equivalent resistance of the bridge between point D and B

$$= \frac{\text{p.d. between point B and D}}{\text{current between points B and D}} = \frac{88/91}{47/91} = \frac{88}{47} = 1.87\ \Omega \text{ (approx)}$$

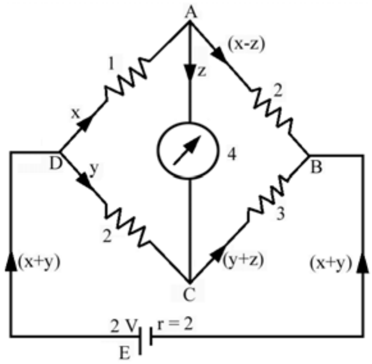


Fig. 1.67.

*** P.D. between D and B = drop across DC + drop across CB = 2×17/91+3×18/91 = 88/91 V.**

Example 2. Two batteries A and B are connected in parallel and load of 10Ω is connected across their terminals. A has an e.m.f of 12 V and an internal resistance of 2Ω ; B has an e.m.f. of 8 V and an internal resistance of 1Ω . Use Kirchhoff's laws to determine the values and directions of the currents flowing in each of the batteries and in the external resistance. Also determine the potential difference across the external resistance.

Sol:- Applying KVL to the closed circuit ABCDA of (Fig.1.68), we get

$-12 + 2x - 1y + 8 = 0$ or $2x - y = 4$ ....(1)

Similarly, from the closed circuit ADCEA, we get

$-8 + 1y + 10(x + y) = 0$ or $10x + 11y = 8$ ....(2)

From Eq. (1) and (2), we get

x = 1.625 A and y = - 0.75 A

The negative sign of y shows that the current is flowing into the 8-V battery and not out of it. In other words, it is a charging current and not a discharging current.

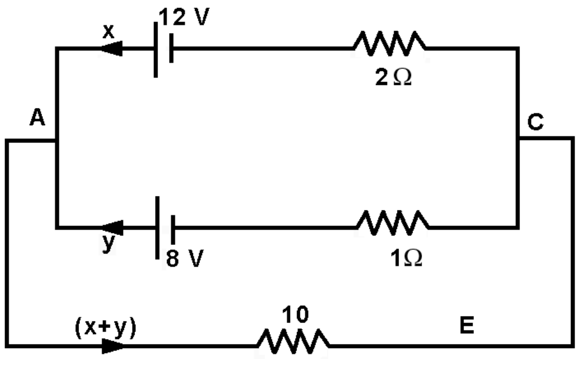


Fig. 1.68.

Current flowing in the external resistance = $x + y$ = 1.625 - 0.75 = 0.875 A

P.D. across the external resistance = 10 × 0.875 = 8.75 V

Note. To confirm the correctness of the answer, the simple check is to find the value of the external voltage available across point A and C with the help of the two parallel branches. If the value of the voltage comes out to be the same, the answer is correct, otherwise it is wrong. For example, V_{CBA} = - 2 × 1.625 + 12 = 8.75 V. From the second branch V_{CDA}=1 × 0.75 + 8 = 8.75 V. Hence, the answer found above is correct.

■■■

CHAPTER - 2
MAGNETISM AND PRINCIPLE OF ELECTROMAGNETIC INDUCTION, THEIR APPLICATION

THE MAGNETIC FIELD

As shown in Fig. 2.1, the north and south poles of a magnet are the points of concentration of magnetic strength. The practical effects of this ferromagnetism result from the magnetic field of force between the two poles at opposite ends of the magnet. Although the magnetic field is invisible, evidence of its force can be seen when small iron filings are sprinkled on a glass or paper sheet placed over a bar magnet in Fig. 2.2 (a). Each iron filing becomes a small bar magnet. If the sheet is tapped gently to overcome friction so that the filings can move, they become aligned by the magnetic field.

Many filings cling to the ends of the magnet, showing that the magnetic field is strongest at the poles. The field exits in all direction but decreases in strength with increasing from the poles of the magnet.

FIELD LINES

In order to visualize the magnetic field without iron filings, we show the field as lines of force, as in Fig. 2.2 (b). The direction of the lines outside the magnet shows the path a north pole would follow in the field, repelled away from the north pole of the magnet and attracted to its south pole. Although we cannot actually have a unit north pole by itself, the field can be explored by noting how the north pole on a small compass needle moves.

The magnet can be considered as the generator for an external magnetic field, provided by the two opposite magnetic poles at the ends. This idea corresponds to the two opposite terminals on a battery as the source for an external electric field provided by opposite charges.

Magnetic field lines are unaffected by nonmagnetic materials such as air, vacuum, paper, glass, wood, or plastics. When these materials are placed in the magnetic field of a magnet, the field lines are same as though the material were not there.

However, the magnetic field lines become concentrated when a magnetic substance like iron is placed in the field. Inside the iron, the field lines are more dense, compared with the field in air.

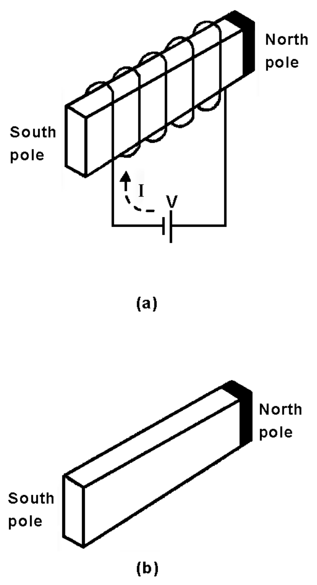


Fig. 2.1. Poles of a magnet. (a) Electromagnet (EM) produced by current from a battery. (b) Permanent magnet (PM) without any external source of current.

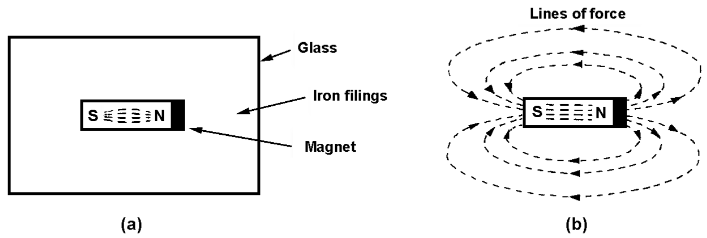


Fig. 2.2. Magnetic field of force around a bar magnet. (a) field outlined by iron fittings (b) Field indicated by lines of force

NORTH AND SOUTH MAGNETIC POLES

The earth itself is a huge natural magnet, with its greatest strength at the north and south poles. Because of the earth's magnetic poles, if a small bar magnet is suspended so that it can turn easily, one end will always point north. This end of the bar magnet is defined as the north-seeking pole, as shown in Fig. 2.3. The opposite end is the south - seeking pole. When polarity is indicated on a magnet, the north-seeking end is the north pole (N) and the opposite end is the south pole (S). It should be noted that the magnetic north pole deviates from true geographic north, the amount depending on location.

Similar to the force between electric charges is a force between magnetic poles causing attraction of opposite poles and repulsion between similar poles.

1. A north pole (N) and a south pole (S) tend to attract each other.
2. A north pole (N) tends to repel another north pole (N), whereas a south pole (S) tends to repel another south pole (S).

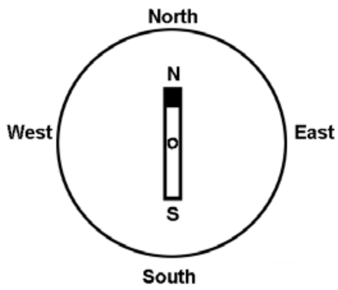


Fig. 2.3. Definition of north and south poles of bar magnet.

MAGNETIC FLUX ϕ

The entire group of magnetic field lines, which can be considered to flow outward from the north pole of a magnet, is called magnetic flux. Its symbol is the Greek letter ϕ (phi). A strong magnetic field has more lines of force and more flux than a weak magnetic field.

THE MAXWELL

One maxwell (Mx) unit equals one magnetic field line. In Fig. 2.4 p. 45, as an example, the flux illustrated is 6 Mx because there are 6 field lines flowing in or out for each pole. A 1-1b magnet can provide a magnetic flux ϕ of about 5000 Mx. This unit is named for James Clerk Maxwell (1831-1879), an important Scottish mathematical physicist who contributed much to electrical and field theory.

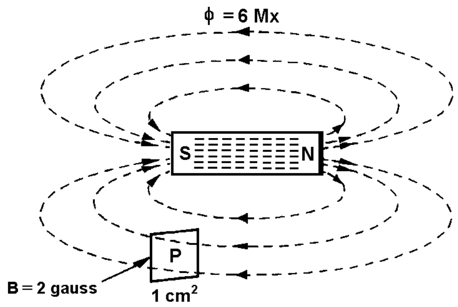


Fig. 2.4. Total flux is 6 lines or 6 Mx. Flux density B at point P is 2 lines per square Centimeter or 2 G.

THE WEBER

This is a large unit of magnetic flux. One weber (Wb) equals 1×10^8 lines or maxwells. Since the weber is a large unit for typical fields, the microweber unit can be used. Then $1\ \mu\text{ Wb} = 10^{-6}\text{ Wb}$. This unit is named for Wilhelm Weber (1804-1890), a German physicist.

To convert the microwebers to lines, multiply the conversion factor 10^8 lines per weber, as follows :

$$1\mu\text{ Wb} = 1\times10^{-6}\text{ Wb}\times10^{8}\ \frac{\text{lines}}{\text{Wb}}$$

$$= 1 \times 10^{2}\text{ lines}$$

$$1\mu\text{ Wb} = 100\ \text{ lines or Mx}$$

Note that the conversion is arranged to make the weber units cancel, since we want maxwell units in the answer.
Even the microweber unit is large than the maxwell unit. For the same 1-1b magnet producing the magnetic flux of 5000 Mx, it corresponds to 50 μWb. The calculations for this conversion of units are

$$\frac{5000\text{ Mx}}{100\text{ Mx}/\mu\text{ Wb}} = 50\ \mu\text{Wb}$$

Note that the maxwell units cancel. Also, the $1/\mu\text{ Wb}$ becomes inverted from the denominator to μ Wb in the numerator.

SYSTEMS OF MAGNETIC UNITS

The basic units in metric form can be defined in two ways :

1. The centimeter-gram-second system defines small units. This is the cgs system.
2. The meter-kilogram-second system is for larger units of a more practical size. This is the mks system.

Furthermore, the System International (SI) units provide a worldwide standard in mks dimensions. They are practical values, but the cgs units are still used in many practical applications of magnetism.

FLUX DENSITY B

As shown in Fig. 2.5, the flux density is the number of magnetic field lines per unit area of a section perpendicular to the direction of flux. As a formula,

$$B = \frac{\phi}{A}$$

where ϕ is the flux through an area A, and the flux density is B.

THE GAUSS

In the cgs system, this unit is one line per square centimeter, or 1 Mx/cm^2. As an example, in Fig. 2.5, the total flux ϕ is 6 lines, or 6 Mx. At point P in this field, however, the flux density B is 2 G because there are 2 lines per square centimeter. The flux density has a higher value close to the poles, where the flux lines are more crowded.

As an example of flux density, B for a 1-1b magnet would be 1000 G at the poles. This unit is named for Karl F. Gauss (1777-1855), a German mathematician.

As typical values, B for the earth's magnetic field can be about 0.2 G; a large laboratory magnet produces B of 50,000 G. Since the gauss is so small, it is often used in kilogauss units, where 1 kG = 10^3 G.

THE TESLA

In SI, the unit of flux density B is webers per square meter (Wb/m^2). One weber per square meter is called a tesla, abbreviated T. This unit is named for Nikola Tesla (1857-1943), a Yugoslav-born American inventor in electricity and magnetism.

When converting between cgs and mks units, note that

$$1\ m = 100\ cm \text{ or } 1 \times 10^2\ cm$$
$$1\ m^2 = 10{,}000\ cm^2 \text{ or } 10^4\ cm^2$$

These conversions are from the large m (meter) and m^2 (square meter) to the smaller units of cm (centimeter) and cm^2 (square centimeter). To go the opposite way,

$$1\ cm = 0.01\ m \text{ or } 1 \times 10^{-2}\ m$$
$$1\ cm^2 = 0.0001\ m^2 \text{ or } 1 \times 10^{-4}\ m^2$$

As an example, 5 cm^2 is equal to 0.0005 m^2 or $5 \times 10^{-4}\ m^2$. The calculations for the conversion are

$$5\ cm^2 \times \frac{0.0001\ m^2}{cm^2} = 0.0005\ m^2$$

In power of 10, the conversion is

$$5\ cm^2 \times \frac{1 \times 10^{-4}\ m^2}{cm^2} = 5 \times 10^{-4}\ m^2$$

In both cases, note that the units of cm^2 cancel to leave m^2 for the desired unit.

The tesla is a larger unit than the gauss, as 1 T = 1×10^4 G.

For example, the flux density of 20,000 G is equal to 2 T. The calculations for this conversion are

$$\frac{20{,}000\ G}{1 \times 10^4\ G/T} = \frac{2 \times 10^4}{1 \times 10^4} = 2T$$

Note that the G units cancel to leave T units for the desired answer. Also, the 1/T in the denominator becomes inverted to T units in the numerator.

COMPARISON OF FLUX AND FLUX DENSITY

Remember that the flux ϕ includes total area, whereas the flux density B is for a specified unit area. The difference between ϕ and B is illustrated in Fig. 2.6 with cgs units. The total area A here is 9 cm^2, equal to 3 cm × 3 cm. For one unit box of 1 cm^2, 16 lines are shown. Therefore, the flux density B is 16 lines or maxwells per square centimeter, which equals 16 g. The total area includes nine of these boxes. Therefore, the total flux ϕ id 144 lines or maxwells, equal to 9 × 16 for B×A.

For the opposite case, if the total flux ϕ is given as 144 lines or maxwells, the flux density is found by dividing 144 by 9 cm^2. This division of 144/9 equals 16 lines or maxwells per square centimeter, which is 16 G.

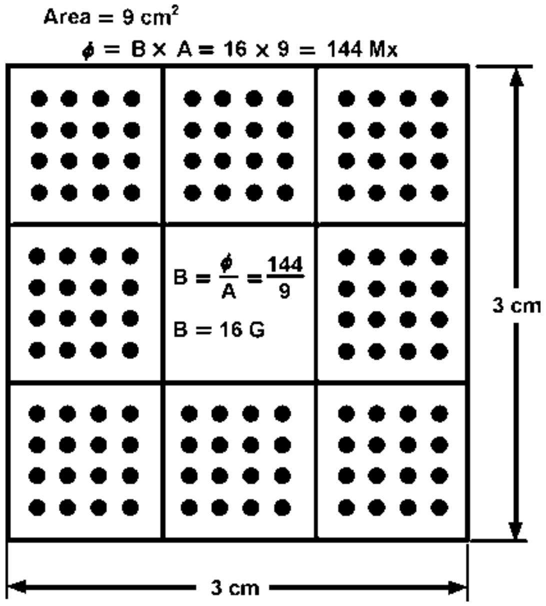


Fig. 2.5 Comparisonal total flux ϕ and density B. Total area of 9cm² has 144 lines or 144 Mx.
For 1 cm² the flux density is 144/9 = 16 G.

ABSOLUTE AND RELATIVE PERMEABILITIES OF A MEDIUM

The phenomenon of magnetism and electromagnetism are dependent upon a certain property of the medium called its permeability. Every medium is supposed to possess two permeabilities :

(i) absolute permeability (μ) and (ii) relative permeability (μ_r).

For measuring relative permeability, vacuum or free space is chosen as the reference medium. It is allotted an absolute permeability of $\mu_0 = 4\pi \times 10^{-7}$ henry/metre. Obviously, relative permeability of vacuum with reference to itself is unity. Hence, for free space,

absolute permeability $\mu_0 = 4\pi \times 10^{-7}$ H/m 3

relative permeability $\mu_0 = 1$

Now, take any medium other than vacuum. If its relative permeability, as compared to vacuum is μ_r, then its absolute permeability is $\mu = \mu_0 \mu_r$ H/m.

LAWS OF MAGNETIC FORCE

Coulomb was the first to determine experimentally the quantitative expression for the magnetic force between two isolated point poles. It may be noted here that, in view of the fact that magnetic poles always exits in pairs, it is impossible, in practice, to get an isolated pole. The concept of an isolated pole is purely theoretical. However, poles of a thin but long magnet may be assumed to be point poles for all practical purposes (Fig. 2.6.). By using a torsion balance, he found that the force between two magnetic poles in a medium is

(i) directly proportional to their pole strengths
(ii) inversely proportional to the square of the distance between them and
(iii) inversely proportional to the absolute permeability of the surrounding medium.

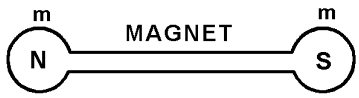


Fig. 2.6.

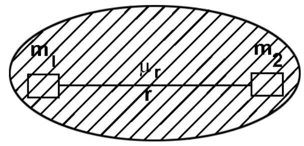


Fig. 2.7.

For example, if m_1 and m_2 represent the magnetic strength of the two poles (its unit as yet being undefined), r the distance between them (Fig. 2.7) and μ the absolute permeability of the surrounding medium, then the force F is given by

$$F \infty \frac{m_1 m_2}{\mu r^r} \quad \text{or} \quad F = k\frac{m_1 m_2}{\mu r^2}$$

MAGNETIC FIELD STRENGTH (H)

Magnetic Field strength at any point within a magnetic field is numerically equally to the force experienced by a N-pole of one weber placed at that point. Hence, unit of H is N/Wb.

Suppose, it is required to find the field intensity at a point A distant r metres from a pole of m webers. Imagine a similar pole of one weber placed at point A. The force experienced by this pole is

$$F = \frac{m \times 1}{4\pi\mu_0 r^2} N \qquad \therefore\ H = \frac{m}{4\pi\mu_0 r^3} \text{ N/Wb (or A/m)}^{***} \text{ or oersted.}$$

Also, if a pole of m Wb is placed in a uniform field of strength HN/Wb, then force experienced by the pole is = mH newtons.

It should be helpful to remember that following terms are sometimes interchangeably used with field intensity : Magnetising force, strength of field, magnetic intensity and intensity of magnetic field. It is given by

$$M = \frac{m}{4\pi\mu_0 r} \text{ J/Wb}$$

It is a scalar quantity.

INTENSITY OF MAGNETISATION (I)

It may be defined as the induced pole strength developed per unit area of the bar. Also, it is the magnetic moment developed per unit volume of the bar.

Let m = pole strength induced in the bar in Wb

A = face or pole area of the bar in m^2

I = m/A Wb/n^2

Hence, it is seen that intensity of magnetisation of a substance may be defined as the flux density produced in it due to its own induced magnetism.

If ℓ is the magnetic length of the bar, then the product ($m \times \ell$) is known as its magnetic moment M/

$$I = \frac{m}{A} = \frac{m \times \ell}{A \times \ell} = \frac{M}{V} = \text{magnetic moment/volume}$$

SUSCEPTIBILITY (K)

Susceptibility is defined as the intensity of magnetisation I to the magnetising force H.

WEBER AND EWING'S MOLECULAR THEORY

This theory was first advanced by Weber in 1852 and was, later on, further developed by Ewing in 1890. The basic assumption of this theory is that molecules of all substances are inherently magnets in themselves, each having a N and S pole. In an unmagnetised state, it is supposed that these small molecular magnets lie in all sorts of haphazard manner forming more or less closed loops (Fig. 2.6). According to the laws of attraction and repulsion, these closed magnetic circuits are satisfied internally, hence there is no resultant external magnetism exhibited by the iron bar. But when such an iron bar is placed in a magnetic field or under the influence of a magnetising force, then these molecular magnets start turning round their axes and orientate themselves more or less along straight lines parallel to the direction of the magnetising force. This linear arrangement of the molecular magnets result in N polarity at one end of the bar and S polarity at the other (Fig. 2.7). As the small magnets turn more nearly in the direction of the magnetising force, it requires more and more of this force to produce a given turning moment, thus molecular friction of these turning magnets.

Because of the limited knowledge of molecular structure available at the time of Weber, it was not possible to explain firstly, as the why the molecules themselves are magnets and secondly, why it is impossible to magnetise certain substances like wood etc. The first objection was explained by Ampere who maintained that orbital movement of the electrons round the atom of a molecule constituted a flow of current which, due to its associated magnetic effect, made the molecule constituted a flow of current which, due to its associated magnetic effect, made the molecule a magnet.

Later on, it became difficult to explain the phenomenon of diamagnetism (shown by materials like water, quartz, silver and copper etc.) erratic behaviour of ferromagnetic (intensely magnetisable) substances like iron, steel, cobalt, nickel and some of their alloys etc. and the paramegnetic (weakly magnetisable) substances like oxygen and aluminium etc. Moreover, it was asked: if molecules of all substances are magnets, then why does not wood or air etc. become magnetised ?

All this has been explained satisfactorily by the atom-domain theory which has superseded the molecular theory. It is beyond the scope of this book to go into the details of this theory. The interested reader is advised to refer to some standard book on magnetism. However, it may just be mentioned that this theory takes into account not only the planetary motion of an electron but its rotation about its own axis as well. This latter rotation is called 'electron spin'. The gyroscopic behaviour of an electron gives rise to a magnetic moment which may be either positive or negative. A substance is ferromagnetic or diamagnetic accordingly as there is an excess of unbalanced positive spins or negative spins. Substances like wood or air are non-magnetisable because in their case, the positive and negative electron spins are equal, hence they cancel each other out.

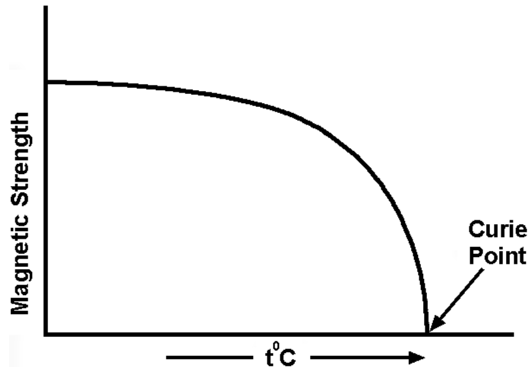


Fig. 2.8.

CURIE POINT

As a magnetic material is heated, its molecules vibrate more violently. As a consequence, individual molecular magnets get our of alignment as the temperature is increased, thereby reducing the magnetic strength of the magnetised substance. Fig. 2.8. shows the approximate decrease of magnetic strength with rise in temperature. Obviously, it is possible to partially or even completely destroy the magnetic properties of a material by heating. The temperature at which the vibrations of the molecular magnets become so random and out of alignment as to reduce the magnetic strength to zero is called Curie point. More accurately, it is that critical temperature above which is ferromagnetic material becomes paramagnetic.

INDUCTION BY THE MAGNETIC FIELD

The electric or magnetic effect of one body on another without any physical contact between them is called induction. For instance, a permanent magnet can induce an unmagnetized iron bar to become a magnet, without the two touching. The iron bar then becomes a magnet, as shown in Fig. 2.12, p.386. What happens is that the magnetic lines of force generated by the permanent magnet make the internal molecular magnets in the iron bar line up in the same direction, instead of the random directions in unmagnetized iron. The magnetized iron bar then has magnetic poles at the ends, as a result of the magnetic induction.

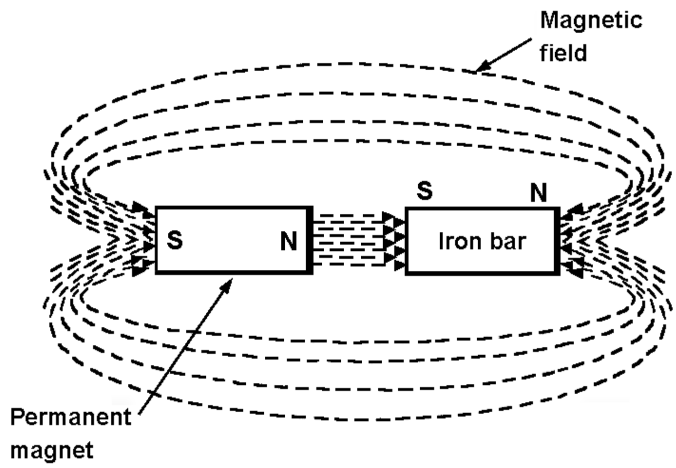


Fig. 2.9. Magnetizing an iron bar by induction.

Note that the induced poles in the iron have opposite polarity from the poles of the magnet. Since opposite poles attract, the iron bar will be attracted. Any magnet attracts to itself all magnetic materials by induction.

Although the two bars in Fig. 2.9 are not touching, the iron bar is in the magnetic flux of the permanent magnet. IT is the invisible magnetic field that links the two magnets, enabling one to affect the other. Actually, this idea of magnetic flux extending outward from the magnetic poles is the basis for many inductive effects in ac circuits. More generally, the magnetic field between magnetic poles and the electric field between electric charges form the basis for wireless radio transmission and reception.

POLARITY OF INDUCED POLES

Note that the north pole of the permanent magnet in Fig. 2.9 induces an opposite south pole at his end of the iron bar. If the permanent magnet were reversed, its south pole would induce a north pole. The closet induced pole will always be of opposite polarity. This is the reason why either end of a magnet can attract another magnetic material to itself. No matter which pole is used, it will induce an opposite pole, and the opposite poles are attracted.

RELATIVE PERMEABILITY

Soft iron, as an example, is very effective in concentrating magnetic field lines, by induction in the iron. This ability to concentrate magnetic flux is called permeability. Any material that is easily magnetized has high permeability, therefore, as the field lines are concentrated because of induction.

Numerically values of permeability for different materials compared with air or vacuum can be assigned. For example, if the flux density in air is 1 G but an iron core in the same position in the same field has a flux density of 200 G, the relative permeability of the iron core equals 200/1, or 200.

The symbol for relative permeability is μ_r (mu), where the subscript r indicates relative permeability. Typical values for m_r are 100 to 9000 for ion and steel. There are no units, because μ_r is a comparison of two flux densities and the units cancel. The symbol k_m may also be used for relative permeability, to indicate this characteristics of a material for a magnetic field, corresponding to K_e for an electric field.

AIR GAP OF A MAGNET

As shown in Fig. 2.10, the air space between poles of a magnet is its air gap. The shorter the air gap, the stronger the field in the gap for a given pole strength. Since air is not magnetic and cannot concentrate magnetic lines, a larger air gap only provides additional space for the magnetic lines to spread out.

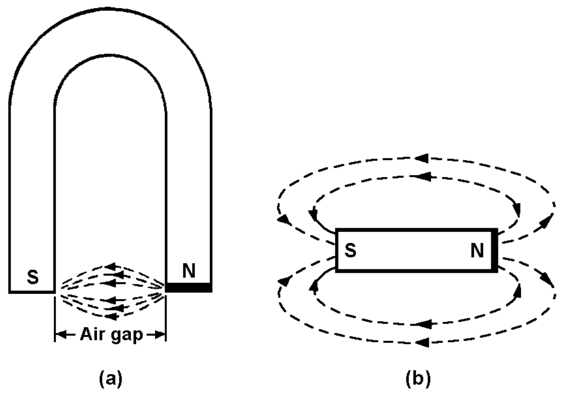
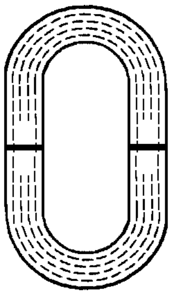


Fig. 2.10. The horseshoe magnet in (a) has a smaller air gap than the bar magnet in (b)

Referring to Fig. 2.10 (a), note that the horseshoe magnet has more crowded magnetic lines in the air gap, compared with the widely separated lines around the bar magnet in Fig. 2.10 (b). Actually, the horseshoe magnet can be considered as a bar magnet bent around to place the opposite poles closer. Then the magnetic lines of the poles reinforce each other in the air gap. The purpose of a short air gap is concentrate the magnetic field outside the magnet, for maximum induction in a magnetic material placed in the gap.

RING MAGNET WITHOUT AIR GAP

When it is desired to concentrate magnetic lines within a magnet, however, the magnet can be formed as a closed magnetic loop. This method is illustrate in Fig. 2.11 (a) by the two permanent horseshoe magnets placed in a closed loop with opposite poles touching. Since the loop has no open ends, there can be no air gap and no poles. The north and south poles of each magnet cancel as opposite poles touch.



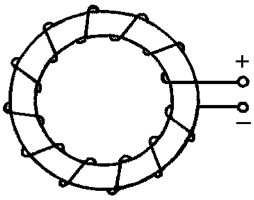


Fig. 2.11. Examples of a closed magnetic ring without any air gap.
a. Two PM horseshoe magnets with opposite poles touching.
b. Toroid magnet.

Each magnet has its magnetic lines inside, plus the magnetic lines of the other magnet, but outside the magnets the lines cancel because they are in opposite directions. The effect of the closed magnetic loop, therefore, is maximum concentration of magnetic lines in the magnet with minimum lines outside.

The same effect of a closed magnetic loop is obtained with the toroid or ring magnet in Fig. 2.11 (b), made in the form of a doughnut. Iron is often used for the core. This type of electromagnet has maximum strength in the iron ring, with little flux outside. As a result, the toroidal magnet is less sensitive to induction from external magnetic fields and, conversely, has little magnetic effect outside the coil.

It should be noted that, even if the winding is over only a small part of the ring, practically all the flux is in the iron core because its permeability is so much greater than that of air. The small part of the field in the air is called leakage flux.

KEEPER FOR A MAGNET

The principle of the closed magnetic ring is used to protect permanent magnets in storage. In Fig.2.12 (a), four permanent-magnet bars are in a closed loop, while Fig.2.12 (b) shows a stacked pair. Additional even pairs can be stacked this way, with opposite poles touching. The closed loop in Fig.2.12 (c) shows one permanent horseshoe magnet with a soft-iron keeper across the air gap. The keeper maintains the strength of the permanent magnet as it becomes magnetized by induction to form a closed loop. Then any external magnetic field is concentrated in the closed loop without inducing opposite poles in the permanent magnet. If permanent magnets are not stored this way, the polarity can be reversed with induced poles produced by a strong external field from a dc source, an alternating field can demagnetize the magnet.

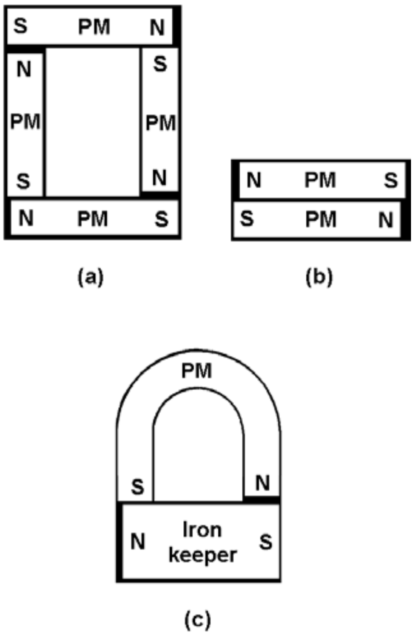


Fig. 2.12. Storing permanent magnets in a closed loop, with opposite poles touching.
a. Four bar magnets.
b. Two bar magnets.
c. Horseshoe magnet with iron keeper across air gap.

TYPES OF MAGNETS

The two broad classes are permanent magnets and electromagnets. An electromagnet needs current from an external source to maintain its magnetic field. With a permanent magnet, not only is its magnetic field present without any external current, but the magnet can maintain its strength indefinitely. Sharp mechanical shock as well as extreme heat, however, can cause demagnetization.

ELECTROMAGNETS

Current in a wire conductor has an associated magnetic field. If the wire is wrapped in the form of a coil, as in Fig. 2.13, the current and its magnetic field become concentrated in a smaller space, resulting in a stronger field. With the length much greater than its width, the coil is called a solenoid. It acts like a bar magnet, with opposite poles at the ends.

More current and more turns make a stronger magnetic field. Also, the iron core concentrates magnetic lines inside the coil. Soft iron is generally used for the core because it is easily magnetized and demagnetized.

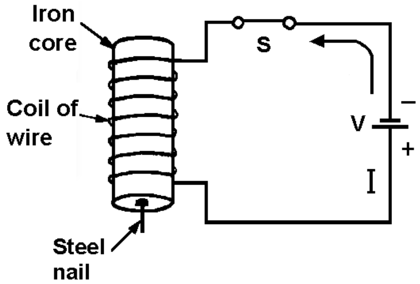


Fig. 2.13 Electromagnet holding nail when switch S is closed for current in coil.

The coil in (Fig. 2.13), with the switch closed and current in the coil, is an electromagnet that can pick up the steel nail shown. If the switch is opened, the magnetic field is reduced to zero, and the nail will drop off. This ability of an electromagnet to provide a strong magnetic force of attraction that can be turned on or off easily has many applications in lifting magnets, buzzers, bells or chimes, and relay. A relay is a switch with contacts that are opened or closed by an electromagnet.

Another common application is magnetic tape recording. The tape is coated with fine particles of iron oxide. The recording head is a coil that produces a magnetic field in proportion to the current. As the tape passes through the air gap of the head, small areas of the coating become magnetized by induction. On playback, the moving magnetic tape produces variations in electric current.

PERMANENT MAGNETS

These are made of hard magnetic material, such as cobalt steel, magnetized by induction in the manufacturing process. A very strong field is needed for induction in these materials. When the magnetizing field is removed, however, residual induction makes the material a permanent magnet. A common PM material is alnico, a commercial alloy of aluminium, nickel and iron, with cobalt, copper and titanium added to produce about 12 grades. The Alnico V grade is often used for PM loudspeakers (Fig. 2.14). In this application, a typical size of PM slug for a steady magnetic field is a few ounces to about 5 lb, with a flux ϕ of 500 to 25,000 lines or maxwells. One advantage of a PM loudspeaker is that only two connecting leads are needed for the voice coil, as the steady magnetic field of the PM slug is obtained without any field-coil winding.

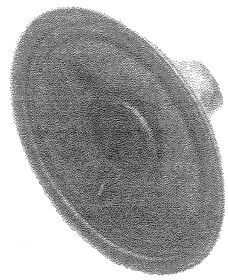


Fig.2.14. Example of a PM loudspeaker.

Commercial permanent magnets will last indefinitely if they are not subjected to high temperature, to physical shock, or to a strong demagnetizing field. If the magnet becomes hot, however, the molecular structure can be rearranged, resulting in loss of magnetism that is not recovered after cooling. The point at which a magnetic material loses its ferromagnetic properties is the Curie temperature. For iron, this temperature is about 800°C, when the relative permeability drops to unity. A permanent magnet does not become exhausted with use, as its magnetic properties are determined by the structure of the internal atoms and molecules.

CLASSIFICATION OF MAGNETIC MATERIALS

When we consider material simply as either magnetic or nonmagnetic, this division is really based on the strong magnetic properties of iron. However, weak magnetic materials can be important in some applications. For this reason, a more exact classification includes the following three groups :

1. Ferromagnetic materials. These include iron, steel, nickel, cobalt, and commercial alloys such as alnico and Permalloy. They become strongly magnetized in the same direction as the magnetizing field, with high values of permeability from 50 to 5000. Permalloy has μ_r of 100,000 but is easily saturated at relatively low values of flux density.
2. Paramagnetic materials. These include aluminium, platinum, manganese, and chromium. The permeability is slightly more than 1. They become weakly magnetized in the same direction as the magnetizing field.
3. Diamagnetic materials. These include bismuth, antimony, copper, zinc, mercury, gold, and silver. The permeability is less than 1. They become weakly magnetized, but in opposite direction from the magnetizing field.

The basis of all magnetic effects is the magnetic field associated with electric charges in motion. Within the atom, the motion of its orbital electrons generates a magnetic field. There are two kind of electron motion in the atom. First is the electron revolving in its orbit. This motion provides a diamagnetic effect. However, this magnetic effect is weak because thermal agitation at normal room temperature results in random directions of motion that neutralize each other.

More effective is the magnetic effect from the motion of each electron spinning on its own axis. The spinning electron serves as a tiny permanent magnet. Opposite spins provide opposite polarities. Two electrons spinning in opposite directions form a pair, neutralizing the magnetic fields. In the atoms of ferromagnetic materials, however, there are many unpaired electrons with spins in the same direction, resulting in a strong magnetic effect.

In terms of molecular structure, iron atoms are grouped in microscopically small arrangements called domains. Each domain is an elementary dipole magnet, with two opposite poles. In crystal form, the iron atoms have domains that are parallel to the axes of the crystal. Still, the domains can point in different directions, because of the different axes. When the material becomes magnetized by an external magnetic field, though, the domains become aligned in the same direction. With PM materials, the alignment remains after the external field is removed.

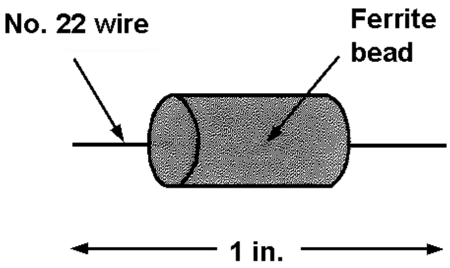


Fig.2.15. Ferrite bead equivalent to coil with 20 μH of inductance at 10 MHz.

FERRITES

Ferrites is the name for nonmetallic materials that have the ferromagnetic properties of iron. The ferrites have very high permeability, like iron. However, a ferrite is a nonconducting ceramic material, whereas iron is a conductor. The permeability of ferrites is in the range of 50 to 3000. The specific resistance is 10^5 Ω cm, which makes the ferrite an insulator.

A common application is a ferrite core, usually adjustable, in the coils for RF transformers. The ferrite core is much more efficient than iron when the current alternates at a high frequency. The reason is that less $I^2 R$ power is lost by eddy current in the core because of its very high resistance.

A ferrite core is used in small coils and transformers for signal frequencies up to 20 MHz, approximately. The high permeability means that the transformer can be very small. However, the ferrites are easily saturated at low values of magnetizing current. This disadvantage means the ferrites are not used for power transformers.

Another application is in ferrite beads (Fig.2.15). A bare wire is used as a string for one or more beads. The bead concentrates the magnetic field of the current in the wire. This construction serves as a simple, economical RF choke, instead of a coil. The purpose of the choke is to reduce the current just for an undesired radio frequency.

MAGNETIC SHIELDING

The idea of preventing one component from affecting another through their common electric or magnetic field is called shielding. Examples are the braided copper-wire shield around the inner conductor of a coaxial cable, a metal shield can that encloses an RF coil, or a shield of magnetic material enclosing a cathode-ray tube.

The problem in shielding is to prevent one component from inducing an effect in the shielded component. The shielding materials are always metals, but there is a difference between using good conductors with low resistance like copper and aluminium and using good magnetic materials like soft iron.

A good conductor is best for two shielding functions. One is to prevent induction of static electric charges. The other is to shield against the induction of a varying magnetic field. For static charges, the shield against the induction of a varying magnetic field. For static charges, the shield provides opposite induced charges, which prevent induction inside the shield. For a varying magnetic field, the shield has induced currents that oppose the inducing field. Then there is little net field strength to produce induction inside the shield.

The best shield for a steady magnetic field is a good magnetic material of high permeability. A steady field is produced by a permanent magnet, a coil with steady direct current, or the earth's magnetic field. A magnetic shield of high permeability concentrates the magnetic flux. Then there is little flux to induce poles in a component inside the shield. The shield can be considered as a short circuit for the lines of magnetic flux.

THE HALL EFFECT

In 1879, E.H. Hall observed that a small voltage is generated across a conductor carrying current in an external magnetic field. The Hall voltage was very small with typical conductors, and little use was made of this effect. However, with the development of semiconductors, larger values of Hall voltage can be generated. The semiconductor material indium arsenide (InAs) is generally used. As illustrated in (Fig.2.16), the InAs element inserted in the magnetic field can generate 60 mV with B equal to 10 kG and an I of 100 mA. The applied flux must be perpendicular to the direction of current. With current in the direction of the length of conductor, the generated voltage is developed across the width.

The amount of Hall voltage v_H is directly proportional to the value of flux density B. This means that values of B can be measured by means of v_H. As an example, the gaussmeter in Fig. 2.17 uses an InAs probe in the magnetic field of generate a proportional Hall Voltage v_H. This value of v_H is then read by the meter, which is calibrated in gauss. The original calibration is made in terms of a reference magnet with a specified flux density.

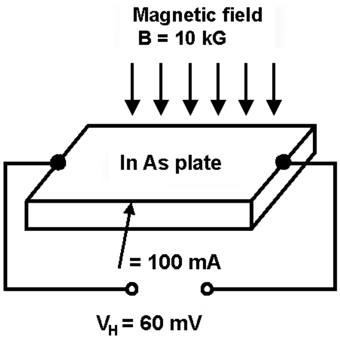


Fig. 2.16. The Hall effect. Hall voltage V_H generated across the element is proportional to the perpendicular flux density B.

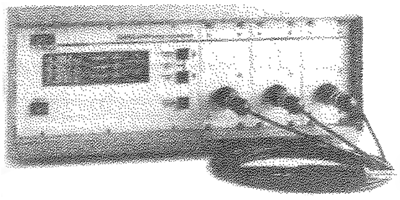


Fig. 2.17. Gaussmeter to measure flux density, with probe containing indium arsenide element.

MAGNETIC HYSTERESIS

Hysteresis means "a lagging behind". With respect to the magnetic flux in an iron core of an electromagnet, the flux lags the increase or decrease in magnetizing force. The hysteresis results from the fact that the magnetic dipoles are not perfectly elastic. Once aligned by an external magnetizing force, the dipoles do not return exactly to their original positions when the force is removed. The effect is the same as if the dipoles were forced to move against an internal friction between molecules. Furthermore, if the magnetizing force is reversed in direction by reversal of the current in an electromagnet, the flux produced in the opposite direction lags behind the reversed magnetizing force.

HYSTERESIS LOSS

When the magnetizing force reverse thousands or millions of times per second, as with rapidly reversing alternating current, the hysteresis can cause a considerable loss of energy. A large part of the magnetizing force is then used just to overcome the internal friction of the molecular dipoles. The work done by the magnetizing force against this internal friction produces heat. This energy wasted in heat as the molecular dipoles lag the magnetizing force is called hysteresis loss. For steel and other hard magnetic materials, the hysteresis losses are much higher than in soft magnetic materials like iron.

When the magnetizing force varies at a slow rate, the hysteresis losses can be considered negligible. An example is an electromagnet with direct current that is simply turned on and off, or the magnetizing force of an alternating current that reverse 60 times on and off, or the magnetizing force of an alternating current that reverses 60 times per second or less. The faster the magnetizing force changes, however, the greater the hysteresis effect.

HYSTERESIS LOOP

To show the hysteresis characteristics of a magnetic material, its values of flux density B are plotted for a periodically reversing magnetizing force. (See Fig.2.18). This curve is the hysteresis loop of the material. The larger the area enclosed by the curve, the greater the hysteresis loss. The hysteresis loop is actually a B-H curve with an ac magnetizing force.

On the vertical axis, values of flux density B are indicated. The units can be gauss or teslas.
The horizontal axis indicates values of field intensity H. On this axis the units can be oersteds, ampere-turns per meter, ampere-turns, or just magnetizing current, as all factors are constant except I.

Opposite directions of current results in the opposite directions of +H and -H for the field lines. Similarly, opposite polarities are indicated for flux density as +B or -B.

The current starts from zero at the center, when the material is unmagnetized. Then positive H values increase B to saturation at $+B_{max}$. Next H decreases to zero, but B drops to the value B_R, instead of to zero, because of hysteresis. When H becomes negative, B drops to zero and continues to $-B_{max}$ which is saturation in the opposite direction from $+B_{max}$ because of the reversed magnetizing current.

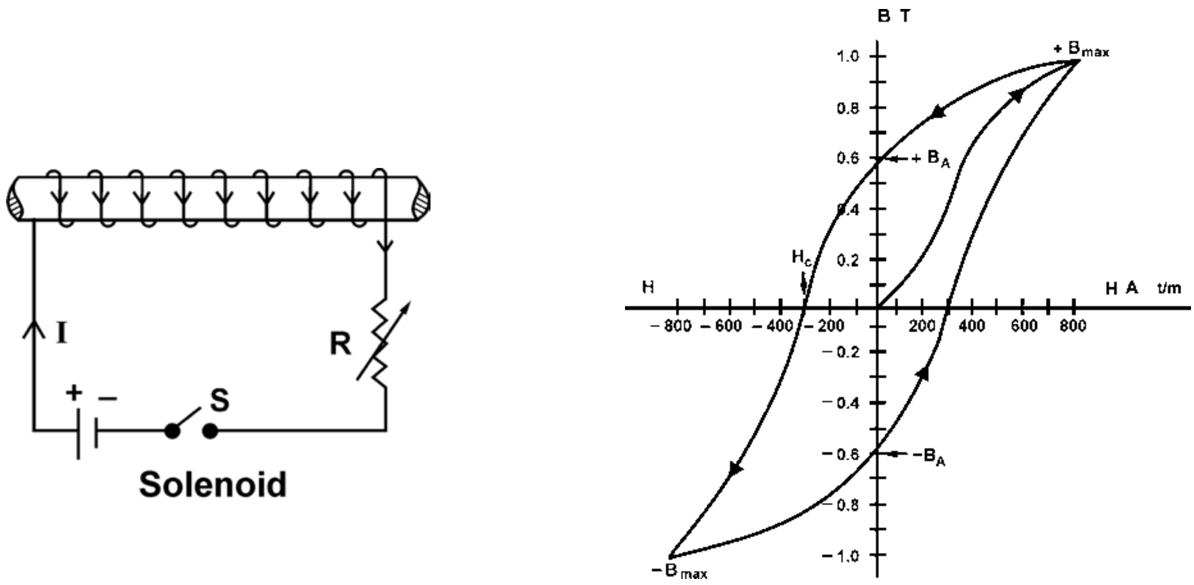


Fig. 2.18 Hysteresis loop for magnetic materials. This graph is a B-H curve, but H alternates in polarity with alternating current.

Then, as the -H values decrease, the flux density is reduced to $-B_R$. Finally, the loop is completed, with positive values of H producing saturation at B_{max} again. The curve does not return to the zero origin at the center, because of hysteresis. As the magnetizing force periodically reverse, the values of flux density are repeated to trace out the hysteresis loop.

The value of either $+B_R$ or $-B_R$, which is the flux density remaining after the magnetizing force has been reduced to zero, is the residual induction of a magnetic material, also called its retentivity. In Fig. 2.22, the residual induction is 0.6 T, in either the positive or the negative direction.

The value of $-H_C$, which equals the magnetizing force that must be applied in the reverse direction to reduce the flux density to zero, is the coercive force of the material. In Fig. 2.22, the coercive force $-H_C$ is 300A. t/m.

DEMAGNETIZATION

In order to demagnetize a magnetic material completely, the residual induction B_R must be reduced to zero. This usually cannot be accomplished by a reversed dc magnetizing force, because the material then would just become magnetized with opposite polarity. The practical way is to magnetize and demagnetize the material with a continuously decreasing hysteresis loop. This can be done with a magnetic field produced by alternating current. Then as the magnetic field and the material are moved away from each other, or the current amplitude is reduced, the hysteresis loop becomes smaller and smaller. Finally, with the weakest field, the loop collapses practically to zero, resulting in zero residual induction.

This method of demagnetization is also called degaussing. One application is degaussing the metal electrodes in a color picture tube, with a deguassing coil providing alternating current from the power line. Another example is erasing the recorded signal on magnetic tape by demagnetizing with an ac bias current. The average level of the erase current is zero, and its frequency is much higher than the recorded signal.

MAGNETIC CIRCUIT

It may be defined as the path which is followed by magnetic flux. The law of magnetic circuit are quite similar to (but not the same as) those of the electric circuit.

DEFINITIONS CONCERNING MAGNETIC CIRCUIT

1. Magnetomotive force (m.m.f.). It drives or tends to drive flux through a magnetic circuit and corresponds to electromotive force (e.m.f.) in an electric circuit.

M.M.F. is equal to the work done in joules in carrying a unit magnetic pole once through the entire magnetic circuit. It is measured in ampere-turns.

In fact, as p.d. between any two points is measured by the work done in carrying a unit charge from one point to another, similarly, m.m.f. between two points is measured by the work done in joules in carrying a unit magnetic pole from one point to another.

2. Ampere-turns (AT). It is the unit of magnetometre force (m.m.f.) and is given by the product of number of turns of a magnetic circuit and the current in amperes in those turns.

3. Reluctance. It is the name given to property of a material which opposes the creation of magnetic flux in it. It, in fact, measures the opposition offered to the passage of magnetic flux through a material and is analogous to resistance in an electric circuit even in form. Its units is **AT/Wb.****

$$\textbf{reluctance} = \; = \frac{\ell}{\mu A} = \frac{\ell}{\mu_0 \mu_r A}; \qquad \textbf{resistance} = \rho\frac{\ell}{A} = \frac{\ell}{\sigma A}$$

In other words, the reluctance of a magnetic circuit is the number of amp-turns required per weber of magnetic flux in the circuit. Since 1 AT/Wb = 1/henry, the unit of reluctance is 'reciprocal henry."

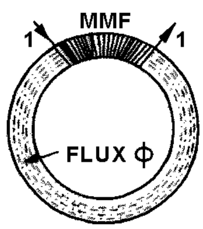
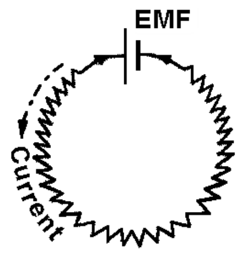
** **From the ration $\Phi = \frac{\text{m.m.f.}}{\text{reluctance}}$, it is obvious that reluctance = m.m.f./Φ. Since m.m.f. is in ampere-turns and flux in webers, unit of reluctance is ampere-turn/weber (AT/Wb) or A/Wb.**

4. Permeance. It is reciprocal of reluctance and implies the case or readiness with which magnetic flux is develop. It is analogous to conductance in electric circuits. It is measured in terms of Wb/AT or henry.

5. Reluctivity. It is specific reluctance and corresponds to resistivity which is 'specific resistance'.

COMPARISON BETWEEN MAGNETIC AND ELECTRIC CIRCUITS

SIMILARITIES

Magnetic Circuit	Electric Circuit
	
1. Flux $= \frac{\text{m.m.f.}}{\text{reluctance}}$	Current $= \frac{\text{e.m.f.}}{\text{resistance}}$
2. M.M.F. (ampere - turns)	E.M.F. (volts)
3. Flux Φ (Webers)	Current I (amperes)
4. Flux density B (Wb/m^2)	Current density (A/m^2)
5. Reluctance $S = \frac{\ell}{\mu A}\left(= \frac{\ell}{\mu_0 \mu_r A}\right)$	resistance $R = \rho\frac{\ell}{A} = \frac{\ell}{\rho A}$
6. Permeance (= 1/reluctance)	Conductance (= 1/resistance)
7. Reluctivity	Resistivity
8. Permeability	Conductivity (= 1/resistivity)
9. Total m.m.f. $= \Phi S_1 + \Phi S_2 + \Phi S_3 + ...$	9. Total e.m.f. $= IR_1 + IR_2 + IR_3 + ...$

MAGNETIC FIELD AROUND AN ELECTRIC CURRENT

In (Fig.2.19), the iron fillings aligned in concentric rings around the conductor show the magnetic field of current in the wire. The iron fillings are dense next to the conductor , showing that the field is strongest at this point. Furthermore, the field strength decreases inversely as the square of the distance from the conductor. It is important to note the following two factors about the magnetic lines of force :

1. The magnetic lines are circular, as the field is symmetrical with respect to the wire in the center.
2. The magnetic field with circular lines of force is in a plane perpendicular to the current in the wire.

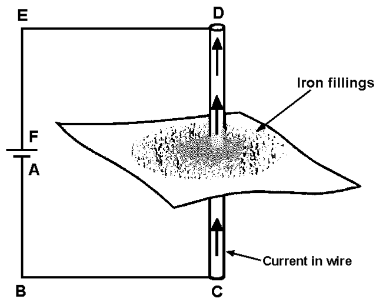


Fig. 2.19. How iron fillings can be used to show the invisible magnetic field around the electric current in a wire conductor.

From points C to D in the wire, the circular magnetic field is in the horizontal plane because the wire is vertical. Also, the vertical conductor between points EF and AB has the associated magnetic field in the horizontal plane. Where the conductor is horizontal, as from B to C and D to E, the magnetic field is in a vertical plane.

These two requirements of a circular magnetic field in a perpendicular plane apply to any charge in motion. Whether electron flow or a motion of positive charges is considered, the associated magnetic field must be at right angles to the direction of current.

In addition, the current need not be in a wire conductor. As an example, the beam of moving electrons in the vacuum of a cathode-ray tube has an associated magnetic field. In all cases, the magnetic field has circular lines of force in a plane perpendicular to the direction of motion of the electric charges.

CLOCKWISE AND COUNTERCLOCKWISE FIELDS

With circular lines of force, the magnetic field would tend to move a magnetic pole in a circular path. Therefore, the direction of the lines must be considered as either clockwise or counterclockwise. This idea is illustrated in Fig. 2.24 showing how a north pole would move in the circular field.

The directions are tested with a magnetic compass needle. When the compass is in front of the wire, the north pole on the needle points up. On the opposite side, the compass points down. IF the compass were placed at the top, its needle would point toward the back of the wire; below the wire, the compass would point forward.

When all these direction are combined, the result is the circular magnetic field shown, with couterclockwise lines of force. This field has the magnetic lines upward at the front of the conductor and downward at the back.

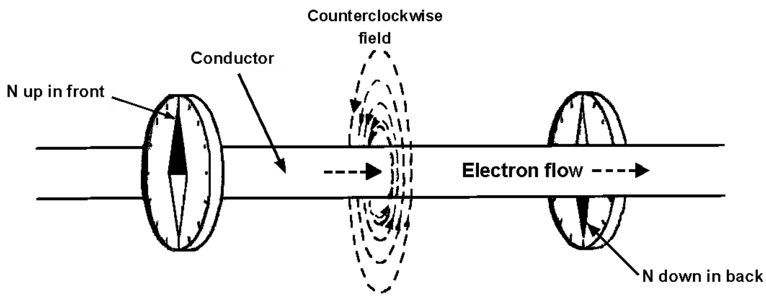


Fig. 2.20. Rule for determining direction of circular field around straight conductor. Field is counterclockwise for direction of electron flow shown here. Circular field is clockwise for conventional current.

Instead of testing every conductor with a magnetic compass, however, we can use the following rule to determine the circular direction of the magnetic field: If you look along the wire in the direction of electron flow, the magnetic field is couterclockwise. In (Fig.2.20), the line of electron flow is from left to right. Facing this way, you can assume that the circular magnetic flux in a perpendicular plane has lines of force in the counterclockwise direction.

The opposite direction of electron flow produces a reversed field. Then the magnetic lines of force clockwise rotation. If the charges were moving from right to left in (Fig.2.20), the associated magnetic field would be in the opposite direction, with clockwise lines of force.

FIELD AIDING OR CANCELLING

When the magnetic lines of two fields are in the same direction, the lines of force aid each other, making the field stronger. With magnetic lines in opposite directions, the fields cancel.

In (Fig.2.21) the fields are shown for two conductors with opposite directions of electron flow. The dot in the middle of the field at the left indicates the tip of an arrowhead to show current up from the paper. The cross symbolizes the back of an arrow to indicate electron flow into the paper.

Notice that the magnetic lines between the conductors are in the same direction, although one field is clockwise and the other counterclockwise. Therefore, the fields aid here, making a stronger total field. On either side of the conductors, the two fields are opposite in direction and tend to cancel each other. The net result, is to strengthen the field in the space between the conductors.

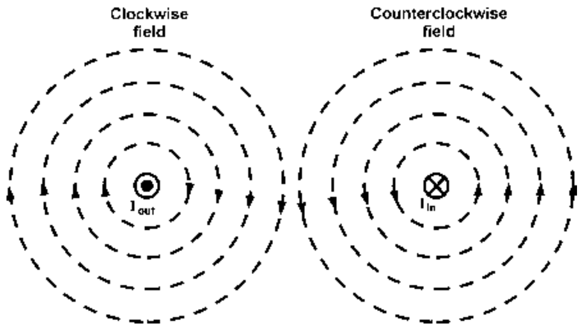


Fig. 2.21. Magnetic fields aiding between parallel conductors with opposite directions of current.

MAGNETIC POLARITY OF A COIL

Bending a straight conductor into the form of a loop, as shown in (Fig.2.22), has two effects. First, the magnetic field lines are more dense inside the loop. The total number of lines is the same as for the straight conductor, but inside the loop the lines are concentrated in a smaller space. Furthermore, all the lines inside the loop are aiding in the same direction. This makes the loop field effectively the same as bar magnet with opposite poles at opposite faces at the loop.

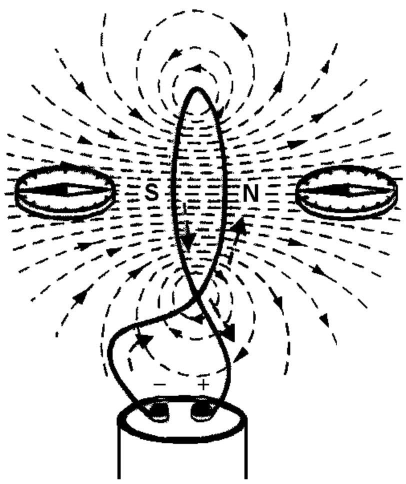


Fig. 2.22. Magnetic poles of a current loop.

SOLENOID AS A BAR MAGNET

A coil of wire conductor with more than one turn is generally called a solenoid. An ideal solenoid, however, has a length much greater than its diameter. Like a single loop, the solenoid concentrates the magnetic field inside the coil and provides opposite magnetic poles at the ends. These effects are multiplied, however, by the number of turns as the magnetic field lines aid each other in the same direction inside the coil. Outside the coil, the field corresponds to a bar magnet with north and south poles at opposite ends, as illustrated in (Fig. 2.23).

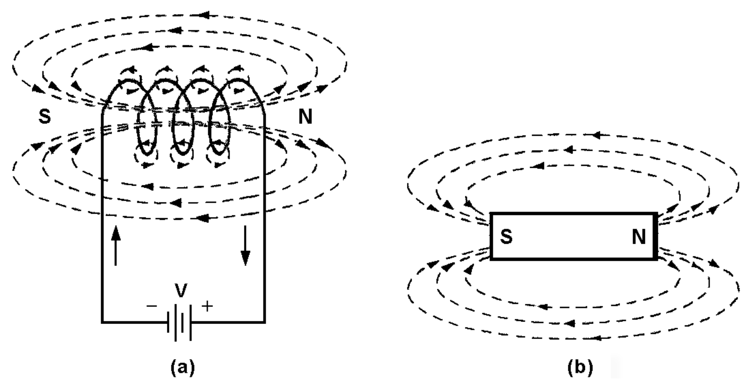


Fig. 2.23. Magnetic poles of a solenoid (a) Coil winding (b) Equivalent bar magnet.

MAGNETIC POLARITY

To determine the magnetic polarity, use the left hand rule illustrated in (Fig. 2.24). If the coil is grasped with the fingers of the left hand curled around the coil in the direction of electron flow, the thumb points to the north pole of the coil. The left hand is used here because the current is electron flow.

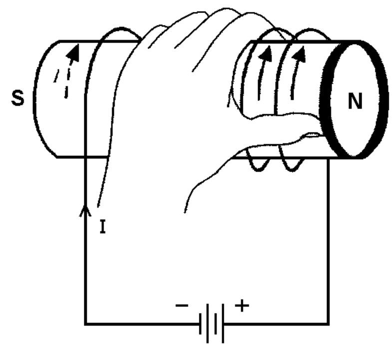


Fig. 2.24. Left-hand rule for north pole of a coil with current I. The I is electron flow.

The solenoid acts like a bar magnet whether it has an iron core or not. Adding an iron core increases the flux density inside the coil. In addition, the field strength then is uniform for the entire length of the core. The polarity is the same, however, for air-core and iron-core coils.

The magnetic polarity depends on the direction of current flow and the direction of winding. The current is determined by the connections to the voltage source. Electron flow is from the negative side of the voltage source, through the coil, and back to the positive terminal.

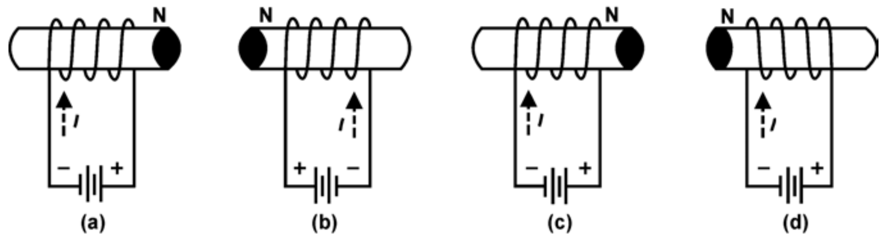


Fig. 2.25. Example for determining the magnet polarity of a coil with direct current I. The I is electron flow. The polarities are reversed in (a) and (b) because the battery is reversed to reverse the direction of current. Also, (d) is the opposite of (c) because of the reversed winding.

The direction of winding can be over and under, starting from one end of the coil, or under and over with respect to the same starting point. Reversing either the direction of winding or the direction of current reverses the magnetic poles of the solenoid. (See Fig. 2.25). With both reversed, though, the polarity is the same.

MOTOR ACTION BETWEEN TWO MAGNETIC FIELDS

The physical motion resulting from the forces of magnetic fields is called motor action. One example is the simple attraction or repulsion between bar magnets.

We know that like poles repel and unlike poles attract. It can also be considered that fields in the same direction repel and opposite fields attract.

Consider the repulsion between two north poles, illustrated on the next page in (Fig. 2.26). Similar poles have fields in the same direction. Therefore, the similar fields of the two like poles repel each other.

A more fundamental reason for motor action, however, is the fact that the force in a magnetic field tends to produce motion from a stronger field toward a weaker field. In (Fig. 2.26), note that the field intensity is greatest in the space between the two north poles. Here the field lines of similar poles in both magnets reinforce in the same direction. Farther away the field intensity is less, for essentially one magnet only. As a result there is a difference in field strength, providing a net force that tends to produce motion. The direction of motion is always toward the weaker field.

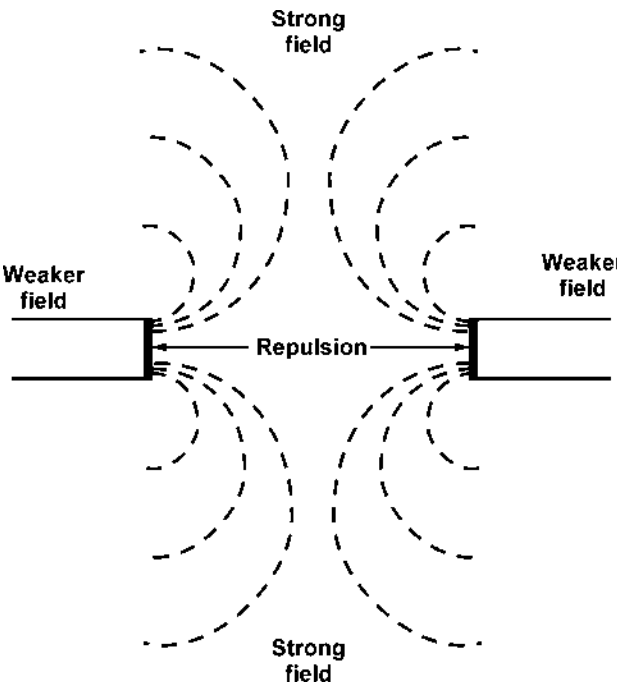


Fig. 2.26. Repulsion between similar poles of two bar magnets. The motion is from the stronger field to the weaker field.

To remember the directions, we can consider that the stronger field moves to the weaker field, tending to equalize the filed intensity. Otherwise, the motion would make the strong field stronger and the weak field weaker. This must be impossible, because then the magnetic field would multiply its own strength without any work being added.

FORCE ON A STRAIGHT CONDUCTOR IN A MAGNETIC FIELD

Current in a conductor has its associated magnetic field. When this conductor is placed in another magnetic field from a separate source, the two fields can react to produce motor action. The conductor must be perpendicular to the magnetic field, however, as shown in (Fig. 2.27). This way, the perpendicular magnetic field produced by the current then is in the same plane as the external magnetic field.

Unless the two fields are in the same plane, they cannot affect each other. In the same plane, however, lines of force in the same direction reinforce to make a stronger field, whereas lines in the opposite direction cancel and result in a weaker field.

1. With the conductor at 90^0, or perpendicular to the external field, the reaction between the two magnetic fields is maximum.
2. With the conductor at 0^0, or parallel to the external field, there is not effect between them.
3. When the conductor is at an angle between 0 and 90^0, only the perpendicular component is effective.

In (Fig. 2.27), electrons flow in the wire conductor in the plane of the paper, from the bottom to the top of the page. This flow provides the counterclockwise field H_I around the wire, in a perpendicular plane cutting through the paper. The external field H_M has lines of force from left to right in the plane of the paper. Then lines of force in the two fields are parallel above and below the wire.

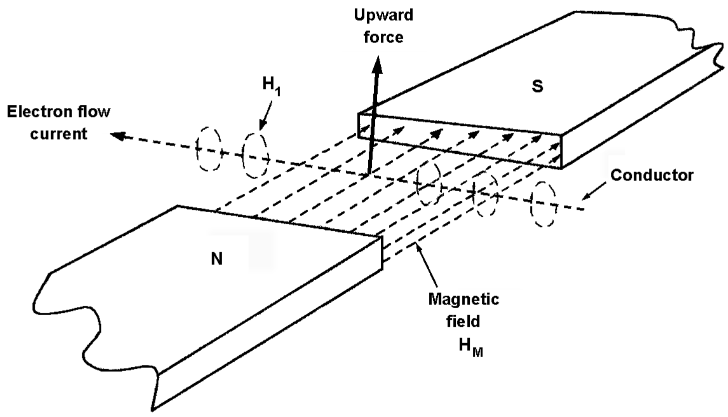


Fig. 2.27. Motor action of current in a straight conductor when it is in an external magnetic field. The H_I is the circular field of the current. The H_M indicates field lines between the north and south poles of the external magnet.

Below the conductor, its field lines are left to right in the same direction as the external field. Therefore, these lines reinforce to produce a stronger field. Above the conductor the lines of the two fields are in opposite directions, causing a weaker field. As a result, the net force of the stronger field makes the conductor move upward out of the page, toward the weaker field.

If electrons flow in the reverse direction in the conductor, or if the external field is reversed, the motor action will be in the opposite direction. Reversing both the field and the current, however, results in the same direction of motion.

ROTATION OF A CONDUCTOR LOOP IN A MAGNETIC FIELD

With a loop of wire in the magnetic field, opposite sides of the loop have current in opposite directions. Then the associated magnetic fields are opposite. The resulting forces are upward on one side of the loop and downward on the other side, making it rotate. This effect of a force in producing rotation is called torque.

The principle of motor action between magnetic fields producing rotational torque is the basis of all electric motors. Also, the moving-coil meter described in Sec. 8-1 is a similar application. Since the torque is proportional to current, the amount of rotation indicates how much current flows through the coil.

INDUCED CURRENT

Just as electrons in motion provide an associated magnetic field, when magnetic flux moves, the motion of magnetic lines cutting across a conductor forces free electrons in the conductor to move, producing current. This action is called induction because there is no physical connection between the magnet and the conductor. The induced current is a result of generator action as the mechanical work put into moving the magnetic field is converted into electric energy when current flows in the conductor.

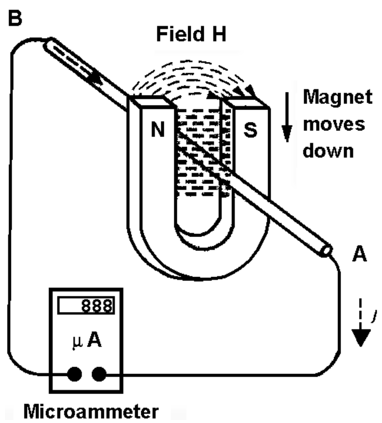


Fig. 2.28. Induced current produced by magnetic flux cutting across a conductor. Direction of I here is for electron flow.

Referring to (Fig. 2.28), let the conductor AB be placed at right angles to the flux in the air gap of the horseshoe magnet. Then, when the magnet is moved up or down, its flux cuts across the conductor. The action of magnetic flux cutting across the conductor generates current. The fact that current flows is indicated by the microammeter.

When the magnet is moved downward, current flows in the direction shown. If the magnet is moved upward, current will flow in the opposite direction. Without motion, there is no current.

DIRECTION OF MOTION

Motion is necessary in order to have the flux lines of the magnetic field cut across the conductor. This cutting can be accomplished by motion of either the field or the conductor. When the conductor is moved upward or downward, it cuts across the flux. The generator action is the same as moving the field, except that the relative motion is opposite. Moving the conductor upward, for instance, corresponds to moving the magnet downward.

CONDUCTOR PERPENDICULAR TO EXTERNAL FLUX

In order to have electromagnetic induction, the conductor and the magnetic lines of flux must be perpendicular to each other. Then the motion makes the flux cut through the cross-sectional area of the conductor. As shown in (Fig. 2.33), the conductor is at right angles to the lines of force in the field H.

The reason the conductor must be perpendicular is to make its induced current have an associated magnetic field in the same plane as the external flux. If the field of the induced current does not react with the external field, there can be no induced current.

HOW INDUCED CURRENT IS GENERATED

The induced current can be considered the result of motor action between the external field H and the magnetic field of free electrons in every cross-sectional area of the wire. Without an external field, the free electrons move at random without any specific direction, and they have no net magnetic field. When the conductor is in the magnetic field H, there still is no induction without relative motion, since the magnetic fields for the free electrons are not disturbed. When the field or conductor moves, however, there must be reaction opposing the motion. The reaction is a flow of free electrons resulting from motor action on the electrons.

Referring to (Fig. 2.29), for example, the induced current must flow in the direction shown because the field is moved downward, pulling the magnet away from the conductor. The induced current of electrons then has a clockwise field, with lines of force aiding H above the conductor and cancelling H below. With motor action between the two magnetic fields tending to move the conductor toward the weaker field, the conductor will be forced downward, staying with the magnet to oppose the work of pulling the magnet away from the conductor.

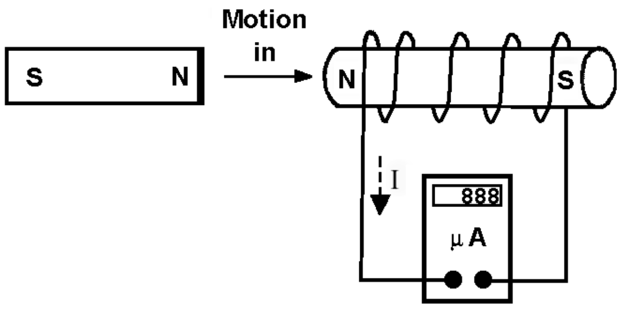


Fig. 2.29. Induced current produced by magnetic flux cutting across turns of wire in a coil. Direction of I here is for electron flow.

The effect of electromagnetic induction is increased where a coil is used for the conductor. Then the turns concentrate more conductor length in a smaller area. As illustrated in (Fig. 2.34), moving the magnet into the coil enables the flux to cut across turns of conductors.

LENZ'S LAW

Lenz's law is the basic principle that is used to determine the direction of an induced voltage or current. Based on principle of conservation of energy, the law simply states that the direction of the induced current must be such that its own magnetic field will oppose the action that produced the induced current.

In (Fig.2.33), for example, the induced current has the direction that produces a north pole at the left to oppose the motion by repulsion of the north pole being moved in. This is why it takes some work to push the permanent magnet into the coil. The work expended in moving the permanent magnet is the source of energy for the current induced in the coil. Using Lenz's law, we can start with the fact that the left end of the coil in (Fig. 2.33) must be north pole to oppose the motion. Then the direction of the induced current is determined by the left-hand rule for electron flow. If the fingers coil around the direction of electron flow shown, under and over the winding, the thumb will point to the left for the north pole.

For the opposite case, suppose that the north pole of the permanent magnet in (Fig. 2.29) is moved away from the coil. Then the induced pole at the left end of the coil must be a south pole, by Lenz's law. The induced south pole will attract the north pole to oppose the motion of the magnet being moved away. For a south pole at the left end of the coil, then, the electron flow will be reversed from the direction shown in (Fig. 2.29). We could actually generate an alternating current in the coil by moving the magnet periodically in and out.

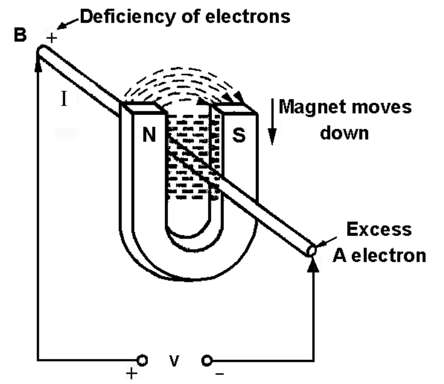


Fig. 2.30. Voltage induced across open ends of conductor cut by magnetic flux.

GENERATING AN INDUCED VOLTAGE

Consider the case of magnetic flux cutting a conductor that is not in a closed circuit, as shown in (Fig. 2.30). The motion of flux across the conductor forces free electrons to move, but with an open circuit, the displaced electrons produce opposite electric charges at the two open ends.

For the directions shown, free electrons in the conductor are forced to move to point A. Since the end is open, electrons accumulate here. Point A then develops a negative potential.

At the same time, point B loses electrons and becomes charged positive. The result is a potential difference across the two ends, provided by the separation of electric charges in the conductor.

The potential difference is an electromotive force (emf), generated by the work of cutting across the flux. You can measure this potential difference with a voltmeter. However, a conductor cannot store electric charge. Therefore, the voltage is present only while the motion of flux cutting across the conductor is producing the induced voltage.

Induced Voltage across a Coil

With a coil , as in Fig. 2.31 (a), the induced emf is increased by the number of turns. Each turn cut by flux adds to the induced voltage, since each turn cut forces free electrons to accumulate at the negative end of the coil, with a deficiency of electrons at the positive end.

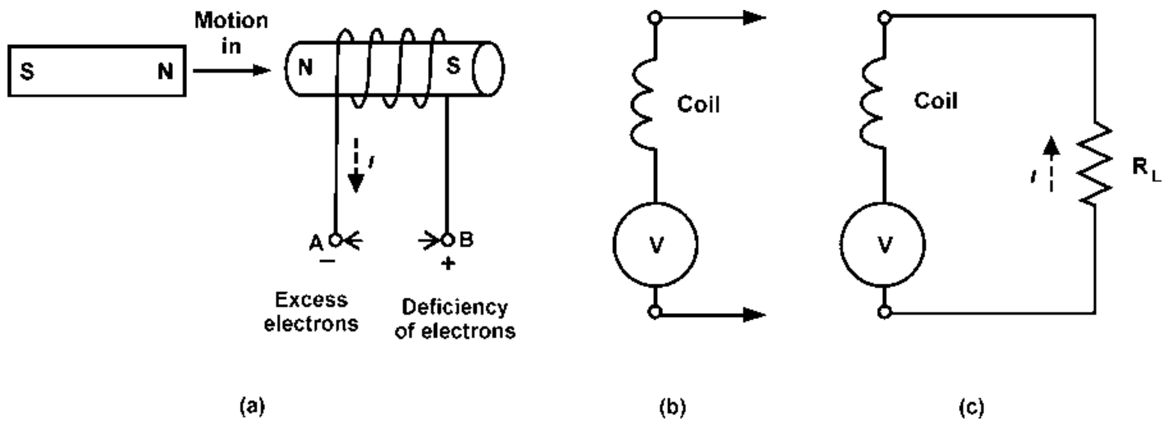


Fig. 2.31. Voltage induced across coil cut by magnetic flux. (a) Motion of flux generating voltage across coil. (b) Induced voltage acts in series with coil. (c) Induced voltage is a source that can produce current in an external load resistor R_L connected across coil.

The polarity of the induced voltage follows from the direction of induced current. The end of the conductor to which the electrons go and at which they accumulate is the negative side of the induced voltage. The opposite end, with a deficiency of electrons, is the positive side. The total emf across the coil is the sum of the induced voltages, since all the turns are in series.

Furthermore, the total induced voltage acts in series with the coil, as illustrated by the equivalent circuit in Fig. 2.31 (b), showing the induced voltage as a separate generator. This generator represents a voltage source with a potential difference resulting from the separation of charges produced by electromageneic induction. The source v then can produce current in an external load circuit connected across the negative and positive terminals, as shown in Fig. 2.31(c).

The induced voltage is in series with the coil because current produced by the generated emf must flow through all the turns. An induced voltage of 10 V, for example, with R_L equal to 5 Ω, results in a current of 2 A, which flows through the coil, the equivalent generator v, and the load resistance R_L.

The direction of current in Fig. 2.31(c) shows electron flow around the circuit. Outside the source v, the electrons move from its negative terminal, through R_L, and back to the positive terminal of v because of its potential difference.

Inside the generator, however, the electron flow is from the + terminal to the - terminal. This direction of electron flow results from the fact that the left end of the coil in Fig. 2.31(a) must be a north pole, by Lenz' law, to opose the north pole being moved in.

Notice how motors and generators are similar in using the motion of a magnetic field, but with opposite applications. In a motor, current is supplied so that an associated magnetic field can react with the external flux to produce motion of the conductor. In a generator, motion must be supplied so that the flux and conductor can cut across each other to induce voltage across the ends of the conductor.

FARADAY'S LAW OF INDUCED VOLTAGE

The voltage induced by magnetic flux cutting the turns of a coil depends upon the number of turns and how fast the flux moves across the conductor. Either the flux or the conductor can move. Specifically, the amount of induced voltage is determined by the following three factors.

1. Amount of flux. The more magnetic lines of force that cut across the conductor, the higher the amount of induced voltage.
2. Number of turns. The more turn in a coil, the higher the induced voltage. The v_{ind} is the sum of all the individual voltages generated in each turn in series.
3. Time rate of cutting. The faster the flux cuts a conductor, the higher the induced voltage. Then more lines of force cut the conductor within a specific period of time.

These factors are of fundamental importance in many applications. Any conductor with current will have voltage induced in it by a change in current and its associated magnetic flux.
The amount of induced voltage can be calculated by Faraday's law.

$$v_{ind} = N\frac{d\phi\,(\text{webers})}{dt\,(\text{seconds})} \qquad (2-1)$$

where N is the number of turns and $d\phi/dt$ specifies how fast the flux ϕ cuts across the conductor. With $d\phi/dt$ in webers per second, the induced voltage is in volts.
As an example, suppose that magnetic flux cuts across 300 turns at the rate of 2 Wb/s.
The calculate the induced voltage,

$$v_{ind} = N\frac{d\phi}{dt}$$

$$= 300 \times 2$$

$$v_{ind} = 600\text{V}$$

It is assumed that all the flux links all the turns, which is true with an iron core.

TIME RATE OF CHANGE

The symbol d in $d\phi$ and dt is an abbreviation for change. The $d\phi$ means a change in the flux ϕ, and dt means a change in time. In mathematics, dt represents an infinitesimally small change in time but in this book we are using the d to mean rate of change in general. The results are exactly the same for the practical changes used here because the rate of change is constant.

As an example, if the flux ϕ is 4 Wb one time but then changes to 6 Wb, the change in flux $d\phi$ is 2Wb. The same idea applies to a decrease as well as an increase. If the flux changed from 6 to 4 Wb, $d\phi$ would still be 2 Wb. However, an increase is usually considered a change in the positive direction, with an upward slope, whereas a decrease has a negative slope downward.

Similarly, dt means a change in time. If we consider the flux at a time 2 s after the start and at a later time 3 s after the start, the change in time is 3 - 2, or 1 s for dt. Time always increases in the positive direction.

Combining the two factors of $d\phi$ and dt, we can say that for magnetic flux increasing by 2 Wb in 1 s, $d\phi/dt$ equals 2/1, 2 Wb/s. This states the time rate of change of the magnetic flux.

As another example, suppose that the flux increases by 2 Wb in the time of ½ or 0.5 s. Then

$$\frac{d\phi}{dt} = \frac{2\text{ Wb}}{0.5\text{ s}} = 4\text{ Wb/s}$$

ANALYSIS OF INDUCED VOLTAGE AS N (dϕ/dt)

This fundamental concept of voltage induced by a change in flux is illustrated by the graph in Fig. 2.32, for the values listed in Table 2.1. The linear rise in Fig. 2.32 (a) shows values of flux ϕ increasing at a uniform rate. In this case, the curve goes up 2 Wb for every 1-s interval of time. The slope of this curve, then, equal to dϕ/dt, is 2 Wb/s. Note that, although ϕ increases, the rate of change in constant because the linear rise has a constant slope.

TABLE 2.1 INDUCED-VOLTAGE CALCULATIONS FOR FIG. 2.32

ϕ, Wb	dϕ, Wb	t,s	dt, s	dϕ/dt, Wb/s	N, TURNS	N(dϕ/dt), v
2	2	1	1	2	300	600
4	2	2	1	2	300	600
6	2	3	1	2	300	600
8	2	4	1	2	300	600

For induced voltage, only the dϕ/dt factor is important, not the actual value of flux. To emphasize this basic concept, the graph in Fig. 2.32(b) shows the dϕ/dt values alone. This graph is just a straight horizontal line for the constant value of 2 Wb/s.

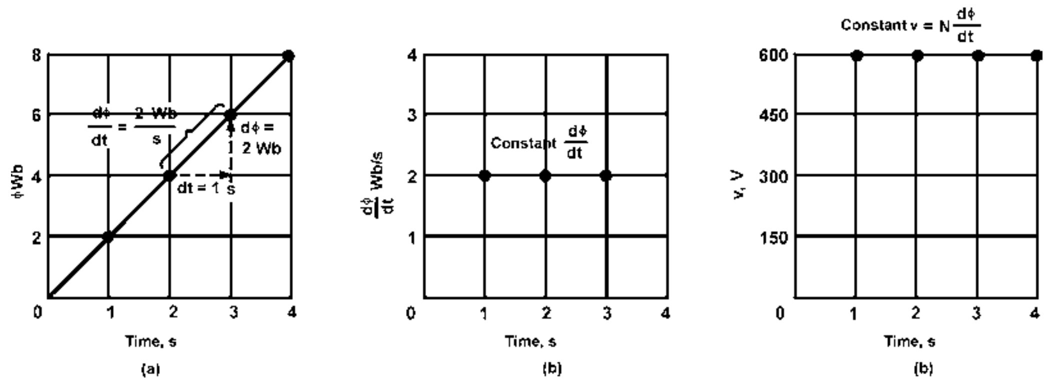


Fig. 2.32. Graphs of induced voltage produced by magnetic flux changes in a coil. (a) Linear increase of flux ϕ. (b) Constant rate of change for dϕ/dt at w Wb/s. (c) Constant induced voltage of 600 V, for a coil with 300 turns.

The induced - voltage graph in Fig. 2.32(c) is also a straight horizontal line. Since $v_{ind} = N(d\phi / dt)$, the graph of induced voltage is just the dϕ/dt values multiplied by the number of turns. The result is constant 600 V, with 300 turns cut by flux changing at the constant rate of 2 Wb/s.

The example illustrated here can be different in several ways without changing the basic fact that the induced voltage is equal to N(dϕ/dt). First, the number of turns or the dϕ/dt values can be greater than the values assumed here, or less. More turns will provide more induced voltage, whereas fewer turns mean less voltage. Similarly, a higher value for dϕ/dt results in more induced voltage.

Note that two factors are included in dϕ/dt. Its value can be increased by a higher value of dϕ or a smaller value of dt. As an example, the value of 2 Wb/s for dϕ/dt is 4/1 or 2/0.5, which equals 4 Wb/s in either case. The same flux changing within a shorter time means a faster rate of flux cutting the conductor, resulting in a higher value of dϕ/dt and more induced voltage.

For the opposite case, a smaller value of dϕ/dt, with less flux or a slower rate of change, resulting in a lower value of induced voltage. As dϕ/dt decreases, the induced voltage will reverse polarity.

Finally, it should be noted that the dϕ/dt graph in Fig. 2.32(b) has the constant value of 2 Wb/s because the flux is increasing at a linear rate. However, the flux need not have a uniform rate of change. Then the dϕ/dt values will not be constant. In any case, though, the values of dϕ/dt at all instants of time will determine the values of the induced voltage equal to N(dϕ/dt).

POLARITY OF THE INDUCED VOLTAGE

The polarity is determined by Lenz's law. Any induced voltage has the polarity that oppose the change causing the induction. Sometimes this fact is indicated by using a negative sign for v_{ind} in formula (2-1). However, the absolute polarity depends on whether the flux is increasing or decreasing, the method of winding, and which end of the coil is reference.

When all these factors are considered, v_{ind} has the polarity such that the current it produced and the associated magnetic field will oppose the change in flux producing the induced voltage. If the external flux increases, the magnetic field of the induced current will be in the opposite direction. IF the external field decreases, the magnetic field of the induced current will be in the same direction as the external field to oppose the change by sustaining the flux. In short, the induced voltage has the polarity that opposes the change.

STATICALLY INDUCED E.M.F.

It can be further sub-divided into (a) mutually induced e.m.f. and (b) self-induced e.m.f.

(a) Mutually-induced e.m.f.

Consider two coils A and B laying close to each other (Fig. 2.33).

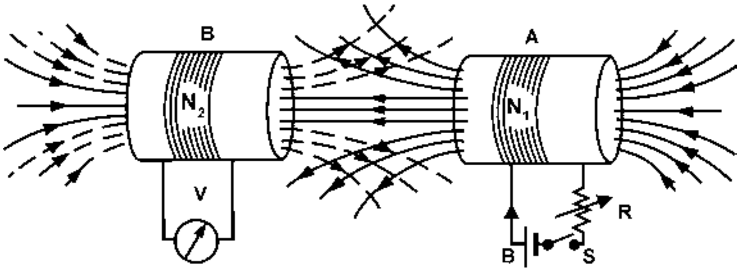


Fig. 2.33.

Coil A is joined to battery, a switch and a variable resistance R whereas coil B is connected to a sensitive voltmeter V. When current through A is established by closing the switch, its magnetic field is set up which partly links with or threads through the coil B. As current through A is changed, the flux linked with B is also changed. Hence, mutually induce e.m.f. is produced in B whose magnitude is given by Faraday's Laws and direction by Lenz's Law .

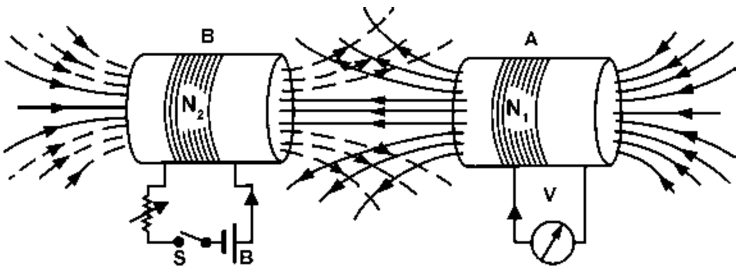


Fig. 2.34.

If now, battery is connected to B and the voltmeter across A (Fig. 2.34), then the situation is reversed and now a change of current in B will produce mutually-induced e.m.f. in A.

It is obvious that in the examples considered above, there is no movement of any conductor, the flux variations being brought about by variations in current strength only. Such an e.m.f. induced in one coil by the influence of the other coil is called (statically but) mutually induced e.m.f.

(b) Self-induced e.m.f.

This is the e.m.f. induced in a coil due to the change of its own flux linked with it. If current through the coil (Fig. 2.35) is changed, then the flux linked with its own turns will also change, which will produced in its what is called self-induced e.m.f. The direction of this induced e.m.f (as given by Lenz's law) would be such as to oppose any change of flux which is, in fact, very cause of its production. Hence, it is also known as the opposing or counter e.m.f. or self induction.

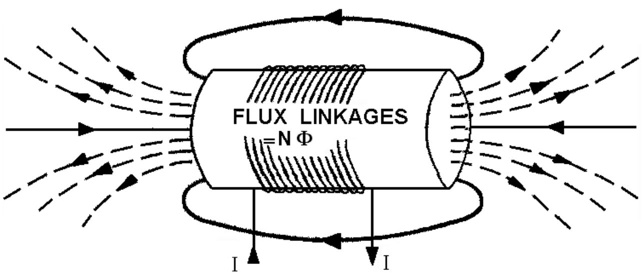


Fig. 2.35.

SELF INDUCTANCE

Imagine a coil of wire similar to the one shown in (Fig. 2.35) connected to a battery through a rheostate. It is found that whenever an effort is made to increase current (and hence flux) through it, it is always opposed by the instantaneous produced of counter e.m.f. of self-induction. Energy required to overcome this opposition is supplied by the battery. As will be fully explained later on, this energy is stored in the additional flux produced.

If, now an effort is made to decrease the current (and hence the flux), then again it is delayed due to the production of self-induced e.m.f., this time in the opposite direction. This property of the coil due to which it opposes any increase or decrease or current of flux through, it, is known as self inductance. It is quantitatively measured in terms of coefficient of self induction L. This property is analogous to inertia in a material body. We know by experience that initially it is difficult to set a heavy body into motion, but once in motion, it is equally difficult to stop it. Similarly, in a coil having large self-induction, it is initially difficult to establish a current through it, but once established, it is equally difficult to withdraw it. Hence, self-induction is sometimes analogously called electrical inertia or electromagnetic inertia.

COEFFICIENT OF SELF-INDUCTION (L)

It may be defined in any one of the three ways given below :

(i) First Method for L

The coefficient of self-induction of a coil is defined as

the weber - turns per ampere in the coil

By 'weber-turns' is meant the product of flux in webers and the number of turns with which the flux is linked. In other words, it is the flux-linkage of the coil.

Consider a solenoid having N turns and carrying a current of I amperes. If the flux produced is Φ webers, the weber-turns are NΦ. Hence, weber-turns per ampere are NΦ/I.

By definition, $L = \frac{N\phi}{I}$. The unit of self-induction is henry *.

If in the above relation, $N\Phi = 1$ Wb-turn, I= 1 ampere, then L = 1 henry (H)

Hence a coil is said to have a self-inductance of one henry if a current of 1 ampere when flowing through it produced flux linkages of 1 Wb-turn in it.

Therefore, the above relation becomes $L = \frac{N\Phi}{I}$ henry

*** After the American scientist Joseph Henry (1797-1878), a company of Faraday.**

MUTUAL INDUCTANCE

In (Fig.2.33) we have that any change of current in coil A is always accompanied by the production of mutually-induced e.m.f. in coil B. Mutual inductance may, therefore, be defined as the ability of one coil (or circuit) to produce an e.m.f. in a nearby coil by when the current in the first coil changes. This action being reciprocal, the second coil can also induce an e.m.f. in the first when current in the second coil changes. This ability of reciprocal induction is measured in terms of the coefficient of mutual induction M.

COEFFICIENT OF MUTUAL INDUCTANCE (M)

It can also be defined in three ways as given below :

(i) First Method for M

Let there be two magnetically -coupled coils have N_1 and N_2 turns respectively (Fig. 2.35). Coefficient of mutual inductance between the two coils is defined as

the weber - turns in one coil due to one ampere current in the other.

Let a current I_1 ampere when flowing in the first coil produce a flux Φ_1 webers in it. It is supposed that whole of this flux links with the turns of second coil*. Then, flux-linkage i.e., webers-turns in the second coil for unit current in the first coil are $N_2 \Phi_1 / I_1$. Hence, by definition

$$M = \frac{N_2 \Phi_1}{I_1}$$

If weber-turns in second coil due to one ampere current in the first coil i.e. $N_2 \Phi_1 / I_1 = 1$ then, as seen from above, M = 1H. Hence, two coils are said to have a mutual inductance of 1 henry is one ampere current when flowing in one coil produces flux linkages of one Wb-turn in the other.

■■■

CHAPTER - 3
DETAILED KNOWLEDGE OF THE ALTERNATING CURRENT AND CALCULATION OF INSTANTANEOUS VALUE, RMS VALUE FREQUENCY AND AMPLITUDE FROM THE GIVEN DATA, STAR AND DELTA CONNECTIONS AND CALCULATION OF POWER IN THREE PHASE SYSTEM

ALTERNATING CURRENT APPLICATION

Fig. 3.1 shows the output from an ac voltage generator, with the reversals between positive and negative polarities and the variations in amplitude. In Fig. 3.1 (a), the waveform shown simulates an ac voltage as it would appear on the screen of an oscilloscope, which is an important test instrument for ac voltages. The oscilloscope shows a picture of any ac voltage connected to its input terminals. It also indicates the amplitude. The details of how to use the oscilloscope for ac voltage measurement are explained in App. D, "Using the Oscilloscope".

In Fig. 3.1 (b), the graph of the ac waveform shows how the output from the generator in Fig. 3.1 (c) varies with respect to time. Assume that this graph shows V at terminal 2 with respect to terminal 1. Then the voltage at terminal 1 corresponds to the zero axis in the graph as reference level. At terminal 2, the output voltage has positive amplitude variations from zero up to the peak value and down to zero. All these voltage values are with respect to terminal 1. After a half cycle, the voltage at terminal 2 becomes negative, still with respect to the other terminal. Then the same voltage variations are repeated at terminal 2, but they have negative polarity compared to the reference level. It should be noted that if we take the voltage at terminal 1 with terminal 2 as the reference, the waveform in Fig. 3.1 (b) would have the same shape but the inverted in polarity. The negative half-cycle would come first, but it does not matter which is first or second.

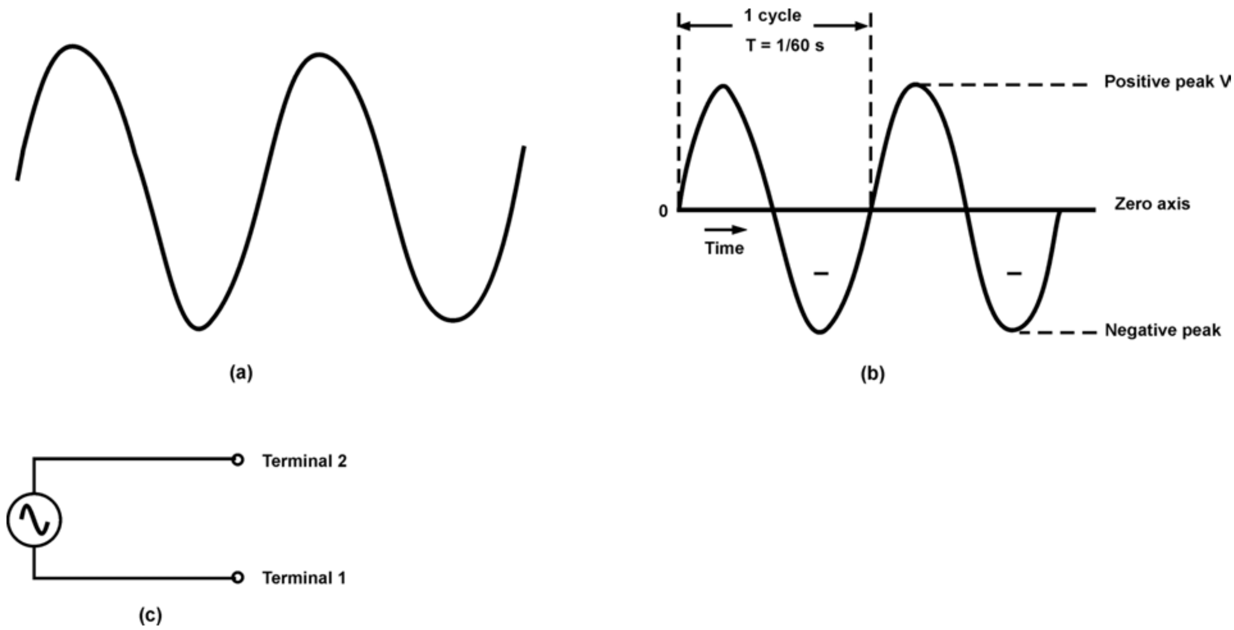


Fig. 3.1. Wave form of ac power-line voltage with frequency of 60 Hz. two cycles are shown. (a) Oscilloscope readout. (b) Details of waveform and alternating polarities. (c) Symbol for an ac voltage source.

The characteristics of varying values is the reason why ac circuit have so many uses. For instance, a transformer can operate only with alternating current, to step up or step down an ac voltage. The reason is that the changing current produces changes in its associated magnetic field. This application is just an example of inductance L in ac circuit, where the changing magnetic flux of a varying current can produce induced voltage.

A similar but opposite effect in ac circuits is capacitance C. The capacitance is important with the changing electric field of a varying voltage. Just as L has an effect with alternating current, C has an effect that depends on alternating voltage.

The L and C are additional factors, besides resistance R, in the operation of ac circuit. It should be noted that R in the operation same for either a dc or an ac circuit. However, the effects of L and C depend on having an ac source. The rate at which the ac variations occur, which determines the frequency, allows a greater or lesser reaction by L and C. Therefore, the effect is different for different frequencies. One important application is a resonant circuit with L and C that is tuned to a particular frequency. Tuning in radio and television stations is an application of resonance in an LC circuit.

In general, electronic circuit are combinations of R, L and C with both direct current and alternating current. The audio, video, and radio signals are ac voltage and currents. However, the amplifiers that use transistors need dc voltages in order to conduct any current in all. The resulting output of an amplifier circuit, therefore, consists of direct current with a superimposed ac signal.

ALTERNATING - VOLTAGE GENERATOR

We can define an ac voltage as one that continuously varies in magnitude and periodically reverses in polarity. In (Fig.3.1), the variations up and down on the waveform show the changes in magnitude. The zero axis is a horizontal lines across the center. Then voltages above the center have positive polarity, and values below center are negative polarity.

On the next, (Fig.3.2) shows how such a voltage waveform is produced by a rotary generator. The conductor loop rotates through the magnetic field to generate the induced ac voltage across its open terminals. The magnetic flux shown here is vertical, with lines of force down in the plane of the paper.

In Fig.3.2 (a) the loop is in its horizontal starting position in a plane perpendicular to the paper. When the loop rotates counterclockwise, the two longer conductors move around a circle. Note that in the flat position shown, the two long conductors of the loop move vertically up or down but parallel to the vertical flux lines. In this position, motion of the loop does not induce a voltage because the conductors are not cutting across the flux.

When the loop rotates through the upright position in Fig.3.2 (b), however, the conductors cut across the flux, producing maximum induced voltage. The shorter connecting wires in the loop do not have any appreciable voltage induced in them.

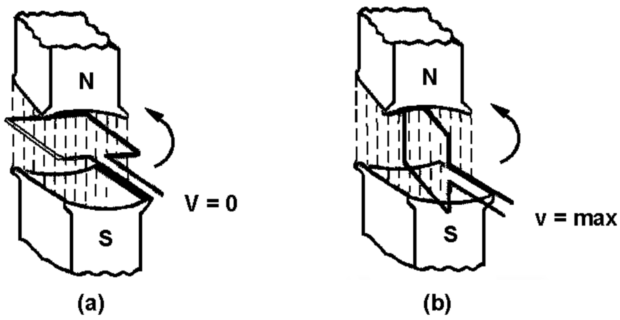


Fig. 3.2. Loop rotating in magnetic field to produce induced voltage v with alternating polarities. (a) Loop conductors moving parallel to magnetic field results in zero voltage. (b) Loop conductors cutting across magnetic field produce maximum induced voltage.

Each of the longer conductors has opposite polarity of induced voltage because the conductor at the top is moving to the left while the bottom conductor is moving to the right. The amount of voltage varies from zero to maximum as the loop moves from a flat position to upright, where it can cut across the flux. Also, the polarity at the terminals of the loop reverse as the motion of each conductor reverses during each half-revolution.

With one revolution of the loop in a complete circle back to the starting position, therefore, the induced voltage provides a potential difference *v* across the loop, varying in the same way as the wave of voltage shown in (Fig. 3.1). If the loop rotates at the speed of 60 revolutions per second, the ac voltage will have the frequency of 60 Hz.

THE CYCLE

One complete revolution of the loop around the circle is a cycle. In (Fig. 3.3), the generator loop is shown in its position at each quarter-turn during one complete cycle. Although not shown, the magnetic field is from top to bottom of the page as in (Fig. 3.2).

At position A in (Fig. 3.3), the loop is flat and moves parallel to the magnetic field, so that the induced voltage is zero. Counterclockwise rotation of the loop moves the dark conductor to the top at position B, where it cuts across the field to produce maximum induced voltage. The polarity of the induced voltage here makes the open end of the dark conductor positive. This conductor at the top is cutting across the flux from right to left. At the same time, the opposite conductor below is moving from left to right, causing its induced voltage to have opposite polarity. Therefore, maximum induced voltage is produced at this time across the two open ends of the loop. Now the top conductor is positive with respect to the bottom conductor.

In the graph of induced voltage values below the loop in (Fig. 3.3), the polarity of the dark conductor is shown with respect to the other conductor. Positive voltage is shown above the zero axis in the graph. As the dark conductor rotates from its starting position parallel to the flux toward the top position, where it cuts maximum flux, more and more induced voltage is produced, with positive polarity.

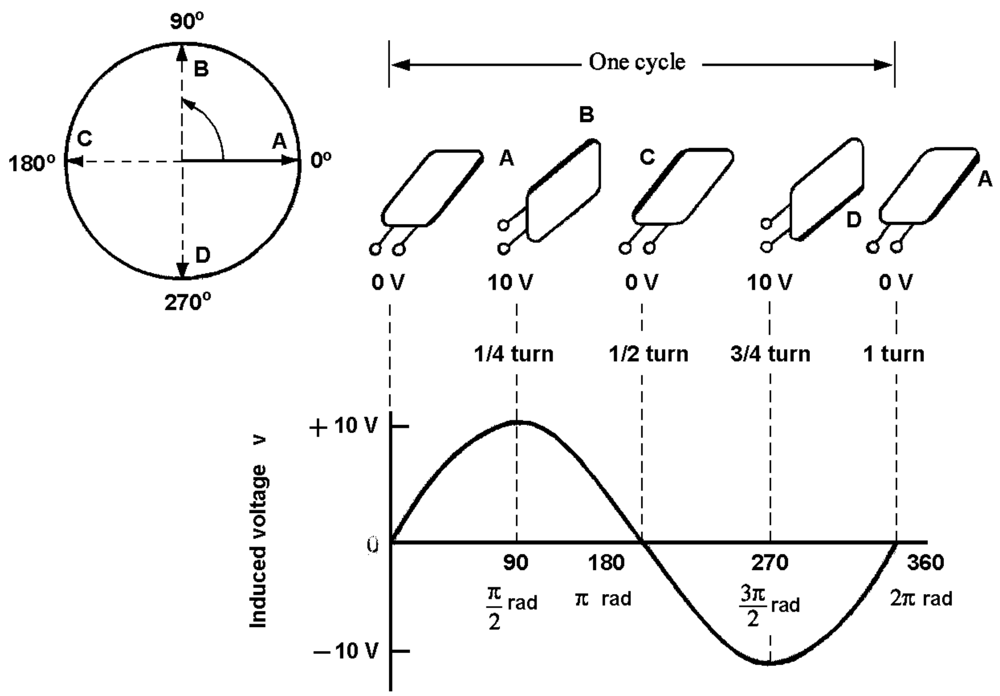


Fig. 3.3. One cycle of alternating voltage generated by rotating loop. Magnetic field, not shown here, is directed from top to bottom, as in Fig. 3.2.

When the loop rotate through the next quarter-turn, it returns to the flat position shown in C, where it cannot cut across flux. Therefore, the induced voltage values shown in the graph decrease from the maximum value to zero at the half-turn, just as the voltage was zero at the start. The half-cycle of revolution is called an alternation.

The next quarter-turn of the loop moves it to the position shown at D in (Fig. 3.3), where the loop cuts across the flux again for maximum induced voltage. Note, however, that here the dark conductor is moving left to right at the bottom of the loop. This motion is reversed from the direction it had when it was at the top, moving right to left. Because the direction of motion is reversed during the second half-revolution, the induced voltage has opposite polarity, with the dark conductor negative. This polarity is shown as negative voltage, below the zero axis. The maximum value of induced voltage at the third quarter-turn is the same as at the first quarter-turn but with opposite polarity.

When the loop completes the last quarter-turn in the cycle, the induced voltages returns to zeros as the loop returns to its flat position at A, the same as the start. This cycle of values of induced voltage is repeated as the loop continues to rotate, with the complete cycle of values, as shown, for each circle of revolution.

Note that zero at the start and zero after the half-turn of an alternation are not the same. At the start, the voltage is zero because the loop is flat, but the dark conductor is moving upward in the direction that produces positive voltage. After one half-cycle, the voltage is zero with the loop flat, but the dark conductor is moving downward in the direction that produces negative voltage. After one complete cycle, the loop and its corresponding waveform of induced voltage are the same as at the start. A cycle can be defined, therefore, as including the variations between two successive points having the same value and varying in the same direction.

ANGULAR MEASURE

Because the cycle of voltage in (Fig. 3.3) corresponds to rotation of the loop around a circle, it is convenient to consider parts of the cycle in angles. The complete circle includes 360°. One half-cycle, or one alternation, is 180° of revolution. A quarter-turn is 90°. The circle next to the loop positions in (Fig. 3.3) illustrate the angular rotation of the dark conductor as it rotates counterclockwise from 0 to 90 to 180° for one half-cycle, then to 270°, and returning to 360° to complete the cycle. Therefore, one cycle corresponds to 360°.

RADIAN MEASURE

In angular measure it is convenient to use a specific unit angle called the radian (abbreviated rad), which is an angle equal to 57.3°. Its convenience is due to the fact that a radian is the angular part of the circle that includes an arc equal to the radius *r* of the circle, as shown in (Fig. 3.4). The circumference around the circle equals $2\pi r$. A circle includes 2π rad, then, as each radian angle includes one length *r* of the circumference. Therefore, one cycle equals 2π rad.

As shown in the graph in (Fig. 3.3), divisions of the cycle can be indicated by angles in either degrees or radian. The comparison between degrees and radian can be summarized as follows :

Zero degree is also zero radian

$360^0 = 2\pi$ rad $\qquad$ $180^0 = \frac{1}{2} \times 2\pi$ rad $= \pi$ rad

$90^0 = \frac{1}{2} \times \pi$ rad $= \pi/2$ rad $\qquad$ $270^0 = 180^0 + 90^0$ or π rad $+ \pi/2$ rad $= 3\pi/2$ rad

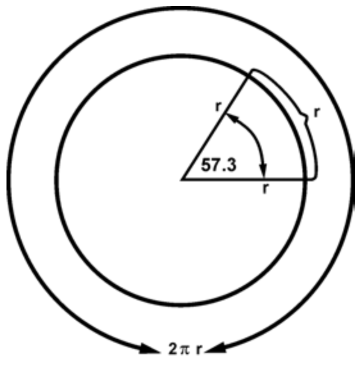


Fig. 3.4. One radian (rad) is the angle equal.

The current 2π in circular measure is numerically equal to 6.2832. This is double the value of 3.1416 for π. The Greek letter π (pi) is used to represent the ratio of the circumference to the diameter for any circle, which always has the numerical value of 3.1416. The fact that 2π rad is 360° can be shown as $2 \times 3.1416 \times 57.3° = 360°$ for a complete cycle.

THE SINE WAVE

The voltage waveform in (Fig. 3.1) and (Fig. 3.3) is called a sine wave, sinusoidal wave, or sinusoid because the amount of induced voltage is proportional to the sine of the angle of rotation in the circular motion producing the voltage. The sine is a trigonometric function* of an angle; it is equal to the ratio of the opposite side to the hypotenuse in a right triangle. This numerical ratio increases from zero for 0° to a maximum value of 1 for 90° as the side opposite the angle becomes larger.

The characteristics of the sine wave ac waveform are :

1. The cycle includes 360° or 2π rad.
2. The polarity reverses each half-cycle.
3. The maximum values are at 90° and 270°.
4. The zero values are at 0 and 180°.
5. The waveform changes its values the fastest when it crosses the zero axis.
6. The waveform changes its values the slowest when it is at its maximum value. The values must stop increasing before they can decrease.

ALTERNATING CURRENT

When a sine wave of alternating voltage is connected across a load resistance, the current that flows in the circuit is also a sine wave. In (Fig. 3.5), let the sine-wave voltage at the left in the diagram be applied across R of 100Ω. The resulting sine wave of alternating current is shown at the right in the diagram. Note that the frequency is the same for *v* and *i*.

During the first alternation of *v* (Fig. 3.5), terminal 1 is positive with respect to terminal 2. Since the direction of electrons flow is from the negative side of *v*, through R, and back to the positive side of *v*, current flows in the direction indicated by arrow A for the half-cycle. This direction is taken as the positive direction of current in the graph for *i*, corresponding to positive values of *v*.

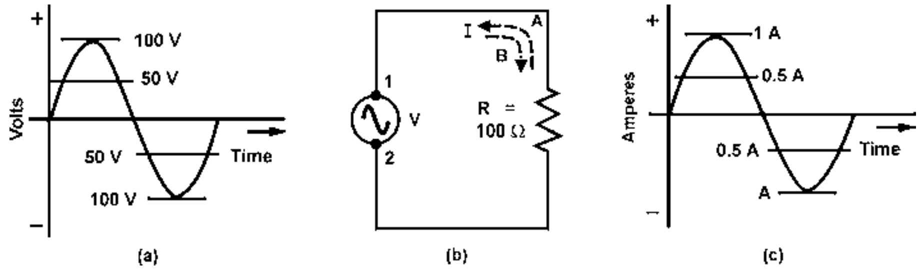


Fig. 3.5. A sine wave of alternating voltage applied across R produce a sine wave of alternating current in the circuit. (a) Waveform of applied voltage. (b) AC circuit. Note the symbol for sine-wave generator V. (c) Wave form of current in the circuit.

The amount of current is equal to *v/R*. If several instantaneous values are taken, when *v* is zero, *i* is zero; when *v* is 50 V, *i*, equals 50 V/100, or 0.5 A; when *v* is 100 V, *i* equals 100 V/ 100, or 1A. For all values of applied voltage with positive polarity, therefore, the current is in one direction, increasing to its maximum value and decreasing to zero, just like the voltage.

On the next half-cycle, the polarity of the alternating voltage reverses. Then terminal 1 is negative with respect to terminal 2. With reversed voltage polarity, current flows in the opposite direction. Electron flow is from terminal 1 of the voltage source, which is now the negative side, through R, and back to terminal 2. This direction of current, as indicated by arrow B in (Fig. 3.5), is negative.

The negative values of *i* in the graph have the same numerical values as the positive values in the first half-cycle, corresponding to the reversed values of applied voltage. As a result, the alternating current in the circuit has sine-wave variations corresponding exactly to the sine-wave alternating voltage.

Only the waveforms for *v* and *i* can be compared. There is no comparison between relative values, because the current and voltage are different quantities.

It is important to note that the negative half-cycle of applied voltage is just as useful as the positive half-cycle in producing current. The only difference is that the reversed polarity of voltage produces the opposite direction of current.

Furthermore, the negative half-cycle of current is just as effective as the positive values when heating the filament to light a bulb. With positive values, electrons flow through the filament in one direction. Negative values produce electron flow in the opposite direction. In both cases, electrons flow from the negative side of the voltage source, through the filament, and return to the positive side of the source. For either direction, the current heats the filament. The direction does not matter, since it is just the motion of electrons against resistance that produces power dissipation. In short, resistance R has the same effect in reducing *I* for either direct current or alternating current.

VOLTAGE AND CURRENT VALUES FOR A SINE WAVE

Since an alternating sine wave of voltage or current has many instantaneous values through the cycle, it is convenient to define specific magnitudes for comparing one wave with another. The peak, average, and root-mean-square (rms) values can be specified, as indicated in (Fig. 3.6). These values can be used for either current or voltage.

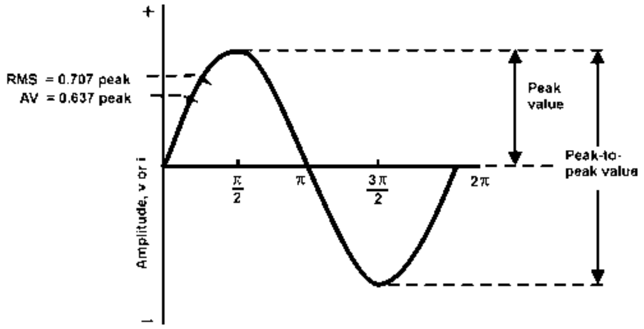


Fig. 3.6. Definitions of important amplitude values for a sine wave of voltage or current.

PEAK VALUE

This is the maximum value V_M or I_M. For example, specifying that a sine wave has a peak value of 170 v states the highest value the sine wave reaches. All other values during the cycle follow a sine wave. The peak value applies to either the positive or the negative peak.

In order to include both the peak amplitude, the peak-to-peak (p-p) value may be specified. For the same example, the peak-to-peak value is 340 V, double the peak value of 170 V, since the positive and negative peaks are symmetrical. It should be noted, though, that the two opposite peak values cannot occur at the same time. Furthermore, in some waveforms the two peaks are not equal.

AVERAGE VALUE

This is an arithmetic average of all the values in a sine wave for one alternation, or half-cycle. The half-cycle is used for the average because over a full cycle the average value is zero, which is useless for comparison purposes. If the sine values for all angles up to 180°, for one alternation, are added and then divided by the number of values, this average equals 0.637. These calculations are shown in Table 3.1.

TABLE - 3.1 DERIVATION OF AVERAGE AND RMS VALUES FOR A SINE-WAVE ALTERNATION

Interval	Angle θ	Sinθ	(Sinθ)²
1	15	0.26	0.07
2	30	0.50	0.25
3	45	0.71	0.50
4	60	0.87	0.75
5	75	0.97	0.93
6	90	1.00	1.00
7*	105	0.97	0.93
8	120	0.87	0.75
9	135	0.71	0.50
10	150	0.50	0.25
11	165	0.26	0.07
12	180	0.00	0.00
	total	7.62	6.00
		Average voltage	RMS value
		$\frac{7.62}{12} = 6.325^{**}$	$\sqrt{6/12} = \sqrt{0.5} = 0.707$

* **For angles between 90° and 180°, sinθ = sin (180°-θ)**

** **More intervals and precise values are needed to get the exact average of 0.637.**

Since the peak value of the sine function is 1 and the average equals 0.637, then

Average value = 0.637 × peak value 3.2

With a peak of 170 V, for example, the average value is 0.637×170 V, which equals approximately 180 V.

ROOT - MEAN SQUARE, OR EFFECTIVE, VALUE

The most common method of specifying the amount of a sine wave of voltage or current is by relating it to the dc voltage and current that will produce the same heating effect. This is called its root-mean-square value, abbreviated rms. The formula is

rms value = 0.707 × peak value 3.3

$V_{rms} = 0.707\ V_{max}$ and $I_{rms} = 0.707\ I_{max}$

With a peak of 170 V, for example, the rms value is 0.707 × 170, or 120 V, approximately. This is a voltage of the commercial ac power line, which is always given in rms value.

It is often necessary to convert from rms to peak value. This can be done by inverting formula (3.3), as follows :

$$\text{Peak} = \frac{1}{0.707} \times \text{rms} = 1.141 \times \text{rms} \qquad 3.4$$

or

$$V_{max} = 1.141 V_{rms} \text{ and } I_{max} = 1.414\, I_{rms}$$

Dividing by 0.707 is the same as multiplying by 1.414.

For example, the commercial power-line voltage with an rms value of 120 V has a peak value of 120 × 1.414, which equals 170 V, approximately. Its peak-to-peak value is 2 × 170, or 340 V, which is double the peak value.

As a formula

$$\text{Peak-to-peak value} = 2.828 \times \text{rms value} \qquad 3.5$$

The factor 0.707 for rms value is derived as the square root of the average (mean) of all the squares of the sine values. If we take the sine for each angle in the cycle, square each value, add all the squares, divide by the number of values added to obtain the average square, and then take the square root of this mean value, the answer is 0.707. These calculations are shown in Table 3.1 for one alternation from 0 to 180°. The results are the same for the opposite alternation.

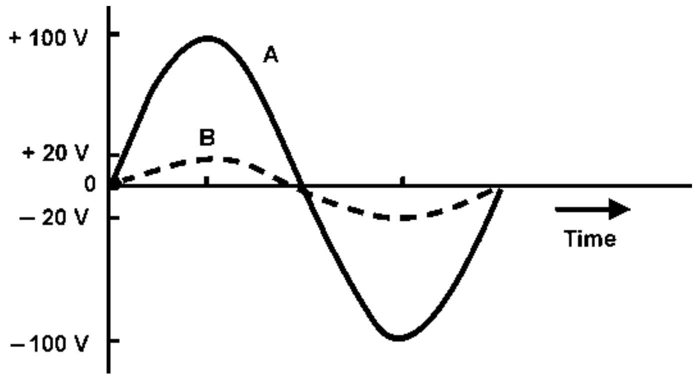


Fig. 3.7. Waveforms A and B have different amplitudes, but they are both sine waves.

The advantage of the rms value derived in terms of the squares of the voltage or current values in that it provides a measure based on the ability of the sine wave to produce power, which is $I^2 R$ or V^2/R. As a result, the rms value of an alternating sine wave corresponds to the same amount of direct current or voltage in heat power. An alternating voltage with an rms value of 120 V, for instance, is just as effective in heating the filament of a light bulb as 120 V from a steady dc voltage source. For this reason, the rms value is also called the effective value.

Unless indicated otherwise, all sine-wave ac measurements are in rms values. The capital letters V and I are used, corresponding to the symbols for dc values. As an example, V = 120 V for the ac power-line voltage.

The ratio of the rms to average values is the form factor. For a sine wave, this ratio is 0.707/0.637 = 1.11

Note that sine waves can have different amplitudes but still follow the sinusoidal waveform. (Fig. 3.7) compares a low-amplitude voltage with a high-amplitude voltage. Although different in amplitude, they are both sine waves. In each wave, the rms value = 0.707 × peak value.

FREQUENCY

The number of cycles per second is the frequency, with the symbol f. In (Fig. 3.3), if the loop rotates through 60 complete revolutions, or cycles, during 1 s, the frequency of the generated voltage is 60 cps, or 60 Hz. You see only one cycle of the sine waveform, instead of 60 cycles, because the time interval shown here is $\frac{1}{60}$ s. Note that the factor of time is involved. More cycles per second means a higher frequency and less time for one cycle, as illustrated in (Fig. 3.8). Then the changes in values are faster for higher frequencies.

A complete cycle is measured between two successive points that have the same value and direction. In (Fig. 3.8) the cycle is between successive points where the waveform is zero and ready to increase in the positive direction. Or the cycle can be measured between successive peaks.

On the time scale of 1 s, waveform a goes through one cycle; waveform b has much faster variations, with four complete cycles during 1 s. Both waveforms are sine waves, even though each has a different frequency.

In comparing sine waves, the amplitude has no relation to frequency. Two waveforms can have the same frequency with different amplitudes (Fig.3.7), the same amplitude but different frequencies (Fig.3.8); or different amplitudes and frequencies. The amplitude indicates how much the voltage or current is , and the frequency indicates the time rate of change of the amplitude variations, in cycles per second.

FREQUENCY UNITS

The unit called the hertz (Hz), named after Heinrich Hertz, is used for cycles per second. Then 60 cps = 60 Hz. All the metric prefixes can be used. As examples

1 kilocycle per second = 1×10^3 Hz = 1 kHz
1 megacycle per second = 1×10^6 Hz = 1 MHz
1 gigacycle per second = 1×10^9 = 1 GHz

AUDIO AND RADIO FREQUENCIES

The entire frequency range of alternating voltage or current from 1 Hz to many megahertz can be considered in two broad groups: audio frequencies (AF) and radio frequencies (RF). Audio is an Latin word meaning "I hear." The audio range includes frequencies that can be heard in the form of sound waves by the human ear. This range of audible frequencies is approximately 16 to 16,000 Hz.

The higher the frequency, the higher the pitch or tone of the sound. High audio frequencies, about 3000 Hz and above, can be considered to provide treble tone. Low audio frequencies, about 300 Hz and below, provide bass tone.

Loudness is determined by amplitude. The greater the amplitude of the AF variation, the louder is its corresponding sound.

Alternating current and voltage above the audio range provide RF variations, since electrical variations of high frequencies can be transmitted by electromagnetic radio wave.

SONIC AND ULTRASONIC FREQUENCIES

These terms refer to sound waves, which are variations in pressure generated by mechanical vibrations, rather than electrical variations. The velocity of transmission for sound waves equals 1130 ft/s, through dry air is 20°C. Sound waves above the audible range of frequencies are called ultrasonic waves. The range of frequencies for ultrasonic applications, therefore, is form 16,000 Hz up to several megahertz. Sound waves in the range of frequencies below 16,000 Hz can be considered sonic or sound frequencies. The term audio is reserved for electrical variations that can be heard when converted to sound waves.

PERIOD

The amount of time it takes to go through one cycle is called the period. Its symbol is T for time. With a frequency of 60 H, as an example, the time for one cycle is $\frac{1}{60}$ s. Therefore, the period is $\frac{1}{60}$ s in this case. The frequency and period are reciprocals of each other :

$$T = \frac{1}{f} \quad \text{or} \quad f = \frac{1}{T} \qquad (3\text{-}6)$$

The higher the frequency, the shorter the period. In Fig. 3.8 (a), the period for the wave, with a frequency of 1 Hz, is 1 s, and the higher-frequency wave of 4 Hz in Fig. 3.8 (b) has the period of $\frac{1}{4}$ s for a complete cycle.

UNITS OF TIME

The second is the basic unit of time, but for higher frequencies and shorter periods, smaller units of time are convenient. Those used most often are :

T = 1 millisecond = 1 ms = 1×10^{-3} s
T = 1 microsecond = 1 μs = 1×10^{-6} s
T = 1 nanosecond = 1 ns = 1×10^{-9} s

These units of time for period are reciprocals of the corresponding units for frequency. The reciprocal of frequency in kilohertz gives the period T in milliseconds; the reciprocal of megahertz is microseconds; the reciprocal of gigahertz is nanoseconds.

PHASE

The phase of an alternating current or a voltage is the angular distance it has moved from 0° in a positive direction. The phase angle in electrical equations is usually represented by the Greek letter theta (θ). The **phase angle** is the difference in degrees of rotation between two alternating currents or voltages, or between a voltage and a current. For example, when one voltage reaches maximum value 120^0 between the two voltages. Fig. 3.9 (a) shows a 120^0 phase difference between three different voltage curves. This type of phase relationship is very common in aircraft circuits that employ a three-phase ac electrical system. Three-phase systems are known as **polyphase circuits**.

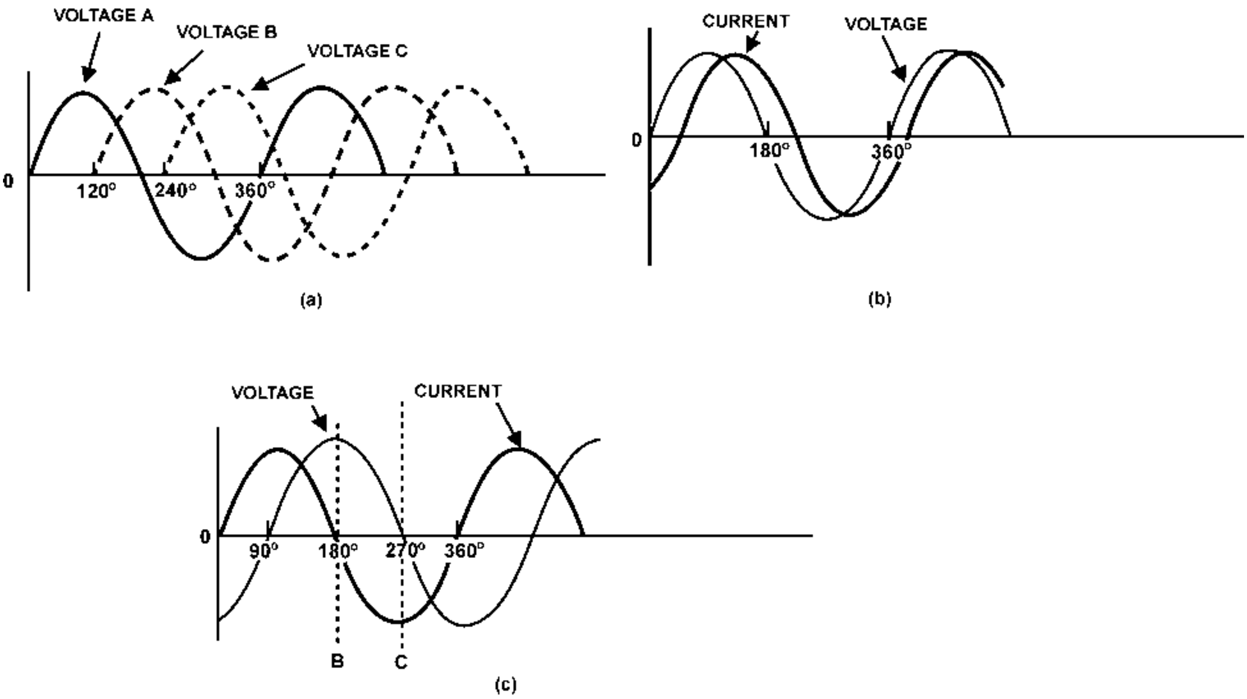


Fig. 3.9. Out-of-phase voltage and current curves. (a) Voltage curves of a three-phase circuit; (b) voltage leads current; (c) current leads voltage.

In most ac circuits a phase shift exists between voltage and current. Fig. 3.9 (b) shows sine curves representing a current lagging the voltage, or voltage leading the current. In circuits where the current and voltage do not reach maximum at the same time, they are said to out of phase. In Fig. 3.9 (b), notice that the heavy current line crosses it. This means that the current reaches zero after the voltage. In like manner, the peak value of current occurs after the peak value of voltage. For this reason we know that the current is lagging the voltage by several degrees. In Fig. 3.9 (c), it will be seen that the voltage is approximately 90^o out of phase with the current. That is, the voltage follows the current by approximately 90^o.

CAPACITANCE IN AC CIRCUITS

Capacitance can be defined as the ability to store an electric charge. Most capacitance in a circuit is created by a device called a **capacitor**. Capacitor theory is that section should be studies carefully to gain a full understanding of how capacitors react in an ac circuit. In short, capacitors oppose the change of current flow in a circuit. In an ac circuit, since the current is constantly changing in magnitude and direction, a capacitor will create a constant opposition to the applied current. This opposition to current is similar to a resistance; however, it also creates a phase shift within the circuit.

When a capacitor is connected in series in an ac circuit, it appears that the alternating current is passing through the capacitor. In reality, electrons are stored first on one side of the capacitor and then on the other. Thus permitting the alternating current to flow back and forth in the circuit without actually passing through the capacitor.

A hydraulic analogy can be used to explain the operation of a capacitor in a circuit see Fig.3.10 (a). The capacitor is represented by a chamber separated into two sections by an elastic diaphragm. The ac generator is represented by the piston-type pump. As the piston moves in one direction, it forces fluid into one section of the chamber and draws it out of the other section. The fluid flow represents the flow of electrons in an electric circuit. Thus it can be seen that there is an alternating flow of fluid in the lines and that work is done as the fluid moves back and forth, first filling one side of the chamber and then the other.

As seen in Fig. 3.10 (b), the operation of a capacitor in an ac circuit is for all practical purposes identical to the operation of the chamber just described. The electrons build up on one plate of the capacitor, and this negative charge forces the electrons to flow away from the other plate. As the ac current reverses direction, the capacitor is charged with the negative charge moving to the opposite plate on the capacitor. With ac cycle, as voltage from the source begins to drop, the current starts to flow out of one plate of the capacitor and into the other; and the cycle repeats as long as the current is flowing.

This constant charging and discharging of the capacitor creates an electrostatic field and dielectric stress within the capacitor. A **dielectric** is an insulating material used to separate plates of a capacitor. The dielectric stress is similar to the stress of the elastic diaphragm of the hydraulic circuit Fig. 3.10 (a). The dielectric stress creates a force that opposes the applied current. In other words, the capacitor will create a current flow in the opposite direction of the applied current. This current flow has two effects on the circuit: (1) it oppose, or "resist,' the applied current, and (2) it creates a**phase shift** between voltage and current.

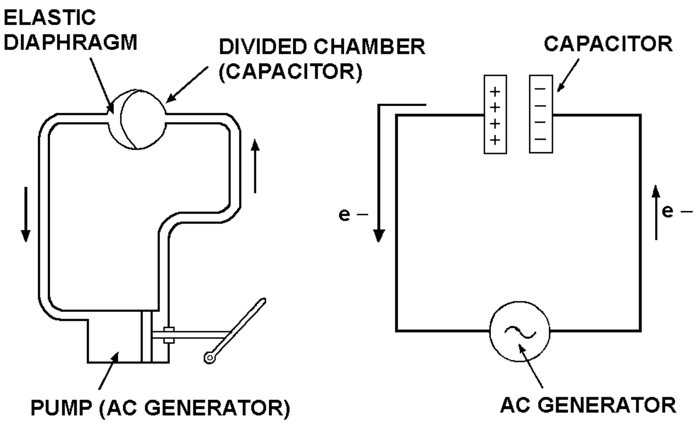


Fig. 3.10. Hydraulic analogy of a capacitor. (a) The hydraulic pump forces fluid into the right side of the divided chamber; (b) the ac generator forces electrons into the right side of the capacitor.

The phase shift in capacitive circuits causes the current to lead the voltage. This phase shift causes current to reach its maximum and minimum values before the voltage of the circuit. If it were possible to have a circuit with only capacitance and no resistance, the current would lead the voltage by 90° Fig. 3.9 (c). Studying Fig. 3.9 (c), it can be seen that as the voltage rises, the current begins to drop because of the dielectric stress in the capacitor. This, of course, means that opposition to the flow of current is developing. By the time the voltage has reached its maximum value, the capacitor is completely charged; hence no current can flow. At this point B the current flows out of the capacitor in the opposite direction because the potential of the capacitor is higher than the potential on the applied voltage. By the time the voltage has dropped to zero, the current is flowing at a maximum rate because there is no opposition. This point on the curve is represented by the letter C.

It must be remembered that the above action takes place only when there is no resistance in the circuit. Since this is impossible, a circuit in which the current leads the voltage by as much as 90° does not exist. However, the study of such a circuit gives the student a clear understanding of the effect of capacitance. In an ac circuit where both capacitance and resistance are present, the phase shift will be between 0 and 90°.

The effects of capacitance in ac circuits are most pronounced at higher frequencies. Modern electronic circuits often produce frequencies of many millions of cycles per second (Hz). For this reason special types of electronic and electric devices and equipment have been designed to reduce the effects of capacitance where these effects are detrimental to the operation of the circuit.

CAPACITIVE REACTANCE

If capacitance is considered the ability to oppose changes in current flow, then **capacitive reactance** is the actual opposition to current flow in a given ac circuit. Since capacitive reactance opposes the flow of current in ac circuits, it is measured in ohms. It should be noted that capacitive reactance also creates a phase shift in the circuit and therefore cannot be thought for as resistance. Capacitive reactance is represented by X_C and is a function of both the circuit's ac frequency and the total capacitance.

The capacitive reactance in a circuit is inversely proportional to the capacitance and the ac frequency. This is because a large-capacity capacitor will take a greater charge than a low-capacity capacitor; hence it will allow more current to flow in the circuit. IF the frequency increases, the capacitor charges and discharges more times per second; hence more current flows in the circuit. From the following equation for capacitive reactance, it can be seen that reactance will decreases as capacitance or frequency increases.

The formula for capacitive reactance is

$$X_C = \frac{1}{2\pi fC}$$

where X_C = capacitive reactance, Ω
f = frequency, Hz
C = capacitance, F

To determine the capacitive reactance in a circuit in which the frequency is 60 Hz and the capacitance is 100 μF, substitute the known values in the formula. Then

$$X_C = \frac{1}{2\pi \times 60 \times 100/1{,}000{,}000}$$

Remember that 1 μF is one-millionth of a farad; hence 100 μF is equal to 100/1,000,000 F. Therefore,

$$X_C = \frac{1}{6.283 \times 0.006} = \frac{1}{0.037698} = 26.5\,\Omega$$

INDUCTION IN AC CIRCUIT

The effect of **inductance** in ac circuits is exactly opposite to that of capacitance. Capacitance causes the current to lead the voltage, and inductance causes the current to lag. (Fig.3.11) shows the voltage and current curves for a purely inductive circuit. In order to completely understand the effects of inductive reactance.

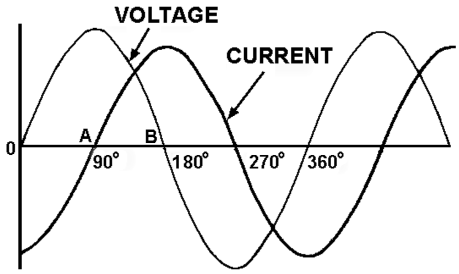


Fig. 3.11. Current lagging voltage.

According to **Lenz's law,** whenever a current change takes place in an inductance coil, an emf (voltage) is induced that opposes the change in current. The induced voltage will then be maximum when the rate of current change is the greatest. Since the current change is most rapid in an ac circuit when the current is passing through the zero point, the induced voltage will be maximum at this same time, marked A in (Fig. 3.11). When the current reaches maximum, there is momentarily no current change, and hence the induced voltage is zero at point B. Remember, to induce a voltage in any circuit, there must be a current change; thus a "moving" magnetic field is created around the inductor coil. So at point B, where there is no current change, there will be no induced voltage. This effect causes the current to lag the voltage by 90° in a purely inductive circuit. But since a purely inductive circuit is impossible because there is always resistance present, the current lag of 90° is purely, theoretical. In an ac circuit where both resistance and inductance are present, the current will lag the voltage somewhere between 0 and 90°.

INDUCTIVE REACTANCE

The effect of inductance in an ac circuit is called **inductive reactance** is measured in ohms because it "resist" the flow of current in the circuit. Inductive reactance (X_L) is the actual opposition to current flow created by inductors in an ac circuit. Inductance L is the ability of a coil to oppose changes in current flow. The inductive reactance of any given circuit is a function of the ac frequency and the inductance of that circuit.

The inductive reactance in a circuit is proportional to the inductance of the circuit and the frequency of the alternating current. As the inductance is increased, the induced voltage (Which opposes the applied voltage) is increased; hence the current flow is reduced. Likewise, when the frequency of the circuit is increased, the rate of current change in the inductance coil is also increased; hence the induced (opposing) voltage is higher and the inductive reactance is increased. As inductive reactance increases, current in the circuit flow is reduced.

We can clearly see that the effects of capacitance and inductance are opposite, since inductive reactance increases as the frequency increases and capacitive reactance decreases as the frequency increases. The formula for inductive reactance is

$$X_L = 2\pi fL$$

where X_L = inductive reactance, Ω
f = frequency, Hz
L = inductance, H

Let us assume that an inductance coil of 7 H is connected in a 60-Hz circuit and it is necessary to find the inductive reactance. By substituting the known values in the formula

$$X_L = 2 \times 3.1416 \times 60 \times 60 \times 7 = 2638.94\,\Omega$$

COMBINING RESISTANCE, CAPACITANCE, AND INDUCTANCE

In practical applications found on a typical aircraft, there are various components that have resistance, capacitance, and inductance. In that case the circuit is known as an RCL circuit. A circuit containing only resistance is called a resistance circuit (R). Other circuits are known as resistive inductive (RL), and resistance capacitive (RC). Each name describes the types of elements, that the contained in the circuit. For example, and RC circuit contains both resistive units and capacitive units. For any circuit that is not purely resistive, the total opposition to current flow is called impedance. As noted earlier, all circuit contain some resistance, inductance, and capacitance; however, in some cases the inductance and capacitance effects are considered negligible.

IMPEDANCE

In the study of Ohm's law for dc circuits, it was found that the current in a circuit was equal to the voltage divided by the resistance. In an ac circuit it is necessary to consider capacitive reactance and inductive reactance before the net current in such a circuit can be determined. The combination of resistance, capacitive reactance, and inductive reactance is called **impedance, and** the formula symbol is Z.

It might appear that we could add the capacitive reactance, inductive reactance, and resistance to find the impedance, but this is not true. Remember that capacitive reactance and inductive reactance have opposite effects in an ac circuit. For this reason, to find the total reactance we use the difference in the reactances. If we consider inductive reactance as positive, because inductance causes the voltage to lead the current, and capacitive reactance as negative, because it causes the voltage to lag, then we can add the two algebraically; that is

$$X_L + (-X_C) = X_t \quad \text{or total reactance}$$

Now it might appear that we could add this result to the resistance to find the impedance, but again we must consider the effect of resistance in the circuit. We know that resistance in a circuit does not cause the current to lead or lag, and for this reason its effect is 90° ahead of inductance and 90° behind capacitance. Therefore, it is necessary to add resistance and reactance vectorially.

A vector is a quantity having both magnitude and direction. Vectors are often represented graphically by a line pointing in a given direction. Vectors may be used to represent a given force. The strength of the force is indicated by the length of the line representing the vector. The values of X_L, X_C and R can be represented using a vector diagram as illustrated in Fig. 3.12 (a). Resistance is always shown on the horizontal axis, inductive reactance on the vertical axis pointing down. As illustrated, it is easy to see that the effect of XL and X_C cancel each other, and the effects of resistance are 90° from either reactance. As demonstrated in Fig. 3.12 (b), using vector addition, the three vector X_L, X_C and R can be combined into one resultant vector called impedance (Z). The length of the impedance vector can be determined graphically or algebraically. The Phythagorean theorem, $A^2 + B^2 = C^2$, can easily be applied to solve for Z; that is,

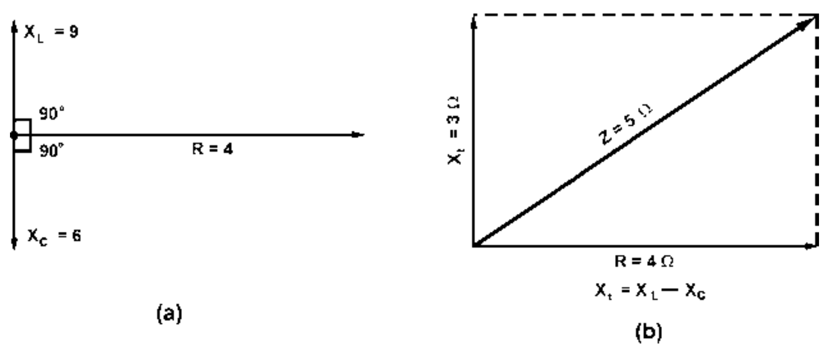
$$X_t^2 + R^2 = Z^2$$

or

$$Z = \sqrt{R^2 + X_t^2}$$

Substituting for Xt,

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$



NOTE : X_t IS CONSIDERED TO BE INDUCTIVE BECAUSE X_L IS LARGER THAN X_c.

Fig. 3.12. Vector diagrams of resistance, reactance, and impedance.

This formula is typically used to solve for Z or an unknown R or X value. It should be noted that this formula can be applied to determine the impedance in series circuits only. That is, the total values of resistance, capacitance, and inductance must be in series with each other, as shown in (Fig. 3.13). The equations for parallel circuits will be discussed later.

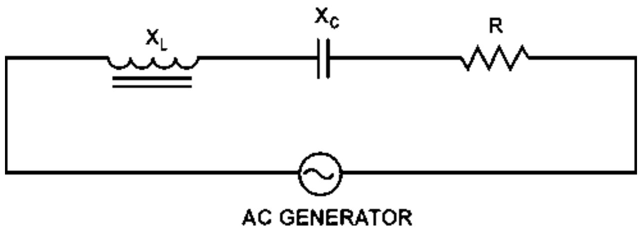


Fig. 3.13. A simple series ac circuit.

After the impedance is found in an ac circuit, the other values can be found by Ohm's law for alternating current. In this formula we merely substitute the symbol Z, meaning impedance, for the normal symbol R, meaning resistance. The formula then reads

$$I = \frac{E}{Z}$$

Sample Problem. If a series ac circuit contains an inductor with inductive reactance X_L equal to 12 Ω, a capacitive reactance X_C of 18 Ω, a resistance R of 5Ω, and an applied voltage of 120 V, what is the current flow through the circuit ?

Sol:- In an ac circuit, I = E/Z; therefore, the value for Z must be determined.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$= \sqrt{5^2 + (12-18)^2}$$

$$= \sqrt{25+36} \; = \; 7.8\,\Omega$$

Note: Always subtract X_C and X_L, then square the result; X_L - X_C may produce a negative number. This negative number will become positive when it is squared.

To find I, used I = E/Z:

$$I = \frac{120V}{7.8\Omega} = 15.4\,A$$

Current will lead voltage in this circuit because X_C is larger than X_L and therefore has a greater effect on the phase shift.

PHASE ANGLE

As stated earlier, a phase angle is the angular distance between current and voltage in an ac circuit. The phase angle is designated by the Greek letter theta (θ). To better understand the phase shift created in an ac circuit, study the vector diagrams in (Fig. 3.14). As illustrated, θ is always measured between the horizontal line and resultant Z vector. For a simple R, C or L circuit, the resultant vector equals the R, C, or L vector. For a pure resistive (R) circuit, the phase shift is 0°. For a pure inductive (L) or capacitive (C) circuit, the phase shift angle is always 90'. Voltage leads current in the inductive circuit, and current leads voltage in the capacitive circuit.

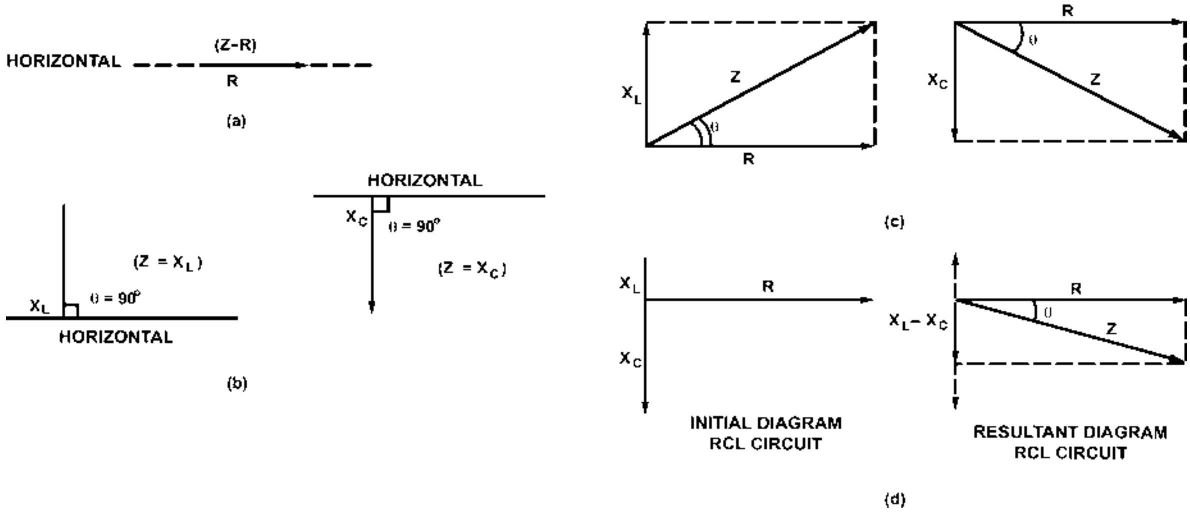


Fig. 3.14. Various phase shift angles. (a) Pure resistive (R) circuit; θ = 0°. (b) Pure inductive (L) or pure capacitive (C) circuit; θ = 90° . (c) Resistive inductive (RL) or resistive capacitive (RC) circuit; θ is greater than 0° but less than 90°. (d) Resistive capacitive inductive (RCL) circuit; θ is greater than 0° but less than 90°.

To determine the exact value of a phase shift angle, the trigonometry function of sine, cosine, or tangent is used. (Fig.3.15) demonstrates the calculations to find θ in an RL circuit. The sine of θ is employed in this case to find the angle's value. The sine of θ is determined to be 0.446; a calculator is then used to determine the actual angle of 26.5^0. If the tangent was used to find θ, the calculations would be as follows:

$$\tan\theta = \frac{\text{opposite side}}{\text{adjacent side}}$$

$$\tan\theta = \frac{10}{20} = 0.5$$

$$\theta = \tan^{-1} 0.5 = 26.5^0$$

The cosine function could be used in a similar manner to find the angle θ.

The value of the phase angle has great importance when an ac circuit is designed. A small phase angle means the resistance vector is large compared with the reactance vectors. A large phase angle occurs when the inductive or capacitive reactance vector is much larger than the resistance vector. If this situation occurs, the ac circuit becomes very inefficient and may overload the power source. The aircraft technician must be aware of this potential problem because of the large number of ac electrical systems found on modern aircraft.

Sample Problem. In a series ac circuit (see Fig. 3.16), determine the total impedance Z, the total current flow I_t, and the phase angle θ.

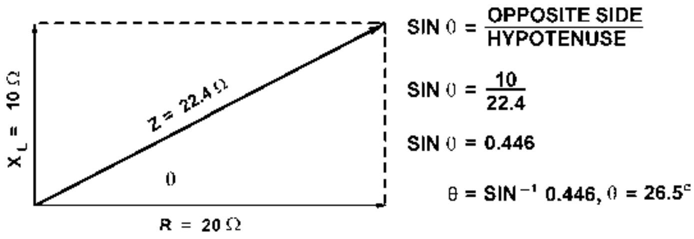


Fig. 3.15. Phase angle calculations.

Step 1. Find the inductive and capacitive reactance (Note: Remember to convert microfarads to farads).

$$X_L = 2\pi fL$$

$$= 2\pi 60(0.2)$$

$$= 75.4\,\Omega$$

$$X_C = \frac{1}{2\pi fC}$$

$$= \frac{1}{2\pi 60(0.00001)}$$

$$= \frac{1}{0.0038} = 265.26\,\Omega$$

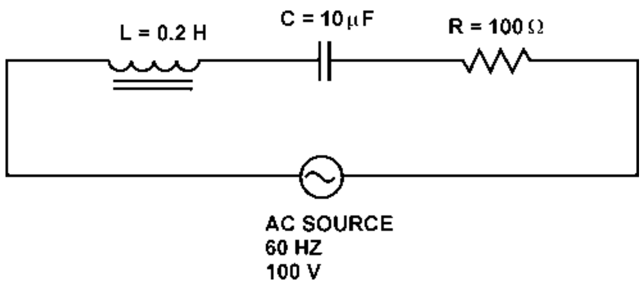


Fig. 3.16. The sample series ac circuit for sample problem.

The inductive reactance is 75.4 Ω; rounding gives 75 Ω. The capacitive reactance is 265.26 Ω; round gives 265 Ω.

Step 2. Find the circuit's impedance

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$= \sqrt{100^2 + (75.4 - 265.26)^2}$$

$$= \sqrt{46.046} = 214.58\ \Omega$$

The impedance is 214.58 Ω; rounding gives 214 Ω.

Step 3. Determine the phase shift angle (Fig. 3.17). Note: Current will lead the voltage, since X_C is larger than X_L.

$$\sin\theta = \frac{190}{214}$$

$$\sin\theta = 0.8879$$

$$\theta = 62.6^0$$

The phase shift angle is 62.6°.

Step 4. Find the total current flow.

$$I_t = \frac{E_t}{Z}$$

$$= \frac{100V}{214\Omega} = 0.47\ A$$

The total current flow equals is 0.47 A.

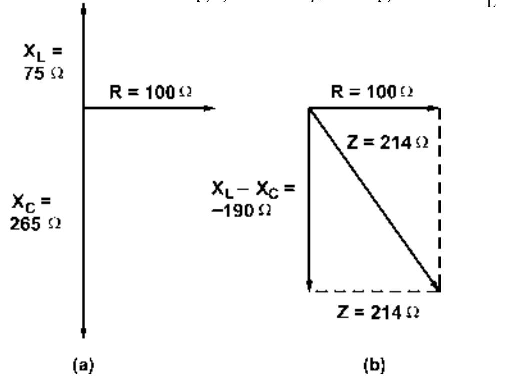


Fig. 3.17. Vector diagram of the series ac circuit for sample problems.

POWER FACTOR CALCULATIONS FOR AC CIRCUITS

There are typically two types of power used to describe the work performed by an ac circuit. **True power** is the power consumed by the resistance of an ac circuit. **Apparent power** is the power consumed by the entire ac circuit. Thus apparent power takes into consideration the power consumed because of the resistance and the inductive and capacitive reactances. True power considers only resistance. Just as impedance is found vectorially. So is apparent power, as illustrated in (Fig. 3.18). Reactive power Q is placed on the vertical axis. Reactive power is a function of the total reactance of a circuit. True Power P is placed on the horizontal axis, and its magnitude is found by $P=I^2R$. Apparent power U is the resultant vector and can be found using

$$U = \sqrt{P^2 + Q^2}$$

To distinguish between the types of power, true power is measured in watts (W), apparent power is measured in volt-amps (VA) and reactive power is measured in volt-amps-reactive (VAR).

Power factor (PF) is the ratio of true power to apparent power; a circuit's efficiency will determine the power factor. That is, the more inductive or capacitive reactance, the lower the circuit's efficiency and the smaller the power factor. Power can be calculated by

$$PF = \frac{\text{true power}}{\text{apparent power}}$$

$$= \frac{P}{U}$$

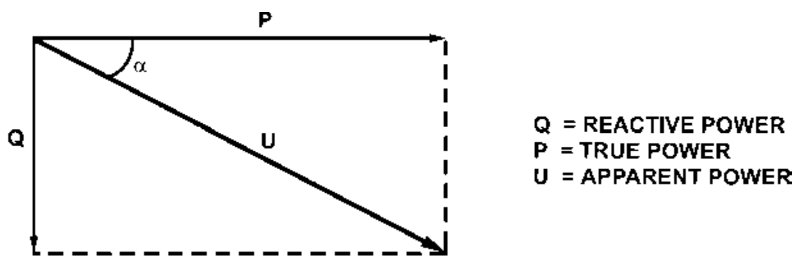


Fig. 3.18. Apparent power vector diagram.

since power factor is a ratio, it has no units of measure. IF P = 130 W and U = 140 VA, the power factor can be calculated as follows :

$$PF = \frac{P}{U}$$

$$= \frac{130}{140} = 0.928$$

A power factor of 1.0 indicates a purely resistive circuit. A power factor of zero indicates a purely reactive circuit. Power factor can also be calculated by using the cosine of the phase shift angle. That is,

$$PF = \text{cosine } \theta$$

Therefore, if the power factor is known, the phase shift angle (not direction) is also known. The greater the reactance in a circuit for a given resistance, the larger the phase shift angle, the lower the power factor, and the lower the circuit's efficiency. Once you understand this relationship, it is easy to see why large quantities of inductive or capacitive reactance create inefficiencies and are undesirable in an ac circuit.

Most aircraft ac alternators contain critical specifications for both apparent power and a power factor range. Apparent power is used because it describes the power used by the entire circuit - that is, both resistance and reactive power. Apparent power would be measured in kilovolt-amps (kVA), and the power factor would be given as a range. For example, a particular aircraft alternator may be rated as follows: apparent power maximum of 200 kVA and a power factor range of 0.90 to 1.0. These specifications must never be exceeded; otherwise, the alternator may be internally damaged.

PARALLEL AC CIRCUIT

As mentioned earlier, the calculations used to find impedance for parallel circuits are different from those used with series circuits. The letter Z is still used to represent impedance; however, for parallel circuits $Z_1 = 1/Y$. To solve for Y, one must use the following equation:

$$Y = \sqrt{G^2 + (B_L - B_C)^2}$$

where $G_1 = 1/R$

$B_L = 1/X_L$

$B_C = 1/X_C$

Here we can see that G, B_L, and B_C are simply the inverse of the resistance R, the inductive reactance X_L, and the capacitive reactance X_C for a given circuit. G, B_L, and B_C have no practical value in electrical terms; however, they must be used as an interim step whenever the total impedance of a parallel circuit is determined. Once you have calculated these values, the equation

$$Y = \sqrt{G^2 + (B_L - B_C)^2}$$

can be used to find Y. The value for Y must then be inverted to find Z, as shown next.

$$Z = \frac{1}{Y}$$

For parallel ac circuits, voltage leads current if B_L is greater than B_C. Voltage will lag current if B_C is greater than B_L Fig. 3.19(a). The phase shift angle (θ) is determined by the angle between the resultant vector Y and the horizontal vector G as seen in Fig. 3.19(b).

As seen in the following example, the calculation of impedance Z for parallel circuits is relatively easy if you always remember to invert the values for R, X_L and X_C before calculating for Y. Then simply invert Y to find total impedance Z.

Sample Parallel Problem. To find the total impedance and the phase shift angle for the circuit in (Fig. 3.20), take the following steps:

Step 1. Convert R, X_L and X_C to G, B_L and B_C

$$G = \frac{1}{R} \qquad G = \frac{1}{5} \qquad G = 0.20\Omega$$

$$B_L = \frac{1}{X_L} \qquad B_L = \frac{1}{12} \qquad B_L = 0.083\Omega$$

$$B_C = \frac{1}{X_C} \qquad B_C = \frac{1}{4} \qquad B_C = 0.25\Omega$$

Step 2. Solve for Y.

$$Z = \sqrt{G^2 + (B_L - B_C)^2}$$

$$= \sqrt{0.02^2 + (0.083 - 0.25)^2} = \sqrt{0.0283} = 0.2606\,\Omega$$

Step 3. Invert Y to determine Z.

$$Z = \frac{1}{Y}$$

$$= \frac{1}{0.2606} = 3.84\Omega$$

The total impedance Z is equal to 3.84Ω.

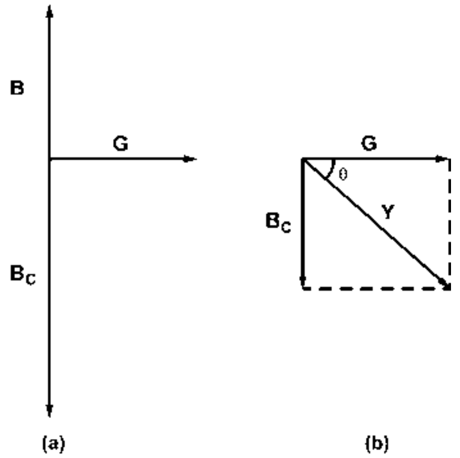


Fig. 3.19.

Step 4. Calculate the phase shift angle for the vector diagram in (Fig.3.21).

$$\sin\theta = \frac{\text{opposite side}}{\text{hypotenuse}}$$

$$\sin\theta = \frac{0.167}{0.2606} = 0.641$$

$$\theta = 39.8^0$$

This circuit has a phase shift angle of 39.8° and voltage lags current.

To determine the total current for the circuit, divide the total voltage by the total impedance as shown below.

$$I_t = \frac{E_t}{Z}$$

$$= \frac{120V}{3.84\Omega} = 31.25\text{ A}$$

Total current is 31.25 A.

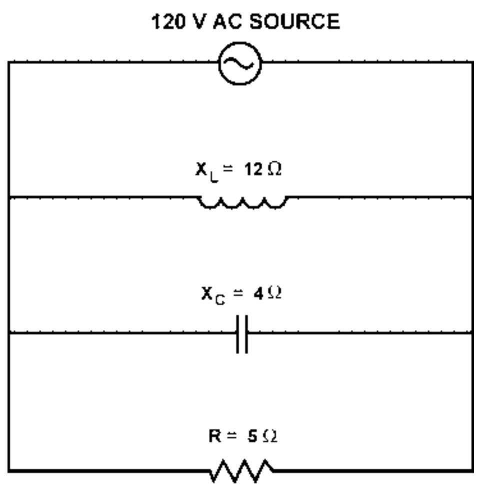


Fig. 3.20.

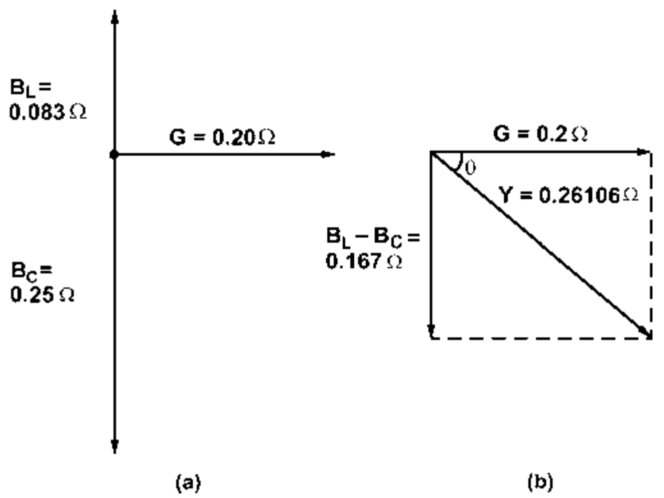


Fig. 3.21.

VECTOR ADDITION OF VOLTAGE AND CURRENT

In a series dc circuit, total voltage is equal to the sum of the individual voltage drops. In a series ac circuit, however, the voltage total is equal to the voltage drops summed vectorially. That is, the voltage drops created by the resistance are summed, the voltage drops across the inductances are also summed. These three totals are then added vectorially with resistance voltage drops placed on the horizontal axis, inductive voltage drops placed vertically pointing up and capacitive voltage drops placed vertically pointing down. This is illustrated in (Fig. 3.22). The total voltage drop is then calculated using the equation

$$E_t = \sqrt{E_R^2 + (E_{X_L} - E_{X_C})^2}$$

The total current in a parallel dc circuit can be found by summing the current flows through each individual path. Total current in a parallel ac circuit is found by adding currents vectorially. The vector diagrams in Fig. 3.22 (b) demonstrate the summation of ac current flows. The equation

$$I_t = \sqrt{I_R^2 + (I_{X_L} - I_{X_C})^2}$$

is used to find I, where I_t is the total current in the ac circuit, I_R is the sum of the resistive current flows, I_{X_L} is the sum of the inductive currents, and I_{X_C} is the sum of the capacitive currents.

The following is a sample problem: If a parallel ac circuit contains two inductors carrying 2A each, a capacitor carrying 1A, and three resistors carrying 1.5A, 0.5A, and 3A, what is the circuit's total current flow ?

First add the individual current flows for resistance, inductance, and capacitance.

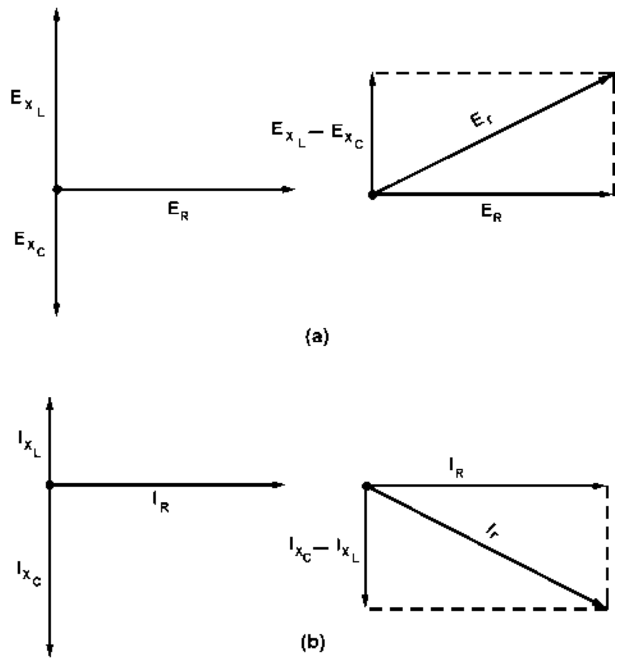


Fig. 3.22.

$$I_R = 1.5A + 0.5A + 3.0A = 5A$$

$$I_{X_L} = 2A + 2A = 4A$$

$$I_{X_C} = 1A$$

To find I_t, use $I_t = \sqrt{I_R^2 + (I_{X_L} - I_{X_C})^2}$

$$= \sqrt{(5A)^2 + (4A - 1A)^2} = \sqrt{34A} = 5.8A$$

POLYPHASE AC CIRCUITS

A **polyphase** ac circuit consists of two or more circuits that are usually interconnected and so energized that the currents through the separate conductors and the voltages between them have exactly equal frequencies but differ in phase. A difference in phase means that the voltages do not reach peak positive or peak negative values at the same time. Also, the corresponding values of current are usually separated by an equal number of degrees. For example, in a three-phase ac system, no. 1 phase will reach a peak voltage 120^0 before the no. 2 phase, the no. 2 phase will reach the maximum positive voltage 120^0 before no. 3 phase, and so on. Thus the three phases are separated by an angle of 120^0 (Fig. 3.22). Modern, large, transport-category aircraft of all types employ a three-phase ac electrical system. This system is considerably more efficient than a comparable single-phase ac system or a dc electrical system. Because of the great electric power requirements on large aircraft, a dc power system would add hundreds of pounds of weight in comparison

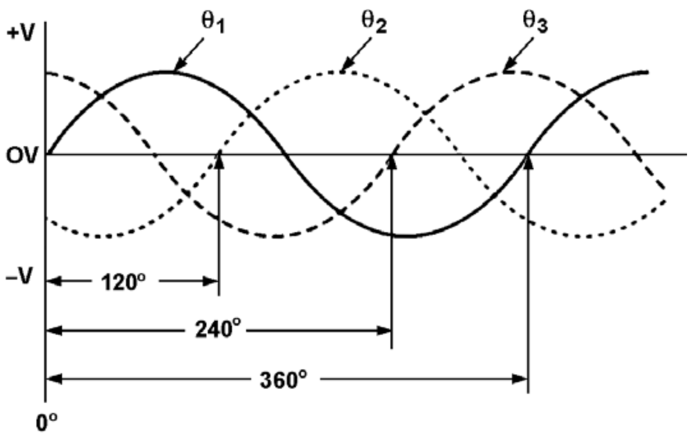


Fig. 3.23.

with a three-phase ac system. The three-phase system found on these aircraft uses a polyphase ac generator that produces three ac voltage 120° apart.

GENERATION OF THREE-PHASE VOLTAGES

The kind of alternating currents and voltages are known as single-phase voltages and current because they consist of a single alternating current and voltage wave. A single phase alternator shown to have one armature winding only. But if the number of armature windings is increased to three, then it becomes three-phase alternator and it produces as many independent voltages waves as the number of windings or phases. These windings are displaced from one another by equals angles, the value of these angles being determined by the number of phases or windings.

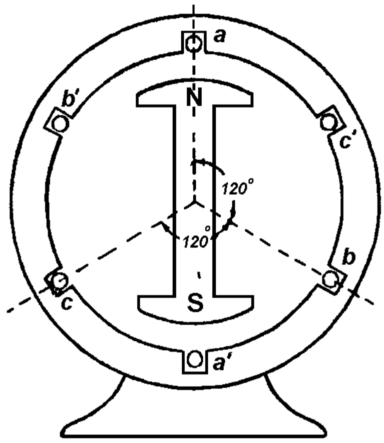


Fig. 3.24.

In a two-phase alternator, the armature windings are displaced 90 electrical degrees apart. A 3-phase alternator, as the name shows, has three independent armature windings which are 120 electrical degrees apart. A 3-phase alternator, as the name shows, has three independent armature windings which are 120 electrical degrees apart. Hence, the voltages induced in the three windings are 120° apart in time phase. With the exception of two-phase windings, it can be stated that, in general, the electrical displacement between different phases is 360/n where n is the number of phases or windings.

Three-phase systems are the most common although, for certain special jobs, greater number of phase is also used. For example, almost all mercury-arc rectifiers for power purposes are either six-phase or twelve-phase and most of the rotary convectors in use are six phase. All modern generators are practically three-phase. For transmitting large amounts of power, three-phase is invariably used. The reason for the immense popularity of three-phase apparatus are that (i) it is more efficient (ii) it uses less material for a given capacity and (iii) it costs less than single-phase apparatus etc.

In (Fig. 3.23) is shown a two -pole stationary-armature, rotating-field type three-phase alternator. It has three armature coils aa', bb', cc' displaced 120° apart from one another. With the position and clockwise rotation of the poles shown in (Fig. 3.23), it is found that the e.m.f. it is found that the e.m.f. induced in conductor 'a' of coil aa' is maximum and its direction is away from

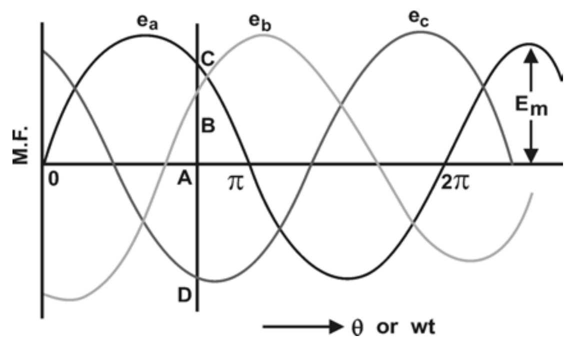


Fig. 3.25.

the reader when the N-pole has turned through 120° i.e. when N-S axis lies along bb'. It is clear that the induced e.m.f. in conductor 'b' reaches its maximum value 120° later than the maximum value in conductor 'a'. In the like manner, the maximum e.m.f. induced (in the direction away from the reader) in conductor 'c' would occur 120° later than in 'b' or 240° later than that in 'a'.

Thus, the three coils have three e.m.fs. induced in them which are similar in all respect except that they are 120° out of time phase with one another as pictured in (Fig. 3.24). Each voltage wave is assumed to be sinusoidal and having maximum value of E_m.

PHASE SEQUENCE

By phase sequence is meant the order in which the three phases attain their peak or maximum values. In the development of the three-phase e.m.fs. in (Fig.3.24), clockwise rotation of the field system in (Fig. 3.22) was assumed. This assumption made the e.m.f. of phase 'b' lag behind that of 'a' by 120° and in a similar way, made that of 'c' lag behind that of 'b' by 120° (or that of 'a' by 240°). Hence, the order in which the e.m.fs. of phase, a, b and c attain their maximum values is a b c. It is called the phase order or phase sequence a →b →c.

If, now, the rotation of the field structure of (Fig. 3.22) is reversed i.e. made anti-clockwise, then the order in which the three phases would attain their corresponding maximum voltages would also be reversed. The phase sequence would become a c b. This means that e.m.f. of 'c' would now lag behind that of phase 'a' by 120° instead of 240° as in the previous case.

In general, the phase sequence of the voltages applied to a load is determined by the order in which the 3-phase lines are connected. The phase sequence can be reversed by interchanging any pairs of lines. In the case of an induction of motor rotation. In the case of 3-phase unbalanced loads, the effect the sequence reversal is, in general, to cause a completely different set of values of line currents. Hence, when working on such systems, it is essential that phase sequence be clearly specified otherwise unnecessary confusion will arise.

NUMBERING OF PHASE

The three phases may be number 1, 2, 3 or a, b, c or as is customary, they may be given three colours. The colours used commercially are red, yellow (or sometimes white) and blue. In that case, the sequence is RYB.

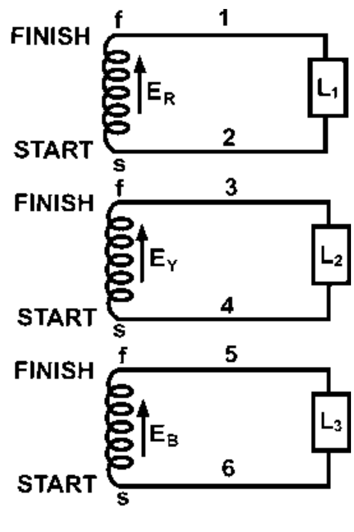


Fig. 3.26.

Obviously, in any three-phase system, there are two possible sequences in which three coil or phase voltages may pass through their maximum value i.e. red →yellow→blue (RYB) or red →blue→yellow (RYB). By convention, RYB is regarded as positive sequence and RBY as negative sequence.

INTERCONNECTION OF THREE PHASES

If the three armature coils of the 3-phase alternator are not interconnected but are kept separate as shown in (Fig. 3.24), then each phase or circuit would need two conductors, the total number of conductors, in that case, being six. It means that each transmission cable would contain six conductors which will make the whole system complicated and expensive. Hence, the three phases are, generally, inter-connected which results in substantial saving of copper. The general methods of inter connection are :

a. Star or Wye (Y) connection and
b. Mesh or Delta (Δ) connection.

STAR OR WYE (Y) CONNECTION

In this method of interconnection, the similar ends, say start ends of three coils (it could be finishing ends also) are joined together at point N as shown in Fig. 3.25(b).

The point N is known as star point or neutral point. The three conductors meeting at point N are replaced by a single conductor known as neutral conductor as shown in Fig.3.25 (b). Such as interconnected system is known as 3-phase four-wire system and is diagrammatically shown in Fig. 3.25 (b). If this three-phase voltage is applied across a balanced symmetrically load, the neutral wire will be carrying three currents which are exactly equal in magnitude but are 120° out of phase with each other. Hence, their vector sum is zero.

i.e. $I_R + I_Y + I_B = 0$

The neutral wire, in that case, may be omitted although its retention is useful for supplying loads at low voltages. The p.d. between any terminal (or line) and neutral (or star) point gives the phase or star voltage. But the p.d. between any two lines gives the line voltage. This connection is also referred to as 3-phase, 4-wire system.

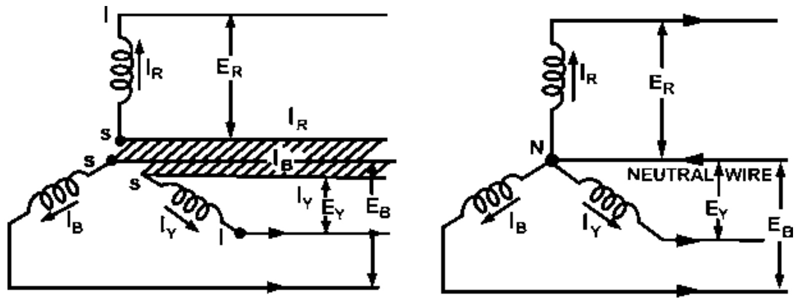


Fig. 3.27.

Note: When considering the distribution of current in a 3-phase system, it is extremely important to bear in mind that :

(i) the arrows placed alongside the current I_R, I_Y and I_B flowing in three phases Fig. 3.25 (b) indicate the directions of currents when they are assumed to be positive and not the directions at a particular instant. It should be clearly understood that at no instant will all the three current flow in the same direction either outwards or inwards. The three arrows indicate that first the current flows outwards in phase R, then after a, phase-time of 120°, then after a phase-time of 120°, it will flow outwards from phase Y and after a further 120°, outwards from phase B.

(ii) the current flowing outwards in one or two conductors is always equal to that flowing inwards in the remaining conductor or conductors. In other words, each conductor, in turn, provides a return path for the currents of the other conductors.

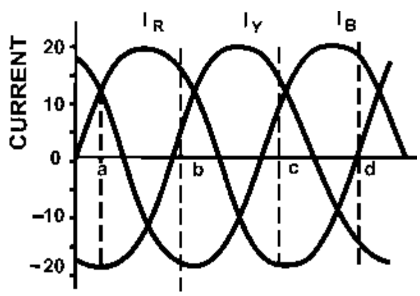


Fig. 3.28.

In (Fig. 3.26) are shown the three phase currents having the same peak value of 20A but displaced from each other by 120°. At instant 'a', the currents in phase R and B are each + 10A (i.e. flowing outwards) whereas the currents in phase Y is -20A (i.e. flowing inwards). In other words, at the instant 'a' phase Y is acting as return path for the currents in phases R and B. At instant b, I_R = +15A and I_Y = +5A and I_B = -20A which means that now phase B is providing the return path. As instant c, I_Y = +15A and I_B = +5A and I_R = -20 A.

Hence, now phase R carries current inwards whereas Y and B carry currents outwards. Similarly, at point d, I_R = 0, I_B=17.3A and I_Y = -17.3A. In other words, current is flowing outwards from phase B and returning via phase Y.
In addition, it may be noted that although the distribution of current between the three lines is continuously changing, yet at any instant, the algebraic sum of the instantaneous values of the three currents is zero i.e.,

$$i_R + i_Y + i_B = 0 \quad \text{- algebraically}$$

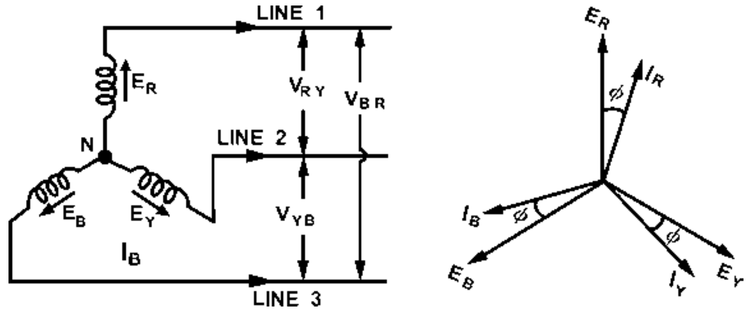


Fig. 3.29.

VOLTAGES AND CURRENTS IN Y-CONNECTION

The voltage induced in each winding is called the 'phase' voltage and current in each winding is likewise known as 'phase' current. However, the voltage available between any pair of terminals (or outers) is called line voltage (V_L) and the current flowing in each line is called line current (I_L).

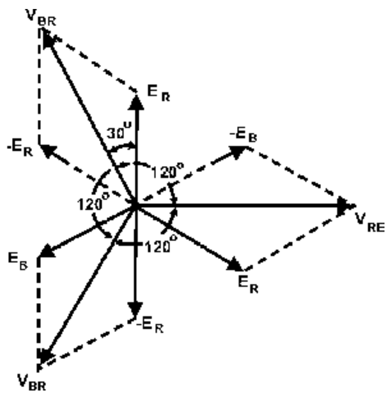


Fig. 3.30.

As seen from Fig. 3.27(a), in this form of interconnection, there are two phase windings between each pair of terminals but since their similar ends have been joined together, they are in opposition. Obviously, the instantaneous value of p.d. between any two terminals is the difference of the two phase e.m.fs. concerned. However, the r.m.s. value of this p.d. is given by the vector difference of two phase e.m.fs.

The vector diagram for phase voltages and currents in a star connection is shown in Fig. 3.27(b) where a balanced system has been assumed. It means that $E_R = E_r = E_x = E_{pA}$ (phase e.m.f.).

Line voltage V_{RY} between line 1 and 2 is the vector difference of E_R and E_r.
Line voltage V_{YB} between line 2 and line 3 is the vector difference of E_Y and E_B.
Line voltage V_{BR} between line 3 and line 1 is the vector difference of E_B and E_R.

(i) Line Voltages and Phase Voltages

The p.d. between lines 1 and 2 is

$$V_{RY} = E_R - E_Y \qquad \text{.................. vector difference.}$$

Hence, V_{RY} is found by compounding E_R and E_y reversed and its value is given by the diagonal of the parallelogram of (Fig. 3.28). Obviously, the angle between E_R and E_Y reversed is 60°. Hence, if $E_R = R_Y = E_B =$ say , E_{ph} - the phase e.m.f., then

$$V_{RY} = 2 \times E_{ph} \times \cos(60^o / 2)$$

$$= 2 \times E_{ph} \times \cos 30^o$$

$$= 2 \times E_{ph} \times \frac{\sqrt{3}}{2} = \sqrt{3}\, E_{ph}$$

Similarly

$V_{YB} = E_Y - E_B$ (vector difference)

$= \sqrt{3}.E_{ph}$

and $V_{BR} = E_B - E_R$ (vector difference)

$= \sqrt{3}.E_{ph}$

Now $V_{RY} = V_{YB} = V_{BR}$

= line voltage, say, V_L

Hence, in star connection

$V_L = \sqrt{3}.E_{ph}$

It will be noted from (Fig. 3.28) that

a. Line voltages are 120° apart.

b. Line voltages are 30° ahead of their respective phase voltages.

c. The angle between the line currents and the corresponding line voltages is $(30 + \phi)$ with current lagging.

(ii) Line Currents and Phase Currents

It is seen from Fig. 3.28(a) that each line is in series with its individual phase winding, hence the line current in each line is the same as the current in the phase winding to which it is connected.

Current in line = 1 = I_R
Current in line = 2 = I_y
Current in line = 3 = I_B

Since $I_R = I_Y = I_B =$ say, I_{ph} - the phase current

$\therefore$ line current $I_L = I_{ph}$

(iii) Power

The total power in the circuit is the sum of three phase powers. Hence

Total power = 3 × phase power

or $P = 3 \times E_{ph}\ I_{ph} \cos\phi$

Now $E_{ph} = V_L / \sqrt{3}$ and $I_{ph} = I_L 3$

Hence, in terms of line values, the above expression becomes,

$$P = 3 \times \frac{V_L}{\sqrt{3}} \times I_L \times \cos\phi$$

or $P = \sqrt{3}\ V_L I_L \cos\phi$

It should be noted that ϕ is the angle between phase voltage and phase current and not between the line voltage and line current.

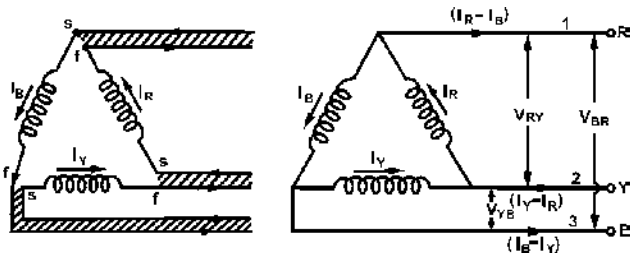


Fig. 3.31.

DELTA (Δ) OR MESH CONNECTION

In this form of interconnection, the dissimilar ends of the three phase windings are joined together i.e. the 'starting' end of one phase is joined to the 'finishing' end of the other phase and so on as shown in Fig. 3.29(a). In other words, the three windings are joined in series to form a closed mesh as shown in Fig. 3.29(b).

Three leads are taken out from the three junction as shown and outwards directions are taken as positive.

It might look as if this sort of interconnection results in short-circuiting the three windings. However, if the system is balanced, then sum of three voltages round the closed mesh is zero, hence no current of fundamental frequency can flow around the mesh when the terminals are open. It should be clearly understood that at any instant, the e.m.f. in one phase is equal and opposite to the resultant of those in the other two phases.

This type of connection is also referred to as 3-phase, 3-wire system.

(i) Line Voltages and Phase Voltages

It is seen from Fig. 3.29(b) that there is only one phase winding completely included between any pair of terminals. Hence in Δ-connection, the voltage between any pair of lines is equal to the phase voltage of the phase winding connected between the two lines considered. Since phase sequence is R, Y, B hence the voltage having its positive direction from

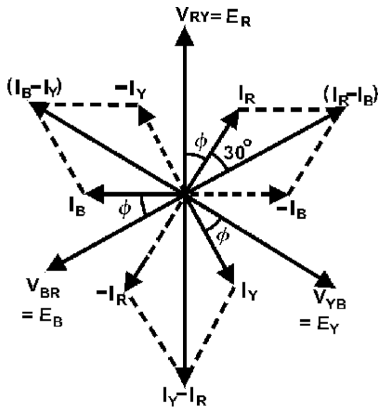


Fig. 3.32.

R to Y leads by 120° on that having its positive direction from Y to B. Calling the voltage between lines 1 and 2 as V_{RY} and that between lines 2 and 3 as V_{YB}, we find that V_{RY} leads V_{YB} by 120° (because vectors are supposed to rotate anticlock wise). Similarly, V_{YB} leads V_{BR} by 120° as shown in (Fig. 3.30). Let $V_{RY} = V_{YB} = V_{BR}$ = line voltage V_L. Then, it is seen that

$$V_L = V_{ph}$$

(ii) Line Currents and Phase Currents

It will be seen from fig. 3.29(b) that current in each line is the difference of the two phase currents flowing through that line. For example

$$\left.\begin{array}{l}\text{Current in line 1 is } I_1 = I_R - I_B \\ \text{Current in line 2 is } I_2 = I_Y - I_R \\ \text{Current in line 3 is } I_3 = I_B - I_Y\end{array}\right\} \text{ vector difference}$$

Current in line No. 1 is found by compounding I_R with I_B reversed and its value is given by the diagonal of the parallelogram of (Fig. 3.30). The angle between I_R & I_B reversed (i.e. phase current I_{ph} (say), then Current in line No. 1 is

$$I_1 = 2 \times I_{ph} \times \cos(60^0/2)$$

$$= 2 \times I_{ph} \times \sqrt{3}/2$$

$$= \sqrt{3}\, I_{ph}$$

Similarly, current in line No. 2 is

$$I_2 = I_Y - I_R \quad \text{......... vector difference}$$

and current in line No. 3 is

$$I_3 = I_B = I_Y \quad \text{.......... vector difference}$$

$$= \sqrt{3}\, I_{ph}$$

Since all line currents are equal in magnitude i.e.

$$I_1 = I_2 = I_3 = I_L$$

$$I_L = \sqrt{3}\, I_{ph}$$

With reference to (Fig. 3.30) it should be noted that

a. line currents are 120° apart
b. line currents are 30° behind the respective phase currents
c. the angle between the line current and the corresponding line voltage is $(30 + \phi)$ with the current lagging.

(iii) Power

$$\text{Power/phase} = V_{ph} I_{ph} \cos\phi$$

$$\text{Total power} = 3 \times V_{ph} I_{ph} \cos\phi$$

Now $V_{ph} = V_L$, but $I_{ph} = I_L / \sqrt{3}$

Hence, in terms of line values, the above expression for power becomes

$$P = 3V_L \times \frac{I_L}{\sqrt{3}} \times \cos\phi$$

$$= \sqrt{3}\, V_L I_L \cos\phi$$

where ϕ is the phase power factor angle.

ALTERNATING CURRENT AND THE AIRPLANE

You might be wondering, why use alternating current to power aircraft electrical systems ? Simply stated, ac power is much more flexible that dc power. Alternating current is produced by all aircraft generators and alternators. This power must be converted to dc if such power is desired. Since converting ac to dc does require some power itself, it only makes sense to convert as little as possible and use mainly ac electrical systems.

There are three principal advantages in the use of alternating current for electric power systems. (1) The voltage of ac power can be changed easily by means of transformers. This makes it possible to transmit power at a high voltage with low current, thus reducing the size and weight of wire required. (2) Alternating current can be produced in a three-phase system, thus making it possible to use motors of less weight for the same amount of power developed. (3) Ac machinery, such as alternators and motors, does not required the use of commutators; hence service and upkeep are greatly reduced.

A simple example will demonstrate the advantage of using high voltages for power transmission. We shall assume that we have a 1-hp [746-W] motor that must be driven at a distance of 100 ft [30.5 m] from the source of electric power. With a dc source of 10 V, the motor will require approximately 125 A, assuming that the motor is 60 percent efficient. Now when we consider the current-carrying capacity of copper wire, we find that a No. 1 cable is required to carry the current for the motor. One hundred feet of this wire weighs approximately 25 Ib [11 kg]. If we substitute a 1-hp, 200-V ac motor for the 10-V dc motor, the current required is only about 5 or 6 A, depending on the efficiency of the motor. This will require a No. 18 wire, which weighs about 1 Ib [0.5 kg] for 100 ft. This comparison clearly demonstrates the advantage of higher voltages for power transmission.

On large transport-category aircraft, three-phase alternating current is produced by the engine-driven generator (alternator). Three-phase current is used to power most of the large motors found on this type of aircraft. Three-phase ac motors are much lighter and smaller than if they were produced as single-phase ac or a direct-current motor. Three-phase motors are typically used to power hydraulic pumps, equipment-cooling blower fans, and other systems that require large amounts of mechanical energy. Single-phase ac is used to power light-duty motors, such as those used to operate a valve assembly. Single-phase ac is also used to power a variety of other systems, such as lighting.

Alternating current can be converted to different voltages much more easily than direct current. Through the principle of electromagnetic induction, ac voltage can easily be increased or decreased to virtually any desired level. A device called a transformer is used for this purpose. Most aircraft alternators produce power at 115 V and 400 cycles per second (Hz). However, various voltages are often desirable for specific electrical equipment. For example, fluorescent lamps operate on a relatively high voltage obtained from the output of a ballast transformer. If the same amount of light was to be produced using dc, a much greater amount of power would be consumed. Just as voltage can be increased, it can also be decreased to a relatively low level for charging a battery or operating other systems requiring only 28 V.

Even in large aircraft, some dc power is required for specific systems. Alternating current can easily be converted to dc when this becomes necessary. Usually, the dc power required is only a very small percentage of the total electric power consumed in the aircraft.

In some cases, light aircraft use ac power systems for the operation of certain equipment. Since light aircraft generate electric power using dc generators or alternators, they require an inverter to produce ac. An inverter is a device that changes dc voltage to ac voltage. An inverter is used only when a small amount of ac is required. Inverters can be designed to produce virtually any voltage value. Typically, 26-or 115-V inverters are used for light-aircraft systems.

Alternating - current system do have certain disadvantages, such as the radiation of an electromagnetic field around each conductor. This field can interfere with communication or navigation systems if not properly controlled. For the most part, however, the advantages of ac far outweigh the disadvantages. For this reason, the majority of transport-category aircraft contain ac electrical systems.

■■■

CHAPTER - 4
DETAILED KNOWLEDGE OF SERIES AND PARALLEL RESONANCE OF AC CIRCUITS AND THEIR USE, CALCULATION OF RESONANT FREQUENCY OF A CIRCUIT FROM A GIVEN INFORMATION, EFFECT OF CHANGE IN THE FREQUENCY ON THE IMPEDANCE, CURRENT AND PHASE ANGLE

THE RESONANCE EFFECT

Inductive reactance increases as the frequency is increased, but capacitive reactance decreases with higher frequencies. Because of these opposite characteristics, for any LC combination there must be a frequency at which the X_L equals the X_C, for one increases while the other decreases. This case of equal and opposite reactances is called resonance, and the ac circuit is then a resonant circuit.

Any LC circuit can be resonant. It all depends on the frequency. At the resonant frequency, an Lc combination provides the resonance effect. Off the resonant frequency, either below or above, the Lc combination is just another ac circuit.

The frequency at which the opposite reactance are equal is the resonant frequency. This frequency can be calculated as $f_r = 1 f_r = 1/(2\pi\sqrt{LC})$, where L is the inductance in henrys, C is the capacitance in farads, and f_r is the resonant frequency in hertz that makes $X_L = X_C$.

In general, we can say that large values of L and C provide a relatively low resonant frequency. Smaller values of L and C allow higher values for f_r. The resonance effect is most useful for radio frequencies, where the required values of microhenrys for L and picofarads for C are easily obtained.

The most common application of resonance in RF circuit is called turning. In this use, the Lc circuit provides maximum voltage output at the resonant frequency, compared with the amount of output at any other frequency either below or above resonance. This idea is illustrated in (Fig. 4.1), where the LC circuit resonant is maximum output at 1000 kHz, compared with lower or higher frequencies.

Tuning in radio and television ae applications of resonance. When you tune a radio to one station, the LC circuits are tuned to resonance for that particular carrier frequency. Also, when you tune a television receiver to a particular channel, the LC circuits are tuned to resonance for that station. There are almost unlimited uses for resonance in ac circuits.

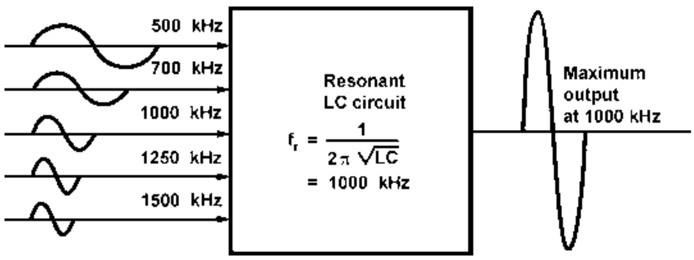


Fig. 4.1. LC circuit resonant at f_r of 1000 kHz to provide maximum output at this frequency.

TEST-POINT QUESTION 'A'

Answer the following questions

a. Give the resonant frequency ? Ans. 1000 kHz

b. Give the frequency that has maximum output ? Ans. 1000 kHz

SERIES RESONANCE

In the series ac circuit in Fig. 4.2 (a) when the frequency of the applied voltage is 1000 kHz, the reactance of the 239-µH inductance equals 1500 Ω. At the same frequency, the reactance of the 106-pF capacitance also is 1500 Ω. Therefore, this LC combination is resonant at 1000 kHz. This is f_r, because the inductive reactance and capactive reactance are equal at this frequency.

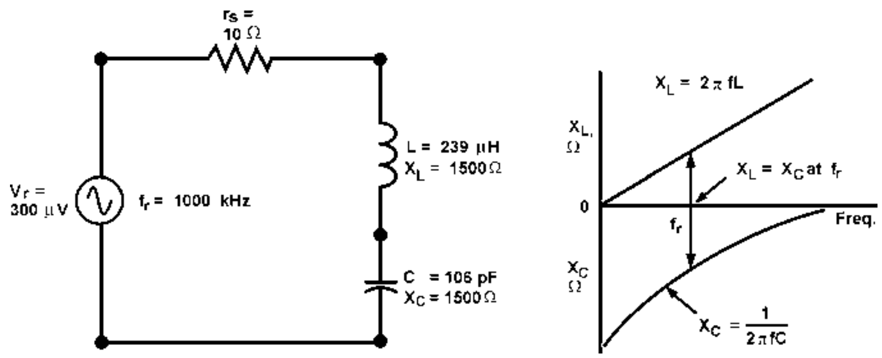


Fig. 4.2. Series resonance. (a) Schematic diagram of series r_s, L, and C. (b) Graph to show that reactances X_c and X_L are equal and opposite at the resonant frequency f_r. Insuctive reactance is shown up for jX_L and capacitive reactance is down for $-jX_C$.

In a series ac circuit, inductive reactance leads by 90º, compared with the zero reference angle of the resistance, and capacitive reactance lags by 90º. Therefore, X_L and X_C are 180^0 out of phase. The opposite reactance cancel each other completely when they are equal.

Fig. 4.2 (b) shows X_L and X_C equal, resulting in a net reactance of zero ohms. The only opposition to current, then, is the coil resistance r_S, which is the limit on how low the series resistance in the circuit can be. With zero reactance and just the low value of series resistance, the generator voltage produces the greatest amount of current in the series LC circuit at the resonant frequency. The series resistance should be as small as possible for a sharp increase in current at resonance.

MAXIMUM CURRENT AT SERIES RESONANCE

The main characteristics of series resonance is the resonant rise of current to its maximum value or V_T/r_S at the resonant frequency. For the circuit in Fig. 4.2 (a), the maximum current at series resonance is 30 µA, equal to 300µV / 10 Ω. At any other frequency, either below or above the resonant frequency, there is less current in the circuit.

This resonant riese of current to 30 µA at 1000 kHz is shown in (Fig. 4.3). In Fig. 4.3 (a), the amount of current is shown as the amplitude of individual cycles of the alternating current produced in the circuit by the ac generator voltage. Wheather the amplitude of one ac cycle is considered in terms of peak, rms, or average value, the amount of current is greatest at the resonant frequency. In Fig. 4.3 (b), the current amplitudes are plotted on a graph for frequencies at and

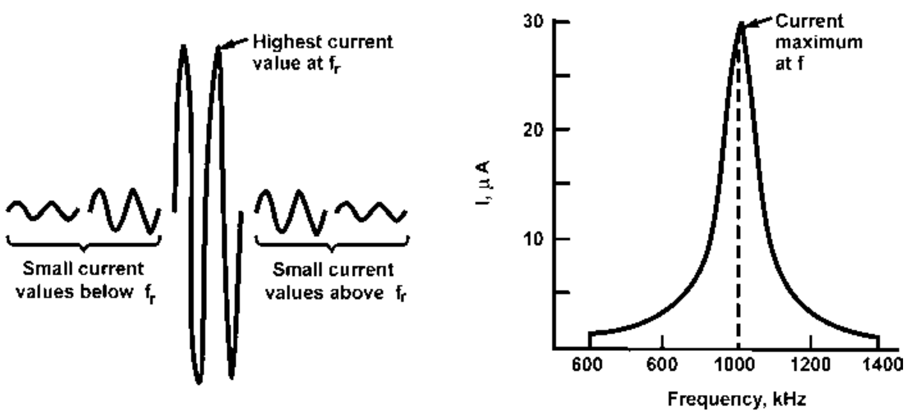


Fig. 4.3. Graphs showing maximum current at resonance for the series circuit in fig. 4.2. (a) Amplitudes of individual cycles. (b) Responce curve to show amount of I below and above resonance. Values of I are in Table 4.1.

near the resonant frequency, producing a typical response curve for a series resonant circuit. The response curve in Fig. 4.3 (b) can be considered as an outline of the increasing and decreasing amplitude for the individual cycles shown in Fig. 4.3 (a).

The response curve of the series resonant circuit shows that the current is small below resonance, rises to its maximum value at the resonant frequency, and then drops off to small values above resonance. To prove this fact, Table 4.1 lists the calculated values of impedance and current in the circuit of (Fig. 4.2) at the resonant frequency of 1000 kHz and at two frequencies below and two frequencies above resonance.

Below resonance, at 600 kHz, X_C is more than X_L and there is appreciable net reactance, which limits the current to a relatively low value. At the higher frequency of 800 kHz, X_C decreases and X_L increases, making the two reactances closer to the same value. The net reactance is then smaller, allowing more current.

AT the resonant frequency, X_L and X_C are equal, the net reactance is zero, and the current has its maximum value equal to V_T/r_S.

Above resonance at 1200 and 1400 kHz, X_L is greater than X_C, providing net reactance that limits the current to much smaller values than at resonance.

TABLE 4.1 SERIES - RESONANCE CALCULATIONS FOR THE CIRCUIT IN FIG. 4.2

Frequency kHz	$X_L = 2\pi f L\Omega$	X_C $1/(2\pi fC), \Omega$	Net Reactance, Ω $X_C - X_L$	Net Reactance, Ω $X_L - X_C$	Z_T, Ω**	$I = V_T/Z_T$ μA	$V_L = IX_L$ μV	$V_C = IX_C$, μV
600	900	2500	1600		1600	0.19	171	475
800	1200	1875	675		675	0.44	528	825
$f_r \rightarrow$ 1000	1500	1500	0	0	10	30	45,000	45,000
1200	1800	1250		550	550	0.55	990	688
1400	2100	1070		1030	1030	0.29	609	310

*** L 239 μH, C = 106 pF, V_T = 300μV, r_s = 10Ω.**

**** Z_T and I calculated without r_S when its resistance is very small compared with the net X_L or X_C. Z_T and I are resistive at f_r.**

1. Below the resonant frequency, X_L is small, but X_C has high values that limit the amount of current.
2. Above the resonant frequency, X_C is small, but X_L has high values that limit the amount of current.
3. At the resonant frequency, X_L equals X_C and they cancel to allow maximum current.

MINIMUM IMPEDANCE AT SERIES RESONANCE

Since the reactances cancel at the resonant frequency, the impedance of the series circuit is minimum, equal to just the low value of series resistance. This minimum impedance at resonance is resistive, resulting in zero phase angle. At resonance, therefore, the resonant current is in phase with the generator voltage.

RESONANT RISE IN VOLTAGE ACROSS SERIES L OR C

The maximum current in a series Lc circuit at resonance is useful because it produces maximum voltage across either X_L or X_C at the resonant frequency. As a result, the series resonant circuit can select one frequency by providing much more

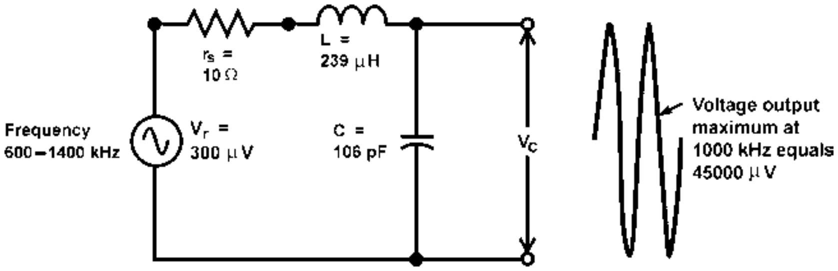


Fig. 4.4. Series circuit selects frequency by producing maximum IX_c voltage output across c at resonance.

voltage output at the resonant frequency, compared with frequencies above and below resonance. (Fig. 4.4) illustrate the resonant rise in voltage across the capacitance in a series ac ciricuti. At the resonant frequency of 1000 kHz, the voltage across C rises to the value of 45,000 μV, and the input voltage is only 300 μV.

In Table 4.1, the voltage across C is calculated as IX_C, and across L as IX_L. Below the resonant frequency, X_C has a higher value than at resonance, but the current is small. Similarly, above the resonant frequency, X_L is higher than at resonance, but the current has a low value because of the inductive reactance. At resonance, although X_L and X_C cancel each other to allow maximum current, each reactance by itself has an appreciable value. Since the current is the same in all parts of a series circuit, the maximum current at resonance produces maximum voltage IX_C across C and an equal IX_L voltage across L for the resonant frequency.

Although the voltage across X_C and X_L is reactive, it is an actual voltage that can be measured. In (Fig. 4.5), the voltage drops around the series resonant circuit are 45,000 μV across C and 45,000 μV across L, with 300 μV across r_S. The voltage across the resistance is equal to and in phase with the generator voltage.

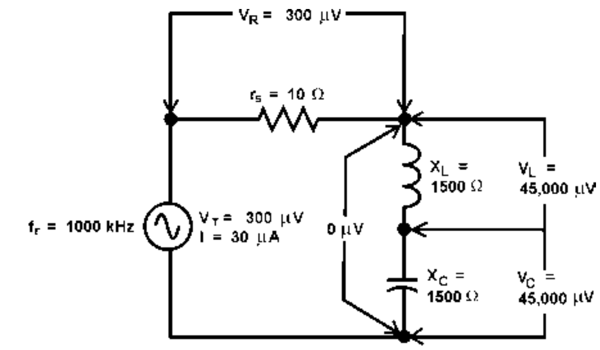


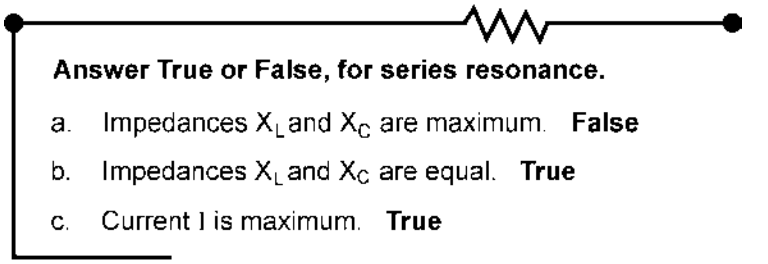
Fig. 4.5. Voltage drops around series resonant circuit.

Across the series combination of both L and C, the voltage is zero because the two series voltage drops are equal and opposite. In order to use the resonant rise of voltage, therefore, the output must be connected across either L or C alone. We can consider the V_L and V_C voltages as similar to the idea of two batteries connected in series opposition. Together, the resultant is zero for the equal and opposite voltages, but each battery still has its own potential difference.

In summary, for a series resonant circuit the main characteristics are:

1. The current I is maximum at the resonant frequency f_r.
2. The current I is in phase with the generator voltage, or the phase angle of the circuit is 0°.
3. The voltage is maximum across either L or C alone.
4. The impedance is minimum at f_r, equal only to the low r_S.

TEST-POINT QUESTION 'B'



PARALLEL RESONANCE

With L and C in parallel as shown in (Fig. 4.6), when X_L equals X_C, the reactive branch current are equal and opposite at resonance. Then they cancel each other to produce minimum current in the main line. Since the line current is minimum, the impedance is maximum. These relations are based on r_S being very small compared with X_L at resonance. In this case, the branch currents are practically equal when X_L and X_C are equal.

MINIMUM LINE CURRENT AT PARALLELN RESONANCE

To show how the current in the main line dips to its minimum value when the parallel LC circuit is resonant, Table 4.2 lists the values of branch currents and the total line current for the circuit in (Fig. 4.6).

TABLE 4.2 PARALLEL-RESONANCE CALCUALTIONS FOR THE CIRCUIT IN FIG. 4.6**

Generator voltage is 300 μv.					Net Reactance,Ω			
Frequency	X_C	X_L	I_C =	I_L =	Line Current, μA		I_T,	$Z_{EQ} = V_A/I_T$
kHz	$1/(2\pi fC)$,	$2\pi f L$, Ω	V/X_C,	V/X_L,			μA *	Ω*
	Ω	Ω	μA	μA *	$I_L - I_C$	$I_C - I_L$		
600	2500	900	0.12	0.33	0.21		0.21	
800	1200	1875	0.16	0.25	0.09		0.09	3333
$f_r \to$ 1000	1500	1500	0.20	0.20	0	0	0.00133	2,25,000
1200	1250	1800	0.24	0.17	550	0.07	0.07	3800
1400	1070	2100	0.28	0.14	1030	0.14	0.14	2143

* L 239 μH, C = 106 pF, V_T = 300μV, r_s = 10Ω.

** Z_T and I calculated without r_S when its resistance is very small compared with the net X_L or X_C. Z_T and I are resistive at f_r.

With L and C the same as in the series circuit of Fig. 4.2m X_L and X_C have the same values at the same frequencies. Since L, C, and the generator are in parallel, the voltage applied across the branches equals the generator voltage of 300 μV. Therefore, each reactive branch current is calculated as 300 μV divided by the reactance of the branch.

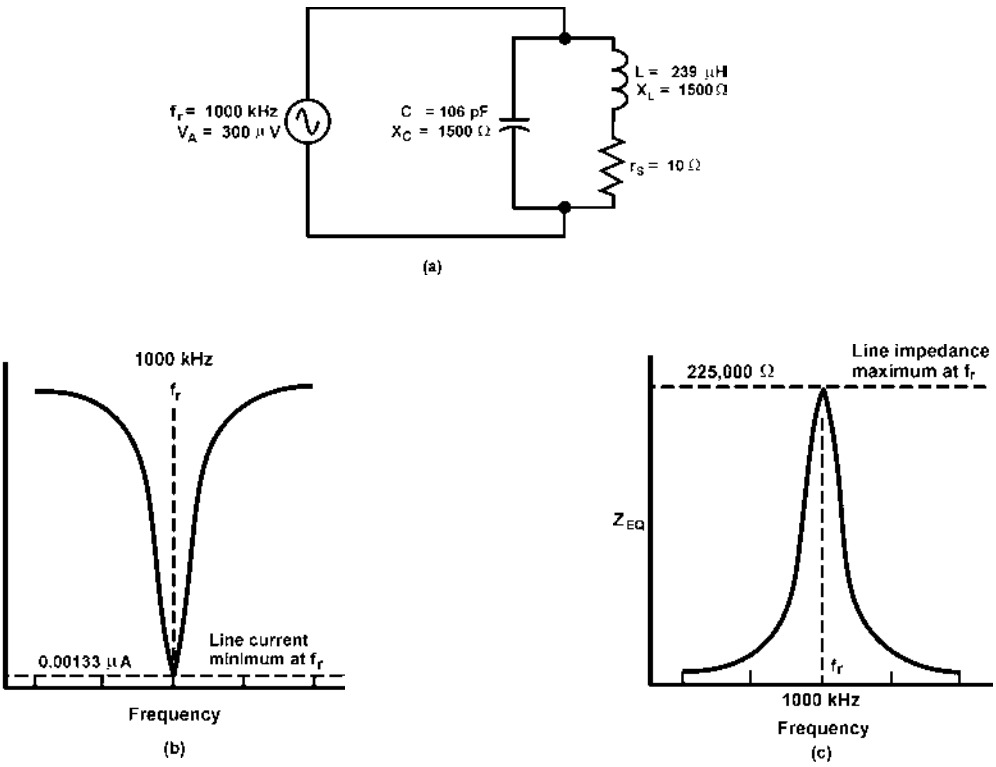


Fig. 4.6. Parallel resonant circuit. (a) Schematic diagram of L *and* C *in parallel branches. (b) Response curve of I_r shows that the line current dips to minimum at f_r. (C) Response curve of Z_{EQ} shows that it rises to maximum at f_r.*

The value in the top row of Table 4.2 are obtained as follows: At 600 kHz the capacitive branch current equals 300 μ V/2500 Ω, or 0.12 μ A. the inductive branch current at this frequency is 300 μ V/900 Ω, or 0.33 μ A. Since this is a parallel as circuit, the capacitive current lags by 90°, compared with the reference angle of the generator voltage, which is applied across the parallel branches. Therefore, the opposite currents are 180° out of phase. The net current in the line, then, is the difference between 0.33 and 0.12, which equals 0.21 μA.

Following this procedure, the calculations show that as the frequency is increased toward resonance, the capacitive branch current increases because of the lower value of X_C , and the inductive branch current decreases with higher values of X_L. As a result, there is less net line current as the two branch currents become more nearly equal.

At the resonant frequency of 1000 kHz, both reactances are 1500 Ω, and the reactive branch currents are both 0.20 μ A, canceling each other completely.

Above the resonant frequency, there is more current in the capacitive branch than in the inductive branch, and the net line current increases above its minimum value at resonance.

The dip in I_T to its minimum value at f_r is shown by the graph in (Fig). At parallel resonance, I_T is minimum and Z_{EQ} is maximum.

The in-phase current due to r_S in the inductive branch can be ignored off resonance because it is so small compared with the reactive line current. At the resonant frequency when the reactive currents cancel, however, the resistive component is the entire line current. Its value at resonance equals 0.00133 μA in this example. This small resistive current is the minimum value of the line current at parallel resonance.

MAXIMUM LINE IMPEDANCE AT PARALLEL RESONANCE

The minimum line current resulting from parallel resonance is useful because it corresponds to maximum impedance in the line across the generator. Therefore, an impedance that has a high value for just one frequency but a low impedance for other frequencies, either below or above resonance, can be obtained by using a parallel LC circuit resonant at the desired frequency. This is another method of selecting one frequency by resonance. The response curve in (Fig.) shows how the impedance rises to maximum for parallel resonance.

The main application of parallel resonance is the use of an LC tuned circuit as the load impedance Z_L in the output circuit of RF amplifiers. Because of the high impedance, then, the gain of the amplifier is maximum at f_r . The voltage gain of an amplifier is directly proportional to Z_L. The advantage of a resonant LC circuit is that Z is maximum only for an ac signal at the resonant frequency. Also, L has practically no dc resistance, which means practically no dc voltage drop.

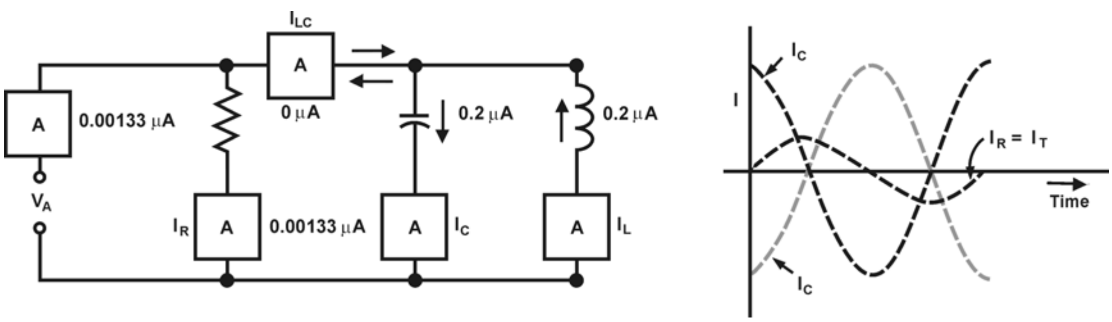


Fig. 4.7. Distribution of currents in parallel circuit at resonance. Resistive current shown as an equivalent branch for I_R(a) circuit with branch currents for R,L, and C. (b) Graph of equal and opposite reactive currents I_L and I_C.

Referring to to Table 4.2, the total impedance of the parallel ac circuit is calculated as the generator voltage divided by the total line current. At 60 kHz, for example, Z_{EQ} equals 300 μ V/0.21 μ A, or 1400 Ω . At 800 kHz, the impedance is higher because there is less line current.

At the resonant frequency of 1000 kHz , the line current is at its minimum value of 0.00133 μ A. Then the impedance is maximum and is equal to 300 μ V/0.00133 μ A, or 225,000 Ω .

Above 1000 kHz, the line current increases, and the impedance decreases from its maximum value.

The idea of how the line current can have a very low value even though the reactive branch currents are appreciable is illustrated in (Fig.). In (Fig.), the resistive component of the total line current is shown as though it were a separate branch drawing an amount of resistive current from the generator in the main line equal to the current resulting from the coil resistance. Each reactive branch current has its value equal to the generator voltage divided by the reactance. Since they are equal and of opposite phase, however, in any part of the circuit where both reactive currents are present, the net amount of electron flow in one direction at any instant of time corresponds to zero current. The graph in (Fig.) shows how equal and opposite currents for I_L and I_C cancel.

If a meter is inserted in series with the main line to indicate total line current I_T, it dips sharply to the minimum value of line current at the resonant frequency. With minimum current in the line, the impedance across the line is maximum at the resonant frequency . The maximum impedance at parallel resonance corresponds to a high value of resistance, without reactance, since the line current is then resistve with zero phase angle.

In summary, for a parallel resonant circuit, the main characteristics are

1. The line current I_T is minimum at the resonant frequency.
2. The current I_T is in phase with the generator voltage V_A, or the phase angle of the circuit is 0^o.
3. The impedance Z_{EQ} , equal to V_A / I_T , is maximum at f_r because of the minimum I_T.

THE LC TANK CIRCUIT

It should be noted that the individual branch currents are appreciable at resonance, although I_T is minimum. For the example in Table 4.2, at f_r either the I_L or the I_C equals 0.2 μ A. This current is greater than the I_C values below f_r or the I_L values above f_r. The branch currents cancel in the main line because I_C is at 90^o with the respect to the source V_A while I_L is at -90^o, making them opposite with respect to each other.

However, inside the LC circuit, I_L and I_C do not cancel, because they are in separate branches. Then I_L and I_C provide a circulating current in the LC circuit, which equals 0.2 μ A in this example. For this reason, a parallel resonant LC circuit is often called a tank circuit.

Because of the energy stored by L and C, the circulating tank current can provide full sine waves of current and voltage output when the input is only a pulse. The sine-wave output is always at the natural resonant frequency of the LC tank circuit. This ability of the LC circuit to supply complete sine waves is called the flywheel effect. Also, the process of producing sine waves after a pulse of energy has been applied is called ringing of the LC circuit.

TEST-POINT QUESTION 'C'

Answer True or False, for parallel resonance.

a. Currents I_L and I_C are maximum. **False**

b. Currents I_L and I_C are equal. **True**

c. Current I_T is minimum. **True**

RESONANT FREQUENCY

$f_r = 1/(2\pi\sqrt{LC})$

The formula for the resonant frequency is derived from $X_L = X_C$. Using f_r to indicate the resonant frequency in the formulas for X_L and X_C , we have

$$2\pi f_r L = \frac{1}{2\pi f_r C}$$

Inverting the factor f_r gives

$$2\pi L(f_r)^2 = \frac{1}{2\pi C}$$

Inverting the factor 2π L gives

$$(f_r)^2 = \frac{1}{(2\pi)^2 LC}$$

The square root of both sides is then

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Where L is in henry, C is in farads, and the resonant frequency f_r is in hertz (Hz) units. For example, to find the resonant frequency of the LC combination in (Fig.) the values of 239×10^{-6} and 106×10^{-12} are substituted for L and C. Then :

$$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{239\times10^{-6}\times106\times10^{-12}}}$$

$$= \frac{1}{6.28\sqrt{25{,}334 \times 10^{-18}}} = \frac{1}{6.28 \times 159.2 \times 10} = \frac{1}{1000 \times 10^{-9}}$$

$$f_r = 1 \times 10^6 \text{ Hz} = 1 \text{ MHz} = 1000 \text{ kHz}$$

For any LC circuit , series or parallel, the f_r equal to $1/(2\pi\sqrt{LC})$ is the resonant frequency that makes the inductive and capacitive reactances equal.

HOW THE F_r VARIES WITH L AND C

It is important to note that higher values of L and C result in lower values of f_r Either L or C , or both, can be varied. An LC circuit can be resonant at any frequency, from a few hertz to many megahertz.

As examples, an LC combination with the relatively large values of an 8-H inductance and a 20 - μ F capacitance is resonant at the low audio frequency of 12.6 Hz. For a much higher frequency in the RF range, a small inductance of 2 μ H will resonate with the small capacitance of 3 pF for an f_r of 64.9 MHz. These examples are solved in the next two problems for more practice with the resonant frequency formula. Such calculations are often used in practical applications of tuned circuits. Probably the most important feature of any LC combination is its resonant frequency, especially in RF circuits. The applications of resonance are mainly for radio frequencies.

EXAMPLE 1

Calculate the resonant frequency for an 8-H inductance and a 20-μ F capacitance.

Answer

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{8 \times 20 \times 10^{-6}}}$$

$$= \frac{1}{6.28\sqrt{160 \times 10^{-6}}}$$

$$= \frac{1}{6.28 \times 12.65 \times 10^{-3}}$$

$$= \frac{1}{79.44 \times 10^{-3}}$$

$$f_r = 0.0126 \times 10^3$$

$$= 12.6 \text{ Hz}$$

EXAMPLE 2

Calculate the resonant frequency for a 2-μ H inductance and a 3-pF calacitance.

Answer

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{2 \times 10^{-6} \times 3 \times 10^{-12}}}$$

$$= \frac{1}{6.28\sqrt{6 \times 10^{-18}}}$$

$$= \frac{1}{6.28 \times 2.45 \times 10^{-9}}$$

$$= \frac{1}{15.4 \times 10^{-9}} = 0.065 \times 10^9$$

$$f_r = 65 \times 10^6 \text{ Hz} = 65 \text{ MHz}$$

Specifically, because of the square root in the denominatorof Formula (26-1), the f_r decreases inversely as the square root of L or C. For instance, if L or C is quadrupled, the f_r is reduced by one-half. The 1/2 is equal to the square root of 1/4.

As a numerical example, suppose f_r is 6 MHz with particular values of L and C. If either L or C is made four times larger, then f_r will be reduced to 3 MHz.

Or, to take the opposite case of doubling the frequency from 6 MHz to 12 MHz, the following can be done:

1. Use one-fourth the L with the same C.
2. Use one-fourth the C with the same L.
3. Reduce both L and C by one-half.
4. Use any new combination of L and C whose product will be one-fourth the original product of L and C.

LC PRODUCT DETERMINES F_r

There are any number of LC combinations that can be resonant at one frequency. With more L, then less C can be used for the same f_r. Or less L can used with more C. Table 4.3 lists five possible combinations of L and C resonant at 1000 kHz, just as an example of one f_r. The resonant frequency is the same 1000 kHz here for all five combinations. When either L or C is increased by a factor of 10 or 2, the other is decreased by the same factor resulting in a constant value for the LC product.

The reactance at resinance changes with different combinations ofc L and C, but in all five cases X_L and X_C are equal to each other at 1000 kHz. This is the resonant frequency by the value of the LC product in $f_r = 1/(2\pi\sqrt{LC})$.

TABLE 4.3 LC COMBINATIONS RESONANT AT 1000 KHZ

L, μH	C,pF	L×C	X_L, Ω	X_C, Ω
		LC Product	at 1000 kHz	at 1000 kHz
23.9	1060	25,334	150	150
119.5	212	25,334	750	750
239	106	25,334	1,500	1,500
478	53	25,334	3,000	3,000
2390	10.6	25,334	15,000	15,000

MEASURING L OR C BY RESONANCE

Of the three factors L,C, and f_r in the resonant-frequency formula, any one can be calculated when the other two are known .

The resonant frequency of the LC combination can be found experimentally by determining the frequency that produces the resonant response in an LC combination. With a known value of either L or C, and the resonant frequency determined, the third factor can be calculated. Thos method is commonly used for measuring inductance or capacitance. A test instrument for this purpose is the Q meter, which also measures the Q of a coil.

Calculating c from f_r

The C can be taken out of the square root sign or radical in the resonance fromula, as follows :

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Squaring both sides to eliminate the radical gives

$$f_r^2 = \frac{1}{(2\pi)^2 LC}$$

Inverting C and f_r^2 gives

$$C = \frac{1}{4\pi^2 f_r^2 L} \qquad (26\text{-}2)$$

where f_r is in hertz, C is in farads, and L is in henrys.

Calculating L from f_r

Similarly, the resonance formula can be transposed to find L. Then

$$L = \frac{1}{4\pi^2 f_r^2 C} \qquad (26\text{-}3)$$

With Formula (26-3), L is determined by its f_r with a known value of C.

Similarly, C is determined from Formula (26-2) by its f_r with a known value of L.

Example - 3

What value of C resonates with a 239 - µ H L at 1000 kHz ?

Answer

$$C = \frac{1}{4\pi^2 f_r^2 L}$$

$$= \frac{1}{4\pi^2 (1000 \times 10^3)^2 \; 239 \times 10^{-6}}$$

$$= \frac{1}{39.48 \times 1 \times 10^6 \times 239}$$

$$= \frac{1}{9435.75 \times 10^6}$$

$$C = 0.000106 \times 10^{-6}\,F = 106pF$$

Note that 39.48 is a constant for 4 π^2.

Example - 4

What value of L respnates with a 106-pF C at 1000 lHz, equal to 1 MHz?

Answer

$$L = \frac{1}{4\pi^2 f_r^2 C}$$

$$= \frac{1}{39.48 \times 1 \times 10^{12} \times 106 \times 10^{-12}}$$

$$= \frac{1}{4184.88}$$

$$L = 0.000239 \; H = 239 \; \mu H$$

Note that 10^{12} and 10^{-12} in the denominator cancel each other. Also, 1 × 10^6, or 1 MHz.

The value in Example 3 and 4 are from the LC circuit illustrated in (Fig. 26.2) for series resonance and (Fig. 26.6) for parallel resonance.

TEST-POINT QUESTION 'D'

Answer the following questions

a. To increase f_r , must the C be increased or decreased ? Ans. Decreased

b. If C is increased from 100 to 400 pF, L must be decreased from 800 µH to what value for the same f_r ? Ans. -200 µH

c. Give the constant value for $4\pi^2$? Ans. 39.48

Q MAGNIFICATION FACTOR OF RESONANT CIRCUIT

The quality, or figure of merit, of the resonant circuit, in sharpness of resonance, is indicated by the factor Q. In general, the higher the ratio of the reactance at resonance to the series resistance, the higher the Q and the sharper the resonance effect.

Q of Series Circuit In a series resonant circuit we can calculate Q from the following formula:

$$Q = \frac{X_L}{r_s} \qquad (26\text{-}4)$$

Where Q is the figure of merit, X_L is the inductive reactance in ohms at the resonant frequency, and r_s is the resistance in ohms in series with X_L. For the series resonant circuit in (Fig.26.2).

$$Q = \frac{1500\Omega}{10\Omega} = 150$$

The Q is a numerical factor without any units, because it is a ratio of reactance to resistance and the ohms cancel.. Since the series resistance limits the amount of current at resonance, the lower the resistance, the sharper the increase to maximum current at the resonant frequency, and the higher the Q. Also, a higher value of reactance at resonance allows the maximum current to produce a higher value of voltage for the output.

The Q has the same value if it is calculated with X_C instead of X_L, since they are equal at resonance. However, the Q of the circuit is generally considered in terms of X_L, because usually the coil has the series resistance of the circuit. In this case, the Q of the coil and the Q of the series resonant circuit are the same. If extra resistance is added, the Q of the circuit will be less than the Q of the coil. The highest possible Q for the circuit is the Q of the coil.

The value of 150 can be considered as a high Q. Typical values are 50 to 250, approximately. Less than 10 is a low Q; more than 300 is a very high Q.

HIGHER L/C RATIO CAN PROVIDE HIGHER Q

As shown before in Table 4.3, different combinations of L and C can be resonant at the same frequency. However, the amount of reactance at resonance is different. More X_L can be obtained with a higher L an lower C for resonance, although X_L and X_C must be equal at the resonant frequency. Therefore, both X_L and X_C are higher with a higher L/C ratio for resonance.

More X_L can allow a higher Q if the ac resistance does not increase as much as the reactance. With typical RF coils, an approximate rule is that maximum Q can be obtained when X_L is about 1000 Ω . In many cases, though, the minimum C is limited by the stray capacitance in the circuit.

Q RISE IN VOLTAGE ACROSS SERIES L OR C

The Q of the resonant circuit can be considered a magnification factor that determines how much the voltage across L or C is increased by the resonant rise of current in a series circuit. Specifically, the voltage output at series resonance is Q times the generator voltage:

$$V_L = V_C = Q \times V_{gen} \qquad (26\text{-}5)$$

In Fig. 26-4, for example, the generator voltage is 300 μ V and Q is 150. The resonant rise of voltage across either L or C then equals 300 μ V × 150, or 45,000 μ V. Note that this is the same value calculated in Table 26-1 for V_C or V_L at resonance.

HOW TO MEASURE Q IN A SERIES RESONANT CIRCUIT

The fundamental nature of Q for a series resonant circuit is seen from the fact that the Q can be determined experimentally by measuring the Q rise in voltage across either L or C and comparing this voltage. As a formula,

$$Q = \frac{V_{out}}{V_{in}} \qquad (26\text{-}6)$$

Where V_{out} is the ac voltage measured across the coil or capacitor and V_{in} is the generator voltage.

Referring to Fig. 26-5, suppose that you measure with an ac voltmeter across L or C and this voltage equals 45,000 μV at the resonant frequency. Also, measure the generator input of 300 μ V. Then

$$Q = \frac{V_{out}}{V_{in}}$$

$$= \frac{45{,}000\mu V}{300\mu V}$$

$$Q = 150$$

This method is better than the X_L / r_s formula for determining Q because r_s is the ac resistance of the coil, which is not so easily measured. Remember that the coil's ac resistance can be more than double the dc resistance measured with an ohm meter. In fact, measuring Q with Formula (26-6) makes it possible to calculate the ac resistance. These points are illustrated in the following example.

Example 5

A series circuit resonant at 0.4 MHz develops 100 mV across a 250-μ H L with a 2-mV input. Calculate Q.

Answer

$$Q = \frac{V_{out}}{V_{in}} = \frac{100mV}{2mV}$$

$$Q = 50$$

Example 6

What is the ac resistance of the coil in the preceding example ?

Answer

The Q of the coil is 50. We need to know the reactance of this 250-μ H coil at the frequency of 0.4 MHz. Then,

$$X_L = 2\pi fL = 6.28 \times 0.4 \times 10^6 \times 250 \times 10^{-6}$$

$$X_L = 628\,\Omega$$

Also, $Q = \frac{X_L}{r_s}$ or $r_s = \frac{X_L}{Q}$

$$r_s = \frac{628\Omega}{50}$$

$$r_s = 12.56\Omega$$

Q OF PARALLEL CIRCUIT

In a parallel resonant circuit, where r_s is very small compared with X_L, the Q also equals X_L/r_s. Note that r_s is still the resistance of the coil in series with X_{Ls} (see Fig.). The Q of the coildetermines the Q of the parallel circuit here because it is less than the Q of the capacitive branch. Capacitors used in tuned circuits generally have a very high Q because of their low losses. In (Fig.), the Q is 1500 Ω or 150, the same as the series resonant circuit with the same values.

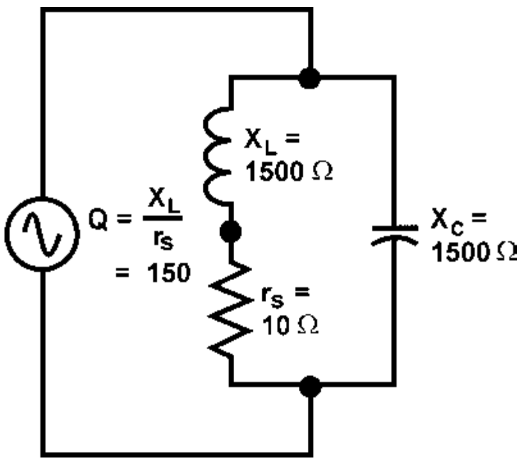


Fig. 4.8. The Q of a parallel resonant circuit in terms of X_L and its series resonance r_S.

This example assumes that the generator resistance is very high and that there is no other resistance branch shunting the tuned circuit. Then the Q of the parallel resonant circuit is the same as the Q of the coil. Actually, shunt resistance can lower the Q of a parallel resonant circuit, as analyzed in Sec. 26-10.

Q RISE IN IMPEDANCE ACROSS PARALLEL RESONANT CIRCUIT

For parallel resonance, the Q magnification factor determines by how much the impedance across the parallel LC circuit is increased because of the minimum line current. Specifically, the impedance across the parallel resonant circuit is Q times the inductive reactance at the resonant frequency:

$$Z_{EQ} = Q \times X_L \qquad (26\text{-}7)$$

Referring back to the parallel resonant circuit in Fig. 26-6, as an example, X_L is 1500 Ω and Q is 150. The result is a rise of impedance to the maximum value of 150×1500 Ω, or 225,000 Ω, at hte resonant frequency.

Since the line curent equals V_A/Z_{EQ}, the minimum value of line current is 300 μV/225,000 Ω, which equals 0.00133 μA.

At f_r the minimum line current is 1/Q of either branch current. In Fig. 26-7, I_L or I_C is 0.2 μA and Q is 150. Therefore, I_T is 0.2/150, or 0.00133 μA, which is the same answer as V_A/Z_{EQ}. Or, stated another way, the circulating tank current is Q times the minimum I_T.

HOW TO MEASURE Z_{EQ} OF A PARALLEL RESONANT CIRCUIT

Formula (26-7) for Z_{EQ} is also useful in its inverted form as $Q = Z_{EQ} / X_L$. We can measure Z_{EQ} by the method illustrated in **Fig. 26-9.** Then Q can be calculated from the value of Z_{EQ} and the inductive reactance of the coil.

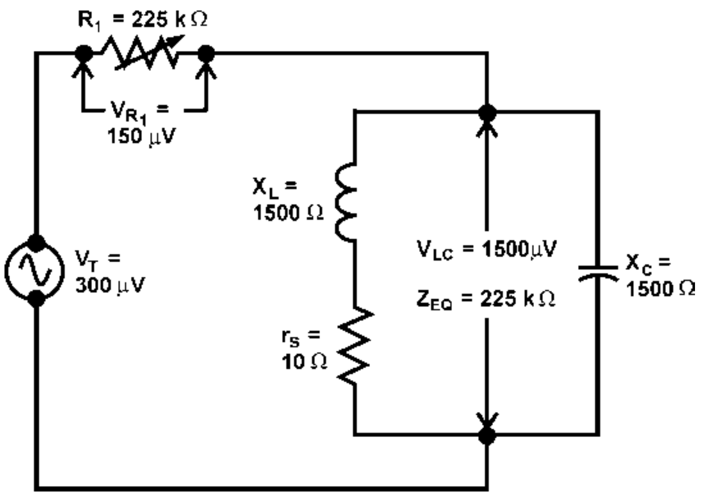


Fig. 4.9. How to measure Z_{Eq} of a parallel resonant circuit. Adjust R_1 to make its V_R equal to V_{LC}. Then $Z_{EQ} = R_1$.

To measure $Z_{EQ,}$ first tune the LC circuit to resonance. Then adjust R_1 in (Fig. 26-9) to the resistance that makes its ac voltage equal to the ac voltage across the tuned circuit. With equal voltages, the Z_{EQ} must be the same value as R_1.

For the example here, which corresponds to the parallel resonance shown in (Figs. 26-6) and (26-8), the Z_{EQ} is equal to 225,000 Ω. This high value is a result of parallel resonance. The X_L is 1500 Ω. Therefore, to determine Q, the calculations are

$$Q = \frac{Z_{EQ}}{X_L} = \frac{225{,}000}{1500} = 150$$

CHOOSING L AND C FOR A RESONANT CIRCUIT

The following example illustrates how resonance is really just an application of X_L and X_C. Suppose that we have the problems of determining the inductance and capacitance for a circuit to be resonant at 159 kHz. First, we need a known value for either L or C, in order to calculate the other, which one to choose depends on the application. In some cases, particularly at very high frequencies, C must be the minimum possiblevalue, which might be about 10 pF. At medium frequencies, though, we can choose L for the general case when an X_L of 1000 Ω is desirable and can be obtained. Then the inductance of the required L, equal to $X_L/2\pi f$, is 0.001 H or 1 mH, for the inductive reactance of 1000 Ω.

For resonance at 159 kHz with a 1-mH L, the required C is 0.001 μF or 1000 pF. This value of C can be calculated for an X_C of 1000 Ω, equal to X_L at the f_r of 159 kHz, or from Formula (26-2). In either case, if you substitute 1×10^{-9} F for C and 1×10^{-3} H for L in the resonant frequency formula, f_r will be 159 kHz.

This combinationis resonant at 159 kHz whether L and C are in series or parallel. In series, the resonant effect is to produce maximum current and maximum voltage across L or C at 159 kHz. The effect is desirable for the input circuit of an RF amplifier tuned to f_r because of the maximum signal. In parallel, the resonant effect at 159 kHz is minimum line current and maximum impedance across the generator. This effect is desirable for the output circuit of an RF amplifier, as the gain is maximum at f_r because of the high Z.

If we assume that the 1-mH coil used for L has an internal resistance of 20Ω, the Q of the coil is 1000 Ω/20 Ω, which equals 50. This value is also the Q of the series resonant circuit. If there is no shunt damping resistance across the parallel LC circuit is 159 kHz/50, which equals 3.18 kHz for Δ f.

TEST-POINT QUESTION 'E'

Answer the following questions

a. What is f_r for 1000 pF of C and 1 mH of L ? Ans. f_r = 159 kHz

b. What is f_r for 250 pF of C and 1 mH of L ? Ans. f_r = 318 kHz

CHAPTER - 5
DETAILED KNOWLEDGE OF THE COMPOSITION, PERFORMANCE (STABILITY AND TOLERANCE) AND LIMITATIONS OF THE FIXED RESISTORS (CARBON COMPOSITION, CARBON FILM, WIRE WOUND AND METALLIC FILM) AND DESCRIPTION OF VARIOUS TYPES OF VARIABLE RESISTORS (WIRE WOUND, CARBON FILM, THERMISTERS AND VARISTORS). KNOWLEDGE OF RESISTOR COLOUR CODES, VALUE AND TOLERANCE, AND THE SYSTEM OF PREFERRED VALUES AND WATTAGE RATINGS.

RESISTOR

A resistor is an electrical component which can conduct current in both directions. The resistors are used mainly for two purpose namely controlling the flow of electric current and providing desired amount of voltage in electronic or electric circuit.

CHARACTERISTICS OF RESISTOR

The two main characteristics of a resistor are its resistance R in ohms and its power rating W in watts. Resistors are available in a very wide range of R values, from a fraction of an ohm to many kilohms (k Ω) and megohms (M Ω). One kilohm is 1000 Ω, and one megohm is 1,000,000 Ω. The power rating for resistors may be as high as several hundred watts or as low as 1/10 W.

The R is the resistance value required to provide the desired current I or voltage. Also important is the wattage rating, because it specifies the maximum power the resistor can dissipate without excessive heat. Dissipation means that the power is wasted, since the resultant heat is not used. Too much heat can make the resistor burn. The wattage rating of the resistor is generally more than the actual power dissipation, as a safety factor.

Most common in electronic equipment are carbon resistors with a power rating of 1 W or less. The construction is illustrated in (Fig.5.1). The leads extending out from the resistor body can be inserted through the holes on a printed-circuit (PC) board for mounting as shown in (Fig.5.1). The resistors on a PC board are often inserted automatically by machine. It should be noted that resistors are not polarity-sensitive devices. This means that it does not matter which way the leads of a resistor are connected into a circuit.

Resistors with higher R value usually have lower wattage ratings because they have less current. As an example, a common value is 1 MΩ at 1/4 W, for a resistor only 1/4 in long. The lower the power rating, the smaller the actual physical size of the resistor. However, the resistance value is not related to physical size (Fig.5.1) shows several carbon resistors with the same physical size but different resistance values. The different color bands on each resistor indicates a different ohmic value. The carbon resistors in (Fig.5.1) each have a power rating of 1/2 W, which is based on their physical size.

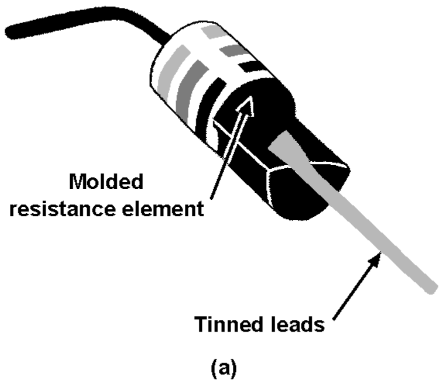
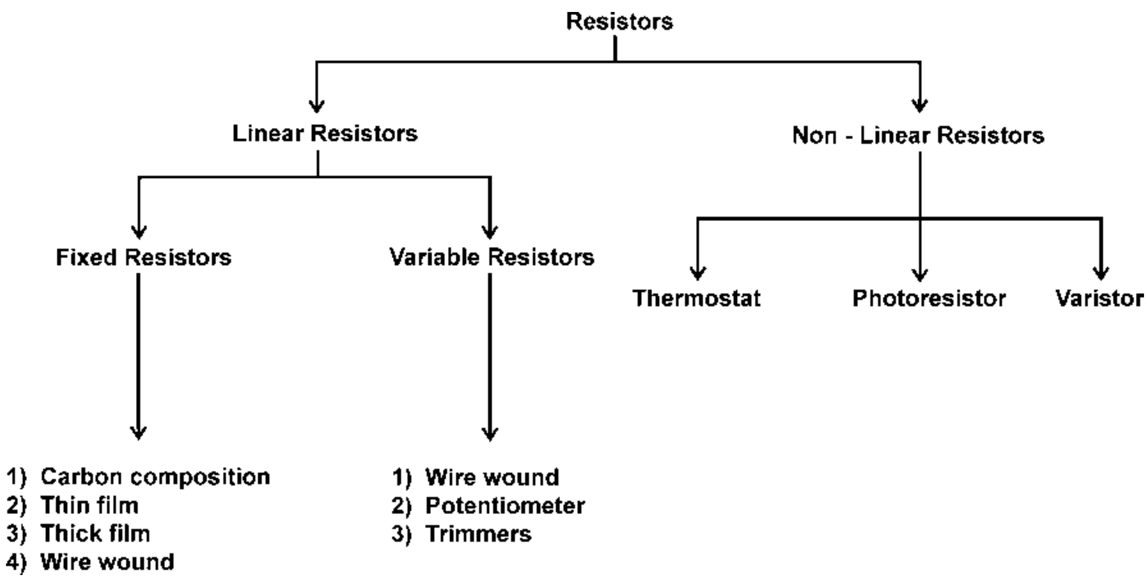


Fig. 5.1. Carbon-composition resistors. (a) Internal construction. Length is about in. without leads for W power rating. Color stripes give R in ohms. Tinned leads have coating of solder. (b) Resistors mounted on printed-circuits (PC) board.



TYPES OF RESISTOR

LINEAR RESISTOR

The resistor through which the current is directly proportional to the applied voltage are called linear resistors. Such resistors have a property that their resistance value does not changer with the variations in applied voltage, temperature or light intensity. The linear resistors are of two types namely fixed resistors and variable resistors

WIRE-WOUND RESISTORS

In this construction, a special type of wire called resistance wire is wrapped around an insulating core. The length of wire and its specific resistivity determine the R of the unit. Types of resistance wire include tungsten and manganin, "Conductors and Insulators." The insulated core is commonly porcelain, cement, or just plain pressed paper. Bare wire is used, but the entire unit is generally encased in an insulating material. Typical fixed and variable wire-wound resistors are shown in (Fig.5.2).

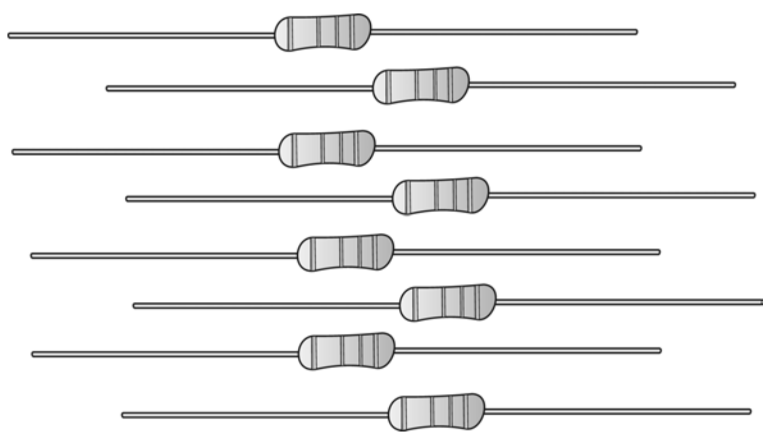


Fig. 5.2. Carbon resistors with same physical size but different resistance values. The physical size indicates a power rating of $\frac{1}{2}$ *W.*

Since they are generally used for high-current applications with low resistance and appreciable power, wire-wound resistors are available in wattage ratings from 5 W up to 100 W or more. The resistance can be less than 1 Ω up to several thousand ohms.

In addition, wire-wound resistors are used where accurate, stable resistance values are necessary. Examples are precision resistors for the function of an ammeter shunt or a precision potentiometer to adjust for an exact amount or R.

For 2 W or less, carbon resistors are preferable because they are small and cost less. Between 2 and 5 W, combinations of carbon resistors can be used. Also, small wire-wound resistors are available in a 3- or 4-W rating.

CARBON-COMPOSITION RESISTORS

These resistors are made of finely divided carbon or graphite mixed with a powdered insulating material as a binder, in the proportions needed for the desired R value. As shown in (Fig.5.3), the resistor element is enclosed in a plastic case for insulation and mechanical strength. Joined to the two ends of the carbon resistance element are metal caps with leads of tinned copper wire for soldering the connections into a circuit. These are called axial leads because they come straight out from the ends. Carbon-composition resistors are commonly available in R values of 1 Ω to 20 M Ω. Examples are 10 Ω, 220 Ω,4.7 k Ω and 68 k Ω. The power rating is generally $\frac{1}{10}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$, 1, or 2 W.

Fig.5.3. Large wire-wound resistors with 50-W power rating.* (a) *fixed* R, *Length of 5 in.* (b) *Variable* R, *diameter of 2 in.

FILM-TYPE RESISTORS

There are two kinds of film-type resistors : carbon-film and metal film resistors. The carbon-film resistor, whose construction is shown in (Fig. 5.4), is made by depositing a thin layer of carbon on an insulated substrate. The carbon film is then cut in the form of a spiral to form the resistive element. The resistance value is controlled by varying the proportion of carbon to insulator. As compared to carbon-composition resistors, carbon-film resistors have the following advantages : tighter tolerances, less sensitivity to temperature changes and aging, and less noise generated internally.

Metal-film resistors are constructed in a manner similar to the carbon-film type. However, in a metal film resistor a thin film of metal is sprayed onto a ceramic substrate and then cut in the form of a spiral. The construction of a metal-film resistor is shown in (Fig.5.5). The length, thickness, and width of the metal spiral determine the exact resistance value.

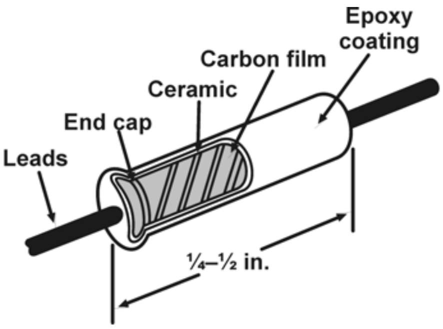


Fig.5.4. Construction of carbon film resistor.

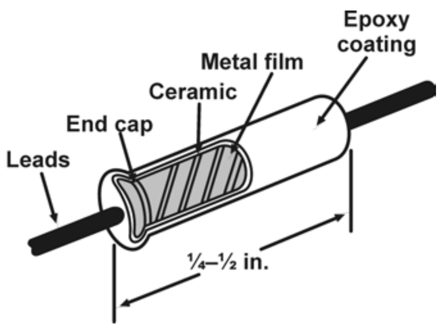


Fig.5.5. construction of metal-film resistor.

Metal-film resistors have even more precise R values than do carbon-film resistors. Like carbon-film resistors, metal-film resistors are affected very little by temperature changes and aging. They also generate very little noise internally. In terms of overall performance, metal-film resistors are the best, carbon-film resistors are next, and carbon-composition resistors are last. Both carbon and metal-film resistors can be distinguished from carbon-composition resistors by the fact that the diameter of the ends is a little larger than that of the body.

Surface Mount Resistors

Surface-mount resistors, also called chip resistors, are constructed by depositing a thick carbon film on a ceramic base. The exact resistance value is determined by the composition of the carbon itself, as well as by the amount of trimming done to the carbon deposit. The resistance can vary from a fraction of an ohm to well over a million ohms. Power dissipation ratings are typically 1/8 to 1/4 W. (Fig.5.6) shows typical chip resistors. Electric connection to the resistive element is made via two leadless solder end electrodes (terminals). The end electrodes are C-shaped. The physical dimensions of a 1/8-W chip resistor are 0.125 in. Long by 0.063 in wide and approximately 0.28 in. Chip resistors are very temperature-stable and also very rugged. The end electrodes are soldered directly to the copper traces of a circuit board, hence the name surface-mount.

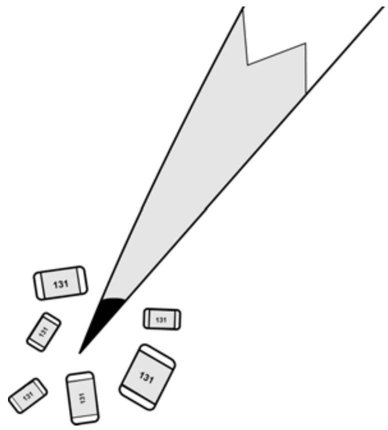


Fig.5.6.Typical chip resistors.

FUSIBLE RESISTORS

This type is a wire-wound resistor made to burn open easily when the power rating is exceeded. It then serves the dual functions of a fuse and a resistor to limit the current.

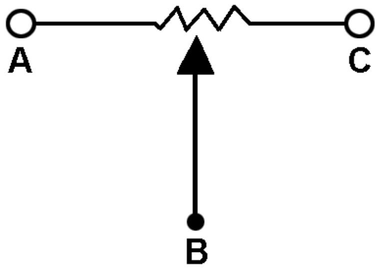


Fig. 5.7.

VARIABLE RESISTORS

Variable wire wound resistor

These resistors are made of nichrome wire wound on a ceramic case and covered within insulating coating. A window is left in the insulating cover, which exposes the resistive wire, and adjustable tap rides along the exposed wire, which makes electrical contact with the wire.

In (Fig.5.7) the points A & C represent the end points and B indicates the adjustable point. The variable wire wound resistance are used in power supplied and low frequency a.c. circuits. Because of their inductive and capacitive properties, the wire wound resistors are not suitable for high frequency applications. It may be noted that the wire wound resistor are not used for continuously variable control but they are present at a given value and held at that value for extended period of operation. The wire wound resistors are available with resistance values from 1 ohm to 150 k ohms with ± 5% ± 10% tolerances and power rating from 3 to 200w.

CARBON COMPOSITION

Variable resistors can be wire-wound, as in (Fig.5.8), or the carbon type, illustrated in (Fig.). Inside the metal case of (Fig.), the control has a circular disk, shown in (Fig.), that is the carbon-composition resistance element. It can be a thin coating on pressed paper or a molded carbon disk. Joined to the two ends are the external soldering-lug terminals 1 and 3. The middle terminal is connected to the variable arm that contacts the resistor element by a metal spring wiper. As the shaft of the control is turned, the variable arm moves the wiper to make contact at different points on the resistor element. The same idea applies to the slide control in (Fig.), except that the resistor element is straight instead of circular.

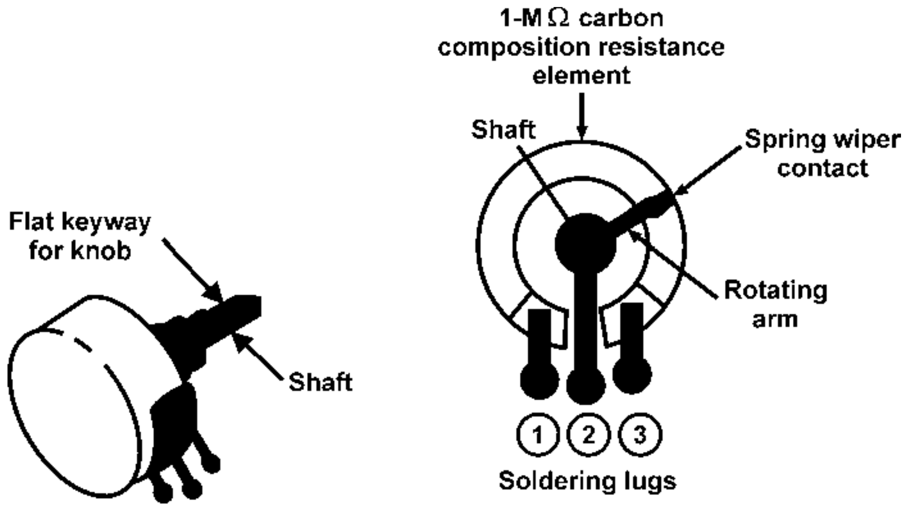


Fig.5.8. Construction of variables carbon resistance control. Diameter is 3/4 in. (a) External view. (b) Internal view of circular resistance element.

When the contact moves closer to one end, the R decreases between this terminal and the variable arm. Between the two ends, however, R is not variable but always has the maximum resistance of the control.

Carbon controls are available with total R from 1000 Ω to 5 M Ω, approximately. Their power rating is usually 1/2 to 2 W.

RHEOSTATS AND POTENTIOMETERS

Rheostats and potentiometers are variable resistances, either carbon or wire-wound, used to vary the amount of current or voltage for a circuit. The controls can be used in either dc or ac applications.

A rheostat is a variable R with two terminals connected in series with a load. The purpose is to vary the amount of current.

A potentiometer, generally called a pot for short, has three terminals. The fixed maximum R across the two ends is connected across a voltage source. Then the variable arm is used to vary the voltage division between the center terminal and the ends. This function of a potentiometer is compared with a rheostat in Table 5.1.

TABLE 5.1 POTENTIOMETERS AND RHEOSTATS

Rheostat	Potentiometer
Two terminals	Three terminals
In series with load and V source	Ends are connected across V source
Varies the I	Taps off part of V

RHEOSTAT CIRCUIT

The function of the rheostat R_2 in (Fig. 5.9) is to vary the amount of current through R_1. For instance, R_1 can be a small light bulb that requires a specified I. Therefore, the two terminals of the rheostat R_2 are connected in series with R_1 and the source V in order to vary the total resistance R_T changes, as read by the meter.

In (Fig.5.9), R_1 is 5 Ω and the rheostat R_2 varies from 0 to 5 Ω. With R_2 at its maximum of 5 Ω, then R_T equals 5+5 = 10 Ω. The I equals 0.15 A or 150 mA. (The method for calculating I given R and V is covered in "Ohm's Law.")

When R_2 is at its minimum value of 0 Ω, R_T equals 5 Ω. Then I is 0.3 A or 300 mA for the maximum current. As a result, varying the rheostat changes the circuit resistance to vary the current through R_1. The I increases as R decreases.

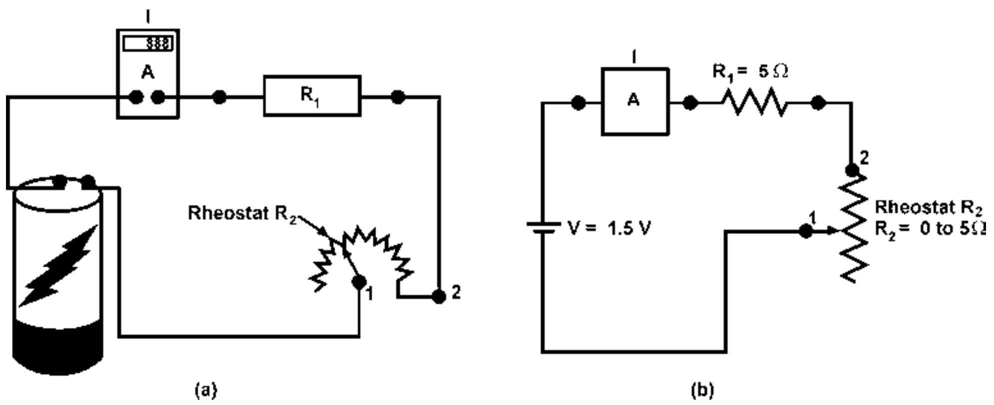


Fig.5.9 Rheostat connected in series circuit to vary the current* I *symbol for current meter is* A, *for amperes.
(a) Wiring diagram with digital meter for* I *.(b) Schematic diagram.

It is important that the rheostat have a wattage rating high enough for the maximum I when R is minimum. Rheostats are often wire-wound variable resistors used to control relatively large values of current in low-resistance circuits for ac power applications.

POTENTIOMETER CIRCUIT

The purpose of the circuit in (Fig.5.10) p.60, is to tap off a variable part of the 100 V from the source. Consider this circuit in two parts:

1. The applied V is input to the two end terminals of the potentiometer.
2. The variable V is output between the variable arm and an end terminal.

Two pairs of connections to the three terminals are necessary, with one terminal common to the input and output. One connects the source V to the end terminals 1 and 3. The other pair of connections is between the variable arm at the center terminal and one end. This end has double connections for input and output. The other end has only an input connection.

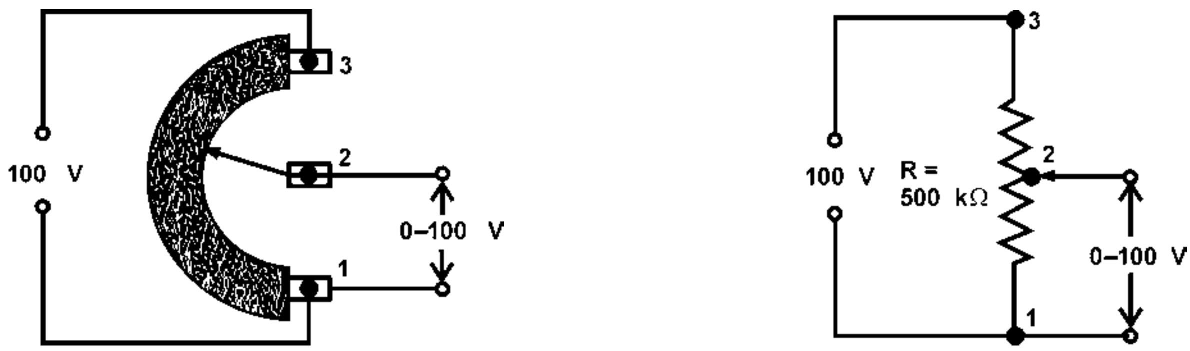


Fig.5.10. Potentiometer connected across voltage source to function as a voltage divider. Writing diagram. (b) Schematic diagram.

When the variable arm is at the middle value of the 500-k Ω R in (Fig.5.11), the 50 V is tapped off between terminals 2 and 1 as one-half the 100-V input. The other 50V is between terminals 2 and 3. However, this voltage is noit used for output.

As the control is turned up to move the variable arm closer to terminal 3, more of the input voltage is available between 2 and 1. With the control at its maximum R, the voltage between 2 and 1 is the entire 100 V. Actually, terminal 2 is then the same as 3.

When the variable arm is at minimum R, rotated to terminal 1, the output between 2 and 1 is zero. Now all the applied voltage is across 2 and 3, with no output for the variable arm. It is important to note that the cource voltage is not short-circuited. The reason is that the maximum R of the potentiometer is always across the applied V, regardless of where the variable arm is set. Typical examples of small potentiometers used in electronic circuits are shown in (Fig.5.11).

Fig.5.11. Small potentiometers and trimmers often used for variable controls in electronic circuits. Terminals leads formed for insertion into a PC board.

POTENTIOMETER USED AS A RHEOSTAT

Commercial rheostats are generally wire-wound high-wattage resistors for power applications. However, a small low-wattage rheostat is often needed in electronic circuits. One example is a continuous tone control in a receiver. The control requires the variable series resistance of a rheostat but dissipates very little power.

A method of wiring a potentiometer as a rheostat is to connect just one end of the control and the variable arm, using only two terminals. The third terminals is open, or floating, not connected to anything.

Another method is to wire the unused terminal to the center terminal. When the variable arm is rotated, different amounts of resistance are short-circuited. This method is preferable because there is no floating resistance.

Either end of the potentiometer can be used for the rheostat. The direction of increasing R with shaft rotation reverses, though, for connections at opposite ends. Also, the taper is reversed on a nonlinear control.

The resistance of a potentiometer is sometimes marked on the enclosure which houses the resistance element. The marked value indicates the resistance between the outside terminals.

NON LINEAR RESISTORS

The resistors through which current is not directly proportional to the applied voltage is a non linear resistor. They are of three types namely thermistor, photo resistors and varistor

(i) Thermistors

The word thermistor is an acronym (short from) for thermal resistor, is a temperature sensitive resistor. It is used to detect very small changes in temperature. The variation in temperature is reflected through an appreciable variation of the resistance of device.

Thermistor with both negative temperature coefficient (NTC) and positive temperature coefficient (PTC) are available but NTC thermostats are more common. The negative temperature coefficient means that the resistance decreases with the increase in temperature. The positive temperature coefficient means that the resistance increases with the increase in temperature.

The NTC thermistors are manufactured by centering semiconductor ceramic materials prepare from mixtures of metallic oxides of cobalt, nickel, manganese etc. These materials have high negative temperature coefficient.

The PTC thermistors are made from doped barium titrate semi conducting material. Their material has a very large change in resistance for a small change in temperature. Thermistors are manufactured in the form of beads, probes, disc, washers and rods, The beads are made in diameter ranging from 0.15 mm to 2.5 mm. They are useful where temperature sensing must be done in very limited space. The probes are formed by limited space. They are more rugged then beads and work well in liquids.

The discs and washer are made to meet certain industrial requirements. The discs are used in moderate power applications in conjunction with time response applications the rods and washers are used for higher power applications.

Thermistor applications :

1. Temperature measurement and control
2. Liquid level measurement
3. Temperature compensation in electronic circuits
4. Flow rate measurement
5. Radio frequency power measurement
6. Time delay circuits

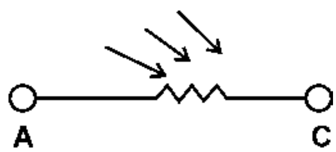
(ii) Varistor or voltage dependent resistors

The word varistor is an acronym from variable resistor. The varistors are voltage dependent resistors they are used to protect circuitry from high energy voltage transients by rapidly changing from high stand by resistance to low conducting resistance. Thus action of a varistor clamps the voltage treatment is an abnormal short living disturbance in the circuit which is produced by switching operation sudden fault in electrical equipment or lightening stroke.

The varistor protects the circuit from destructive energy by dissipating energy in its body. The varistor are available in a variety of packages they are capable of handling current up to 2000A with ac operating voltage ranging from 10 V to 300 V and at temperatures from -40°C to 85°C.

(iii) LDR - light dependent resistor or photoresistor

In certain semiconductor, light energy falling on them is of the correct order of magnitude to release charge carriers, which increase flow of current produced by an applied voltage. The increase in current with increase in light intensity with the applied voltage remaining constant means that the resistance of semiconductor decreases with increase in light intensity. Therefore these semiconductors are called light dependant resistors. Since incident light effectively varies their resistance.



Two commonly used semiconductors are materials for LDR are cadmium suiphide (CDS) and cadmium solenide (cdse) LDR's are made buy chemically sintering the required power (cds) or (cdse) into table a protective envelope of glass or plastic.

Electrodes are deposited on the tablet surface gold is typically used. The electrodes used are usually inter digital is in the form of interlocked fingers.

When the top is kept in darkness its resistance is called dark resistance is high. If the LDR is illuminated its resistance decreases. The decrease in resistance depends upon the physical character of the photo conductive layer as well as on its dimensions.

The LDR has a relatively large sensitive area a small change in light intensity causes a large in its resistance.

RESISTOR COLOR CODING

Because carbon resistors are small physically, they are color-coded to mark their R value in ohms. The basis of this system is the use of colors for numerical values, as listed in Table 5.2. In memorizing the colors, note that the darkest colors, black and brown, are for the lowest numbers, zero and one, whereas white is for nine. The color coding is standardized by the Electronic Industries Association (EIA).

TABLE 5.2 COLOR CODE

Color	Value	Color	Value
Black	**0**	**Green**	**5**
Brown	**1**	**Blue**	**6**
Red	**2**	**Violet**	**7**
Orange	**3**	**Gray**	**8**
Yellow	**4**	**White**	**9**

RESISTANCE COLOR STRIPES

The use of bands or stripes is the most common system for color-coding carbon resistors, as shown in (Fig.5.12). Color stripes are printed at one end of the insulating body, which is usually tan. Reading from left to right, the first band closest to the edge gives the first digit in the numerical value of R. The next band marks the second digit. The third band is the decimal multiplier, which gives the number of zeroes after the two digits.

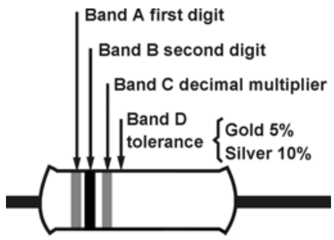


Fig.5.12. How to read color stripes on carbon resistors for **R** *in ohms.*

On the next page in (Fig. 5.12), the first stripe is red for 2 and the next stripe is green for 5. The red multiplier in the third stripe means add two zeroes to 25, or "this multiplier is 10^2." The result can be illustrated as follows:

Red	Green		Red
2	5	×	100 = 2500

Therefore, this R value is 2500 Ω.

The example in (Fig. 5.13) illustrates that black for the third stripe just means "do not add any zeroes to the first two digits." Since this resistor has red, and black stripes, the R value is 25 Ω.

RESISTORS UNDER 10 Ω

For these values, the third stripe is either gold or silver, indicating a fractional decimal multiplier. When the third stripe is gold, multiply the first two digits by 0.1. In (Fig. 5.13), the R value is

$$25 \times 0.1 = 2.5\,\Omega$$

Silver means a multiplier of 0.01. If the third band in (Fig. 5.13) were silver, the R value would be

$$25 \times 0.01 = 0.25\,\Omega$$

It is important to realize that the gold and silver colors are used as decimal multipliers only in the third stripe. However, gold and silver are used most often as a fourth stripe to indicate how accurate the R value is resistor tolerance. The amount by which the actual R can be different from the color-coded value is the tolerance, usually given in percent. For instance, a 2000-Ω resistor with ± 10 percent tolerance can have resistance 10 percent above or below .the coded value. This R, therefore, is between 1800 and 2200 Ω. The calculations are as follows :

$$10 \text{ percent of } 2000 \text{ is } 0.1 \times 2000 = 200$$

For + 10 percent, the value is

$$2000 + 200 = 2200\,\Omega$$

For -10 percent, the value is

$$2000 - 200 = 1800\,\Omega$$

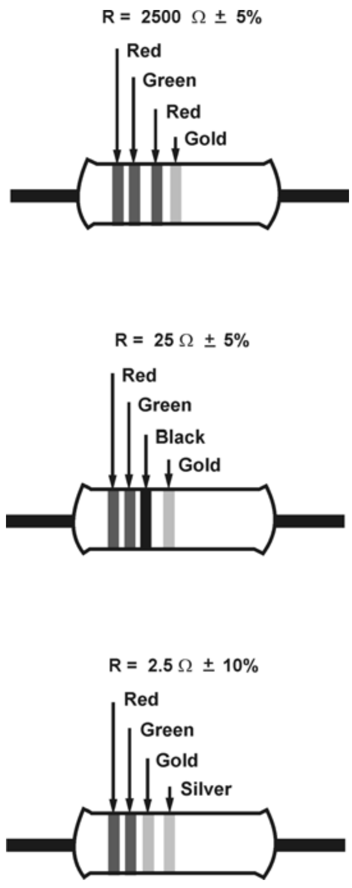


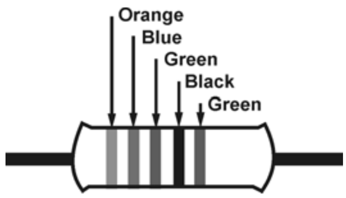
Fig. 5.13. Examples of color-coded **R** *values, with percent tolerance.*

As illustrated in (Fig.), silver in the fourth band indicates a tolerance of ± 10 percent; gold indicates ± 5 percent. If there is no color band for tolerance, it is ± 20 percent. The inexact value of carbon-composition resistors is a disadvantage of their economical construction. They usually cost only a few cents each, or less in larger quantities. In most circuits, though, a small difference in resistance can be tolerated.

FIVE-BAND CODE

Precision resistors often use a five-band code rather than the four-band code shown in (Fig.). The purpose is to obtain more precise R values. With the five-band code, the first three color stripes indicate the first three digits, followed by the decimal multiplier in the fourth stripe and the tolerance in the fifth stripe. In the fifth stripe, the colors brown, red, green, blue, and violet represent the following tolerances:

Brown ± 1%
Red ± 2%
Green ± 0.5%
Blue ± 0.25%
Violet ± 0.1%



Example

What is the resistance indicated by the five-band color code in (Fig.) ? Also, what ohmic range is permissible for the specified tolerance ?

Answer

The first stripe is orange for the number 3, the second stripe is blue for the number 6, and third stripe is green for the number 5. Therefore, the first three digits of the resistance are 3, 6 and 5, respectively. The fourth stripe, which is the multiplier, is black, which means add no zeros. The fifth stripe, which indicates the resistor tolerance, is green for $\pm$ 0.5%. Therefore R = 365 Ω $\pm$ 0.5%. The permissible ohmic range is calculated as 365 × 0.005 = $\pm$ 1.825 Ω, or 363.175 to 366.825 Ω.

WIRE-WOUND-RESISTOR MARKING

Usually, wire-wound resistors are big enough physically to have the R value printed on the insulating case. The tolerance is generally ± 5 percent, except for precision resistors, which have a tolerance of ± 1 percent or less.

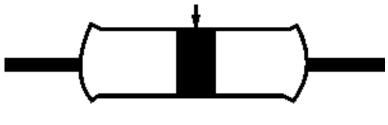
Some small wire-wound resistors may be color-coded with stripes, however, like carbon resistors. In this case, the first stripe is double the width of the others to indicate a wire-wound resistor. This type may have a wattage rating of 3 or 4 W.

PREFERRED RESISTANCE VALUES

In order to minimize the problem of manufacturing different R values for an almost unlimited variety of circuits, specific values are made in large quantities so that they are cheaper and more easily available than unusual sizes. For resistors of ± 10 percent, the preferred values are 10, 12, 15, 18, 22, 33, 39, 47, 56, 68, and 82 with their decimal multiples. As examples, 47, 470, 4700, and 47,000 are preferred values. In this way, there is a preferred value available within 10 percent of any R value needed in a circuit. See Appendix A for a listing of preferred resistance values for tolerances of ± 20%, ± 10%, and ± 5%.

ZERO-OHM RESISTORS

Believe it or not, there is such a thing as a zero-ohm resistor. In fact, zero-ohm resistors are quite common. The zero-ohm value is denoted by the use of a single black band around the center of the resistor body, as shown in Fig.2-11. Zero-ohm resistors are available in $1/8$ -or $1/4$ -W sizes. The actual resistance of a so-called $1/8$ -W zero-ohm resistor is about 0.004 Ω, where a $1/4$ -W zero-ohm resistor has a resistance of approximately 0.003 Ω.



But why are zero-ohm resistors used in the first place? The reason is that for most printed-circuit boards, the components are inserted by automatic insertion machines (robots) rather than by human hands. In some instances it may be necessary to short two points on the printed-circuit board, in which case a piece of wire has to be placed between the two points. Because the robot can handle only components such as resistors, and not wires, zero-ohm resistors are used. Before zero-ohm resistors were developed, jumpers had to be installed by hand, which was time-consuming and expensive. Zero-ohm resistors may need to be used as a result of an after-the-fact design change which requires new points connections in a circuit.

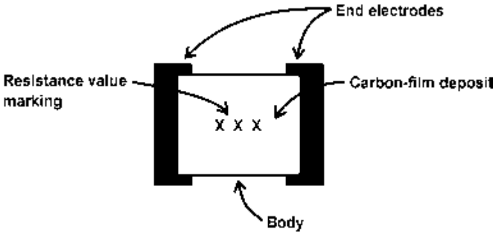


Fig. 5.14. Typical chip resistor coding system

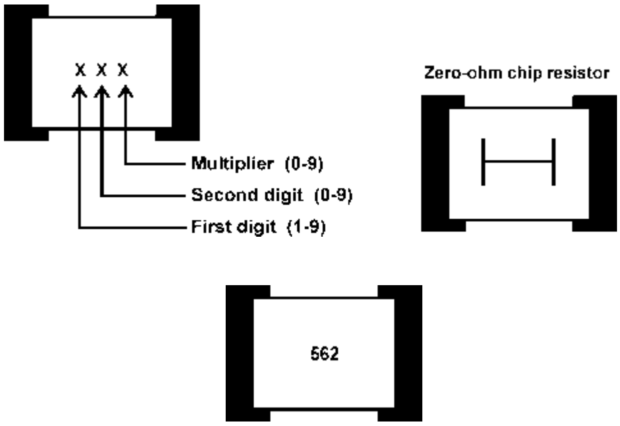


Fig. 5.15. Chip resistor with number coding.

CHIP RESISTOR CODING SYSTEM

A chip resistor, shown in (Fig.) has the following identifiable features.
Body color : white or off-white
Dark film on one side only (usually black, but may also be dark gray or Dark gray or green)
End electrodes (terminals) are C-shaped
Three or four-digit marking on either the film or the body side (usually the film)

The resistance value of a chip resistor is determined from the three-digit number printed on the film or body side of the component. The three digits provide the same information as the first three color stripes on a four-band resistor. This is shown in (Fig.). The first two digits indicate the first two numbers in the numerical value of the resistance; the third digit indicates the multiplier. If a four-digit number is used, the first three digits indicate the first three numbers in the numerical value of the resistance, and the fourth digit indicates the multiplier. The letter R is used to signify a decimal point for values between 1 and 10 ohms as in 2R7 = 2.7 Ω. Fig. 2-12(c) shows the symbol used to denote a zero-ohm chip resistor. Chip resistors are typically available in tolerances of ± 1 percent and ± 5 percent. It is important to note, that the tolerance of a chip resistor is not indicated by the three-or four-digit code.

THERMISTOR VALUES

Thermistors are normally rated by the value of their resistance at a reference temperature T of $25^{\circ}C$. The value of R at $25^{\circ}C$ is most often referred to as the zero power resistance and is designated R_o. The term zero power resistance refers to the resistance of the thermistor with zero power dissipation. Thermistors normally do not use a code or marking system to indicate their resistance value in ohms. In rare cases, however, a three-dot code is used to indicate the value of R_o. In this case, the first and second dots indicate the first two significant digits and the third dot is the multiplier. The colors used are the same as for carbon resistors.

POWER RATING OF RESISTORS

In addition to having the required ohms value, a resistor should have a wattage rating high enough to dissipate the power produced by the current flowing through the resistance, without becoming too hot. Carbon resistors in normal operation often become warm, but they should not get so hot that they "sweat" beads of liquid on the insulating case. Wire-wound resistors operate at very high temperatures, a typical value being $300^{\circ}C$ for the maximum temperature. If a resistor becomes too hot because of excessive power dissipation, it can change appreciably in resistance value or burn open.

The power rating is a physical property that depends on the resistor construction, especially physical size. Note the following :

1. A large physical size indicates a higher power rating.
2. Higher-wattage resistors can operate at higher temperatures.
3. Wire-wound resistors are physically larger with higher wattage ratings than carbon resistors.

For approximate size, a 2-W carbon resistor is about 1 in. long with a 1/4 in. diameter; a 1/4-W resistor is about 0.25 in. long with a diameter of 0.1 in.

For both types, a higher power rating allows a higher voltage rating. This rating gives the highest voltage that may be applied across the resistor without internal arcing. As examples for carbon resistors, the maximum voltage is 500 V for a 1-W rating, 350 V for 1/2-W, 250 V for 1/4 -W, and 200 V for 1/8-W. In wire-wound resistors, excessive voltage can produce an arc between turns; in carbon composition resistors, the arc is between carbon granules.

Power Derating Curve

When a carbon resistor is mounted on a PC board in close proximity to other resistors and components, all of which are producing heat enclosed in a confined space, the ambient temperature can rise appreciably above 25°C. When carbon resistors are operated in ambient temperatures of 70°C or less, the commercial power rating, indicated by the physical size, remains valid. However, for ambient temperatures greater than 70°C, the power rating must be reduced or derated. This is shown in (Fig.). Notice that for ambient temperatures up to 70°C the commercial power rating is the same (100 percent) as that determined by the resistor's physical size. Note, however, that above 70°C the power decreases linearly.

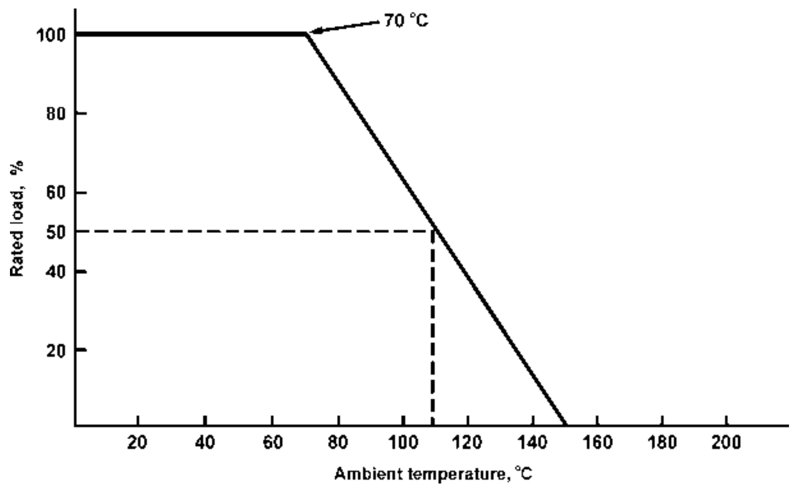


Fig. 5.16. Resistor power derating curve.

For example, at an ambient temperature of 110°C, the power rating must be reduce to 50 percent of its rated value. This means that a 1-k Ω 1/2-W resistor operating at 110°C can safely dissipate only 1/4 W of power. Therefore, the physical size of the resistor must be increased if it is to safely dissipate 1/2 W at 110°C. In this case a 1-k Ω 1-W resistor would be necessary.

The curve in (Fig.) is called a power derating curve and is supplied by the resistor manufacturer. For a 1/2-W carbon resistor, the power derating curve corresponds to a 6.25 mW reduction in the power rating for each degree Celsius rise in temperature above 70°C.This corresponds to a derate factor of 6.25 m W/°C.

SHELF LIFE

Resistors keep their characteristics almost indefinitely when not used. Without any current in a circuit to heat the resistor, it has practically no change with age. The shelf life of resistors is therefore usually no problem.

RESISTOR TROUBLES

The most common trouble in resistors is an open. When the open resistor is a series component, there is no current in the entire series path.

NOISY CONTROLS

In applications such as volume and tone controls, carbon controls are preferred because the smoother change in resistance results in less noise when the variable arm is rotated. With use, however, the resistance element becomes worn by the wiper contact, making the control noisy. When a volume or tone control makes a scratchy noise as the shaft is rotated, it indicates either a dirty or worn-out resistance element. If the control is just dirty, it can be cleaned by spraying the resistance element with a special contact cleaner. If the resistance element is worn out, the control must be replaced.

CHECKING RESISTORS WITH AN OHMMETER

Resistance measurements are made with an ohmmeter. The ohmmeter has its own voltage source so that it is always used without any external power applied to the resistance being measured. Separate the resistance from its circuit by disconnecting one lead of the resistor. Then connect the ohmmeter leads across the resistance to be measured.

An open resistor reads infinitely high ohms. For some reason, infinite ohms is often confused with zero ohms. Remember, though , that infinite ohms means an open circuit. The current is zero, but the resistance is infinitely high. Furthermore,

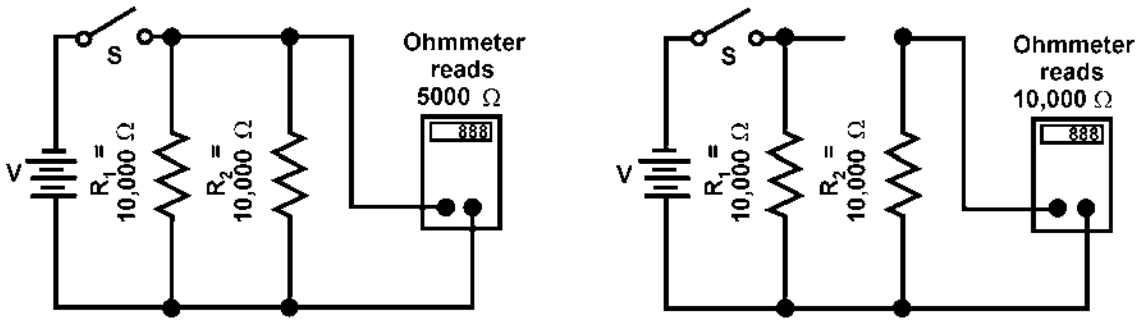


Fig.5.17. Parallel R_1 *can lower the ohmmeter reading for testing* R_2. (a) *The two resistances* R_1 *and* R_2 *are in parallel.*
(b) R_2 *is isolated by disconnecting one enf of* R_1.

it is practically impossible for a resistor to become short-circuited in itself. The resistor may be short-circuited by some other part of the circuit. However, the construction of resistors is such that the trouble they develop is an open circuit, with infinitely high ohms.

The ohmmeter must have an ohms scale capable of reading the resistance value, or the resistor cannot be checked. In checking a 10-M Ω resistor, for instance, if the highest R the ohmmeter can read is 1 MΩ, it will indicate infinite resistance, even if the resistor has its normal value of 10 MΩ. An ohms scale of 100 M Ω or more should be used for checking such high resistances.

To check resistors of less than 10 Ω, a low -ohms scale of about 100 Ω or less is necessary. Center scale should be 6 Ω or less. Otherwise, the measured resistance can be much lower than the actual resistor value, as illustrated in Fig.. Here, the ohmmeter reads the resistance of R_2 in parallel with R_1. To check across R_2 alone, one end is disconnected, as in Fig

For very high resistances, it is important not to touch the ohmmeter leads. There is no danger of shock, but the body resistance of about 50,000 Ω as a parallel path will lower the ohmmeter reading.

CHANGED VALUE OF R

In many cases, the value of a carbon composition resistor can exceed its allowed tolerance; this is caused by normal resistor heating over a long period of time. In most instances the value change is seen as an increase in R. This is known as aging. Surface-mount resistors should never be rubbed or scraped, as this will remove some of the carbon deposit and cause its resistance to change.

■■■

CHAPTER - 6
DETAILED KNOWLEDGE OF CONSTRUCTION, PRINCIPLES OF OPERATION, APPLICATION AND COLOR CODING OF VARIOUS TYPES OF CAPACITORS

CAPACITANCE

Capacitance is the ability of a dielectric to store electric charge. The more charge that is stored for a given voltage, the higher is the value of capacitance. The symbol for capacitance is C, and the unit is the farad (F), named after Michael Faraday.

A capacitor consists of an insulator (also called a dielectric) between two conductors. The conductors make it possible to apply voltage across the insulator. Different types of capacitors are manufactured for specific values of C. They are named according to the dielectric. Common types are air, ceramic, mica, paper, film and electrolytic capacitors. Capacitors used in electronic circuits are small and economical. Different types of capacitors connected in circuit are shown in (Fig. 6.1).

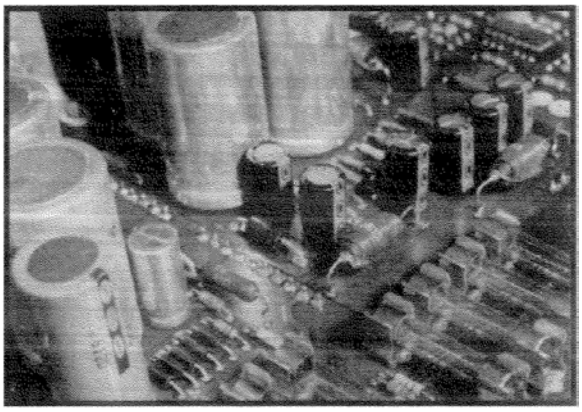


Fig. 6.1. Different type of capacitors connected in circuit.

The most important property of a capacitor is its ability to block a steady dc voltage while passing ac signals. The higher the frequency is, the less the opposition for ac voltage.

HOW CHARGE IS STORED IN THE DIELECTRIC

It is possible for dielectric materials such as air or paper to hold an electric charge because free electrons cannot flow through an insulator. However, the charge must be applied by some source. In (Fig. 6.2) , the battery can charge the capacitor shown. With the dielectric contacting the two conductors connected to the potential difference V, electrons from the voltage source accumulate on the side of the capacitor connected to the negative terminal of V loses electrons.

As a result, the excess of electrons of electrons produces a negative charge on one side of the capacitor, and the opposite side has a positive charge. As an example, if 6.25×10^{18} electrons are accumulated, the negative charge equals 1 coulomb (C). The charge on only one plate need be considered, as the number of electrons accumulated on one plate is exactly the same as the number taken from the opposite plate.

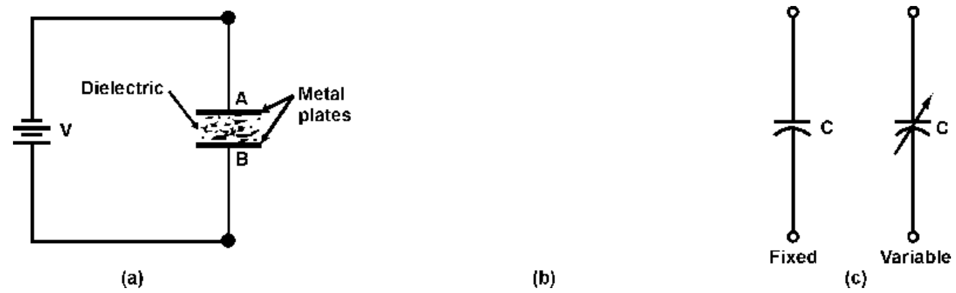


Fig. 6.2. Capacitance stores the charge in the dielectric between two conductors. (a) Structure. (b) Air-dielectric variable capacitor. Length is 2 in. (c) Schematic symbols for fixed and variable capacitors.

What the voltage source does is simply redistribute some electrons from one side of the capacitor to the other. This process is called charging the capacitor. Charging continues until the potential difference across the capacitor is equal to the applied voltage. Without any series resistance, the charging is instantaneous. Practically, however, there is always some series resistance. This charging current is transient, or temporary, as it flows only until the capacitor is charged to the applied voltage. Then there is no current in the circuit.

The result is a device for storing charge in the dielectric. Storage means that the charge remains even after the voltage source is disconnected. The measure of how much charge can be stored is the capacitance C. More charge stored for a given amount of applied voltage means more capacitance. Components made to provide a specified amount of capacitance are called capacitors, or by their old name condensers.

Electrically, then, capacitance is the ability to store charge. Physically, a capacitor consists simply of two conductors separated by an insulator. For example, Fig. 6.2 (c) shows a variable capacitor using air for the dielectric between the metal plates. There are many types with different dielectric materials, including paper, mica, and ceramics, but the schematic symbols shown in Fig. 6.2 (c) apply to all capacitors.

ELECTRIC FIELD IN THE DIELECTRIC

Any voltage has a field of electric lines of force between the opposite electric charges. The electric field corresponds to the magnetic lines of force of the magnetic field associated with electric current. What a capacitor does is concentrate the electric field in the dielectric between the plates. This concentration corresponds to a magnetic field concentrated in the turns of a coil. The only function of the capacitor plates and wire conductors is to connect the voltage source V across the dielectric. Then the electric field is concentrated in the capacitor, instead of being spread out in all directions.

ELECTROSTATIC INDUCTION

The capacitor has opposite charges because of electrostatic induction by the electric field. Electrons that accumulate on the negative side of the capacitor provide electric lines of force that repel electrons from the opposite side. When this side loses electrons, it becomes positively charged. The opposite charges induced by an electric field correspond to the idea of opposite poles induced in magnetic materials by a magnetic field.

TEST-POINT QUESTION 'A'

Answer the following questions

a. In a capacitor, is the electric charge stored in the dielectric or in the metal plates ? Ans. Dielectric

b. What is the unit of capacitance ? Ans. Farad

CHARGING AND DISCHARGING A CAPACITOR

Charging and discharging are the two main effects of capacitors. Applied voltage puts charge in the capacitor. The accumulation of charge results in a buildup of potential difference across the capacitor plates. When the capacitor voltage equals the applied voltage, there is no more charging. The charge remains in the capacitor, with or without the applied voltage connected.

The capacitor discharges when a conducting path is provided across the plates, without any applied voltage. Actually, it is necessary only that the capacitor voltage be more than the applied voltage. Then the capacitor can serve as a voltage source, temporarily, to produce discharge current in the discharge path. The capacitor discharge continues until the capacitor voltage drops to zero or is equal to the applied voltage.

APPLYING THE CHARGE

In Fig.6.3 (a) the capacitor is neutral with no charge because it has not been connected to any source of applied voltage and there is no electrostatic field in the dielectric. Closing the switch in Fig.6.3 (b), however, allows the negative battery terminal to repel free electrons in the conductor to plate A. At the same time, the positive terminal attracts free electrons because they cannot flow through the insulator, the plate B has an equal surplus of protons.

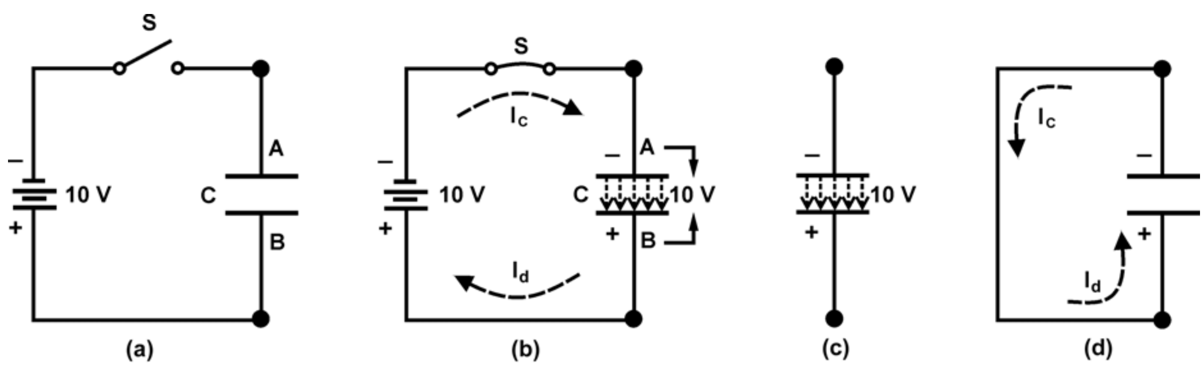


Fig. 6.3. Storing electric charge in a capacitance. (a) Capacitor without any charge. (b) Battery charges capacitor to applied voltage of 10 v. (c) Stored charge remains in capacitor, providing 10 v without the battery. (d) Discharging the capacitor.

Remember that the opposite charges have an associated potential difference, which is the voltage across the capacitor. The charging process continues until the capacitor voltage equals the battery voltage, which is 10V in this example. Then no further charging is possible because the applied voltage cannot make free electrons flow in the conductors.

Note that the potential difference across the charged capacitor is 10V between plates A and B. There is no potential difference from each plate to its battery terminal , however, which is the reason why the capacitor stops charging.

STORING THE CHARGE

The negative and positive charges on opposite plates have an associated electric field through the dielectric, as shown by the dotted lines in Fig. 6.3 (c). The direction of these electric lines of force is shown repelling electrons from plate B, making this side positive. It is the effect of electric lines of force through the dielectric that results in storage of the charge. The electric field distorts the molecular structure so that the dielectric is no longer neutral. The dielectric is actually stressed by the invisible force of the electric field. As evidence, the dielectric can be ruptured by a very intense field with high voltage across the capacitor.

The result of the electric field, then , is that the dielectric has charge supplied by the voltage source. Since the dielectric is an insulator that cannot conduct, the charge remains in the capacitor even after the voltage source is removed, as illustrated in (Fig.). You can now take this charged capacitor by itself out of the circuit, and it still has 10V across the two terminals.

DISCHARGING

The action of neutralizing the charge by connecting a conducting path across the dielectric is called discharging the capacitor. In Fig. 6.3 (d) , the wire between plates A and B is a low-resistance path for discharge current. With the stored charge in the dielectric providing the potential difference, 10 V is available to produce discharge current. The negative plate repels electrons, which are attracted to the positive plate through the wire, until the positive and negative charges are neutralized. Then there is no net charge. The capacitor is completely discharged, the voltage across it equals zero, and there is no discharge current. Now the capacitor is in the same uncharged condition as in Fig. 6.3 (a). It can be charged again, however, by a source of applied voltage.

NATURE OF THE CAPACITANCE

A capacitor has the ability to store the amount of charge necessary to provide a potential difference equal to the charging voltage. If 100 V were applied in (Fig.), the capacitor would charge to 100 V.

The capacitor charges to the applied voltage because, when the capacitor voltage is less, it takes on more charge. As soon as the capacitor voltage equals the applied voltage, no more charging current can flow. Note that any charge or discharge current flows through the conducting wires to the plates but not through the dielectric.

CHARGE AND DISCHARGE CURRENTS

In Fig. 6.3 (b), i_C is in the opposite direction from i_D in Fig. 6.3 (d). In both cases the current shown is electron flow. However, i_C is charging current to the capacitor and i_D is discharge current from the capacitor. The charge and discharge currents must always be in opposite directions. In Fig.), the negative plate of C accumulates electrons from the voltage source. In Fig. 6.3 (c) the charged capacitor serves as a voltage source to produce electron flow around the discharge path.

More charge and discharge current result with a higher value of C for a given amount of voltage. Also, more V produces more charge and discharge current with a given amount or capacitance . However, the value of C does not change with the voltage, as the amount of C depends on the physical construction of the capacitor.

TEST-POINT QUESTION 'B'

Answer the following questions

a. If the applied voltage were 14.5 V, how much would the voltage be across C after it has charged ? Ans. 14.5 V

b. How much is the voltage across C after it is completely discharged ? Ans. O V

c. Can a capacitor be charged again after it is discharged ? Ans. Yes

THE FARAD UNIT OF CAPACITANCE

With more charging voltage, the electric field is stronger and more charge is stored in the dielectric. The amount of charge Q stored in the capacitance is therefore proportional to the applied voltage. Also, a larger capacitance can store more charge. These relation are summarized by the formula

$Q = CV$ coulombs (17-1)

Where Q is the charge stored in the dielectric in coulombs (c), V is the voltage across the plates of the capacitor, and C is the capacitance in farads.

The C is a physical constant, indicating the capacitance in terms of how much charge can be stored for a given amount of charging voltage. When one coulomb is stored in the dielectric with a potential difference of one volt, the capacitance is one farad.

Practical capacitors have sizes in millionths of a farad, or smaller. The reason is that typical capacitors store charge of microcoulombs or less. Therefore, the common units are

1 microfarad = 1 μF = 1×10^{-6} F
1 nanofarad = 1 nF = 1×10^{-9} F
1 picofarad = 1 pF = 1×10^{-12} F

Although traditional it has not been used, the nanofarad unit of capacitance is gaining acceptance in the electronics industry.

Example 1

How much charge is stored in a 2-μ F capacitor connected across a 50-V supply?

Answer $Q = CV = 2 \times 10^{-6} \times 50$

$Q = 100 \times 10^{-6}$ C

Example 2

How much charge is stored in a 40-μ F capacitor connected across a 50-V supply?

Answer

$Q = CV = 40 \times 10^{-6} \times 50$

$Q = 2000 \times 10^{-6}$C

Note that the larger capacitor stores more charge for the same voltage, in accordance with the definition of capacitance as the ability to store charge.

The factor in Q = CV can be inverted to

$$C = \frac{Q}{V} \qquad (17\text{-}2)$$

or

$$V = \frac{Q}{C} \qquad (17\text{-}3)$$

For all three formulas, the basic units are volts for V, coulombs for Q, and farads for C. Note that the formula C = Q/V actually defines one farad of capacitance as one coulomb of charge stored for one volt of potential difference. The letter C (in italic, or slanted, type) is the symbol for capacitance. The same letter C (in roman, or upright, type) is the abbreviation for coulomb unit of charge. The difference between C and C will be made clearer in the examples that follow.

Example 3

A constant current of 2 μ A charges a capacitor for 20s. How much charge is stored ? Remember I = Q/t or Q = I × t.

Answer

$Q = I \times t$

$= 2 \times 10^{-6} \times 20$

$Q = 40 \times 10^{-6}$ or 40 μ C

Example 4

The voltage across the charged capacitor in Example 3 is 20V. calculate C.

Answer $C = \frac{Q}{V} = \frac{40 \times 10^{-6}}{20} = 2 \times 10^{-6}$

C = 2 μ F

Example 5

A constant current of 5 mA charges a 10-μ F capacitor for 1s. How much is the voltage across the capacitor?

Answer Find the stored charge first:

$Q = I \times t = 5 \times 10^{-3} \times 1$

$Q = 5 \times 10^{-3}$ C or 5 mC

$$V = \frac{Q}{C} = \frac{5 \times 10^{-3}}{10 \times 10^{-6}} = 0.5 \times 10^{3}$$

V = 500 V

LARGER PLATE AREA INCREASES CAPACITANCE

As illustrated in (Fig. 6.4), when the area of each plate is doubled, the capacitance in Fig. 6.4 (b) stores twice the charge of Fig. 6.4 (a). The potential difference in both cases is still 10 V. This voltage produces a given strength of electric field. A larger plate area, however, means that more of the dielectric surface can contact each plate, allowing more lines of force through the dielectric between the plates and less flux leakage outside the dielectric. Then the field can store more charge in the dielectric. The result of larger plate area is more charge stored for the same applied voltage, which means that the capacitance is larger.

THINNER DIELECTRIC INCREASES CAPACITANCE

As illustrated in (Fig.) , when the distance between plates is reduced by one-half, the capacitance stores twice the charge of Fig. 6.4 (a). The potential difference is still 10 V, but its electric field has greater flux density in the thinner dielectric. Then the field between opposite plates can store more charge in the dielectric. With less distance between the plates, the stored charge is greater for the same applied voltage, which means that the capacitance is greater.

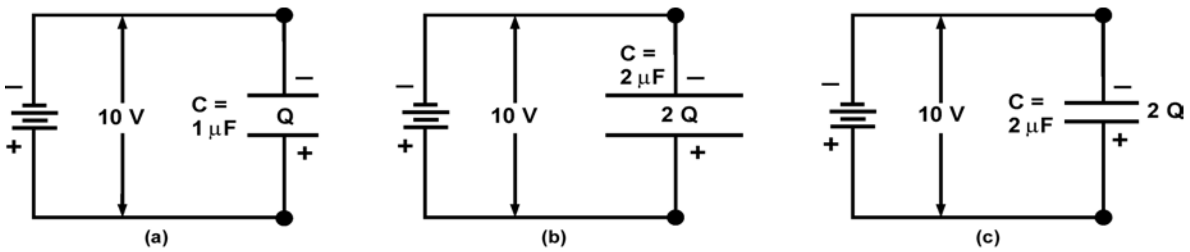


Fig. 6.4. Increasing stored charge and capacitor by increasing the plate area and decreasing the distance between plates. (a) Capacitance of 1 μ F. (b) A 2 - μ F capacitance with twice the plate area and the same distance. (c) A 2- μ F capacitance with one-half the distance and the same plate area.

DIELECTRIC CONSTANT K_E

This indicates the ability of an insulator to concentrate electric flux. Its numerical value is specified as the ratio of flux in the insulator compared with the flux in air or vacuum. The dielectric constant of air or vacuum is 1, since it is the reference.

Mica, for example, has an average dielectric constant of 6, which means that it can provide a density of electric flux six times as great as that of air or vacuum for the same applied voltage and equal physical size. Insulators generally have a dielectric constant K_E greater than 1, as listed in Table 4.1. Higher values of K_E allow greater values of capacitance.

It should be noted that the aluminium oxide and tantalum oxide listed in Table 4.6 are used for the dielectric in electrolytic capacitors. Also, plastic film is often used instead of paper for the rolled-foil type of capacitor.

The dielectric constant for an insulator is actually its relative permittivity, with the symbol E_r or K_E, indicating the ability to concentrate electric flux. This factor corresponds to relative permeability, with the symbol μ_r or K_m for magnetic flux. Both E_r and μ_r are pure numbers without units, as they are just ratios.

These physical factors for a parallel -plate capacitor are summarized by the formula

$$C = K_E \times \frac{A}{d} \times 8.85 \times 10^{-12} F$$

Where A is the area in square meters of either plate, d is the distance in meters between plates, K_E is the dielectric constant, or relative permittivity, as listed in Table 4.1, and C is capacitance in farads. The constant factor 8.85×10^{12} is the absolute permittivity of air or vacuum, in SI, since the farad is an SI unit.

TABLE 4.1 DIELECTRIC MATERIALS

Material	Dielectric Constant K_E	Dielectric Strength V/MIL
Air or vacuum	1	20
Aluminium oxide	7	
Ceramics	80-200	600-1250
Glass	8	335-2000
Mica	3-8	600-1500
Oil	2-5	275
Paper	2-6	1250
Plastic film	2-3	
Tantalum oxide	25	

*Exact values depend on the specific composition of different types.

Example 6

Calculate C for two plates, each with an area 2 m^2, separated by 1 cm, or 10^{-2} m, with a dielectric of air.

Answer

Substituting in Formula (17-4),

$$C = 1 \times \frac{2}{10^{-2}} \times 8.85 \times 10^{-12}\,F$$

$$= 200 \times 8.85 \times 10^{-12}$$

$$C = 1770 \times 10^{-12}\ F \quad \text{or } 1770\ pF$$

This value means that the capacitor can store 1770×10^{-12} C of charge with 1 V. Note the relatively small capacitance, in picofarad units, with the extremely large plates of 2 m^2, which is really the size of a tabletop or a desktop.

If the dielectric used is paper with a dielectric constant of 6, then C will be six times greater. Also, if the spacing between plates is reduced by onehalf to 0.5 cm, the capacitance will be doubled. It should be noted that practically capacitors for electronic circuits are much smaller than this parallel-plate capacitor. They use a very thin dielectric, with a high dielectric constant, and the plate area can be concentrated in a small space.

DIELECTRIC STRENGTH

Table 4.1 also lists breakdown-voltage ratings for typical dielectrics. Dielectrics strength is the ability of a dielectric to withstand a potential difference without arcing across the insulator. This voltage rating is important because rupture of the insulator provides a conducting path through the dielectric. Then it cannot store charge, because the capacitor has been short-circuited. Since the breakdown voltage increases with greater thickness, capacitors with higher voltage ratings have more distance between the plates. This increased distance reduces the capacitance, however, all other factors remaining the same.

TEST-POINT QUESTION 'C'

Answer the following questions

a. A capacitor charged to 100 V has 1000 μC of charge. How much is C ? Ans. 10 μF

b. A mica capacitor and ceramic capacitor have the same physical dimensions. Which has more C ? Ans. Ceramic

TYPICAL CAPACITORS

Commercial capacitors are generally classified according to the dielectric. Most common are air, mica, paper, plastic film, and ceramic capacitors, plus the electrolytic type. Electrolytic capacitors use a molecular-thin oxide film as the dielectric, resulting in large capacitance values in little space. These types are compared in Table 4.7 and discussed in the sections that follow.

TABLE 4.2 TYPES OF CAPACITORS

Dielectric	Construction	Capacitance	Breakdown, V
Air	Meshed plates	10 - 400pF	400 (0.02 - in. air gap)
Ceramic	Tubular	0.5 - 1600 pF	500 - 20,000
	Disk	1 pF to 1 μF	
Electrolytic	Aluminium	1- 6800 μF	10 - 450
	Tantalum	0.047 to 330 μF	6 - 50
Mica	Stacked sheets	10 - 5000 pF	500 - 20,000
Paper	Rolled foil	0.001 - 1μF	200 - 1600
Plastic film	Foil or metalized	100 pF to 100 μF	50 - 600

Except for electrolytic capacitors, capacitors can be connected to a circuit without regard to polarity, since either side can be the more positive plate. Electrolytic capacitors are marked to indicate the side that must be connected to the positive or negative side of the circuit. It should be noted that it is the polarity of the charging source that determines the polarity of the capacitor voltage. Failure to observe the correct polarity can damage the dielectric and lead to the complete destruction of the capacitor.

MICA CAPACITORS

Thin mica sheets as the dielectric are stacked between tinfoil sections for the conducting plates to provide the required capacitance. Alternate strips of tinfoil are connected and brought out as one terminal for one set of plates, and the opposite terminal connects to the other set of interlaced plates. The construction is shown in Fig. 6.5 (a). The entire unit

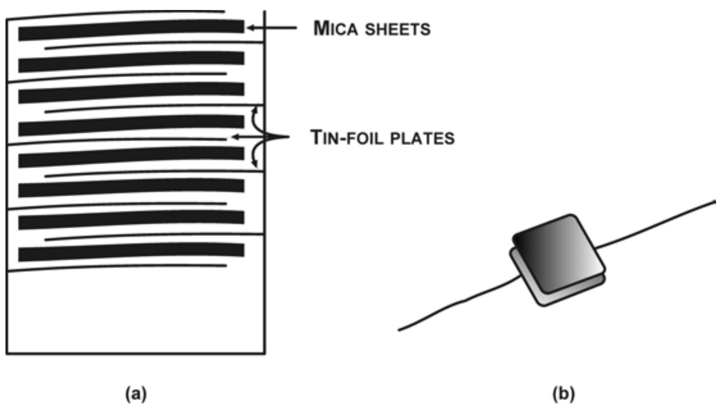


Fig. 6.5. Mica capacitor. (a) Physical construction. (b) Example of a mica capacitor.

is generally in a moulded Bakelite case. Mica capacitors are often used for small capacitance values of about 10 to 5000 pF; their length is 3/4 in. or less with about 1/8-in. thickness. A typical mica capacitor is shown in Fig. 6.5 (b).

PAPER CAPACITORS

In this construction, shown in (Fig. 6.6) , two rolls of tinfoil conductor separated by a paper dielectric are rolled into a compact cylinder. Each outside lead connects to its roll of tinfoil as a plate. The entire cylinder is generally placed in a cardboard

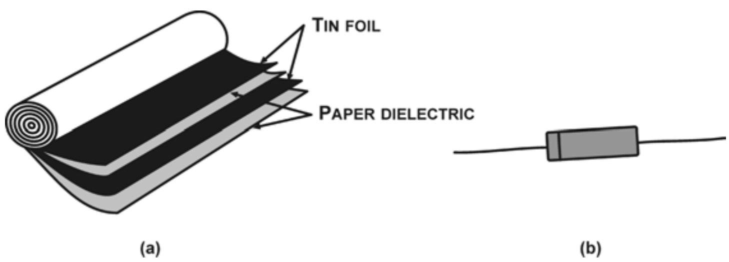


Fig. 6.6. Paper capacitor (a) Physical construction (b) Example of a paper capacitor.

container coated with wax or encased in plastic. Paper capacitors are often used for medium capacitance values of 0.001 to 1.0 μ F, approximately. The physical size for 0.05 μ F is typically 1 in. long with 3/8-in. diameter. A paper capacitor is shown in (Fig. 6.6).

A black or a white band at one end of a paper capacitor indicates the lead connected to the outside foil. This lead should be used for the ground or low potential side of the circuit to take advantage of shielding by the outside foil. There is no required polarity, however, since the capacitance is the same no matter which side is grounded. It should also be noted that in the schematic symbol for C the curved line usually indicates the low-potential side of the capacitor.

FILM CAPACITORS

Film capacitors are constructed much like paper capacitors except that the paper dielectric is replaced with a plastic film such as polypropylene, polystrene, polycarbonate, or polyethelene terepthalate (Mylar). There are two main types of film capacitors : the foil type and the metalized type. The foil type uses sheets of metal foil, such as aluminium or tin, for its conductive plates. The metalized type is constructed by depositing (spraying) a thin layer of metal, such as aluminium or zinc, on the plastic film. The sprayed-on metal serves as the plates of the capacitor. The advantage of the metalized type over the foil type is that the metalized type is much smaller for a given capacitance value and breakdown voltage rating. The reason is that the metalized type is that it is self-healing. This means that if the dielectric is punctured, because of exceeding its breakdown voltage rating, the capacitor is not damaged permanently. Instead, the capacitor heals itself. This is not true of the foil type.

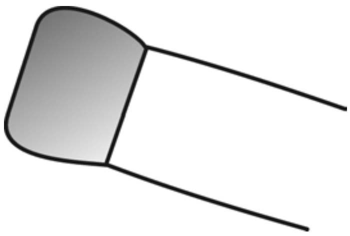


Fig. 6.7. Film capacitor.

Film capacitors are very much temperature-stable and are therefore used frequently in circuit which requires very stable capacitance values. Some examples are, radio frequency oscillators and timer circuits. Film capacitors are available with values ranging from about 100 p F to 100 μ F. (Fig. 6.7) shows a typical film capacitor.

CERAMIC CAPACITORS

The ceramic materials used in ceramic capacitors are made from earth fired under extreme heat. With titanium dioxide or one of several types of silicates, very high values of dielectric constant K_E can be obtained. Most ceramic capacitors come in disk form, as shown in (Fig. 6.8). In the disk form, silver is deposited on both sides of the ceramic dielectric to form the capacitor plates. Ceramic capacitors are available with values of 1 pF (or less) up to about 1 μ F. The wide range of values is possible because the dielectric constant K_E can be tailored to provide almost any desired value of capacitance.

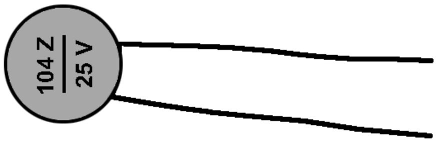


Fig. 6.8. Disk ceramic capacitor.

It should be noted that ceramic capacitors are also available in forms other than disk form. Some ceramic capacitors are available with axial leads and use a color code similar to that of a resistor.

SURFACE-MOUNT CAPACITORS

Like resistors, capacitors are also available as surface-mounted components. Surface-mounted capacitors are often called chip capacitors. Chip capacitors are constructed by placing a ceramic dielectric material between layers of conductive film which form the capacitor plates. The capacitance is determined by the dielectric constant K_E and the physical area of the plates. Chip capacitors are available in many different sizes. A common size is 0.125 in. long by 0.063 in. wide in various thickness. Another common size is 0.080 in. long by 0.050 in. wide in various thicknesses. Figure shows two different sizes of chip capacitors. Like chip resistors, chip capacitors have their end electrodes soldered directly to the copper traces of the printed-circuit board. Chip capacitors are available with values ranging from a fraction of a picofarad up to several microfarads.

VARIABLE CAPACITORS

Figure shows a variable air capacitor. In this construction, the fixed metal plates are connected together to form the stator. The movable plates are connected together on the shaft to form the rotor. Capacitance is varied by rotating the shaft to make the rotor plates mesh with the stator plates. They do not touch, since air is the dielectric. Full mesh gives maximum capacitance. Moving the rotor completely out of mesh, provides minimum capacitance.

A common application is the tuning capacitor in radio receivers. When you tune to different stations, the capacitance varies as the rotor moves in or out of mesh. Combined with an inductance, the variable capacitance then tunes the receiver to a different resonant frequency for each station. Usually two or three capacitor sections are ganged on one common shaft.

TEMPERATURE COEFFICIENT

Ceramic capacitors are often used for temperature compensation, to increase or decrease capacitance with a rise in temperature. The temperature coefficient is given in parts per million (ppm) per degree Celsius, with a reference of 25°C. As an example, a negative 750-ppm unit is stated as N750. A positive temperature coefficient of the same value would be stated as P750. Units that do not change in capacitance are labeled NPO.

CAPACITANCE TOLERANCE

Ceramic disk capacitors for general applications usually have a tolerance of ± 20 percent. For closer tolerances, mica or film capacitors are used. These have tolerance values of ± 2 to 20 percent. Silver-plated mica capacitors are available with a tolerance of ± 1 percent.

The tolerance may be less on the minus side to make sure that there is enough capacitance, particularly with electrolytic capacitors, which have a wide tolerance. For instance, a 20-µ F electrolytic with a tolerance of -10 percent, +50 percent may have a capacitance of 18 to 30 µ F. However, the exact capacitance value is not critical in most applications of capacitors for filtering, ac coupling, and bypassing.

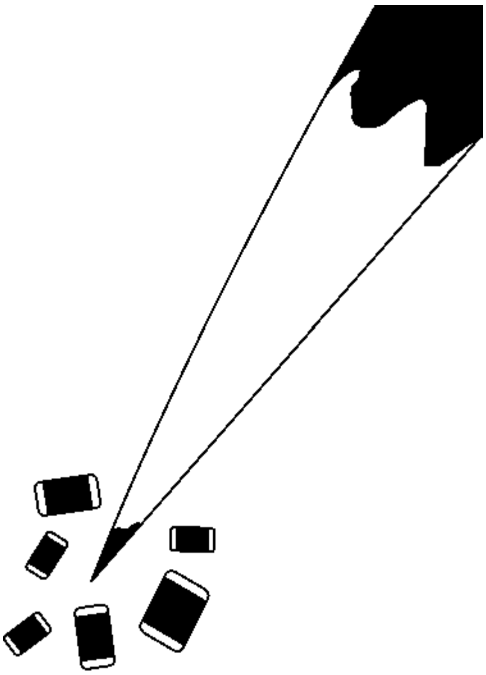


Fig. 6.9. Chip capacitors.

VOLTAGE RATING OF CAPACITORS

This rating specifies the maximum potential difference that can be applied across the plates without puncturing the dielectric. Usually the voltage rating is for temperatures up to about 60°C. Higher temperatures result in a lower voltage rating. Voltage ratings for general-purpose paper, mica, and ceramic capacitors are typically 200 to 500V. Ceramic capacitors with ratings of 1 to 20 kV are also available.

Electrolytic capacitors are typically available in 16-, 35-, and 50-V ratings. For applications where a lower voltage rating is permissible, more capacitance can be obtained in a smaller physical size.

The potential difference across the capacitor depends upon the applied voltage and is not necessarily equal to the voltage rating. A voltage rating higher than the potential difference applied across the capacitor provides a safety factor for long life in service. With electrolytic capacitors, however, the actual capacitor voltage should be close to the rated voltage to produce the oxide film that provides the specified capacitance.

The voltage ratings are for dc voltage applied. The breakdown rating is lower for ac voltage because of the internal heat produced by continuous charge and discharge.

CAPACITOR APPLICATIONS

In most electronic circuits, a capacitor has dc voltage applied, combined with a much smaller ac signal voltage. The usual function of the capacitor is to block the dc voltage but pass the ac signal voltage, by means of the charge and discharge current. These applications include coupling, bypassing, and filtering for ac signals.

TEST-POINT QUESTION 'D'

Answer True or False.

a. An electrolytic capacitor must be connected in the correct polarity. **True**

b. The potential difference across a capacitor is always equal to its maximum voltage rating. **False**

c. Ceramic and paper capacitors generally have less C than electrolytic capacitors. **True**

d. The letters NPO indicate zero temperature coefficient. **True**

ELECTROLYTIC CAPACITORS

Electrolytic capacitors are commonly used for C values ranging from about 1 to 6800 μ F, because electrolytics provide the most capacitance in the smallest space with least cost.

Construction

Figure shows the aluminium-foil type. The two aluminium electrodes are in an electrolyte of borax, phosphate, or carbonate. Between the two aluminium strips, absorbent gauze soaks up electrolyte to provide the required electrolysis that produces an oxide film. This type is considered a wet electrolytic, but it can be mounted in any position.

When dc voltage is applied to form the capacitance in manufacture, the electrolytic action accumulates a molecular-thin layer of aluminium oxide at the junction between the positive aluminium foil and the electrolyte. The oxide film is an insulator. As a result, capacitance is formed between the positive aluminium electrode and the electrolyte in the gauze separator. The negative aluminium electrode simply provides a connection to the electrolyte. Usually, the metal can itself is the negative terminal of the capacitor, as shown in Fig.

Because of the extremely thin dielectric film, very large C values can be obtained. The area is increased by using long strips of aluminium foil and gauze, which are rolled into a compact cylinder with very high capacitance. For example, an electrolytic capacitor the same size as a 0.1-μ F paper capacitor, but rated at 10V breakdown, may have 1000 μ F of capacitance or more. Higher voltage ratings, up to 450 V, are available, with typical C values up to about 6800 μ F. The very high C values usually have lower voltage ratings.

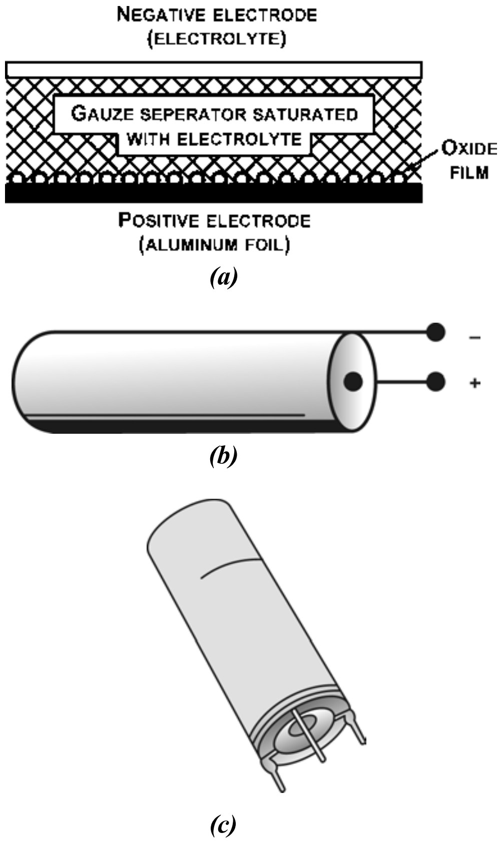


Fig. 6.10. Construction of aluminum electrolytic capacitor. (a) Internal electrodes (b) Foil rolled into cartridge (c) Typical capacitor with multiple sections.

Polarity

Electrolytic capacitors are used in circuits that have a combination of dc voltage and ac voltage. The dc voltage maintains the required polarity across the electrolytic capacitor to form the oxide film. A common application is for electrolytic filter capacitors to eliminate the 60- or 120-Hz ac ripple in a dc power supply. Another use is for audio coupling capacitors in transistor amplifiers. In both these applications, for filtering or coupling, electrolytics are needed for large C with a low-frequency ac component, while the circuit has a dc component for the required voltage polarity. Incidentally, the difference between filtering an ac component out or coupling it into a circuit is only a question of parallel or series connections. The filter capacitors for a power supply are typically 100 to 1000 μ F. Audio capacitors are usually 10 to 47 μ F.

If the electrolytic is connected in opposite polarity, the reversed electrolysis forms gas in the capacitor. It becomes hot and may explode. This is a possibility only with electrolytic capacitors.

Leakage Current

The disadvantage of electrolytics, in addition to the required polarization, is their relatively high leakage current compared with other capacitors, since the oxide film is not a perfect insulator. The problem with leakage current in a capacitor is that it allows part of the dc component to be coupled into the next circuit along with the ac component. In the newer electrolytic capacitors, the leakage current is quite small. Section 17-10 takes a closer look at leakage current in capacitors.

Nonpolarized Electrolytics

This type is available for applications in circuits without any dc polarizing voltage, as in the 60-Hz ac power line. One application is the starting capacitor for ac motors. A nonpolarized electrolytic actually contains two capacitors, connected internally in series opposing polarity.

Tantalum Capacitors

This is another form of electrolytic capacitor, using tantalum (Ta) instead of aluminium. Titanium (Ti) is also used. Typical tantalum capacitors are shown in (Fig. 6.11). They feature :

1. Larger C in a smaller size
2. Longer shelf life
3. Less leakage current.

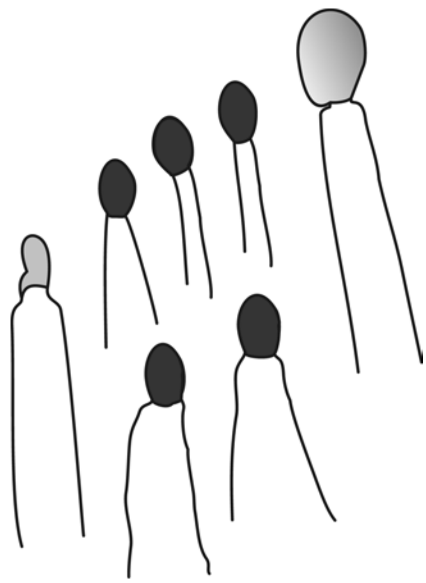


Fig.6.11. Tantalum capacitors.

However, tantalum electrolytics cost more than the aluminium type. Method of construction for tantalum capacitors include the wet-foil type and a solid chip or slug. The solid tantalum is processed in manufacture to have an oxide film as the dielectric constant of 25, compared with 7 for aluminium oxide.

Film as the dielectric. Referring back to Table ,note that tantalum oxide has a dielectric constant of 25, compared with 7 for aluminium oxide.

TEST-POINT QUESTION 'E'

Answer True or False.

a. The rating of 1000 μf at 25 V is probably for an electrolytic capacitor. **True**

b. Electrolytic capacitors allow more leakage current than a mica capacitor. **True**

c. Tantalum capacitors have a longer shelf life than aluminum electrolytics. **True**

CAPACITOR CODING

The value of a capacitor is always specified in either microfarads or picofarads units of capacitance. This is true for all types of capacitors. As a general rule, if a capacitor (other than an electrolytic capacitor) is marked using a whole number such as 33, 220, or 680, the capacitance C is in picofarads (pF). Conversely, if a capacitor is labelled using a decimal fraction such as 0.1, 0.047, or 0.0082, the capacitance C is in microfarads (μ F). There are a variety of different ways in which a manufacturer may indicate the value of a capacitor. What follows is an explanation of the most frequently encountered coding systems.

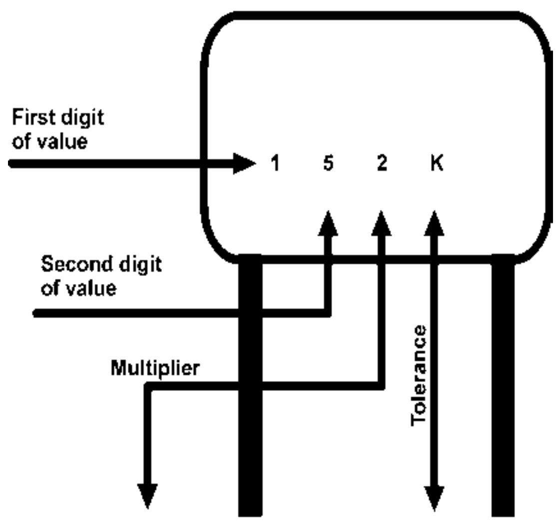


Fig. 6.12. Film type capacitor.

Multiplier		**Tolerance of Capacitor**		
For the Number	Multiplier	Letter	10pF of less	Over 10 pF
0	1	B	± 0.1. pF	
1	10	C	± 0.25 pF	
2	100	D	± 0.5pF	
3	1,000	F	± 1.0 pF	± 1%
4	10,000	G	± 2.0 pF	± 2%
5	100,000	H		± 3%
		J		± 5%
8	0.01	K		± 10%
9	0.1	M		± 20%

Examples:

1152K = 15 $\times$ 100 = 1500 pF or 0.0015 μF, ± 105

759J = 75 $\times$ 0.1 = 7.5 pF, ± 5%

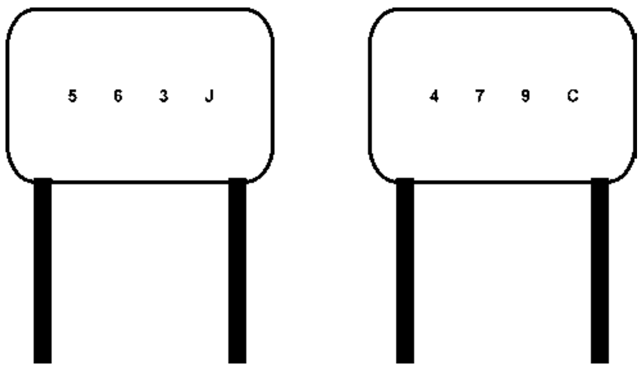
Note: The letter R may be used at times to signify a decimal point, as in 2R2 = 2.2 (pF or μF).

Film-Type Capacitors

Figure shows a popular coding system used with film-type capacitors. The first two numbers printed on the capacitor indicate the first two digits in the numerical value of the capacitance. The third number is the multiplier, indicating by what factor the first two digits must be multiplied. The letter at the far right indicates the capacitor's tolerance. With this coding system the capacitance is always in picofarad units. The capacitor's breakdown voltage rating is usually printed on the body directly below the coded value of capacitance.

Example 7

Determine the value of capacitance for the film capacitors in Fig. 6.13 (a) and Fig. 6.13 (b).



(a) *(b)*

Fig. 6.13. Film capacitor coding system.

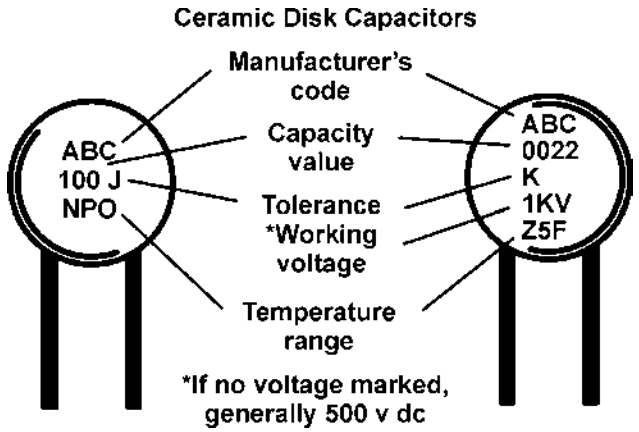
Answer

In Fig. 6.13 (a) the first two numbers are 5 and 6, respectively, for 56 as the first two digits in the numerical value of the capacitance. The third number, 3, indicates a multiplier of 1000, or 56 × 1000 = 56,000 pF. The letter J indicates a capacitor tolerance of ± 5 percent.

In Fig. 6.13 (b), the first two numbers are 4 and 7, respectively, for 47 as the first two digits in the numerical value of the capacitance. The third number, 9, indicates a fractional multiplier of 0.1, or 47 × 0.1 = 4.7 pF. The letter C indicates a capacitor tolerance of ± 0.25 pF.

Disk Ceramic Capacitors

On (Fig. 6.14) shows the way in which most disk ceramic capacitors are marked to indicate their capacitance. As you can see, the capacitance is expressed either as a whole number or as a decimal fraction. The type of coding system used depends on the manufacturer. Disk ceramic capacitors are often used for coupling and bypassing ac signals, where it is allowable to have a wide or lopsided tolerance.



Z 5 F 1 0 0 J

(a) *(b)*

Fig. 6.14. Ceramic Disc capacitors.

Low Temp.	Letter Symbol	High Temp.	Numerical symbol	Max. capacitance change over Temp. Range	Letter Symbol
+10°C	Z	+ 45°C	2	+ 1.0%	A
- 30°C	Y	+ 65°C	4	± 1.5%	B
- 55°C	X	+ 85°C	5	± 1.1%	C
		+ 105°C	6	± 3.3%	D
		+ 125°C	7	± 4.7%	E
				± 7.5%	F
				± 10.0%	P
				± 15.0%	R
				± 22.0%	S
				± 22%,- 33%	T
				± 22%,- 56%	U
				± 22%,- 82%	V

1st% 2nd Fig. of Capacitance	Multiplier	Numerical symbol	Tolerance on capacitance	Letter Symbol
	1	0		
	10	1		
	100	2	± 5%	J
	1,000	3	± 10%	K
	10,000	4	± 20%	M
	100,000	5	± 100%,- 0%	P
		-	± 80%,- 20%	Z
		-		
	0.01	8		
	0.1	9		

Example 8

In (Fig. 6.14) determine : (a) the capacitance value and tolerance; (b) the temperature range identification information.

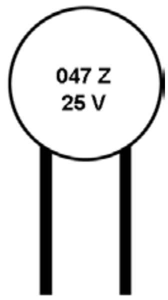


Fig. 6.15.Disk ceramic capacitor for Example.

Answer

(a) Since the capacitance is expressed as a decimal fraction, its value is in microfarads. In this case, C = 0.047 μ F. The letter Z, to the right of 0.047, indicates a capacitor tolerance of +80 percent, -20 percent. Notice that the actual capacitance value can be as much as 80 percent above its coded value but only 20 percent below its coded value.

(b) The dots in the top row are read from left to right, in the direction of the arrow. In the bottom row they are read in the reverse order, from right to left. The first dot at the left in the top row is black, indicating a mica capacitor. The next two color dots are blue and red, for 62 as the first two digits in the numerical value of the capacitance. The next dot, at the far right in the bottom row, is red, indicating a multiplier of 100. Therefore, C = 62 × 100 = 6200 pF. The next dot is gold, indicating a capacitor tolerance of ± 5 percent. Shown in (Fig. 6.15).

Chip Capacitors

Before determining the capacitance value of a chip capacitor, make sure it is a capacitor and not a resistor. Chip capacitors have the following identifiable features :

1. The body is one solid color, such as off-white, beige, gray, tan, or brown.
2. The end electrodes completely enclose the end of the part.

Three popular coding system are used by the different manufacturers of chip capacitors. In all three systems, the values represented are in picofarads. One system, shown in Fig. 6.16 (a) uses a two-place system in which a letter indicates the first and second digits of the capacitance value and a number indicates the multiplier (0 to 9). Thirty - three symbols are used to represent the two significant figures. The symbols used include 24 uppercase letters and 9 lowercase letters. In (Fig. 6.16) note that J3 represents 22,000 pF.

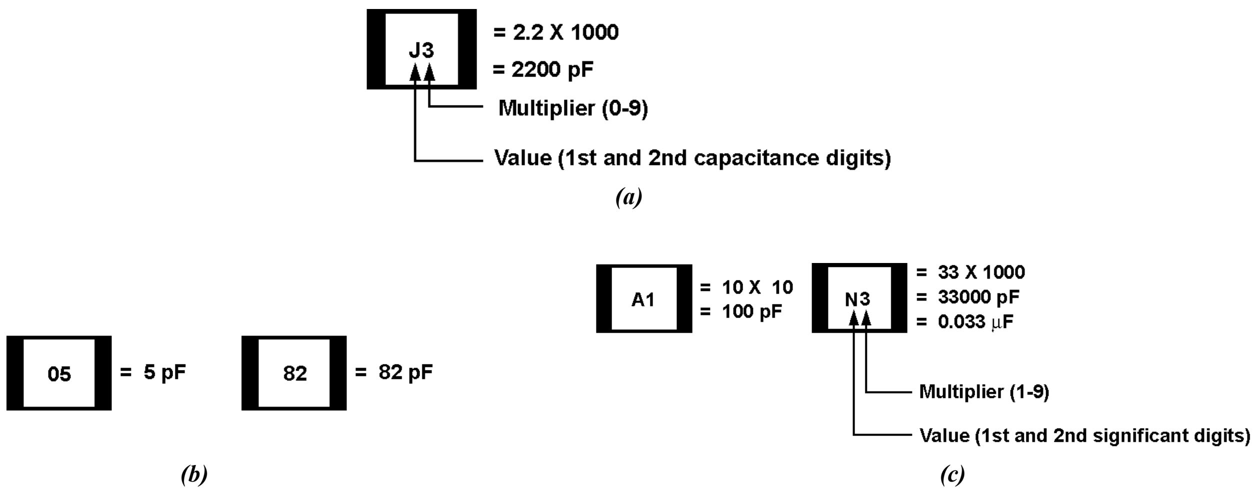


Fig. 6.16. Chip capacitor coding system.

Another system, shown in Fig. 6.16 (a) also uses two places. In this case, however, values below 100pF are indicated using two numbers from which the capacitance value is read directly Fig. 6.16 (b). Values above 100 pF are indicated by a letter and a number as before. In this system, only 24 uppercase letters are used. Also note that the alphanumeric codes in this system are 10 times higher than in the system shown in Fig. 6.16 (c).

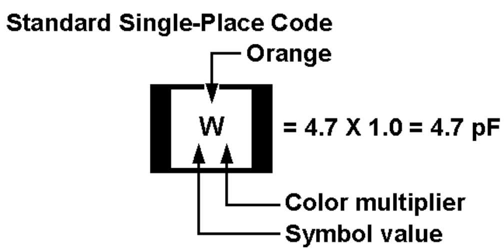


Fig. 6.17. Chip capacitor coding system.

Fig. 6.17 shows yet another system, in which a single letter or number is used to designate the first two digits in the capacitance value. The multiplier is determined by the color of the letter. In the example shown, an orange colored W represents a capacitance C of 4.7 pF.

It should be noted that other coding systems are used with chip capacitors; these systems are not covered here. However, the three coding system shown in this section are the most common systems presently in use. It should also be noted that some chip capacitors found on printed-circuit boards are not marked or coded in any way. When this is the case, the only way to determine the capacitance value is to check it with a capacitance tester.

Value (33 Value Symbols)-- Upper and Lowercase Letters					Multiplier
A - 1.0	H-2.0	b-3.5	f-5.0	X - 7.5	0 = x 1.0
B - 1.1	J - 2.2	P - 3.6	T - 5.1	t - 8.0	1 = x 10
C - 1.2	K - 2.4	Q - 3.9	U - 5.6	Y - 8.2	2 = x 100
D - 1.3	a - 2.5	d - 4.0	m - 6.0	y - 9.0	3 = x 1,000
E - 1.5	L - 2.7	R - 4.3	V - 6.2	Z - 9.1	4 = x 10,000
F - 1.6	M -3.0	e - 4.5	W - 6.8		5 = x 100,000
G - 1.8	N - 3.3	S - 4.7	n - 4.7		etc.

Value (24 Value Symbols) -- Uppeercase Letters Only					Multiplier
A-10	F -16	L - 27	R - 43	W - 68	1 = x 10
B -11	G-18	M- 30	S - 47	X - 75	2 = x 100
C -12	H -20	N - 33	T - 51	Y - 82	3 = x 1,000
D -13	J - 22	P - 36	U - 56	Z - 91	4 = x 10,000
E -15	K -24	Q - 39	V - 62		5 = x 100,000 etc.

Examples : R (Green) = 3.3 x 100 = 330 pF
7 (Blue) = 8.2 x 1000 = 8200 pF

Value (24 Value Symbols) - Uppercase Letters and Numberals)					Multiplier (Color)
A - 1.0	H - 1.6	N - 2.7	V - 4.3	3 - 6.8	Orange = x 1.0
B - 1.1	I - 1.8	O - 3.0	W- 4.7	4 - 7.5	Black = x 10
C - 1.2	J - 2.0	R - 3.3	X - 5.1	7 - 8.5	Green = x 100
D - 1.2	K - 2.2	S - 3.6	Y - 5.6	9 - 9.1	Blue = x 1,000
E - 1.5	L - 2.4	T - 3.9	Z - 6.2		Violet = x 10,000
					Red = x 100,000

Tantalum Capacitors

Tantalum capacitors are frequently coded to indicate their capacitance in picofarads. (Fig. 6.18) shows how to interpret this system.

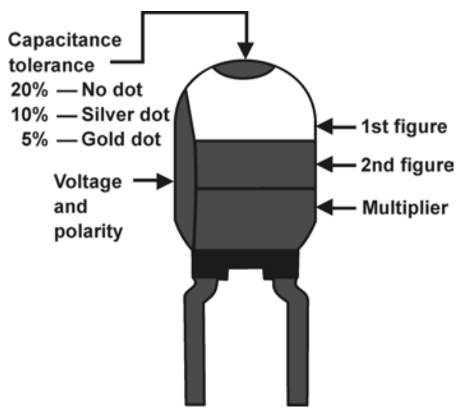


Fig. 6.18. Tantalum capacitor coding system.

Capacitance in Picofarads

Color	Rated Voltage	1st Figure	2nd Figure	Multiplier
Black	4	0	0	---
Brown	6	1	1	---
Red	10	2	2	---
Orange	15	3	3	---
Yellow	20	4	4	10,000
Green	25	5	5	100,000
Blue	35	6	6	1,000,000
Violet	50	7	7	10,000,000
Grey	---	8	8	---
White	3	9	9	---

Example 10

For the tantalum capacitor shown in (Fig. 6.19), determine the capacitance C in both pF and μF units. Also, determine the voltage rating and tolerance.

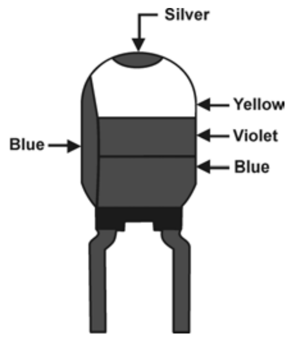


Fig. 6.19. Tantalum capacitor for Example.

Answer

Moving from top to bottom, the first two color bands are violet, which represent the digits 4 and 7, respectively. The third color band is blue, indicating a multiplier of 1,000,000 pF, or 47μ F. The blue color at the left indicates a voltage rating of 35 V. And, finally, the silver dot at the very top indicates a tolerance of ± 10 percent.

TEST-POINT QUESTION 'F'

Answer True or False.

a. A disk ceramic capacitor that is marked .01 has a capacitance of 0.01 pF. **False**

b. A film capacitor that is marked 224 has a capacitance of 220,000 pF. **True**

c. A chip capacitor has a green letter E marked on it. Its capacitance is 150 pF. **True**

d. A disk ceramic capacitor is marked .001 P. Its tolerance is + 100 percent, 0 percent. **True**

Parallel Capacitance

Connecting capacitances in parallel is equivalent to adding the plate areas. Therefore, the total capacitance is the sum of the individual capacitances. As illustrated in (Fig. 6.20).

$$C_r = C_1 + C_2 + ... + \text{etc.}$$

A 10-μ F capacitor in parallel with a 5-μ F capacitor, for example, provides a 15-μ F capacitance for the parallel combination. The voltage is the same across the parallel capacitors. Note that adding parallel capacitance is opposite to the cases of inductance in parallel and resistance in parallel.

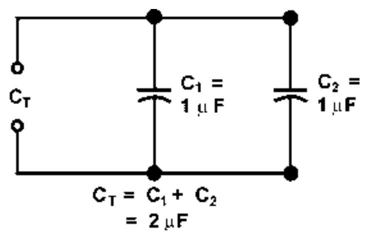


Fig. 6.20. Capacitance in parallel.

TEST-POINT QUESTION 'G'

Answer the following questions

a. How much is C_T for 0.01 μF in parallel with 0.02 μF ? Ans. 0.03 μF

b. What C must be connected in parallel with 100 pf to make C_T of 250 pF ? Ans. 150 pF

Series Capacitances

Connecting capacitances in series is equivalent to increasing the thickness of the dielectric. Therefore, the combined capacitance is less than the smallest individual value. The combined equivalent capacitance is calculated by the reciprocal formula;

$$\frac{1}{C_{EQ}} = \frac{1}{C_1} + \frac{1}{C_2} ... + \text{etc.}$$

Any of the short-cut calculations for the reciprocal formula apply. For example, the combined capacitance of two equal capacitances of 10 μF in series is 5 μF.

Capacitors are used in series to provide a higher working voltage rating for the combination. For instance, each of three equal capacitances in series has one-third the applied voltage.

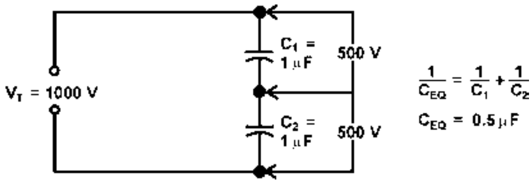


Fig. 6.21. Capacitance in series.

Division of Voltage across Unequal Capacitances

In series, the voltage across each C in inversely proportional to its capacitance as illustrated in (Fig. 6.21). The smaller capacitance has the larger proportion of the applied voltage. The reason is that the series capacitance all have the same charge because they are in one current path. With equal charge, a smaller capacitance has a greater potential difference.

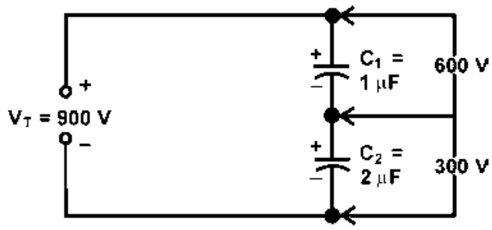


Fig. 6.22. With series capacitors, the smaller C has more voltage for the same change.

We can consider the amount of charge in the series capacitors in (Fig.__). Let the charging current be 600μ A flowing for 1 s. The charge Q equals I × t or 600 μ C. Both C_1 and C_2 have Q equal to 600 μ C, as they are in the same series path for charging current.

Although the charge is the same in C_1 and C_2 , but they have different voltage because of different capacitance values. For each capacitor V = Q/C. For the two capacitors in (Fig.__) then:

$$V_1 = \frac{Q}{C_1} = \frac{600\mu C}{1\mu F} = 600V$$

$$V_2 = \frac{Q}{C_2} = \frac{600\mu C}{2\mu F} = 300V$$

Charging Current for Series Capacitances

The charging current is the same in all parts of the series path, including the junction between C_1 and C_2 , even though this point is separated from the source voltage by two insulators. At the junction, the current is the resultant of electrons repelled by the negative plate of C_2 and attracted by the positive plate of C_1. The amount of current in the circuit is determined by the equivalent capacitance of C_1 and C_2 in series. In (Fig.___) the equivalent capacitance is 2/3 μ F.

TEST-POINT QUESTION 'H'

Answer the following questions

a. How much is C_{EQ} for two 0.2-μF capacitors in series ? Ans. 0.01 μ F

b. With 50 V applied across both, how much is V_C across each capacitor ? Ans. 25 V

c. How much is C_{EQ} for 100 pF in series with 50 pF ? Ans. 33.3 pF

Energy stored in Electrostatic Field of Capacitance

The electrostatic field of the charge stored in the dielectric has electric energy supplied by the voltage source that charges C. This energy is stored in the dielectric. The proof is the fact that the capacitance can produce discharge current when the voltage source is removed. The electric energy stored is

Energy $E = \frac{1}{2}\ CV^2$ joules

Where C is the capacitance in farads, V is the voltage across the capacitor, and E is the electric energy in joules. For example, a 1-μ F capacitor charges to 400 V has stored energy equal to

$$E = ½CV^2 = \frac{1\times10^{-6}\times(4\times10^2)}{2}$$

$$= \frac{1\times10^{-6}\times(16\times10^4)}{2} = 8\times10^{-2}$$

$E = 0.08$ J

This 0.08 J of energy is supplied by the voltage source that charges the capacitor to 400 V. When the charging circuit is opened, the stored energy remains as charge in the dielectric. With a closed path provided for discharge, the entire 0.08 J is available to produce discharge current. As the capacitor discharges, the energy is used in producing discharge current. When the capacitor is completely discharged, the stored energy is zero.

The stored energy is the reason why a charged capacitor can produce an electric shock, even when not connected into a circuit. When you touch the two leads of the charged capacitor, its voltage produces discharge current through your body. Stored energy greater than 1 J can be dangerous with a capacitor charged to a voltage high enough to produce an electric shock.

Notice that the energy is less, even with 30 kV, because C is so small.

Example 11

The high-voltage circuit for a color picture tube can have 30 kV across 500 pF of C. Calculate the stored energy.

Answer

$$E = ½CV^2 = \frac{500\times10^{-12}\times(30\times10^3)^2}{2}$$

$$= 250\times10^{-12}\times900\times10^6$$

$$= 225\times10^{-3}$$

$E = 0.225$ J

TEST-POINT QUESTION 'I'

Answer True or False.

a. The stored energy in C increases with more V. **True**

b. The stored energy decreases with less C. **True**

Measuring and Testing Capacitors

A capacitance meter is a piece of test equipment specifically designed to measure the capacitance value of capacitors. Although capacitance meters can be purchased as stand-alone units, many handheld and benchtop digital multimeters (DMMs) are capable of measuring a wide range of capacitance values. For example, the benchtop DMM shown in (Fig. 6.23) has five capacitance ranges : 2 nF, 20 nF, 200 nF, 2000 nF, and 20μF. To measure the value of a capacitor using this meter, insert the leads of the capacitor into the capacitance socket, labeled CX, located in the upper right-hand corner of the meter. Next, depress the CX (capacitance) button and select the desired capacitance range. The meter will display the measured capacitance value. For best accuracy, always select the lowest range setting that still displays the measured capacitance value. Note that the polarity markings next to the capacitance socket need to be observed when electrolytic capacitors, lead polarity does not matter. Before inserting any capacitor in the socket, it must be fully discharged to avoid damage to the meter.

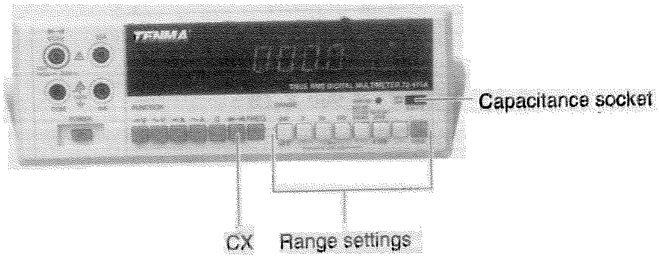


Fig. 6.23. Typical DMM with capacitance measuremant capability.

Recall from Sec. 17-6 that capacitors are always coded in either microfarad or picofarad units but never in nanofarad units. Although this is standard industry practice, you will nevertheless encounter the nanofarad unit of capacitance when you use meters capable of measuring capacitance, such as the one shown in (Fig.__), Therefore, it is important to know how to convert between the nanofarad unit and either microfarad or picofarad units. To convert from nanofarad units to picofarad units, simply move the decimal point three places to the right. For example, 33 nF = 33×10^{-9} F = 33,000 $\times 10^{-12}$ F = 33,000 pF. To convert from nanofarads to microfarads, move the decimal point three places to the left. For another example, 470×10^{-9} F = 0.47×10^{-6} F = 0.47 μ F. When using meters having nanofarad capacitance ranges, you will need to make these conversions to compare the measured value of capacitance with the coded value.

Example 12

Suppose a film capacitor, coded 393 J, is measured using the meter shown in (Fig. 6.23). If the meter reads 37.6 on the 200-nF range : (a) What is the capacitance value in picofarad units ? (b) Is the measured capacitance value within its specified tolerance ?

Answer

The capacitor code, 393J, corresponds to a capacitance value of 39,000 pF ± 5 percent. (a) A reading of 37.6 on the 200-nF range corresponds to a capacitance of 37.6 nF. To convert 37.6 nF to picofarad units, move the decimal point three places to the right. This gives an answer of 37,600 pF. (b) The acceptable capacitance range is calculated as follows : 39,000 pF × 0.05 = ± 1950 pF. Therefore, the measured value of capacitance can range anywhere from 37,050 pF to 40,950 pF and still be considered within tolerance. Note that in nanofarad units this corresponds to a range of 37.05 to 40.95 nF. Since the measured value of 37.6 nF falls within this range, the measured capacitance value is within tolerance.

Leakage Resistance of a Capacitor

Consider a capacitor charged by a dc voltage source. After the charging voltage is removed, a perfect capacitor would hold its charge indefinitely. Because there is no such thing as a perfect insulator, however, the charge stored in the capacitor will eventually leak or bleed off, thus neutralizing the capacitor. There are three leakage paths through which the capacitor might discharge : (1) leakage through the dielectric, (2) leakage across the insulated case or body between the capacitor leads, and (3) leakage through the air surrounding the capacitor. For paper, film, mica, and ceramic the leakage current is very slight, or inversely, the leakage resistance is very high. The combination of all leakage paths can be represented as a single parallel resistance R_l across the capacitor plates as shown in (Fig. 6.24). For paper, film, mica, and ceramic capacitors the leakage resistance R_l is typically 100,000 M Ω or more. The leakage resistance is much less for larger capacitors, such as electrolytics, however, with a typical value of R_l ranging anywhere from about 500 k Ω up to 10 M Ω. In general, the larger the capacitance of a capacitor, the lower its leakage resistance. It should be noted that the leakage current in capacitors is fairly temperature-sensitive. The higher the temperature, the greater the leakage (because of lower leakages resistance).

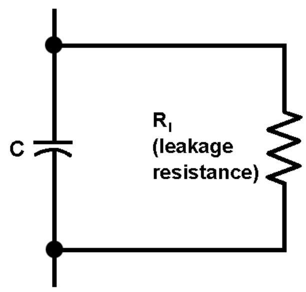


Fig.6.24. Leakage resistance R_l of a capacitor.

The leakage resistance of a capacitor can be measured with a DMM or an analog ohmmeter, but this is not the best way to test a capacitor for leakage. The best

Fig. 6.25. Capacitor-inductor analyzer.

way is to measure the leakage current in the capacitor while the rated working voltage is applied across the capacitor plates. A capacitor is much more likely to show leakage when the dielectric is under stress from the applied voltage. In fact, a capacitor may not show any leakage at all until the dielectric is under stress from the applied voltage. To measure the value of a capacitor and test it for leakage, technicians often use a capacitor-inductor analyzer like the one shown in (Fig. 6.25). This analyzer allows the user to apply the rated working voltage to the capacitor while testing for leakage. How much leakage is acceptable depends on the type of capacitor. Most nonpolarized capacitors should show no leakage at all, whereas electrolytics will almost always show some. Pull-out charts showing the maximum allowable leakage for the most common electrolytic capacitors are usually provided with a capacitor-inductor analyzer.

Dielectric Absorption

Dielectric absorption is the inability of a capacitor to completely discharge to zero. It is sometimes referred to as battery action or capacitor memory and is due to the dielectric of the capacitor retaining a charge after it is supposedly discharged. The effect of dielectric absorption is that it reduces the capacitance value of the capacitor. All capacitors have at least some dielectric absorption, but electrolytics have the highest amount. Dielectric absorption has an undesirable effect on circuit operation if it becomes excessive. The dielectric absorption of a capacitor can be checked using the capacitor-inductor analyzer in (Fig.__). It should be noted that there is no way to test for dielectric absorption with an ohmmeter.

Equivalent Series Resistance (ESR)

With ac voltage applied to a capacitor, the continuous charge, discharge, and reverse charging action cannot be followed instantaneously in the dielectric. This corresponds to hysteresis in magnetic materials. With a high-frequency charging voltage applied to the capacitor, there may be a difference between the amount of ac voltage applied to the capacitor and the actual ac voltage across the dielectric. The difference, or loss, can be attributed to the effects of hysteresis in the dielectric. As you might expect, dielectric hysteresis losses increase with frequency.

All the losses associated with a capacitor can be represented as a resistor either in series or in parallel with an ideal capacitor. For example, the losses associated with dielectric hysteresis can be represented as a single resistor in series with the capacitor as shown in (Fig. 6.26). The other resistor shown in series with the capacitor represents the resistance of the capacitor leads and plates. It also includes and resistance that may exist at point at which the capacitor leads are bonded to the metal plates. As before, the leakage resistance R_l is shown directly in parallel with the capacitor. Collectively, the resistances shown in Fig. This is an accurate and convenient way to represent all the losses that exist in a capacitor.

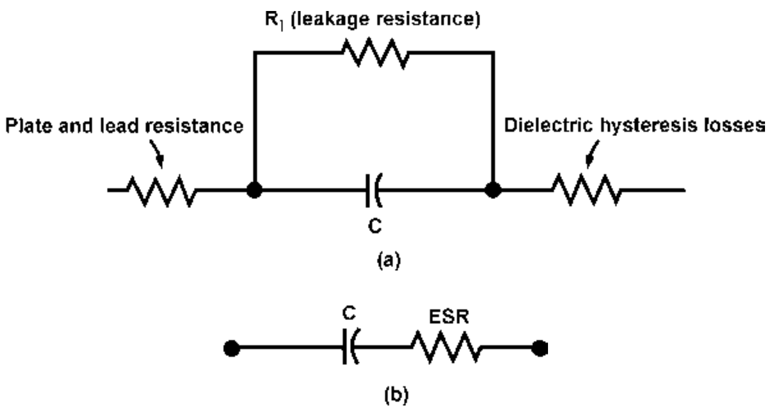


Fig. 6.26. Resistances representing losses in a capacitor. (a) Series and parallel resistance represents capacitor losses. (b) Equivalent series resistance (ESR) represents the total losses in a capacitor.

Ideally, the ESR of a capacitor should be zero. For paper, film, ceramic, and mica capacitors, the ESR value is approximately zero. For electrolytics, however, the ESR may be several ohms or more depending on the way they are constructed. It should be noted that ESR is most often a problem in capacitors that are used in high-frequency filtering applications. For example, most computers use switching power supplies to power the computer. These power supplies require the use of capacitors for filtering high frequencies. In these application a high ESR interferes with the normal filtering action of the capacitor and therefore causes improper circuit operation. In some cases the power dissipated by the ESR may cause the capacitor to overheat.

TEST-POINT QUESTION 'J'

Answer True or False.

a. A 150-nF capacitor is the same as a 0.15-μF capacitor. **True**

b. It is best to test a capacitor for leakage with the rated working voltage applied. **True**

c. Ideally, the ESR of an electrolytic capacitor should be infinite. **False**

d. Dielectric absorption in a capacitor can be detected with an ohmmeter. **False**

The ESR of a capacitor cannot be checked with an ohmmeter. This is because the ESR is in series with the very high resistance of the dielectric. To check a capacitor for ESR, you must use a capacitor-inductor analyzer like the one shown in Fig. Pull-out charts showing the maximum allowable ESR for different types of capacitors are usually provided with the analyzer.

Troubles in Capacitors

Capacitors can become open or short-circuted. In either case, the capacitor is useless because it cannot store charge. A leaky capacitor is equivalent to a partial short circuit where the dielectric gradually loses its insulating properties under the stress of applied voltage, thus lowering its resistance. A good capacitor has very high resistance of the order of several megohms; a short-circuted capacitor has zero ohms resistance, or continuity; the resistance of a leaky capacitor is lower than normal. Capacitor-inductor analyzers, like the one shown in (Fig. 6.25) should be used when it is necessary to test a capacitor. However, if a capacitor-inductor analyzer is not available, an ohmmeter (preferably analog) may be able to identify the problem. What follows is a general procedure for testing capacitors using an ohmmeter.

Checking Capacitors with an Ohmmeter

A capacitor usually can be checked with an ohmmeter. The highest ohms range, such as R × 1 M Ω, is preferable. Also, disconnect one side of the capacitor from the circuit to eliminate any parallel resistance paths that can lower the resistance. Keep your fingers off the connections, since body resistance lowers the reading.

In (Fig. 6.27), the ohmmeter leads are connected across the capacitor. For a good capacitor, the meter pointer moves quickly toward the low-resistance side of the scale and then slowly recedes towards infinity.

The reading when the pointer stops moving is the dielectric resistance of the capacitor, which is normally very high. For paper, film, mica, and ceramic capacitors, the resistance is usually so high that the needle of the meter rests on the infinity mark (∞). However, electrolytic capacitors will usually measure a much lower resistance of about 500 k Ω. to 10 M Ω. In all cases, discharge the capacitor before checking with the ohmmeter.

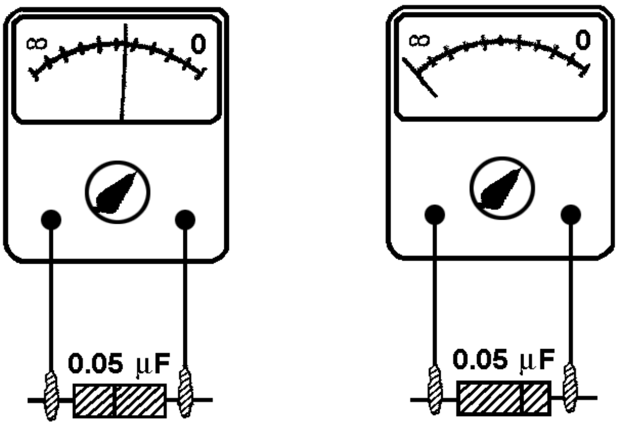


Fig. 6.27. Checking a capacitor with an ohmeter. the R scale is shown right to left, as on a VOM. Use the highest ohms range.
(a) Capacitor action as neddle is moved by the charging current from the battery in the ohmmeter.
(b) Practically infnite leakage resistance reading after the capacitor has been charged.

When the ohmmeter is initially connected, its battery charges the capacitor. This charging current is the reason the meter pointer moves away from infinity, since more current through the ohmmeter means less resistance. Maximum current flows at the first instant of charge. Then the charging current decreases as the capacitor voltage increases toward the applied voltage; therefore, the needle pointer slowly moves toward infinite resistance. Finally, the capacitor is completely charged to the ohmmeter battery voltage, the charging current is zero, and the ohmmeter reads just the small leakage current through the dielectric. This charging effect, called capacitor action, shows that the capacitor can store charge, indicating a normal capacitor. It should be noted that both the rise and the fall of the meter readings are caused by charging. The capacitor discharges when the meter leads are reversed.

Ohmmeter Readings

Troubles in a capacitor are indicated as follows :

1. If an ohmmeter reading immediately goes practically to zero and stays there, the capacitor is short-circuited.
2. If a capacitor shows charging, but the final resistance reading is appreciably less than normal, the capacitor is leaky. Such capacitors are particularly troublesome in high-resistance circuits. When checking electrolytics, reverse the ohmmeter leads and take the higher of the two readings.
3. If a capacitor shows no charging action but just reads very high resistance, it may be open. Some precautions must be remembered, however, since very high resistance is a normal condition for capacitors. Reverse the ohmmeter leads to discharge the capacitor, and check it again. In addition, remember that capacitance values of 100 pF, or less, normally have very little charging current for the low battery voltage of the ohmmeter.

Short-Circuited Capacitors

In normal service, capacitors can become short-circuited because the dielectric with age, usually over a period of years under the stress of charging voltage, especially with higher temperatures. This effect is more common with paper and electrolytic capacitors. The capacitor may become leaky gradually, indicating a partial short circuit, or the dielectric may be punctured, causing a short circuit.

Open Capacitors

In addition to the possibility of an open connection in any type of capacitor, electrolytics develop high resistance in the electrolyte with age, particularly at high temperatures. After service of a few years, if the electrolyte dries up, the capacitor will be partially open. Much of the capacitor action is gone, and the capacitor should be replaced.

Leaky Capacitors

A leaky capacitor reads R less than normal with an ohmmeter. However, dc voltage tests are more definite. In a circuit, the dc voltage at one terminal of the capacitor should not affect the dc voltage at the other terminal.

Shelf Life

Except for electrolytics, capacitors do not deteriorate with age while stored, since there is no applied voltage. Electrolytic capacitors, however, like dry cells, should be used fresh from manufacture. The reason is that the wet electrolyte may dry out over a period of time.

Capacitor Value Change

All capacitors can change value over time, but some are more prone to change than others. Ceramic capacitors often change value by 10 to 15 percent over the first year, as the ceramic material relaxes. Electrolytics change value from simply sitting, because the electrolytic solution dries out.

Replacing Capacitors

Approximately the same C and V ratings should be used when installing a new capacitor. Except for tuning capacitors, the C value is usually not critical. Also, a higher voltage rating can be used. An important exception, however, is the electrolytic capacitor. Then the ratings should be close to the original values for two reasons. First, the specified voltage is needed to form the internal oxide film that provides the required capacitance. Also, too much C may allow excessive charging current in the circuit that charges the capacitor. Remember that electrolytics generally have large values of capacitance.

TEST-POINT QUESTION 'K'

Answer the following questions

a. What is the ohmmeter reading for a shorted capacitor ? Ans. 0 Ω

b. Does capacitor action with an ohmmeter show that the capacitor is good or bad ? Ans. Good

c. Which type of capacitor is more likely to develop trouble, mica or electrolytic ? Ans. Electrolytic

CHAPTER - 7
DETAILED KNOWLEDGE OF CIRCUIT CONTROLLING AND CIRCUIT PROTECTION DEVICES

CIRCUIT CONTROLLING DEVICES

In aircraft electrical installations the function of initiating, and subsequently controlling the operating sequences of constituent circuits is performed principally by switches and relays, and the construction and operation of some typical devices form the subject of this chapter. It may be noted that although circuit breakers may also come within the above functional classification, they are essentially circuit protection devices and, as such, are separately described in the appropriate chapter.

Switches

In its simplest form, a switch consists of two contacting surfaces which can be isolated from each other or brought together as required by a movable connecting link.

PRIMARY METHOD OF ACTUATING COTACT ASSEMBLIES

Switching Device					**Remarks**
	Manual	**Mechanical**	**Electrical**	**Electromagnetic**	
SWITCHES					
Toggle	X				
Push	X			X	Certain types in corporate a "hold-in" coil; lights.
Rotary	X				
Micro	X	X	X		
Rheostat	X				
Time		X			Mechanical timing device operated in turn by an electric motor.
Mercury		X			
Pressure		X			
Thermal		X			Effects of metal expansion and also of electric current.
Proximity		X	X X		
Solid-state					Transistor type "on-off". Used in the internal circuits of units such as control and protection.
RELAYS				X	Electromagnetic, in turn controlled by a circuit incorporating one or more manual switches, mechanical switches or a combination of these.
BREAKERS or Contactors				X	

This connecting link is referred to as a pole and when it provides a single path for a flow of current as shown in Fig. 7.1(a), the switch is designated as a *single pole, single-throw* switch. The term *throw* thus indicates the number of circuits each pole can complete through the switch. In many circuits, various switching combinations are usually required, and in order to facilitate the make and break operations, the contact assemblies of switches (and certain relays) may be constructed as integrated units. For example, the switch at Fig. 7.1(b) can control two circuits in one single make or break operation, and is therefore known as a *double-pole, single-throw* switch, the poles being suitably insulated from each other. Two further examples are illustrated in diagrams Fig. 7.1(c) and Fig. 7.1(d) and are designated *single-pole, double-throw* and *double-pole, double-throw* respectively.

Fig. 7.1. Switch contact arrangements.

In addition to the number of poles and throws, switches (toggle types in particular) are also designated by the number of positions they have. Thus, a toggle switch which is spring-loaded to one position and must be held at the second to complete a circuit, is called a single-position switch. If the switch can be set at either of two positions, e.g. opening the circuit it in another, it is then called a two-position switch. A switch which can be set at any one of three positions, e.g. a centre "off" and two "on" position, is a three-position switch, also known as a selector switch.

TOGGLE SWITCHES

Toggle or tumbler-type switches, as they are sometimes called, perform what may be regarded as "general-purpose" switching functions and are used extensively in the various circuits. A typical switch is illustrated in (Fig. 7.2).

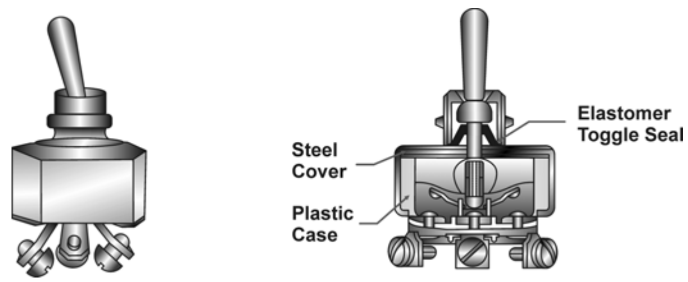


Fig. 7.2. Toggle switch.

In some applications it may be necessary for the switches in several in dependent circuits to actuated simultaneously. This is accomplished by "ganging" the switches together by means of a bar linking each toggle as shown in Fig.7.3 (a). A variation of this method is used in certain types of aircraft for simultaneous action of switch toggles in one direction only (usually to a "system off" position). This is accomplished by a separate gang-bar mounted on the control panel in such a way that it can be pulled down to bear against the toggles of the switches to push them in the required direction. When the bar is released it is returned under the action of a spring.

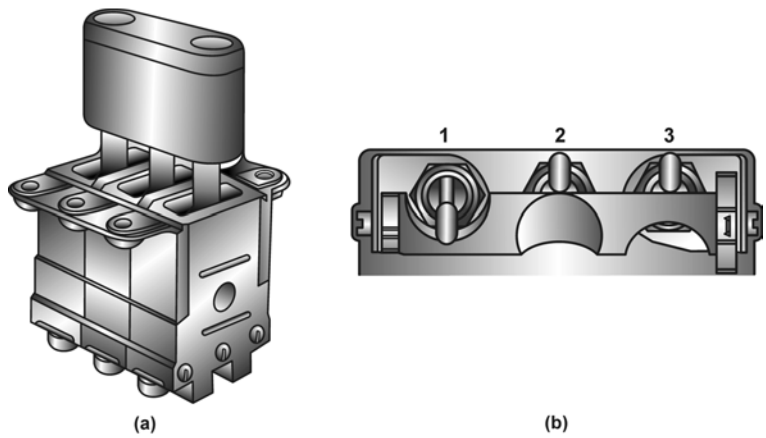


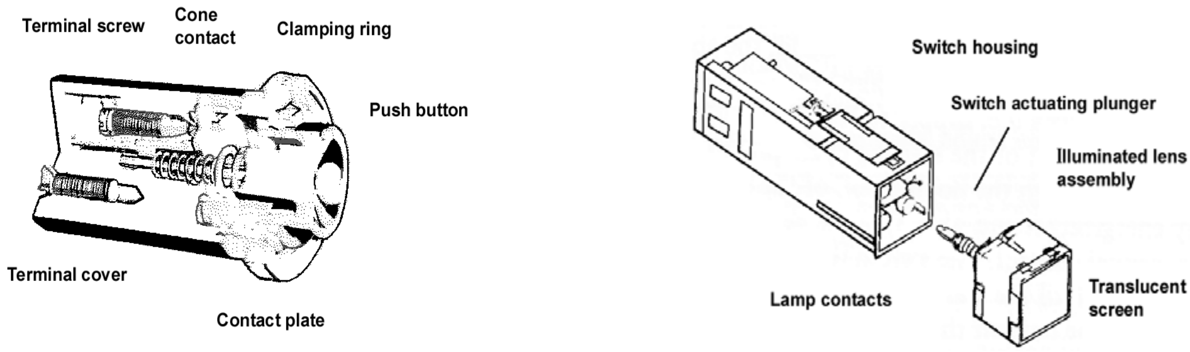
Fig. 7.3. "Ganging" and locking of switches.

A further variation is one in which the operation of a particular switch, or all in a series, may be constrained. A typical application to a triple generator system is shown in Fig.7.1 (b) the switches being used for the alternative disposition of busbar loads in the event of failure of any of the three generators.

A locking bar is free to rotate in mounting brackets anchored by the locking nuts of the No. 1 and No.2 switches. The rediused cut-outs, at 90 degrees to each other, are provided along the length of the bar at positions coincident with the toggles of each switch. A steel spring provides for tensioning of the bar at each selected position, and is inserted around the circumference at the right-hand end. Markings 1, 2, 3 and "N" correspond to the positions of the cut-outs on the bar relative to the switch toggles. If, for example, there is a failure of No. 1 generator the bar is rotated to the position 1 permitting operation of failure switch No.1, but constraining the toggles of the other two switches. The action for switch operation at positions 2 and 3 is similar. Thus, the busbar loads of a failed generator can be distributed between remaining serviceable generators at the same time avoiding inadvertent switch operation. When the letter "N" is evident the bar and the cut-outs are positioned so that none of the switches can be operated.

PUSH-SWITCHES

Push-switches are used primarily for operations of short duration, i.e. when a circuit is to be completed or interrupted momentarily, or when an alternative path is to be made available for brief periods. Other variants are designed to close one or more circuits (through separate contacts) while opening another circuit, and in these types, provision may be made for contact-action in the individual circuits to occur in sequence instead of simultaneously. In basic form a push-switch consists of a button-operated spring-loaded plunger carrying one or more contact plates which serve to establish electrical connection between fixed contact surfaces. Switches may be designed as independent units for either "push-to-make" or "push-to-break" operation, or designed to be double-acting. For certain warning and indicating purposes, some types contain miniature lamps positioned behind a small translucent screen in the push-button. When illuminated, legends such as "on", "closed" or "fail" are displayed on the screen and in the appropriate colours.



Simple type *Illuminated type*

Fig. 7.4. Push switches.

The construction of a simple type of "push-to-make" switch and the arrangement of an illuminated type are shown in (Fig.7.4). In some circuits, for example in a turbopropeller engine starting circuit, switches are designed to be both manual and electromagnetic in operation. A typical example, normally referred to as a "push-in solenoid switch", is shown in (Fig.7.5). The components are contained within a casing comprising an aluminium housing having an integral mounting flange, a sleeve and an end cover. The solenoid coil is located at the flange-end of the housing, and has a plunger passing through it. One end of the plunger extends beyond the housing flange and has a knob secured to it, while the other end terminates in a spring-loaded contact assembly. A combined terminal and fixed contact block is attached to the end of the housing and is held in place by a knurled end cover nut.

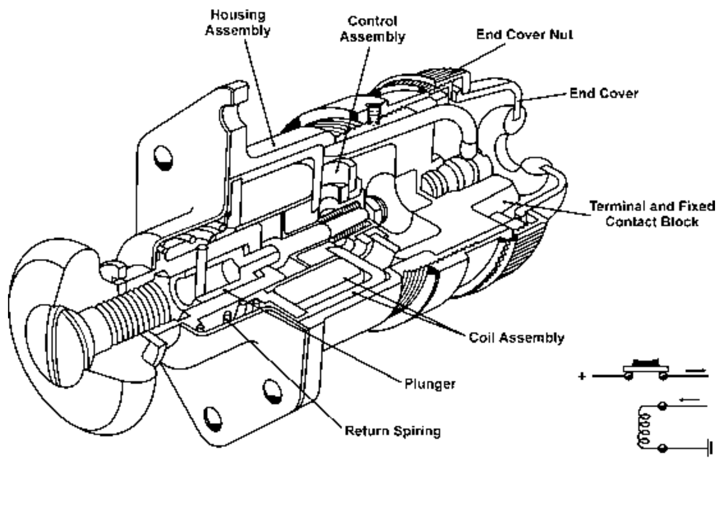


Fig. 7.5. Push-in solenoid switch.

When the plunger is depressed and held, the spring-loaded contact assembly bears against the fixed contacts and connects a d.c. supply to the starter motor. The commencement of the starting cycle provides a current flow through the hold-in coil of the switch thereby energizing it and obviating the necessity for further manual control. The switch remains in the "on" position until the starting cycle is completed. At this stage, the current through the solenoid coil will have dropped sufficiently to permit the spring to return the plunger and contacts to the "off" position.

ROCKER-BUTTON SWITCHES

Rocker-button switches combine the action of both toggle and push-button type switches and are utilized for circuit control of some systems and equipment. A typical switch is shown in Fig.7.6. For certain warning and indicating purposes, some types are provided with a coloured cap or screen displaying legend information, illuminated by a miniature lamp.

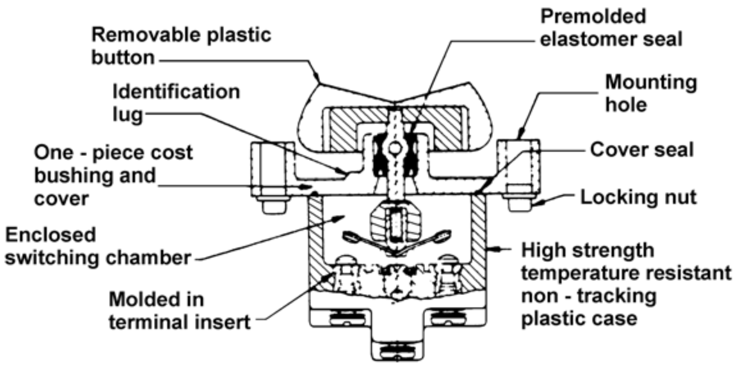


Fig. 7.6. Rocker-button switch.

ROTARY SWITCHES

These are manually operated, and for certain operating requirements they offer an advantage over toggle switches in that they are less prone to accidental operation. Furthermore, the rotary principle and positive engagement of contacts made possible by the constructional features make these switches more adaptable to multi-circuit selection than toggle type switches. A typical application is the selection of a single voltmeter to read the voltages at several bus-bars. In the basic form a rotary switch consists of a central spindle carrying one or more contact plates or blades which engage with corresponding fixed contacts mounted on the switch base. The movement its usually spring-loaded and equipped with some form of eccentric device to give a snap action and position engagement of the contact surfaces.

MICRO-SWITCHES

Micro-switches are a special category of switch and are one of the most extensively applied electrical devices in aircraft, performing a wide range of operations to ensure safe control of a variety of systems and components. The term "micro-switch" designates a switching device in which the differential travel between "make" and "break" of the operating mechanism is of the order of a few thousandths of an inch. Magnification and snap action of contact mechanism movements are derived from a pre-tensioned mechanically baised spring. The principle is shown in (Fig.7.7). The long

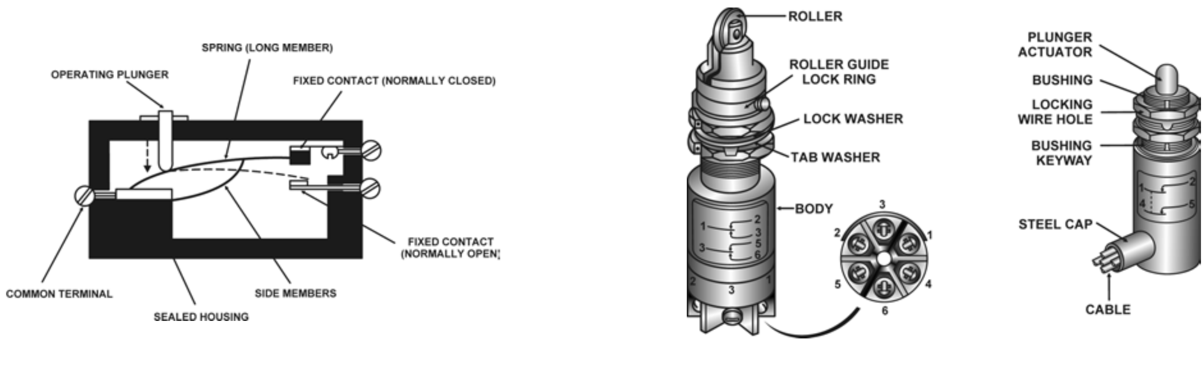


Fig. 7.7. Micro-switches.

member of the one-piece spring is cantilever supported and the operating button or plunger bears against the spring. Two shorter side members are anchored in such a way that they are bowed in compression. In the inoperative position the contact mounted on the free end of the spring is held against the upper fixed contact by the couple resulting from both tension and compression force. Depression of the operating button deflects the long member downwards thereby causing a reversal of the couple which "snaps" the spring and contact downward. Upon removal of the operating force, cantilever action restores the spring and contact system to its initial position with a snap action.

The method of actuating micro-switches depends largely on the system to which it is applied but usually it is either by means of a lever, roller or cam, these in turn being operated either manually or electrically. The operating cycle of a micro-switch is defined in terms of movement of the operating plunger. This has a specified amount of pre-travel, or free movement before the switch snaps over. Following the operating point, there is some over-travel, while on the return stroke some differential travel beyond the operating point is provided before the release action of the switch takes place. The contacts of the switches shown in (Fig.7.7) operate within sealed evacuated chambers filled with an inert gas, e.g. nitrogen.

RHEOSTATS

These are controlling devices containing a resistance the magnitude of which can be varied, thereby adjusting the current in the circuit in which it is connected. A typical example of this method of control is the one adopted for varying the instrument panel and certain cockpit lighting.

Rheostats normally adjust circuit resistance without opening the circuit, although in some cases, they are constructed to serve as a combined on-off switch and variable resistor.

TIME SWITCHES

Certain consumer services are required to operate on a pre-determined controlled time sequence basis and as this involves the switching on and off of various components or sections of circuit, switches automatically operated by timing mechanisms are necessary. The principle of time switch operation varies, but in general it is based on the one in which a contact assembly is actuated by a cam driven at constant speed by either a speed-controlled electric motor or a spring-driven escapement mechanism. In some specialized consumer services, switches which operate on a thermal principle are used. In these the contact assembly is operated by the distortion of a thermal element when the latter has been carrying a designed current for a pre-determined period.

An example of a motor-driven time switch unit is shown in Fig.7.8. It is designed to actuate relays which, in turn, control the supply of alternating current to the heating elements of a power unit de-icing system. Signals to the relays are given in repeated time cycles which can be of short or long duration corresponding respectively to "fast" and "slow" selections made on the appropriate system control switch.

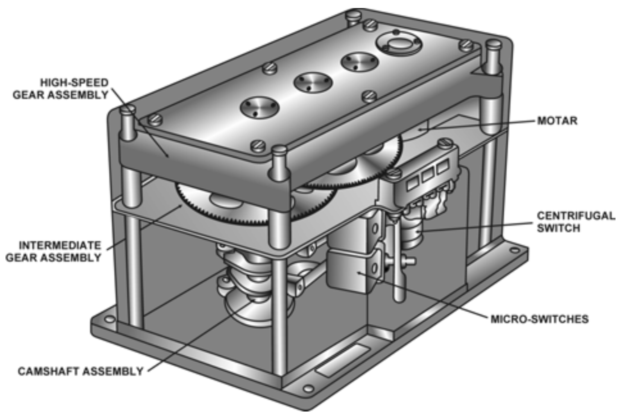


Fig. 7.8. Time switch unit.

The unit comprises an assembly of five cam and lever-actuated micro-switches driven by an a.c. motor through a reduction gearbox.

The motor runs at constant speed and drives the camshaft at one revolution per 240 seconds. Two of the cams are of the three-lobed type and they switch on two micro-switches three times during one revolution, each "on" period corresponding to 20 seconds. Two other cams are of the single-lobed type and they switch on two associated micro-switches once during one revolution, the "on" periods in this case corresponding to 60 seconds. Thus the foregoing cam and micro-switch operations correspond respectively to "fast" and "slow" selections of power to the heating elements, which are accordingly heated for short or long periods. The fifth cam and its micro-switch constitute what is termed a "homing" control circuit, the purpose of which is to re-set the time switch after use so that it will always re-commence at the beginning of an operating cycle.

When the "homing" micro-switch closes. it completes an external relay circuit whose function is to continue operation of the motor whenever the deicing system is switched off. On completion of the full revolution of the camshaft, the homing microswitch is opened, thereby stopping the motor and resetting the timer for the next cycle of operation.

MERCURY SWITCHES

Mercury switches are glass tubes into which stationary contacts, or electrodes, and a pool of loose mercury are hermetically sealed. Tilting the tube causes the mercury to flow in a direction to close or open a gap between the electrodes to "make" or "break" the circuit in which the switch is connected.

The rapidity of "make" and "break" depends on the surface tension on the mercury rather than on externally applied forces. Thus, mercury switches are applied to systems is which the angular position of a component must be controlled within a narrow band of operation and in which the mechanical force required to tilt a switch is very low. A typical application is in torque motor circuits of gyro horizons in which the gyros must be processed to, and maintained in, the vertical position.

Mercury switches are essentially single-pole, single-throw devices but, as will be noted from Fig.7.9, some variations in switching arrangements can be utilized.

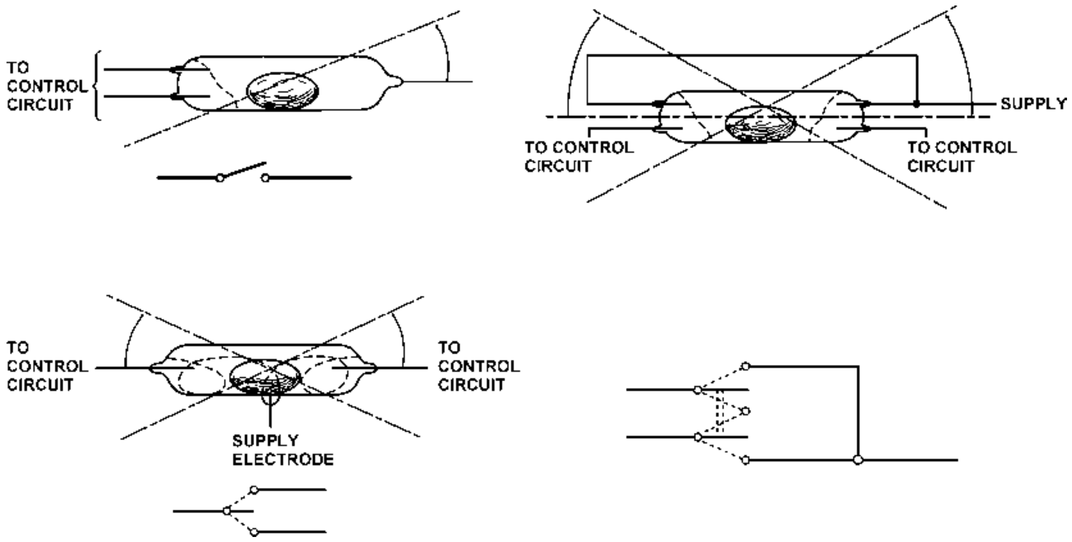


Fig. 7.9. Mercury switches.

PRESSURE SWITCHES

In many of the aircraft systems in which pressure measurement is involved, it is necessary that a warning be given of either low or high pressures which might constitute hazardous operating conditions. In some systems also, the frequency of operation may be such that the use of a pressure-measuring instrument is not justified since it is only necessary for some indication that an operating pressure has been attained for the period during which the system is in operation. To meet this requirement, pressure switches are installed in the relevant systems and are connected to warning or indicator lights located on the cockpit panels.

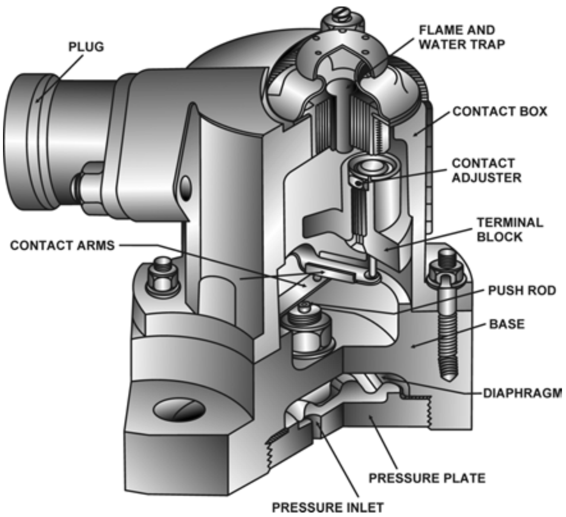


Fig. 7.10. Typical pressure switch unit.

A typical switch is illustrated in (Fig.7.10). It consists of a metal diaphragm bolted between the flanges of the two sections of the switch body. As may be seen, a chamber is formed on one side of the diaphragm and is open to the pressure source. On the other side of the diaphragm a push rod, working through a sealed guide, bears against contacts fitted in a terminal block connected to the warning or indicator light assembly. The contacts may be arranged to "make" on either decreasing or increasing pressure, and their gap settings may be preadjusted in accordance with the pressures at which warning or indication is required.

Pressure switches may also be applied to systems requiring that warning or indication be given of changes in pressure with respect to certain datum pressure; in other words, as a differential pressure warning device. The construction and operation are basically the same as the standard type, with the exception that the diaphragm is subjected to a pressure on each side.

THERMAL SWITCHES

Thermal switches are applied to systems in which a visual warning of excessive temperature conditions, automatic temperature conditions, automatic temperature control and automatic operation of protection devices are required. Example of such applications are, respectively, overheating of a generator, control of valves in a thermal de-icing system and the automatic operation of fire extinguishers.

A principle commonly adopted for thermal switch operation is based on the effects of differences of expansion between two metals, usually invar and steel. In some cases mercury contact switches may be employed.

An example of a differential expansion switch employed in some cases as a fire deteching device, is shown in (Fig.7.11). The heat-sensitive element is an alloy steel barrel containing a spring bow assembly of low coefficient of expansion. Each limb of the bow carries a silver-rhodium contact connected by fire-resistant cable to a terminal block located within a steel case.

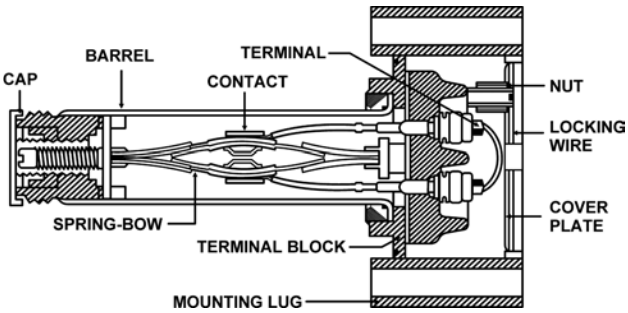


Fig. 7.11. Fire detector switch.

In the event of a fire or sufficient rise in temperature at the switch location (a typical temperature is 300°C) the barrel will expand and remove the compressive force from the bow assembly, permitting the contact to close the circuit to its relevant warning lamp. When the temperature drops, the barrel contracts, thus compressing the bow assembly and reopening the contacts.

PROXIMITY SWITCHES

These switches are used in several types of aircraft as part of circuits required to give warning of whether or not passenger entrance doors, freight doors, etc. are fully closed and locked. Since they have no moving parts they offer certain advantages over micro-switches which are also applied to such warning circuits.

A typical switch shown in (Fig.7.12) consists of two main components, one of which is an hermetically-sealed permanent magnet actuator, and the other a switch unit comprising two reeds, each having rhodium-plated contacts connected to the warning circuit. The two components are mounted in such a manner that when they contact each other, the field from the permanent magnet closes the reeds and contacts together, to complete a circuit to the "door closed" indicator.

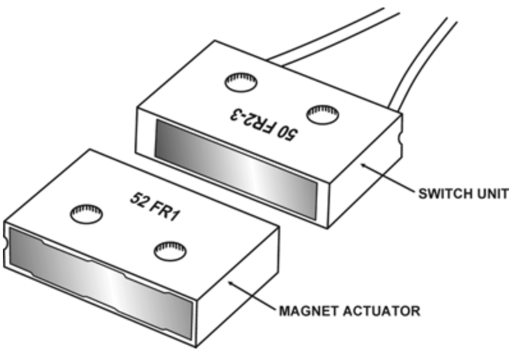


Fig. 7.12. Proximity switch.

Relays

Relays are in effect, electromagnetic switching devices by means of which one electrical circuit can be indirectly controlled by a change in the same or another electrical circuit.

Various types of relay are in use, their construction, operation, power ratings, etc., being governed by their applications, which are also varied and numerous. In the basic form, however, a relay may be considered as being made up of two principal elements, one for sensing the electrical changes and for operating the relay mechanism, and the other for controlling the changes. The sensing and operating element is a solenoid and armature, and the controlling element is one or more pairs or contacts.

As in the case of switches, relays are also designated by their "pole" and "throw" arrangements and these can range from the simple single-pole, single-throw type to complex multiple contact assemblies controlling a variety of circuits and operated by the one solenoid.

In many applications the solenoid is energized directly from the aircraft power supply, while in others it may be energized by signals from an automatic device such as an amplifier in a cabin temperature-control system, or a fire detector unit. When the solenoid coil is energized a magnetic field is set up and at a pre-determined voltage level (called the "pull-in" voltage) the armature is attracted to a pole piece against spring restraint, and actuates the contact assembly, this in turn either completing or interrupting the circuit being controlled. When the solenoid coil circuit is interrupted at what is termed the "drop-out" voltage, the spring returns the armature and contact assembly to the inoperative condition.

In addition to the contact assembly designations mentioned earlier, relays are also classified by the order of making and breaking of contacts, whether normally open ("NO") or normally closed ("NC") in the de-energized position, rating of the contacts in amperes and the voltage of the energizing supply. The design of a relay is dictated by the function it is required to perform in a particular system or component, and as a result many types are available, making it difficult to group them neatly into specific classes. On a very broad basis, however, grouping is usually related to the basic form of construction, e.g. attracted core, attracted-armature, polarized armature, and "slugged", and the current-carrying ratings of the controlling element contacts, i.e. whether heavy-duty or light-duty. The descriptions given in the following paragraphs are therefore set out on this basis and the relays selected are typical and generally representative of applications to aircraft systems.

ATTRACTED-CORE, HEAVY-DUTY RELAY

The designation "heavy-duty" refers specifically to the amount of current to be carried by the contacts. These relays are therefore applied to circuits involving the use of heavy-duty motors which may take starting currents over a range from 100A to 1500 A, either short-term, as for starter motors for example, or continuous operation.

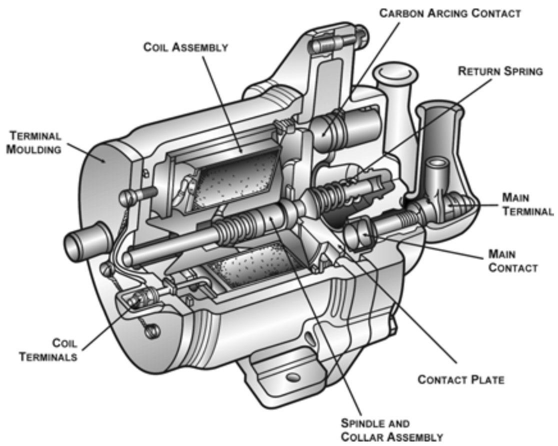


Fig.7.13.Attraction core heavy-duty relay.

A relay of the type used for the control of a typical turbopropeller engine starter motor circuit is illustrated in Fig.7.13. The contact assembly consists of a thick contact plate and two suitably insulated fixed contact studs connected to the main terminals.

The contact plate is mounted on a supporting spindle and this also carries a soft inner core located inside the solenoid coil. The complete moving component is spring-loaded to hold the contact plate from the fixed contacts and to retain the core at the upper end of the coil. When the coil is energized the polarities of the magnetic fields established in the coil and core are such that the core moves downwards against spring pressure, until movement is stopped by the contact plate bridging across the fixed contacts, thus completing the main circuit. Carbon contacts are provided to absorb the initial heavy current and thereby reduce arcing to a minimum before positive connection with the main contacts is made.

ATTRACTED-ARMATURE, LIGHT-DUTY RELAY

A relay designed for use in a 28-volt d.c. circuit and having a contact rating of 3 A is shown in Fig.7.14.

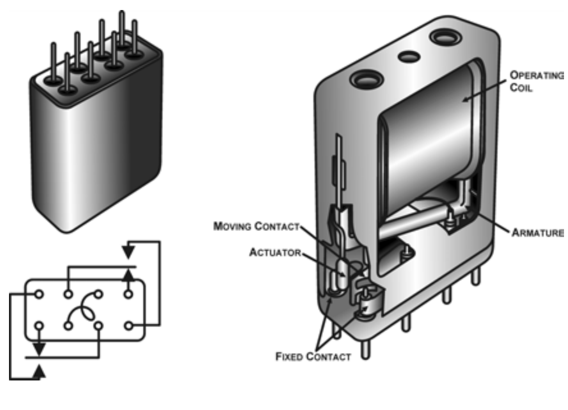


Fig.7.14. Attraction armature light-duty relay (sealed).

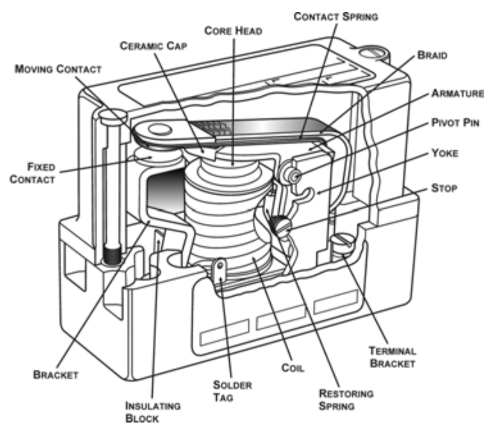


Fig. 7.15. Attracted armature relay (unsealed type).

The contacts are of a silver alloy and are actuated in the manner shown in the inset diagram, by a pivoted armature. In accordance with the practice adopted for many currently used relays, the principal elements are enclosed in an hermetically-sealed case filled with dry nitrogen and the connection in the circuit is made via a plug-in type base. Fig.7.15 illustrates another example of attracted armature relay. This is of the unsealed type and is connected into the relevant circuit by means of terminal screws in the base of the relay.

POLARIZED ARMATURE RELAYS

In certain specialized applications, the value of control circuit currents and voltages may be only a few milliamps and millivolts , and therefore relays of exceptional sensitivity are required. This requirement cannot always be met by relays which employ spring-controlled armatures, for although loading may be decreased to permit operation at a lower "pull-in" voltage, effective control of the contacts is decreased and there is a risk of contact flutter. A practical solution to this problem resulted in a relay in which the attraction and repulsion effects of magnetic forces are substituted for the conventional spring-control of the armature and contact assembly. Fig.7.16 shows, in diagrammatic form, the essential features and operating principle of such a relay.

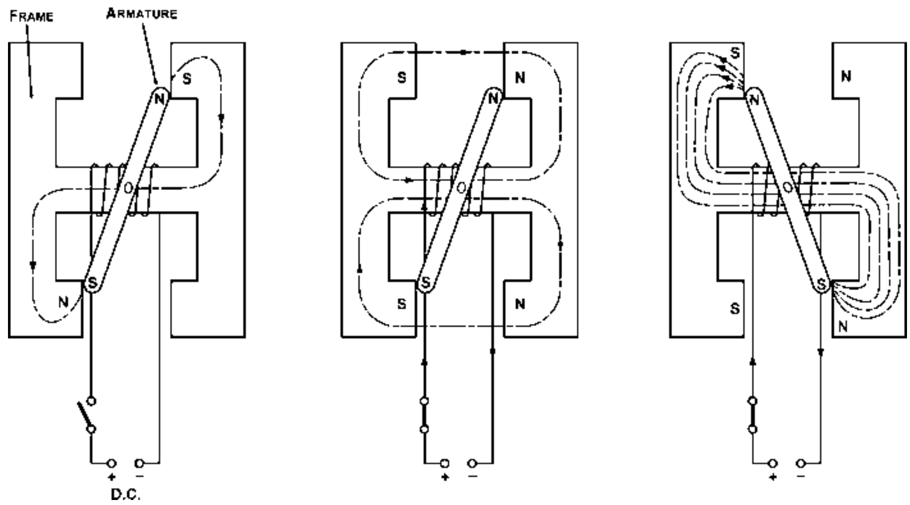


Fig. 7.16. Principle of a polarized armature relay.

The armature is a permanent magnet and is pivoted between two sets of pole faces formed by a frame of high permeability material (usually mu-metal). It is lightly biased to one side to bring the contact assembly into the static condition as in Fig.7.16 (a). The centre limb of the frame carries a low-inductance low-current winding which exerts a small magnetizing force on the frame when it is energized from a suitable source of direct current. With the armature in the static condition, the frame pole-faces acquire, by induction from the armature, the polarities shown, and the resulting forces of magnetic attraction retain the armature firmly in position.

When a d.c. voltage is applied to the coil the frame becomes, in effect, the core of an electromagnet. The flux established in the core opposes and exceeds the flux due to the permanent magnet armature, and the frame pole-faces acquire the polarities shown in Fig.7.16 (b). As the armature poles and frame pole-faces are now of like polarity, the armature is driven to the position shown in Fig.7.16 (c) by the forces of repulsion. In this position it will be noted that poles and pole-faces are now of unlike polarity, and strong forces of attraction hold the armature and contact assembly in the operating condition. The fluxes derived from the coil and the armature act in the same direction to give a flux distribution as shown in Fig. 6.16 (c). When the coil circuit supply is interrupted, the permanent magnet flux remains, but the force due to it is weaker than the armature bias force and so the armature and contacts are returned to the static condition [Fig.7.16 (a)].

SLUGGED RELAYS

For some application requirements arise for the use of relays which are slow to operate the contact assembly either at the stage when the armature is being attracted, or when it is being released.

Some relays are therefore designed to meet these requirements, and they use a simple principle whereby the build-up or collapse of the main electromagnet flux is showed down by a second and opposing magnetizing force. This procedure is known as "slugging" and a relay to which it is applied is called a "slug" relay. The relay usually incorporates a ring of copper or other non-magnetic conducting material (the "slug") in the magnetic circuit of the relay, in such a way that changes in the operating flux which is linked with the slug originate the required opposing magnetic force. In some slug relays the required result is obtained by fitting an additional winding over the relay core and making provision for short-circuiting the winding, as required, by means of independent contacts provided in the main contact assemblies.

BREAKERS

These devices sometimes referred to as contactors, are commonly used in power generation systems for the connection of feeder lines to busbars, and also for interconnecting or "tying" of busbars. The internal arrangement of one such breaker is shown in Fig.7.17.

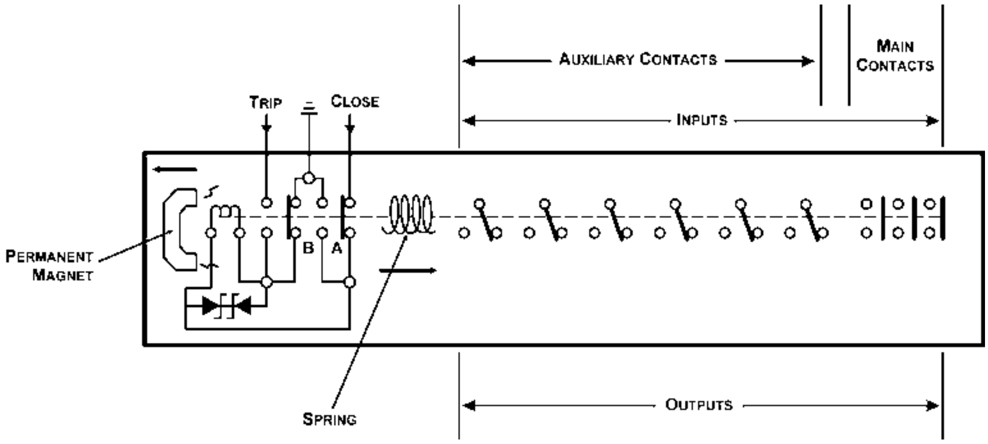


Fig. 7.17. Breaker.

It consists of main heavy-duty contacts for connecting a.c. feeder lines, and a number of smaller auxiliary contacts which carry d.c. for the control of other breakers, relays, indicating lights as appropriate to the overall system. All contacts are closed and/or tripped by a d.c. operated electromagnetic coil ; a permanent magnet serves to assist the coil in closing, and also to latch the breaker in the closed position. The coil is also assisted in tripping by means of a spring. Two zener diodes are connected across the coil to suppress arcing of the coil circuit contacts during closing and tripping.

When say, a main generator switch is placed in its "on" position, a d.c. "closing" signal will flow through the relaxed contacts "A" and then through the coil to ground via relaxed contacts "B". With the coil energized, the main and other auxiliary contacts will therefore be closed and the spring will be compressed. The changeover of the coil contacts "A" completes a hold-in circuit to ground, and with the assistance of the permanent magnet the breaker remains latched.

A tripping signal resulting from either the generator switch being placed to "off", or from a fault condition sensed by a protection unit, will flow to ground in the opposite direction to that when closing, and via the second set of the "close" contacts. The spring assists the reversed electromagnetic field of the coil in breaking the permanent magnetic latch.

Breakers of this type are installed with their opening-closing axis in the horizontal position.

CIRCUIT PROTECTION DEVICES AND SYSTEMS

In the event of a short circuit, an overload or other fault condition occurring in the circuit formed by cables and components of an electrical system, it is possible for extensive damage and failure to result. For example, if the excessive current flow caused by a short circuit at some section of a cables is left unchecked, the heat generated in the cable will continue to increase until something gives way. A portion of the cable may melt, thereby opening the circuit so that the only damage done would be to the cable involved. The probability exists, however, that much greater damage would result; the heat could char and burn the cable insulation and that of other cables forming a loom, and so causing more short circuits and setting the stage for an electrical fire. It is essential therefore to provide devices in the network of power distribution to systems, and having the common purpose of protecting their circuits, cables and components. The devices normally employed are fuses, circuit breakers and current limiters. In addition, other devices are provided to serve as protection against such fault conditions as reverse current, overvoltage, overfrequency, under-frequency, phase unbalance, etc. These devices may generally be considered as part of main generating systems, and those associated with d.c. power generation, in particular, are normally integrated with the generator control units.

FUSES

A fuse is a thermal device designed primarily to protect the cables of a circuit against the flow of short-circuit and overload currents. In its basic form, a fuse consists of a low melting point fusible element or link, enclosed in a glass or ceramic casing which not only protects the element, but also localizes any flash which may occur when "fusing". The element is joined to end caps on the casing, the caps in turn, providing the connection of the element with the circuit it is designed to protect. Under short-circuit or overload current conditions, heating occurs, but before this can effect the circuit cables or other elements, the fusible element, which has a much lower current-carrying capacity, melts and interrupts the circuit. The materials most commonly used for the elements are tin, lead, alloy of tin and bismuth, silver or copper in either the pure or alloyed state.

The construction and current ratings of fuses vary, to permit a suitable choice for specific electrical installations and proper protection of individual circuits. Fuses are, in general, selected on the basis of the lowest rating consistent with

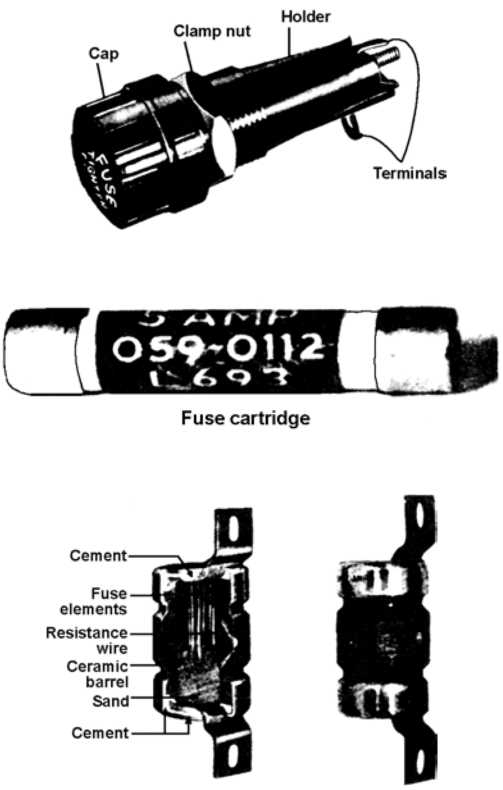


Fig.7.18. Typical fuses
(a) Light-duty circuit fuse
(b) High-rupturing capacity fuse

reliable system operation, thermal characteristics of cables, and without resulting "nuisance tripping". For emergency circuits, i.e., circuits the failure of which may result in the inability of an aircraft to maintain controlled flight and effect a safe landing, fuses are of the highest rating possible consistent with cable protection. For these circuits it is also necessary that the cable and fuse combination supplying the power be carefully engineered taking in to account short-term transients in order to ensure maximum utilization of the vital equipment without circuit interruption.

Being thermal devices, fuses are also influenced by ambient temperature variations. These can affect to some extent the minimum "blowing" current, as well as "blowing" time at higher currents, and so must also be taken in account. Typical examples of fuses currently in use in light and heavy-duty circuits, are shown in Fig.7.18 (a)-(b) respectively. The light-duty fuse is screwed into its holder (in some types a bayonet cap fitting is used) which is secured to the fuse panel by a fixing nut. The circuit cable is connected to terminals located in the holder, the terminals making contact with corresponding connections on the element cartridge. A small hole is drilled through the centre of the cap to permit the insertion of a fuse test probe.

Fuses are located accessible for replacement, and as close to a power distribution point as possible so as to achieve the minimum of unprotected cable.

The heavy-duty or high rupturing capacity fuse Fig.7.18 (b) is designed for installation at main power distribution points (by means of mounting lugs and bolts). It consists of a tubular ceramic cartridge within which a number of identical fuse elements in parallel are connected to end contacts. Fire-clay cement and metallic end caps effectively seal the ends of the cartridge, which is completely filled with a packing medium to damp down the explosive effect of the arc set up on rupture of the fusible elements. The material used for packing of the fuse illustrated is granular quartz; other materials suitable for this purpose are magnesite (magnesium oxide), kieselguhr, and calcium carbonate (chalk). When an overload current condition arises and each element is close to fusing point, the element to go first immediately transfers its load to the remaining elements and they, now being well overloaded, fail in quick succession.

In some transport aircraft, the fuseholders are of the self-indicating type in corporating a lamp and a resistor, connected in such a way that the lamp lights when the fusible element ruptures.

CURRENT LIMITERS

Current limiters, as the name suggests, are designed to limit the current to some pre-determined amperage value. They are also thermal devices, but unlike ordinary fuses they have a high melting point, so that their time/current characteristics permit them to carry a considerable overload current before rupturing. For this reason their application is confined to the protection of heavy-duty power distribution circuits.

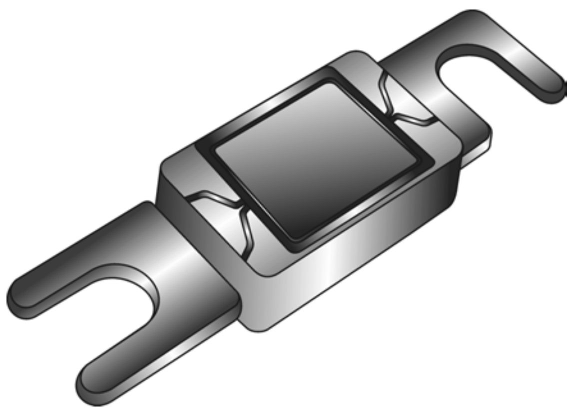


Fig. 7.19. Typical current limiter ("Airfuse").

A typical current limiter (manufactured under the name of "Airfuse") is illustrated in Fig. 7.19. It incorporates a fusible element which is, in effect, a single strip of tinned copper, drilled and shaped at each end to form lug type connections, with the central portion "waisted" to the required width to form the fusing area. The central portion is enclosed by a rectangular ceramic housing, one side of which is furnished with an inspection window which, depending on the type, may be of glass or mica.

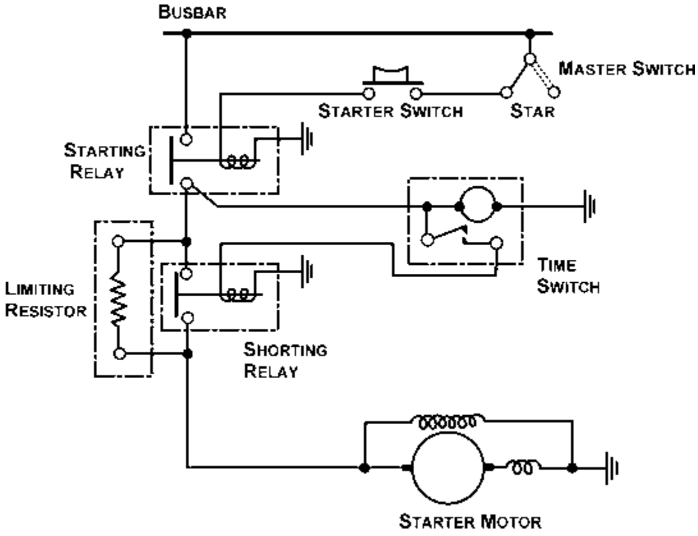


Fig. 7.20. Application of a limiting resistor.

LIMITING RESISTORS

These provide another form of protection particularly in d.c. circuits in which the initial current surge is very high, e.g. starter motor and inverter circuits, circuits containing highly-capacitive loads. When such circuits are switched on they impose current surges of such a magnitudes as to lower the voltage of the complete system for a time period, the length of which is a function of the time response of the generating and voltage regulating system. In order therefore to keep the current surges within limits, the starting sections of the appropriate circuits incorporate a resistance element which is automatically connected in series and then shorted out when the current has fallen to a safe value.

Fig.7.20 illustrates the application of a limiting resistor to a turbine engine starter motor circuit incorporating a time switch; the initial current flow may be as high as 1500 A. The resistor is shunted across the contacts of a shorting relay which is controlled by the time switch. When the starter push switch is operated, current from the busbar flows through the coil of the main starting relay, thus energizing it. Closing of the relay contacts completes a circuit to the time switch motor, and also to the starter motor via the limiting resistor which thus reduces the peak current and initial starting torque of the motor. After a pre-determined time interval, which allows for a build-up of engine motoring speed, the torque load on the starter motor decreases and the time switch operates a set of contacts which complete a circuit to the shorting relay. As will be clear from Fig.7.20, with the relay energized the current from the busbar passes direct to the starter motor, and the limiting resistor is shorted out. When ignition takes place and the engine reaches what is termed "self-sustaining speed", the power supply to the starter motor circuit is then switched off.

CIRCUIT BREAKERS

Circuit breakers, unlike fuses or current limiters, isolate faulted circuits and equipment by means of a mechanical trip device actuated by the heating of a bi-metallic element through which the current passes to a switch unit. We may therefore consider them as being a combined fuse and switch device. They are used for the protection of cables and components and, since they can be reset after clearance of a fault, they avoid some of the replacement problems associated with fuses and current limiters. Furthermore, close tolerance trip time characteristics are possible, because the linkage between the bi-metal element and trip mechanism may be adjusted by the manufacturer to suit the current ratings of the element. The mechanism is of the "trip-free" type, i.e. it will not allow the contacts of the switch unit to be held closed while a fault current exists in the circuit.

The factors governing the selection of circuit breakers rating and locations, are similar to those already described for fuses.

The design and construction of circuit breakers varies, but in general they consist of three main assemblies; a bi-metal thermal element, a contact type switch unit and a mechanical latching mechanism. A push-pull button is also provided for manual resetting after thermal tripping has occurred, and for manual tripping when it is required to switch off the supply to the circuit of a system. The construction and operation is illustrated schematically in Fig.7.21. At (a) the circuit breaker is shown in its normal operating position; current passes through the switch unit contacts and the thermal element, which thus carries the full current supplied to the load being protected. At normal current values heat is produced in the thermal element, but is radiated away fairly quickly, and after an initial rise the temperature remains constant. If the current should exceed the normal operating value due to a short circuit, the temperature of the element begins to build up, and since metals comprising the thermal elements have different

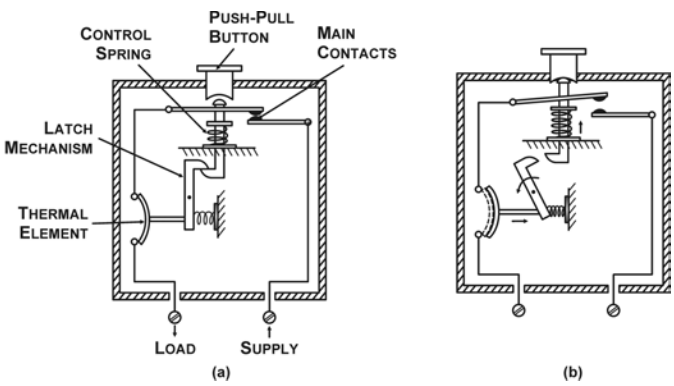


Fig.7.21. Schematic diagram of circuit breaker operation.
(a) Closed (b) Tripped condition

coefficients of expansion, the element becomes distorted as indicated in Fig.7.21 (b). The distortion eventually becomes sufficient to release the latch mechanism and allows the control spring to open the switch unit contacts, thus isolating the load from the supply. At the same time, the push-pull button extends and in many types of circuit breaker a white band on the button is exposed to provide a visual indication of the tripped condition.

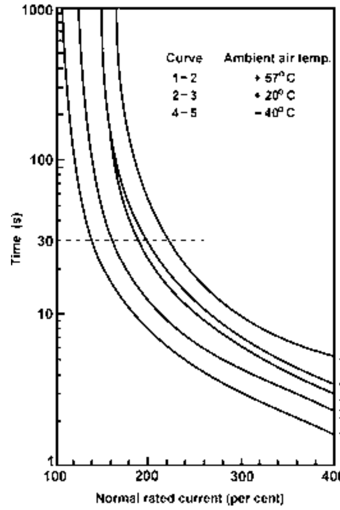


Fig.7.22. Characteristics curves of a typical breaker tripping times

The temperature rise and degree of distortion produced in the thermal element are proportional to the value of the current and the time for which it is applied. The ambient temperature under which the circuit breaker operates also has an influence on circuit breaker operation and this, together with operating current values and tripping times, is derived from characteristic curves supplied by the manufacturer. A set of curves for a typical 6 A circuit breaker is shown in Fig. 7.22. The current values are expressed as a percentage of the continuous rating of the circuit breaker, and the curves are plotted to cover specified tolerance bands of current and time for three ambient temperatures. If, for example, the breaker was operating at an ambient temperature of +57°C, then in say 30 seconds it would trip when the load current reached a value between 140 and 160 percent of the normal rating, i.e. between 8.4 and 9.6 A. At an ambient temperature of +20°C it would trip in 30 seconds at between 160 and 190 percent of the normal rating (between 9.6 and 11.4 A) while at -40°C the load current would have to reach a value between 195 and 215 percent of the normal rating (between 11.7 and 12.9 A) in order to trip in the same time interval.

After a circuit breaker has tripped, the distorted element begins to cool down and reverts itself and the latch mechanism back to normal, and once the fault which caused tripping has been cleared, the circuit can again be completed by pushing in the circuit breaker button. This "resetting" action closes the main contacts and re-engages the push -button with the latch mechanism. If it is required to isolated the power supply to a circuit due to a suspected fault, or during testing, a circuit breaker may be used as a switch simply by pulling out the button. In some designs a separate button is provided for this purpose.

The external appearance of two typical single-pole, single-throw "trip-free" circuit breakers is illustrated in Fig. 7.23. The circuit breaker shown at (b) incorporates a separate manual trip push button. A cover may sometimes be fitted to prevent inadvertent operation of the button.

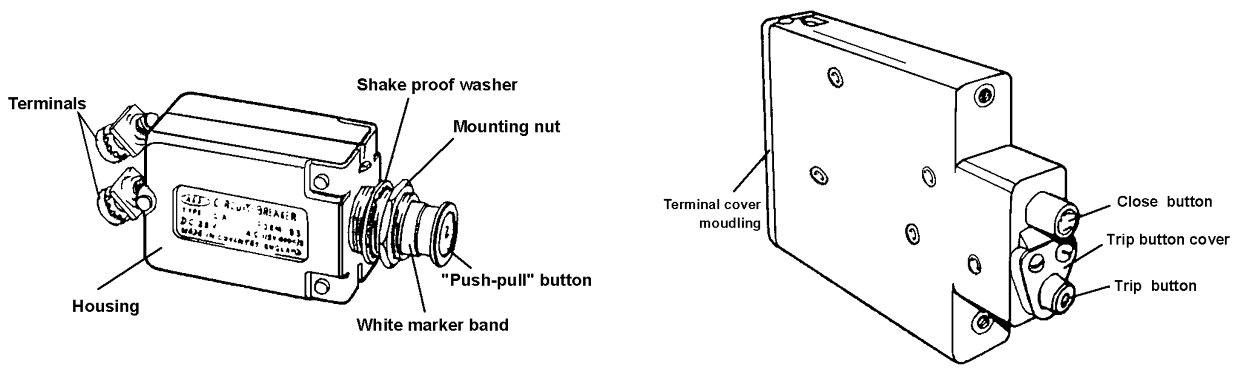


Fig.7.23. Circuit breakers (a) Typical (b) Circuit breaker with a "manual trip" button.

In three-phase a.c. circuits, triple-pole circuit breakers are used, and their mechanisms are so arranged that in the event of a fault current in any one or all three of the phases, all three poles will trip simultaneously. Similar tripping will take place should an unbalanced phase condition develop as a result of a phase becoming "open-circuited". The three trip mechanisms actuate a common push-pull button.

PROTECTION AGAINST REVERSE CURRENT

In all types of electrical systems the current flow is, of course from the power source of the distribution busbar system and finally to the power consuming equipment; the interconnection throughout being made by such automatic devices as voltage regulators and control units, and by manually controlled switches. Under fault conditions, however, it is possible for the current flow to reverse direction, and as this would be of detriment to a circuit and associated equipment, it is therefore necessary to provide some automatic means of protection. In order to illustrate the fundamental principles we may consider two commonly used methods, namely reverse current relays and reverse current circuit breakers.

Reverse Current Cut-Out Relay

A reverse current cut-out relay is used principally in a d.c. generating system either as a separate unit or as part of a voltage regulator. The circuit arrangement, as applied to the generating system typical of several types of small aircraft, is shown in Fig.7.24. The relay consists of two coils wound on a core and a spring-controlled armature and contact assembly. The shunt winding is made up of many turns of fine wire connected across the generator so that voltage is impressed on it at all times. The series winding, of a few turns of heavy wire, is in series with the main supply line and is designed to carry the entire line current. The winding is also connected to the contact assembly, which under static conditions is held in the open position by means of a spring.

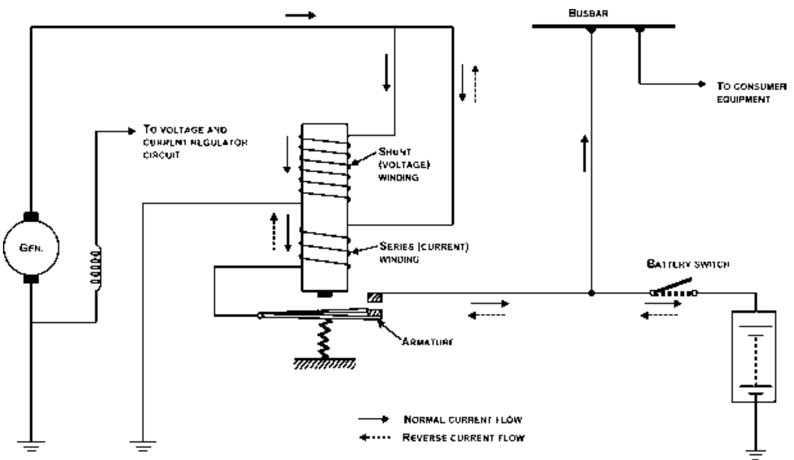


Fig. 7.24. Reverse current cut-out operation.

When the generator starts operating and the voltage builds up to a value which exceeds that of the battery, the shunt winding of the relay produces sufficient magnetism in the core to attract the armature and so close the contacts. Thus the relay acts as an automatic switch to connect the generator to the busbar, and also to the battery so that it is supplied with charging current. The field produced by the series winding aids the shunt-winding field in keeping the contacts firmly closed.

When the generator is being shut down or, say, a failure in its output occurs, then the output falls below the battery voltage and there is a momentary discharge of current from the battery; in other words, a condition of reverse current through the cut-out relay series winding is set up. As this also causes a reversal of its magnetic field, the shunt winding-field will be opposed, thereby reducing core magnetization until the armature spring opens the contacts. The generator is therefore switched to the "off-line" condition to protect it from damaging effects which would otherwise result from "motoring" current discharging from the battery.

Switched Reverse Current Relay

This relay is adopted in d.c. generator systems of some types of small aircraft, its purpose being to permit switching of a generator on to the main bus-bar, and at the same time retain the disconnect function in the event of reverse current The circuit arrangement is shown in Fig. 7.25.

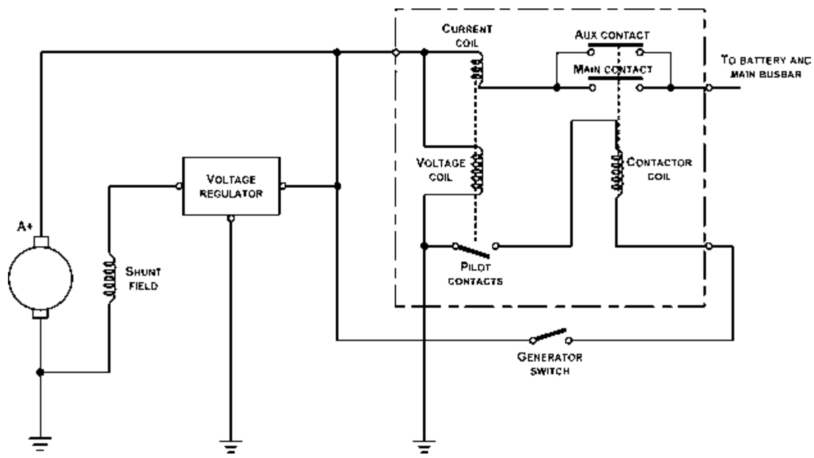


Fig. 7.25. Switched reverse current relay.

In addition to a current coil the relay has a voltage coil, and a pair of contacts actuated via a contactor coil. When the voltage output is at a regulated value, the current through the voltage coil is sufficient to actuate its contacts which then connect the generator switch and contactor coil to ground. The contactor coil is thus energized from the A+ output of the generator and so the auxiliary and main contacts close to connect the generator output to the battery and main busbar. The magnetic effect of the current passing through the current coil assists that of the voltage coil in keeping the pilot contacts closed.

During engine shut-down, the generator output voltage decreases thereby initiating a reverse current condition, and because the magnetic effect of the current through the current coil now oppose that of the voltage coil, the pilot contacts open to de-energize the contactor coil; thus, the main and auxiliary contacts are opened to disconnect the generator from the battery and main busbar.

Reverse Current Circuit Breakers

These circuit breakers are designed to protect power supply systems and associated circuit against fault currents of a magnitude greater than those at which cut-outs normally operate. Furthermore, they are designed to remain in a "locked-out" condition to ensure complete isolation of a circuit until a fault has been cleared.

An example of a circuit breaker designed for use in a d.c. generating system is shown in (Fig.7.26). It consists of a magnetic unit, the field strength and direction of which are controlled by a single-turn coil connected between the generator positive output and the busbar via a main contact assembly. An auxiliary contact assembly is also provided for connection in series with the shunt-field winding of the generator. The opening of both contact assemblies is controlled by a latching mechanism actuated by the magnet unit under heavy reverse current conditions. In common with other circuit breakers, resetting after a tripping operation has to be done manually, and is accomplished by a lever which is also actuated by the laching mechanism. Visual indication of a tripped condition is provided by a coloured indicator flag which appears behind a window in the circuit breaker cover. Manual tripping of the unit is effected by a push-button adjacent to the resetting lever.

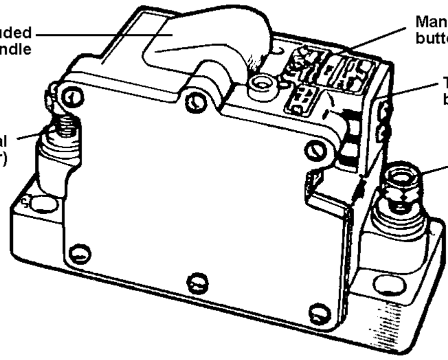


Fig. 7.26. Reverse current circuit breaker.

Fig.7.27 is based on the circuit arrangement of a d.c. generating system used in a particular type of aircraft, and is an example of the application of a reverse current circuit breaker in conjunction with a cut-out relay. Unlike the circuit shown in (Fig.7.24), the relay controls the operation of a line contactor connected in series with the coil of the reverse current circuit breaker. Under normal current flow conditions closing of the relay energizes the line contactor, the heavy-duty contacts of which connect the generator output to the busbar via the coil and main contacts of the normally closed reverse current circuit breaker. The magnetic field set up by the current flow assists that of the magnet unit, thus, maintaining the breaker contacts in the closed position. The generator shunt field circuit is supplied via the auxiliary contacts.

When the generator is being shut down, or a failure of its output occurs, the reverse current resulting from the drop in output to a value below that of the battery flows through the circuit as indicated, and the cut-out relay is operated to de-energize the line contactor which takes the generator "off line". Under these conditions the reverse current circuit breaker will remain closed, since the current magnitude is much lower than that at which a specific type of breaker is normally rated (some typical ranges are 200-250 A and 850-950 A).

Let us consider now what would happen in the event of either the cut-out relay or the line contactor failing to open under the above low magnitude reverse current conditions, e.g. contacts have welded due to wear and excessive arcing. The reverse current would feed back to the generator, and in addition to its motoring effect on the generator, it would also reverse the generator field polarity. The reverse current passing through the circuit breaker coil would continue to increase in trying to overcome mechanical loads due to the engine and generator coupling, and so the increasing reverse field reduces the strength of the magnet unit. When the reverse current reaches the pre-set trip value of the circuit breaker, the field of the magnet unit is neutralized and repelled, causing the latch mechanism to release the main and auxiliary contacts to completely isolate the generator from the busbar. The breaker must be reset after the circuit fault has been cleared.

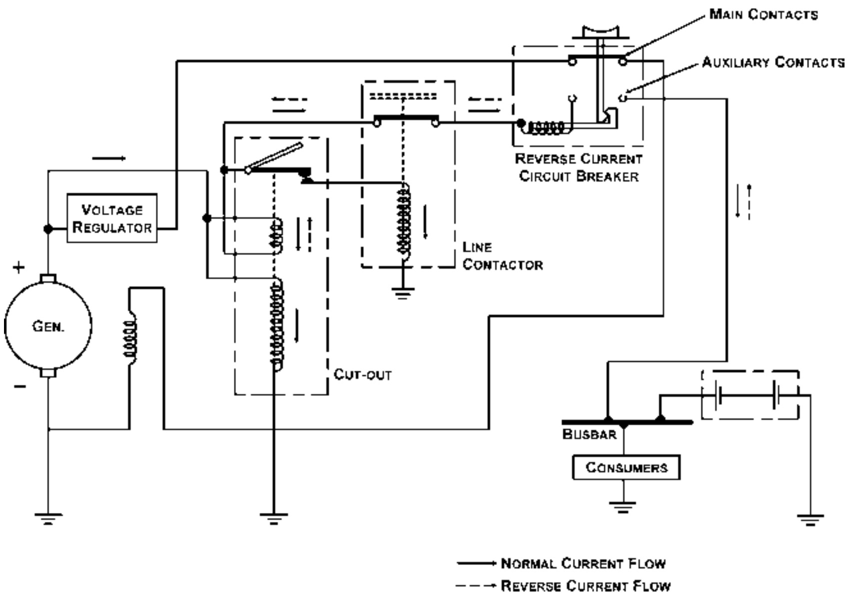


Fig. 7.27. Reverse current circuit breaker operation.

The circuit breaker embodies a spring loaded contact assembly which is closed manually by a setting handle and is then held in this condition by a latch assembly. The controlled generator is then connected to the busbar through a series connection consisting of the main contacts and a single turn coil. The main contacts open to disconnect the generator from the busbar when the latch assembly is released; this action is performed by the displacement of a trip lever, which in turn is operated either manually (by pressing the trip button), by remote control through the attracted armature electromagnet system or automatically when a reverse current condition ,of sufficient magnitude and duration ,develops in the single turn coil. After tripping by an as shown in (Fig. 7.28) of these methods, the circuit beaker must be reset by operating the setting handle.

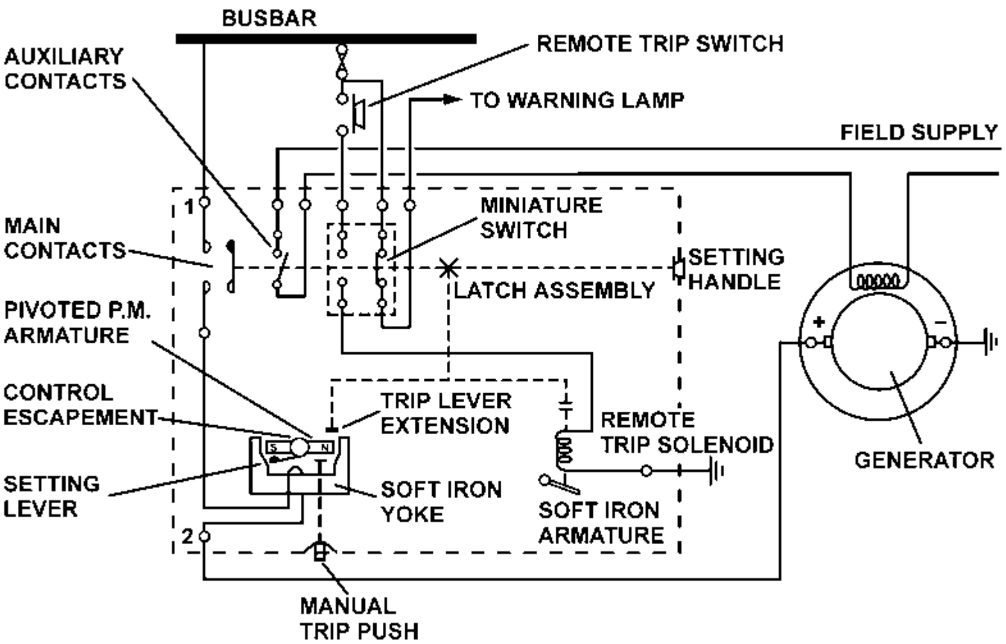


Fig. 7.28. Reverse Current Circuit Breaker Operation.

OVERVOLTAGE PROTECTION

Overvoltage is a condition which could arise in a generating system in the event of a fault in the field excitation circuit, e.g. internal grounding of the field winding or an open-circuit in the voltage regulator sensing lines. Devices are therefore necessary to protect consumer equipment against voltages higher than those at which they are normally designed to operate. The methods adopted vary between aircraft systems and also on whether they supply d.c. or a.c. An example of an overvoltage relay method applied to one type of d.c. system is shown in (Fig.7.29).

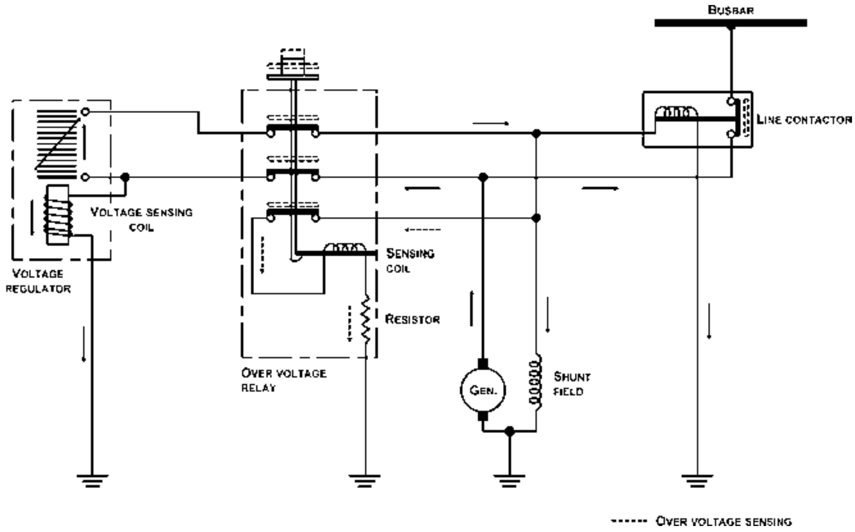


Fig. 7.29. Overvoltage protection d.c. generating system.

The relay consists of a number of contacts connected in all essential circuits of the generator system, and mechanically coupled to a latching mechanism. This mechanism is electromagnetically controlled by a sensing coil and armature assembly, the coil being connected in the generator shunt-field circuit and in series with a resistor, the resistance of which decreases as the current through it is increased. Under normal regulated voltage conditions, the sensing coil circuit resistance is high enough to prevent generator shunt-field current from releasing the relay latch mechanism, and so the contacts remain closed and the generator remains connected to the busbar. If, however, an open circuit occurs in the regulator voltage coil sensing line, shunt-field current increases and, because of the inverse characteristics of the relay sensing coil resistor, the electromagnetic field set up by the coil causes the latch mechanism to release all the relay contacts to the open position, thereby isolating the system from the busbar. After the fault has been cleared, the contacts are reset by depressing the push button.

The overvolt unit comprises two relay coils. One having a pair of normally closed contacts and the other, a pair of normally open contacts. The generator field supply passes via the normally closed contacts to the voltage regulator. Should the generator output voltage rise to a pre-determined value both relay coils become energised via the resistor; opening the generator field circuit causing the generator output to fall to zero, while a permanently connected battery supply will hold on the overvolt relays via the now closed set of contacts.

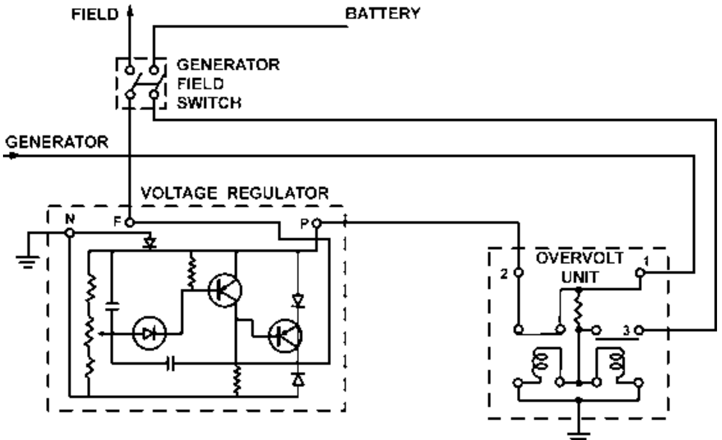


Fig. 7.30. Over voltage protection (D.C.)

To reset the system, the generator field switch should first be selected to the OFF position which will reset the generator field circuit so that the generator may be brought on line by returning the field switch to the ON position. If the cause of the overvoltage condition still exists the generator will automatically be tripped off again and no further attempt at resetting should be made until the cause has been established and rectified.

A.C. Supply Systems

A typical method of overvoltage protection, as used in an a.c. power supply system utilising magnetic amplifiers for the control and protection, is illustrated in (Fig.7.31). The circuit is formed by the combination of a single-phase magnetic amplifier and a rectifier bridge, the output of which is applied to the operating coil of a protection relay. The a.c. winding of the magnetic amplifier are normally supplied from a supply and reference transformer, while a voltage sensing network is used in conjunction with the control winding.

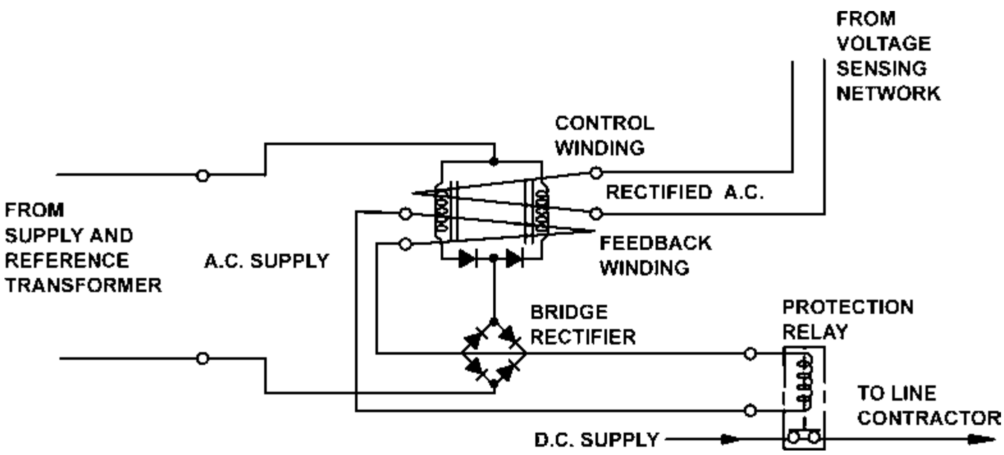


Fig. 7.31. Over voltage protection (A.C.)

At the nominal supply voltage the circuit is adjusted so that the protection relay is de-energised; with an increase of supply voltage, the magnetic amplifier saturates and energises the protection relay which interrupts the d.c. supply to the hold-in circuit of a line contactor which then disconnects the generator from the busbar. At the same time, the main control unit interrupts the supply to the generator field, causing its output to collapse to zero.

An overvoltage protection system adopted in one example of a constant frequency (non-paralleled) a.c. generating system is shown in basic form in (Fig. 7.32).

The detector utilizes solid-state circuit elements which sense all three phases of the generator output, and is set to operate at a level greater than 130 ± 3 volts. An overvoltage condition is an excitation-type fault probably resulting from loss of sensing to, or control of, the voltage regulator such that excessive field excitation of a generator is provided.

The signal resulting from an overvoltage is supplied through an inverse time delay to two solid-state switches. When switch S_1 is made it completes a circuit through the coil of the generator excitation field circuit. The other contact closes and completes a circuit to the generator breaker trip relay, this in turn, de-energizing the generator breaker to disconnect the generator from the busbar. At the same time, the main control unit interrupts the supply to the generator field, causing its output to collapse to zero.

An overvoltage protection system adopted in one example of a constant frequency (non-parallel) a.c. generating system is shown in basic form in (Fig.7.32).

The detector utilizes solid-state circuit elements which sense all three phases of the generator output, and is set to operate at a level greater than 130±3 volts. An overvoltage condition is an excitation-type fault probably resulting from loss of sensing to, or control of, the voltage regulator such that excessive field excitation of a generator is provided.

The signal resulting from an overvoltage is supplied through an inverse time delay to two solid-state switches. When switch S_1 is made it completes a circuit through the coil of the generator control relay, one contact of which opens to interrupt the generator excitation field circuit. The other contact closes and completes a circuit to the generator breaker trip relay, this in turn, de-energizing the generator breaker to disconnect the generator from the busbar. The making of solid-state switch S_2 energizes the light relay causing it to illuminate the annunciator light which is a white one in the actual system on which (Fig.7.32) is based. The purpose of the inverse time delay is to prevent nuisance tripping under transient conditions.

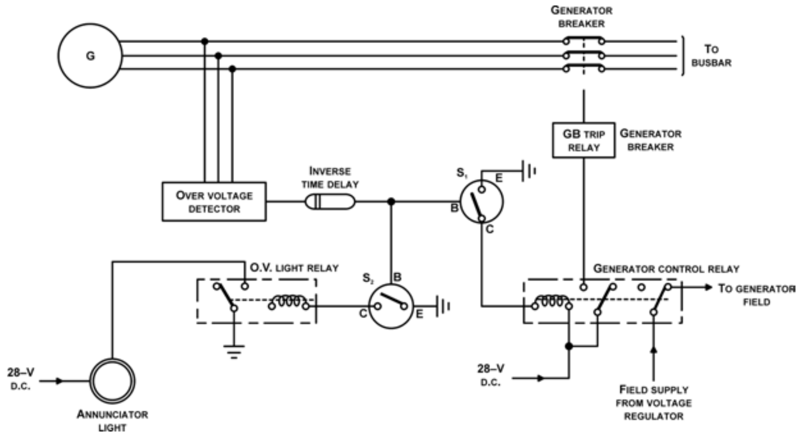


Fig. 7.32. Overvoltage protection (constant frequency system).

UNDERVOLTAGE PROTECTION

1. **General.** Undervoltage occurs in the course of operation when a generator is being shut down, and reverse current flow from the battery to the generator is a normal indication of this condition.

2. **D.C. Supply System.** In a single d.c. generator power supply system, additional undervoltage protection is not essential since the reverse current is sensed and checked by the reverse current cut-out relay.

3. In a multi-generator system additional protection is required and usually takes the form of a polarized relay designed to be energised by a voltage rising to a pre-determined level and to be de-energised as the voltage falls approximately 2 volts below that level. A typical circuit, as used on a twin-engined light aircraft, is illustrated in (Fig.7.33).

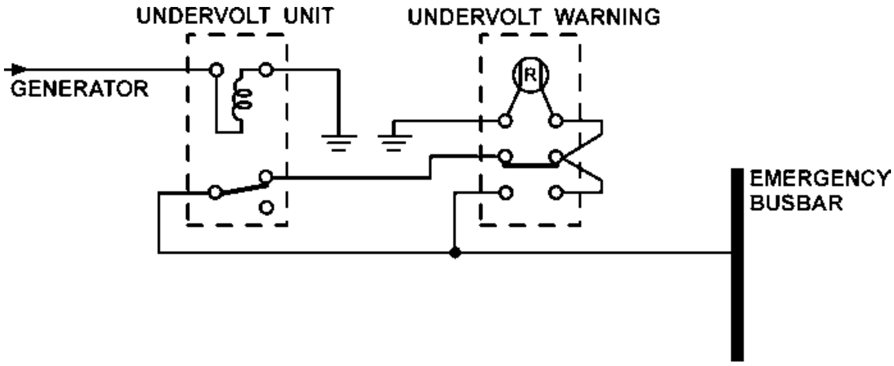


Fig.7.33. O.

4. The undervolt relay is energised by the generator supply through the generator field switch, and a warning light is connected in series with the normally closed contacts of the unit. When the engine and generator is at rest, or the generator isolated or fault, the undervolt unit will be de-energised and the warning light illuminated.

In a constant frequency a.c. system, considering the case of the one referred, the circuit arrangement for undervoltage protection is similar in many respects to that shown in (Fig. 7.), since it must also trip the generator control relay, the generator breaker, and must also annunciate the condition. The voltage level at which the circuit operates is less than 100±3 volts. A time delay is also included and is set at 7±2 seconds; its purpose being to prevent tripping due to transient voltages, and also to allow the CSD to slow down to an underfrequency condition on engine shutdown and so inhibit tripping of the generator control relay.

When generators are operating in parallel, under-voltage protection circuits are allied to reactive load-sharing circuits.

OVER-EXCITATION AND UNDER-EXCITATION PROTECTION

Over-excitation and under-excitation are conditions which are closely associated with those of overvoltage and undervoltage, and when generators are operating in parallel, the conditions are also associated with reactive current. Protection is therefore afforded by a mixing circuit. If the reactive current is the same in the generators paralleled, there will be no output from the circuit. When an unbalance occurs, e.g. a generator is over-excited, voltages will be produced in both over-excitation and under-excitation sections of the circuit, and these voltages will be fed to the overvoltage and undervoltage circuits. As a result, the overvoltage circuit will be biased down so that it will trip the generator breaker at a lower level. The undervoltage circuit will also be biased down so that it will trip the breaker at a lower voltage. Since the overall effect of over-lower voltage. Since the overall effect of over-excitation is to raise the busbar voltage then the overvoltage circuit provides the protective function.

With an under-excited generator, the voltages fed to the overvoltage and undervoltage circuits cause the biasing to have the opposite effect to over-excitation. Since under-excitation lowers the busbar voltage, then the undervoltage circuit provides the protective function.

UNDERFREQUENCY AND OVERFREQUENCY PROTECTION

Protection against these faults applies only to a.c. generating systems and is usually effected by the real load-sharing circuit of a generating system.

DIFFERENTIAL CURRENT PROTECTION

The purpose of a differential current protection system is to detect a short-circuited feeder line or generator busbar which would result in a very high current demand on a generator, and possibly result in an electrical fire. Under these conditions, the difference between the current leaving the generator and the current arriving at the busbar is called a differential fault or a feeder fault. In an a.c. system, current comparisons are made phase for phase, by two three-phase current transformers, one on the ground or neutral side of the generator (ground DPCT) and the other (the load DPCT) on the down-stream side of the busbar. (Fig.7.34) illustrates the arrangement and principle of a system as applied to a single-phase line.

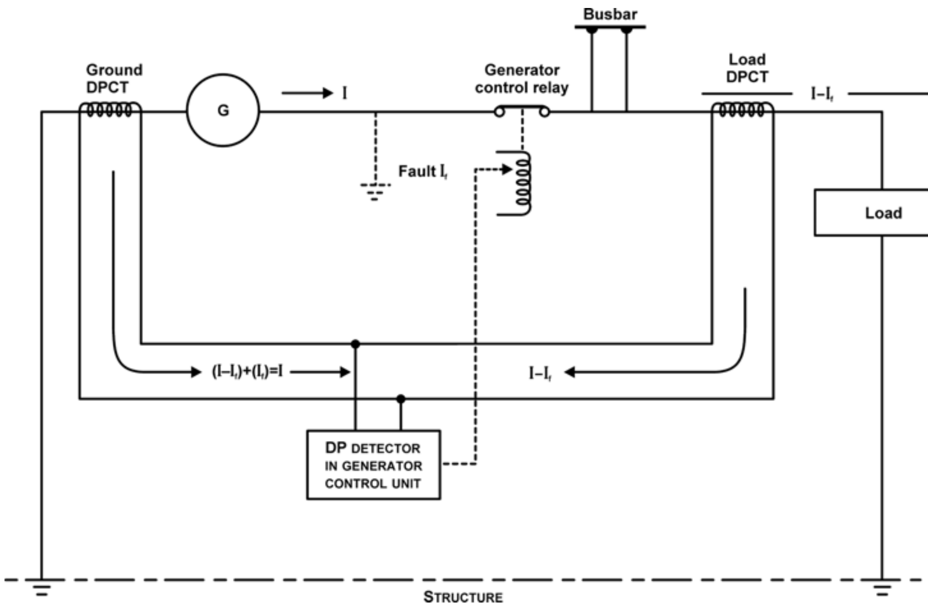


Fig.7.34. Differential current protection.

If the current from the generator is I, and the fault current between the generator and busbar equals I_f, then the net current at the busbar will be equal to I - I_f. The fault current will flow through the aircraft structure and back to the generator through the ground DPCT. The remainder of the current I - I_f, will flow through the load DPCT, the loads, the aircraft structure, and then back to the generator via the ground DPCT. Thus, the ground DPCT will detect the generator's total current (I - I_f) + (I_f) which is equal to I, and the load DPCT will detect I - I_f.

If the difference in current (i.e. the fault current) between the two current transformers on the phase line is sensed to be greater than the specified limit (20 or 30 amperes are typical values) a protector circuit within a generator control unit will trip the generator control relay.

MERZ-PRICE PROTECTION SYSTEM

This system is applied to some a.c. generating systems to provide protection against faults between phases or between one of the phases and ground. The connections for one phase are shown in Fig.7.35 ; those for other phases (or other feeders in a single-phase system) being exactly the same. Two similar current transformers are connected to the line, one

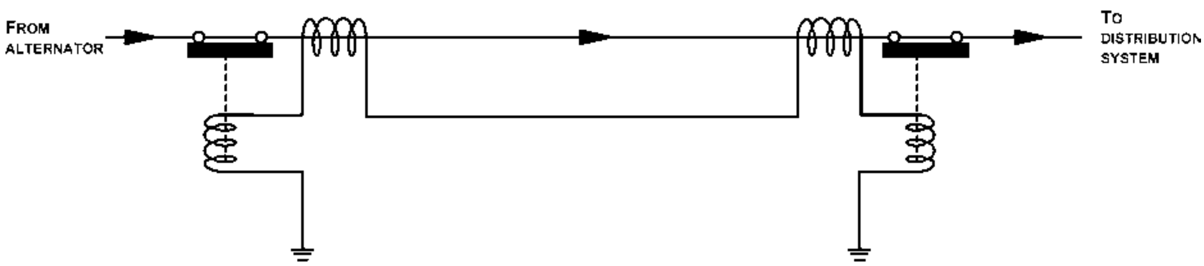


Fig.7.35. Merz-Price protection system.

at each end, and their secondary windings are connected together via two relay coils. Since the windings are in opposition, and as long as the currents at each end of the line are equal, the induced e.m.f's are in balance and no current flows through the relay coils. When a fault occurs, the fault current creates an unbalanced condition causing current to flow through the coils of the relays thereby energizing them as to open the line at each end.

MAINTENANCE PRACTICES

The method of installing the principal protection devices of aircraft electrical circuits, and the carrying out of the relevant maintenance procedures, will vary between types of aircraft. For precise details of any particular aircraft, reference should be made to the Maintenance Manual and Wiring Diagram Manual for the aircraft concerned. Certain aspects are, however, of a general nature and the information given in the following paragraphs is intended only as a general guide.

General Precautions

On aircraft which have three-phase a.c. primary power supply, the voltage potential between phases is 200 volts RMS and can be lethal. Therefore, before carrying out any maintenance on the aircraft's electrical power supply and distribution system, it should be ensured that the system is de-energised and that no external supplies are connected to the aircraft.

To eliminate the possibility of damage to equipment or the structure of the aircraft by the shorting of live terminals to earth, and before removing any circuit protection device, it should be ensured that all electrical power is off, by disconnecting ground power supplies and the aircraft batteries. Notices should be prominently displayed adjacent to the ground power plugs and aircraft battery connections stating that electrical power supplies are not to be connected.

Sufficient time must always be allowed for the thermal element to cool adequately before attempting to reset a circuit breaker which has tripped on overload. If the breaker trips again shortly after resetting, it must be assumed that a fault condition exists, so further attempts at resetting should not be made until the fault has been investigated and cleared.

Checking of Components

Whenever the serviceability of a protection device is suspect, or at specific inspection periods, components should be subjected to the following checks :-

a. Check component for proper installation, security of attachment, physical damage, and for evidence of overheating.
b. Check that electrical connections are secure and free from contamination.
c. Check all wiring for physical damage such as chafing, fraying or cut insulation.

Removal/Installation

Procedures for the less complex protection devices, such as fuse-holders and circuit breakers, will usually be provided within the relevant aircraft Wiring Diagram Manual. Procedures for the more complex units, Such as reverse current cut-out relays and reverse current circuit breakers, will be in the relevant aircraft Maintenance Manual. The information given in the following paragraphs is intended only as a general guide to the safety precautions that should be observed.

Following removal of circuit protection devices, and where replacements are not readily available, to ensure that the aircraft remains electrically safe, all exposed terminations on cables should be covered with insulating boots or tubing. In addition, all plugs and sockets should be protected with plastic, or equivalent, dust caps to prevent damage to pins and the possible ingress of moisture or foreign matter. Electrical power supplies may then be re-connected to the aircraft power distribution system to permit operation of other services.

Power Supplies for Testing

Power supplies for the testing and ground operation of aircraft electrical systems should be those obtainable from either ground supply sources or the auxiliary power supply of the aircraft. Use of the aircraft battery power supply should be severely restricted. Before applying external power to an aircraft distribution system, it should be ascertained that all associated switches located in the crew compartment, on the ground power control panel and on the cabin ground service panel, as applicable, are selected to the off, normal or open position as required.

Damage to the equipment of the aircraft can occur if the electrical power supply circuits have been subjected to an abnormally high or abnormally low voltage, extreme frequency variations or to the application of incorrect phase rotation.

Prior to carrying out any functional tests or adjustment procedures, it should be ensured that all applicable fuses have been refitted and circuit breakers reset. Relevant warning notices should be removed.

■■■

CHAPTER - 8
AIRCRAFT BATTERIES
KNOWLEDGE OF THE CONSTRUCTION AND PRINCIPLE OF OPERATION OF LEAD-ACID AND NICKEL-CADMIUM BATTERIES, COMPOSITION OF ELECTROLYTES AND PLATES. KNOWLEDGE OF THE EFFECT RESISTIVITY, CHARGER AND DISCHARGER RATES, EFFECTS OF SPECIFIC GRAVITY ON FREEZING TEMPERATURE AND RESISTIVITY OF ELECTROLYTES. KNOWLEDGE OF METHODS OF CHARGING OF BATTERIES, PRECAUTIONS AND PROCEDURES DURING CHARGING, MIXING AND NEUTRALIZATION OF ELECTROLYTES, IMPORTANCE OF VENTILATION OF BATTERY COMPARTMENTS.

GENERAL CONSTRUCTION

Lead-acid batteries vary in type principally in the thickness of their plates and the type of separators employed. In the conventional type, groups of positive plates, negative plates and separators, are assembled in such a way that the electrolyte solution of sulphuric acid and distilled water can flow freely around the plates. In some types of battery however, the plates and separators are compressed to form a solid block, the separator material being such that it absorbs electrolyte and leaves only a small amount free above the block.

The cell groups are located within containers made of a shock-resistant and acid-resistant material, e.g., polystyrene, and are linked by terminal connecting strips. Vents and plugs are fitted to each cell and are designed to allow gas to escape without leakage of electrolyte. In batteries utilising solid block type cells, the cells are grouped into single blocks (e.g. a 24-volt battery has two single blocks each comprising six individual cells) and are usually enclosed within a polyester bonded fibreglass outer container which also supports the main terminal receptacle.

CHEMICAL PRINCIPLE

During charging the active material on the positive plates of a cell is converted to lead peroxide and the material on the negative plates to spongy or porous lead. Sulphuric acid is returned to the electrolyte during the charge, gradually strengthening it until the fully charged state is reached. In the charged condition and after a battery has been standing for a specified time (e.g. 8 hours) the open circuit voltage of a cell should be 2.10 to 2.20 volts.

When discharging, both the positive and the negative plates are partially converted to lead sulphate. The sulphuric acid is diluted as part of the process by the formation of water. If lead sulphate in a more permanent form is produced on the plates due to excessive discharge, or other misuse, this will act as a high-resistance component impairing the efficiency and recoverability of the battery.

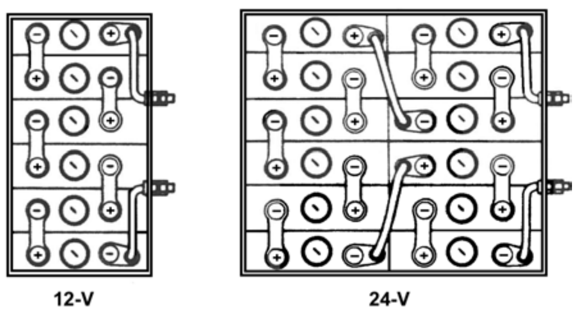


Fig. 8.1. Arrangement of cells in a lead acid storage battery.

Lead-Acid Battery Construction

A storage battery consists of a group of lead-acid cells connected in series and arranged somewhat as shown in (Fig. 8.1). Under moderate load the closed circuit voltage

(CCV) of the 6-cell battery is approximately 12V, and that of a 12-cell battery is about 24 V. As stated earlier, CCV is the voltage of the battery when connected to a load.

	CHARGED STATE	CHEMICAL CHARGE	DISCHARGE
POSITIVE PLATE	PbO_2	LOOSES O_2 GAINS SO_4	$PbSO_4$
NEGATIVE PLATE	Pb	GAINS SO_4	$PbSO_4$
ELECTROLTE	H_2SO_4	LOOSES SO_4 GAINS O_2	H_2O

Fig.8.2. Chemical changes of a lead-acid battery during charge and discharge.

Each cell of a storage battery has positive and negative plates arranged alternately and insulated from each other by separators. Each plate consists of a framework, called the **grid**, and the **active material** held in the grid. A standard formula for the grid material is 90 percent lead and 10 percent antimony. The purpose of the antimony is to harden the lead and make it less susceptible to chemical action. Other metals, such as silver, are also used in some grids to increase their durability.

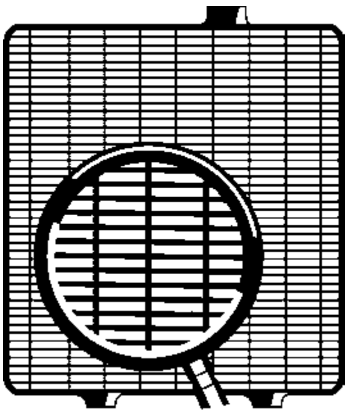


Fig.8.3.Grid for a lead-acid cell plate.

A typical grid is illustrated in (Fig. 8.3). The heavy border adds strength to the plate, and the small horizontal and vertical bars form cavities to hold the active material. The structural bars also act as conductors for the current, which is distributed evenly throughout the plate. Each plate is provided with extensions, or feet, which rest upon ribs on the bottom of the cell container. These feet are arranged so the positive plates rest upon two of the ribs and the negative plates upon the two alternative ribs. The purpose of this arrangement is to avoid the short-circuiting that could occur as active material is shed from the plates and collects at the bottom of the cell.

The plates are made by applying a lead compound to the grid. The paste is mixed to the proper consistency with diluted sulphuric acid, magnesium sulphate, or ammonium sulphate and is applied to the grid in much the same manner as plaster is applied to a lath wall. The paste for the positive plates is usually made of red lead (Pb_3O_4) and a small amount of litharge (PbO). In the case of the negative plates, the mixture is essentially litharge with a small percentage of red lead. The consistency of the various materials and the manner of combining them have considerable bearing on the capacity and life of the finished battery.

In compounding the negative-plate paste, a material called an **expander** is added. This material is relatively inert chemically and makes up less than I percent of the mixture. Its purpose is to prevent the loss of porosity of the negative material during the life of the battery. Without the use of an expander, the negative material contracts until it becomes quite dense, thus limiting the chemical action to the immediate surface. To obtain the maximum use of the plate material, the chemical action must take place throughout the plate from the surface to the center. Typical expanding materials are lampblack, barium sulphate, graphite, fine sawdust, and ground carbon. Other materials, known as hardness and porosity agents, are sometimes used to give the positive plate desired characteristics for certain applications. One or more manufacturers reinforce the active material of the battery plates with plastic fibers 0.118 to 0.236 in. [3 to 6mm] long. This adds substantially to the active life of the battery.

After the active-material paste is applied to the grids, the plates are dried by a carefully controlled process until the paste is hardened. They are then given a forming treatment in which a large number of positive plates are connected to the positive terminal of a charging apparatus and a like number of negative plates, plus one, are connected to the negative terminal. They are placed in a solution of sulphuric acid and water (electrolyte) and charged slowly over a long period of time. A few cycles of charging and discharging convert the lead compounds in the plates into active material. The positive plates thus formed are chocolate brown in color and of a hard texture. The negative-plate material has been converted into spongy lead of a pearl-gray color. After forming, the plates are washed and dried. They are then ready to be assembled into **plate groups.**

Plate groups are made by joining a number of similar plates to a common terminal post (see Fig. 8.4). The number of plates in a group is determined by the capacity designed, in as much as capacity is determined by the amount (area) of active material exposed to the electrolyte.

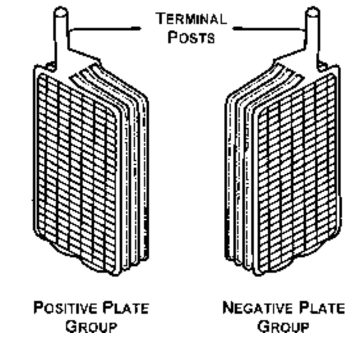


Fig. 8.4. Plate Groups.

Since increasing plate area will increase a battery's capacity, many manufacturers strive for the maximum in internal battery dimensions. That is, if the inside of the battery can be kept as large as possible, the plate area can be increased. To do this, ultrathin plastic cases have been employed to "squeeze" the maximum plate area inside the battery of a given size. It also stands to reason that increasing the battery's outer (and inner) dimensions could be a means to increase capacity. However, for aircraft use, we typically strive for the smallest, lightest battery with a relatively high capacity.

Each plate is made with a lug at the top to which the **plate strap** is fused. A positive-plate group consists of a number of positive plates connected to a plate strap, and a negative group is a number of negative plates connected in the same manner. The two groups meshed together with separators between the positive and negative plates constitute a **cell element** (see Fig. 8.5). It will be noted in the illustrations that there is one less positive plate than negative plates. This arrangement provides protection for the positive plates, inasmuch as they are more subject to warping and deterioration than the negative plates. By placing negative plates on each side of every positive plate, the chemical action is distributed evenly on both sides of the positive plate, and there is less tendency for the plate to wrap.

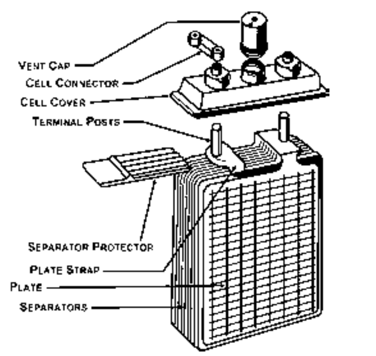


Fig. 8.5. Cell element for a lead-acid cell.

The **separators** used in lead-acid storage batteries are made of fiberglass, rubber, or other insulating materials. Their purpose is to keep the plates separated and thus prevent an internal short circuit. Without separators, even if the containers were slotted to keep the plates from touching, material might flake off the positive plates and fall against the negative plates. Negative material might expand sufficiently to come in contact with the positive plates, or the positive plates might buckle enough to touch the negative plates.

The material of the separators must be very porous so that it will offer a minimum of resistance to the current passing through. The separators are saturated with electrolyte during operation, and it is this electrolyte that conducts the electric current. It is obvious also that the separators must resist the chemical action of the electrolyte.

Glass-wool separators are used by some manufacturers. Fine glass fibers are laid together at different angles and cemented on the surface with a soluble cement. The glass wool is placed in the cell adjacent to the positive plate. Because of the compressibility of glass wool, it comes into very close contact with the positive plate and prevents the loosened active material from shedding. It is claimed that batteries with this type of separator have a longer life than those without it.

Another very effective method for providing plate separation is to enclose the positive plates in microporous polyethylene pouches. This increases the efficiency of the battery because the plates are much closer together, approximately 0.05 in. [1.25mm], than they are with other types of separators. The pouches also prevent the shedding of active material from the positive plates.

When the cell elements are assembled, they are placed in the **cell container,** which is made of hard rubber or a plastic composition. Cell containers are usually made in a unit with as many compartments as there are cells in the battery. In the bottom of the container are four ribs. Two of these ribs support the positive plates, and the other two support the negative plates. This arrangement leaves a space underneath the plates for the accumulation of sediment, thus preventing the sediment from coming in contact with the plates and causing a short circuit. The construction of the cell bottom and of the plate-supporting ribs is shown in (Fig. 8.6).

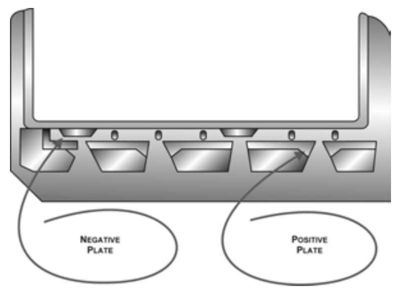


Fig. 8.6. Sediment space in a cell container.

The sediment space provided in storage batteries is of such capacity that it is not necessary to open the cells to clean out the sediment. When the sediment space is full to the point at which the spent material may come in contact with the plates, the cell is worn out.

The assembled cell of a storage battery has a cover made of material similar to that of the cell container. The cell cover is provided with two holes into which is screwed the vented cell cap. When the cover is placed on the cell, it is sealed in with a special sealing compound. This is to prevent spillage and loss of electrolyte.

When a storage battery is on charge and approaching the full-charge point or is at the full-charge point, there is a liberal release of hydrogen and oxygen gases. It is necessary to provide a means whereby these gases can escape, and this is accomplished by placing a vent in the cell cap . This vent contains a lead valve that is so arranged that it will close the vent when the battery is inverted or in any other position at which there is danger of spillage. A vent cap of this type is illustrated within the circles of (Fig. 8.7). Another type of vent system, also illustrated (within the large arrows) in (Fig. 8.7), incorporates a tube that extends almost to the top of the plates. With this type of construction, the battery plates fill only slightly more than one-half the cell container. The space in the top of the container is provided to hold the electrolyte when the battery is on its side or in an inverted position. A baffle plate is placed slightly above the plates to prevent splashing of the electrolyte. A hole in the baffle plate for the escape of gas and for access to the electrolyte is located to one side of the bottom of the gas-escape tube. If the electrolyte level is flush with the baffle plate, the end of the tube will always by above the electrolyte level, regardless of the position of the battery.

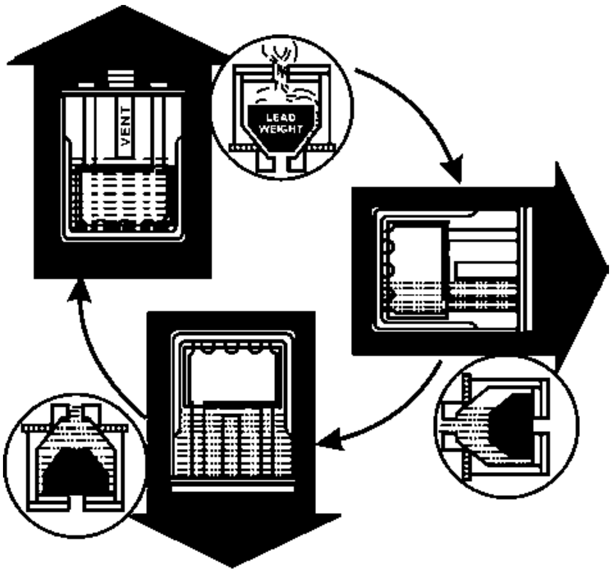


Fig. 8.7. Battery vent caps.

Another type of battery vent contains a sintered alumina (aluminium oxide) plug instead of the heavy lead one used in many other types of batteries. This plug permits the diffusion of gases through it without letting fluids pass. It is much smaller and lighter than the lead-valve plug; hence it saves both weight and space. The construction of this plug is illustrated in (Fig. 8.8).

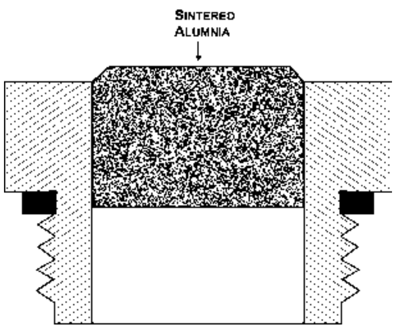


Fig. 8.8. Vented plug with a sintered alumina varrier.

A battery vent cap that is particularly well adapted to acrobatic and military aircraft is shown in (Fig. 8.9). As shown in the drawing, there is a valve in the bottom of the unit, and this valve is opened and closed by the action of the conical weight in the upper part of the cap. When the battery is tilted approximately 45^{o}, the weight drops against the side of the cap, pulling up on the valve stem and closing the valve. When the battery is brought back to a position approximately 32^{o} from vertical, the weight centers itself again, allowing the valve stem to lower and open the vent valve.

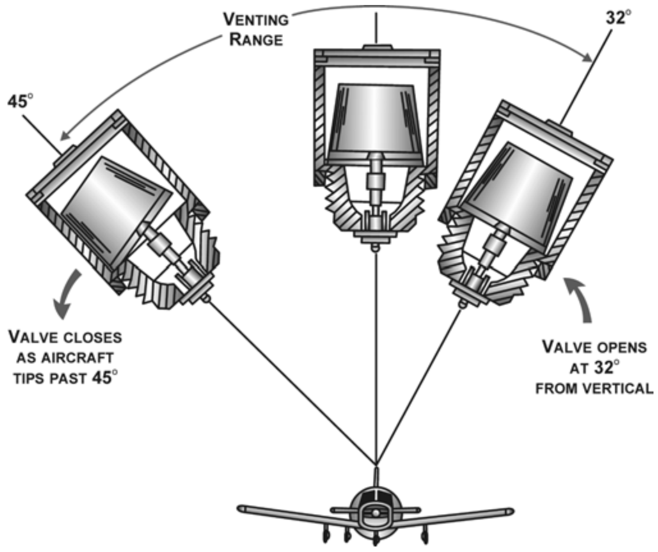


Fig. 8.9. Vented cell cap for acrobatic aircraft. (Teledyne Battery Products).

MAINTENANCE

The information given in the following paragraphs is intended to serve as a general guide to maintenance practice and precautions to be observed. Precise details concerning a specific type of battery are given in the relevant manuals and approved Maintenance Schedules, and reference must be made to such documents.

Safety Precautions

Lead-acid batteries must be prepared for service, charged, tested, and generally maintained, in a well ventilated workshop area entirely separate from that used for the servicing of nickel-cadmium batteries. This also applies to servicing and test equipment, tools and protective clothing, all of which should be identified as being for use in lead-acid battery servicing only.

Alkaline solutions must not be allowed to come into contact with batteries, otherwise severe damage to cells will result.

When handling batteries, or acid, a rubber apron and rubber gloves should be worn; in addition, when dealing with acid, goggles should be worn. After use, these articles should be rinsed free of acid and dried thoroughly. To avoid cracking, or perishing, they should be stored in a cool place, the aprons being hung with as few folds as possible. The gases given off by batteries are highly explosive. Naked lights therefore, should not be used at any time to examine a battery.

Containers made of a suitable material such as glass, glazed earthenware or ebonite or, alternatively, utensils having a lead lining, should always be used for handling acid or distilled water. When transferring fluids from containers a suitable funnel should be employed.

NOTE : Containers filled with distilled water should be stored separately from those containing acid. All containers should be suitably marked, indicating their contents.

When acid has been spilt on the floor of the workshop area or on benches, it should be removed by firstly, washing the affected surfaces with water, then neutralised by washing with sodium bicarbonate solution and lastly, washed again with water.

NOTE : Water and neutralising solution should be soaked up with sawdust, which should afterwards be removed and buried or burned.

If electrolyte comes into contact with the skin, the affected area should firstly be washed with cold water, then neutralised by washing with a sodium bicarbonate solution and lastly, washed with warm water. In the event of electrolyte being splashed into the eyes, they should firstly be washed with cold water, then bathed with 5 per cent solution of sodium bicarbonate, and then again washed with cold water. Immediate medical attention should be obtained in the event of skin burns or eye injury.

Inspection Before Charging

All batteries must be inspected before charging and before installation. The following checks are typical of those comprising a battery inspection schedule :-

(i) The outside of the battery case should be examined for signs of damage and evidence of locally overheated areas.
(ii) The cover, sealing gaskets, or mats, as appropriate to the type of battery, should be in good condition.
(iii) There should be no evidence of arcing having occurred between the battery and the aircraft structure. If signs of arcing are present, the aircraft battery compartment should be checked to determine whether any insulation provisions have failed, and the necessary remedial action taken. The battery should be cleaned as necessary.
(iv) The tops of cells should be inspected for signs of electrolyte leakage, and cleaned and dried where necessary.
(v) The battery receptacle should be checked for evidence of burns, cracks and bent or pitted terminals. Defective receptacles should be replaced, because they cause overheating and arcing, and may depress output voltage, which will result in premature battery failure.
(vi) All terminals and any exposed cell connecting links must be checked for security, evidence of over-heating and corrosion. The terminal nuts, where appropriate, should be tightened to the specified torque values. An acid-free petroleum jelly (e.g. white vaseline) or a silicone base grease, should be lightly smeared onto terminal contacts, connector pins, etc.

NOTE : A loose cell link can generate heat and cause arcing which may ignite battery gases.

(vii) Vent caps should be checked for security and to ensure that gas exit holes are clear.

Extreme care must be exercised when working around the top of a battery with the cover removed to avoid dropping tools onto the cell connecting links as severe arcing will result, with possible injury to personnel and damage to the battery. Rings, metal watch straps and identification bracelets should not be worn, thereby preventing contact with connecting with links and terminals.

Initial Filling

A dry uncharged battery must be filled with an electrolyte consisting of battery grade sulphuric acid (see BS 3031) at the relative density recommended by the manufacturer of the particular type of battery, this data being given with the other instructions for filling and charging.

NOTE : The relative density of the acid should not be more than 1.300. I is recommended that the acid suppliers be required to lower the relative density to 1.300 (corrected to a temperature of 15°C (60°F) prior to delivery.

Filling should be carried out methodically to avoid missing any cells. This can be ensured by removing the plug from No.1 cell and filling as required, then removing the plug from No.2 cell and fitting it to No. 1 cell, after which No.2 cell should be filled and fitted with the plug from No.3 cell. This procedure should be followed for each cell in numerical order, until the last cell is fitted with the plug from No.1 cell. On batteries that fill slowly, e.g. those with a solid block plate arrangement which fill by absorption, the vent plugs should be left off until no more electrolyte is absorbed and the free electrolyte level remains constant.

Although the required electrolyte level will vary with the type and make of battery concerned, in all cases it must cover the top of the plates.

NOTE : When poured into the cells, the electrolyte must be at, or only very slightly above, ambient temperature and, if it is obtained by diluting concentrated acid, it must be allowed to cool before use. When diluting concentrated acid, the acid must always be added to the water (at a controlled rate) and never vice versa, since the latter procedure can be extremely dangerous.

After filling, the battery should be allowed to stand for 6 to 8 hours (depending on the manufacturer's instructions for the particular type of battery) so that the battery can cool down, after which the electrolyte level should be restored by adding more electrolyte of the same relative density; the battery is then ready for initial charge.

The relative density of the electrolyte is generally related to a temperature of 15°C (60°F). Readings taken at other temperatures should, therefore, be corrected to 15°C (60°F) as follows :- For the Celsius scale, 0.003 (3 points) should be added to the hydrometer reading for each 4°C by which the temperature of the electrolyte is above 15°C, or 0.003 (3 points) should be subtracted from the hydrometer reading for each 4°C by which the temperature of the electrolyte is below 15°C. Similarly, for the Fahrenheit scale, to correct to 60°F, 0.001 (1 point) should be added or subtracted for every 2.5°F above or below 60°F.

For batteries which are to be used in climates where the temperature frequently exceeds 32°C (90°F) manufacturers sometimes recommend the use of an electrolyte of reduced relative density. For example, a battery may be filled with electrolyte of density 1.260 in temperate conditions, but in tropical conditions the density of the electrolyte may be reduced to 1.230 resulting in a fully charged density of 1.240 to 1.255.

Charging Conditions

When charging several batteries, they should be of the same capacity rating, at the same state of discharge and the same recommended charging rate, and connected in series. The number of batteries which may be so connected depends on the voltage available in the charging circuit.

Each group of batteries should be connected to a separate circuit containing an ammeter, voltmeter, variable resistance and other relevant controls.

NOTE : Ammeters and voltmeters should be of the moving coil type, or digital presentation type, and checked for accuracy at the periods specified for the charging equipment. Accuracy should be within the values specified for the appropriate type of instrument.

All supply leads and connecting cables must be well insulated, of ample cross-sectional area and kept as short as possible. Free ends of cable wires should not be connected to batteries; use should be made of cable end lugs or connector plugs of the type specified for the battery. All connections should be firmly made to give good electrical contact before switching on the charging equipment. To prevent reverse charging, the polarity of the supply leads should be checked with the aid of a centre zero type voltmeter.

It is preferable that neither pole of the charging circuit should be earthed, but if one pole is earthed, it is recommended that the controlling resistance should be between the battery and the unearthed pole.

Batteries requiring different charging rates should not be charged in series, but if this is not possible the limiting current should be that of the battery requiring the lowest charging current.

Vent plugs should be completely unscrewed and lifted, but left in the vent holes before charging is commenced. They should remain in this position during the whole period of charge.

When ready to charge, the variable resistance in the charging circuit should be set in the position of maximum resistance (i.e. minimum current) the charging circuit should be switched on, and the current should be adjusted to the value specified for the particular type of battery.

Charging should, when practicable, be continuous until a fully charged condition is indicated. If charging is interrupted, and batteries are to be left unattended after switching off, both positive and negative supply leads should be disconnected from the batteries.

When cells commence gassing, the voltage and relative density should be measured periodically. In the fully-charged state both values should remain steady.

If a battery in a group should be switched off and the charged battery disconnected. The charging current should then be re-adjusted to a value suitable for continuing the charge of the remaining batteries, and the charging circuit switched on again.

If there is any indication of electrolyte spillage, the affected parts should first be rinsed with water, then with a solution of water and washing soda, and finally sponged with clean water and thoroughly dried. A re-check should be made after 24 hours for any further signs of electrolyte spillage, or corrosion.

Charging

The charging of batteries may be related to the three conditions under which they are normally available. The three conditions are :

a. dry and uncharged and requiring filling and initial charge,
b. filled but uncharged and requiring initial charge
c. in service and requiring recharging.

NOTE : In tropical conditions it is often recommended that the batteries are charged at half the usual rate, with double the charging time.

Batteries Received Dry and Uncharged

After filling in accordance with specified procedure batteries should be charged, using direct current of correct polarity, at the "initial" charging rate recommended by the battery manufacturer; this will vary from 1 ampere to 5 amperes for a total charging time of about 24 hours.

(i) The charge should not be considered complete until the voltage and the relative density (if applicable) of each cell remain constant for the period specified for the type of battery. This period is usually between 3 and 5 hours.

(ii) The electrolyte temperature should be checked frequently during the charging period and must not exceed the temperature specified by the battery manufacturer. If the maximum temperature is exceeded the charge should be stopped until the electrolyte temperature has dropped by the specified amount (usually about 12°C (22°F); or the charging may be halved and the charging time doubled.

(iii) On completion of the charge, any gas in the electrolyte should be released by gently rocking the battery, the electrolyte level then being adjusted as specified by the battery manufacturer.

Batteries Received with Electrolyte

A battery of the type which forms a solid block with the plates and separators is normally despatched already filled with electrolyte.

(i) On receipt of the battery the vent plugs should be removed and the level of the electrolyte checked to ensure that it is approximately ¼ in above the perforated strip and, if necessary, adjusted to this level using sulphuric acid of relative density 1.270.

(ii) The battery should receive a charge current at a value appropriate to the ampere-hour rating of the battery, until the voltage is stable over five consecutive half-hourly readings Should the temperature of the electrolyte reach 60°C (140°F), the charge should be interrupted until the temperature falls below 43°C (110°F).

(iii) During the charge the vent plugs should be kept in, but not screwed down. If the battery was properly filled it should not require any topping up during this time. If the electrolyte level disappears, acid of relative density 1.270 should be added; if the electrolyte level is high the excess should be withdrawn.

Re-Charging a Battery in Service

The electrolyte level should be checked and, if necessary, adjusted with distilled water, and the battery put on charge at the normal rate recommended. In a fully charged condition, all the cells should gas freely and the relative density of the electrolyte should be within the limits given when corrected for temperature. The main terminal voltage should, under normal temperature conditions, be between 30 and 32.4 volts when measured with the charging current flowing. The charge should be continued until the readings are constant for 3 hours.

NOTE : At all times during charging, a check should be kept on the battery temperature to ensure that the maximum permissible limit is not exceeded.

Electrolyte Level and Adjustments

The Periods at which adjustments to the electrolyte should be carried out vary largely with the state of charge and duty cycle of the battery.

The level in the cells must be maintained by the addition of distilled water, as only the water from the electrolyte is lost through electrolysis or evaporation. After initial charge the relative density of the electrolyte should not normally require adjustments, but, in exceptional cases, it may be adjusted in accordance with the manufacturer's instructions.

In order to ensure the mixing of acid with the distilled water, topping-up should be done immediately before a battery is put on charge. Adjustments must be to the correct level to prevent overflow of the electrolyte which could occur as a result of gassing and expansion during the charge. If a battery is to be exposed to very low temperatures, its charge after topping-up, should be prolonged for at least one hour. This will ensure thorough mixing of the electrolyte and thereby avoid the possibility of the water freezing. An additional precaution against freezing is to maintain the battery in a fully-charged state.

For some types of battery, special fillers may be necessary to ensure correct electrolyte level but, in general, the level is specified as a measurement taken from the top of the separator guards of plates.

After adding distilled water, it should be borne in mind that relative density readings cannot be relied upon until the electrolyte and water have been mixed by the gassing of the cells whilst on charge.

A record of the quantity of water added to battery cells should be maintained, since frequent additions are grounds for rejection of cells.

If, one hour after charging, the electrolyte level falls below the specified value, the battery should be reconnected to the charging equipment and the electrolyte level adjusted with the battery on a low charge and slightly gassing.

State of Charge

On reaching the fully-charged condition, a lead-acid battery displays three distinct indications : (i) the terminal voltage cease to rise and remains steady (e.g. 31 volts for a new battery) with charging current flowing, (ii) the specific gravity of the electrolyte ceases to rise and remains constant, and (iii) both sets of plates gas freely. In the conventional type of lead-acid battery all three indications must be in evidence before the battery can be regarded as being completely charged.

NOTE : The terminal voltage at the end of charge normally diminishes with the age of battery. If it is equal to, or below, 28.5 volts a battery should not be put back into service.

In the case of batteries using cells of solid block construction, the state of charge is indicated by the open circuit voltage and gassing. Relative density readings cannot be made since there is insufficient free electrolyte. The method of carrying out an open-circuit voltage check is given in the following paragraphs, the current and voltage values being based on a typical 24-volts 18 ampere-hour (one-hour rate) battery.

(i) Connect the battery to a load that will take approximately 20 amperes, and after current has been flowing for 15 seconds, measure the on-load voltage.

(ii) Disconnect the load and take an off-load voltage reading immediately; the increase in reading from on-load to off-load should be approximately 1 volt if the battery is in good condition.

(iii) The state of charge is assessed from the off-load voltage. If the voltage is between 25.1 volts and 25.8 volts the battery may be regarded as fully charged. An off-load voltage of between 24.5 volts and 25.1 volts indicates a battery that is from half to quarter discharged. A half-discharged will indicate an off-load voltage of between 24.2 to 24.5 volts.

Capacity Tests

A capacity test should be carried out after initial charge, and thereafter at intervals of three months, or at any time the capacity of a battery is in doubt. Details of test methods are given in the relevant manuals.

The battery should be fully charged and then connected to a suitable discharge control panel incorporating a variable-load resistance, an ammeter and an ampere-hour meter. A separate voltmeter is necessary to measure voltage at the battery terminals, or cell connecting strips.

NOTE : If the control panel is not of the automatic type, or if no ampere-hour meter is incorporated, accurate monitoring and control of current must be maintained throughout the tests.

The battery should then be discharged at a rate corresponding to the rating of the battery (as detailed in the appropriate manuals, e.g. an 18. All battery rated at the one hour rate would be discharged at 18 amps.) until the battery reaches its fully discharged condition. This condition is denoted by the main terminal voltage, or the relative density of the electrolyte, falling to the respective fully discharged values for the particular type of battery. The minimum acceptable capacity for use on aircraft is 80 per cent which, in the case of the example rating quoted, provides a duration of discharge equal to 48 minutes. The result, however, should be compared with previous readings to assess rate of deterioration.

Insulation Resistance Test

This test should be carried out at the periods specified in the approved Maintenance Schedule and at any time that electrolyte leakage is suspected.

The battery should be fully charged and the case and cell tops wiped dry. It should then be fitted to a metal base plate by the fixing method normally used in the aircraft. A test should be made between one terminal of the battery and the base plate, using a 250-volt insulation tester, and the minimum insulation resistance obtained must be not less that one megohm. If a reading below this value is obtained, the battery should be checked for presence of moisture, leaking case, or vented electrolyte, and remedial action take in accordance with the procedure specified in the relevant manual.

Leakage Test

This test should be carried out before initial filling. If there is no apparent visible damage to a battery, it should be given a leak test using the tester designed for the particular type of battery. Vent caps should be removed, and with the tester held firmly over each vent in turn, a pressure of $14kN/m^2$ ($2\ lbf/in^2$) should be applied by means of the pump on the tester. There should be no detectable leakage after a period of not less than 15 seconds.

INSTALLATION

Before installing a battery it should be ensured that it is of the correct type, fully charged and the electrolyte is at the correct level. A capacity test and insulation resistance test must also have been carried out in the manner prescribed for the particular battery in aircraft using batteries in parallel, it is important to ensure that all batteries are at the same state of charge. Reference should be made to the relevant aircraft Maintenance manual for detail of battery system and associated installation instruction. Before coupling the battery connecting plug, a check should be made to ensure that the battery system is switched off and that all electrical services are isolated.

NOTE : Batteries are heavy units and require the use of approved and careful handling methods to prevent possible injury to personnel, and damage to the cases or components adjacent to the battery location.

The battery compartment should be clean, dry and free of any acid corrosion or damage. Apart from the mounting tray, which is usually made of an acid-resistant material, the structure adjacent to the battery compartment should be treated with an acid-resistant paint as a protection against the corrosive acid fumes from the battery.

When a battery is located in its compartment, it should be ensured that it is securely attached and that the appropriate clamps, or bolts are not over-tightened.

Terminal contacts or connector pins should be lightly coated with an acid free petroleum jelly (e.g. white vaseline) or a silicon base grease.

The Supply cables from the battery should be checked for signs of chafing or other damage; connecting terminals or plugs must be secured without any strain on the terminals, plugs or cables.
Battery installations are normally designed so that in flight, sufficient air is passed through the compartments to dilute the gases given off by the battery, to a safe level. Ventilation systems should therefore be checked to ensure there is no obstruction or, if integral venting is used, the system connections should be checked for security and freedom from leaks.

NOTE : In some ventilation systems, non-return valves are incorporated in the battery compartment vent lines. These valves should also be checked for sevurity and correct location.

After installation, a check should be made that the electrical connections of the battery supply cables have been correctly made by switching on variors electrical services for a specific time period and noting that reading of the aircraft voltmeter remain steady.

MAINTENANCE OF INSTALLED BATTERIES
Batteries should be inspected at the periods specified in the approved Maintenance Schedule. The degails given in the following paragraphs serve as a guide to the checks normally required.

The battery mounting should be checked for security and the outside of the battery base examined for signs of damage and evidence of local overheating. The latches of the cover should operate smoothly and firmly secure it in position.

Connector lugs or plug pins, should be checked for security and for signs of contamination, burns, cracks, bending or pitting.

Cables should be examined to ensure that their protective covering has not been damaged, and that they have not been affected by dampness or by general climatic conditions prevailing in the battery compartment.

The tops of all cells and vent caps should be inspected for signs of electrolyte leakage and cleaned where necessary.

NOTE : When removed, the cover of a battery and cell vent should not be placed on any part of the aircraft structure or equipment.

Depending on the type of battery installed, either the relative density, or open-circuit voltage, should be checked to ensure that the values obtained are within the permissible limits.

The electrolyte level should be checked and, if necessary, adjusted with distilled water. The amount of water added to the cells should be recorded. A cell requiring more than the specified amount should be regarded as suspect and the battery should be replaced by a serviceable unit.

NOTE : Batteries should be removed from aircraft in order to carry out electrolyte level adjustments.

The battery ventilation system should be checked to ensure security of connections and freedom from obstruction. Acid drain traps, where fitted, should be checked for signs of acid overflow and, if necessary, removed for cleaning.

During checks on a generator voltage regulator system, it must be ensured that the voltage setting does not cause excessive charging current to be fed to the battery system. A voltage set higher than the specified value, coupled with high ambient temperature, is the most common cause of battery overheating, resulting in a 'thermal runaway' condition and damage to the battery. In some cases consideration may have to be given to aircraft operating in extremely hot climates and the system voltage may have to be reduced. In such cases, the battery may then have to be operated slightly below its maximum capacity.

NOTE : Other factors which may cause 'thermal runaway' are inadequate battery ventilation, high relative density of the electrolyte or a low end-of-charge reading.

At the period specified in the approved maintenance schedule, the battery must be removed from the aircraft for capacity and insulation resistance tests.

STORAGE AND TRANSPORTAION

Lead -acid batteries should be stored in a clean, dry, cool, well-ventilated area entirely separate from nickel-cadmium batteries. The area should also be free from corrosive liquids or gases. New batteries may be stored either dry and uncharged, or filled and charged. Batteries of solid block construction may also be stored in the condition in which they are despatched by the manufacturer i.e. filled and uncharged. In this condition only the positive plates are formed so that the batteries remain inert until they are prepared for use. Batteries removed from service must always be stored in the fully-charged condition. The appropriate storage limiting periods must be in accordance with those specified in the relevant manuals.

Typical periods are 5 years in a temperate climate for charged or uncharged batteries and from 2 to 3 years in a tropical climate for uncharged batteries, and 18 months for charged batteries. If the storage limiting periods have been exceeded, uncharged batteries should be charged, bench checked or returned to the manufacturer for examination and re-lifting.

Charged batteries should be periodically inspected and given a freshening charge every 2 to 4 weeks. The capacity of batteries should also be checked during the storage period at a frequency which is dictated mainly by their condition. It is recommended that capacity tests be carried out every 6 months for new batteries, and every 3 months for batteries returned from service.

Batteries which have been in use and are discharged, should not be allowed to remain, or be stored in this condition, because of the danger of sulphation of the plates. The lower main terminal voltage limit appropriate to the type of battery should be checked and recharging carried out as necessary ; a typical lower limit is 21.6 volts.

If it is necessary to return a battery to the manufacturer, or to an approved overhaul Organisation, it should be prepared in accordance with the transportation requirements specified by the manufacturer for the appropriate battery condition i.e. charged or uncharged. An up-to-date service record should accompany the battery and "This Way Up" international signs affixed to the container.

NOTE : If transportaion is to be by air, the container must comply with ATA regulations concerning the carriage of batteries.

GENERAL DESCRIPTION

Nickel-cadmium batteries may be divided into three ranges of basic design, as described in the following paragraphs.

Sealed Batteries

This range of batteries consists of those having the cell completely sealed. In general the batteries are of small capacity, and may be used for emergency lighting purposes.

Semi-Sealed Batteries

The cells in this range of batteries are usually mounted in steel containers and are fitted with safety valves. The batteries may be charged fairly rapidly but are very sensitive to overcharge, thus, for aircraft usage, they are usually fitted with a thermal protective device. Under normal conditions the battery requires practically no maintenance beyond periodic cleaning and capacity checks.

Semi-open Batteries.

These batteries are generally used as the main aircraft batteries. The cells are similar in appearance to those of the semi-sealed type, but are deliberately allowed to 'gas' to avoid excessive heating should the battery be on overcharge. The cell cases are usually manufactured from nylon. Because of gassing, the electrolyte has to be 'topped-up' at periods which vary according to the duty cycle of the battery and the conditions under which it is operated . 'Topping -up' periods are specified in the approved Maintenance Schedule for the aircraft concerned.

CONSTRUCTION

The plates comprise a sintered base on a nickel-plated steel support. The active materials are nickel hydroxide on the positive plates, and cadmium hydroxide on the negative plates, and theses are impregnated into the sintered base by chemical precipitation. This type of plate construction allows the maximum amount of active material to be employed in the electrochemical action.

After impregnation with the active materials, the plates are stamped out to the requisite size. The plates are then sorted into stacks according to the type of cell into which they are to be mounted. Usually there is one additional negative plate for a given number of positive plates. The plates are then welded to connecting pieces carrying the cell terminals, after which a separator is wound between the plates and the insulation is checked under pressure. The plate group is then inserted in the container, the lid secured and pressure-tested for leaks. The separators are usually of the triple-layer type, one layer being made from cellophane film, the other two being woven nylon cloth. Cellophane is used because it has low electrical resistivity and is a good barrier material which contributes to the electrical and mechanical separation of the positive and negative plates, and keeps finely divided metal powder particles from shorting out the plates while still permitting current flow. It also acts as a gas barrier, preventing oxygen given off at the positive plate during overcharge from passing to the negative plate where it would combine with active cadmium, reduce cell voltage, and produce heat as a result of chemical reaction. The cellophane is prone to damage at high operating temperatures, and failure will result in an adverse change in the operating characteristics of a battery.

The electrolyte is a solution of potassium hydroxide and distilled water, having a relative density of 1.24 to 1.30. It is impregnated into cells under vacuum, after which the cells are given three formation cycles, re-charged, and then allowed to stand for a minimum period of 21 days. The discharge characteristics at the end of this period enable the cells to be matched.

In a typical battery each component cell is insulated from the others by its moulded plastic case All the cells are interconnected via links secured to the terminals of the cells, and are contained as a rigid assembly in the battery case. A vent cap assembly is provided on the top of each cell and, in general, is constructed of plastic, and is fitted with an elastomer sleeve valve. The vent cap can be removed for adjustment of the electrolyte level, and acts as a valve to release gas pressure generated during charging. Except when releasing gas, the vent automatically seals the cell to prevent electrolyte spillage and entry of foreign matter into the cell.

Two venting outlets, a pair of carry-strap shackles, and a two-pin plug for quick-release connection of the aircraft battery system cables, are embodied in the battery case. A removable cover completes the case, and incorporates a pair of slotted lugs which engage with attachment bolts at the battery stowage location.

Chemical Principle

During charging an exchange of ions takes place; oxygen is removed from the negative plates and is added to the positive plates, bringing them to a higher state of oxidation. These changes continue in both sets of plates for as long as the charging current is applied or until both materials are converted; i.e. all the oxygen is driven out of the negative plates and only metallic cadmium remains, and the positive plates become nickel hydroxide.

The electrolyte acts only as an ionized conductor and is forced out of the plates during charging. It does not react with either set of plates in any way, and its relative density remains almost unchanged. Towards the end of the charging process and during overcharging, gassing occurs as a result of electrolysis which reduces only the water content of the electrolyte. Gassing is dependent on the temperature of the electrolyte and the charging voltage.

During discharge, the chemical action is reversed; the positive plates gradually losing oxygen while the negative plates simultaneously regain lost oxygen. The plates absorb electrolyte to such an extent that it is not visible at the top of the cells.

MAINTENANCE

Nickel-cadmium batteries must be prepared for service, charged, tested and otherwise generally maintained, in a well ventilated workshop area which is entirely separate from that used for the servicing of lead-acid batteries. This also applies to servicing and test equipment, tools and protective clothing, all of which should carry some form of identification. Anything associated with lead-acid batteries (acid fumes included) that comes into contact with a nickel-cadmium battery or its electrolyte can cause severe damage to this type of battery.

Precise details of inspection and maintenance procedures, and the sequence in which they should be carried out, are given in the relevant battery maintenance and overhaul manuals, and other approved supplementary servicing instructions; reference should, therefore, always be made to such documents. The information given in the following paragraphs is intended to serve as a general guide to the procedure to be carried out appropriate to battery service life and condition, and also to the precautions to be observed.

Inspection

The following checks are typical of those comprising a battery inspection schedule :-

a. The battery should be identified to establish any known history. If the battery is a new one a servicing record card should be raised.
b. The outside of the battery case should be examined for evidence of damage, and of locally overheated areas.
c. The battery cover should be removed and its rubber lining inspected for condition. Cover latches should operate smoothly and provide proper security of the cover. Extreme care must be exercised when working around the top of a battery with its cover removed. Tools should not be dropped onto the cell connecting links, as severe arcing will result with possible injury to personnel and damage to the battery. Such personal items as rings, metal watch straps and identification bracelets should be removed, to avoid contact with connecting links and terminals.

d. There should be no evidence of arcing having occurred between the battery and the aircraft structure. The section near the bottom of the case and the slotted lugs of the cover tie-down strap are areas which are most likely to be affected. If signs of arcing are present, the aircraft battery compartment should be inspected and the battery should be completely dismantled and overhauled.

e. The battery should be inspected for signs of electrolyte leakage and should be cleaned where necessary.

f. The battery receptacle should be checked for evidence of burns, cracks and bent or pitted terminals. Defective receptacles, which can overheat, cause arcing and depress output voltage, should be replaced.

g. All cell links should be checked for security and evidence of overheating, and their terminal nuts should be tightened to the specified torque values. Any cell link showing damage to its plating should be replaced.

h. Vent caps should be checked for security and also to ensure that gas exit holes are free from dirt or potassium carbonate crystals. Clogging of vents causes excessive pressures to build up, resulting in cell rupture or distortion of parts. Cell valves when fitted, should also be checked for security and freedom from dirt or crystal formation. Dirty vent caps or valves should be removed and cleaned.

NOTE : Potassium carbonate is a white crystal formed by the reaction of potassium hydroxide with carbon dioxide in the air; it is non-corrosive, non-toxic, and non-irritating.

i. Temperature sensing devices, when installed, should be checked for secure attachment with leads and connectors showing no signs of chafing or other damage. Electrical checks and/or calibration or these device should be carried out at the periods specified in the approved Maintenance Schedule.

Electrolyte Level and Adjustments

The level of the electrolyte should, depending on manufacturer's recommendations, only be adjusted when a battery is at the end of charge, while still charging, or after a specified standing time. If electrolyte level adjustments were to be made in the discharged or partially discharged condition, then during a charge electrolyte would be expelled from the cells, resulting in corrosive effects on cell links, current leakage paths between cells and battery case, and a reduction of electrolyte density. The manufacturer's instructions regarding checks on electrolyte level and adjustments should be carefully followed and the maintenance kit equipment designed for a particular type of battery should be used.

NOTE : Adjustments should not be made when batteries are installed in aircraft.

Only the purest water available, preferably pure de-mineralised or distilled water, should be used for adjusting electrolyte levels, and a record of the quantity added to all cells should be maintained, because it is largely on this evidence that periods between servicing are determined. The 'consumable' volume of electrolyte is normally specified in manufacturer's manuals, but in the absence of such information, a useful guide line is that batteries should not be left for periods which would require the addition of water to any cell by an amount in excess of 1 cc per ampere-hour capacity.

In the event that the electrolyte becomes contaminated, particularly with oil, foaming of the electrolyte will occur. In such cases, a neutralizing fluid, which is available from the relevant battery manufacturer, should be added to the electrolyte, strictly in accordance with the manufacturer's instructions.

Additional potassium hydroxide should not normally be required, but if electrolyte in solution is necessary for topping-up it must be ensured that it is in the proportions specified in the relevant manual.

NOTE : Contamination of the electrolyte with tap water, acids, or other non-compatible substances, will result in poor performance or complete failure of a battery.

Potassium hydroxide should be kept in special containers, and because of its caustic nature, should be handled with extreme care to avoid contamination of the person or clothing. Rubber gloves, a rubber apron and protective goggles should always be worn. If contamination does occur, the affected parts should be immediately rinsed with running water. If available, vinegar, lemon juice or a mild boric acid solution may also be used for treatment of the skin. Immediate medical attention is required if the eyes have been contaminated. As a first-aid precaution, they should be bathed with water or a weak boric acid solution, applied with an eye bath.

Battery Cleaning

Dirt, potassium carbonate crystals, or other contaminating products, can all contribute towards electrical leakage paths and be a prime cause of unbalanced cells. Cleanliness of batteries is therefore essential.

Deposits should be removed from the tops of cells by using a cloth soaked in de-mineralised or distilled water and a stiff fibre bristle brush. Wire brushes or solvents should not be used. If any contaminating product is caked under and around cell connecting links, the links should be removed, if necessary, to facilitate cleaning. Care should always be taken to ensure that debris is not forced down between cells, and in some cases it may be better to scrape deposits loose and then blow them with low-pressure compressed air. The air itself should be clean and dry, and goggles should be worn to protect the eyes.

Some manufacturers specify periodic flushing of cell tops and battery case with de-mineralised or distilled water while brushing away deposits. This method is not recommended, and batteries in a dirty condition, or showing low resistance, should be dismantled and completely serviced.

When it is necessary to clean vent caps and valves, they should be removed from the cells, using the correct extractor tool, and should be washed in warm water to dissolve any potassium carbonate crystals which may have accumulated within the outlet orifices. They should then be rinsed in de-mineralised or distilled water, dried and re-fitted. Valves should also be tested for correct functioning in accordance with manufacturer's instructions before re-fitting.

NOTE : Cells should not remain open for longer period than is necessary.

Charging of Batteries

New nickel-cadmium batteries are normally delivered complete with the correct amount of electrolyte, and in the fully discharged condition. Following a visual check for condition, they must, therefore, be charged in accordance with the manufacturer's instructions before being put into service. Once in service, batteries must then be charged at the periods stated in the approved aircraft Maintenance Schedule. The following information on charging methods and associated aspects is of a general nature only. Precise details are given in relevant manufacturer's manuals and reference must, therefore, always be made to such documents.

Constant-Current Charging

This method is the one which should normally be adopted for the workshop charging of batteries the charging equipment being adjusted and monitored throughout the charging period to supply current at either a single rate, or at several different rates in a stepped sequence. Although more time-consuming than the constant potential method which is often adopted in aircraft battery systems, constant current charging is more effective in maintaining cell balance and capacity. The hour rate of charge current required must be in accordance with that specified by the relevant battery manufacturer.

NOTE : The 'hour rate' of a battery refers to the rate of charge and discharge expressed in multiples of 'C' amperes, where 'C' is the 1-hour rate. For example, if a battery has a capacity of 23 ampere-hours, then 'C' would be 23 amperes and for a 10-hour rate the charge or discharge current rate would be $\frac{C}{10}$ amperes, i.e. 2.3 amperes.

Vent Caps

Before charging, the battery cover should be removed, and with the aid of the special wrench provided in the battery maintenance kit, the vent cap of each cell should also be removed.

Connection to Charging Equipment

Charging equipment should not be switched on until after a battery has been connected and the charging circuit has been checked for correct polarity connections.

Electrolyte Level

The electrolyte level should be checked and adjusted, as necessary, in accordance with the manufacturer's recommendations.

Gassing

Gassing of cells occurs within the region of final charge, as a result of the electrolysis of water into hydrogen and oxygen gases. When gases escape from a cell, the quantity of fluid electrolyte is reduced; vigorous prolonged gassing should therefore be avoided. A "dry" cell is more likely to suffer separator damage, and any cell running hotter than its neighbours should be investigated.

a. The gassing/temperature phenomena provide a useful indication of impending failure of cells; e.g. a cell that gasses sooner and more actively than its neighbours is going to lose more electrolyte, and as a result will run hotter and tend to dry out. Minor difference in gassing are hard to detect, but large difference should be noted and investigated.

State of Charge

The state of charge cannot be determined by measurement of the electrolyte relative density or battery voltage. Unlike the lead-acid battery, the relative density of the nickel-cadmium battery electrolyte does not change. Except for 'dead' batteries, voltage measurements at either open circuit or on-load conditions do not vary appreciably with state of charge. The only way to determine the state of charge is to carry out a measured discharge test.

Charging of Individual Cells

Individual cells must be in an upright position and adequately supported at the sides parallel to the plates during charging. A special frame may be built to fit a cell, or boards or plates may be placed on each side and held together with a clamp. After charging and removal from its support, the sides of a cell should be inspected to ensure there are no bumps or bulges which would indicate an internal failure.

NOTE : Cells should always be fully discharged before removal from a battery and before reassembly.

Thermal Runaway

In some small aircraft the battery may be charged by constant potential supplied directly from the d.c. bus-bar. Under correct conditions of temperature and voltage, the internal voltage of the cells rises gradually as the electro-chemical action takes place, and it opposes the charging voltage until this is decreased to a trickle sufficient to balance continuous losses from the cells. The energy supplied to a fully charged battery results in water loss by electrolysis and in heat generation. For a battery in good condition, a point of stability will be reached where heat as a result of trickle current will just balance radiated and conducted heat losses. At low temperatures, a battery will appear to have a limited capacity, and will require more voltage to accept a given amount of charge. As the battery becomes warm, however, its responses return to normal. Operation at high temperatures also limits the capacity, but in such conditions, a battery is subjected to the danger of a 'thermal runaway' condition.

a. At higher than normal temperatures, the heat loss of the battery through radiation and conduction is lower than the heat generating rate and this results in a higher battery temperature. This, in turn, reduces the internal resistance of the battery, so that higher than normal charge current is admitted resulting in an increase in chemical activity, additional heat and a further increase in charging current. This recurring cycle of temperature rise, resistance and voltage drop, and charge current rise, progressively increases the charging rate until sufficient heat is generated to completely destroy a battery.

b. Other factors which can cause overheating of a battery are as follows : -

i. Voltage regulator of aircraft generating system incorrectly adjusted.

ii. Frequent or lengthy engine starts at very high discharge rates.

iii. Loose link connections between cells.

iv. Low electrolyte level.

v. Leakage currents between a cell and battery container and the airframe structure. Periodic measurement of leakage current and removal of any electrolyte that may have accumulated around and between cells should be carried out to prevent high leakage and short circuits from developing.

vi. Use of unregulated, or poorly regulated, ground support equipment to charge a battery, particularly a battery which has become hot as a result of excessive engine cranking or an aborted engine start.

vii. High initial charging currents imposed on a hot battery.

viii. Unbalanced cells. Cell unbalance refers to an apparent loss of capacity and to variations in cell voltage at the end of charging cycles. These variations can develop over a period of time, particularly when subjected to operating conditions like those occuring in aircraft utilising charging circuits of the constant potential type. Other factors which may also contribute to cell unbalance are cell position in the battery, e.g. centre cells run warmer than outer cells, and the self-discharge of individual cells.

c. In some types of aircraft, the batteries specified for use incorporate with a thermostat type detector which illuminates a warning light at a pre-set temperature condition. In addition, a thermistor type sensing network may also be incorporated. The network operates in conjunction with a special solid-state, pulse-charging unit, and its function is to monitor the charging current and to de-energize the charging circuit when the battery temperature exceeds a safe operating limit. Detection devices should be checked at the periods stated in the approved aircraft Maintenance Schedule and in accordance with the relevant manufacturer's instructions.

Electrical Leakage Check

Electrical leakage refers to current flowing in a path other than that desired, and in connection with batteries, this means current between the terminals or connectors of cells and any exposed metal on the battery case. The only pertinent measure of leakage of importance to a cell is the rate of discharge caused by the leakage, and this is only significant when its value approaches that specified for the particular type of battery. In one type for example, a leakage of up to 0.020 amps is quoted as the permissible value. Typical methods of determining electrical leakage are described in the following paragraphs.

The positive lead from the terminal of a multi-range testmeter should be connected to the positive terminal of the battery and, after selecting the appropriate scale range (usually the one amp. range) the negative terminal lead from the testmeter should be touched on any exposed metal of the battery case. If a pointer deflection is obtained it will denote a leakage and the testmeter scale setting should be adjusted, if necessary, to obtain an accurate reading which should be within the limits specified.

The foregoing check should be between the battery negative terminal and battery case, when again any readings obtained should be within limits. If either of the readings obtained exceed the specified limits the battery should be thoroughly cleaned and the checks again repeated.

If, after through cleaning, the leakage current is in excess of the limits it is probable that one of the cells is leaking electrolyte and is therefore defective. This cell may be found by measuring the voltage between each cell connecting link and the battery case. The lowest voltage will be indicated at the connecting links on each side of the defective cell which should be replaced.

Capacity Test

The capacity or state-of charge of a fully-charged battery is checked by discharging it at a specified rate (preferably automatically controlled) after it has been standing for a certain time period, and noting the time taken for it to reach a specified on-load voltage. For example, a 23 ampere-hour battery is left to stand for 15 to 24 hours and is then discharged at 23 amperes, i.e. the 1-hour rate, to 20 volts. A battery should give at least 80% of the capacity specified on its nameplate, or the minimum authorised design capacity, whichever is the greater.

NOTE : Some batteries of U.S. origin have initial capacity ratings which are significantly higher than those specified on their nameplates. When the nameplate ratings are no longer obtainable such batteries are rejected.

True capacity must always be recorded, meaning that a full discharge is required, and not one which is terminated when the minimum acceptable level has been reached. Because it is essential to monitor a number of cell voltages very closely, the service of two persons is desirable towards the end of discharge for measurement and recording. At this stage, voltages fall very quickly, and it is highly desirable that measurements be made with a digital voltmeter.

NOTE : No cell should be allowed to go into reverse polarity before the measured discharge is complete, and the terminal voltage should not go below 1 volt per cell, since excessive gassing may result.

Capacity Recycling Procedures

The purpose of recycling is to restore a battery to its full capability and to prevent premature damage and failure. The discharge rates and voltage values appropriate to the recycling procedures vary between types of battery, and reference should always be made to the relevant manual. The figures quoted in the following paragraphs are typical, and serve only as a guide to the limits normally specified.

The battery should be discharged at a current equal to or less than the one-hour rate, and as each cell drops below 0.5 volts (measured by a digital voltmeter) it should be shorted out by means of a shorting strip. The cells should remain in this condition for a minimum period of 16 hours, preferably 24 hours.

NOTE : A battery should not be discharged at an excessively high rate and cells then short-circuited, since this produces severe arcing and excessive heat generation.

The shorting strips should then be removed, and the battery charged for 24 hours at the specified recycling charging rate. After approximately five minute of charge, individual cell voltages should be measured and if any cell voltage is greater than 1.50 volts, distilled water should be added. The amount of water required depends on the reated ampere-hour capacity; a typical maximum value is approximately 1 cc per rated ampere-hour.

After approximately 10 minutes of charge, individual cell voltages should again be measured. Any cell measuring below 1.20 volts or above 1.55 volts should be rejected and replaced.

After 20 hours of charging, individual cell voltage should be measured and recorded, and, if necessary, distilled water should be added to the normal level appropriate to the type of battery.

At the end of the 24 hours charge period, cell voltages should again be measured and compared with those obtained after 20 hours. If the 24 hour voltage reading is below the 20 hour reading by more than 0.04 volts, the cell concerned should be rejected and replaced.

Cell Balancing

If a battery fails to give 80% capacity on test, and if premature ageing of some cells is suspected, a cell balancing test should be carried out. The procedure for carrying out the test appropriate to a particular type of battery is prescribed in the relevant manual, and reference should always be made to such document. The following details, based on the test specified for a typical 23 ampere-hour battery, are given only as a general guide.

Note the time, and discharge the battery at 23 amperes until the terminal on-load voltage falls to 20 volts, then stop the discharge. During the discharge, the voltage of each cell should be frequently checked with a digital voltmeter. A zero reading early in the discharge indicates a short circuit cell; a reverse reading indicates a weak cell. In either case the discharge should be stopped, even if the overall battery voltage has not yet fallen to 20 volts. The weak or faulty cell should be shorted out, preferably through a 1 ohm resistor.

Note the time and recommence the discharge at the lower rate of 2.3 amperes. Frequently check the voltage of the cells and short out each cell (with individual shorting strips) as it falls below 1 volt, thereby obtaining an indication of the relative efficiency of the cells.

a. Some manufacturers specify 0.5 volts as the point at which shorting of the cells should be carried out. This is satisfactory providing that sufficient time is available to permit shorting of all cells before any are subjected to reverse voltage resulting from the charging effect of stronger cells.

The discharge should be stopped when all the cells are shorted out. The battery should be left in this condition, and also with the main terminals shorted together, for as long as possible, but never less than 16 hours.

The battery should then be charged and the cell-balancing procedure repeated. The discharge times recorded for each cell to fall below 1 volt should show an improvement over those previously recorded.

Weak and internally short-circuited cells should be replaced in accordance with the instructions detailed in the relevant battery Maintenance Manual.

Voltage Recovery Check

This check, which should be made at a given time after shorting strips have been removed from the cells or main battery terminals, provides a ready means of detecting high resistance short-circuit and damaged connections within a battery. A typical procedure for this check is given in the following paragraphs.

Shorting strips of one ohm resistance should be connected between cells, and the battery should be allowed to stand for 16 to 17 hours. At the end of this period, the voltage of individual cells should be measured to ensure that they do not exceed the voltage of individual cells should be measured to ensure that do not exceed the minimum value specified for the battery (a typical minimum value is 0.20 volts).

The shorting strips should then be removed, and after a further standing period of 24 hours, individual cell voltages should again be measured to check their recovery to within normal operating values. A typical minimum value specified as a basis for rejection of a cell is 1.08 volts.

Insulation Resistance Test

A test for insulation resistance may be specified by some manufacturers as the means of checking for electrical leakage. Reference should, therefore, be made to the appropriate maintenance manual for the procedure to be adopted, for permissible values, and for any remedial action to be taken.

Cell Removal and Replacement

Cells should be removed from a battery whenever they are suspected of leakage of electrolyte, internal short-circuits, when they fail to balance or if the insulation resistance is found to be below the value specified for the particular battery. The method of removing and replacing cell may vary between types of battery, and the instructions issued by the relevant manufacturers must, therefore, always be carefully followed. The information given in the following paragraphs, although based on a specific type of battery, is intended to serve only as a guide to the practical aspects generally involved.

The battery should be discharged and the cell links disconnected and removed both from the faulty cell and from the adjoining cells. The cell position should be noted for subsequent entry in the battery record card.

The vent cap should be loosened using the special key provided with the battery maintenance kit.

A cell extractor tool should then be fitted to the cell on the terminals normally used for connecting the cell links. The battery is then held firmly and the cell withdrawn vertically upwards without using undue force. When one cell is removed and all other cell links are disconnected, it is relatively simple to withdraw the remaining cells without the aid of the extractor.

NOTE : After removing a cell, its vent cap should be re-tightened. Cells and the inside of the battery case should be thoroughly cleaned and dried.

After carrying out all necessary checks, serviceable cells should be replaced in the battery case in their correct positions, and a cell-to-cell voltage check should be carried out to ensure that polarities are not reversed. It must be ensured that any new cells are of the same manufacture, part number, and are of matched capacity rating.

NOTE: A steady force should be used on terminals to press cells into place. Tight cells should not be hammered into place. For easiest assembly, the cell at the middle of a row should be inserted last.

The surfaces of cell terminals and connecting links should be clean, and, after ensuring the correct position of links, terminal nuts should be tightened to the specified torque value, and in a sequence commencing from the battery positive terminal. Care should always be taken to ensure that nuts actually tighten the connector assemblies, and are not binding as a result of thread damage or bottoming.

NOTE : Once a tightening sequence has been started it should be completed, thereby ensuring that a nut has not been overlooked. One loose connection can permanently damage a battery and may cause an explosion.

On completion of cell replacement procedures, the battery should be re-charged, tested for insulation resistance, and, if any new cells have been fitted, a capacity test should also be carried out.

Rejected Batteries or Cells

Any batteries or cells which are rejected should be conspicuously and permanently marked on their cases to indicate that they are to be used only for general ground use.

INSTALLATION

It should be ensured that the battery is of the correct ampere-hour rating, fully charged, and that the electrolyte is at the correct level. Depending on the service history of the battery, appropriate tests, e.g. capacity test, capacity recycling and cell balancing, must also have been carried out in the manner prescribed for the particular battery. Reference should be made to the relevant aircraft Maintenance Manual for details of the battery system and associated installation instructions. Before coupling the system connecting plug, a check should be made to ensure that the battery system switch is OFF, and that all electrical services are isolated.

NOTE : Batteries and heavy units, and they require the use of approved handling methods to prevent possible injury to personnel and damage to the cases or components adjacent to the battery location. Vent pipes should not be used for lifting purposes.

The battery compartment should be thoroughly clean and dry, and the battery should be securely attached in its mounting. Clamp nuts should not be over-tightened since distortion of the battery cover may result, which could affect the venting arrangements.

NOTE : If a battery compartment has been previously used for lead-acid batteries, it should be washed out with an acid neutralising agent, dried thoroughly, and painted with an alkaline-resistant paint.

The supply cables from the battery, and, where appropriate, thermostat and battery charging system cables, should be checked for signs of chafing or other damage. Cable connecting plugs should be securely made, without any strain on the plugs or cables.

Battery installations are normally designed so that in flight, sufficient air is passed through the compartment to dilute the hydrogen gas given off by a battery, to a safe level. Ventilation systems should therefore be checked to ensure there is no obstruction or, if integral venting is used, the connections should be checked for security and leaks.

NOTE : In some ventilation systems, non-return valves are incorporated in the battery compartment vent lines. These valves should also be checked for security and correct location.

After installation, a check should be made that the electrical connections of the battery supply cables have been correctly secured by switching on some electrical services for a specific time period and noting that readings of the aircraft voltmeter remain steady. A typical load and time is 30 amperes for 30 seconds. For battery system having a separate 'in-situ' charging unit, the unit should be switched on and its electrical settings checked to ensure proper charging of the battery.

MAINTENANCE OF INSTALLED BATTERIES

Batteries should be inspected at the periods specified in the approved aircraft Maintenance Schedule. The details given in the following paragraphs serve as a general guide to the checks normally required.

The battery mounting should be checked for security, and the outside of the battery case should be examined for signs of damage and for evedence of locally overheated areas. The latches of the cover should operate smoothly and should firmly secure the cover in position.

Connecting plugs of the battery receptacle, thermostat and battery charger units, where fitted, should be checked for signs of contamination, burns, cracks, and bent or pitted terminal fittings.

The tops of all cells and vent caps should be inspected for signs of electrolyte leakages and should be cleaned where necessary.

The electrolyte level should be checked, and if any adjustments are necessary, these should be made after removing the battery from the aircraft and checking that it is in the fully charged condition. The amount of water added to the cells should be noted on the battery record card. A cell requiring more than the specified amount should be regarded as suspect, and the battery should be replaced by a serviceable unit. In aircraft having an independent charging unit, the unit should be switched on and the battery charged in accordance with the procedure specified in the relevant aircraft Maintenance Manual.

NOTE : When removed, the battery cover and cell vent caps should not be placed on any part of the aircraft structure or equipment.

The battery ventilation system should be checked to ensure security of connection, and freedom from obstruction.

STORAGE AND TRANSPORTATION

Nickel-cadmium batteries should be stored in a clean, dry, well-ventilated area and should be completely segregated from lead-acid batteries. The area should also be free from corrosive liquids or gases. It is recommended that they should be stored in the condition in which they are normally received from the manufacturer, i.e. filled with electrolyte, discharged and with shorting strips fitted across receptacle pins. Cell connecting strips and terminals should be given a coating of acid- free petroleum jelly (e.g. white vaseline).

The temperatures at which batteries may be stored are quoted in the relevant manuals, and reference should therefore be made to these. In general, a temperature of 20°C is recommended for long-term storage.

If batteries are to be stored in a charged condition, they must be trickle charged periodically in order to balance the inherent self-discharge characteristic. Since this discharge is temperature sensitive, the trickle charge rate is therefore dependent on the storage temperature conditions.

If it is necessary to return a battery to the manufacturer or to an approved overhaul organisation, it should be discharged, but not drained of electrolyte. It should be packed in its original container, together with its service record and 'This Way Up' international signs affixed to the outside.

NOTE : If transportation is to be by air, the container must comply with IATA regulations concerning the carriage of batteries containing alkaline electrolyte.

BUILDING AND EQUIPMENT

General

In no circumstance should the same facility be used for both nickel-cadmium and lead-acid battery charging; and the ventilation arrangements shall be such that no cross contamination can occur.

Buildings and rooms used for the purpose of charging batteries should be well lit and cool, and should have a ventilation system which is capable if exhausting all the gases and fumes which may be present during the servicing and charging operations. The floor surface should be of a material which is impervious to acid and alkali, has non-slip qualities and is quick drying and able to be washed down easily. Examples of such materials are dustless concrete, bituminous compound or tiling. Adequate and suitable drainage should be provided for washing down purposes. Because of the fire risk, it is strongly recommended that doors should be fitted so that they open outwards, thus facilitating easy evacuation from the building in the event of fire. To permit free and easy movement of batteries, steps and thresholds should, where possible, be eliminated. If, however, different levels are unavoidable they should be linked by inclines.

Water Supply

At least one tap in each room where battery charging is carried out should be connected to a mains fresh water supply. Sinks and draining boards and a hot water supply should also be provided.

Lighting

The level of lighting within the charging rooms should be sufficient to enable the level of the electrolyte in individual cells of batteries to be easily determined without additional lighting. To prevent accidental ignition of gases all electrical fittings should be of a spark proof design.

Temperatures

1. Electrolyte Temperature.

The maximum permissible electrolyte temperature during charging is normally 50°C (122°F), but some batteries of special design, however, have lower limits; for such batteries the temperature limitations will be specified in the manufacturer's publication for that battery.

2. Environmental Temperature

Environmental temperatures exceeding 27°C (81°F) for lead-acid batteries and 21°C (70°F) for nickel-cadmium batteries impose time penalties in reaching the fully charged state and may also be deleterious to the batteries. The temperature of battery charging rooms should, therefore, be maintained at a temperature consistent with specified limitations, and with a free air flow around each battery or cell..

CHARGING BOARDS AND BENCHES

Detailed differences exist between the various types of charging board, but in general each board consists of a pair of terminals, to which the rectified a.c. supply is connected (or in the case of a board which has a build-in rectifier unit, to which the mains supply is connected), together with a number of pairs of output terminals, to which the batteries are connected for charging.

All the output circuits are internally connected in parallel, and are, therefore, independent of each other, with the level of charge being controlled separately for each output circuit. Each pair of output terminals is normally designed to have one group of batterie or cells connected in series.

NOTE : Parallel connection of batteries to one pair of output terminals is not permitted.

Charging boards should be mounted directly above the rear of the benches so that the necessity for long connecting cables is avoided.

Battery connecting cables should be well insulated and should be of a sufficient capacity to carry the charging current required. The free ends of connecting cables should be fitted with suitable connectors, which should be firmly secured to the battery and charging board before commencing charging operations. Connections to the charging boards should not be made or broken when power is switched on. On completion of the charging cycle, power should be switched off and the charging cables should be disconnected, first from the battery and then from the charging board.

Benches

Benches and associated equipment should be sited so that the need for personnel to lean over batteries is kept to a minimum. It is recommended that the height of battery charging benches be approximately 0.5m (20 in) from the floor. At this height, lifting strain is minimised, and a more effective visual inspection of the batteries can be made.

The surfaces of battery charging benches should be acid and alkali resistive, and should facilitate cleaning. It is generally considered that batteries should not be allowed to stand directly on wood or concrete, but should rest on suitable grids.

POWER SUPPLIES

Transformer/rectifiers which normally provide rectified a.c. for charging board supplies should be sited in a fume free, dry and cool position, preferably in a separate room, located as near as possible to the charging boards. Charging boards which require 240 volts mains supply, should be supplied from a ring main system.

STORAGE

Batteries

In order to preserve an orderly flow of work through a battery charging room, storage facilities should be provided such that incoming unserviceable batteries may be separated from those ready for issue, preferably in clearly placarded areas. The storage facilities should be further grouped for those batteries requiring initial charge and those awaiting routine servicing. Batteries which are serviceable and awaiting issue are best stored in an area which is not subjected to excessive vibration. It is essential that whilst in store, lead-acid batteries be segregated at all times from nickel-cadmium batteries ; preferably in separate store rooms.

Electrolytes

The handling and storage of electrolyte materials should always be in accordance with the manufacturer's instructions. It is, however, essential that when undertaking the mixing or breaking down of these chemicals, separate areas are provided. Glass, earthenware or lead-lined wood containers are suitable for the storage of lead-acid battery electrolyte (sulphuric acid), whilst plain iron, glass or earthenware containers are suitable for the storage of nickel-cadmium battery electrolyte (potassium hydroxide). Galvanised containers or containers with soldered seams must not be used. Each container should be clearly marked as to its contents and should be stored accordingly. Waste or surplus materials should be disposed of in accordance with locally approved instructions. If, however doubt exists, all electrolytes should be neutralised prior to disposal. All mixing vessels, mixing rods and other similar items should be clearly marked with "acid only" or "alkaline only", and their use should be restricted accordingly.

Stocks of electrolyte materials which are retained in a battery charging room should be restricted to the quantities required for immediate use. The storing of electrolyte mixed ready for use should be avoided as far as possible.

a. Sulphuric acid containers should be kept tightly sealed when not in use, to prevent contamination. Only the container which is required for immediate use should be retained in the charging room.
b. Potassium hydroxide is supplied in solid form contained in steel drums. Once a drum has been opened the contents are liable to carbon dioxide contamination. The entire contents should, therefore, always be mixed as soon as a drum has been opened. Any unused mixture should be stored in a stoppered glass container.

De-mineralised and distilled water are generally supplied in carboys, and should be stored separately from the electrolytes so as to avoid contamination. Carboys should be firmly stoppered when not in use, and should be clearly marked as to the contents. Only the water container used for 'topping up' should be kept in the charging room, and the stopper should be refitted immediately after use.

The neutralising agents for the two types of electrolytes are given below, together with the action that should be taken in the event of contamination and/or spillage.

Sulphuric Acid

The neutralising agents are : -
a. Saturated solution of bicarbonate of soda.
b. Ammonia powder.
c. Borax powder.

The acid should be soadked up with sawdust which should then be removed and buried. The affected area should be treated with one of the above, followed by washing down with copious amounts of fresh water.

Potassium Hydroxide

The neutralising agents are :-
a. Boric acid solution.
b. Boric acid crystals or powder.

The alkali should be soaked up with sawdust, which should then be removed and buried. The affected area should be treated with one of the above, followed by washing down with copious amounts of fresh water.

Containers of sawdust and neutralising agents should be clearly marked with their contents and use, and sited in readily accessible positions.

PROTECTION

To prevent the risk of burns, such personal items as rings, metal watches, watchstraps and identification bracelets should be removed, to avoid contact with connecting links and terminals. Personal protection against the harmful effects of acid and alkali contamination should be in accordance with the provisions of the Factories Act.

In general, smoking should only be permitted in rooms which do not have a direct access to battery charging rooms or chemical mixing areas. Naked lights, non-safety matches and automatic lighters should not be taken into battery charging rooms.

Fire extinguishers of the CO_2 type and buckets of sand should be placed at strategic points inside the building for use in the event of any chemical fires.

DOCUMENTATION

Records of battery servicing should be maintained to the standard recommended by Leaflets for lead-acid batteries and for nickel-cadmium batteries.

SERVICING AND TEST EQUIPMENT

Servicing of aircraft batteries should be carried out in accordance with the instructions contained in the manufacturers' Maintenance Manual.

In addition to the general engineering hand tools which may be required for aircraft battery servicing, the following specialised items will also be required :-

a. Hydrometers.
b. Thermometers,
c. Battery kits (as supplied by battery manufacturers).
d. Capacity test sets.
e. Leakage tester (lead-acid batteries).
f. Filler pumps (for transferring of liquids from one container to another).
g. Calibrated test equipment :
   i. Insulation resistance tester.
   ii. Universal test meter.
   iii. Digital voltmeter.

To prevent cross-contamination between the two types of aircraft batteries, two sets of equipment should be held, each being contained in separate cupboards and clearly marked "acid only" or "alkaline only" as appropriate to the application. Whenever possible, tools and equipment comprising the sets should be those constructed of an insulating material. Each item should be identified as to its application, and in the case of hydrometers and thermometers, this is usually best done on the instrument case.

TYPICAL BATTERY SYSTEMS

(Fig. 8.10) shows the circuit arrangement for a battery system which is employed in a current type of turboprop airliner; the circuit serves as a general guide to the methods adopted. Four batteries, in parallel are directly connected to a battery busbar which, in the event of an emergency, supplies power for a limited period to essential consumer services, i.e. **radio, fire-warning and extinguishing systems, a compass system, etc**. Direct connections are made to ensure that battery power is available at the busbar at all times.

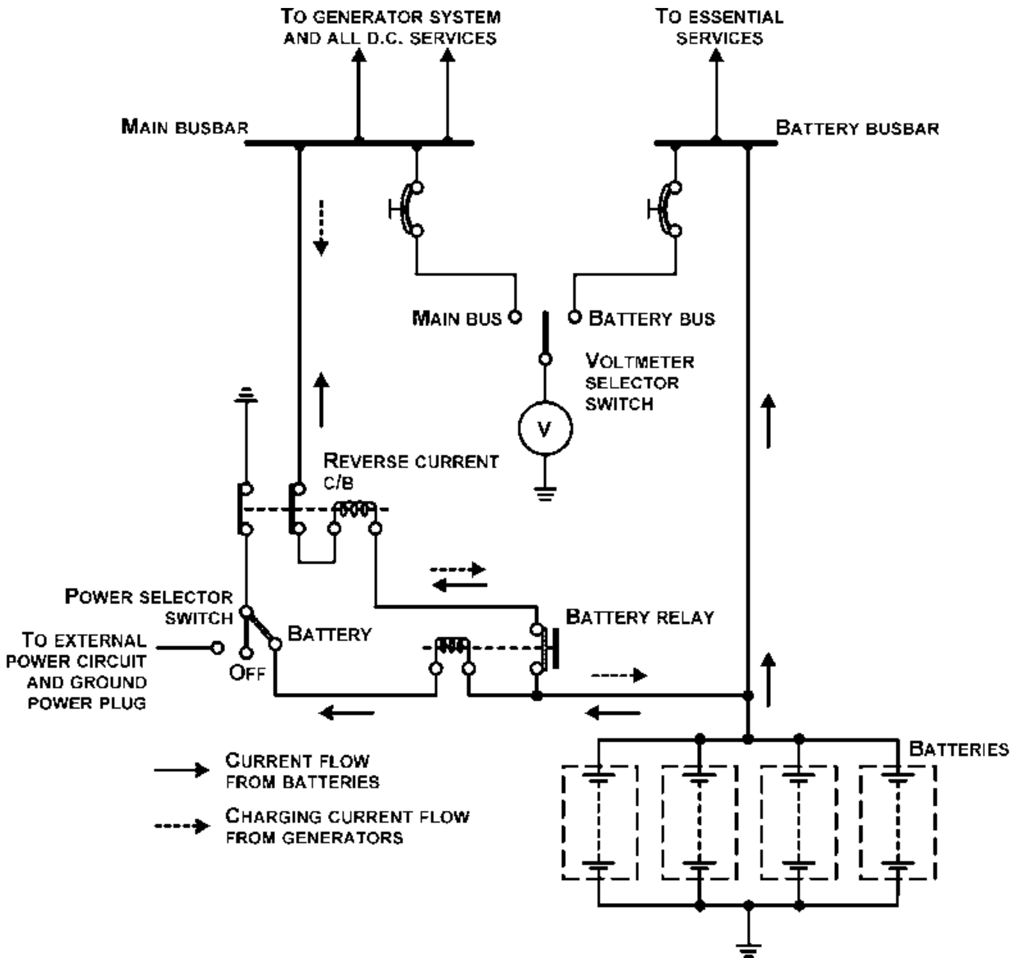


Fig. 8.10. Typical battery system circuit.

The batteries also require to be connected to ensure that they are maintained in a charged condition. In the example illustrated this is accomplished by connecting the batteries to the main d.c. busbar via a battery relay, power selector switch and a reverse current circuit breaker.

Under normal operating conditions of the d.c. supply system, the power selector switch is set to the "battery" position (in some aircraft this may be termed the "flight" position) and, as will be noted, current flows from the batteries through the coil of the battery relay, the switch, and then to ground via the reverse current circuit breaker contacts. The current flow through the relay coil energizes it, causing the contacts to close thereby connecting the batteries to the main busbar via the coil and second set of contacts of the reverse current circuit breaker. The d.c. services connected to the main busbar are supplied by the generators and so the batteries will also be supplied with charging current from this source.

Under emergency conditions, e.g. a failure of the generator supply or main busbar occurs, the batteries must be isolated from the main busbar since their total capacity is not sufficient to keep all services in operation. The power selector switch must therefore be put to the "off" position, thus de-energizing the battery relay. The batteries then supply the essential services for the time period pre-calculated on the basis of battery capacity and current consumption of the essential services.

The reverse current breaker in the system shown is of the electromagnetic type and its purpose is to protect the batteries against heavy current flow from the main busbar. Should this happen the current reverses the magnetic field causing the normally closed contacts to open and thereby interrupt the circuit between the batteries and main busbar, and the battery relay coil circuit.

The battery system in some types of turboprop powered aircraft is so designed that the batteries may be switched from a parallel configuration to a series configuration for the purpose of starting an engine from the batteries. The circuit arrangement of one such system using two 24-volt nickel-cadmium batteries is shown in simplified form in (Fig.8.11).

Under normal parallel operating conditions, battery 1 is connected to the battery busbar via its own battery relay, and also contacts 1a-1b of a battery switching relay. Battery 2 is directly connected to the busbar via its relay.

When it is necessary to use the batteries for starting an engine, i.e. to make an "internal" start, both batteries are first connected to the battery busbar in the normal way, and the 24-volt supply is fed to the starter circuit switch from the busbar. Closing of the starter switch energizes the corresponding starter relay, and at the same time the 24-volt supply is fed via the starting circuit, to the coil of the battery switching relay thereby energizing it. Contacts 1a-1b of the relay are now opened to interrupt the direct connection between battery 1 and the busbar. Contacts 3a-3b are also opened to interrupt the grounded side of battery 2. However, since contacts 2a-2b of the switching relay are simultaneously moved to the closed position, they connect both batteries in series so that 48 volts is supplied to the busbar and to the starter motor.

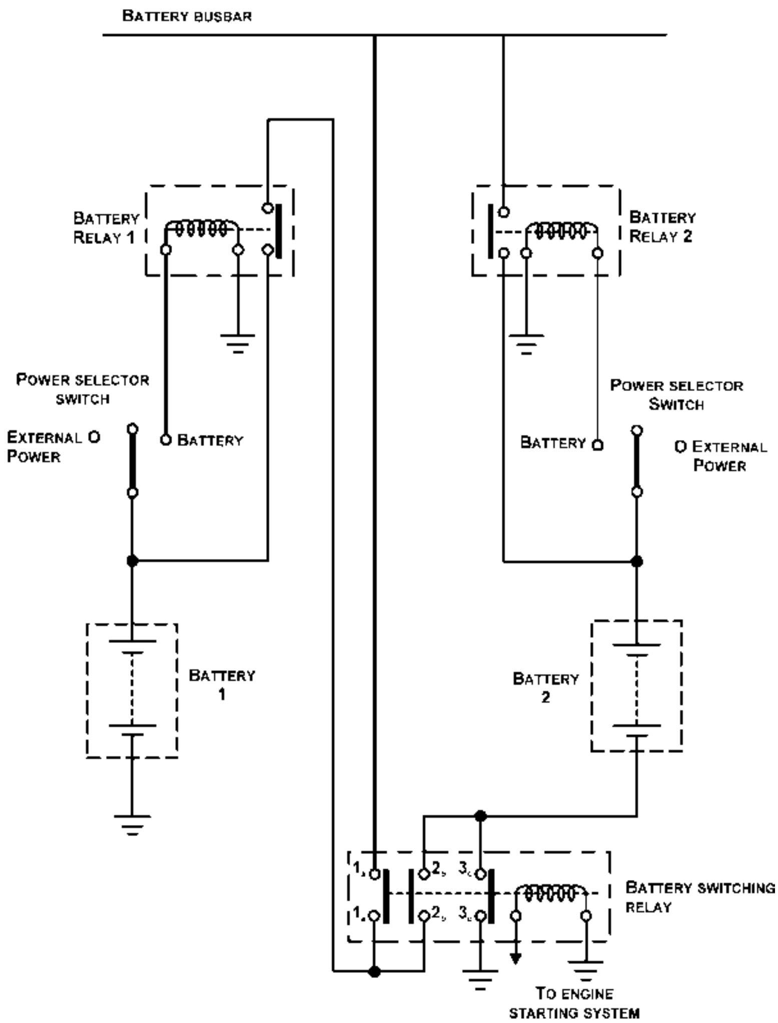


Fig. 8.11. Parallel/series connection of batteries.

After the engine has started and reached self-sustaining speed, the starter relay automatically de-energizes and the battery switching relay coil circuit is interrupted to return the batteries to their normal parallel circuit configuration.

The power selector switches are left in the "battery" position so that when the engine-driven generator is switched onto the busbar, charging current can flow to the batteries.

Battery Charging from External Power

In some single-engined aircraft systems, the battery may be charged when an external power unit is plugged into the aircraft. This is achieved by a battery relay closing circuit connected across the main contacts of the relay as shown in (Fig. 8.12).

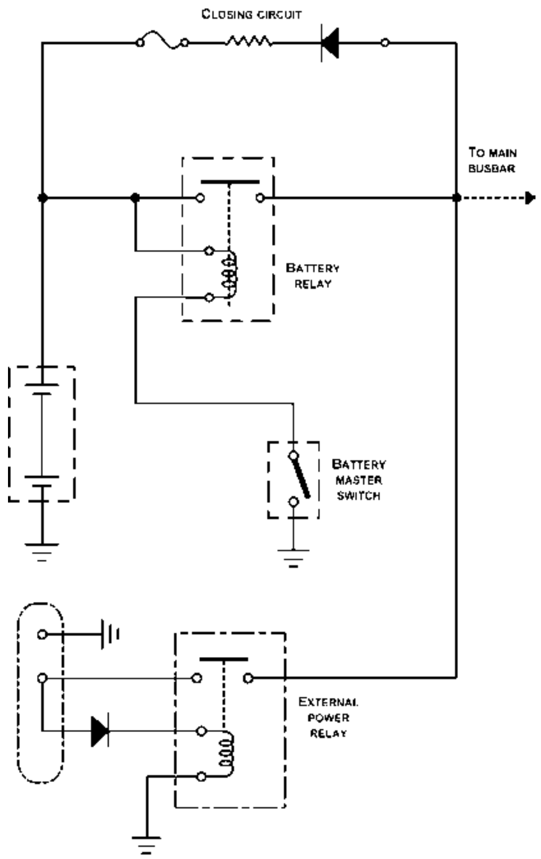


Fig. 8.12. Battery charging from external power.

With the external power connected and switched on, power is available to the battery relay output terminal via the closed contacts of the external power relay. At the same time, power is applied to the battery relay closing circuit via its diode and resistor which reduces the voltage to the input side of the battery relay's main contacts and coil.

When the battery master switch is selected to "on", sufficient current flows through the coil of the battery relay to energize it. The closed contacts of the relay then allow full voltage from the external power unit to flow to the battery for the purpose of charging it. The purpose of the fuse in the closing circuit is to interrupt the charge in the event of a "shorted" battery.

When the battery is being charged in this manner, the voltage and current output from the external power unit must be properly regulated.

"On-board" Battery Charger Units

In most types of turbojet transport aircraft currently in service, the battery system incorporates a separate unit for maintaining the batteries in a stage of charge. Temperature-sensing elements are also normally provided in order to automatically isolate the charging circuit whenever there is a tendency for battery over-heating to occur. The circuits of "on-board" charger units as they are generally termed, vary between aircraft types, and space limits description of all of them. We may however, consider two examples which hightlight some of the variations to be found.

The much simplified circuit shown in (Fig 8.13), is based on the system adopted for the Mc Donnell Douglas DC-10. In this particular application, the required output of 28 volts is achieved by connecting two 14-volt batteries in series. The batteries are only connected to the battery busbar whenever the normal d.c. supply (in this case from transformer/ rectifier units) is not available. Connection to the busbar and to the charger unit is done automatically by means of a "charger/battery" relay and by sensing relays.

When power is available from the main generating system, d.c. is supplied to the battery busbar from a transformer/ rectifier unit and, at the same time, to the coils of the sensing relays. With the relays energized, the circuit through contacts A2-A3 is interrupted while the circuits through contacts B1-B2 are made. The battery switch, which controls the operation of the charger/battery relay, is closed to the "batt" position when the main electrical power is available, and the emergency power switch is closed in the "off" position.

The charger/battery relay is of the dual type, one relay being a.c. operated and the other d.c. operated. The a.c. relay coil is supplied with power from one phase of the main three-phase supply to the battery charger, and as will be noted from the diagram, the relay is energized by current passing to ground via the contacts B1-B2 of the sensing relays, the battery switch and the emergency switch. Energizing of the relay closes the upper set of contacts (A1-A2) to connect the d.c. positive output from the battery charger to the batteries, thereby supplying them with charging current.

In the event of main power failure, the battery charger will become inoperative, the a.c. charger relay will de-energize to the centre off position, and the two sensing relays will also de-energize, thereby opening the contacts B1-B2 and closing the contacts A2-A3. The closing of contacts A2-A3 now permits a positive supply to flow direct from the battery to the coil of the d.c. battery relay, which on being energized also actuates the a.c. relay, thereby closing contacts B1-B2 which

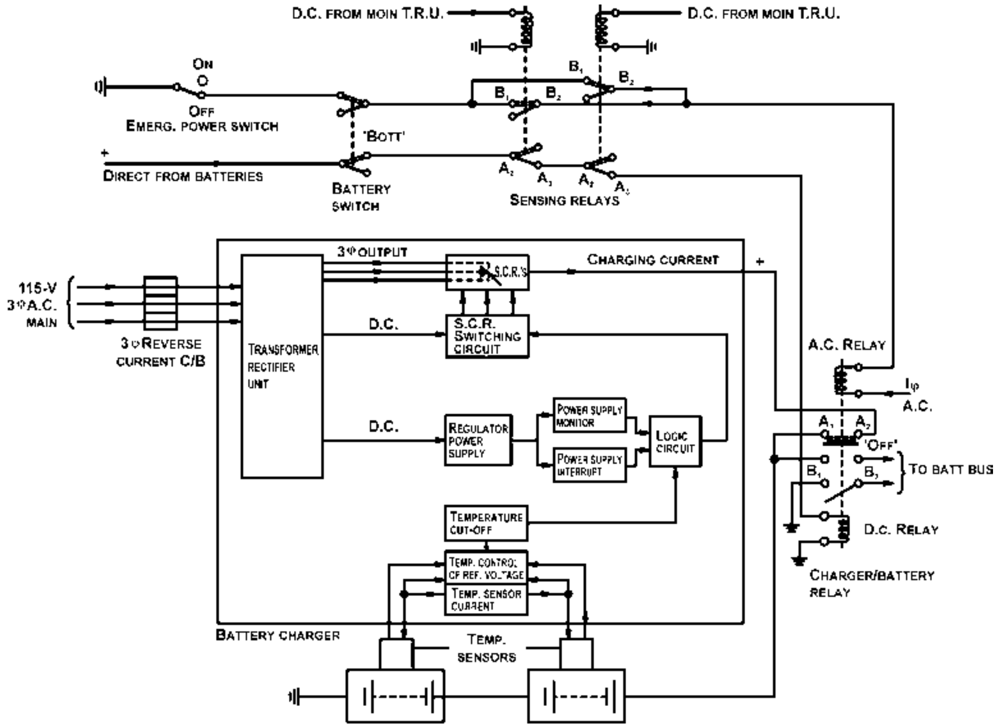


Fig. 8.13. In-situ battery charging system.

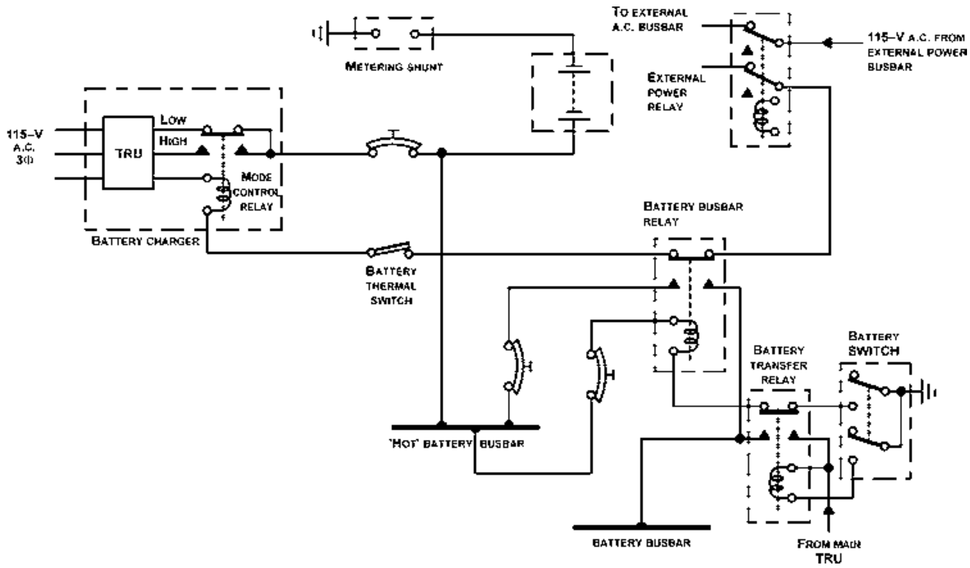


Fig. 8.14. Battery charger control circuit.

connect the batteries direct to the battery busbar. The function of the battery relay contacts is to connect a supply from the battery busbar to the relays of an emergency warning light circuit. The charging unit converts the main three-phase supply of 115/200 volts a.c. into a controlled d.c. output at constant current and voltage, via a transformer and a full-wave rectifying bridge circuit made up of silicon rectifiers and silicon controlled rectifiers. The charging current is limited to approximately 65A, and in order to monitor this and the output voltage as a function of battery temperature and voltage, temperature-sensing elements within the batteries are connected to the S.C.R. "gates" via a temperature and reference voltage control circuit, and a logic circuit. Thus, any tendency for overcharging and overheating to occur is checked by such a value of gate circuit current as will cause the S.C.R. to switch off the charging current supply.

The second example shown in (Fig. 8.14) and (Fig. 8.15), is based on that used in the Boeing 737. The charger operates on 115 volt 3-phase a.c. power supplied from a "ground service" busbar, which in turn, is normally powered from the number 1 generator busbar, and/or from an external power source. Thus, the aircraft's battery is maintained in a state of charge both in flight and on the ground.

In flight the a.c. supply is routed to the charger through the relaxed contacts of a battery charger transfer relay and an APU start interlock relay. The d.c. supply for battery charging is obtained from a transformer-rectifier unit within the charger, and it maintains cell voltage levels in two modes of operation : high and low. Under normal opereating

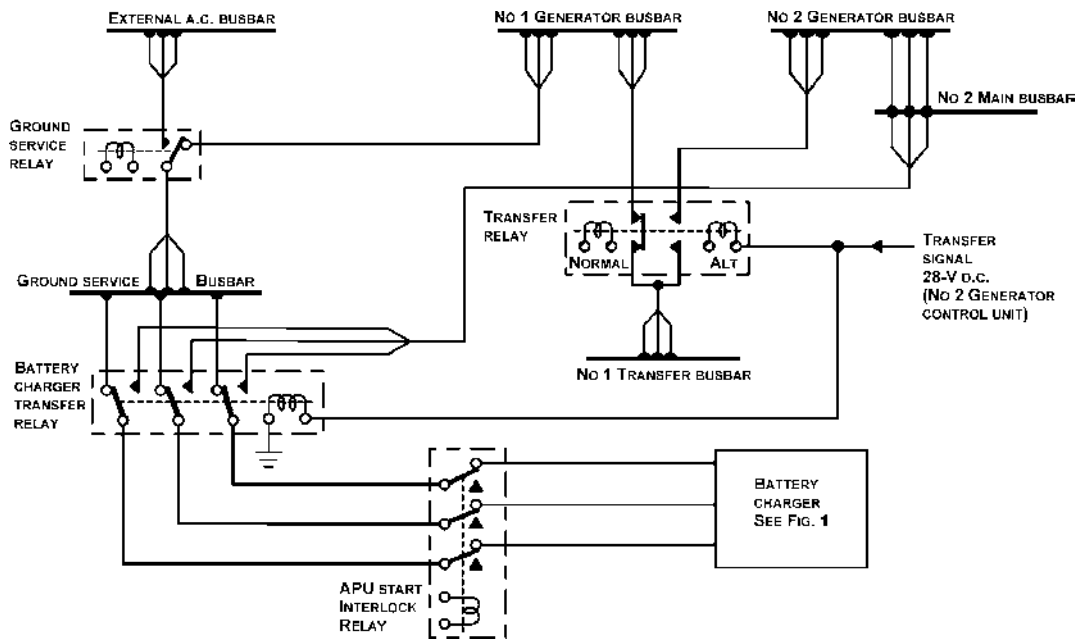


Fig. 8.15. Battery charger.

conditions of the aircraft's power generation system, the charging level is in the high mode since as will be noted from the diagram, the mode control relay within the charger is energized by a rectified output through the battery thermal switch, and the relaxed contacts of both the battery bus relay and the external power select relay. Above 16 amps the charger acts as an unregulated transformer-rectifier unit, and when the battery has sufficient charge that the current tends to go below 16 amps, the charging current is abruptly reduced to zero. The current remains at zero until the battery voltage drops below the charge voltage, at which time the charger provides the battery with a pulsed charge until the control circuits within the charger change the operation to the low mode, approximately two minutes after pulse charging commences.

In the event that the number one generator supply fails there will be a loss of a.c. power to the ground service busbar, and therefore, to the battery charger. However, with number two generator still on line, a transfer signal from its control unit is automatically supplied to the coil of the battery charger transfer relay, and as may be seen from (Fig 8.15), its contacts change over to connect the charger to the a.c. supply from number two generator, and so charger operation is not interrupted.

The APU start interlock relay is connected in parallel with a relay in the starting circuit of the APU, and is only energized during the initial stage of starting the APU engine. This prevents the starter motor from drawing part of its heavy starting current through the battery charger. The interlock relay releases automatically when the APU engine reaches 35% rev/min.

In addition to the control relay within the battery charger, there are three other ways in which the charging mode can be controlled, each of them fulfilling a protective role by interrupting the ground circuit to the mode control relay and so establishing a low mode of charge. They are

(i) opening of the battery thermal switch in the event of the battery temperature exceeding 46°C (115°F)

(ii) loss of d.c. power from the designated transformer-rectifier unit causing the battery transfer relay to relax and the battery bus relay to energize

(iii) energizing of the fuelling panel power select relay when external a.c. power is connected to the aircraft. The latter is of importance since if the charger was left to operate in the high mode, then any fault in the regulation of the external power supply could result in damage to theaircraft battery.

■■■

CHAPTER - 9
DC GENERATORS AND MOTORS
KNOWLEDGE OF THE CONSTRUCTION, PRINCIPLE OF OPERATION AND CHARACTERISTICS OF DC GENERATORS AND MOTORS. KNOWLEDGE OF THE CONSTRUCTION, PRINCIPLES OF OPERATION OF VOLTAGE REGULATORS AND PARALLELING OF GENERATORS. DETAILED KNOWLEDGE OF THE FUNCTIONAL TESTS, ADJUSTMENTS AND TROUBLE SHOOTING OF GENERATORS AND MOTORS. KNOWLEDGE OF SPEED CONTROL AND REVERSING THE DIRECTION OF MOTORS

GENERATOR PRINCIPLE

An electrical generator is a machine which converts mechanical energy (or power) into electrical energy (or power). This energy conversion is based on the principle of the production of dynamically (or motionally) induced e.m.f. As seen from (Fig. 9.1) whenever a conductor cuts magnetic flux, dynamically induced e.m.f. is produced in it according to Faraday's Laws of Electromagnetic Induction. This e.m.f. will cause a current to flow if the conductor circuit is closed.

Hence, the basic essential parts of an electrical generator are (i) a magnetic field and (ii) a conductor or conductors which can move so as to cut the flux.

Simple Loop Generator

a. Construction

In (Fig. 9.1) is shown a single-turn rectangular copper coil ABCD rotating about its own axis in a magnetic field provided by either permanent magnets or electromagnets. The two ends of the coil are joined to two sliprings or discs 'a' and 'b' which are insulated from each other and from the central shaft. Two collecting brushes (of carbon) press against the sliprings. Their function is to collect the current induced in the coil and to convey it to the external load resistance R.

The rotating coil may be called as armature and the magnets as field magnets.

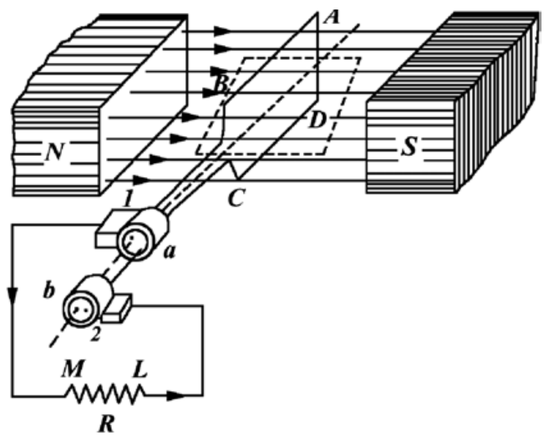


Fig. 9.1.

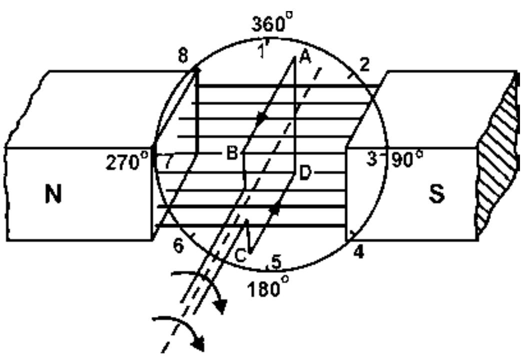


Fig. 9.2.

b. Working

Imagine the coil to be rotating in clockwise direction (Fig. 9.2). As the coil assumes successive positions in the field, the flux linked with it changes. Hence, an e.m.f. is induced in it, which is proportional to the rate of change of flux linkages

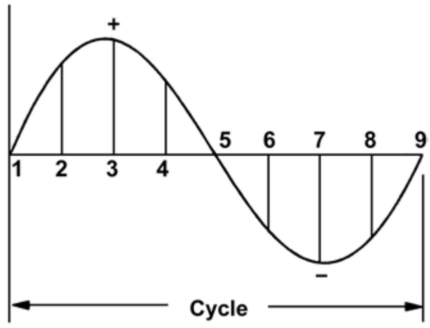


Fig. 9.3.

($e = ND\phi/dt$). When the plane of the coil is at right angles to the lines of flux i.e. when it is in position 1, the flux linked with the coil is maximum but rate of change of flux linkage is minimum. This is so because in this position, the coil sides AB and CD do not cut or shear the lines of flux, rather they slide along them i.e. they move parallel to them. Hence, there is no induced e.m.f. in the coil. Let us take this no. e.m.f. or vertical position of the coil as the starting position. The angle of rotation or time will be measured from this position.

As the coil continues rotating further, the rate of change of flux linkages (and hence induced e.m.f. in it) increases, till position 3 is reached where $\theta = 90^0$. Here, the coil plane is horizontal i.e. parallel to the lines of flux. As seen, the flux linked with the coil is minimum but rate of change of flux linkages or rate of flux cutting is maximum. Hence, maximum e.m.f. is induced in the coil when in this position (Fig. 9.3).

In the next quarter revolution i.e. from 90^0 to 180^0, the flux linked with the coil gradually increases, but rate of change of flux decreases. Hence, the induced e.m.f. decreases gradually till in position 5 of the coil, it is reduced to zero value (Fig. 9.3).

So, we find that in the first half revolution of the coil, no (or minimum) e.m.f. is induced in it when in position 1, maximum e.m.f. is induced when in position 3 and no e.m.f. is induced when in position 5. The direction of this induced e.m.f. can be found by applying Fleming's Right-hand rule which gives its direction from A to B and C to D. Hence, the direction of current flow is ABMLCD (Fig. 9.1). The current through the load resistance R flows from M to L during the first half revolution of the coil.

In the next half revolution i.e. from 180^0 to 360^0, the variations in the magnitude of e.m.f. are similar to those in the first half revolution. Its value is maximum when coil is in position 7 and minimum when it is in position 1. But it will be found that the direction of the induced current is from D to C and B to A. Hence, the path of current flow is along DCLMBA which is just the reverse of the previous direction of flow.

Therefore, we find that the current which we obtain from such a simple generator reverses its direction after every half revolution. Such a current undergoing periodic reversals is known as alternating current (A.C.). It is, obviously, different from a direct current (D.C.) which continuously flows in one and the same direction. It should be noted that A.C. not only reverses its direction, it does not even keep its magnitude constant while flowing in any one direction. The two half-cycles may be called positive and negative half cycles respectively (Fig.9.3).

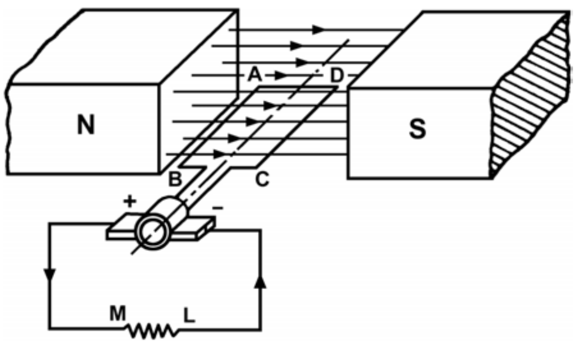


Fig. 9.4.

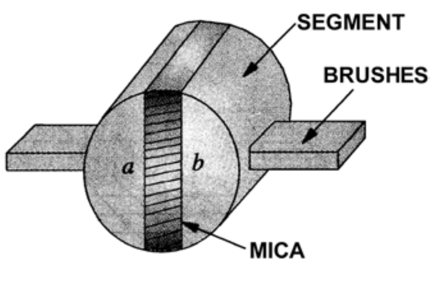


Fig. 9.5.

For making the flow of current unidirectional in the external circuit, the slip-rings are replaced by split-rings (Fig.9.4) The split-rings are made out of a conducting cylinder which is cut into two halves or segments insulated from each other by a thin sheet of mica or some other insulating material (Fig.9.5).

As before, the coil ends are joined to these segments on which rest the carbon brushes.

It is seen [Fig. 9.6 (a)] that in the first half revolution, current flows along ABLMCD i.e. brush No.1 which is in contact with segment 'a', acts as the positive end of the supply and brush No.2 and 'b' as the negative end. In the next half revolution [Fig.9.6 (b)], the direction of the induced current in the coil is reversed. But at the same time, the positions of segments 'a' and 'b' are also reversed with the result that brush No.1 comes in touch with that segment which is positive

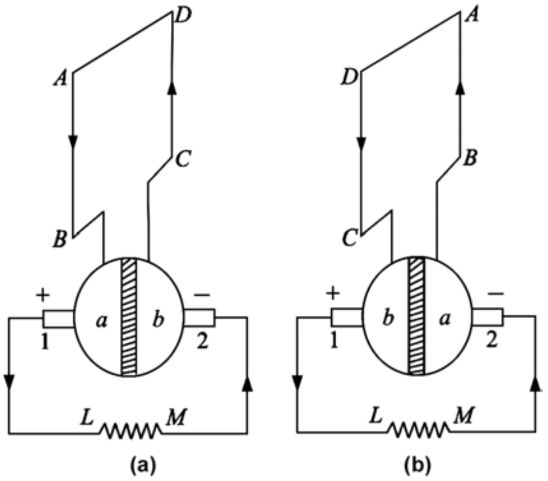


Fig. 9.6.

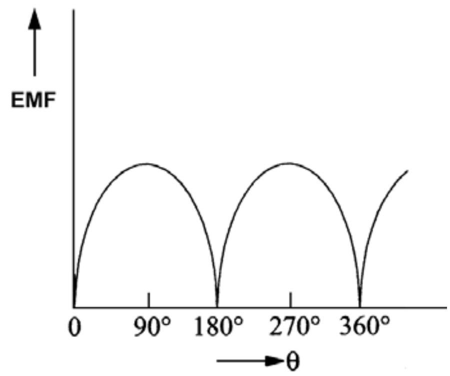


Fig. 9.7.

i.e. segment 'b'. Hence, the current in the load resistance again flows from L to M. The wave-form of the current through the external circuit is as shown in (Fig. 9.7). This current is unindirectional but not continuous like pure direct current.

It should be noted that the position of brushes is so arranged that the changeover of segments 'a' and 'b' from one brush to the other takes place when the plane of the rotating coil is at right angles to the plane of the lines of flux because in that position, the induced e.m.f. in the coil is zero.

Another important point to remember is that even now the current induced in the coil sides is alternating as before. It is only due to the rectifying action of the split-rings (also called commutator) that it becomes unidirectional in the external circuit. Hence, it should be clearly understood that even in armature of a d.c. generator, the induced current is alternating.

Generator Construction

A typical self-excited shunt-wound four-pole generator, which is employed in a current type of turbo-prop civil transport aircraft, is illustrated in (Fig.9.8). It is designed to provide an output of 9 kilowatts at a continuous current of 300 amperes (A) over the speed range of 4,500 to 8,500 rev/min. In its basic form the construction follows the pattern conventionally adopted and consists of five principal assemblies; namely, the yoke, armature, two end frames and brush-gear assembly.

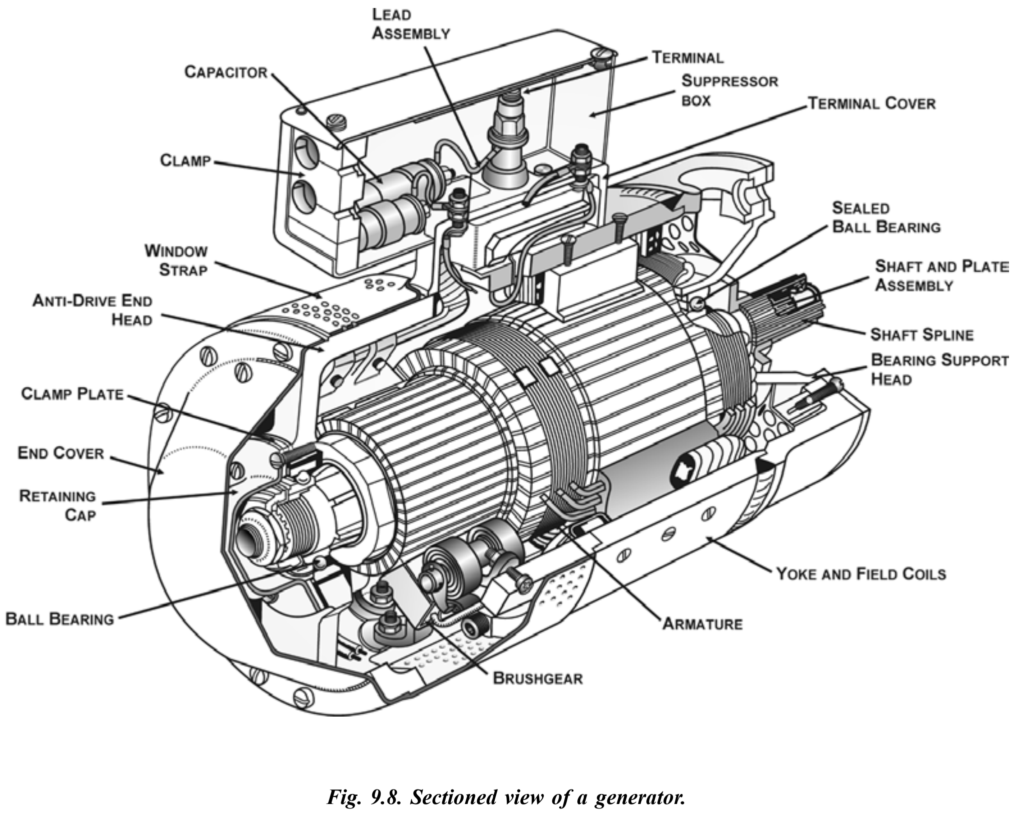


Fig. 9.8. Sectioned view of a generator.

THE YOKE

The yoke forms the main housing of the generator, and is designed to carry the electromagnet system made up of the four field windings and pole pieces. It also provides for the attachment of the end frame assemblies. The windings are pre-formed coils of the required ampere-turns, wound and connected in series in such a manner that when mounted on the pole pieces, the polarity of the field produced at the poles by the coil current is alternately North and South (see Fig. 9.9). The field windings are suitably insulated and are a close fit on the pole pieces which are bolted to the yoke. The face of the pole pieces are subjected to varying magnetic fields caused by rotation of the armature, giving rise to induced e.m.f. which in turn produces eddy currents through the pole pieces causing local heating and power wastage. To minimize these effects the pole pieces are of laminated construction; the thin soft iron laminations being oxidized to insulate and to offer high electrical resistance to the induced e.m.f.

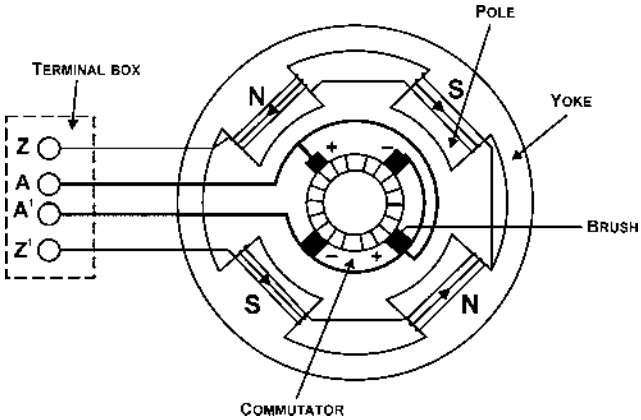


Fig. 9.9. Fixed winding arrangements.

ARMATURE ASSEMBLY

The armature assembly comprises the main shaft (which may be solid or hollow) core and main winding, commutator and bearing; the whole assembly being statically and dynamically balanced. In the generator shown, the shaft is hollow and internally splined to mate with splines of a drive shaft which passes through the entire length of the armature shaft.

Armature windings are made up of a number of individual identical coils which fit into slots at the outer edges of steel laminations which form the core of the armature. The coils are made from copper strip and as security against displacement by centrifugal force, steel wire (in some cases steel strip) is bound round the circumference of the armature. The ends of each coil are brought out to the commutator and silver brazed to separate segments, the finish of one coil being connected to the same segment as the beginning of another coil. The complete winding thus forms a closed circuit. The windings are invariably vacuum-impregnated with silicone varnish to maintain insulation resistance under all conditions.

In common with most aircraft generators, the commutator is of small diameter to minimize centrifugal stressing, and is built up of long, narrow copper segments corresponding in number to that of the field coils (a typical figure is 51 coils). The segment surfaces are swept by brushes which are narrow and mounted in pairs (usually four pairs) to maintain the brush contact area per segment - an essential pre-requisite for effective commutation.

The armatures of all aircraft generators are supported in high efficiency ball or roller bearings, or in combinations of these two types. Where combinations are used in a single generator it will be found that the ball bearing is invariably fitted at the drive end of the armature shaft, and the roller bearing at the commutator end. This arrangement permits lateral expansion of the armature shaft, arising from temperature increases in the generator, without exposing the bearings to risk of damage. Bearings are lubricated either with a specified high-melting-point grease or lubricating oil and may be of the sealed or non-sealed types. Sealed grease-lubricated bearings are pre-packed by the manufacturer and require no further lubrication during the life of the bearing. Non-sealed grease-lubricated bearings are assembled with sufficient lubricant to last for the period of the generator servicing cycle. In general the lubricant for oil-lubricated bearings is introduced into the bearing through the medium of oil-impregnated felt pads. Seals are provided to prevent oil escaping into the interior of the generator.

END FRAME ASSEMBLIES

These assemblies are bolted one at each end of the yoke and house the armature shaft bearings. The drive end frame provides for the attachment of the generator to the mounting pad of the engine or gear-box drive and the commutator and frame provides a mounting for the brush-gear assembly and, in the majority of cases, also provides for the attachment of a cooling air duct. Inspection and replacement of brushes is accomplished by removing a strap which normally covers apertures in the commutator end frame.

BRUSH-GEAR ASSEMBLY

The brush-gear assembly is comprised of the brushes and the holding equipment necessary for retaining the brushes in the correct position, and at the correct angle with respect to the magnetic neutral axis.

Brushes used in aircraft generators are of the electrographitic type made from artificial graphite. The graphite is produced by taking several forms of natural carbons, grinding them into fine powder, blending them together and consolidating the mixture into the desired solid shape by mechanical pressure followed by exposure to very high temperature in an electric furnace. These brushes possess both the robustness of carbon and the lubricating properties of graphite. In addition they are very resistant to burning by sparking, they cause little commutator wear and their heat conductivity enables them to withstand overloads.

As stated earlier, an essential prerequisite for effective commutation is that brush contact area per commutator segment should be maintained. This is accomplished by mounting several pairs of brushes in brush holders; in the generator illustrated in (Fig. 9.8) four pairs of brushes are employed. The holders take the form of open-ended boxes whose inside surfaces are machined to the size of a brush, plus a slight clearance enabling a brush to slide freely without tilting or rocking. Contact between brushes and commutator is maintained by the pressure exerted by the free ends of adjustable springs anchored to posts on the brush holders. Springs are adversely affected by current passing through them; it is usual, therefore, to fit an insulating pad or roller at the end of the spring where it bears on the top surface of the brush.

The brush holders are secured either by bolting them to a support ring (usually called a brush rocker) which is, in turn, bolted to the commutator end frame, or as in the case of the generator illustrated, bolted directly to the end frame. In order to achieve the best possible commutation a support ring, or end frame, as appropriate, can be rotated through a few degrees to alter the position of the brushes relative to the magnetic neutral axis. Marks are provided on each generator to indicate the normal operating position.

When four or more brush holders are provided, they are located diametrically opposite and their brushes are alternately positive and negative, those of similar polarity being connected together by bar and flexible wire type links.

The brushes are fitted with short leads or "pigtails" of flexible copper braid moulded into the brush during manufacture. The free ends of the pigtails terminate in spade or plate type terminals which are connected to the appropriate main terminals of the generator via the brush holders and connecting links.

GENERATOR TERMINALS

On large 24-volt generators, electrical connections are made to terminals marked B, A and E see (Fig. 9.10). The positive armature lead connects to the B terminal, the negative armature lead connects to the E terminal, and the positive end of the shunt field winding connects to terminal A. The negative end of the shunt field winding is connected to the negative terminal brush. Terminal A receives current from the negative generator brush through the shunt field winding. This current passes through the positive brush. Load current, which leaves the armature through the negative brush, comes out of the E lead and passes through the load before returning through the positive brush.

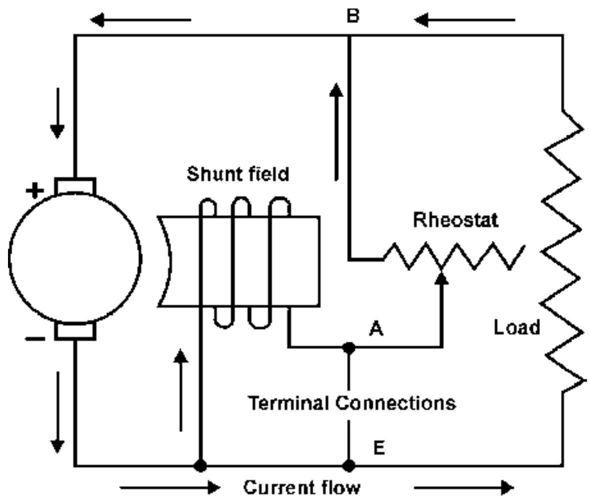


Fig. 9.10. Regulation of generator voltage by field rheostat.

SPARK SUPPRESSION

Sparking at the brushes of a generator, no matter how slight, results in the propagation of electromagnetic waves which interfere with the reception of radio signals. The interference originating in generators may be eliminated quite effectively by screening and suppression. Screening involves the enclosure of a generator in a continuous metallic casing and the sheathing of output supply cables in continuous metallic tubing or conduit to prevent direct radiation. To prevent interference being conducted along the distribution cable system, the screened output supply cables are terminated in filter or suppressor units. These units consist of chokes and capacitors of suitable electrical rating built into metal cases located as close to a generator as possible. Independent suppressor units are rather cumbersome and quite heavy, and it is therefore the practice in the design of current types of generator to incorporate internal suppression systems. These systems do not normally contain chokes, but consist simply of suitably rated capacitors which are connected between generator casing (earth) and terminals. The use of internal suppression systems eliminated the necessity for screened output supply cables and conduits thereby making for a considerable saving in the overall weight of a generator installation.

GENERATOR RATINGS

A generators is rated according to its power output. Since a generator is designed to operate at a specified voltage, the rating is usually given as the number of amperes the generator can safely supply at its rated voltage. For example, a typical generator rating is 300 amps at 30 i.e. kilowatt volts. A generator's rating and performance data are stamped on the name plate attached to the generator. When replacing a generator make sure it is of proper rating.

The rotation of generators is termed as either clockwise or counter clockwise, as viewed from the driven end. If no direction is stamped on the data plate, the rotation is marked by an arrow on the cover plate of the brush housing. To maintain the correct polarity, it is important to use a generator with the correct direction of rotation other wire the voltage will be reversed.

The speed of an aircraft engine varies from idle rpm to takeoff rpm; however, the majority of flight, is conducted at a constant cruising speed. The generator drive is usually geared between 1-1/8 and 1-1/2 times the engine crankshaft speed. Most aircraft generators have a speed at which they begin to produce their normal voltage. Termed the **coming-in speed**, and is typically around 1,500 rpm.

Generator Classifications

Generators are classified according to the method by which their magnetic circuits are energized, and the following three classes are normally recognized -

1. Permanent magnet generators.
2. Separately-excited generators, in which electro-magnets are excited by current obtained from a separate source of d.c.
3. Self-excited generators, in which electromagnets are excited by current produced by the machines themselves. These generators are further classified by the manner in which the fixed windings, i.e. the electromagnetic field and armature windings, are interconnected.

TYPES OF DC GENERATORS

There are three types of DC generators. They are the series-wound, shunt-wound, and shunt-series or compound-wound. The difference between each depends on how the field winding is connected to the external circuit.

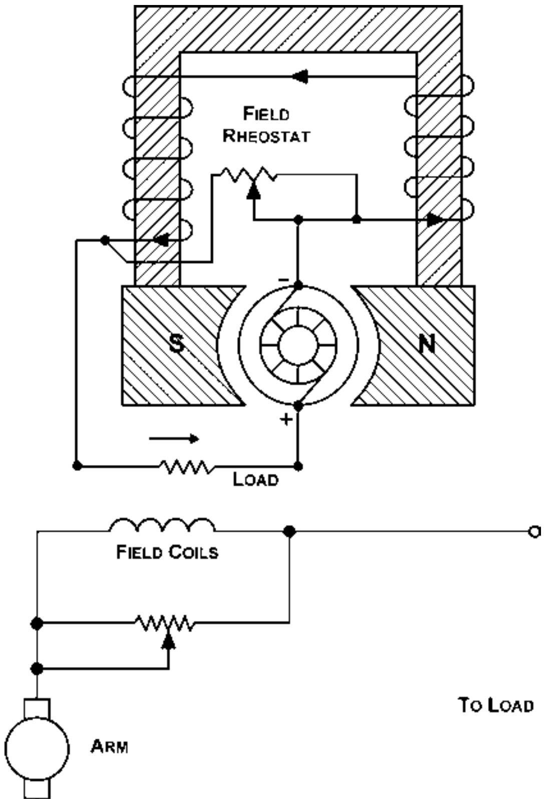


Fig. 9.11, The diagram and schematic of a series-wound generator show that the field windings are connected in series with the external load. A field rheostat is connected in parallel with the field windings to control the amount of current flowing in the field coils.

SERIES-WOUND

The field winding of a series-wound generator is connected in series with the external load circuit. In this type of generator, the field coils are composed of a few turns of thick wire because magnetic field strength depends more on current flow than the number of turns in the coil.

Because of the way series-wound generators are constructed, they possess poor voltage regulation capabilities. For example, as the load increases, the current through the field coils also increases. This induces a greater EMF which, in turn, increases the generator's output voltage. Therefore, when the load increases, voltage increases; likewise, when the load decreases, voltage decreases.

One way to control the output voltage of a series-wound generator is to install a rheostat in parallel with the field windings. This limits the amount of current that flows through the field coils thereby limiting the voltage output.

Since the series-wound generators have such poor voltage regulation capabilities, they are not suitable for use in aircraft. However, they are suitable for situations where a constant RPM and constant load are applied to the generator. See (Fig. 9.11).

SHUNT-WOUND

A generator having a field winding connected in parallel with the external circuit is called a shunt-wound generator. Unlike the field coils in a series-wound generator, the field coils in a shunt-wound generator contain many turns of thin wire. This permits the field coil to derive its magnetic strength from the large number of turns rather than the amount of current flowing through the coils.

In a shunt-wound generator the armature and the load are connected in series; therefore, all the current flowing in the external circuit passes through the armature winding. However, due to the resistance in the armature winding some voltage is lost. The formula used to calculate this voltage drop is :

(IR drop = current × armature resistance)

From this formula you can see that as the load, or current, increases the IR drop in the armature also increases. Since the output voltage is the difference between induced voltage and voltage drop, there is a decrease in output voltage with an increased load. This decrease in output voltage causes a corresponding decrease in field strength because the current in the field coils decreases with a decrease in output voltage. By the same token, when the load decreases, the output voltage increases accordingly, and a larger current flows in the windings. This action is cumulative and, if allowed, the output voltage would rise to a point called field saturation. At this point there is no further increase in output voltage. Because of this, a shunt-wound generator is not desired for rapidly fluctuating loads.

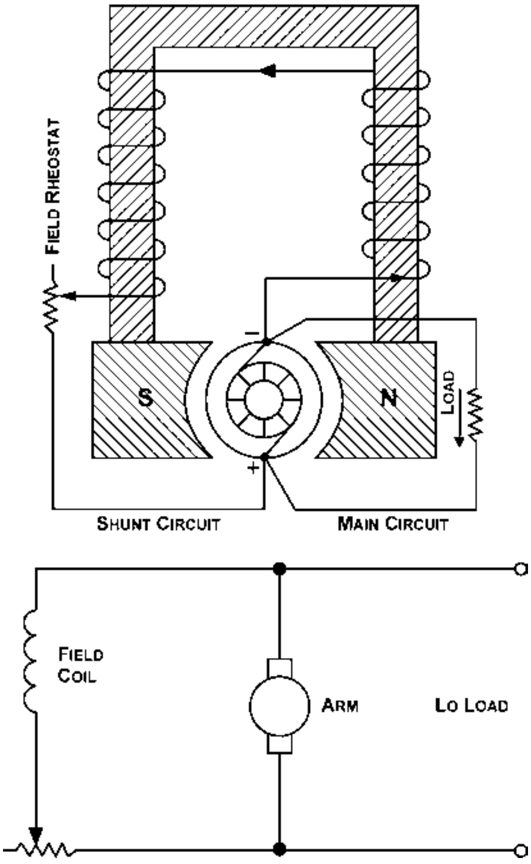


Fig. 9.12, In a shunt-wound generator the field windings are connected in parallel with the external load.

To control the output voltage of a shunt generator, a rheostat is inserted in series with the field winding. In this configuration, for a given setting of the field rheostat, the terminal voltage at the armature brushes is approximately equal to the generated voltage minus the IR drop produced by the armature resistance. However, this also means that the output voltage at the terminals drops when a larger load is applied. Certain voltage-sensitive devices are available which automatically adjust the field rheostat to compensate for variations in load. When these devices are used, the terminal voltage remains essentially constant.

The output and voltage-regulation capabilities of shunt-wound generators make them suitable for use on light to medium duty aircraft. However, most of these units have been replaced by DC alternators.

COMPOUND-WOUND

A compound-wound generator combines a series winding and a shunt winding. In such a way that the characteristics of each are used. The series field coils consist of a relatively small number of turns made of thick copper conductor, either circular or rectangular in cross section. As discussed earlier, series field coils are connected in series with the armature circuit. These coils are mounted on the same poles as the shunt field coils and, therefore, contribute to the magnetizing force, or **magneto motive force,** which influences the generator's main field flux. (Fig. 9.13).

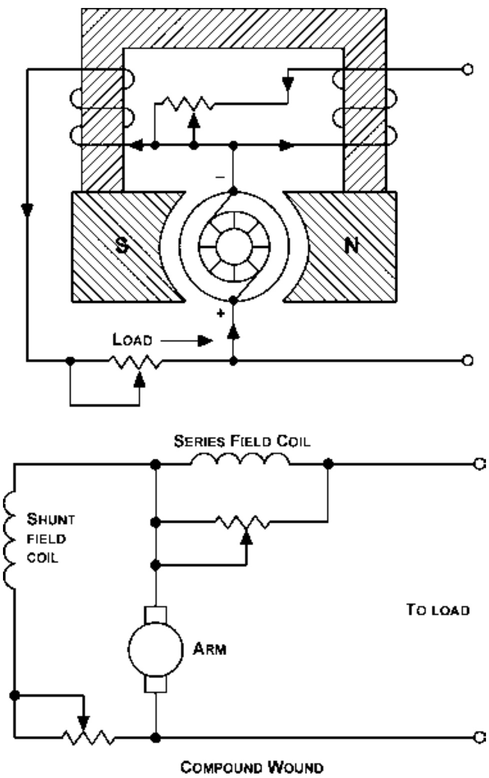


Fig. 9.13. Compound-wound generators utilize both series and shunt windings. In this type of generator, voltage regulation is controlled by a diverter.

If the ampere-turns of the series field act in the same direction as those of the shunt field, the combined magnetomotive force is equal to the sum of the series and shunt field components. Load is added to a compound-wound generator in the same manner as a shunt-wound generator; by increasing the number of parallel paths across the generator. When this is done, the total load resistance decreases causing an increase in armature-circuit and series-field circuit current. Therefore, by adding a series field, the field flux increases with an increased load. Thus, the output voltage of the generator increases or decreases with load, depending on the influence of the series field coils. This influence is referred to as the degree of compounding.

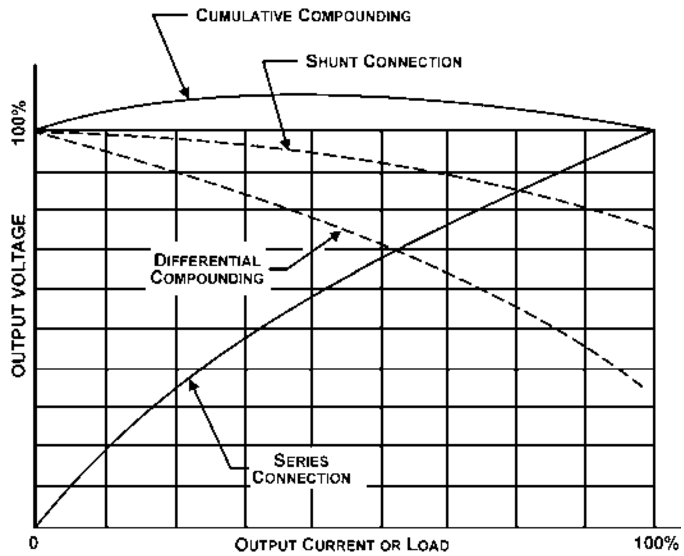


Fig. 9.14, The generator characteristics chart above illustrates a summary of characteristics involving various types of gnerators.

The amount of output voltage produced by a compound-wound generator depends on the degree of compounding. For example, a **flat-compound** generator is one in which the no-load and full-load voltages have the same value. However, an under-compound generator has a full-load voltages less that the no-load voltage, and an **over-compound** generator has a full-load voltage that is higher than the no-load voltage. (Fig. 9.14).

Generators are typically designed to be over-compounded. This feature permits varied degrees of compounding by connecting a variable shunt across the series field. Such a shunt is sometimes called a **diverter**. Compound generators are used where voltage regulation is of prime importance.

If, in a compound -wound generator, the series field aids the shunt field, the generator is said to be comulative-compounded. However, if the series field opposes the shunt field, the generator is said to be **differentially compounded**.

Differentially compounded generators have somewhat the same characteristics as shunt generators in that they are essentially **constant-current generators**. In other words, they produce the same amount of current regardless of the load size. However, they do generate voltage when no load is applied and the voltage drops as the load current increases. Constant-current generators are ideally suited as power sources for electric arc welders and are used extensively for this task.

If the shunt field of a compound-wound generator is connected across both the armature and the series field, it is known as a **long-shunt connection.** However, if the shunt field is connected across the armature alone, it is called a **short-shunt connection.** These connections produce essentially the same generator characteristics. (Fig. 9.15).

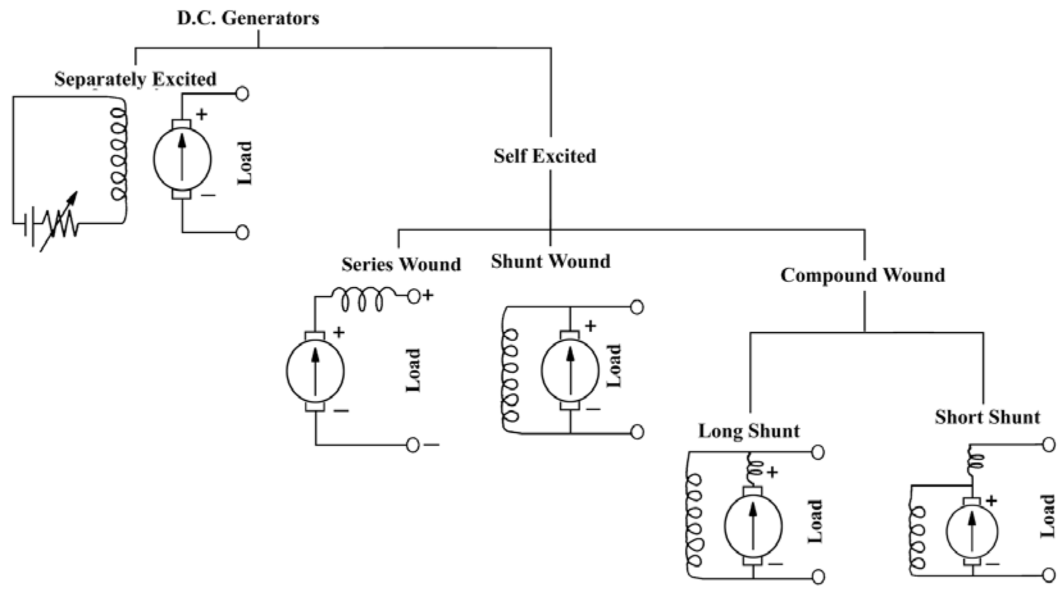


Fig. 9.15.

ARMATURE REACTION

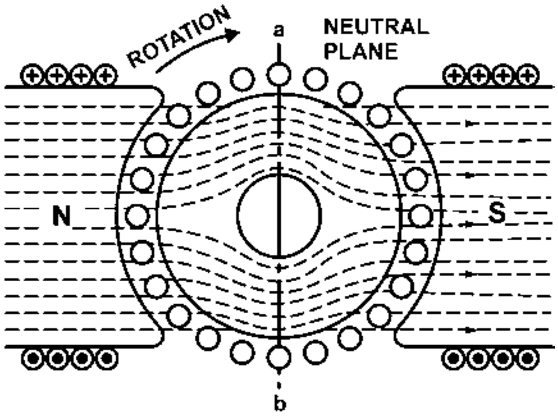
As you know, anytime current flows through a conductor, a magnetic field is produced. Therefore, it stands to reason that when current flows through an armature, electromagnetic fields are produced in the windings. These fields tend to distort or bend the lines of magnetic flux between the poles of the generator. This distortion is called **armature reaction.** Since the current flowing through the armature increases as the load increases, the distortion becomes greater with larger loads.

Armature windings of a generator are spaced so that during rotation there are certain positions when the brushes contact two adjacent segments on the commutator, thereby shorting the armature windings. When the magnetic field is not distorted, there is no voltage induced in the shorted windings and no harmful results occur. However, when the field is distorted by armature reaction, a voltage is induced in the shorted windings and sparking takes place between the brushes and the commutator segments. Consequently, the commutator becomes pitted, the wear on the brushes becomes excessive, and the output of the generator is reduced.

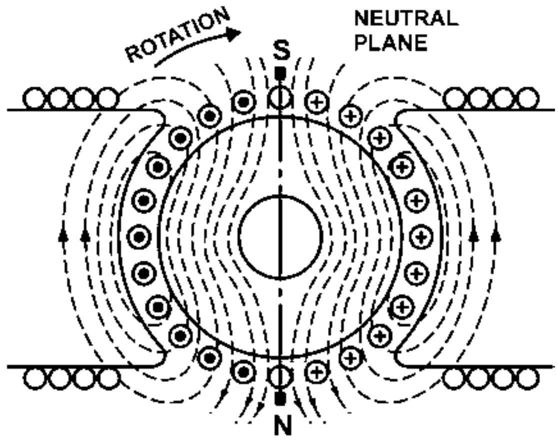
To correct this condition, the brushes are set so that the plane of the coils being shorted is perpendicular to the distorted magnetic field. This is accomplished by moving the brushes forward in the direction of rotation. This operation is called **shifting the brushes** to the neutral plane, or **plane of commutation.** The neutral plane is the position where the plane of the two opposite coils is perpendicular to the magnetic field in the generator. On a few generators, the brushes are shifted manually ahead of the normal neutral plane to the neutral plane caused by field distortion. On nonadjustable brush generators, the manufacturer sets the brushes for minimum sparking.

In some generators, special field poles called **interpoles** are used to counteract some of the effects of field distortion when the speed and load of the generator are changing constantly. An interpole is another field pole that is placed between the main poles.

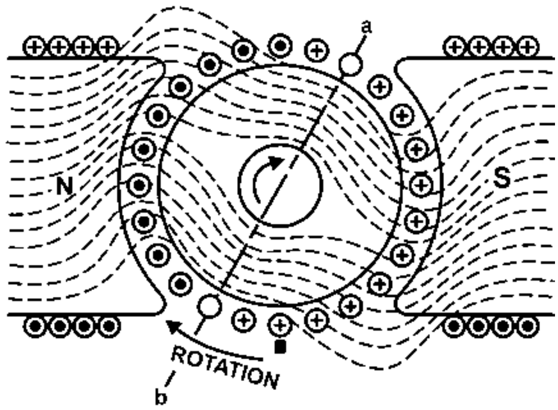
An interpole has the same polarity as the next main pole in the direction of rotation. The magnetic flux produced by an interpole causes the current in the armature to change direction as the armature winding rotates under the interpole's field. This cancels the electromagnetic fields produced by the armature windings. The interpoles are connected in series with the load and, therefore, the magnetic strength of the interpoles varies with the generator load. Since the field distortion also varies with the load, the magnetic field of the interpoles counteract the effects of the field around the armature windings and minimize distortion. In other words, the interpoles keep the neutral plane in the same position for all loads.



FIELD EXCITED, ARMATURE UNEXCITED



ARMATURE EXCITED, FIELD UNEXCITED



BOTH FIELD AND ARMATURE EXCITED

Fig. 9.16. The line of flux in the field coil flow in a horizontal path from north to south and induce voltage into the armature. Howeer, as this is done, magnetic fields are produced in the armature that tend to distort or bend the lines of flux produced by the field coil.

INTERPOL AND COMPENSATING WINDINGS

In order to provide true correction of armature reaction, the effects produced by interpoles must be supplemented, since alone they cannot entirely eliminate all distortion occurring at the main pole face. Compensating windings are therefore connected in series with the interpole and armature windings, and located in slots cut in the faces of the main pole shoes. The sides of the coils thus lie parallel with the sides of the armature coils. The ampere-turns of the winding are equal to those of the armature winding, while the flux due to it is opposite in direction to the armature flux.

AUXILIARY INTERPOLES

The effectiveness of interpoles in minimizing reactance sparking is limited by armature speed, and their application as individual components of a field-winding system is, therefore, restricted to generators operating over a narrow speed range, e.g. the designed range of the generator illustrated in Fig 9.8. In the case of generators designed for operation over a wide range, e.g. 2850 rev/min up to 10,000 rev/min, the use of interpole alone would produce a side effect resulting in reactance sparking as the generator speed is reduced from maximum to minimum. To counteract this, and for a given load on the generator, it is necessary to reduce the magnetomotive force (m.m.f.) of the interpoles. The desired effect may be obtained by winding auxiliary coils over the interpole coils and connecting them in series with the generator shunt field winding in such a way that each coil, when energized by shunt field circuit current, produces an m.m.f. or opposite polarity to that produced by the interpole coil on the same pole shoe. An exact balance between reactance e.m.f. and commutation e.m.f. is maintained over the full working range of generator speed to assist in producing sparkless commutation.

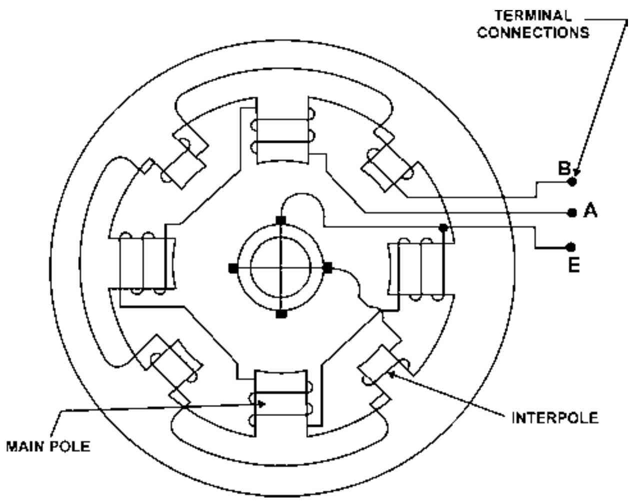


Fig. 9.17. This generator has four poles and four interpoles. The interpoles are used to counter the effect of armature reaction.

Brush Wear

The carbon from which electro-graphitic brushes are made is extremely porous and some of the pores are so very fine that carbon has an exceptional ability to absorb other substances into its structure, and to retain them. Moisture is one of these substances and it plays an important part in the functioning of a brush contact by affording a substantial degree of lubrication. The moisture is trapped under the inevitable irregularities of the contact faces of the brushes and forms an outside film on the commutator and it is with this film that the brushes make contact. Just how vital a part moisture does play was, however, not fully realized until aircraft began operating at high altitudes and the problem arose of brushes wearing out very rapidly under these conditions. Investigations into the problem showed that the fundamental difficulty was the extreme dryness of the atmosphere, this, in its turn, producing three secondary effects: (i) friction between brushes and commutator because the lubricating film cannot form, (ii) contact resistance becomes negligible giving rise to heavy reactive sparking and accelerated brush erosion and (iii) static electrical charges due to friction, producing molecular breakdown of the brushes.

These effects have been largely eliminated by using brushes which have a chemical additive as a means of replacing the function which atmospheric moisture plays in surface skin formation. Two distinct categories are in general use: brushes of one category form a constant-resistance semi-lubricating film on the commutator, while those in the other category are, in effect, self-lubricating brushes which do not form a film.

The composition of the film-forming brushes includes chemicals (e.g. barium fluoride) to build up progressively a constant resistance semi-lubricating film on the commutator surfaces. Brushes of this category do not wear abnormally at altitudes up to 60,000 feet providing that generators to which they are fitted have been previously "bench run" for some hours to allow the formation of the protective film. This film, once formed, is very dark in colour and may often give the impression of a dirty commutator.

Brushes of the non-film-forming category contain a lubricating ingredient such as molybdenum disulphide which is often packed in cores running longitudinally through the brushes. Since the brush is self-lubricating it is unnecessary for generators fitted with this type to be run for hours prior to entering service. However, they do have the disadvantage of appreciably shorted life, due to somewhat more rapid wear, when compared with film-forming brushes.

Armature Winding

Two basic types of windings mostly employed for drum-type armature are known as (i) Wave winding and (ii) Lap winding.

a. Wave Winding

The most distinguishing feature of this winding is that electrically it divides the armature conductors into two parallel paths between the positive and negative brushes irrespective of the number of poles of the machine.

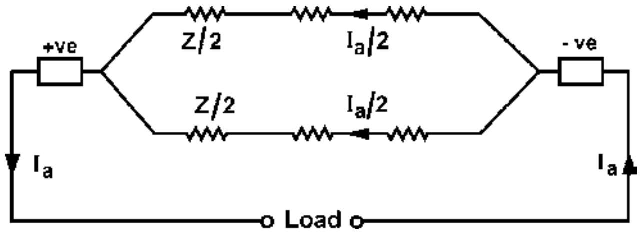


Fig. 9.18.

As shown in (Fig. 9.18) as the armature current enters the negative brush, it finds two parallel paths of equal resistance available for going to the positive brush. Hence, it divides equally into two parts. Each path consists of Z/2 conductors connected in series (Z-being the total number of armature conductors) and each carries a current of $I_a/2$ where I_a is the total armature current.

For example, in the case of a 4-pole, wave-wound generator having 30 armature conductors, each of the two parallel paths will have 15 conductors.

b. Lap Winding

In this case, the armature conductors are divided into as many parallel paths as the number of poles of the generator. If there are P poles and Z armature conductors, then there are P parallel paths, each consisting of Z/P conductors connected in series between the positive and negative set of brushes.

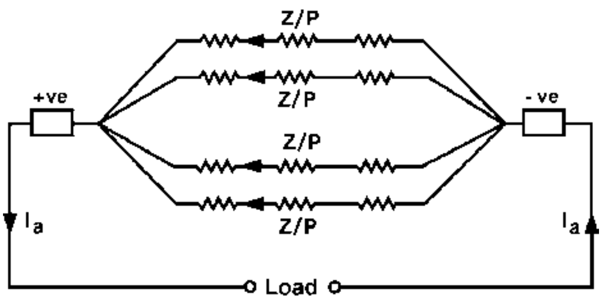


Fig. 9.19.

Fig. 9.19 shows the case of a 4-pole machine. As armature current enters the negative brush, it has four parallel paths available for going to the positive brush. Each path has Z/4 conductors and carries a current of $I_a/4$.

Armature Resistance

Let, l = length of each armature conductor
S = its cross-section
A = No. or parallel paths
= 2--for wave-winding
= P--for lap-winding
R = resistance of the whole winding

Then, $R = \frac{\rho l}{S} \times Z$

Resistance of each parallel path $= \frac{\rho l Z}{SA}$

Generated E.M.F. or E.M.F. Equation of a D.C. Generator

Let Φ = flux/pole in webers

Z = total number of armature conductors

= No. of slots × conductors/slot

P = No. of poles

A = No. of parallel paths in armature

N = armature rotation in r.p.m.

E_g = e.m.f. induced in any parallel path in the armature

Generated e.m.f. E_g

= e.m.f. generated in any one of the armature parallel paths.

Average e.m.f. generated/conductor

$$= n\frac{d\Phi}{dt} \text{ volt}$$

$$= \frac{d\Phi}{dt} \text{ volt} \qquad (\because n = 1)$$

Now, flux cut/conductor in one revolution = Φ P weber

$$\therefore \quad d\Phi = \Phi \times P$$

No. of revolutions/second = N/60

$\therefore$ time for one revolution = 60/N second

$\therefore$ dt = 60/N second

$\therefore$ flux cut per conductor/second

$$= \frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi PN}{60} \text{ Wb/s}$$

$$\therefore \text{ e.m.f. generated/conductor} = \frac{\Phi PN}{60} \text{ volt}$$

For a wave-wound generator

No. of parallel paths = 2

No. of conductors (in series) in one path = Z/2

$\therefore$ E.M.F. generated/path

$$= \frac{\Phi PN}{60} \times \frac{Z}{2} = \frac{\Phi ZPN}{120} \text{ volt}$$

$$\because \quad P = 2 \qquad \therefore \quad E_g = \frac{\phi ZN}{60}$$

For a lap-wound generator

No. of parallel paths = P

No. of conductors (in series) in one path = Z/P

$\therefore$ e.m.f. generated/path

$$= \frac{\Phi PN}{60} \times \frac{Z}{P} = \frac{\Phi ZN}{60} \text{ volt}$$

In general, generated e.m.f. is

$$E_g = \frac{\Phi ZN}{60} \times \left(\frac{P}{A}\right) \text{ volt}$$

where A = 2 --for wave-winding

A = P---for lap-winding.

Iron Loss in Armature

Due to the rotation of the iron core of the armature in the magnetic flux of the field poles, there are some losses taking place continuously in the core and are known as Iron losses or Core losses. Iron loss consists of (i)***Hysteresis loss*** and (ii) ***Eddy Current loss.***

i. Hysteresis Loss (W_h).

This loss is due to the reversal of magnetism of the armature core. Every portion of the rotating core passes under N - and S-pole alternately, thereby attaining S- and N-polarity respectively. The core undergoes one complete cycle of magnetic reversal after passing under one pair of poles. If P is the number of poles and N the armature speed in r.p.m., then frequency of magnetic reversals is

$f = PN/120$ reversals/second

The loss depends upon the volume and grade of iron, maximum value of flux density B_{max} and frequency of magnetic reversals.

$$Wb \propto B^{16} \max f$$

ii. Eddy Current Loss (W_e)

When the armature core rotates, then it also cuts the flux. Hence, an e.m.f. is induced in the body of the core according to the laws of electromagnetic induction. This e.m.f., though small, sets up a large current in the body of the core due to its small resistance. This current is known as eddy current. The power loss due to the flow of this current is known as 'eddy current' loss. This loss would be considerable if solid iron core were used. In order to reduce this loss and the consequent heating of the core to a small value, the core is built up of thin laminations which are stacked and then riveted at right angles to the path of the eddy currents. These core laminations are insulated is shown in Fig. 9.20 (b).

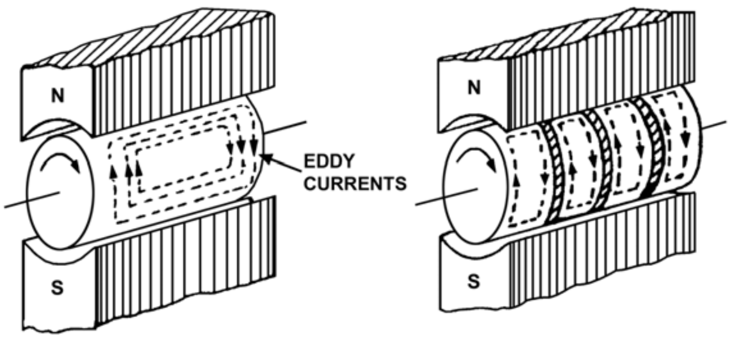


Fig. 9.20.

Due to the core body being one continuous solid iron piece [Fig. 9.20 (a)] the magnitude of eddy current is large. As armature cross-sectional area is large, its resistance is very small, hence eddy current as well as the loss is large. In Fig. 9.20 (b) the same core has been split up into thin circular discs insulated from each other. It is seen that now each current path, being of much less cross-section, has a very high resistance. Hence, magnitude of eddy current is reduced very much, drastically reducing eddy current loss.

$$We \propto B^2 \max f^2$$

Total Loss in a D.C. Generator

The various losses occurring in a generator can be subdivided as follows :

a. Copper Losses (or I^2R loss)

i. Armature copper loss = $I_a 2R_a$

where R_a = resistance of armature and interpoles and series field winding etc.

This loss is about 30 to 40% of full load losses.

ii. Field copper loss : In the case of shunt generators. It is practically constant and = $I_{sh}^2 R_{sh}$ $(\text{or } VI_{sh})$ in the case of series generators it is $I^2{}_{se}R_{se}$ where R_{se} is resistance of the series field winding.

This loss is about 20 to 30% of F.L. losses.

iii. The loss due to brush contact resistance. It is usually included in the armature copper loss.

b. Magnetic Losses (also known as iron or core losses).

i. Hysteresis loss $W_h \propto B_{max}^{1.6} f$

ii. Eddy current loss, $W_\ell \propto B_{max}^2 f^2$

These losses are practically constant for shunt and compound-wound generators, because field current, in their case, is approximately constant.

Both these losses total up to about 20 to 30% of F.L. losses.

c. Mechanical Losses

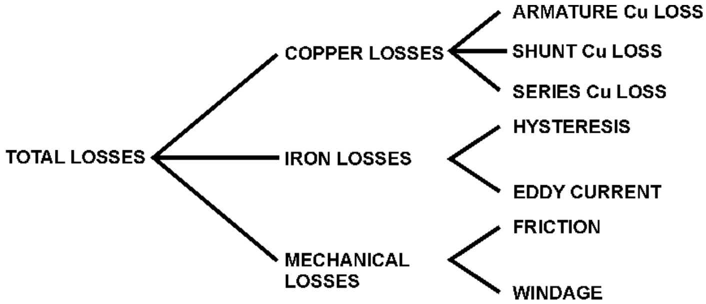
These consist of

i. friction loss at bearings and commutator.

ii. air-friction or windage loss of rotating armature.

These are about 10 to 20% of F.L. losses.

The total losses in a d.c. generator are summed up below.



Stray Losses

Usually magnetic and mechanical losses are collectively known as **stray losses**.

Constant and Standing Losses

As said above, field Cu loss is constant for shunt and compound generators. Hence, stray losses and shunt Cu losses are constant in their case. These losses are known as standing or constant losses W_e.

Hence, for shunt and compound generators,

Total losses = armature copper loss $+W_e$

$$= I_a^2 R_a + W_e = (I + I_{sh})^2 R_a + W_e$$

Armature Cu loss, $I_a^2 R_a$ is known as variable loss because it varies with the load current.

$\therefore$ total losses = variable losses + constant losses W_e.

Following are the three generator efficiencies :

1. Mechanical Efficiency

$$\eta_m = \frac{B}{A} = \frac{\text{total watts generated in armature}}{\text{mechanical power supplied}}$$

2. Electrical Efficiency

$$\eta_c = \frac{C}{B} = \frac{\text{watts available in load circuit}}{\text{total watts generated}} = \frac{VI}{E_g I_a}$$

3. Overall or Commercial Efficiency

$$\eta_c = \frac{C}{A} = \frac{\text{watts available in load circuit}}{\text{mechanical power supplied}}$$

It is obvious that overall efficiency $\eta_c = \eta_m \times \eta_\ell$. For good generators, its value may be as high as 95 %.

Note. Unless specified otherwise, commercial efficiency is always to be understood.

Voltage Regulation

The efficient operation of aircraft electrical equipment requiring d.c. depends on the fundamental requirement that the generator voltage at the distribution busbar system be maintained constant under all conditions of load and at varying speeds, within the limits of a prescribed range. It is necessary, therefore, to provide a device that will regulate the output voltage of a generator at the designed value and within a specified tolerance.

There are a number of factors which, either separately or in combination, affect the output voltage of a d.c. generator, and of these the one which can most conveniently be controlled is the field circuit current, which in turn controls the flux density. This control can be effected by incorporating a variable resistor in series with the field winding as shown in Fig.9.21. Adjustments to this resistor would vary the resistance of the field winding, and the field current and output voltage would also vary and be brought to the required controlling value. The application of the resistor in the manner indicated is, however, limited since it is essential to incorporate a regulating device which will automatically respond to changes of load and speed, and also, automatically make the necessary adjustments to the generator field current. Three of the regulation methods commonly adopted are : the vibrating contact method; the one based on the pressure/ resistance characteristics of carbon, namely, the carbon pile method, and the one based on solid-state circuit principles.

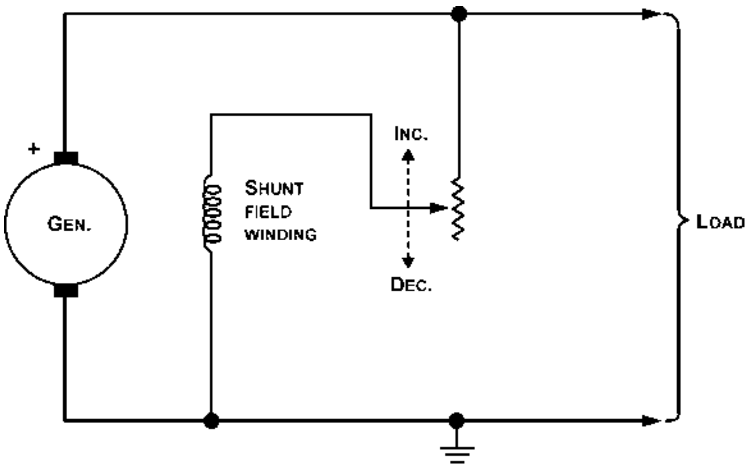


Fig. 9.21. Control of field circuit current.

Vibrating Contact Regulator

Vibrating contact regulators are used in several types of small aircraft employing comparatively low d.c. output generators and a typical circuit for the regulation of both voltage and current of a single generator system is shown in basic form in (Fig. 9.22). Although the coil windings of each regulator are interconnected, the circuit arrangement is such that either the voltage regulator only or the current regulator only can operate at any one time. A third unit, called a reverse current cut-out relay, also forms part of some types of regulator.

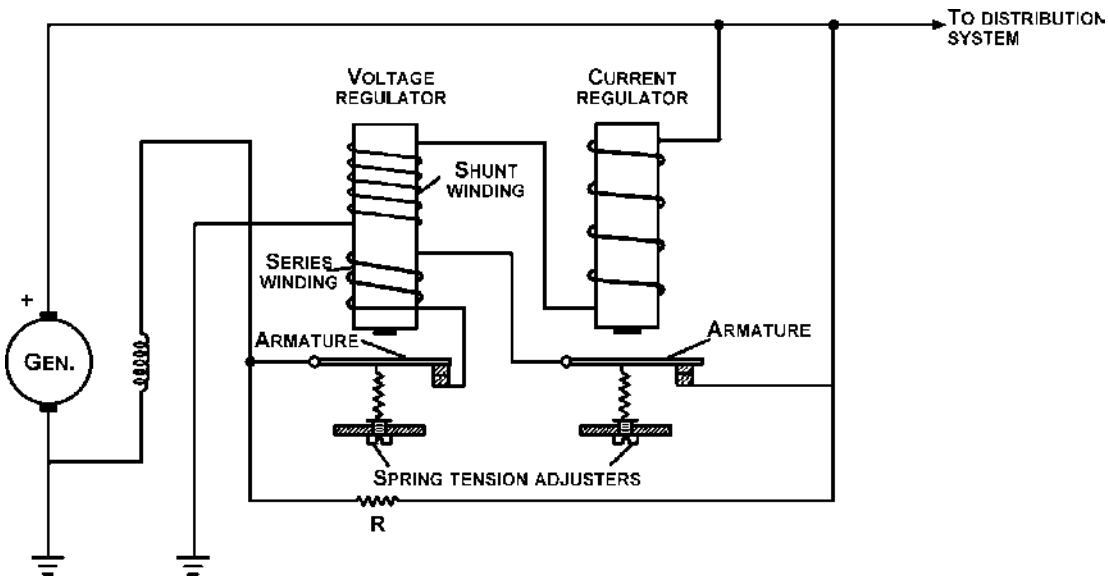


Fig. 9.22. Vibrating contact regulator principle.

Voltage Regulator

This unit consists of two windings assembled on a common core. The shunt winding consists of many turns of fine gauge wire and is connected in series with the current regulator winding and in parallel with the generator. The series winding, on the other hand, consists of a few turns of heavy gauge wire, and is connected in series with the generator shunt-field winding when the contacts of both regulators are closed, i.e. under static condition of the generator system. The contact assembly is comprised of a fixed contact and a movable contact secured to a flexibly hinged-armature. Movement of the armature and, therefore, the point at which contact opening and closing takes place is controlled by a spring which is pre-adjusted to the required voltage setting.

When the generator starts operating, the contacts of both regulators remain closed so that a positive supply can flow through the generator shunt-field winding to provide the necessary excitation for raising the generator output. At the same time current passes through the shunt winding of the voltage regulator and, in conjunction with the series winding, it increases the regulator's electromagnetic field. As soon as the generator output voltage reaches the pre-adjusted regulator setting, the electromagnetic field becomes strong enough to oppose the tension of the armature spring thereby opening the contacts. In this equilibrium position, the circuit to the series winding is opened causing its field to collapse. At the same time, the supply to the generator field winding passes through a resistance (R) which reduces the excitation current and, therefore, the generator output voltage. The reduced output in turn reduces the magnetic strength of the regulator shunt winding so that spring tension closes the contacts again to restore the generator output voltage to its regulated value and to cause the foregoing operating cycle to be electrical load carried by the generator; a typical range is between 50 to 200 times a second.

In regulators designed for use with twin-generator systems, a third coil is also wound on the electromagnet core for paralleling purposes and is connected to separate paralleling relays.

Current Regulator

This unit limits generator current output in exactly the same way as the voltage regulator controls voltage output, i.e. controlling generator field-excitation current. Its construction differs only by virtue of having a single winding of a few turns of heavy wire.

When electrical load demands are heavy, the voltage output value of the generator may not increase sufficiently to cause the voltage regulator to open its contacts. Consequently, the output will continue to increase until it reaches rated maximum current, this being the value for which the current regulator is set. At this setting, the current flowing through the regulator winding establishes a strong enough electromagnetic field to attract the armature and so open the contacts. Thus, it is the current regulator which now inserts resistance R in the generator shunt-field circuit to reduce generator output. As soon as there is sufficient drop in output the field produced by the regulator winding is overcome by spring tension, the contacts close and the cycle again at a frequency similar to that of the voltage regulator.

Carbon Pile Regulator

Carbon has a granular surface and the contact resistance between two carbon faces that are held together depends not only on the actual area of contact, but also on the pressure with which the two faces are held together. If, therefore, a number of carbon discs or washers are arranged in the form of a pile and connected in series with the shunt field of a generator (see Fig. 9.23) the field circuit resistance can be varied by increasing or decreasing the pressure applied to the ends of the pile and changes in generator output voltage therefore counteracted. Since this method eliminates the use of vibrating contacts, it is applied to generators capable of high current output, and requiring higher field excitation current output, and requiring higher field excitation current. The necessary variation of pile pressure or compression under varying conditions of generator speed and load, is made through the medium of an electromagnet and spring-controlled armature which operate in a similar manner to those of a vibrating contact regulator.

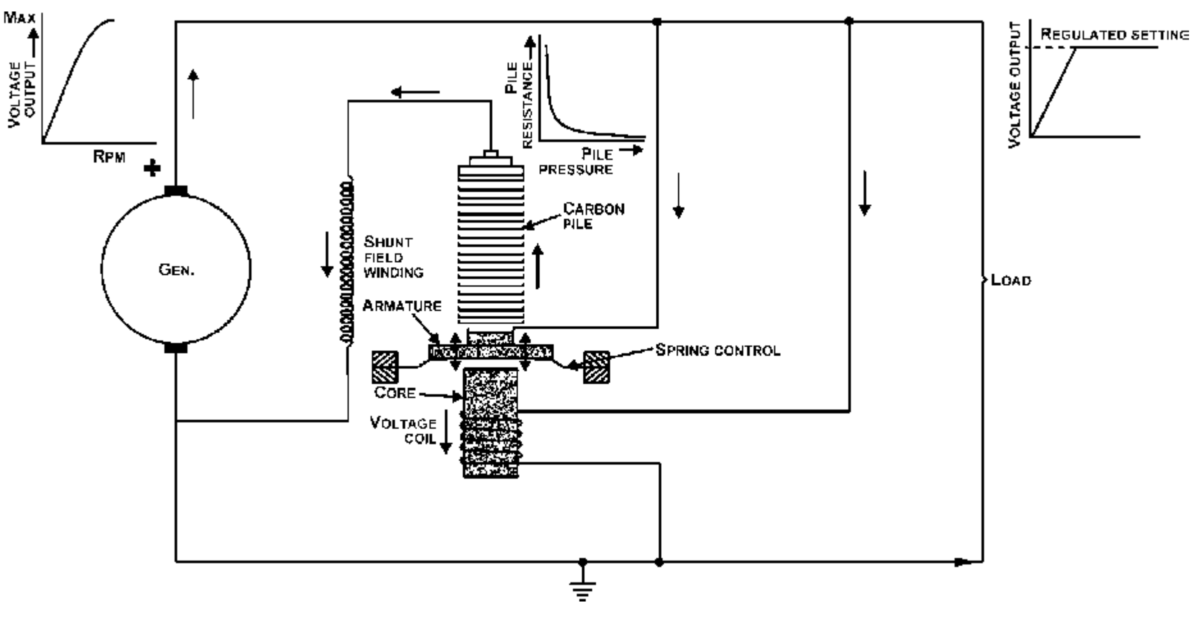


Fig. 9.23. Carbon pile voltage regulation.

Under static conditions of the generator system, the carbon pile is fully compressed and since there is no magnetic "pull" on the armature, the resistance in the generator shunt-field circuit is minimum and the air gap between the regulator armature and electromagnet core is maximum. As the generator starts operating, the progressively increasing "pull" on the armature. During the initial "run-up" stages, the combination of low voltage applied to the regulator coil, and the maximum air gap between armature and core, results in a very weak force of attraction being exerted on the armature. This force is far smaller than that of the spring control, hence the armature maintains its original position and continues to hold the carbon pile in the fully compressed condition; the shunt-field circuit resistance is thus maintained at minimum value during run-up to allow generator output voltage to build up as rapidly as possible. This condition continues unaltered until the voltage has risen to the regulated value, and at which equilibrium is established between magnetic force and spring-control force. The armature is free to move towards the electromagnet core if the force of magnetic attraction is increased as a result of any increase in generator speed within the effective speed range. In these circumstances pile compression is further reduced so that there is more air space between discs to increase resistance and so check a rise in generator output voltage; it also increases the spring loading that holds the armature away from the core. Thus, a condition of equilibrium is re-established with the armature in some new position, but with the output voltage still at the required regulated value.

Any reduction of generator speed, within the effective speed range, produces a reduction in generator output voltage thus disturbing regulator armature equilibrium in such a manner that the spring-control force predominates and the armature moves away from the electromagnet core. The carbon pile is recompressed by this movement to reduce the generator shunt-field circuit resistance and thereby increase generator output voltage, until the regulated output is again brought to a state of equilibrium. When progressive reduction of generator speed results in a condition of maximum pile compression, control of generator output voltage is lost; any further reduction of generator speed, below the lower limit of the effective range, resulting in proportional decrease in output voltage.

When a generator has been run up and connected to its distribution busbar system, the switching on of various requisite consumer services, will impose loads which disturb the equilibrium of the regulator armature. The effect is, in fact, the same as if the generator speed had been reduced, and the regulator automatically takes the appropriate corrective action until the output voltage is stabilized at the critical value. Conversely, a perceptible decrease in load, assuming generator speed to be constant and the regulator armature to be in equilibrium, results in the regulator taking the same action as in the case of an increase in generator speed.

Construction

The pile unit is housed within a ceramic tube which, in turn, is enclosed in a solid casing, or more generally, a finned casing for dissipating the heat generated by the pile. The number, diameter, and thickness of the washers which make up the pile, varies according to the specific role of the regulator. Contact at each end of the pile is made by carbon inserts, or in some types of regulator by silver contacts within carbon inserts. The initial pressure of the pile is set by a compression screw acting through the pile on the armature and plate-type control spring which is supported on a bi-metal washer. The washer compensated for temperature effects on voltage coil resistance and on any expansion characteristics of the regulator, thus maintaining constant pile compression. The electromagnet assembly comprises a cylindrical yoke in which is housed the voltage coil, a detachable end-plate and an adjustable soft-iron core. A locking device, usually in the form of screws, is provided to retain the core in a pre-set position.

Depending on the design of generating system, voltage regulators may be of the single-unit type, shown in (Fig. 9.24), which operates in conjunction with separate reverse current cut-outs, voltage differential sensing relays and paralleling relays, or integrated with these components to form special control units or panels.

Typical single-unit type regulator
1. Armature stop screw
2. Magnet case
3. Heat dissipator
4. Terminal blocks
5. Chassis

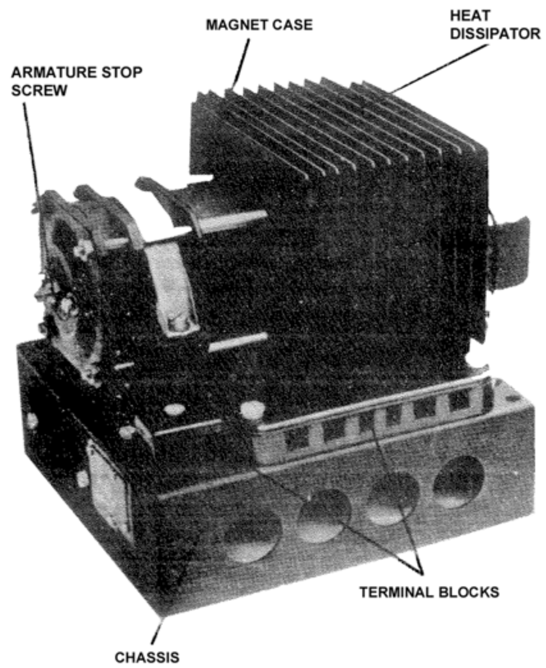


Fig. 9.24. Typical Single-unit type regulator.

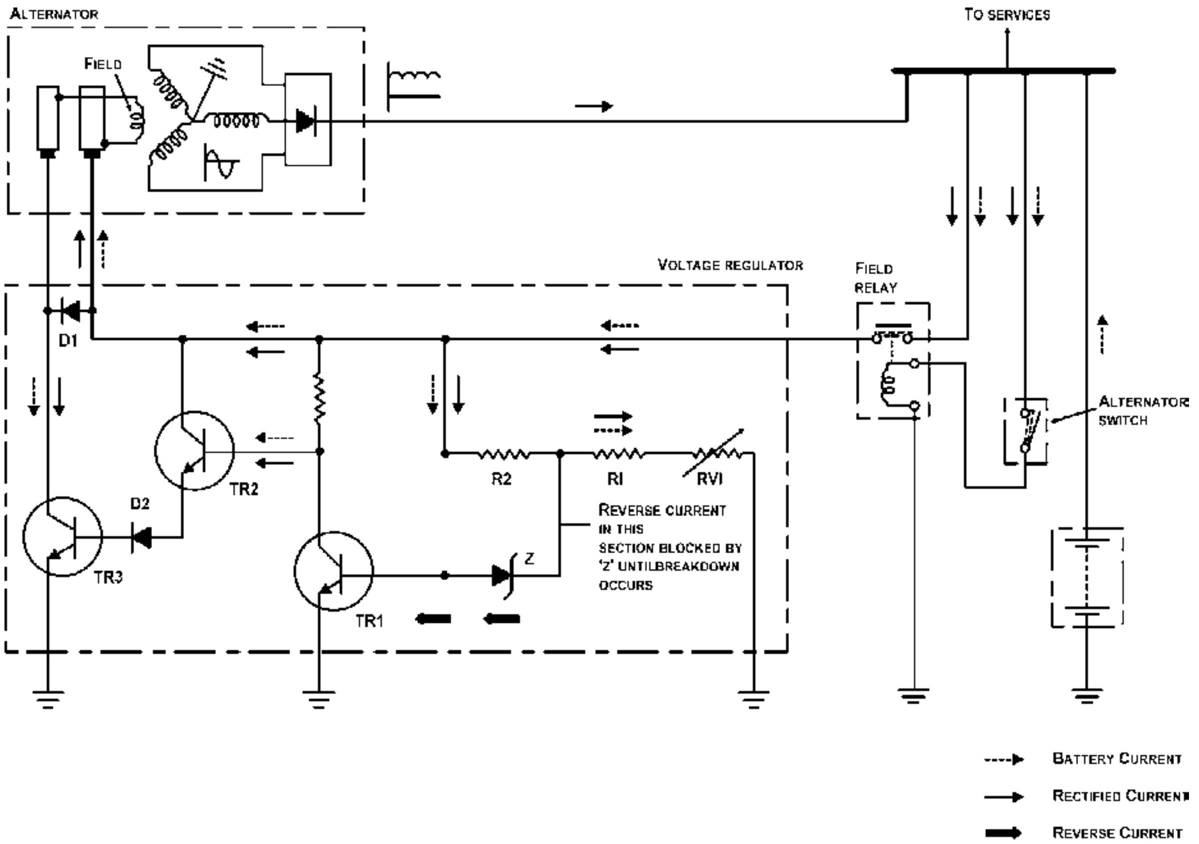


Fig. 9.25, Solid-state voltage regulator

Fig. 9.25 shows the circuit arrangement of a typical solid-state voltage regulator as employed with the type of alternator. Before going into its operation, however, it will be helpful at this stage, to briefly review the primary function and fundamental characteristics of the device known as the transistor.

The primary function of a transistor is to "transfer resistance" within itself and depending on its connection within a circuit it can turn current "on" and "off" and can increase output signal conditions; in other words, it can act as an automatic switching device or as an amplifier. It has no moving parts and is made up of three regions of a certain material, usually germanium, known as a semiconductor and arranged to be in contact with each other in some definite conducting sequence. Some typical transistor contact arrangement are shown in (Fig.9.26) together with the symbols used. The letters "p" and "n" refer to the conductivity characteristic of the germanium and signify positive-type and negative-type respectively. A transistor has three external connections corresponding to the three regions or elements known as the emitter which injects the current carriers at one end, the collector which collects the current at the other end, and the base which controls the amount or current flow. The three elements are arranged to contact each other in sandwich form and in the sequence of either n-p-n or p-n-p. When connected in a circuit the emitter is always forward-baised in order to propel the charged current carriers towards the collector, which is always reverse-baised in order to collect the carriers. Thus, the emitter of an n-p-n transistor has a negative voltage applied to it (with respect to base) so as to repel negative electrons in the forward direction, while a positive voltage is applied to the emitter of a p-n-p transistor so as to repel positively charged "holes" in a forward direction.

Since reverse bias is always applied to collectors then the collector of an n-p-n transistor is made positive with respect to the emitter in order to attract negative electrons. Similarly, the collector of a p-n-p transistor is made negative with respect to the emitter so as to attract positively charged "holes".

The conventional current flow is, of course, opposite to the electron flow and passes through a transistor and the circuit external to it, from emitter to collector and through the base. This is indicated on the symbols adopted for both transistor arrangements, by arrows on the emitter (see Fig. 9.26). Any input voltage that increases the forward bias of the emitter, with respect to the base, increases the emitter-to-collector current flow and conversely, the current flow is decreased when an input voltage decreases forward bias. The characteristics of transistors are such that small changes in the emitter-base circuit current result in relatively large changes in collector current thereby making transistors efficient amplifying devices. By alternately connecting and disconnecting the base circuit to and from a forward biasing voltage, or similarly, by alternately applying a forward and reverse voltage, base current and thus collector current, can be caused to flow and to cease flowing. In this manner, a transistor can thereby also function as a switching device.

In the regulator circuit shown in (Fig. 9.25), the three transistors (TR_1, TR_2 and TR_3) are connected in the n-p-n arrangement. When the system control switch is "on" , excitation current flows initially from the battery to the base of TR_2 and through a voltage dividing network made up of resistances R_1, R_2 and RV_1. The purpose of this network in conjunction with the Zener diode "Z" is to establish the system-operating voltage. With power applied to the base of TR_2, the transistor is switched on and battery current flows to the collector and emitter junction. The amplified output in the emitter circuit flows to the base of TR_3 thereby switching it on so that the battery current supplied to the field winding can be conducted to ground via the collector-emitter junction of TR_3. When the generator is running, the rotating magnetic field induces an alternating current in the stator and this is rectified and supplied to the d.c. power system of the aircraft.

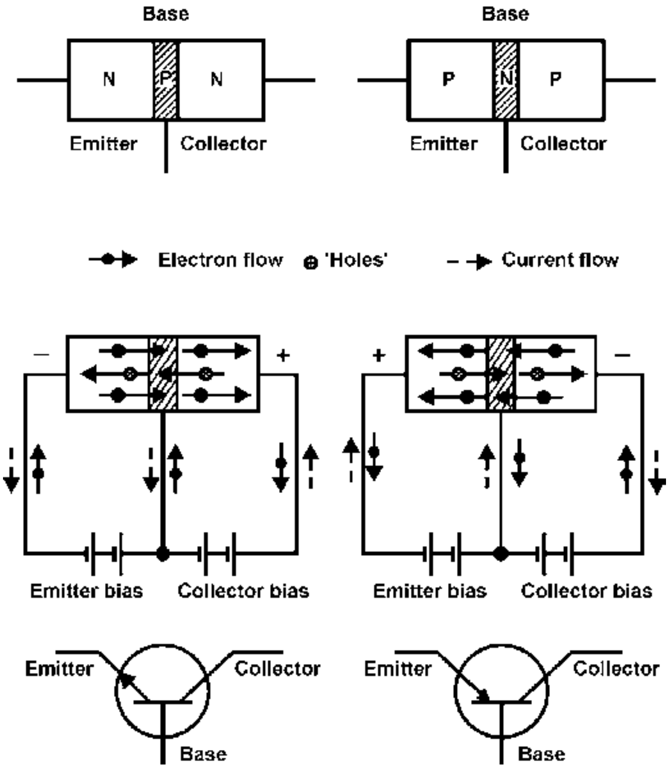


Fig. 9.26. Transistor contact arrangements.

When the alternator output voltage reaches the preset operating value, the current flowing in the reverse direction through the Zener diode causes it to break down and to allow the current to flow to the base of TR_1 thus switching it on. The collector-emitter junction of TR_1 now conducts, thereby diverting current away from the base of TR_2 and switching it off. This action, in turn, switches off TR_3 and so excitation current to the alternator field winding is cut off. The rectifier across the field winding (D_1) provides a path so that field current can fall at a slower rate and thus prevent generation of a high voltage at TR_3 each time it is switched off.

When the alternator output voltage falls to a value which permits the Zener diode to cease conduction, TR_1 will again conduct to restore excitation current to the field winding. This sequence of operation is repeated and the alternator output voltage is thereby maintained at the preset operating value.

Paralleling and Load-Sharing

In multi-engined aircraft, it is generally desirable that the generators driven by each engined should operate in parallel thereby ensuring that in the event of an engine or generator failure, there is no interruption of primary power supply. Parallel operation requires that generators carry equal shares of the system load, and so their output voltages must be as near equal as possible under all operating conditions. As we have already learned, generators are provided with a voltage regulator which exercises are independent control over voltage output, but as variations in output and electrical loads can occur, it is essential to provide additional voltage regulation circuits having the function of maintaining balanced outputs and load sharing. The method most commonly adopted for this purpose is that which employs a "load-equalizing circuit" to control generator output via the voltage regulators. The principle as applied to a twin-generator system is illustrated in much-simplified form by (Fig. 9.27). The generators are interconnected on their negative sides, via a series "load-sharing" or "equalizing" loop containing equalizing coils (C_e) each coil forming part of the individual voltage regulator circuits.

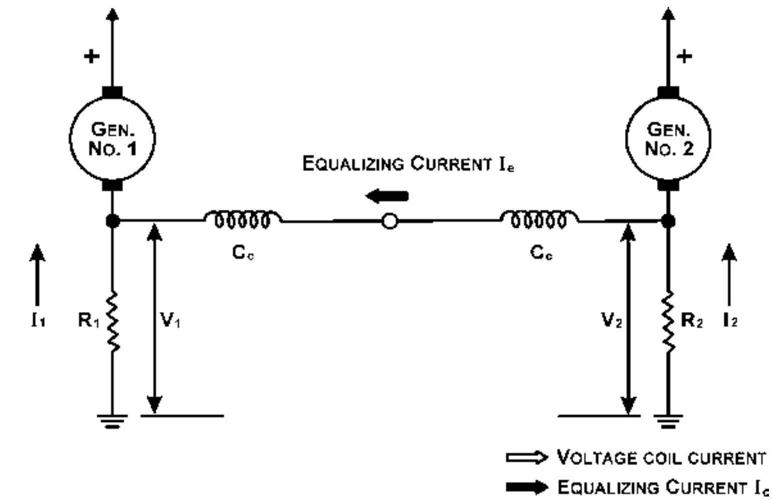


Fig. 9.27. Principle of load-sharing.

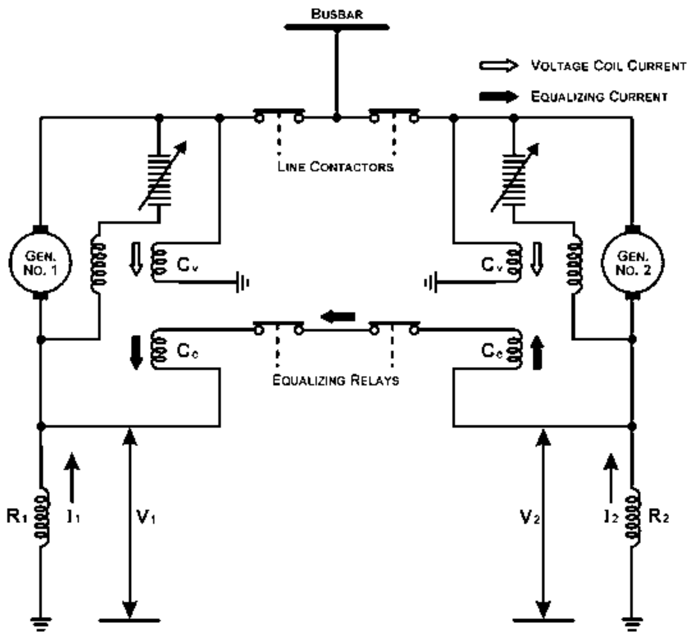


Fig. 9.28. Load sharing (carbon pile regulators).

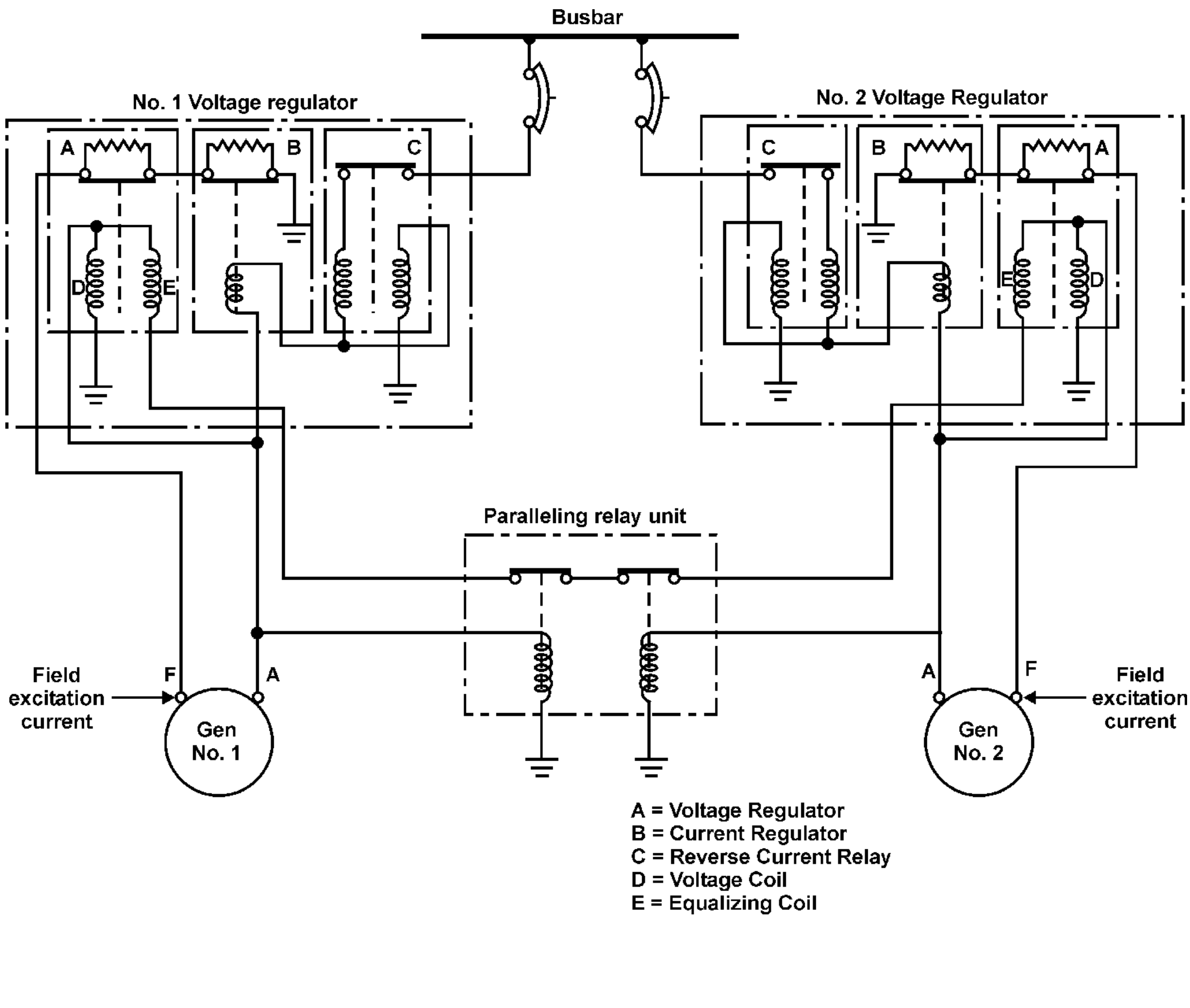


Fig. 9.29. Load sharing (vibrating contact regulators).

The resistances R_1 and R_2 represent the resistances of the negative sections (interpole windings) of the generators, and under balanced load-sharing conditions the volts drop across each section will be the same, i.e. $V_1 = I_1 R_1$ and $V_2 = I_2 R_2$. Thus, the net volts drop will be zero and so no current will flow through the equalizing coils.

Let us now assume that generator No. 1 tends to take a somewhat larger share of the total load than generator No.2. In this condition the volts drop V_1 will now be greater than V_2 and so the negative section of generator No.1 will be at a lower potential. As a result, a current I_e will flow through the equalizing coils which are connected in such a manner that the effect of I_e is to raise the output voltage of generator No.2 and reduce that of No.1 , thereby effectively reducing the unbalance in load sharing. (Fig. 9.28) illustrates the principle as applied to an equalizing circuit which approximates to that of a practical generating system utilizing carbon pile voltage regulators. The equalizing coils are wound on the same magnetic cores as the voltage coils of the regulators, thus, assuming the same unbalanced conditions as before, the current I_e flows in a direction opposite to that flowing through the No.2 generator voltage regulator coil, but in the same direction as the voltage coil current in No.1 regulator. The magnetic effect of the No.2 regulator voltage coil will therefore be weakened resulting in a decrease in carbon pile resistance and an increase in the output of No.2 generator, enabling it to take more of the load. The magnetic effect of the No.1 regulator voltage coil on the other hand, is strengthened, thereby increasing carbon pile resistance and causing No.1 generator to decrease its output and to shed some of its load. The variations in output of each generator continues until the balanced load-sharing condition is once again restored, whereby the equalizing-circuit loop ceases to carry current.

The principle of paralleling as applied to a twin d.c. generator system utilizing vibrating contact regulators is shown in (Fig 9.29). In this case, the equalizing or paralleling circuit comprises an additional coil "Eq" in the voltage regulation sections "A" of each regulator, and a paralleling relay unit.

When both generators are in operation and supplying the requisite regulated voltage, the contacts in the voltage and current ("B") regulation sections of each regulator are closed. The outputs from each generator are also supplied to the coils of the paralleling relay unit and so the contacts of its relays are closed. Thus, together with each of the coils "Eq", the equalizing or paralleling circuit is formed between the generator outputs. Under load-sharing conditions, the current flowing through the coils "Eq" is in the same direction as that through the voltage coils of the voltage regulating sections of each regulator, but in equal and opposite directions at the contacts of the paralleling relay unit.

If the voltage output of one or other generator, e.g. number 1, should rise, there will be a greater voltage input to the voltage regulating section of the number 1 voltage regulator compared to the input at the corresponding section of the number 2 regulator. There will therefore, be an unbalanced flow of current through the equalizing circuit such that the increase in current through the coil "Eq" of the number 1 voltage regulator will now assist the magnetic effect of the voltage coil "D" causing the relay contacts to open. The resistance thereby inserted in the field circuit of number 1 generator reduces its excitation current and its voltage output. Because of the unbalanced condition, the increased current in the equalizing circuit will also flow across the paralleling relay unit contacts to the coil "Eq" in the number 2 voltage regulator so that it opposes the magnetic effect of its associated coil "D".

In paralleled alternator systems using solid-state voltage regulators, any unbalanced condition is detected and adjusted by interconnecting the regulators via two additional paralleling transistors, one in each regulator.

D.C. GENERATOR MAINTENANCE

Inspection

The following information about the inspection and maintenance of d.c. generator systems is general in nature because of the large number of differing aircraft generator systems. These procedures are for familiarization only. Always follow the applicable manufacturer's instructions for a given generator system.

In general, the inspection of the generator installed in the aircraft should include the following items :

1. Security of generator mounting.
2. Condition of electrical connections.
3. Dirt and oil in the generator. If oil is present, check engine oil seal. Blow out dirt with compressed air.
4. Condition of generator brushes.
5. Generator operation.
6. Voltage regulator operation.

A detailed discussion of items 4, 5, and 6 is presented in the following paragraphs.

Condition of Generator Brushes

Sparking of brushes quickly reduces the effective brush area in contact with the commutator bars. The degree of such sparking should be determined. Excessive wear warrants a detailed inspection.

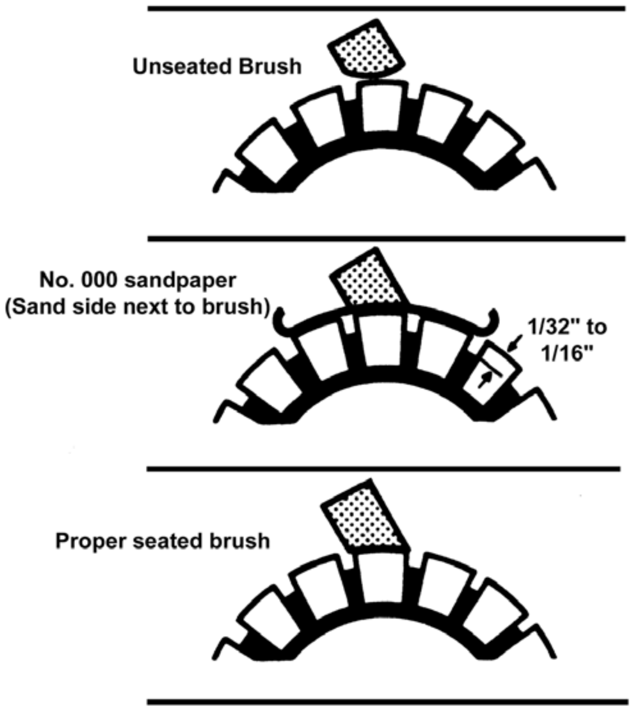


Fig. 9.30. Seating brushes with sandpaper.

The following information pertains to brush seating, brush pressure, high-mica condition, and brush wear.

Manufacturers usually recommend the following procedures to seat brushes which do not make good contact with slip rings or commutators.

The brush should be lifted sufficiently to permit the insertion of a strip of No.000, or finer, sand-paper under the brush, rough side out (Fig. 9.30). Pull sandpaper in the direction of armature rotation, being careful to keep the ends of the sandpaper as close to the slip ring or commutator surface as possible in order to avoid rounding the edges of the brush. When pulling the sandpaper back to the starting point, the brush should be raised so it does not ride on the sandpaper. The brush should be sanded only in the direction of rotation.

After the generator has run for a short period, brushes should be inspected to make sure that pieces of sand have not become embedded in the brush and are collecting copper.

Under no circumstances should emery cloth or similar abrasives be used for seating brushes (or smoothing commutators), since they contain conductive materials which will cause arcing between brushes and commutator bars.

Excessive pressure will cause rapid wear of brushes. Too little pressure, however, will allow "bouncing" of the brushes, resulting in burned and pitted surfaces.

A carbon, graphite, or light metalized brush should exert a pressure of 1½ to 2½ p.s.i. on the commutator. The pressure recommended by the manufacturer should be checked by the use of a spring scale graduated in ounces. Brush spring tension is usually adjusted between 32 to 36 ounces; however, the tesion may differ slightly for each specific generator.

When a spring scale is used, the measurement of the pressure which a brush exerts on the commutator is read directly on the scale. The scale is applied at the point of contact between the spring arm and the top of the brush, with the brush installed in the guide. The scale is drawn up until the arm just lifts off the brush surface. At this instant, the force on the scale should be read.

Flexible low-resistance pigtails are provided on most heavy-current-carrying brushes, and their connections should be securely made and checked at frequent intervals. The pigtails should never be permitted to alter or restrict the free motion of the brush.

The purpose of the pigtail is to conduct the current, rather than subjecting the brush spring to currents which would alter its spring action by overheating. The pigtails also eliminate any possible sparking to the brush guides caused by the movement of the brushes within the holder, thus minimizing side wear of the brush.

Carbon dust resulting from brush sanding should be thoroughly cleaned from all parts of the generators after a sanding operation. Such carbon dust has been the cause of several serious fires as well as costly damage to the generator.

Operation over extended periods of time often results in the mica insulation between commutator bars protruding above the surface of the bars. This condition is called "high mica" and interferes with the contact of the brushes to the commutator.

Whenever this condition exists, or if the armature has been turned on a lathe, carefully undercut the mica insulation to a depth equal to the width of the mica, or approximately 0.20 inch.

Each brush should be a specified length to work properly. If a brush is too short, the contact it makes with the commutator will be faulty, which can also reduce the spring force holding the brush in place. Most manufacturers specify the amount of wear permissible from a new brush length. When a brush has worn to the minimum length permissible, it must be replaced.

Some special generator brushes should not be replaced because of a slight grooving on the face of the brush. These grooves are normal and will appear in a.c. and d.c. generator brushes which are installed in some models of aircraft generators. These brushes have two cores made of a harder material with a higher expansion rate than the material used in the main body of the brush. Usually, the main body of the brush face rides on the commutator. However, at certain temperatures, the cores extend and wear through any film on the commutator.

Generator Operation

If there is no generator output, follow a systematic troubleshooting procedure to locate the malfunction. The following method is an example. Although this method may be acceptable for most 28-volt, twin-engine or four-engine d.c. generator systems using carbon-pile voltage regulators, the applicable manufacturer's procedures should be followed in all cases.

If the generator is not producing voltage, remove the voltage regulator and, with the engine running at approximately 1,800 r.p.m., short circuit terminals A and B at the sub base of the regulator as shown in the diagram of (Fig. 9.31). If this test shows excessive voltage, the generator is not at fault, but the trouble lies in the voltage regulator. If the test fails to produce voltage, the generator field may have lost its residual magnetism.

To restore residual magnetism, flash the generator field by removing the regulator and connect terminal A of the voltage regulator base to the battery at a junction box or a bus bar as indicated by the dotted line in the diagram of (Fig. 9.32), while running the engine at cruising r.p.m. If there is still no voltage, check the leads for continuity shorts and grounds. If the generator is located where the brushes and commutator can be inspected, check each for proper condition as prescribed in the applicable manufacturer's procedures. If necessary, replace the brushes and clean the commutator. If the generator is located so that it cannot be serviced in the airplane, remove it and make the inspection.

VOLTAGE REGULATOR OPERATION

To inspect the voltage regulator, remove it from the sub base and clean all the terminals and contact surface. Examine the base or housing for cracks. Check all connections for security. Remember that the voltage regulator is a precision instrument and cannot withstand rough treatment. Handle it with care. To adjust a voltage regulator, a precision portable voltmeter is required. This, too, must be handled with care, since it will not maintain accuracy under conditions of mishandling, vibration, or shock.

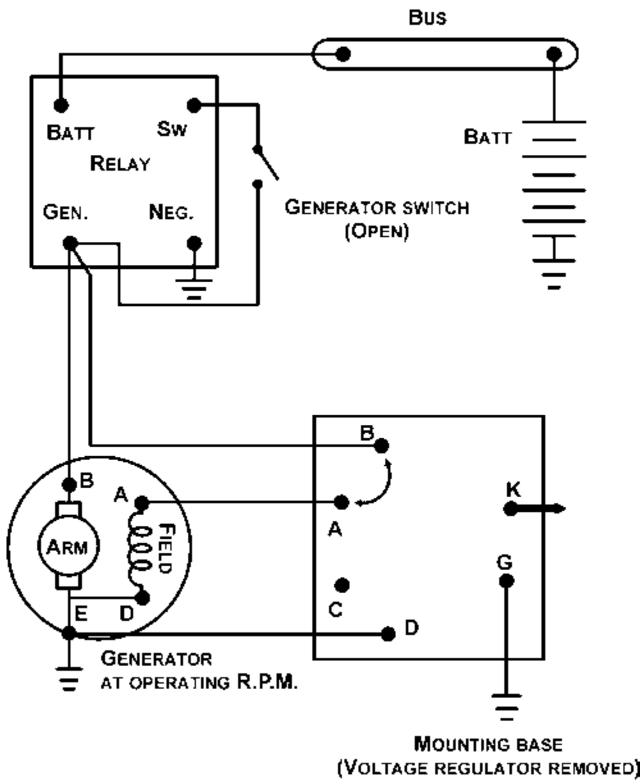


Fig. 9.31. Checking generator by shorting terminals A and B.

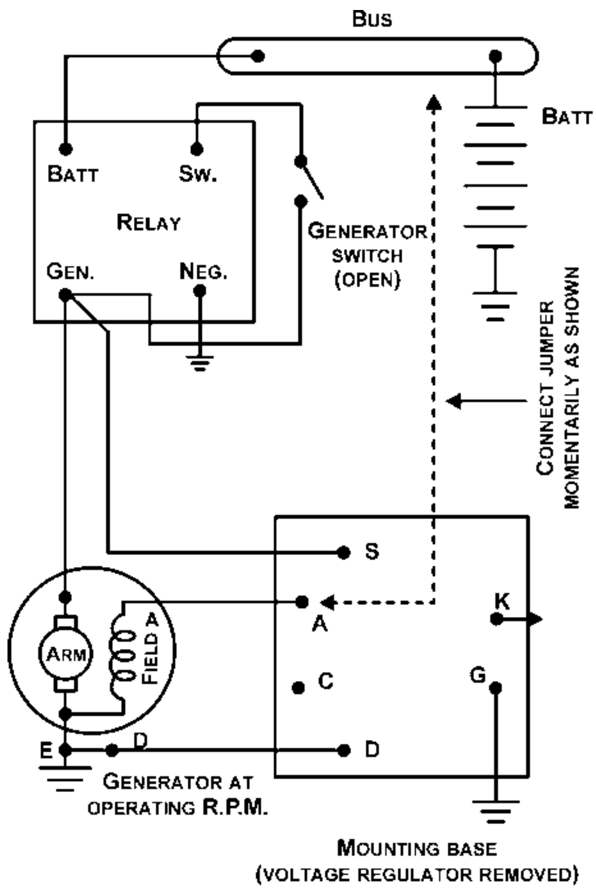


Fig. 9.32. A method of flashing generator field.

Detailed procedures for adjusting voltage regulators are given in applicable manufacturer's instructions. The following procedures are guidelines for adjusting the carbon-pile voltage regulator in a multiengine 28-volt d.c. electrical system:

1. Start and warm up all engines which have installed generators.
2. Turn all generator switches to the "off" position.
3. Connect a precision voltmeter from the B terminal of one voltage regulator to a good ground.
4. Increase the engine speed of the generator being checked to normal cruising r.p.m. Operated remaining engines at idling speed.
5. Adjust the regulator until the voltmeter reads exactly 28 volts. (The location of the adjustment knob on a carbon-pile voltage regulator is shown in Fig. 9.33)

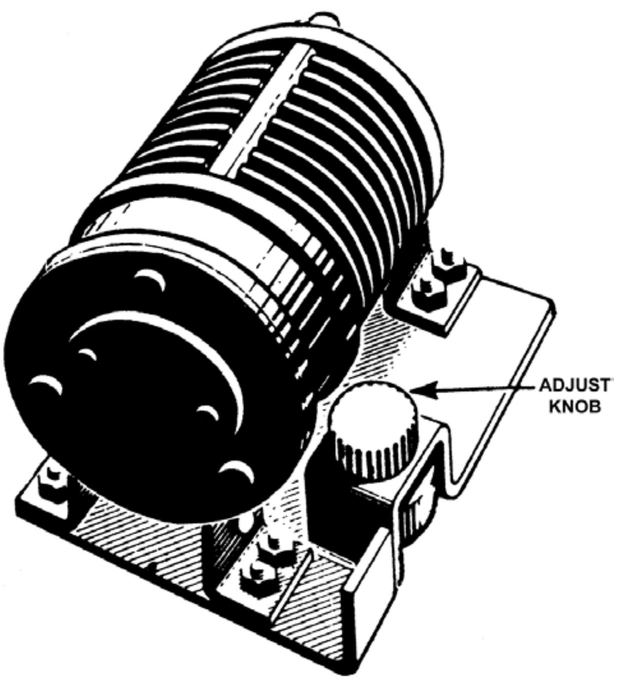


Fig. 9.33. Adjustment knob on carbon-pile voltage regulator.

6. Repeat this procedure to adjust all voltage regulators.
7. Increase the speed of all engines to normal cruising r.p.m.
8. Close all generator switches.
9. Apply a load equivalent to approximately one-half full load rating of one generator when checking a two-generator system or a load comparable to the rating of one generator when checking a system that has more than two generators.
10. Observe the ammeters or load meters. The difference between the highest and lowest generator current should not exceed the value listed in the manufacturer's maintenance instructions.
11. If the generators are not dividing the load equally (unparalled), first lower the voltage of the highest generator and slightly raise the voltage of the lowest generator by adjusting the corresponding voltage regulators. When the generators have been adjusted to share the load equally, they are in "parallel."
12. After all adjustments have been made, make a final check of bus voltage from positive bus to ground, with a precision voltmeter. The voltmeter should read 28 volts, (±0.25 volt on most 28-volt systems). If the bus voltage is not within the proper limits, readjust all voltage regulator rheostats and recheck.

When inspecting the generator relay switch, examine the relay for cleaness and security of mounting and see that all electrical connections are tightly fastened. Look for burned or pitted contacts. Never close the relay manually by pressing the contacts together; this might severely damage the relay or cause an injury. Never adjust the differential type relay, since it closes when the generator voltage exceeds the system voltage by a specified value and is not checked to close at any set voltage; however, check it for proper closing by noting the ammeter indication with the battery generator control switches turned on while running the engines. It is sometimes necessary to put a slight load on the system before the ammeter will show a positive indication when the engine is run up to cruising speed. If the ammeter does not indicate, the relay is probably defective; therefore, remove it and replace it with a new relay. Check the reverse-current relay for proper opening value. If the relay fails to close when the engine speed is increased or fails to disconnect the generator from the bus bar, the relay is defective.

Troubleshooting

If a generator system malfunction, there are two general possibilities : (1) The generator itself may be at fault (burned out, damaged mechanically, etc.), or (2) that part of the circuit leading to or from the generator may be at fault. Continuity testing refers to checking for the existence of a complete electrical system between two points. The three main types of continuity testers are :

1. The portable dry cell tester, having a buzzer or a 3-volt lamp to indicate the completed circuit, is used to test circuits with the main circuit power off.
2. An ordinary lamp bulb (24-volt type), with one lead from the center lamp contact and one ground lead attached to the lamp housing, can be used to test circuits with the main circuit power on.
3. A precision voltmeter is used to test circuits with the main circuit power on by placing the positive lead on the circuit point and the negative lead on any convenient ground.

Tests should be made at each terminal of the circuit. Between the last point at which voltage is indicated and the first point at which zero voltage is indicated, there is an open circuit or a voltage drop caused by unit operation or short to ground. If the same voltage reading is obtained on the negative terminal of a unit as was obtained on the positive terminal, an open ground is indicated. If a small voltage reading is obtained on the negative terminal of the unit, a high resistance is indicated between the unit and ground.

The following troubleshooting chart outlines the most commonly encountered malfunctions, a list of probable causes to isolate the malfunction, and the proper corrective action to be taken. This chart is a general guide for troubleshooting a twin-engine d.c. generator system, which utilizes carbon-pile voltage regulators.

TROUBLE	ISOLATION PROCEDURE	CORRECTION
No voltage indication any one generator	Check for defective generator switchorfieldswtich	Replace generator switch or field swtich
	Determine if genratorpolarity is reversed	Flash generator field.
	Check foropen, shorted, or grounded wiring.	Replace defective wiring.
	Check for defective generator	Replace generator.
Low voltage on any one generator.	Check voltage regulator adjustment	Adjust voltage regulator.
	Check for defective voltage regulator.	Replace voltage regulator
	Check for defective wiring.	Replace defective wiring.
	Check for defective generator.	Replace generator.
Generator cuts out.	Check for defective reverse-current cutout relay.	Replace reverse-current cutout relay.
	Check for defective over voltage relay.	Replace over voltage relay.
	Check for defective field control relay.	Replace field control relay.
	Check for defective voltage regulator.	Replace voltage regulator.
	Check for defective wiring.	Replace defective wiring.
Voltage unsteady for any one generator.	Check for defective wiring.	Replace defective wiring.
	Check for defective generator.	Replace generator.
	Check wear of generator bearings	Replace generator.
No load indication on any one generator. Voltage is normal.	Check for defective reverse-current cutout relay.	Replace reverse-current cutout relay
	Check for defective generator switch.	Replace generator switch.
	Check for defective wiring.	Replace defective wiring.
Low d.c. bus voltage.	Check improper voltage regulator adjustment.	Adjust voltage regulator.
	Check for defective reverse-current cutout relays.	Replace reverse-current coutout relays.

TROUBLE	ISOLATION PROCEDURE	CORRECTION
Voltage high on any one generator	Check for improper voltage-regulator adjustment.	Adjust voltage regulator
	Check for defective voltage regulator.	Replace voltage regulator.
	Determine if generator field lead A is shorted to positive.	Replace shorted wiring or repair connections.
Generator fails to build up more than approximately 2 volts.	Check voltage regulator or base. Take precision voltmeter reading between A terminal and ground. No voltage reading indicates trouble in either regulator or base. Reading of about 2 volts indicates regulator and base are OK.	Check regulator contacts where they rest on the silver contact bar. Any signs of burning at this point is cause for replacement of regulator.
	Check for defective generator. Low ohmmeter readingindicates current is good and trouble must be within the generator	Disconnect generator plug. Place one lead of ohmmeter on A terminal and the other lead on E terminal. High readingindicates that the generator field is open. Replace generator.
Instrument panel voltmeter reading of excessive voltage.	Check for short across A and B terminal of voltage regulator.	If shorted, change voltage regulator
	Check voltage regulator control.	Replace voltage regulator.
Instrument panel voltmeter reading of zero volts.	Check for defective voltmeter circuit.	Place positive lead of voltmeter on positive terminal of instrument panel voltmeter and negative lead to ground. Reading should be 27.5 volts. If not, lead from regulator to instrument is defective. Replace or correct lead. Place positive lead of voltmeter on negative terminal of instrument panel voltmeter and negative lead to ground. If voltmeter readingis zero. instrument panel voltmeter is defective. Replace votmeter.
	Check for broken B or E lead. Remove voltage regulator and take ohmmeter reading between B contact finger or regulator base and ground. Low reading indicates circuit iis OK. High reading indicates that a high resistance is the trouble.	High resistance most likely is caused by oil, dirt,or burning at connector plug or commutator. Replace generator.
	Check for loss of residual magnetism.	Place flasher switch in ON position momentarily. Do not hold. NOTE. If flasher switch isheld ON rather than switched momentarily, damage maybe done to generator field coils.
Voltage does not build up properly when field is flashed.	Check for open field. Disconnect generator connector and take ohmmeter reading between A and E terminals of generator connectors. High reading indicates field circuit is open.	Check and repair lead or connectors
	Check for grounded field. Take ohmmeter reading between A terminal of generator and generator housing. Low reading indicates field is grounded.	Insulation on field winding is broken. Replace generator.
	Check of open armature. Remove generator cover and inspect commutator. if solder is melted and has been thrown off, then armature is open (caused by generator overheating).	Replace generator.

D.C. MOTOR

Most devices in an airplane, from the starter to the automatic pilot, depend upon mechanical energy furnished by direct-current motors. A direct-current motor is a rotating machine which transforms direct-current energy into mechanical energy. It consists of the two principal parts - a field assembly and an armature assembly. The armature is the rotating part in which current-carrying wires are acted upon by the magnetic field.

Whenever a current-carrying wire is placed in the field of a magnet, a force acts on the wire. The force is not one of attraction or repulsion; however, it is at right angles to the wire and also at right angles to the magnetic field set up by the magnet.

The action of the force upon a current-carrying wire placed in a magnetic field is shown in (Fig. 9.32). A wire is located between two permanent magnets. The lines of force in the magnetic field current flows, as in diagram A, no force is exerted on the wire, but when current flows through the wire, a magnetic field is set up about it, as shown in diagram B. The direction of the field depends on the direction of current flow. Current in one direction creates a clockwise field about the wire, and current in the other direction, a counter-clockwise field.

Since the current-carrying wire produces a magnetic field, a reaction occurs between the field about the wire and the magnetic field between the magnets. When the current flows in a direction to create a counter clockwise magnetic field about the wire, this field and the field between the magnets add or reinforce at the bottom of the wire because the lines of force are in the same direction. At the top of the wire, they subtract or neutralize, since the lines of force in the two fields are opposite in direction. Thus, the resulting field at the bottom is strong and the one at the top is weak. Consequently, the wire is pushed upward as shown in diagram C of (Fig. 9.34). The wire is always pushed away from the side where the field is strongest.

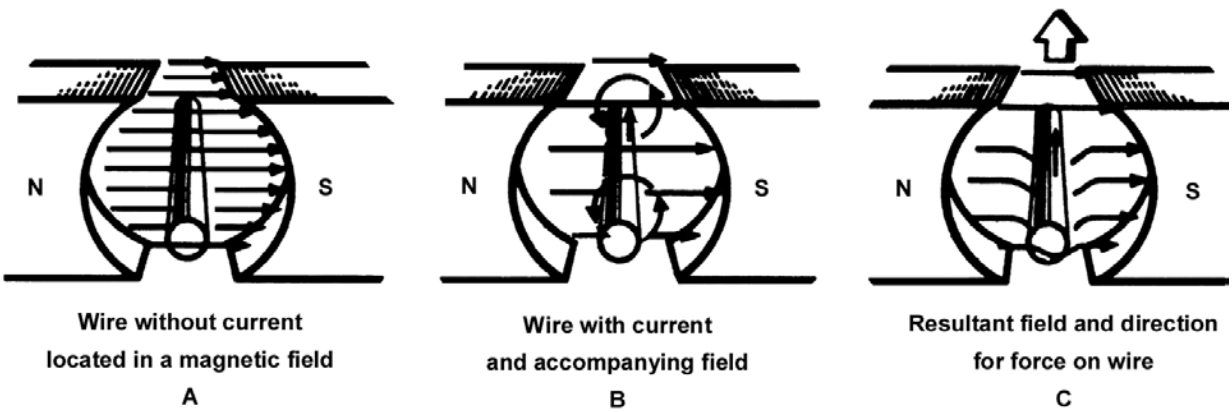


Fig. 9.34. Force on a current-carrying wire.

If current flow through the wire were reversed in direction, the two fields would add at the top and subtract at the bottom. Since a wire is always pushed away from the strong field, the wire would be pushed down.

Developing Torque

If a coil in which current is flowing is placed in a magnetic field, a force is produced which will cause the coil to rotate. In the coil shown in (Fig. 9.33), current flows inward on side A and outward on side B. The magnetic field about B is clockwise and that about A, counter clockwise. As previously explained, a force will develop which pushes side B downward. At the same time, the field of the magnets and the field about A, in which the current is inward, will add at the bottom and subtract at the top. Therefore, A will move upward. The coils will thus rotate until its plane is perpendicular to the magnetic lines between the north and south poles of the magnet, as indicated in (Fig. 9.35) by the white coil at right angles to the black coil.

The tendency of a force to produce rotation is called torque. When the steering wheel of a car is turned, torque is applied. The engine of an airplane gives torque to the propeller. Torque is developed also by the reacting magnetic fields about the current-carrying coil just described. This is the torque which turns the coil.

The right-hand motor rule can be used to determine the direction a current-carrying wire will move in a magnetic field. As illustrated in (Fig. 9.36), if the index finger of the right hand is pointed in the direction of the magnetic field and the second finger in the direction of current flow, the thumb will indicate the direction the current-carrying wire will move.

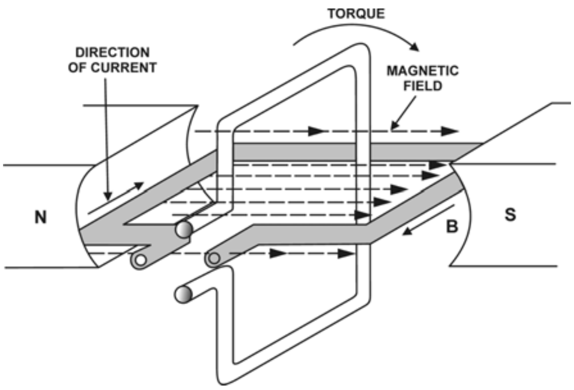


Fig. 9.35. Developing a torque.

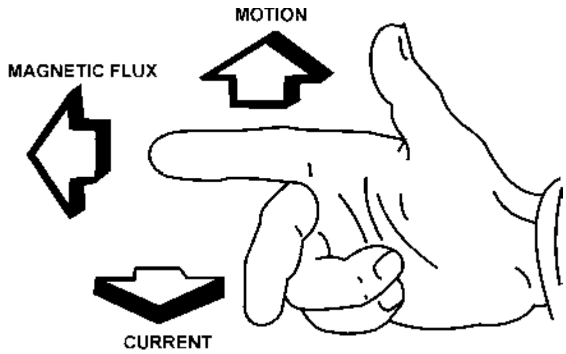


Fig. 9.36. Right-hand motor rule.

The amount of torque developed in a coil depends upon several factors : the strength of the magnetic field, the number of turns in the coil, and the position of the coil in the field. Magnets are made of special steel which produces a strong field. Since there is a torque acting on each turn, the greater the number of turns on the coil, the greater the torque. In a coil carrying a steady current located in a uniform magnetic field, the torque will vary at successive positions of rotation, as shown in (Fig. 9.37). When the plane of the coil is parallel to the lines of force, the torque is zero. When its plane cuts the lines of force at right angles, the torque is 100 percent. At intermediate positions, the torque ranges between zero and 100 percent.

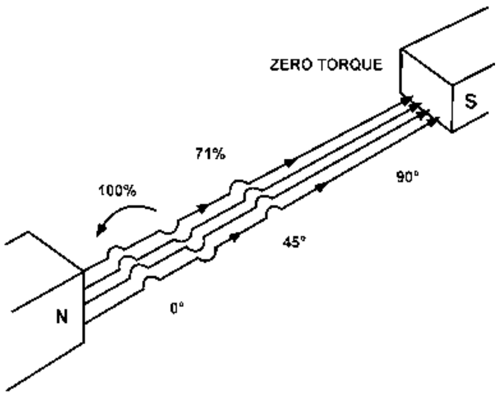


Fig. 9.37. Torque on a coil at various angles of rotation.

Basic D.C. Motor

A coil of wire through which the current flows will rotate when placed in a magnetic field. This is the technical basis governing the construction of a d.c. motor. (Fig. 9.38) shows a coil mounted in a magnetic field in which it can rotate. However, if the connecting wires from the battery were permanently fastened to the terminals of the coil and there was a flow of current, the coil would rotate only until it lined itself up with the magnetic field. Then, it would stop, because the torque at that point would be zero. A motor, of course, must continue rotating. It is necessary, therefore, to design a device that will reverse the current in the coil just at the time the coil becomes parallel to the lines of force. This will create torque again and cause the coil to rotate. If the current-reversing device is set up to reverse the current each time the coil is about to stop, the coil can be made to continue rotating as long as desired.

One method of doing this is to connect the circuit so that, as the coil rotates, each contact slides off the terminal to which it connects and slides off the terminal to which it connects and slides onto the terminal of opposite polarity. In other words, the coil contacts switch terminals continuously as the coil rotates, preserving the torque and keeping the coil rotating. In (Fig. 9.38), the coil terminal segments are labelled A and B. As the coil rotates, the segments slide onto and past the fixed terminals or brushes. With this arrangement, the direction of current in the side of the coil next to the north seeking pole flows toward the reader, and the force acting on that side of the coil turns it downward. The part of the motor which changes the current from one wire to another is called the commutator.

When the coil is positioned as shown in A of (Fig. 9.38), current will flow from the negative terminal of the battery to the negative (-) brush, to segment B of the commutator, through the loop to segment A of the commutator, to the positive (+) brush, and then, back to the positive terminal of the battery. By using the right-hand motor rule, it is seen that the coil will rotate counter clockwise. The torque at this position of the coil is maximum , since the greatest number of lines of force are being cut by the coil.

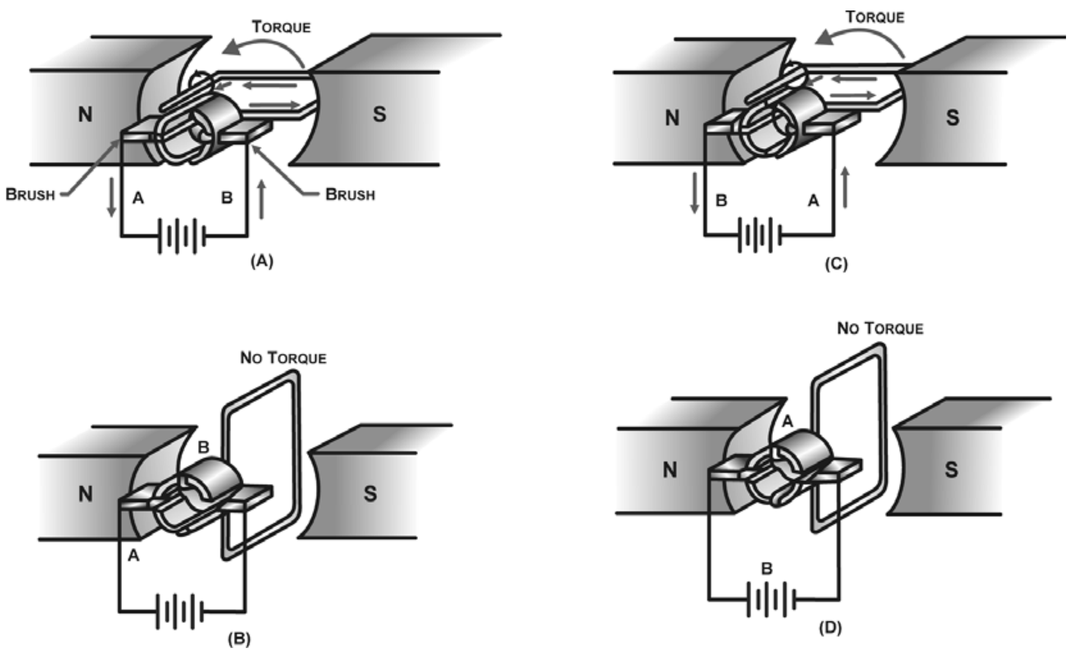


Fig. 9.38. Basic d.c. motor operation.

When the coil has rotated 90^0 to the position shown in B of (Fig. 9.38), segments A and B of the commutator no longer make contact with the battery circuit and no current can flow through the coil. At this position, the torque has reached a minimum value, since a minimum number of lines of force are being cut. However, the momentum of the coil carries it beyond this position until the segments again make contact with the brushes, and current again enters the coil; this time, though, it enters through segment A and leaves through segment B. However, since the positions of segments A and B have also been reversed, the effect of the current is as before, the torque acts in the same direction, and the coil continues its counter clockwise rotation. On passing through the position shown in C of (Fig. 9.38), the torque again reaches maximum. Continued rotation carries the coil again to a position of minimum torque, as in D of (Fig. 9.38). At this position, the brushes no longer carry current, but once more the momentum rotates the coil to the point where current enters through segment B and leaves through A. Further rotation brings the coil to the starting point and, thus, one revolution is completed.

The switching of the coil terminals from the positive to the negative brushes occurs twice per revolution of the coil. The torque in a motor containing only a single coil is neither continuous nor very effective, for there are two positions where there is actually no torque at all. To overcome this, a practical d.c. motor contains a large number of coils wound on the armature. These coils are so spaced that, for any position of the armature, there will be coils near the poles of the magnet. This makes the torque both continuous and strong. The commutator, likewise, contains a large number of segments instead of only two.

The armature in a practical motor is not placed between the poles of a permanent magnet but between those of an electromagnet, since a much stronger magnetic field can be furnished. The core is usually made of a mild or annealed steel, which can be magnetized strongly by induction. The current magnetizing the electromagnet is from the same source that supplies the current to the armature.

Significant of the Back E.M.F.

When the motor armature rotates, the conductors also rotate and hence cut the flux. In accordance with the laws of electromagnetic induction, e.m.f. is induced in them whose direction, as found by Flemming's Right-hand Rule, is in opposition to the applied voltage [(Fig. 9.39 (a)]. Because of its opposing direction, it is referred to as back e.m.f. E_b. The equivalent circuit of a motor is shown in [Fig. 9.39(b)]. The rotating armature generating the back e.m.f. E_b put across a supply mains of V volts. Obviously, V has to drive I_a against the opposition of E_b. The power required to overcome this opposition is E_bI_b watts.

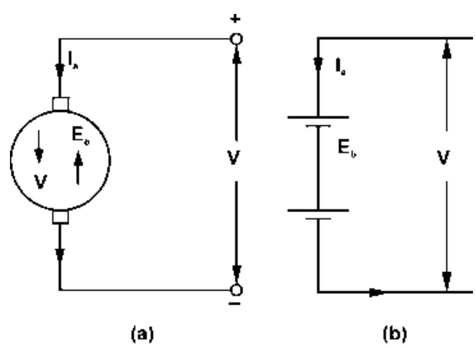


Fig.9.39.

In the case of a battery, this power over an interval of time is converted into chemical energy, but in the present case, it is converted into mechanical energy.

It will be seen that $I_a = \frac{\text{net voltage}}{\text{resistance}} = \frac{V - E_b}{R_a}$ where R_a is the resistance of the armature circuit.

As pointed out above

$E_b = \Phi ZN \times (P/A)$ volts .....N in r.p.s.

$= \frac{\Phi ZN}{60}\left(\frac{P}{A}\right)$ .....N in r.p.m.

Back e.m.f. depends, among other factors, upon the armature speed. If speed is high, E_b is large, hence armature current I_a, as seen from the above equation, is small. If the speed is less, then E_b is less, hence more current flows which develops more torque. So, we find that E_b acts like a governor i.e. it makes a motor self-regulating so that it draws as much current as is just necessary.

Voltage Equation of the Motor

The voltage V applied across the motor armature (Fig. 9.40) has to

i. overcome the back e.m.f. E_b and

ii. supply the armature ohmic drop I_aR_a

$\therefore \quad V = E_b + I_aR_a$

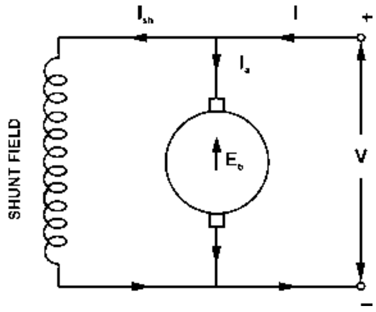


Fig. 9.40.

This is known as voltage equation of a motor.

Now, multiplying both sides by I_a, we get

$VI_a = E_bI_a + I_a^2R_a$

As shown in (Fig. 9.40).

VI_a = electrical input to the armature.

E_bI_a = electrical equivalent of the mechanical power P_m developed in the armature.

$I_a^2R_a$ = Cu loss in the armature.

Hence, out of the armature input, some is wasted as I^2R loss and the rest is converted into mechanical work within the armature.

Condition for Maximum Power

The mechanical power developed by a motor is

$P_m = VI_a - I_a^2R_a$

Differentiating both sides with respect to I_a, we get

$dP_m / dI_a = V - 2I_aR_a = 0 \qquad \therefore I_aR_a = V/2$

As $V = E_b + I_aR_a = V/2 \qquad \therefore E_b = V/2$

The mechanical power developed by a motor is maximum when the back e.m.f. is equal to half the applied voltage. This condition is, however, not realized in practice because in that case, current would be much beyond the normal current of the motor. Moreover, half the input would be wasted in the form of heat and taking other losses (mechanical and magnetic) into consideration, the motor efficiency will be well below 50 per cent.

Speed of a D.C. Motor

From the voltage equation of a motor, we get

$E_b = V - I_aR_a$

or $\Phi ZN(P/A) = V - I_aR_a$

$\therefore \; N = \frac{V - I_aR_a}{\Phi} \times \left(\frac{60A}{ZP}\right)$ r.p.m.

Now $V - I_aR_a = E_b$

$$\therefore\ N = \frac{E_b}{\Phi} \times \left(\frac{60A}{ZP}\right) \text{r.p.m. or } N = \frac{kE_b}{\Phi}$$

It shows that speed is directly proportional to back e.m.f. E_b and inversely to the flux Φ.

or $N \propto \frac{E_b}{\Phi}$

Speed Regulation

The term speed regulation refers to the change in the speed of a motor with change in applied load torque, other conditions remaining constant. By change in speed here is meant the change which occurs under these conditions due to inherent properties of the motor itself and not those changes which are affected through manipulation of rheostats or other speed controlling devices.

The speed regulation is defined as the change in speed when the load on the motor is reduced from rated value to zero, expressed as percent of the rated load speed.

$$\therefore\ \%\ \text{speed regulation} = \frac{\text{N.L. speed} - \text{F.L. speed}}{\text{F.L. speed}} \times 100$$

$$= \frac{N_0 - N}{N} \times 100 = \frac{dN}{N} \times 100$$

D.C. Motor Construction

The major parts in a practical motor are the armature assembly, the field assembly, the brush assembly, and the end frame. (see Fig. 9.41).

Armature Assembly

The armature assembly contains a laminated, soft-iron core, coils, and a commutator, all mounted on a rotatable steel shaft. Laminations made of stacks of soft iron, insulated from each other, form the armature core. Solid iron is not used, since a solid-iron core revolving in the magnetic field would heat and use energy needlessly. The armature windings are insulated copper wire, which are inserted in slots insulated with fiber paper (fish paper) to protect the windings. The ends of the windings are connected to the commutator segments. Wedges or steel bands hold the windings in place to prevent them from flying out of the slots when the armature is rotating at high speeds. The commutator consists of a large number of copper segments insulated from each other and the armature shaft by pieces of mica. Insulated wedge rings hold the segment in place.

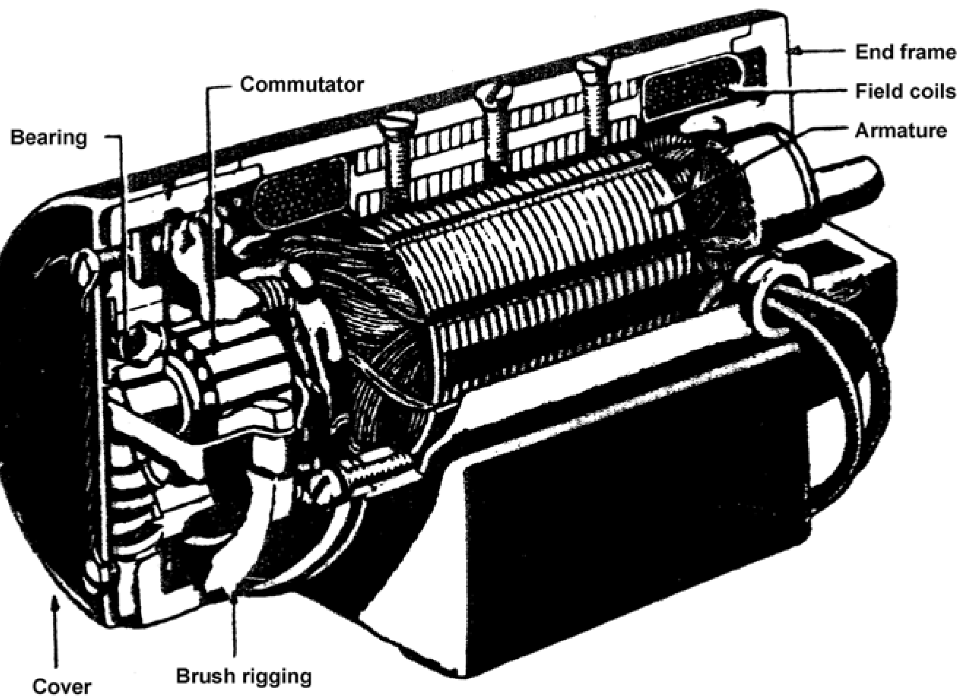


Fig. 9.41. Cutaway view of practical d.c. motor.

Field Assembly

The field assembly consists of the field frame, the pole pieces, and the field coils. The field frame is located along the inner wall of the motor housing. It contains laminated soft steel pole pieces on which the field coils are wound. A coil, consisting of several turns of insulated wire, fits over each pole piece and, together with the pole, constitutes a field pole. Some motors have as few as two poles, others as many as eight.

Brush Assembly

The brush assembly consists of the brushes and their holders. The brush assembly consists of the brushes and their holders. The brushes are usually small blocks or graphic carbon, since this material has a long service life and also causes minimum wear to the commutator. The holders permit some play in the brushes so they can follow any irregularities in the surface of the commutator and make good contact. Spring hold the brushes firmly against the commutator. A commutator and two types of brushes are shown in (Fig. 9.42).

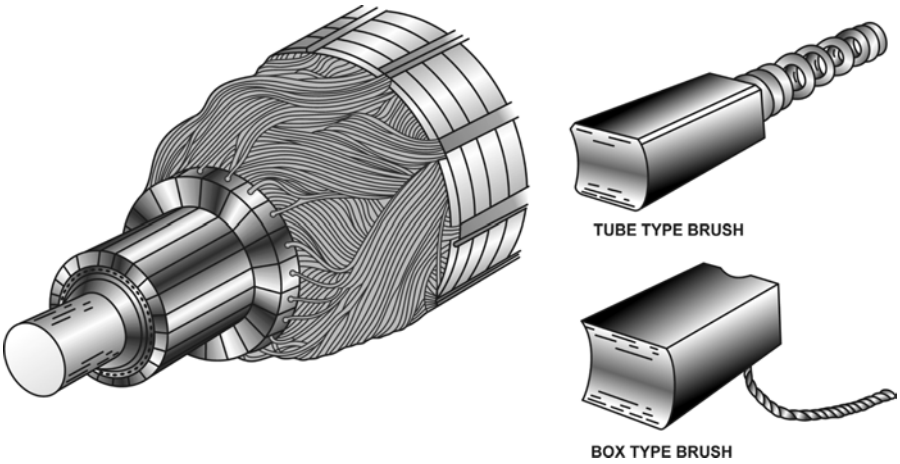


Fig. 9.42. Commutator and brushes.

End Frame

The end frame is the part of the motor opposite the commutator. Usually, the end frame is designed so that it can be connected to the unit to be driven. The bearing for the drive end is also located in the end frame. Sometimes the end frame is made a part of the unit driven by the motor. When this is done, the bearing on the drive end may be located in any one of a number of places.

TYPES OF D.C. MOTORS

There are three basic types of d.c. motors : (1) Series motors, (2) shunt motors, and (3) compound motors. They differ largely in them method in which their field and armature coils are connected.

Series D.C. Motor

In the series motor, the field windings, consisting of a relatively few turns of heavy wire, are connected in series with the armature winding. Both a diagrammatic and a schematic illustration of a series motor is shown in (Fig. 9.43). The same current flowing through the field winding also flows through the armature winding. Any increase in current, therefore, strengthens the magnetism of both the field and the armature.

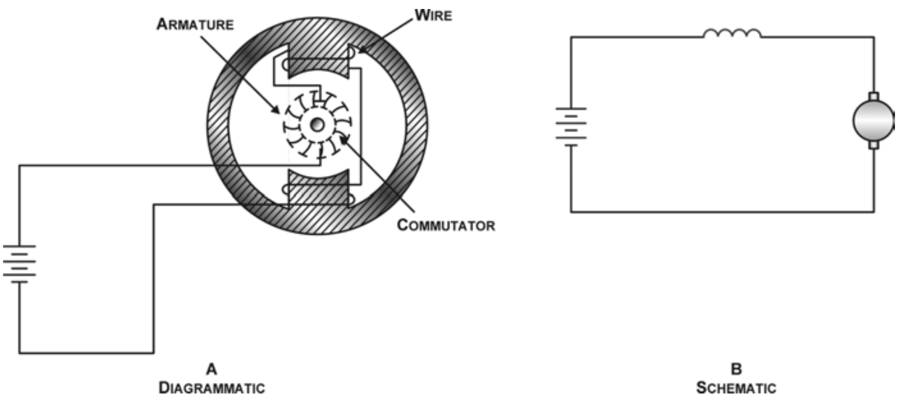


Fig. 9.43. Series motor.

Because of the low resistance in the windings, the series motor is able to draw a large current in starting. This starting current, in passing through both the field and armature windings, produces a high starting torque, which is the series motor's principal advantage.

The speed of a series motor is dependent upon the load. Any change in load is accompanied by a substantial change in speed. A series motor will run at high speed when it has a light load and at low speed with a heavy load. If the load is removed entirely, the motor may operate at such a high speed that the armature will fly apart. If high starting torque is needed under heavy load conditions, series motors have many applications. Series motors are often used in aircraft as engine starters and for raising and lowering landing gears, cowl flaps, and wing flaps.

Shunt D.C. Motor

In the shunt motor the field winding is connected in parallel or in shunt with the armature winding. (See Fig. 9.44) The resistance in the field winding is connected directly across the power supply, the current through the field is constant. The field current does not vary with motor speed, as in the series motor and, therefore, the torque of the shunt motor will vary only with the current through the armature. The torque developed at starting is less than that developed by a series motor of equal size.

The speed of the shunt motor varies very little with changes in load. When all load is removed, it assumes a speed slightly higher than the loaded speed. This motor is particularly suitable for use when constant speed is desired and when high starting torque is not needed.

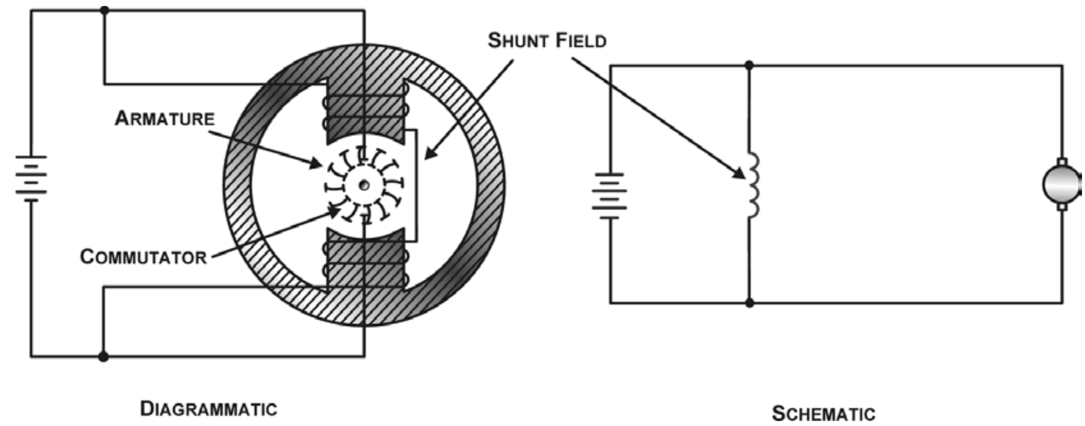


Fig. 9.44. Shunt motor.

Compound D.C. Motor

The compound motor is a combination of the series and shunt motors. There are two windings in the field : a shunt winding and a series winding. A schematic of a compound motor is shown in (Fig. 9.45). The shunt winding is composed of many turns of fine wire and is connected in parallel with the armature winding. The series winding consists of a few turns of large wire and is consists of a few turns of large wire and is connected in series with the armature winding. The starting torque is higher than in the shunt motor but lower than in the series motor. Variation of speed with load is less than in the shunt motor but greater than in the series motor. Variation of speed with load is less than in a series-wound motor but greater than in a shunt motor. The compound motor is used whenever the combined characteristics of the series and shunt motors are desired.

Like the compound generator, the compound motor has both series and shunt field windings. The series winding may either aid the shunt wind (cumulative compound) or oppose the shunt winding (differential compound).

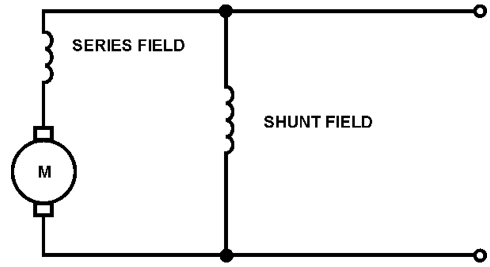


Fig. 9.45 Shunt motor.

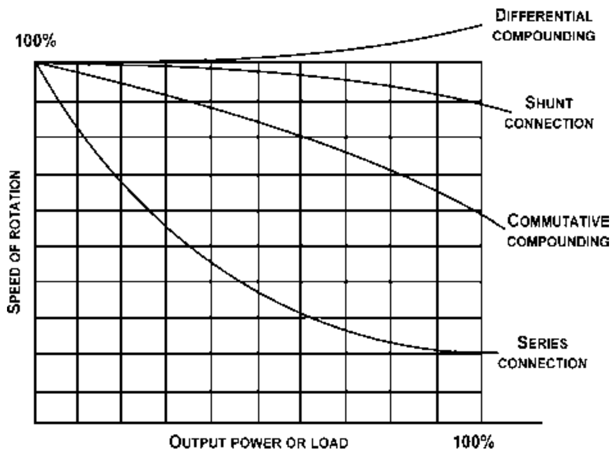


Fig. 9.46 Load characteristics of d.c. motors.

The starting and load characteristics of the cumulative-compound motor are somewhere between those of the series and those of the shunt motor.

Because of the series field, the cumulative-compound motor has a higher starting torque than a shunt motor. Cumulative-compound motors are used in driving machines which are subject to sudden changes in load. They are also used where a high starting torque is desired, but a series motor cannot be used easily.

In the differential compound motor, an increase in load creates an increase in current and a decrease in total flux in this type of motor. These two tend to offset each other and the result is a practically constant speed. However, since an increase in load tends to decrease the field strength, the speed characteristic becomes unstable. Rarely in this type of motor used in aircraft systems.

A graph of the variation in speed with changes of load of the various types of d.c. motors is shown in (Fig. 9.46).

Types of Duty

Electric motors are called upon to operate under various conditions. Some motors are used for intermittent operation; others operate continuously. Motors built for intermittent duty can be operated for short periods only and, then, must be allowed to cool before being operated again. If such a motor is operated for long periods under full load, the motor will be overheated. Motors built for continuous duty may be operated at rated power for long periods.

Reversing Motor Direction

By reversing the direction of current flow in either the armature or the field windings, the direction of a motor's rotation may be reversed. This will reverse the magnetism of either the armature or the magnetic field in which the armature rotates. If the wires connecting the motor to an external source are interchanged, the direction of rotation will not be reversed, since changing these wires reverses the magnetism of both field and armature and leaves the torque in the same direction ad before.

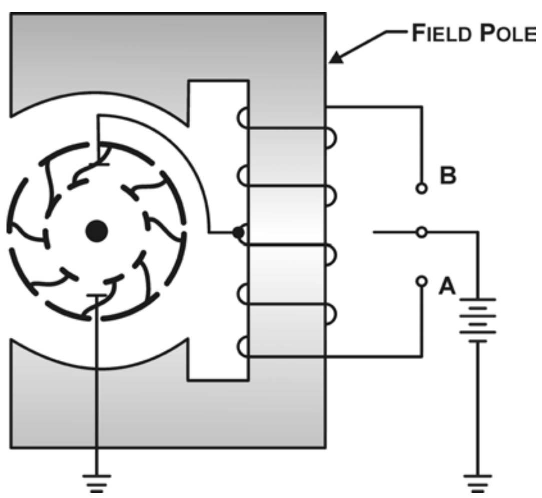


Fig. 9.47. Split field series motor.

One method for reversing direction of rotation employs two field windings wound in opposite directions on the same pole. This type of motor is called a split field motor. (Fig. 9.47) shows a series motor with a split field winding. The single-pole, double-throw switch makes it possible to direct current through either of the two windings. When the switch is placed in the lower position, current flows through the lower field winding, creating a north pole at the lower field winding and at the lower pole piece, and a south pole at the lower pole piece, and a south pole at the upper field winding, the magnetism of the field is reversed, and the armature rotates in the opposite direction. Some split field motors are built with two separate field windings wound on alternate poles. The armature in such a motor, a four-pole reversible motor, rotates in one direction when current flows through the windings of one set of opposite pole pieces, and in the opposite direction when current flows through the other set of windings.

Another method of direction reversal, called the switch method, employs a double-pole, double-throw switch which changes the direction of current flow in either the armature or the field. In the illustration of the switch method shown in (Fig. 9.48), current direction may be reversed through the field but not through the armature.

When the switch is thrown to the "up" position, current flows through the field winding to establish a north pole at the right side of the motor and a south pole at the left side of the motor. When the switch is thrown to the "down" position, this polarity is reversed and the armature rotates in the opposite direction.

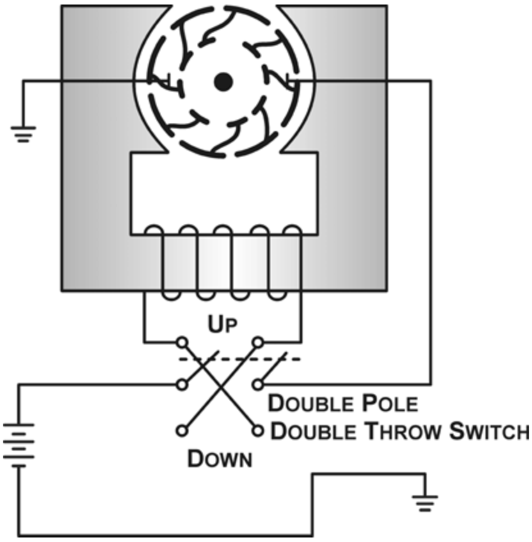


Fig. 9.48. Switch method of reversing motor direction.

Factors Controlling the Speed

It has been shown earlier that the speed of a motor is given by the relation

$$N = \frac{V - I_a R_a}{\Phi} \times \frac{60A}{ZP} = K \frac{V - I_a R_a}{\Phi} \text{ r.p.m.}$$

where R_a = armature circuit resistance.

It is obvious that the speed can be controlled by varying (i) flux per pole, Φ (flux control) (ii) resistance R_a of armature circuit (rheostatic control). These methods as applied to shunt and series motors will be discussed below.

Speed Control of Shunt Motors

i. Variation of Flux or Flux Control Method

It is seen from above that $N \alpha 1/\Phi$. By decreasing the flux, the speed can be increased and vice versa. Hence, the name flux or field control method. The flux of a d.c. motor can be changed by changing I_{sh} with the help of a shunt field rheostat (Fig. 9.49). Since I_{sh} is relatively small, shunt field rheostat has to carry only small current which means I^2R loss is small, so that rheostat is small in size. This method is, therefore, very efficient. In non-interpolar machines, the speed can be increased by this method in the ratio 2:1. Any further weakening of flux Φ adversely affects the commutation and hence puts a limit to the maximum speed obtainable with this method. In machines fitted with interpoles, a ratio of maximum to minimum speeds of 6:1 is fairly common.

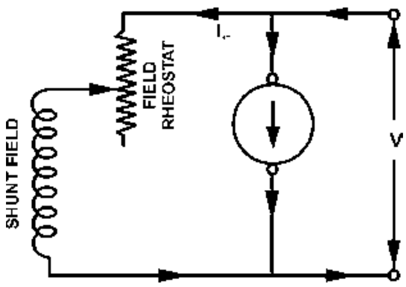


Fig. 9.49.

ii. Armature or Rheostatic Control Method

This method is used when speeds below the no-load speed are required. As the supply voltage is normally constant, the voltage across the armature is varied by inserting a variable rheostat or resistance (called controller resistance) in series with the armature circuit as shown in (Fig. 9.50). As controller resistance is increased, p.d. across the armature is decreased thereby decreasing the armature speed. For a load of constant torque, speed is approximately proportional to the p.d. across the armature. From the speed Vs armature current characteristic (Fig. 9.51) it is seen that greater the resistance in the armature circuit, greater is the fall in speed.

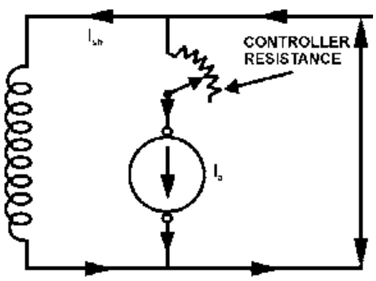


Fig. 9.50.

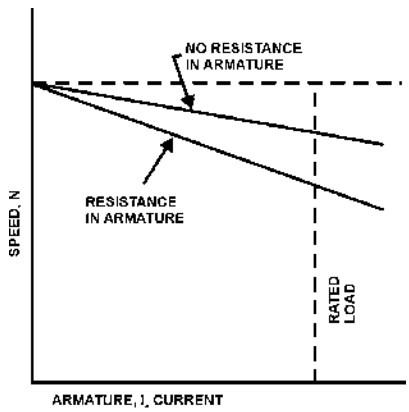


Fig. 9.51.

Speed Control of Series Motors

i. Flux Control Method

Variation in the flux of a series motor can be brought about in any one of the following ways :

a. Field Divertor

The series windings are shunted by a variable resistance known as field divertor (Fig. 9.52). Any desired amount of current can be passed through the divertor by adjusting its resistance. Hence, the flux can be decreased and consequently, the speed of the motor increased.

b. Armature Divertor

A divertor across the armature can be used for giving speeds lower than the normal speeds (Fig. 9.53). For a given constant load torque, if I_a is reduced due to armature divertor, then Φ must increase $\left(\because T_a \alpha \Phi I_a\right)$. This results in an increase in current taken from the supply (which increases the flux) and a fall in speed $(\because N\alpha 1/\Phi)$. The variations is speed can be controlled by varying the divertor resistance.

c. Tapped Field Control

This method is often used in electric traction and is shown in Fig. 9.54.

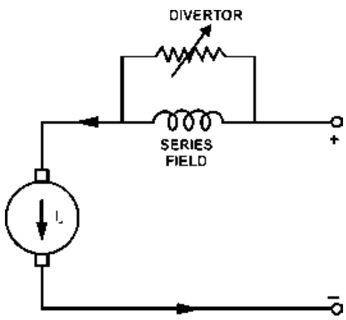


Fig. 9.52.

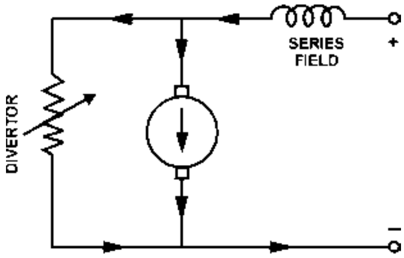


Fig. 9.53.

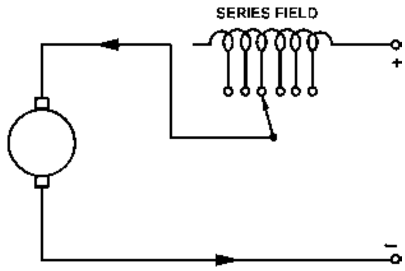


Fig. 9.54.

The number of series field turns in the circuit can be changed at will as shown. With full field, the motor runs at its minimum speed which can be raised in steps by cutting out some of the series turns.

d. Paralleling Field Coils

In this method, used for fan motors, several speeds can be obtained by regrouping the field coils as shown in (Fig. 9.55). It is seen that for a 4-pole motor, three fixed speeds can be obtained easily.

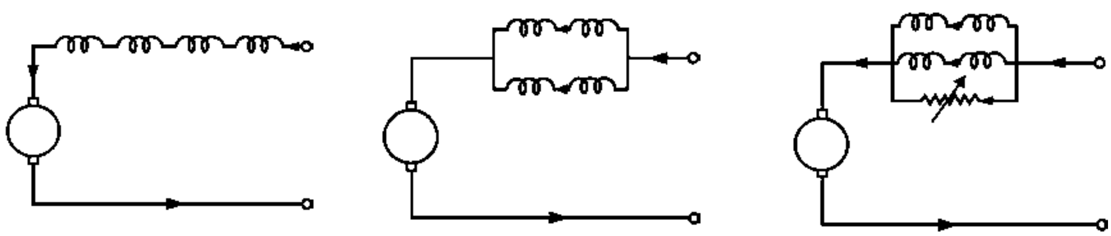


Fig. 9.55.

ii. Variable Resistance in Series with Motor Armature

By increasing the resistance in series with the armature (Fig. 9.56), voltage applied across the armature terminals can be decreased.

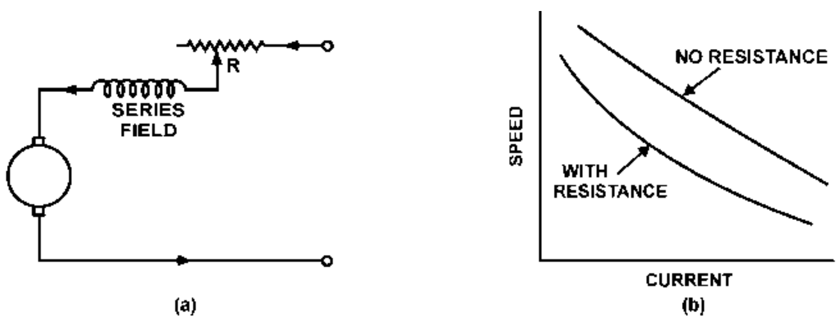


Fig. 9.56.

With reduced voltage across the armature, the speed is reduced. However, it will be noted that since full motor current passes through this resistance, there is a considerable oss of power in it.

Motor Starters-their Necessity

When a motor is at rest, there is, as yet, no back e.m.f. and if full supply voltage is applied, then the starting current is very high because armature resistance is very small. Suppose, a 200-kW motor has a cold armature resistance of 0.28Ω and a F.L. current of 20A. If this motor is directly switched on to a supply of 440-V, an armature current of 440/0.28=1572 A would flow which is 1572/50 = 31.4 times its F.L. current. This excessive current will blow out fuses and may damage the brushes etc. To avoid this excessive starting current, a resistance is inserted in series with the armature and is gradually cut out as the motor gains speed and develops the back e.m.f. which then regulates its speed.

For series motors, the starter resistance is in series with both the armature and the field, but with shunt and compound motors, full shunt field is established on the first contact and maintained during the starting period while the starter resistance is progressively decreased.

Shunt Motor Starter With Protective Devices

It is shown in (Fig. 9.57). It consists of an arm or handle A which moves over the studs. When the arm touches the first stud , field circuit is completed through brass arc B and full resistance is placed in the armature but is gradually cut out as the handle is moved over. The handle moves against a strong spring as shown. It has a piece of soft iron C attached to it which in the 'FULL-ON' position is attracted and held by the electromagnet E which is energised by shut field current. This is known as 'hold-on' coil or low-voltage' (formerly No-voltage) release. The action of this protective device is, in case of a failure or disconnection of the supply or a break in the field circuit, to release the arm and allow the spring to bring it back to 'OFF' position. This prevents the fuses from blowing, as they otherwise would if the supply were restored with the handle in the 'FILL-ON' position.

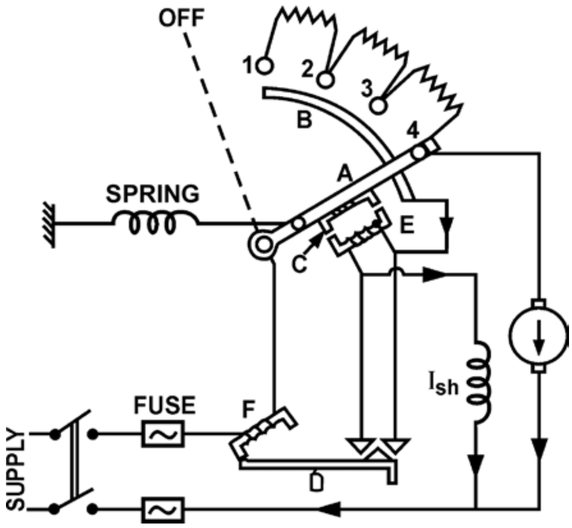


Fig. 9.57.

An over-current (or over-load) release is also fitted in the starter. This consists of an electromagnet F which is connected in the supply line. If the machine becomes over-loaded beyond a certain predetermined value, then D is lifted and short-circuits E. Hence, the handle is released and returns to 'OFF' position.

Merits and Demerits of Rheostatic Control Method

1. Speed changes with every change in load, because speed variations depend not only on controlling resistance but on load current also. This double dependence makes it impossible to keep the speed sensibly constant on rapidly changing loads.
2. A large amount of power is wasted in the controller resistance. Loss of power is directly proportional to the reduction speed. Hence, efficiency is decreased.
3. Maximum output power developed is diminished in the same ration as speed.
4. It needs expensive arrangement for dissipation of heat produced in the controller resistance.
5. It gives speeds below the normal speed, not above it because armature voltage can be decreased (not increased) by the controller resistance.

This method is, therefore, employed when low speeds are required for a short period only and that too occasionally as in printing machines and for cranes and hoists where the motor is continually started and stopped.

Advantages of Field Control Method

This method is economical, more efficient and convenient though it can give speeds above (not below) the normal. The only limitation of this method is that commutation becomes unsatisfactory, because the effect of armature is greater on a weaker field.

It should, however, be noted that by combining the two methods, speeds above and below the normal may be obtained.

Energy Losses in D.C. Motors

Losses occur when electrical energy is converted to mechanical energy (in the motor), or mechanical energy is converted to electrical energy (in the generator). For the machine to be efficient, these losses must be kept to a minimum . Some losses are electrical, others are mechanical. Electrical losses are classified as copper losses and iron losses; mechanical losses occur in overcoming the friction of various parts of the machine.

Copper losses occur when electrons are forced through the copper windings of the armature and the field. These losses are proportional to the squared of the current. They are sometimes called I^2R losses, since they are due to the power dissipated in the form of heat in the resistance of the field and armature windings.

Iron losses are subdivided in hysteresis and eddy current losses. Hysteresis losses are caused by the armature revolving in an alternating magnetic field. It, therefore, becomes magnetized magnetic field. It, therefore, becomes magnetized first in one direction and then in the other. The residual magnetism of the iron or steel of which the armature is made causes these losses. Since the field magnets are always magnetized in one direction (d.c.field), they have no hysteresis losses.

Eddy current losses occur because the iron core of the armature is a conductor revolving in a magnetic field. This sets up an e.m.f. across portions of the core, causing currents to flow within the core. These currents heat the core and, if they become excessive, may damage the windings. As far as the output is concerned, the power consumed by eddy currents is a loss. To reduce eddy currents to a minimum, a laminated core usually is used. A laminated core is made of thin sheets of iron electrically insulated from each other. The insulation between laminations reduces eddy currents, because it is "transverse" to the direction in which these currents tend to flow. However, it has no effect on the magnetic circuit. The thinner the laminations, the more effectively this method reduces eddy current losses.

SPLIT-FIELD MOTORS

In a number of applications involving motors it is required that the direction of motor rotation be reversed in order to perform a particular function, e.g. the opening and closing of a valve by an actuator. This is done by reversing the direction of current flow and magnetic field polarity, in either the field windings or the armature.

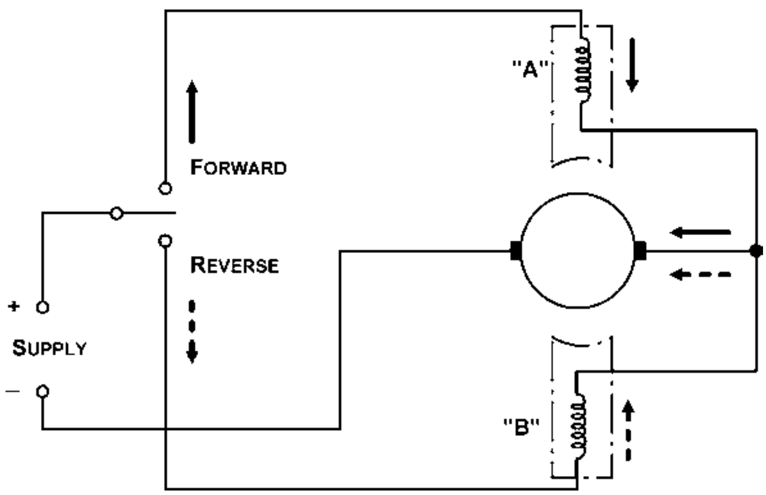


Fig. 9.58. Split field motor circuit.

A method based on this principle, and one most commonly adopted in series-wound motors, is that in which the field winding is split into two electrically separate sections thereby establishing magnetic fields flowing in opposite directions. One of the two windings is used for each direction of rotation and is controlled by a single-pole throw switch. The circuit is shown in (Fig. 9.58). When the switch is placed in the "Forward" position then current will flow in section "A" of the field winding and will establish a field in the iron core of appropriate polarity. Current also flows through the armature winding, the interaction of its field with that established by field winding section "A" causing the armature to rotate in the forward direction. When "Reverse" is selected on the control switch, section "A" is isolated and current flows through section "B" of the feld winding in the opposite direction. The current flow through the armature is in the same direction as before, but as the polarities of the iron core pole pieces fields causes the armature to run in the reverse direction. Some split-field series motors are designed with two separate field windings on alternate poles. The armature in such a motor, a 4-pole reversible motor, rotates in one direction when current flows through the windings of one set of opposite pole pieces, and in the reverse direction when current flows through the other set of windings.

The reversing of motors by interchanging the armature connections is also employed in certain applications, notably when the operating characteristics of compound machines are required. The circuit diagram illustrated in (Fig. 9.59) is based on the arrangement adopted in a compound motor designed for the lowering and raising of an aircraft's landing flaps (see Fig. 9.60). Current flows to the armature winding via the contacts of a relay, since the current demands of the motor are fairly high.

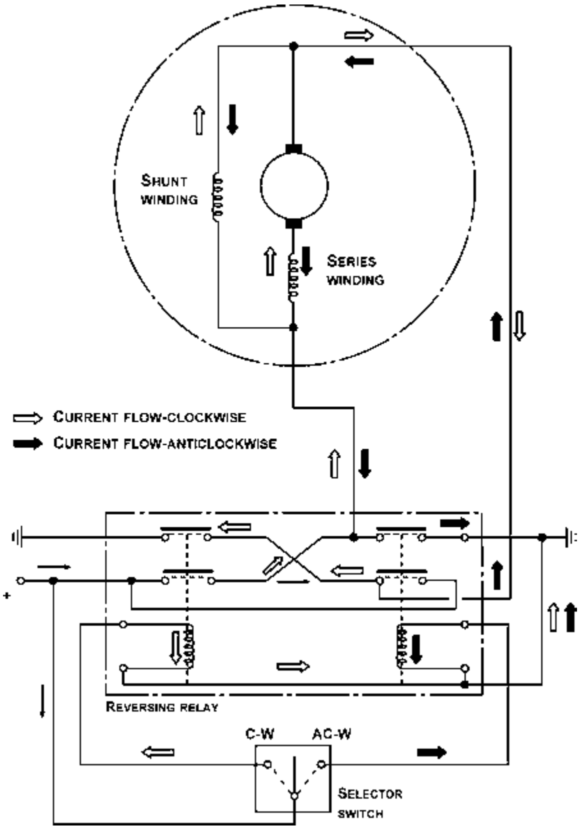


Fig. 9.59. Reversing of a compound motor.

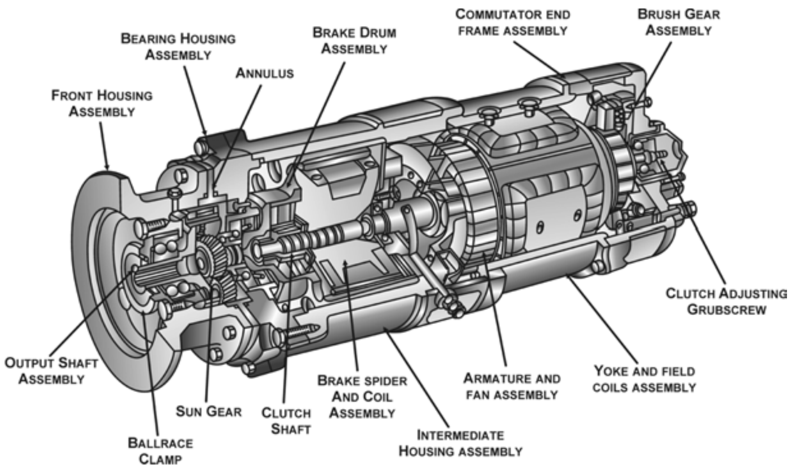


Fig. 9.60. Reversible compound motor.

Motor-Actuators

Motor actrators are self-contained units combining electrical and mechanical devices capable of exerting reversible linear thrust over short distances, or reversible low-speed turning effort. Actuators are thereby classified as either linear or rotary and may be powered by either d.c. or a.c. motors. In the majority of cases d.c. motors are of the split-field series-wound type.

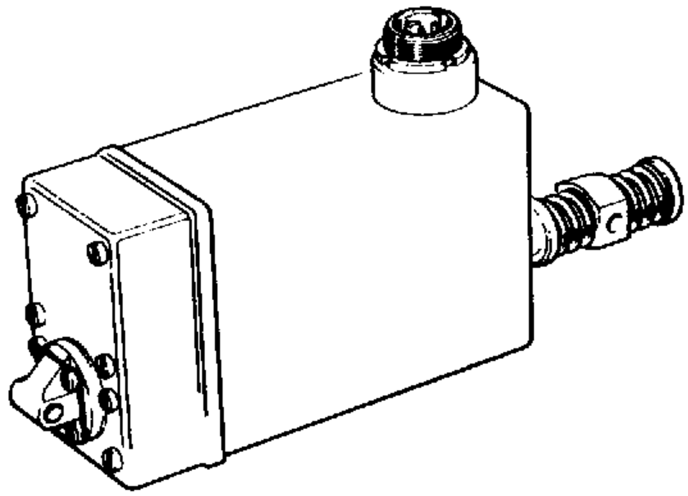


Fig. 9.61. Linear actuator.

LINEAR ACTUATORS

Linear actuators may vary in vertain of their design and constructional features dependent upon the application, load requirements and the manufacturer responsible. In general, however, they consist of the motor which is coupled through reduction gearing to a lead screw which on being rotated extends or retracts a ram or plunger. Depending on the size of actuator, extension and retraction is achieved either by the action of a conventional screw thread or by what may be termed a " ball bearing thread". In the former case, the lead screw is threaded along its length with a square-form thread which mates with a vorresponding thread in the hollow ram. With the motor in operation the rotary motion of the lead screw is thereby converted into linear motion of the ram, which is linked to the appropriate movable component. The ball bearing method provides a more efficient thread and is usually adopted in large actuators designed for operation against heavy loads. In this case, the conventional male and female threads are replaced by two semi-circular helical grooves, and the space between the grooves is filled with steel balls. As the lead screw rotates, the balls exert thrust on the ram, extending or retracting it as appropriate, and at the same time, a recirculating device ensures that the balls are fed continuously into the grooves.

A typical linear actuator is shown in (Fig. 9.61).

ROTARY ACTUATORS

Rotary actuators are usually utilized in components the mechanical elements of which are required to be rotated at low speed or through limited angular travel. As in the case of linear actuators the drive from the motor is transmitted through reduction gearing, the output shaft of which is coupled directly to the relevant movable component, e.g. valve flap. Some typical examples of the application of rotary actuators are air-conditioning system spill valves and fuel cocks.

ACTUATOR GEARING

The reduction gearing generally takes the form of multi-stage spur gear trains for small types of linear and rotary actuators, while in the larger types it is more usual for epicyclic gearing to be employed. The gear ratios vary between types of actuator and specific applications.

LIMIT SWITCHES

Both linear and rotary actuators are equipped with limit switches to stop their respective motors when the operating ram or output shaft, as appropriate, has reached the permissible limit of travel. The switches are of the micro type (see p.104) and are usually operated by a cam driven by a shaft from the actuator gear-box. In some cases, limit switch contacts are also utilized to complete circuits to indicator lights or magnetic indicators. The interconnection of the switches is shown in (Fig. 9.62), which is based on the circuit of a typical actuator-controlled valve system.

In the valve closed position, the cam operates the micro switch "A" so that it interrupts the "close" winding circuit of the motor and completes a circuit to the "closed" indicator. The contacts of the micro switch "B" are at that moment connected to the "open" winding of the motor so that when the control switch is selected, power is supplied to the winding. In running to the valve open position the cam causes micro switch "A" contacts to change over, thereby interrupting the indicator circuit and connecting the "close" winding so that the motor is always ready for operating in either direction. As soon as the "open" position is reached the cam operates micro switch "B", the contacts of which then complete a circuit to the "open" indicator.

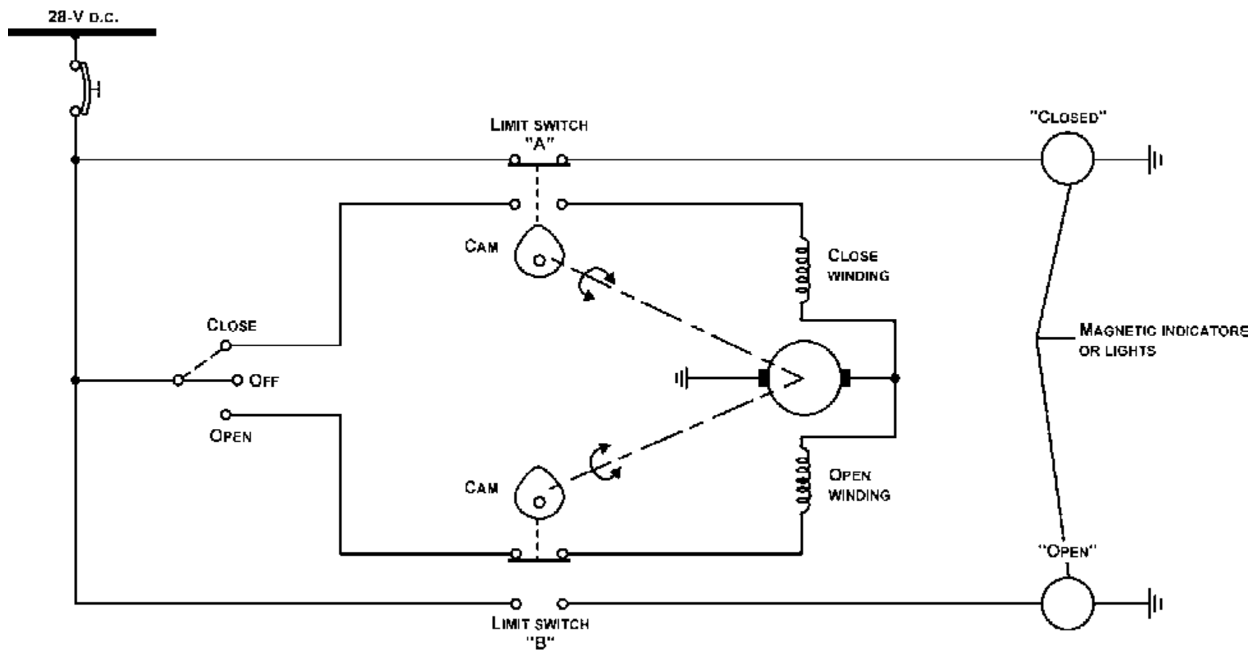


Fig. 9.62. Limit switch operation.

BRAKES

The majority of actuators are fitted with electromagnetic brakes to prevent over-travel when the motor is switched off. The design of brake system varies with the type and size of the actuator, but in all cases the brakes are spring-loaded to the "on" condition when the motor is de-energized, and the operating solenoids are connected in series with the armature so that the brakes are withdrawn immediately power is applied.

CLUTCHES

Friction clutches, which are usually of the single-plate type or multi-plate type dependent on size of actuator, are incorporated in the transmission systems of actuators to protect them against the effects of mechanical over-loading.

Inspection and Maintenance of D.C. Motors

Use the following procedures to make inspection and maintenance checks:

1. Check the operation of the unit driven by the motor in accordance with the instructions covering the specific installation.
2. Check all wiring, connections, terminals, fuses, and switches for general condition and security.
3. Keep motors clean and mounting bolts tight.
4. Check brushes for condition, length, and spring tension. Minimum brush lengths, correct spring tension, and procedures for replacing brushes are given in the applicable manufacturer's instructions.
5. Inspect commutator for cleanness, pitting, scoring, roughness, corrosion or burning. Check for high mica (if the copper wears down below the mica, the mica will insulate the orushes from the commutator). Clean dirty commutators with a cloth moistened with the recommended cleaning solvent. Polish rough or corroded commutators with fine sandpaper (000 or finer) and blow out with compressed air. Never use emery paper since it contains metallic particles which may cause shorts. Replace the motor if the commutator is burned, badly pitted, grooved, or worn to the extent that the mica insulation is flush with the commutator surface.
6. Inspect all exposed wiring for evidence of overheating. Replace the motor if the insulation on leads or windings is burned, cracked, or brittle.
7. Lubricate only if called for by the manufacturer's instructions covering the motor. Most motors used in today's airplanes require no lubrication between overhauls.
8. Adjust and lubricate the gearbox, or unit which the motor drives, in accordance with the applicable manufacturer's instructions covering the unit.

When trouble develops in a d.c. motor system, heck first to determine the source of the trouble. Replace the motor only when the trouble is due to a defect in the motor itself. In most cases, the failure of a motor to operate is caused by a defect in the external electrical circuit, or by mechanical failure in the mechanism driven by the motor.

Check the external electrical circuit for loose or dirty connections and for improper connection of wiring. Look for open circuits, grounds, and shorts by following the applicable manufacturer's circuit-testing procedure. If the fuse is not blown, failure of the motor to operate is usually indicates an accidental ground or short circuit. The chattering or the relay switch which controls the motor is usually caused by a low battery. When the battery is low, the open-circuit voltage of the battery is sufficient to close the relay, but with the heavy current draw of the motor, the voltage drops below the level required to hold the relay closed. When the relay opens, the voltage in the battery increases enough to close the relay again. This cycle repeats and causes chattering, which is very harmful to the relay switch, due to the heavy current causing an arc which will burn the contacts.

Check the unit driven by the motor for failure of the unit or drive mechanism. If the motor has failed as a result of a failure in the driven unit, the fault must be corrected before installing a new motor.

If it has been determined that the fault is in the motor itself (by checking for correct voltage at the motor terminals and for failure of the driven unit), inspect the commutator and brushes. A dirty commutator or defective or binding brushes may result in poor contact between brushes and commutator. Clean the commutator, brushes, and brush holders with a cloth moistened with the recommended cleaning solvent. If brushes are damaged or worn to the specified minimum length, install new brushes in accordance with the applicable manufacturer's instructions covering the motor. If the motor still fails to operate, replace it with a serviceable motor.

■■■

CHAPTER - 10
AC GENERATOR
KNOWLEDGE OF THE CONSTRUCTION, PRINCIPLE OF OPERATION AND CHARACTERISTICS OF AC GENERATORS AND MOTORS. KNOWLEDGE OF THE CONSTRUCTION, PRINCIPLES OF OPERATION OF VOLTAGE REGULATORS AND PARALLELING OF GENERATORS. DETAILED KNOWLEDGE OF THE FUNCTIONAL TESTS, ADJUSTMENTS AND TROUBLE SHOOTING OF GENERATORS AND MOTORS. KNOWLEDGE OF SPEED CONTROL AND REVERSING THE DIRECTION OF MOTORS.

ALTERNATORS

An electrical generator is a machine which converts mechanical energy into electrical energy by electromagnetic induction. A generator which produces alternating current is referred to as an a.c. generator and, through combination of the words "alternating" and "generator", the word "alternator" has come into widespread use. In some areas, the word "alternator" is applied only to small a.c. generators. This text treats the two terms synonymously and uses the term "alternator" to distinguish between a.c. and d.c. generator.

The major difference between an alternator and a d.c. generator is the method of connection to the external circuit; that is, the alternator is connected to the external circuit by slip rings, but the d.c. generator is connected by a commutator.

Types of Alternators

Alternators are classified in several ways in order to distinguish properly the various types. One means of classification is by the type of excitation system used. In alternators used on aircraft, excitation can be affected by one of the following methods:

1. A direct-connected, direct-current generator. This system consists of a d.c. generator fixed on the same shaft with the a.c. generator. A variation of this system is a type of alternator which uses d.c. from the battery for excitation, after which the alternator is self-excited.
2. By transformation and rectification from the a.c. system. This method depends on residual magnetism for initial a.c. voltage buildup, after which the field is supplied with rectified voltage from the a.c. generator.
3. Integrated brushless type. This arrangement has a direct-current generator on the same shaft with an alternating-current generator. The excitation circuit is completed through silicon rectifiers rather than a commutator and brushes. The rectifiers are mounted on the generator shaft and their output is fed directly to the alternating-current generator's main rotating field.

Another method of classification is by the number of phases of output voltage. Alternating-current generators may be single-phase, two-phase, three-phase, or even six-phase and more. In the electrical systems of aircraft, the three-phase alternator is by far the most common.

Still another means of classification is by the type of stator and rotor used. From this stand-point, there are two types of alternators: the revolving-armature type and the revolving-field type. The revolving-armature alternator is similar in construction to the d.c. generator, in that the armature rotates through a stationary magnetic field. The revolving-armature alternator is found only in alternators of low power rating and generally is not used. In the d.c. generator, the e.m.f. generated in the armature windings is converted into a unidirectional voltage (d.c.) by means of the commutator. In the revolving-armature type of alternator, the generated a.c. voltage is applied unchanged to the load by means of slip rings and brushes.

The revolving-field type of alternator (Fig. 10.1) has a stationary armature winding (stator) and a rotating-field winding (rotor). The advantage of having a stationary armature winding is that the armature can be connected directly to the load without having sliding contacts in the load circuit. A rotating armature would require slip rings and brushes to conduct the load current from the armature to the external circuit. Slip rings have a relatively short service life and arcing over is a continuous hazard; therefore, high-voltage alternators are usually of the stationary-armature, rotating-field type. The voltage and current supplied to the rotating field are relatively small, and slip rings and brushes for this circuit are adequate. The direct connection to the armature circuit makes possible the use of large cross-section conductors, adequately insulated for high voltage.

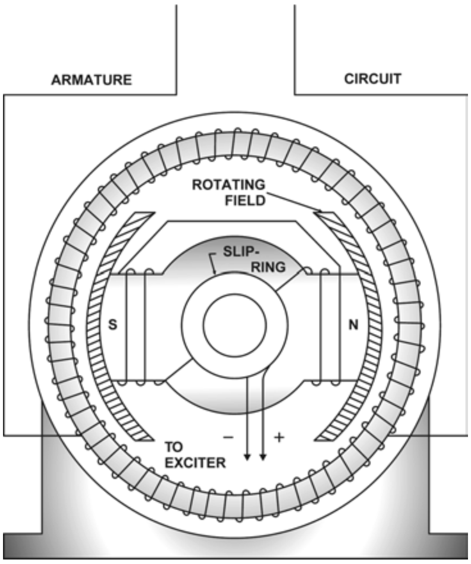


Fig. 10.1. Alternator with stationary armature and rotating field.

Since the rotating-field alternator is used almost universally in aircraft system, this type will be explained in detail, as a single-phase, two-phase, and three-phase, alternator.

Single-Phase Alternator

Since the e.m.f. induced in the armature of a generator is alternating, the same sort of winding can be used on an alternator as on a d.c. generator. This type of alternator is known as a single-phase alternator, but since the power delivered by a single-phase circuit is pulsating, this type of circuit is objectionable in many applications.

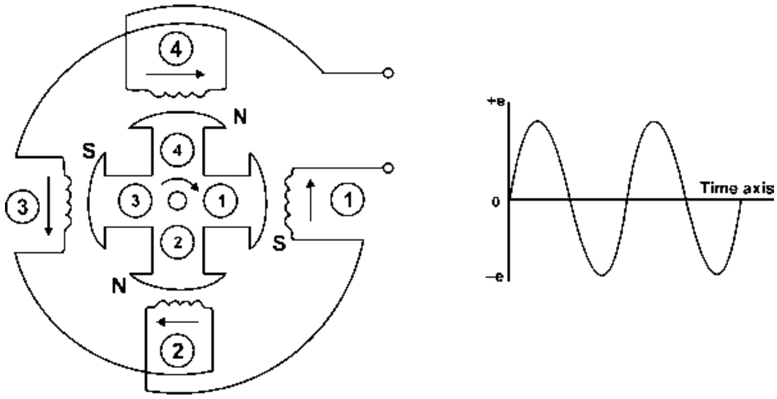


Fig. 10.2. Single-phase alternator.

A single-phase alternator has a stator made up of a number of windings in series, forming a single circuit in which an output voltage is generated. (Fig. 10.2) illustrates a schematic diagram of a single-phase alternator having four poles. The stator has four polar groups evenly spaced around the stator frame. The rotor has four poles, with adjacent poles of opposite polarity. As the rotor revolves, a.c. voltages are induced in the stator windings. Since one rotor pole is in the same position relative to a stator polar groups are cut by equal number of magnetic lines of force at any time. As a result, the voltages induced in all the windings have the same amplitude, or value, at any given instant. The four stator winding are connected to each other so that the a.c. voltages are in phase, or "series adding." Assume that rotor pole 1, a south pole, induces a voltage in the direction indicated by the arrow in stator winding1. Since rotor pole 2 is a north pole, it will induce a voltage in the opposite direction in stator coil 2 with respect to that in coil 1.

For the two induced voltages to be in series addition, the two coils are connected as shown in the diagram. Applying the same reasoning, the voltage induced in Stator - 3 (clockwise rotation of the field) is the same direction (counter clockwise) as the voltage induced in coil 1. Similarly, the direction of the voltage induced in winding 4 is opposite to the direction of the voltage induced in coil 1. All four stator coil groups are connected in series so that the voltages induced in each winding add to give a total voltage that is four times the voltage in any one winding.

Two-Phase Alternator

Two-phase alternators have two or more single-phase windings spaced symmetrically around the stator. In a two-phase alternator there are two single-phase windings spaced physically so that the a.c. voltage induced in one is 90° out of phase with the voltage induced in the other. The windings are electrically separate from each other. When one winding is being cut by maximum flux, the other is being cut by no flux. This condition establishes a 90° relation between the two phases.

Three-Phase Alternator

A three-phase, or polyphase circuit, is used in most aircraft alternators, instead of a single or two-phase alternator. The three-phase alternator has three single-phase windings spaced so that the voltage induced in each winding is 120° out of phase with the voltage in the other two windings. A schematic diagram of a three-phase stator showing all the coils becomes complex and difficult to see what is actually happening.

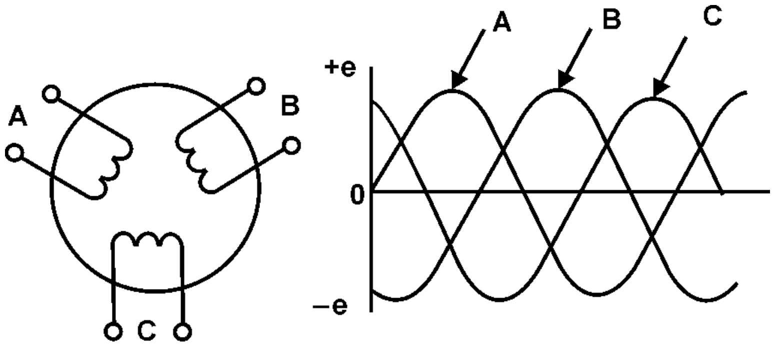


Fig. 10.3. Simplified schematic of three-phase alternator with output waveforms.

A simplified schematic diagram, showing each of three phases, is illustrated in (Fig. 10.3). The rotor is omitted for simplicity. The waveforms of voltage are shown to the right of the schematic. The three voltages are 120° apart and are similar to the voltage which would be generated by three single-phase alternators whose voltages are out of phase by angles of 120°. The three phases are independent of each other.

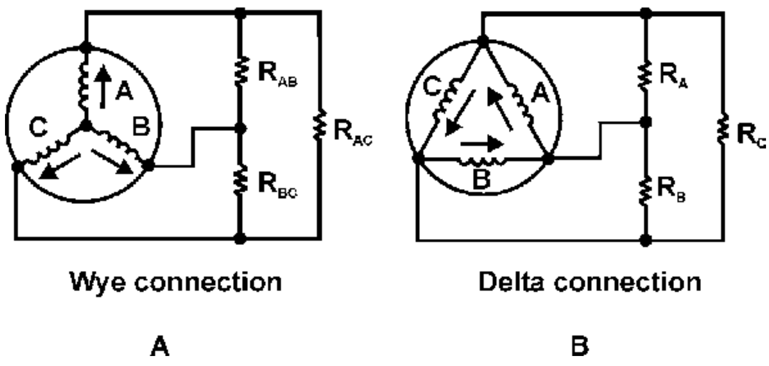


Fig. 10.4. Wye - and delta-connected alternators.

Rather than have six leads from the three-phase alternator, one of the leads from each phase may be connected to form a common junction. The stator is then called wye-or star-connected. The common lead may or may not be brought out of the alternator. If it is brought out, it is called the neutral lead. The simplified schematic (A of Fig.10.4) shows a wye-connected stator with the common lead not brought out. Each load is connected across two phases in series. Thus, R_{AB} is connected across phases A and B in series; R_{AC} is connected across phases A and C in series; and R_{BC} is connected across phases B and C in series. Therefore, the voltage across a single phase. The total voltage, or line voltage, across any two phase is the vector sum of the individual phase voltage. For balanced conditions, the line voltage is 1.73 times the phase voltage. Since there is only one path for current in a line wire and the phase to which it is connected, the line current is equal to the phase current.

A three-phase stator can also be connected so that the phases are connected end-to-end as shown in B of (Fig. 10.4.) This arrangement is called a delta connection. In a delta connection, the voltage are equal to the phase voltage; the line currents are equal to the vector sum of the phase currents; and the line current is equal to 1.73 times the phase current, when the loads are balanced.

For equal loads (equal kw. output), the delta connection supplies increased line current at a value of line voltage equal to phase voltage, and the wye connection supplies increased line voltage at a value of line current equal to phase current.

Generator Power Ratings

The power ratings of a.c. generators are generally given in kilovolt-amperes (kVA) rather than kilowatts (kW) as in the case of d.c. machines. The primary reason for this is due to the fact that in calculating the power, account must be taken of the difference between the true or effective power, and the apparent power. Such a difference arises from the type of circuit which the generator is to supply and the phase relationships of voltage and current, and is expressed as a ratio termed the power factor (P.F.) This may be written:

$$\text{P.F.} = \frac{\text{Effective Power(kW)}}{\text{Apparent Power(kVA)}}$$

= cosine phase angle φ

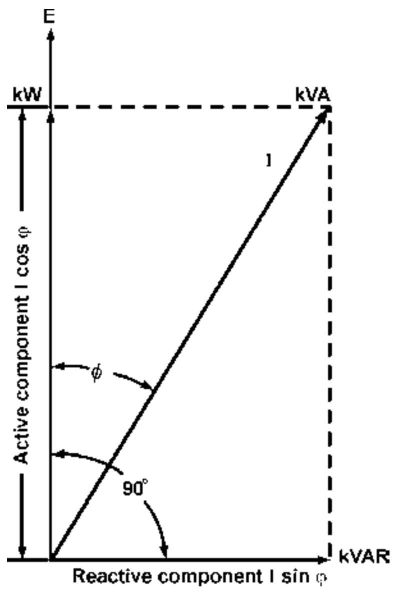


Fig. 10.5. Components of current due to phase difference.

If the voltage and current are in phase (as in a resistive circuit) the power factor is 100 percent or unity, because the effective power and apparent power are equal; thus, a generator rated at 100 kVA in a circuit with a P.F. of unity will have an output 100 percent efficient and exactly equal to 100 kW.

When a circuit contains inductance or capacitance, then as we have already seen (p.33) current and voltage are not in phase so that the P.F. is less than unity. The vector diagram for a current I lagging a voltage E by an angle φ is shown in (Fig. 10.5). The current is resolved into two components at right angles, one in phase with E and given by I cos φ , and the other in quadrature and given by I sin φ . The in-phase component is called the active, wattful or working component (kW) and the quadrature component is the idle, wattless or reactive component (kVAR). The importance of these components will be more apparent when, later in this chapter, methods of load sharing between generators are discussed.

Most a.c. generators are designed to take a proportion of the reactive component of current through their windings and some indication of this may be, obtained from the information given on the generator data plate. For example, the output rating may be specified as 40 kVA at 0.8 P.F. This means that the maximum output in kW is 0.8 × 40 or 32 kW, but that the product of volts and amperes under all conditions of P.F. must not exceed 40 kVA.

FREQUENCY-WILD SYSTEMS

A frequency-wild system is one in which the frequency of its generator voltage output is permitted to vary with the rotational speed of the generator. Although such frequency variations are not suitable for the direct operation of all types of a.c. consumer equipment, the output can (after constant voltage regulation) be applied directly to resistive load circuits such as electrical de-icing systems, for the reason that resistance to alternating current remains substantially constant, and is independent of frequency.

Generator Construction

The construction of a typical frequency-wild generator utilized for the supply of heating current to a turbo-propeller engine de-icing system is illustrated in (Fig. 10.6). It has a three-phase output of 22 kVA at 208 volts and it supplies full load at this voltage through a frequency range of 280 to 400 Hz. Below 280 Hz the field current is limited and the output relatively reduced. The generator consists of two major assemblies: a fixed stator assembly in which the current is induced, and a rotating assembly referred to as the rotor. The stator assembly is made up of high permeability laminations and is clamped in a main housing by an end frame having an integral flange for mounting the generator at the corresponding drive outlet of an engine-driven accessory gear-box. The stator winding is star connected, the star or neutral point being made by linking three ends of the winding and connecting it to ground . The other three ends of the winding are brought out to a three-way output terminal box mounted on the end frame of the generator. Three small current transformers are fitted into the terminal box and form part of a protection system known as a Merz-Price system.

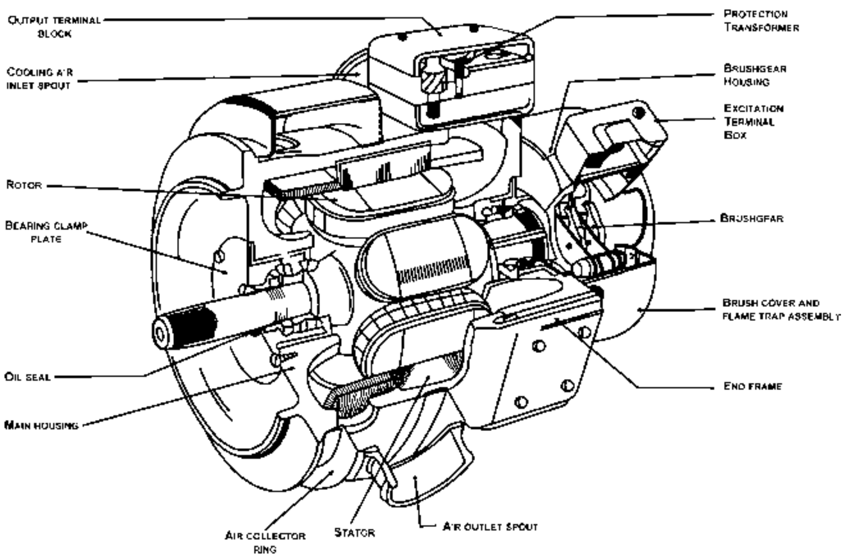


Fig. 10.6. Frequency-wild generator.

The rotor assembly has six salient poles of laminated construction; their series-connected field windings terminate at two slip rings secured at one end of the rotor shaft. Three spring-loaded brushes are equispaced on each slip ring and are contained within a brush-gear housing which also forms a bearing support for the rotor. The brushes are electrically connected to d.c. input terminals housed in an excitation terminal box also houses capacitors which are connected between the terminals and frame to suppress interference in the reception of radio signals. At the drive end, the rotor shaft is serrated and an oil seal, housed in a carrier plate bolted to the main housing, is fitted over the shaft to prevent the entry of oil from the driving source into the main housing.

The generator is cooled by ram air passing into the main housing via an inlet spout at the slip ring end, the air escaping from the main housing through ventilation slots at the drive-end. An air-collector ring encloses the slots and is connected to a vent through which the cooling air is finally discharged. Provision switch to cater for an overheat warning requirement.

CONSTANT FREQUENCY SYSTEMS

In the development of electrical power supply systems, notably for large aircraft, the idea was conceived of an "all a.c." system, i.e. primary generating system to meet all a.c. supply requirements, in particular those of numerous consumer services dependent on constant-frequency, to allow for paralleled generator operation, and to meet d.c. supply requirements via transformer and rectified systems.

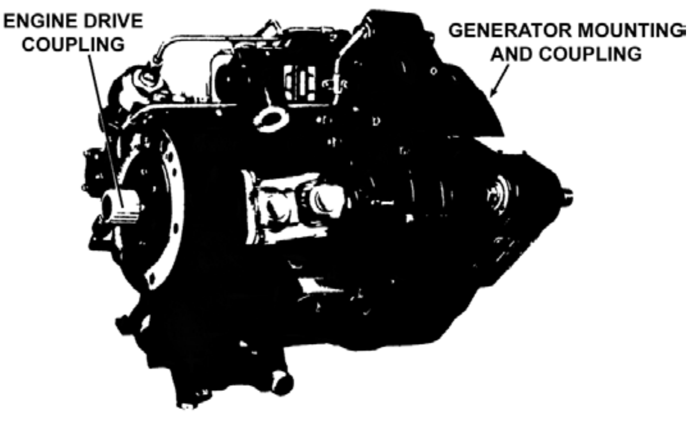


Fig. 10.7. Constant speed drive unit.

A constant frequency is inherent in an a.c. system only if the generator is driven at a constant speed. The engines cannot be relied upon to do this directly and, as we have already learned, if a generator is connected directly to the accessory drive of an engine the output frequency will vary with engine speed. Some form of conversion equipment is therefore required and the type most widely adopted utilizes a transmission device interposed between the engine and generator, and which incorporates a variable-ratio drive mechanism. Such a mechanism is referred to as a constant-speed drive (CSD) unit and an example is shown in (Fig. 10.7).

The unit employs hydromechanical variable ratio drive which in its basic form (see Fig. 10.8) consists of a variable displacement hydraulic unit, a fixed displacement hydraulic unit and a differential gear. The power used to drive the generator is controlled and transmitted through the combined effects of the three units, the internal arrangement of which are shown in (Fig. 10.9). Oil for system operation is supplied from a reservoir via charge pumps within the unit, and a governor.

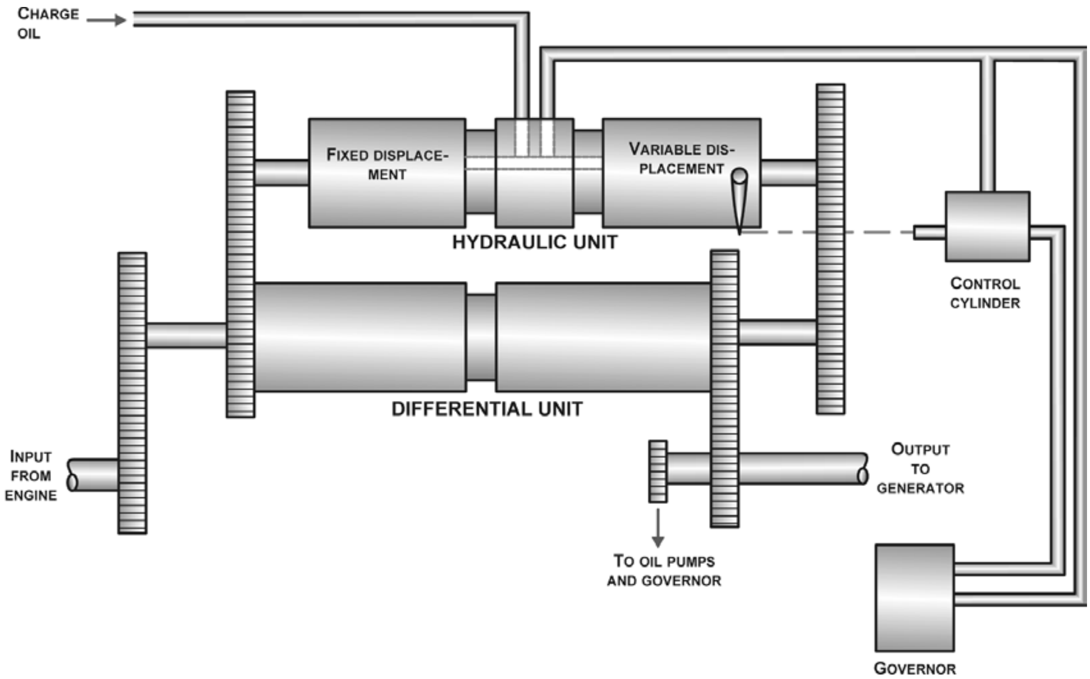


Fig. 10.8. Basic arrangement of a CSD unit.

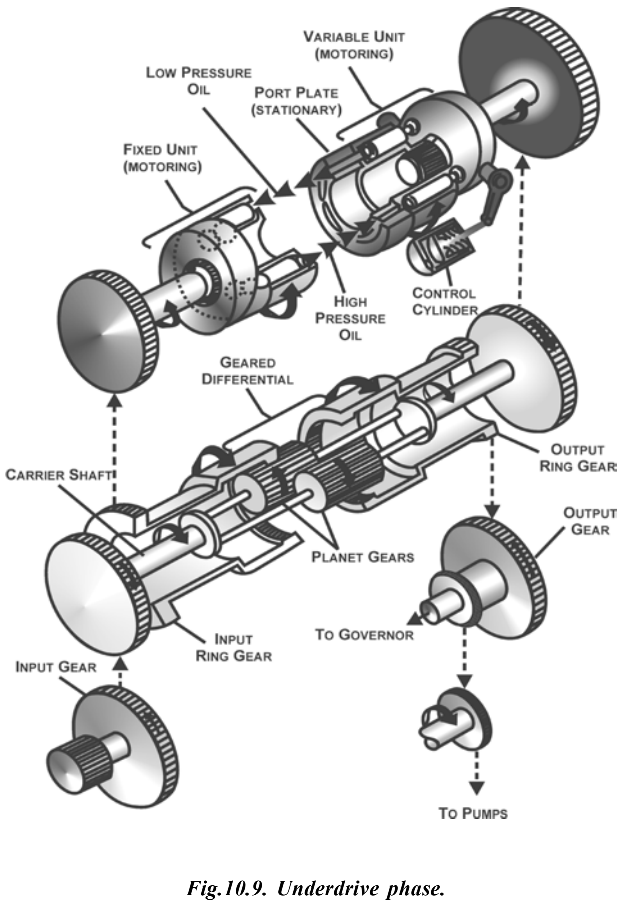


Fig.10.9. Underdrive phase.

The variable displacement unit consists of a cylinder block, reciprocating pistons and a variable angle wobble or swash plate, the latter being connected to the piston of a control cylinder. Oil to this cylinder is supplied from the governor. The unit is driven directly by the input gear and the differential planet gear carrier shaft, so that its cylinder block always rotates (relative to the port plate and wobble plate) at a speed proportional to input gear speed and always in the same direction. When the control cylinder moves the wobble plate to some angular position, the pistons within the cylinder block are moved in and out as the block rotates, and so the charge oil is compressed to a high pressure and then "ported" to the fixed displacement unit. Thus, under these conditions the variable displacement unit functions as a hydraulic pump.

The supply of charge oil to the unit's control valve is controlled by a governor valve which is spring biased, flyweight operated and driven by the output gear driving the generator. It therefore responds to changes in transmission output speed.

The fixed displacement unit is similar to the variable displacement unit, except that its wobble plate which has an inclined face, is fixed and has no connection with the control cylinder. When oil is pumped to the fixed displacement unit by the variable one, it functions as a hydraulic motor and its direction of rotation and speed is determined by the volume of oil pumped to it. It can also function as a pump and therefore supply the variable displacement hydraulic unit.

The differential gear consists of a carrier shaft carrying two meshing (1:1 ratio) planet gears, and a gear at each end; one meshing with the input gear and the other with the gear which continuously drives the variable displacement unit cylinder block. The carrier shaft always rotates in the same direction and at a speed which, (via the input gear) varies with engine speed. Surrounding the carrier shaft are two separate "housing", and since they have internal ring gears meshing with the planet gears, then they can be rotated differentially. Each housing also has an external ring gear; one (input ring gear) meshing with the fixed displacement unit gear, and the other (output ring gear) meshing with the output gear drive to the generator. Thus, with the CSD in operation, the output ring gear "housing" serves as the continuous drive transmission link between engine and generator. Since the input ring gear "housing" is geared to the fixed displacement hydraulic unit, then depending on whether this unit is acting as a motor or a pump, the "housing" can rotate in the same direction as, or opposite to, that of the carrier shaft and the output ring gear "housing". In this way, speed is added to, or subtracted from, the engine speed, and through the gear ratio (2:1) between the ring gears and the carrier shaft planet gears, the output ring gear "housing" rotational speed will be appropriately adjusted to maintain constant governor speed.

When the input speed, via the input gear, is sufficient to produce the required output speed, the drive to the generator is transmitted straight through the differential and output ring gear. The variable displacement hydraulic unit cylinder block is continuously rotating, but the position of its wobble plate is such that no charge oil is pumped to the fixed displacement unit. The cylinder block of this unit and the output ring gear "housing" do not, therefore, rotate during straight through drive.

If the input speed supplied to the transmission exceeds that needed to produce the required output speed, the governor in sensing the speed difference will cause oil to flow away from the control valve. In this condition, the transmission is said to be operating in the underdrive phase and is shown in (Fig.10.9). The control valve changes the angular position of the variable displacement unit's wobble plate so that the volume of oil for accommodating the oil in the bores of the cylinder block is increased, allowing oil to be pumped at high pressure from the fixed displacement unit. The pressure of the pistons against the inclined face of the unit now causes its cylinder block to rotate in the same direction as that of the variable displacement unit. This rotation is transmitted to the input ring gear "housing" of the differential unit, so that it will rotate in the same direction as the output ring gear "housing", and the carrier shaft.

Because the input ring gear "housing" is now rotating in the same direction as the carrier shaft then the speed of the freely rotating planet gear meshing with the housing will be reduced. The speed of the second planet gear will also be reduced in direct ratio thereby reducing the speed of the output ring gear "housing". This hydromechanical process of speed subtraction continues until the required generator drive speed is attained at which the transmission will revert to straight-through drive operation.

When the input speed supplied to the transmission is lower than that needed to produce the required output speed, the governor causes charge oil to be supplied to the control valve. In this condition, the transmission is said to be operating in the overdrive phase and this is shown in (Fig.10.10). As will be noted, the change in angular position of the variable displacement unit's wobble plate now causes it to pump high pressure oil to the fixed displacement unit. The cylinder block and input ring gear "housing" therefore rotate in the opposite direction to that of the underdrive phase, and so it increases the rotational speed of the planet gears and output ring gear "housing". Thus, speed is added to restore the required generator drive speed.

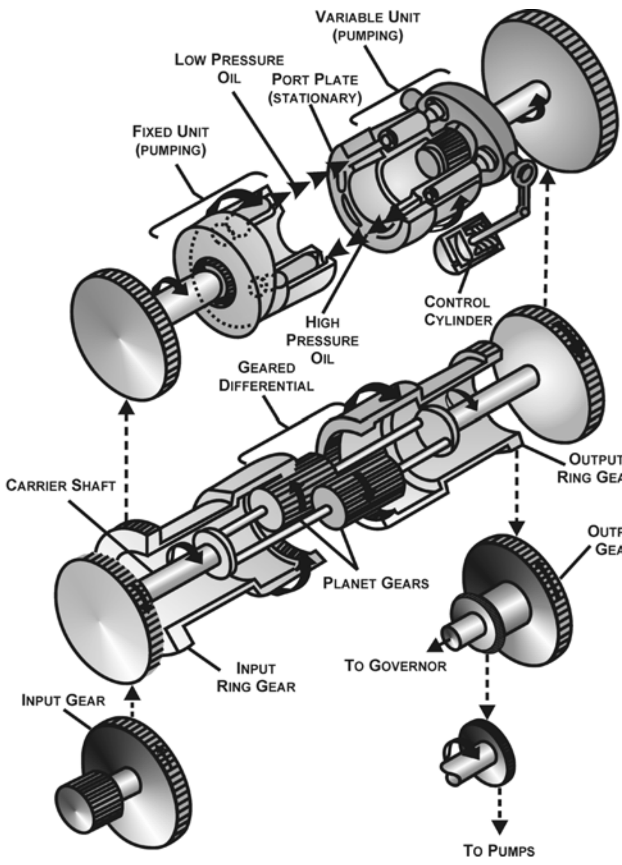


Fig. 10.10. Overdrive phase.

In multi-CSD generator systems the control of the drives is important in order that real electrical load will be evenly distributed between the generators. Any unbalance in real load is automatically sensed by control units and load controllers in the generator systems and, since correction must be made at the generator drive, signals resulting from an unbalance are fed to an electromagnetic coil within the basic governor of each CSD. The electromagnetic field interacts with additional permanent magnet flyweights driven by the governor, to produce a torque which in conjunction with centrifugal force provides a "fine" adjustment or trimming of the governor control valve, and of the output speed to the generators.

A typical CSD/generator installation is shown in (Fig. 10.11).

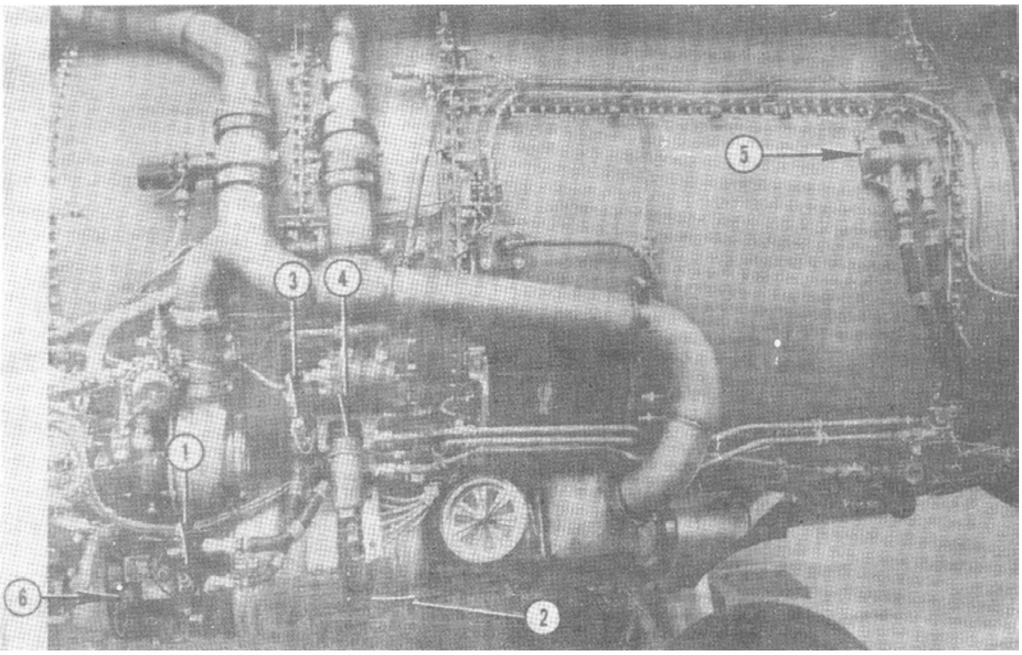


Fig. 10.11. CSD/generator installation.
1. CSD 2. Generator 3. CSD oil service port
4. CSD oil filter 5. CSD oil cooler 6. Wet spline cavity service port

The disconnection of a C.S.D. transmission system following a malfunction, may be accomplished mechanically by levers located in the flight crew compartment, electro-pneumatically, or as is more common, by an electro-mechanical system. In this system (see Fig. 10.12) the drive from the engine is transmitted to C.S.D. via a dog-tooth clutch, and disconnect is initially activated by a solenoid controlled from the flight crew compartment.

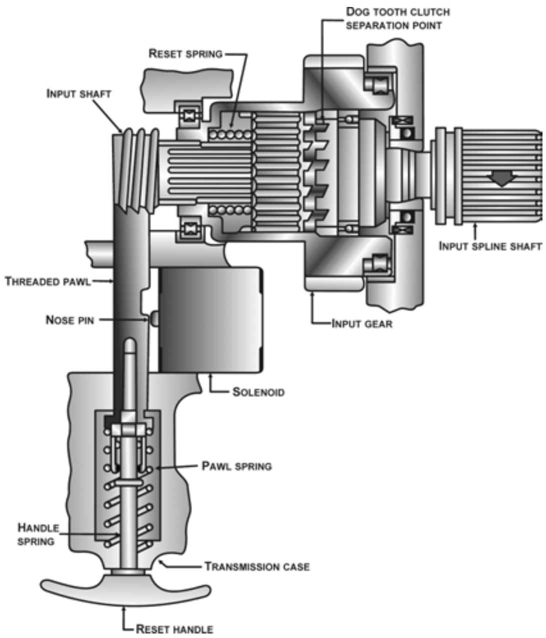


Fig. 10.12. C.S.D./Generator disconnect mechanism.

When the solenoid is energized, a spring-loaded pawl moves into contact with threads on the input shaft and then serves as a screw causing the input shaft to move away from the input spline shaft (driven by the engine) thereby separating the driving dogs of the clutch. In some mechanisms a magnetically-operated indicator button is provided in the reset handle, which lies flush with the handle under normal operating conditions of the drive. When a disconnect has taken place, the indicator button is released from magnetic attraction and protrudes from the reset handle to provide a visual indication of the disconnect.

Resetting of disconnect mechanisms can only be accomplished on the ground following shutdown of the appropriate engine. In the system illustrated, resetting is accomplished by pulling out the rest handle to withdraw the threaded pawl from the input shaft, and allowing the reset spring on the shaft to re-engage the clutch. At the same time, and with the solenoid de-energized, the solenoid nose pin snaps into position in the slot of the pawl.

Generator Construction

A sectioned view of a typical constant frequency generator is illustrated in (Fig. 10.13). It consists of three principal components : a.c. exciter which generates the power for the main generator field; rotating rectifier assembly mounted on, and rotating with, the rotor shaft to convert the exciter output to d.c.; and the main generator. All three components are contained within a cast aluminium casing made up of an end bell section and a stator frame section; both sections are secured externally by screws. A mounting flange, which is an integral part of the stator frame, carries twelve slots reinforced by steel inserts, and key-hole shaped to facilitate attachment of the generator to the mounting studs of the constant-speed drive unit.

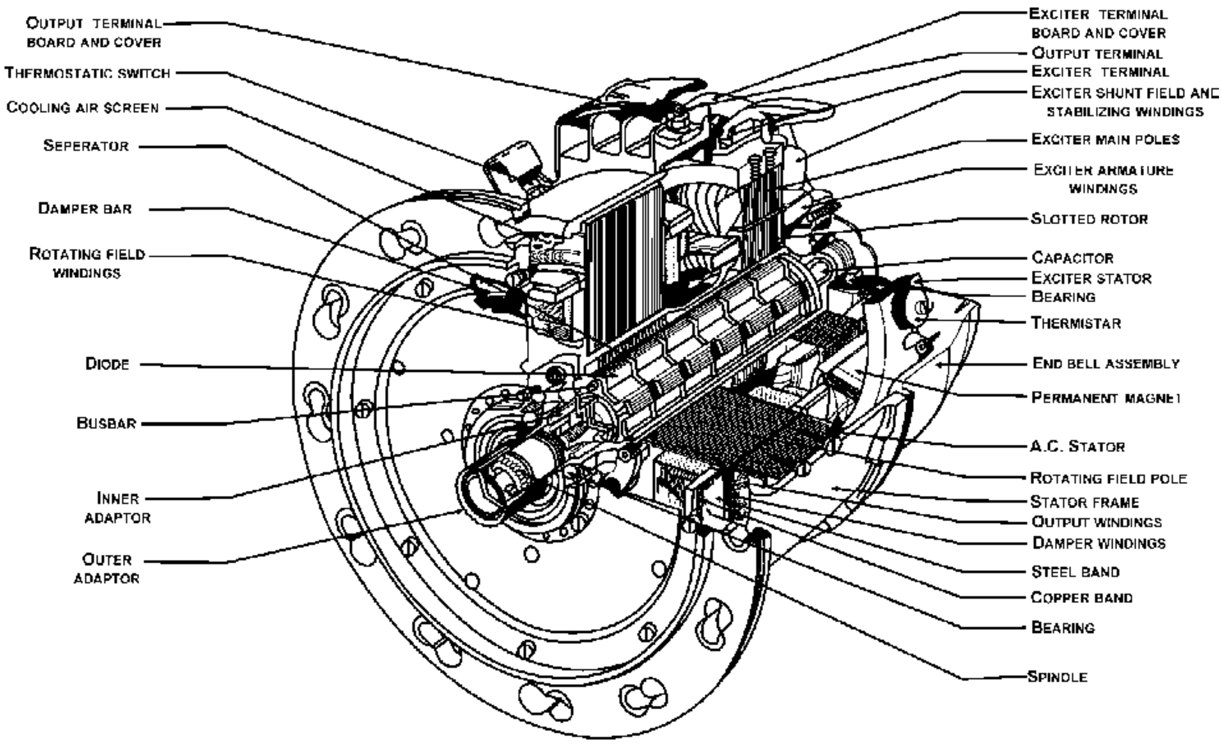


Fig. 10.13. Constant frequency generator.

The exciter, which is located in the end bell section of the generator casing, comprises a stator and a three-phase star-wound rotor or exciter armature. The exciter armature is mounted on the same shaft as the main generator rotor and the output from its three-phase windings is fed to the rotating rectifier assembly.

The rotating rectifier assembly supplies excitation current to the main generator rotor field coils, and since together with the a.c. exciter they replace the conventional brushes and slip rings, they thereby eliminate the problems associated with them. The assembly is contained within a tubular insulator located in the hollow shaft on which the exciter and main generator rotors and mounted; located in this manner they are close to the axis of rotation and are not, therefore, subjected to excessive centrifugal forces. A suppression capacitor is also connected in the rectifier circuit and is mounted at one end of the rotor shaft. Its purpose is to suppress voltage "spikes" created within the diodes under certain operating conditions.

The main generator consists of a three-phase star-wound stator, and an eight-pole rotor and its associated field windings which are connected to the output of the rotating rectifier. The leads from the three stator phases are brought directly to the upper surface of an output terminal board, thus permitting the aircraft wiring to be clamped directly to the upper surface of an output terminal board, thus permitting the aircraft wiring to be clamped directly against the phase leads without current passing through the terminal studs. In addition to the field coils, damper (amortisseur) windings are fitted to the rotor and are located in longitudinal slots in the pole faces. Large copper bands, under steel bands at each end of the rotor stack, provide the electrical squirrel-cage circuit. The purpose of the damper windings is to provide an induction motor effect on the generator whenever sudden changes in load or driving torque tend to cause the rotor speed to vary above or below the normal or synchronous system frequency. In isolated generator operation, the windings serve to reduce excessively high transient voltages caused by line-to-line system faults, and to decrease voltage unbalance, during unbalanced load conditions. In parallel operation, the windings also reduce transient voltages and assist in pulling in, and holding, a generator in synchronism.

The drive end of the main rotor shaft consists of a splined outer adaptor which fits over a stub shaft secured to the main generator rotor. The stub shaft, in turn, fits over a drive spindle fixed by a centrally located screw to the hollow section of the shaft containing the rotating rectifier assembly. The complete shaft is supported at each by pre-greased sealed bearings.

The generator is cooled by ram air which enters through the end bell section of the casing and passes through the windings and also through the rotor shaft to provide cooling of the rectifier assembly. The air is exhausted through a perforated screen around the periphery of the casing and at a point adjacent to the main generator stator. A thermally-operated overheat detector switch is screwed directly through the stator frame section into the stator of the main generator, and is connected to an overheat warning light on the relevant system control panel.

Further information on the circuit arrangement of the generator is given.

Integrated Drive Generators

As will be noted from (Fig. 10.14), an integrated drive generator is one in which the CSD and generator are mounted side by side to form a single compact unit. This configuration reduces weight, requires less space, and in comparison with the "end-to-end" configuration it reduces vibration. The fundamental construction and operation of both the generator and drive units follow that described in the preceding paragraphs. The essential difference relates to the method of cooling the generator. Instead of air being utilized as the cooling medium, oil is pumped through the generator; the oil itself is in turn cooled by means of a heat exchanger system.

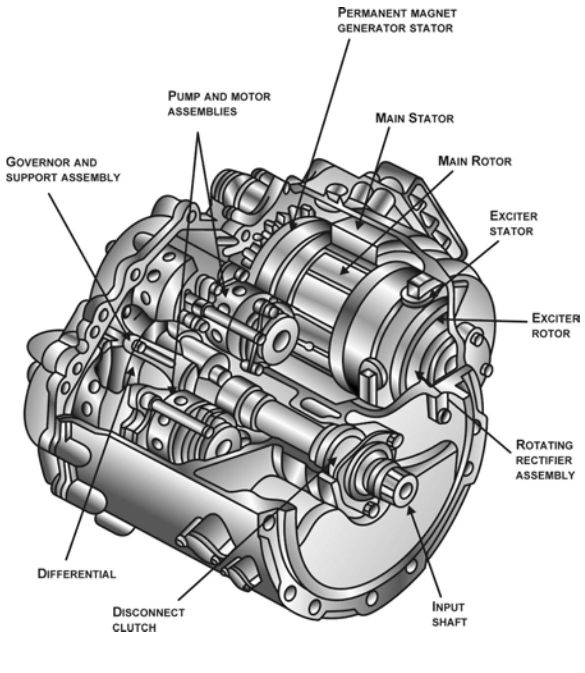


Fig. 10.14. Integrated drive generator.

FIELD EXCITATION OF GENERATORS

The production of a desired output by any type of generator requires a magnetic field to provide excitation of the windings for starting and for the subsequent operational running period. In other words, a completely self-starting, self-exciting sequence is required. In d.c. generators, this is achieved in a fairly straightforward manner by residual magnetism in the electromagnet system and by the build up of current through the field windings. The field current, as it is called, is controlled by a voltage regulator system. The excitation of a.c. generators, on the other hand, involves the use of somewhat more complex circuits, the arrangements of which are essentially varied to suit the particular type of generator and its controlling system. However, they all have one common feature, i.e. supply of direct current to the field winding to maintain the desired a.c. output.

Frequency-Wild Generators

Fig. 10.15 is a schematic illustration of the method adopted for the generator illustrated in (Fig.10.6). In this case, excitation of the rotor field is provided by d.c. from the aircraft's main busbar and by rectified a.c. The principal components and sections of the control system associated with excitation are: the control switch, voltage regulation section, field excitation rectifier and current compounding section consisting of a three-phase current transformer and rectifier.

The primary windings of the compounding transformer are in series with the three phases of the generator and the secondary windings in series with the compounding rectifier.

When the control switch is in the "start" position, d.c. from the main busbar is supplied to the slip rings and windings of the generator rotor; thus, with the generator running, a rotating magnetic field is set up to induce an alternating output in the stator. The output is tapped to feed a magnetic amplifier type of voltage regulator which supplies a sensing current signal to the excitation rectifier. When this signal reaches a pre-determined off-load value, the rectified a.c. through the rotor winding is sufficient for the generator to become self-excited and independent of the main busbar supply which is then disconnected.

The maximum excitation current for wide-speed-range high-output generators of the type shown in (Fig.10.6) is quite high, and the variation in excitation current necessary to control the output under varying "load" conditions is such that the action of the voltage regulator must be supplemented by some other medium of variable excitation current. This is

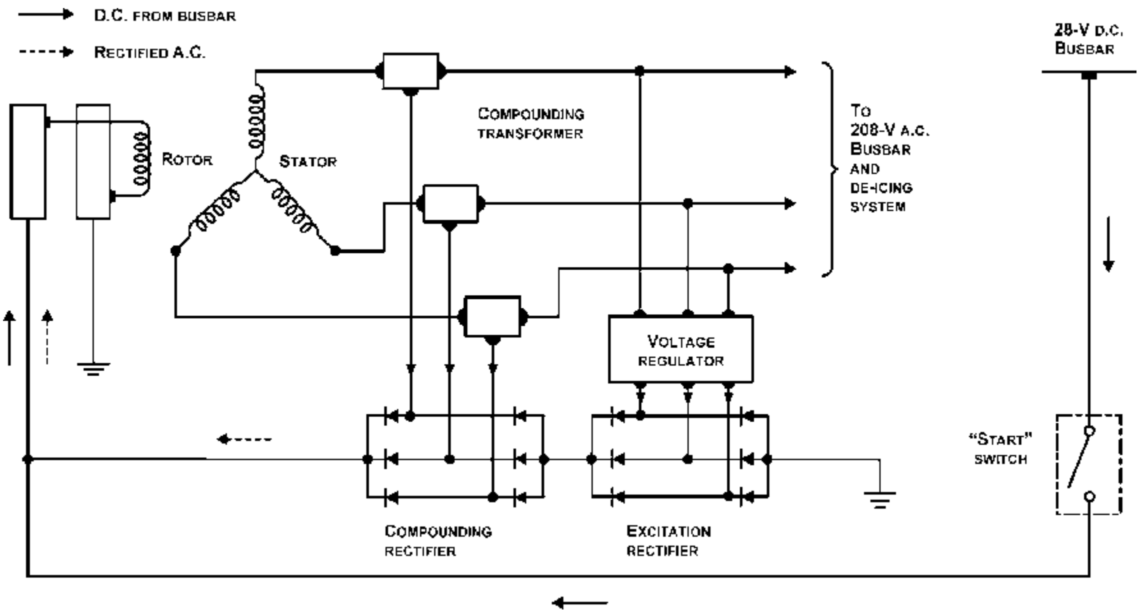


Fig. 10.15. Frequency-wild generator excitation.

provided by the compounding transformer and rectifier, and by connecting them in the manner already described, direct current proportional to load current is supplied to the rotor field windings.

Constant-Frequency Generators

The exciter stator of the generator described is made up of two shunt field windings, a stabilizing winding and also six permanent magnets; the latter provide a residual magnetic field for initial excitation. A thermistor is located in series with one of the parallel shunt field windings and serves as a temperature compensator. At low or normal ambient temperatures, the high resistance of the thermistor blocks current flow in its winding circuit so that it causes the overall shunt field resistance to be about that of the remaining winding circuit. At the higher temperature resulting from normal operation, the resistance of each single circuit increases to approximately double. At the same time, however, the thermistor resistance drops to a negligible value permitting approximately equal current to flow in each winding circuit.

The stabilizing winding is wound directly over the shunt field windings, and with the permanent magnet poles as a common magnetic core, a transformer type of coupling between the two windings is thereby provided. The rectifier assembly consists of six silicon diodes separated by insulating spacers and connected as a three-phase full-wave bridge.

The excitation circuit arrangement for the generator is shown schematically in (Fig.10.16). When the generator starts running, the flux from the permanent magnets of the a.c. exciter provides the initial flow of current in its rotor windings.

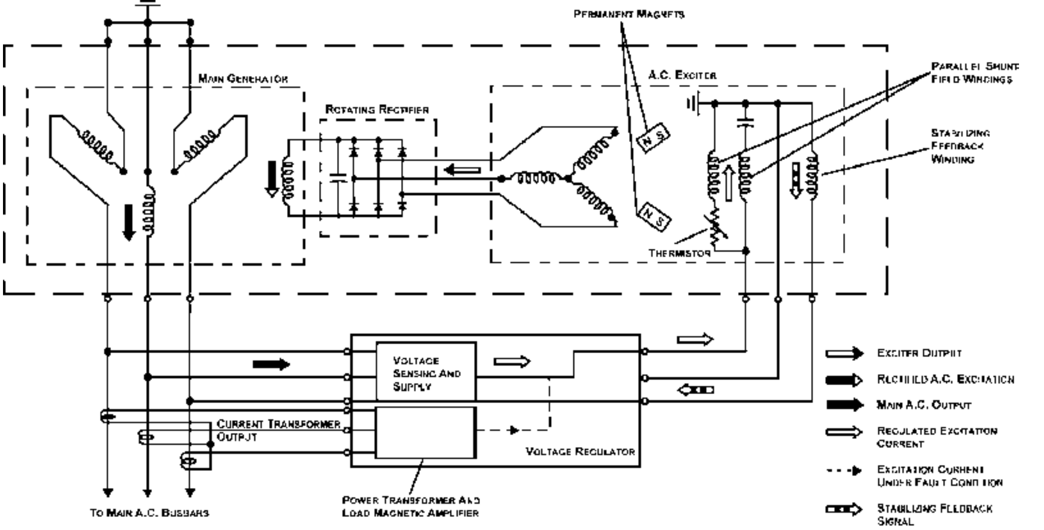


Fig. 10.16. Circuit diagram of constant frequency generator.

As a result of the initial current flow, armature reaction is set up and owing to the position of the permanent magnetic poles, the reaction polarizes the main poles of the exciter stator in the proper direction to assist the voltage regulator in taking over excitation control.

The three-phase voltage produced in the windings is supplied to the rectifier assembly, the d.c. output of which is, in turn, fed to the field coils of the main generator rotor as the required excitation current. A rotating magnetic field is thus produced which induces a three-phase voltage output in the main stator windings. The output is tapped and is fed back to the shunt field windings of the exciter, through the voltage regulator system, in order to produce a field supplementary to that of the permanent magnets. In this manner the exciter output is increased and the main generator is enabled to build up its output at a faster rate. When the main output reaches the rated value, the supplementary electromagnetic field controls the excitation and the effect of the permanent magnets is almost eliminated by the opposing armature reaction. During the initial stages of generator operation, the current flow to the exciter only passes through one of the two shunt field windings, due to the inverse temperature/resistance characteristics of the thermistor. As the temperature of the winding increases, the thermistor resistance decreases to allow approximately equal current to flow in both windings, thus maintaining a constant effect of the shunt windings.

In the event that excitation current should suddenly increase or decrease as a result of voltage fluctuations due, for example, to switching of loads, a current will be induced in the stabilizing winding since it acts as a transformer secondary winding. This current is fed into the voltage regulator as a feedback signal to so adjust the excitation current that voltage fluctuations resulting from any cause are opposed and held to a minimum.

VOLTAGE REGULATION OF GENERATORS

The control of the output voltages of a.c. generators is also an essential requirement, and from the foregoing description of excitation methods, it will be recognized that the voltage regulation principles adopted for d.c. generators can also be applied, i.e. automatic adjustment of excitation current to meet changing conditions of load and/or speed. Voltage regulators normally from part of generator system control and protection units.

Frequency-Wild Generators

Fig. 10.17 is a block functional diagram of the method used for the voltage regulation of the generator illustrated in (Fig 10.6). Regulation is accomplished by a network of magnetic amplifiers or transducers, transformers and bridge rectifiers interconnected as shown. In addition to the control of load current delivered by the generator, a further factor which will affect control of field excitation is the error between the line voltage desired and the actual voltage obtained. As already explained, the compounding transformer and rectifier provides excitation current proportional to load current, therefore the sensing of error voltages and necessary re-adjustment of excitation current must be provided by the voltage regulation network.

It will be noted from the diagram that the three-phase output of the generator is tapped at two points; at one by a three-phase transformer and at the other by a three-phase magnetic amplifier. The secondary winding of one phase of the

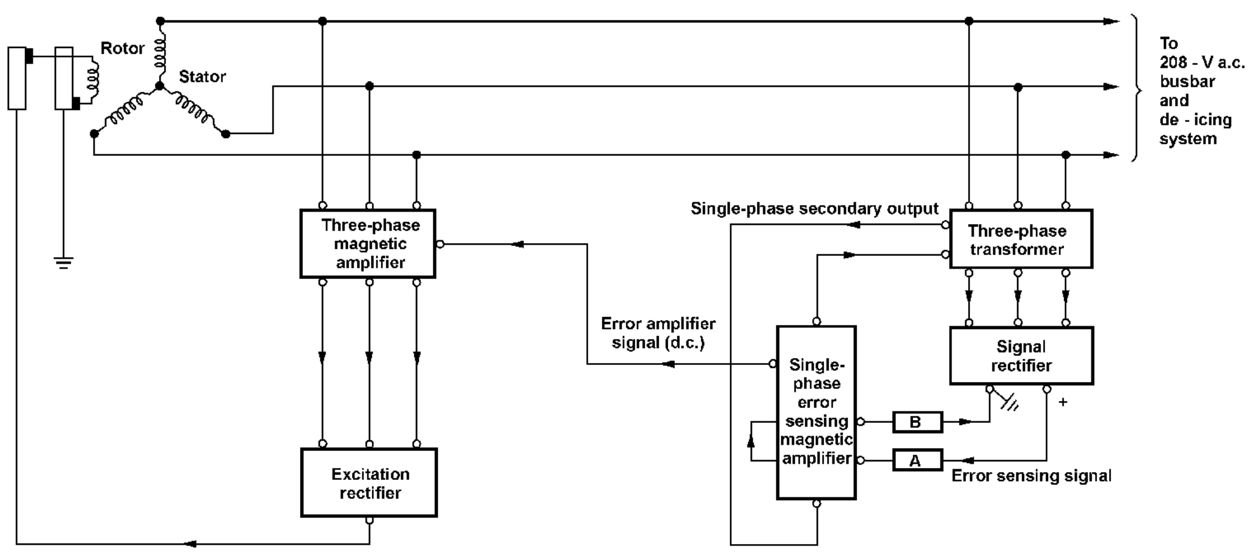


Fig. 10.17. Voltage regulation.

transformer is connected to the a.c. windings of a single-phase "error sensing" magnetic amplifier and the three primary windings are connected to a bridge "signal" rectifier. The d.c. output from the rectifier is then fed through a voltage-sensing circuit made up of two resistance arms, one (arm "A") containing a device known as a barretter the characteristics of which maintain a substantially constant current through the arm, The other (arm "B") of such resistance that the current flowing through it varies linearly with the line voltage. The two current signals, which are normally equal at the desired line voltage, are fed in opposite directions over the a.c. output windings in the error magnetic amplifier. When there is a change in the voltage level, the resulting variation in current flowing through arm "B" unbalances the sensing circuit and, as this circuit has the same function as a d.c. control winding, it changes the reactance of the error magnetic amplifier a.c. output windings and an amplified error signal current is produced. After rectification, the signal is then fed as d.c. control current to the three-phase magnetic amplifier, thus causing its reactance and a.c. output to change also. This results in an increase or decrease, as appropriate, of the excitation current flow to the generator rotor field winding, continuing until the line voltage produces balanced signal conditions once more in the error sensing circuit.

Constant-Frequency Systems

The regulation of the output of a constant-frequency system is also based on the principle of controlling field excitation, and some of the techniques thus far described are in many instances applied. In installations requiring a multi-arrangement of constant-frequency generators, additional circuitry is required to control output under load-sharing or parallel operating conditions and as this control also involves field excitation, the overall regulation circuit arrangement is of an integrated, and sometimes complex, form. At this stage, however, we are only concerned with the fundamental method of regulation and for this purpose we may consider the relevant sections or stages of the circuit shown schematically in (Fig. 10.18).

The circuit is comprised of three main sections: a voltage error detector, pre-amplifier and a power amplifier. The function of the voltage error detector is to monitor the generator output voltage, compare it with a fixed reference voltage and to transmit any error to the pre-amplifier. It is made up of a three-phase bridge rectifier connected to the generator output, and a bridge circuit of which two arms contain gas-filled regulator tubes and two contain resistances. The inherent characteristics of the tubes are such that they maintain an essentially constant voltage drop across their connections for a wide range of current through them and for this reason they establish the reference voltage against which output voltage is continuously compared. The output side of the bridge is connected to an "error" control winding of the pre-amplifier and then from this amplifier to a "signal" control winding of a second stage or power amplifier. Both stage are three-phase magnetic amplifiers. The final amplified signal is then supplied to the shunt windings of the generator a.c. exciter stator (see Fig. 10.16).

The output of the bridge rectifier in the error detector is a d.c. voltage slightly lower than the average of the three a.c. line voltages; it may be adjusted by means of a variable resistor (RV_1) to bring the regulator system to a balanced condition for any nominal value of line voltage. A balanced condition of the bridge circuit concerned is obtained when the voltage

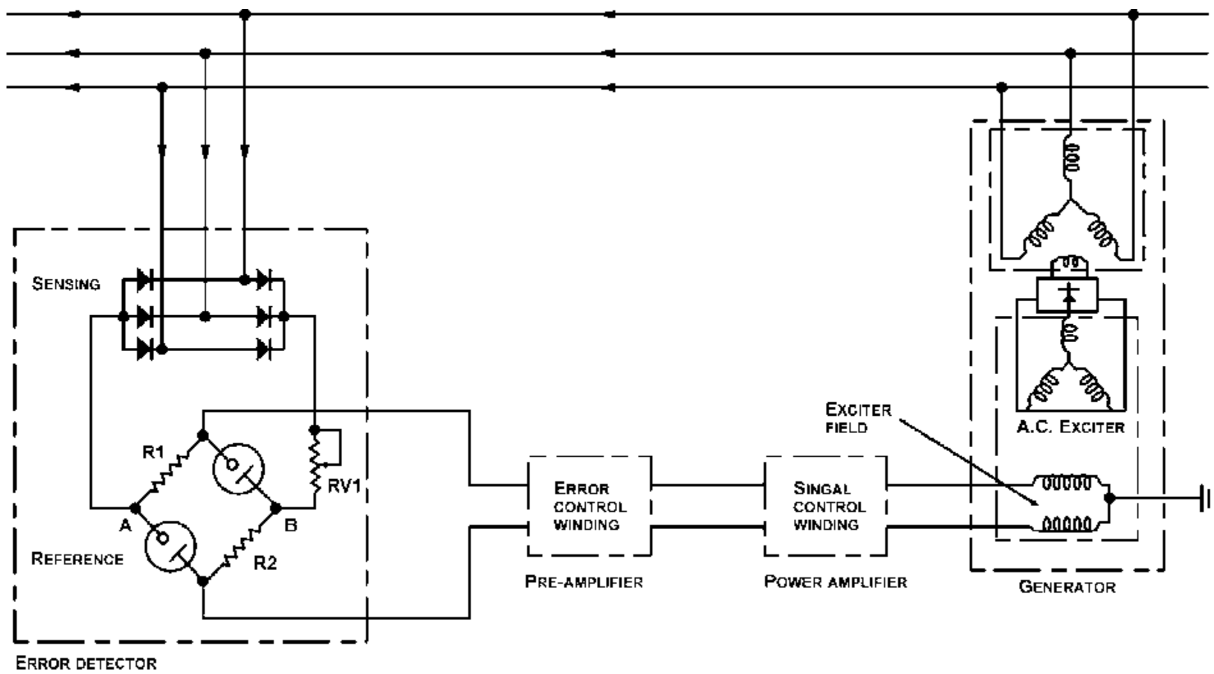


Fig. 10.18. Constant-frequency system voltage regulation.

applied across the bridge (points "A" and "B") is exactly twice that of the voltage drop across the two tubes. Since under this condition, the voltage drop across resistors R_1 and R_2 will equal the drop across each tube, then no current will flow in the output circuit to the error control winding of the pre-amplifier.

If the a.c. line voltage should go above or below the fixed value, the voltage drops across R_1 and R_2 will differ causing an unbalance of the bridge circuit and a flow of current to the "error" control winding of the pre-amplifier. The direction and magnitude of current flow will depend on whether the variation, or error in line voltage, is above (positive error signal) or below (negative error signal) the balanced nominal value, and on the magnitude of the variations.

When current flows through the "error" control winding the magnetic flux set up alters the total flux in the cores of the amplifier, thereby establishing a proportional change in the amplifier output which is applied to the signal winding of the power amplifier. If the error signal is negative it will cause an increase in core flux, thereby increasing the power amplifier output current to the generator exciter field winding. For a positive error signal the core flux and excitation current will be reduced. Thus, the generator output is controlled to the preset value which on being attained restores the error detector bridge circuit to the balanced condition.

Regulators normally incorporate torque-limiting circuitry which limits the torque at mechanical linkages to a safe value by limiting the exciter field current.

LOAD-SHARING OR PARALLELING

Frequency-Wild Systems

In systems of this type, the a.c. output is supplied to independent consumer equipment and since the frequency is allowed to go uncontrolled, then paralleling or sharing of the a.c. load is not possible. In most applications this is by design; for example, in electrical de-icing equipment utilizing resistance type heaters, a variable frequency has no effect on system operation; therefore reliance is placed more on generator dependability and on the simplicity of the generating systems.

Constant-Frequency Systems

These systems are designed for operation under load-sharing or paralleling conditions and in this connection regulation of the two parameters, real load and reactive load, is required. Real load is the actual working load output in kilowatts (kW) available for supplying the various electrical services, and the reactive load is the so-called "Wattless load" which is in fact the vector sum of the inductive and capacitive currents and voltage in the system expressed in kilovolt-amperes reactive (kVAR). (See Fig. 10.5 once again).

Since the real load is directly related to the input power from the prime mover, i.e. the aircraft engine, real load-sharing control must be on the engine. There are, however, certain practical difficulties involved, but as it is possible to reference back any real load unbalance to the constant-speed drive unit between engine and generator, real load-sharing at the output drive shaft.

Reactive load unbalances are corrected by controlling the exciter field current delivered by the voltage regulators to their respective generators, in accordance with signals from a reactive load-sharing circuit.

Real Load-Sharing

The sharing of real load between paralleled generators is determined by the real relative rotational speeds of the generators which in turn influence the voltage phase relationships.

As we learned earlier the speed of a generator is determined by the initial setting of the governor on its associated constant speed drive. It is not possible, however, to obtain exactly identical governor settings on all constant speed drives employed in any one installation, and so automatic control of the governors becomes necessary.

A.C. generators are synchronous machines. Therefore when two or more operate in parallel they lock together with respect to frequency and the system frequency established is that of the generator whose output is at the highest level. Since this is controlled by speed-governing settings then it means that the generator associated with a higher setting will carry more than its share of the load and will supply energy which tends to motor the other machines in parallel with it. Thus, sharing of the total real load is unbalanced, and equal amounts of energy in the form of torque on the generator rotors must be supplied.

Fundamentally, a control system is comprised of two principal sections : one in which the unbalance is determined by means of current transformers, and the other (load controlling section) in which torques are established and applied. A circuit diagram of the system as applied to a four-generator installation is shown schematically in (Fig. 10.19).

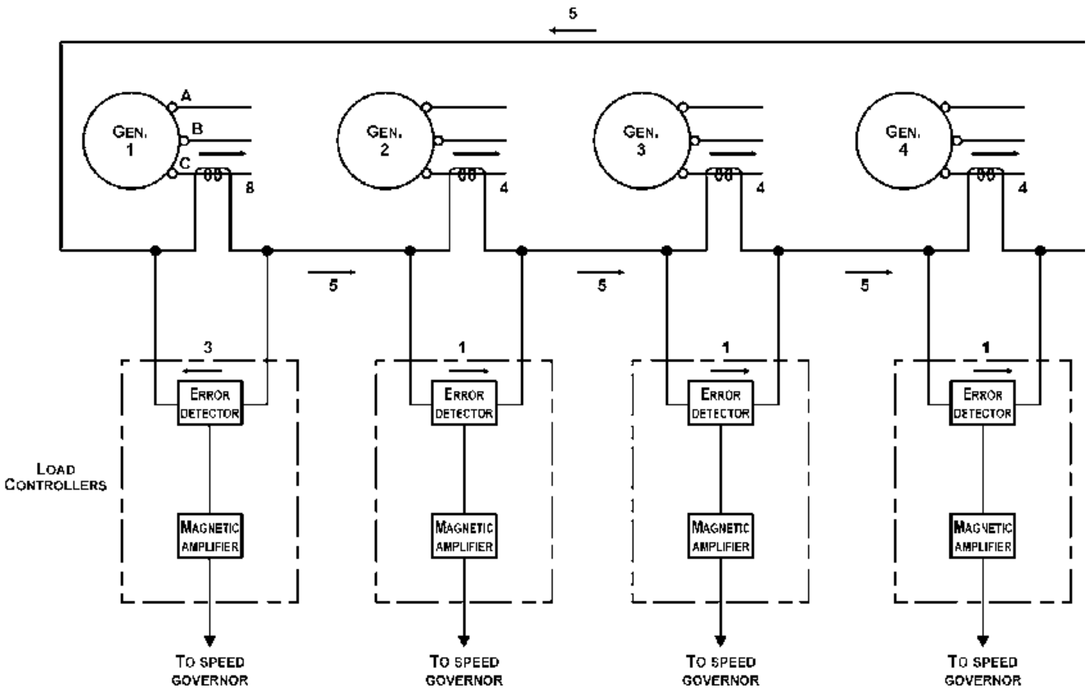


Fig. 10.19. Real load-sharing.

The current transformers sense the real load distribution at phase "C" of the supply from each generator, and are connected in series and together they form a load sharing loop. Each load controller is made up of a two-stage magnetic amplifier controlled by an error sensing element in parallel with each current transformer. The output side of each load controller is, in turn, connected to a solenoid in the speed governor of each constant speed unit.

When current flows through phase "C" of each generator, a voltage proportional to the current is induced in each of the current transformers and as they are connected in series, then current will flow in the load sharing loop. This current is equal to the average of the current produced by all four transformers.

Let us assume that at one period of system operation, balanced load sharing conditions are obtained under which the current output from each transformer is equal to five amps, then the average flowing in the load sharing loop will be five amps, and no current circulates through the error sensing elements. If now a generator, sy No.1, runs at a higher speed governor setting than the other three generators, it will carry more load and will increase the output of its associated current transformer.

The share of the load being carried by the other generators falls proportionately, thereby reducing the output of their current transformers, and the average current flowing in the load sharing loop remains the same, i.e. five amps. If, for example, it is assumed that the output No.1 generator current transformer is increased to eight amps a difference of three amps will flow through the error sensing element of its relevant load controller. The three amps difference divides equally between the other generators and so the output of each corresponding current transformer is reduced by one amp, a difference which flows through the error signals are then applied as d.c. control signals to the two-stage magnetic amplifiers and are fed to electromagnetic coils which are mounted adjacent to permanent magnet flyweight and form part of the governor in each constant speed drive unit. The current and magnetic field simulate the effects of centrifugal force on the fly-weight and are of such direction and magnitude as to cause the flyweights to be attracted or repelled.

Thus, in the unbalanced condition we have assumed, i.e. No.1 generator running at a higher governor setting, the current and field resulting from the error signal applied to the corresponding load controller flows in the opposite sense and repels the flyweights, thereby simulating a decrease of centrifugal force. The movement of the flyweights causes oil to flow to underdrive and the output speed of the constant speed unit drive decreases, thereby correcting the governor setting to decrease the load being taken by No.1 generator. The direction of the current and field in the load controller sensing elements of the remaining generators is such that the governor flyweights in their constant speed drive units are attracted, allowing oil to flow to overdrive, thereby increasing the load being taken by each generator.

Reactive Load-Sharing

The sharing of reactive load between paralleled generators depends on the relative magnitudes of their output voltages which vary, and as with all generator systems are dependent on the settings of relevant voltage regulators and field excitation current. If, for example, the voltage regulator of one generator is set slightly above the mean value of the whole parallel system, the regulator will sense an under-voltage condition and it will accordingly increase its excitation current in an attempt to raise the whole system voltage to its setting. However, this results in a reactive component of current flowing from the "over-excited" generator which flows in opposition to the reactive loads of the other generators. Thus, its load is increased while the loads of the other generators are reduced and unbalance in reactive load sharing exists. It is therefore necessary to provide a circuit to correct this condition.

In principle, the method of operation of the reactive load-sharing circuit is similar to that adopted in the real load-sharing circuit described earlier. A difference in the nature of the circuitry should however be noted at this point. Whereas in the real load-sharing circuit the current transformers are connected directly to the error detecting elements in load controlling units, in a reactive load-sharing circuit (see Fig.10.20) they are connected to the primary windings of devices called mutual reactors. These are, in fact, transformers which have (i) a power source connected to their secondary windings in addition to their primaries; in this instance, phase "C" of the generator output, and (ii) an air gap in the iron core to produce a phase displacement of approximately 90 degrees between the primary current and secondary voltage. They serve the purpose of delivering signals to the voltage regulator which is proportional to the generator's reactive load only.

When a reactive load unbalance occurs, the current transformers detect this in a similar manner to those associated with the real load-sharing circuit and they cause differential currents to flows in the primary windings of their associated mutual reactors. Voltages proportional to the magnitude of the differential currents are induced in the secondary windings and will either lead generator current by 90 degrees. When the voltage induced in a particular reactor secondary winding leads the associated generator current it indicates that a reactive load exists on the generator; in other words, that it is taking more than its share of the total load. In this condition, the voltage will add to the voltage sensed by the secondary winding at phase "C". If, on the other hand, the voltage lags the generator current then the generator is absorbing a reactive load, i.e. it is taking less share of the total load and the voltage will subtract from that sensed at phase "C".

The secondary winding of each mutual reactor is connected in series with an error detector in each voltage regulator, the detector functioning in the same manner as those used for voltage regulation and real load-sharing.

Let us assume that No.1 generator takes the greater share of the load, i.e. it has become over-excited. The voltage induced in the secondary winding of the corresponding mutual reactor will be additive and so the error detector will sense this as an over voltage. The resulting d.c. error signal is applied to the pre-amplifier and then to the power amplifier the output of which is adjusted to reduce the amount of exciter current being delivered to the No.1 generator. In the case

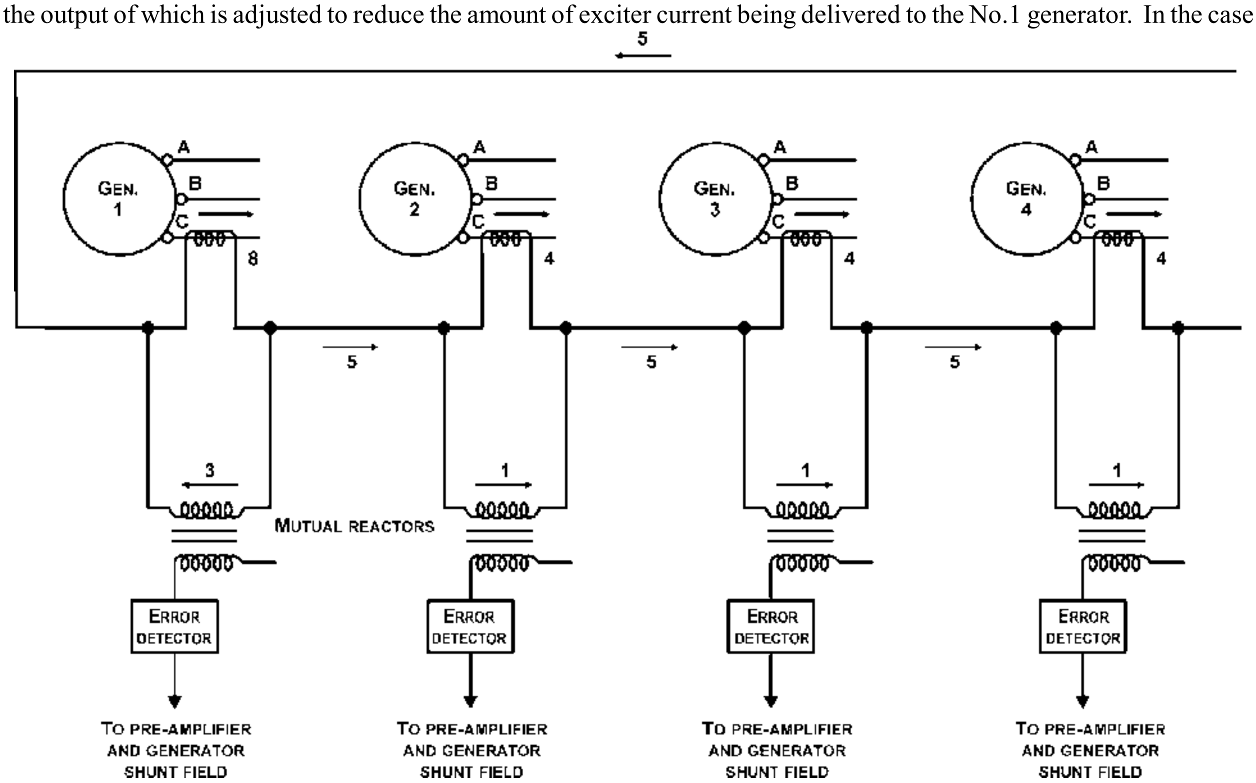


Fig. 10.20. Reactive load-sharing.

of the other three generators they will have been carrying less than their share of the reactive load and, therefore, the voltage induced in their mutual reactors will have lagged behind the currents from the generators, resulting in opposition to the voltage sensed by the secondary windings. Thus, the output of each power amplifier will be adjusted to increase the amount of exciter current being delivered to their associated generators until equal reactive load-sharing is restored between generators within the prescribed limits.

Synchronizing Lights

In some power-generating systems a method of indicating synchronization between generator outputs forms part of the paralleling system, and consists of lights and frequency adjustment controls. A schematic diagram of the method based on that adopted for the triple generator system of the Boeing 727 is given in (Fig.10.21).

The lights are connected into phases "A" and "C" of each generator between the generator breakers and a synchronizing busbar, via a selector switch. The switch is also used for connecting a voltmeter and a frequency meter to each generator output phase "B". The frequency adjustment controls are connected into the circuit of the load controllers.

The generators are connected to their respective load busbars and the synchronizing busbar, via generator breakers and bus-tie breakers respectively; each breaker being closed or tripped by manual operation of switches on a panel at the Flight Engineer's station. The breakers also trip automatically in the event of faults detected by the generator control and protection system. The field relays are similarly operated. Indicator lights are located adjacent to all switches to indicate either of the closed or tripped conditions.

Prior to engine starting, the bus-tie breakers and field relays are closed (indicator lights out) and the generator breakers are tripped (indicator lights on). As the first engine is started, the meter selector switch is positioned at GEN 1 to connect phases "A" and "C" of this generator to the synchronizing busbar via the synchronizing lights. Phase "B" is connected to both the voltmeter and frequency meter the readings of which are then checked. Since at this moment, only the number 1 generator is in operation, then with respect to the other two, it will of course, produce maximum voltage and phase difference and both synchronizing lights will flash at a high frequency as a result of the current flow them. The frequency control knob for the generator is then adjusted until its load controller has trimmed the CSD/generator speed to produce a "master" frequency of about 403 Hz, and simultaneous flashing of both synchronizing lights.

When the second engine is started, the meter selector switch is positioned at GEN 2 to connect the synchronizing lights and meters to the appropriate phases of number 2 generator, and its frequency is also adjusted in the manner just described. The number 1 generator, and its frequency is also adjusted in the manner just described. The number 1 generator is then connected to its load busbar by closing its generator breaker. This action also connects the generator to the synchronizing busbar, and since the synchronizing lights are now sensing the output of the second on-coming generator, their flashing frequency will be very much less as a result of less voltage and phase difference between the two generator output. The frequency of the second generator is then adjusted to obtain the greatest time interval between flashed of the synchronizing lights, and while the lights are out (indicating both sources of power are in phase) the number 2 generator is connected to its load busbar by closing its breaker.

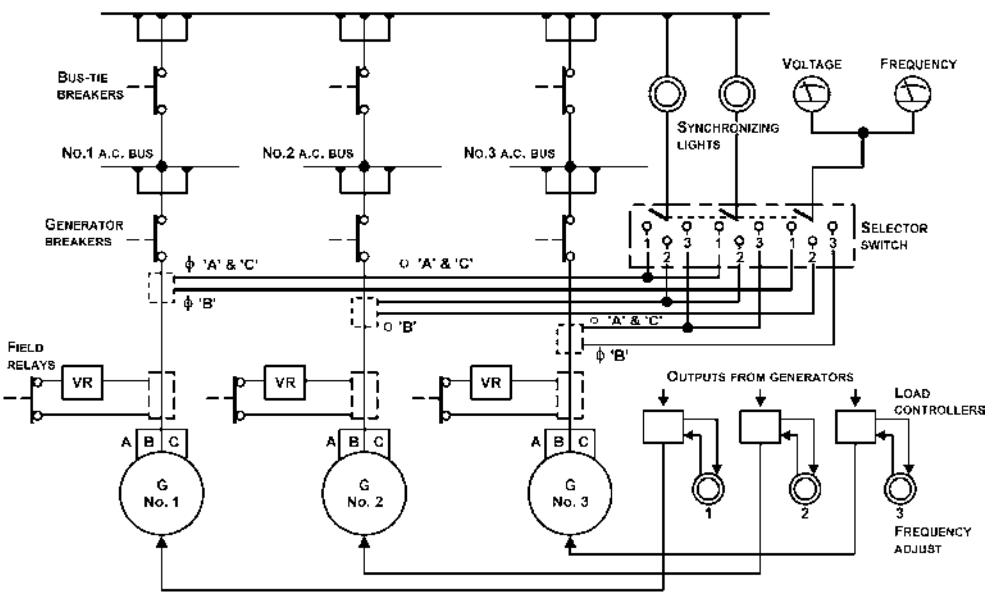


Fig. 10.21. Synchronizing.

As the third engine is started, the meter selector switch is positioned at GEN 3, and by following the same procedure just outlined, number 3 generator is connected to its load busbar. With all three generators thus connected their subsequent operation is taken care of automatically by the load-sharing sensing circuits of the associated control and protection unit.

It is important to note that a generator must never be connected to its load busbar when the synchronizing lights are on. Such action would impose heavy loads on the generator or CSD and possibly cause damage to them. If, at any time the synchronizing lights flash alternately, a phase reversal is indicated and the appropriate generator should not be used.

AIR-DRIVEN GENERATORS

The application of generators dependent upon an airstream as the prime mover is by no means a new one and, having been adopted in many early types of aircraft for the generation of electrical power, the idea of repeating the practice for to-day's advanced electrical systems would, therefore, seem to be retrogressive. However, an air-drive can serve as a very useful stand-by in the event of failure of a complete main a.c. generating system and it is in this emergency role that it is applied to some types of aircraft.

The drive consists of a two-bladed fan or air turbine as it is sometimes called, and a step-up ratio gear train which connects the fan to a single a.c. generator. The generator is of a similar type of the main generator but has a lower output rating since it is only required to supply the consumer equipment essential under emergency conditions. The complete unit is stowed on a special mounting in the aircraft fuselage, and when required is deployed by a mechanically linked release handle in the flight compartment. When deployed at airspeeds of between 120 to 430 knots, the fan and generator are driven up to their appropriate speeds by the airstream, and electrical power is delivered via a regulator at the rated values. A typical nominal fan speed is 4,800 rev/min and is self-governed by varying the blade pitch angles. The gearbox develops a generator shaft speed of 12,000 rev/min. After deployment of the complete unit, it can be restored when the aircraft is on the ground.

ALTERNATOR MAINTENANCE

Maintenance and inspection of alternator systems is similar to that of d.c. systems. Check the exciter brushes for wear and surfacing. On most large aircraft with two or four alternator systems, large aircraft with two or four alternator systems, each power panel has three signal lights, one connected to each phase of the power bus, so the lamp will light when the panel power is on. The individual buses throughout the airplane can be checked by operating equipment from that particular bus. Consult the manufacturer's instructions on operation of equipment for the method of testing each bus.

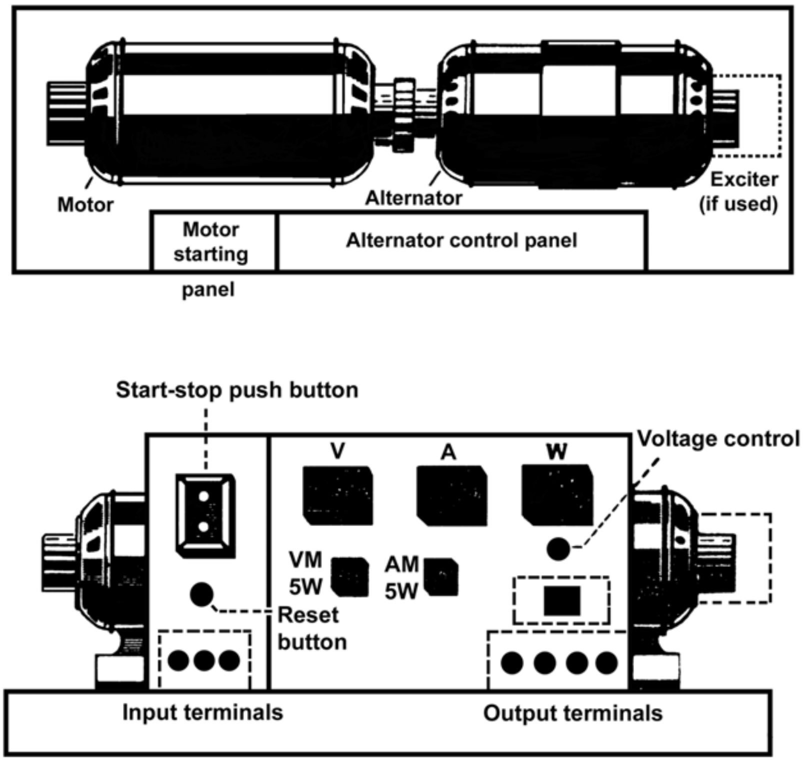


Fig. 10.22. A.C. motor-generator set for ground testing.

A typical, portable, a.c. electrical system test-set is an analyser, consisting of a multirange combination a.c. -d.c. voltmeter, an ammeter with a clip-on current transformer, a vibrating-reed type frequency meter, and an unmounted continuity light.

Alternator test-stands are used for testing alternators and constant-speed drives in a repair facility. They are capable of supplying power to constant-speed drive units at input speeds varying from 2,400 r.p.m. to 9,000 r.p.m. A typical test-stand motor uses 220/440-volt. 60-cycle, e-phase power. Blowers for ventilation, oil coolers, and necessary meters and switches are integral parts of the test-stand. Test circuits are supplied by a load-bank. An a.c. motor-generator set for ground testing is shown in (Fig. 10.22).

A portable load bank unit furnishes a load similar to that on the airplane for testing alternators, either while mounted in the airplane or on the shop test-stand. A complete unit consists of resistive and reactive loads controlled by selector switches and test meters mounted on a control panel. This load unit is compact and convenient, eliminating the difficulty of operating large loads on the airplane while testing and adjusting the alternators and control equipment.

Proper maintenance of an alternator requires that the unit be kept clean and that all electrical connections are tight and in good repair. If the alternator fails to build up voltage as designated by applicable manufacturer's technical instructions, test the voltmeter first by checking the voltages of other alternators, or by checking the voltage in the suspected alternator with another voltmeter and comparing the results. If the voltmeter is satisfactory, check the wiring, the brushes, and the drive unit for faults. If this inspection fails to reveal the trouble, the exciter may have lost its residual magnetism. Residual magnetism is restored to the exciter by flashing the field. Follow the applicable manufacturer's instructions when flashing the exciter field. If, after flashing the field, no voltage is indicated, replace the alternator, since it is probably faulty.

Clean the alternator exterior with an approved fluid; smooth a rough or pitted exciter commutator or slip ring with 000 sandpaper; then clean and polish with a clean, dry cloth. Check the brushes periodically for length and general condition. Consult the applicable manufacturer' instructions on the specific alternator to obtain information on the correct brushes.

Troubleshooting
Use the following table to assist in locating, diagnosing, and correcting alternator troubles;

TROUBLE	PROBABLE CAUSE	REMEDY
VOLTMETER REGISTERS NO VOLTAGE.	VOLTMETER DEFECTIVE VOLTMETER REGULATOR DEFECTIVE. DEFECTIVE EXCITER	REMOVE AND REPLACE VOLTMETER REPLACE REGULATOR REPLACE ALTERNATOR
LOW VOLTAGE	IMPROPER REGULATOR ADJUSTMENT	ADJUST VOLTAGE REGULATOR
ERRATIC METER INDICATION	LOOSE CONNECTIONS DEFECTIVE METER	TIGHTEN CONNECTIONS REMOVE AND REPLACE METER
VOLTAGE FALLS OFF AFTER A PERIOD OF OPERATION	VOLTAGE REGULATORS NOT WARMED UP BEFORE ADJUSTMENT	READJUST VOLTAGE REGULATOR.

Induction Motor : General Principle
As a general rule, conversion of electrical power into mechanical power takes place in the rotating part of an electric motor. In d.c. motors, the electric power is **conducted** directly to the armature (i.e. rotating part) through brushes and commutator

Hence, in this sense, a d.c. motor can be called a **conduction motor**. However, in a.c. motors, the rotor does not receive electric power by conduction motor. However, in a.c. motors, the rotor does not receive electric power by conduction but by **induction** in exactly the same way as the secondary of a 2-winding transformer receives its power from the primary. That is why such motors are known as **induction motors**. In fact, an induction motor can be treated as a rotating transformer i.e. one in which primary winding is stationary but the secondary is free to rotate.

Of all the a.c. motors, the polyphase induction motor is the one which is extensively used for various kinds of industrial drives. It has the following main advantages and also some disadvantages :

Advantages

1. It has very simple and extremely rugged, almost unbreakable construction (especially squirrel-cage type).
2. Its cost is low and it is very reliable.
3. It has sufficiently high efficiency. In normal running condition, no brushes are needed, hence frictional losses are reduced. It has a reasonably good power factor.
4. It requires minimum of maintenance.
5. It starts up from rest and needs no extra starting motor and has not to be synchronised. Its starting arrangement is simple especially for squirrel-cage type motor.

Disadvantages

1. Its speed cannot be varied without sacrificing some of its efficiency.
2. Just like a d.c. shunt motor, its speed decreases with increase in load.
3. Its starting torque is somewhat inferior to that of a d.c. shunt motor.

Construction

An induction motor consists essentially of two main parts :

a. a stator and
b. a rotor.

a. Stator

The stator of an induction motor is, in principle, the same as that of a synchronous motor or generator. It is made up of a number of stampings, which are slotted to receive the windings [Fig. 10.23 (a)]. The stator carries a 3-phase winding [Fig. 10.23 (b)] and is fed from a 3-phase supply. It is wound for a definite number of poles, the exact number of poles being determined by the requirements of speed. Greater the number of poles, lesser the speed and vice versa. It will be shown that the stator windings, when supplied with 3-phase currents, produce a magnetic flux, which is of constant magnitude but which revolves (or rotates) at synchronous speed (given by $N_s = 120\ f/P$). This revolving magnetic flux induces an e.m.f. in the rotor by mutual induction.

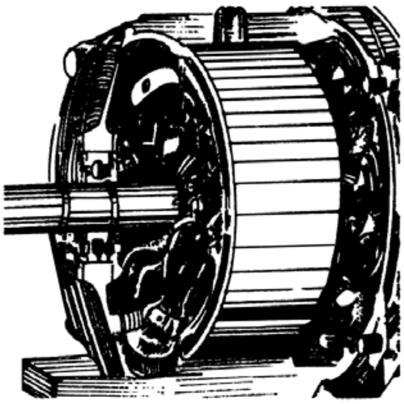


Fig. 10.23. (a) Unwound stator with semi-closed slots. Laminations are of high-quality low-loss silicon steel.

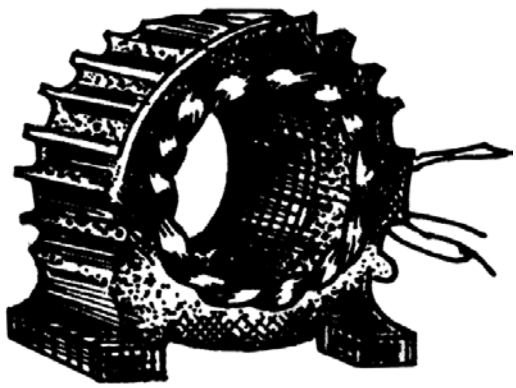


Fig. 10.23. (b) Completely wound stator for an induction motor.

b. Rotor

i. Squirrel-cage rotor : Motors employing this type of rotor are known as squirrel-cage induction motors.
ii. Phase-wound or wound rotor : Motors employing this type of rotor are variously known as 'phase-wound' motors or 'wound' motors or as 'slip-ring' motors.

Squirrel-cage Rotor

Almost 90 per cent of induction motors are squirrel-cage type, because this type of rotor has the simplest and most rugged construction imaginable and is almost indestructible. The rotor consists of a cylindrical laminated core with parallel slots for carrying the rotor conductors which, it should be noted clearly, are not wires but consist of heavy bars of copper, aluminium or alloys. One bar is placed in each slot, rather the bars are inserted from the end when semi-closed slots are used. The rotor bars are brazed or electrically welded or bolted to two heavy and stout short-circuiting end-rings, thus giving us, what is so picturesquely called, a squirrel-cage construction (Fig. 10.24).

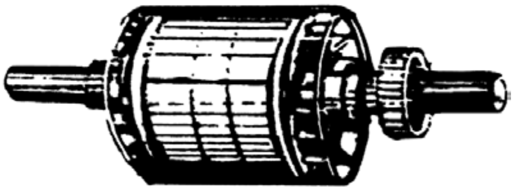


Fig. 10.24 (a). Squirrel-cage rotor with copper bars and alloy brazed end-rings.

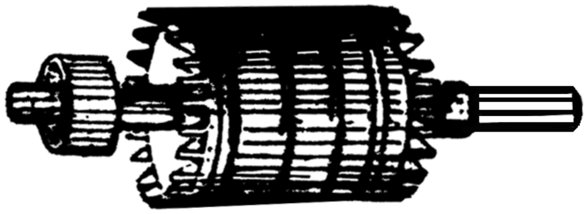


Fig. 10.24 (b). Rotor with shaft and bearings.

It should be noted that the rotor bars are permanently short-circuited on themselves, hence it is not possible to add any external resistance in series with the rotor circuit for starting purposes.

The rotor slots are usually not quite parallel to the shaft but are purposely given a slight skew (Fig.10.25). This is useful in two ways.

i. it helps to make the motor run quietly by reducing the magnetic hum and
ii. it helps in reducing the locking tendency of the rotor i.e. the tendency of the rotor teeth to remain under the stator teeth due to direct magnetic attraction between the two.

In small motors, another method of construction is used. It consists of placing the entire rotor core in a mould and casting all the bars and end-rings in one piece. The metal commonly used is an aluminium alloy.

Another form of rotor consists of a solid cylinder of steel without any conductors or slots at all. The motor operation depends upon the production of eddy currents in the steel rotor.

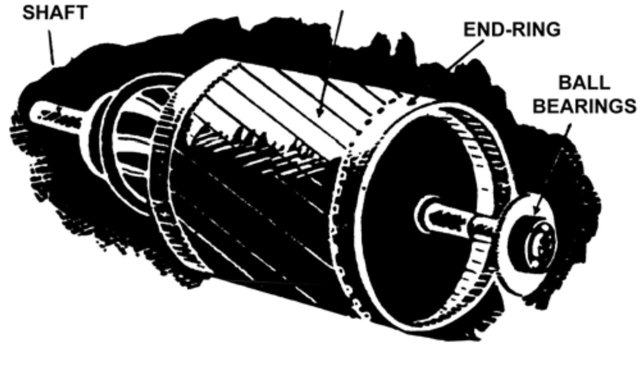


Fig. 10.25.

Phase-wound Rotor

This type of rotor is provided with 3-phase, double-layer, distributed winding consisting of coils as used in alternators. The rotor is wound for as many poles as the number of stator poles and is always wound 3-phase even when the stator is wound two-phase.

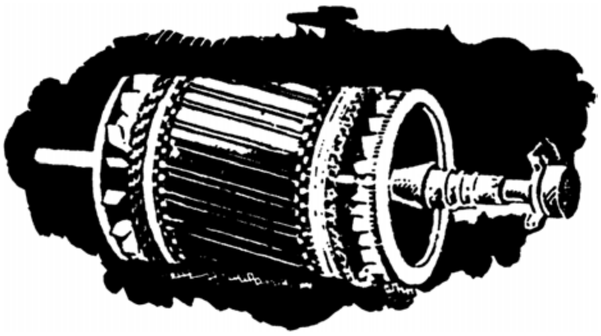


Fig. 10.26 (a).

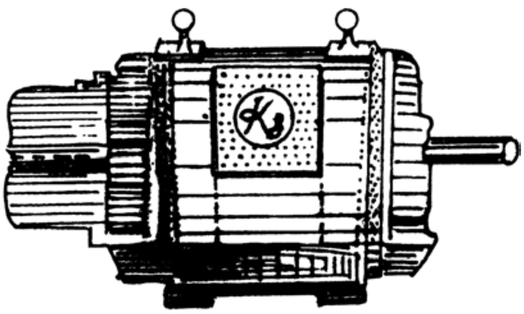


Fig.10.26 (b). Slip-ring motor with slip-rings brushes and short-circuiting devices.

The three phase are starred internally. The other three winding terminals are brought out and connected to three insulated slip-rings mounted on the shaft with brushes resting on them Fig.10.26 (b). These three brushes are further externally connected to a 3-phase star-connected rheostat Fig.10.26 (c). This makes possible the introduction of additional resistance in the rotor circuit during the starting period for increasing the starting torque of the motor, as shown in (Fig.10.27) and for changing its speed-torque/current characteristics. When running under normal conditions, the slip-rings are automatically short-circuited by means of a metal collar, which is pushed along the shaft and connects all the rings together. Next, the brushes are automatically lifted from the slip-rings to reduce the frictional losses and the wear and tear. Hence, it is seen that under normal running conditions, the wound rotor is short-circuited on itself just like the squirrel-cage rotor.

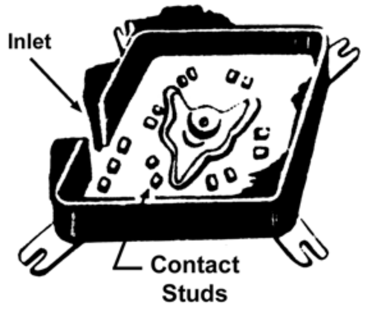


Fig. 10.26 (c).

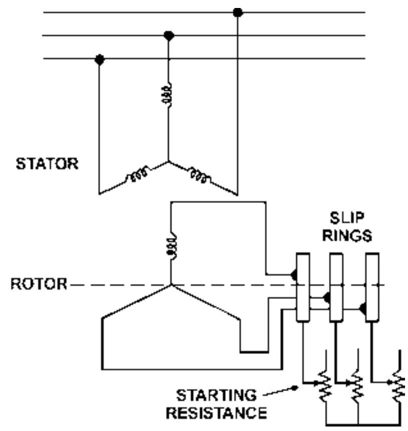


Fig. 10.27.

Rotating Magnetic Field

The field structure shown in A of (Fig. 10.28) has poles whose windings are energized by three a.c. voltages, a,b, and c. These voltages have equal magnitude but differ in phase, as shown in B of (Fig. 10.28).

At the instant of time shown as 0 in B of (Fig. 10.28), the resultant magnetic field produced by the application of the three voltages has its greatest intensity in a direction extending from pole 1 to pole 4. Under this condition, pole 1 can be considered as a north pole and pole 4 as a south pole.

At the instant of time shown as 1, the resultant magnetic field will have its greatest intensity in the direction extending from pole 2 to pole 5; in this case, pole 2 can be considered as a north pole and pole 5 as a south pole. Thus, between instant 0 and instant1, the magnetic field has rotated clockwise.

At instant 2, the resultant magnetic field has its greatest intensity in the direction from pole 3 to pole 6, and the resultant magnetic field has continued to rotate clockwise.

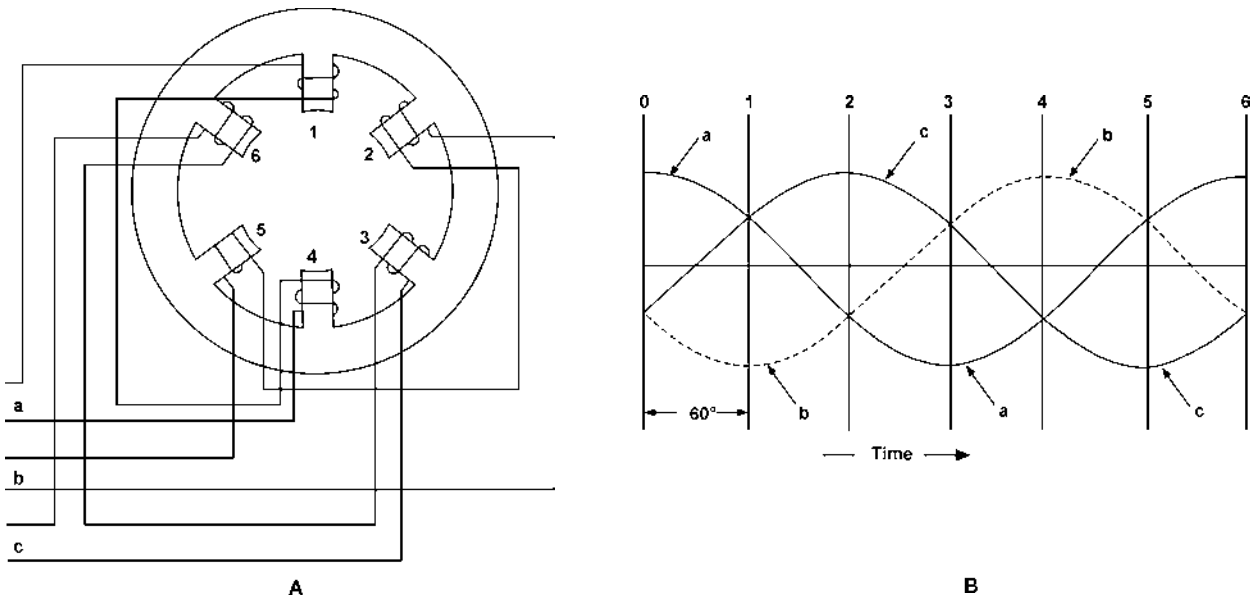
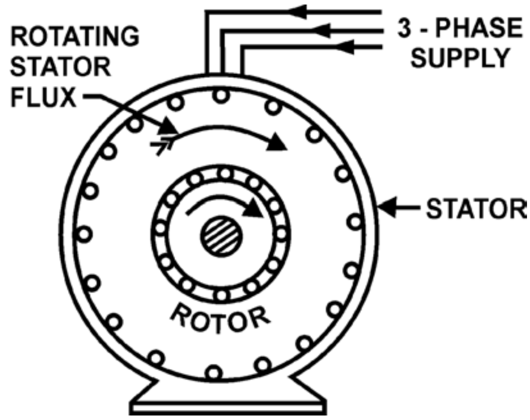


Fig. 10.28. Rotating magnetic field developed by application of three-phase voltages.

At instant 3, Pole 4 and 1 can be considered as north and south poles, respectively, and the field has rotated still further.

At later instants of time, the resultant magnetic field rotates to other positions while travelling in a clockwise direction, a single revolution of the field occurring in one cycle. If the exciting voltage have a frequency of 60 c.p.s., the magnetic field makes 60 revolutions per second, or 3,600 r.p.m. This speed is known as the synchronous speed of the rotating field.

Principle of Operation



The reason why the rotor of an induction motor is set into rotation is as follows : when the 3-phase stator windings are fed by a 3-phase supply, then, as said above, a magnetic flux of constant magnitude but rotating at synchronous speed, is setup. This flux passes through the air-gap, sweeps past the rotor surface and so cuts the rotor conductors which, as yet, are stationary. Due to the relative speed between the rotating flux and the stationary conductors, an e.m.f. is induced in the latter according to Faraday's Law of Electro-magnetic Induction. The frequency of the induced e.m.f. is the same as the supply frequency. Its magnitude is proportional to the relative velocity between the flux and the conductors and its direction is as given by Fleming's Right-hand rule. Since the rotor bars or conductors form a closed circuit, rotor current is produced, whose direction, as given by Lenz's law, is such as to oppose the very cause producing it. In this case, the cause which produces the rotor current is the relative velocity between the rotating flux of the stator and the stationary rotor conductors. Hence to reduce the relative speed, the rotor starts running in the same direction as that of the flux and tries to catch up with the rotating flux.

Slip

In practice, the rotor never succeeds in 'catching up' with the stator flux: If it really did so, then there would be no relative speed between the two, hence no e.m.f., no current, and so, no torque to maintain rotation. That is why the rotor runs at a speed which is always less than the speed of the stator field. The difference in speed depends upon the load on the motor.

The difference between the synchronous speed N_s and the actual speed N of the rotor is known as **slip**. Though it may be expressed in so many rev/s yet it is usual to express it as a percentage of the synchronous speed. Actually, the term 'slip' is descriptive of the way in which the rotor 'slips back' from synchronism.

$$\therefore \quad \% \text{ slip } s = \frac{N_s - N}{N_s} \times 100$$

Sometimes, N_s-N is called the slip speed.

Frequency of Rotor Current

When the motor is stationary, the frequency of rotor current is the same as the supply frequency. But when the rotor starts revolving, then the frequency depends upon the relative speed or on slip-speed. Let at any slip-speed the frequency of the rotor current be f'. Then

$$N_s - N = \frac{120\,f'}{P}$$

Also $$N_s = \frac{120\,f}{P}$$

Dividing one by the other, we get

$$\frac{f'}{f} = \frac{N_s - N}{N_s} = s \qquad \therefore \quad f' = sf$$

Starting Torque of a Squirrel-cage Motor

The resistance of a squirrel-cage rotor is fixed and small as compared to its reactance which is very large especially at the start because at standstill, the frequency of the rotor current equals the supply frequency. Hence, the starting current I_2 of the rotor, though very large in magnitude, lags by a very large angle behind E_2 with the result that the starting torque per ampere is very poor. It is roughly 1.5 times the full-load torque, all through the starting current is 5 to 7 times the full load current. Hence, such motors are not useful where the motor has to start against heavy loads.

Starting Torque of a Slip-ring Motor

The starting torque of such a motor is increased by improving its power factor by adding external resistance in the rotor circuit from the star-connected rheostat, the rheostat resistance being progressively cut out as the motor catches speed. Addition of external resistance, however, increases the rotor impedance and so reduces the rotor current. At first, the effect of improved power factor predominates the current-cedreasing effect of impedance. Hence, starting torque is increased. But after a certain point, the effect of increased impedance predominates the effect of improved power factor and so the torque starts decreasing.

When rotor is stationary i.e. s=1, then frequency of rotor e.m.f. is the same as that of the stator supply frequency. The value of e.m.f. induced in the rotor at standstill is maximum because the relative speed between the rotor and the revolving stator flux is maximum. In fact, the motor is equivalent to a 3-phase transformer with a short-circuited rotating secondary.

When rotor starts running, the relative speed between it and the rotating stator flux is decreased. Hence, the rotor induced e.m.f. which is directly proportional to this relative speed, is also decreased (and may disappear altogether if rotor speed were to become equal to the speed of stator flux). Hence, for a slip s, the rotor induced e.m.f. will be s times the induced e.m.f. at standstill.

Obviously, torque at any speed is proportional to the square of the applied voltage. If stator voltage decreases by 10%, the torque decreases by 20%. Changes in supply voltage not only affect the starting torque T_{st} but torque under running conditions also. If V decreases, then T also decreases. Hence, for maintaining the same torque, slip increases i.e. speed falls.

Let V change to V', s to s' and T to T' ; then $\frac{T}{T'} = \frac{sV^2}{s'V'^2}$

Effect of Changes in supply Frequency on Torque and Speed

Hardly any important changes in frequency take place on a large distribution system except during a major disturbance. However, large frequency changes often take place on isolated, low-power systems in which electric energy is generated by means of diesel engines or gas turbines. Examples of such system are : emergency supply in a hospital and the electrical system on a ship etc.

The major effect of change in supply frequency is on motor speed. If frequency drops by 10%, then motor speed also drops by 10%. Machine tools and other motor-driven equipment meant for 50 Hz causes problem when connected to 60-Hz supply. Everything runs (60-50) × 100/50 = 20% faster than normal and this may not be acceptable in all applications. In that case, we have to use either gears to reduce motor speed or an expensive 50-Hz source.

A 50-Hz motor operates well on a 60-Hz line provided its terminal voltage is raised to 60/50 = 6/5 (i.e. 120%) of the name-plate rating. In that case, the new breakdown torque becomes equal to the original breakdown torque and the starting. In that case, the new breakdown torque becomes equal to the original breakdown torque and the starting torque is only slightly reduced. However, power factor, efficiency and temperature rise remain satisfactory.

Similarly, a 60-Hz motor can operate satisfactorily on 50-Hz supply provided its terminal voltage is reduced to 5/6 (i.e. 80%) of its name-plate rating.

Speed Regulation of an Induction Motor

By speed regulation of a motor is meant the natural change in its speed from no-load to full-load without using any speed controlling apparatus. Suppose that the no-load speed of a motor is 980 rpm and its full-load speed is 940 rpm. Its speed regulation is (980-940) = 40 rpm or percentage speed regulation is 40 × 100/940 = 4.25%.

As we know, in an induction motor, slip is necessary in order to induce the rotor currents required for developing motor torque. At no load, only a small torque is required for overcoming only mechanical losses, hence motor load is increased, the rotor slip has to increase in order to increase induced rotor currents. The increased rotor currents will, in turn, produce higher torque required by the increase in motor load.

Since the short-circuited rotor bars of a squirrel-cage motor have low resistance and their reactance under running conditions is also low, the rotor impedance is also relatively low. Consequently, a small increase in the rotor induced voltage produces a relatively large increase in rotor current. Therefore, as the motor is loaded from no-load to full-load, only a small decrease in speed is required for producing a relatively large increase in rotor currents. That is why the speed regulation of a squirrel-cage induction motor is very small and hence it is often classified as a constant-speed motor.

Induction Motor Power Factor

The presence of air-gap between the stator and rotor of an induction motor increases the reluctance of the stator magnetic circuit. At start-up, the squirrel cage rotor has large reactance because the frequency of its induced currents is the highest (equal to stator supply frequency). Due to these two factors, the starting current drawn by the motor has a very large magnetising component but a very small in-phase component. Hence, motor current lags behind the supply voltage by a very large angle. Consequently, at the instant of start-up, the squirrel cage induction motor has a very low lagging power factor of the order of 0.05.

When running at no-load, the motor draws in-phase current just to meet no-load losses. This component is still relatively small as compared with the magnetising current (which would, of course, be much less than its value at the instant of starting). Hence, at no-load also, the motor will have a low lagging power factor of about 0.1.

However, as load on the motor is increased, the in-phase component of the motor is increased but its magnetising component remains about the same. Hence, the power factor of a squirrel-cage induction motor improves as its load is increased. In fact, it may become as high as 0.9 lagging at rated load.

Starting Methods for Cage Motors
The following three methods are commonly used for starting squirrel-cage induction motors.

a. Direct-on-line (DOL) Starting
It is also called across-the-line starting and is used for small motors below about 5 kW. It is customary to employ a straight single-throw switch or a contactor as shown in (Fig 10.29). The starting current is high i.e. about 4 to 7 times the full-load current, the actual value depending on the size and design of the motor. Such a high starting current causes a relatively large voltage drop in the cables and thereby affects the supplies to other consumers on the same system. If the supply is isolated as in factories having their own generators, there is no such limit and motors of several hundred kW rating are started by direct-on-line (DOL) method.

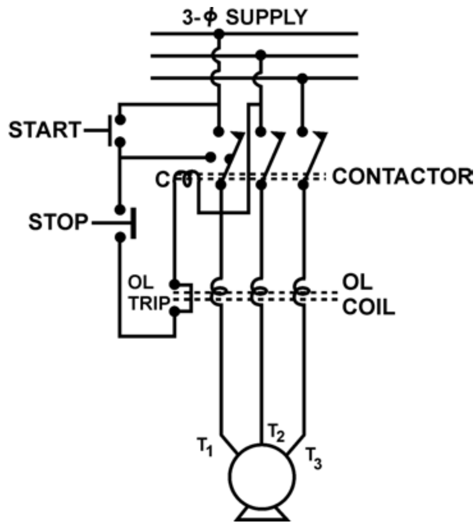


Fig. 10.29.

Large motors fed from a common supply are started with reduced voltage by using any of the following two methods.

b. Auto-transformer Starter
Fig. 10.30 shows a 3-phase star-connected auto-transformer used for applying reduced voltage across motor stator during starting period. In this way, starting current drawn by the motor can be reduced to any desired value. The auto-transformer usually has tappings which reduce the line voltage to 50%, 65% and 80% of the normal value. Since torque developed by the motor varies as the square of the applied voltage as the square of the applied voltage, the starting torque is considerably reduced. If, for example, 50% tap is used, the starting torque developed by the motor would be $(0.5)^2$ or 1/4 or 25% of the full-load torque. For 65% and 80% taps, the starting torques would be $(0.65)^2 = 42.2\%$ and $(0.8)^2$ =64% of the full-load torque respectively.

Generally, a double-throw switch is used for connecting the auto-transformer in the circuit for starting purposes. After the motor has run up to speed, the switch is moved into the RUN position which connects the motor directly to the supply.

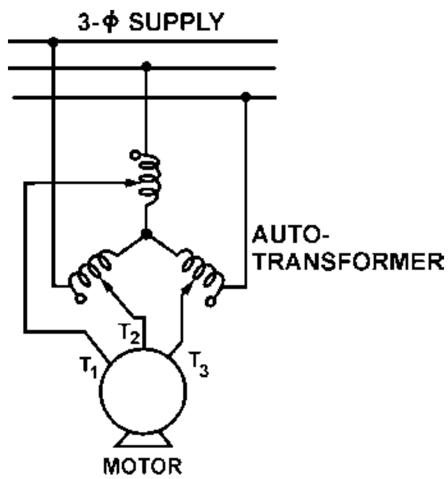


Fig. 10.30.

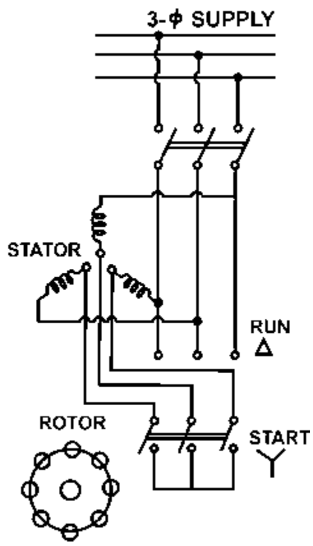


Fig. 10.31.

c. Star-delta Starter

In this method, the stator winding of the motor is connected in star for starting and in delta for normal running (Fig.10.31). The voltage of each phase at starting is reduced to $\frac{1}{\sqrt{3}}$ of the line voltage. The current in each phase is also reduced by the same factor so that line current at starting becomes $\frac{1}{\sqrt{3}} \times \frac{1}{\sqrt{3}} = \frac{1}{3}$ of the current which the motor would have taken if connected directly across the supply. of the line voltage. The current in each phase is also reduced by the same factor so that line current at starting becomes

Since $T \alpha V^2$, the starting torque is reduced to $\left(\frac{1}{\sqrt{3}}\right)^2 = \frac{1}{3}$ = 33.3% of the normal value.

The changeover from star-starting to delta-running is made by a double-throw switch with interlocks to prevent motor starting with the switch in the RUN position.

Starting of Slip-ring Motors

Fig.10.32 shows the schematic diagram of the circuit used for starting wound-rotor or slip-ring induction motor. As seen, variable resistance can be added into the rotor circuit for reducing the starting current and improving the starting torque. The rotor windings are connected to the y-connected external resistors through slip-rings and brushes. The starter resistance is usually of the face-plate type, the starter arms forming the star point. The motor is started with all the starter resistance circuit in thus giving maximum starting torque. As motor speed increases, the starter resistance, is reduced to zero and the slip-rings are short-circuited.

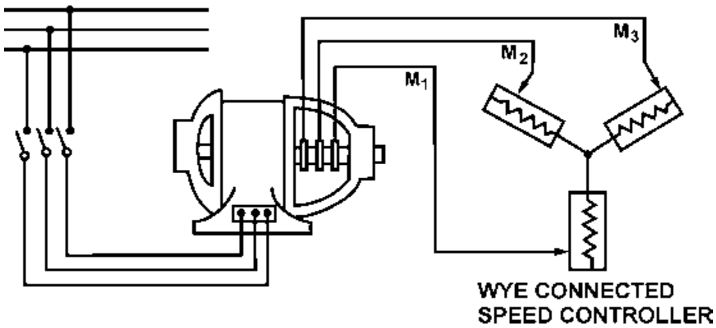


Fig. 10.32.

Synchronous Motor-General

A synchronous motor (Fig. 10.33) is electrically identical with an alternator or a.c. generator. In fact, a given synchronous machine may be used, at least theoretically, as an alternator, when driven mechanically or as a motor, when driven electrically, just as in the case of d.c. machines. Most synchronous motors. Most synchronous motors are rated between 150 kW and 15 MW and run at speeds ranging from 150 to 1800 r.p.m.

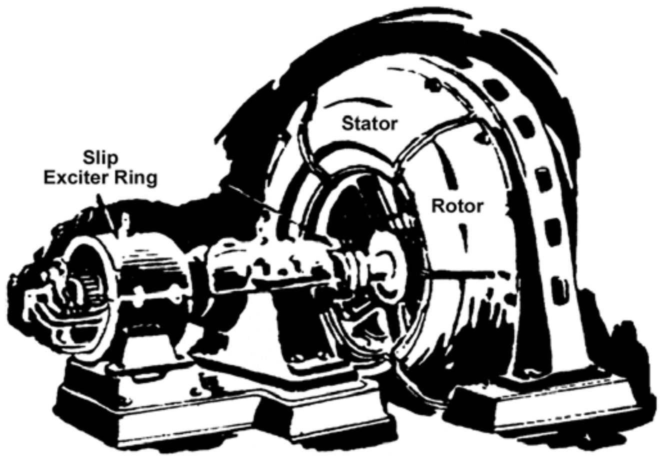


Fig. 10.33.

Some characteristic features of a synchronous motor are worth nothing

1. It runs either at synchronous speed or not at all i.e. while running it maintains a constant speed. The only way to change its speed is to vary the supply frequency (because $N_S = 120$ f/P)
2. It is not inherently self-starting. It has to be run upto synchronous (or near synchronous) speed by some means, before it can be synchronized to the supply.
3. It is capable of being operated under a wide range of power factors, both lagging and leading. Hence, it can be used for power correction purposes, in addition to supplying torque to drive loads.

Principle of Operation

When a 3-ϕ winding is fed by a 3-ϕ supply, then a magnetic flux of constant magnitude but rotating at synchronous speed, is produced. Consider a two-pole stator of (Fig.10.34), in which are shown two stator poles (marked N_S and S_S) rotating at synchronous speed, say, in clockwise direction. With the rotor position as shown, suppose the stator poles are at that instant situated at points A an B. The two similar poles, N (of rotor) and N_S (of stator) as well as S and S_S will repel each other, with the result that the rotor tends to rotate in the anti-clockwise direction.

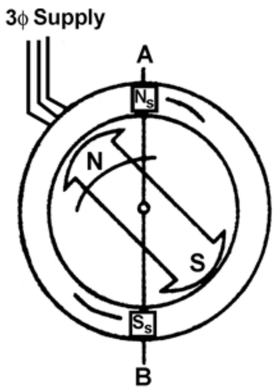


Fig. 10.34.

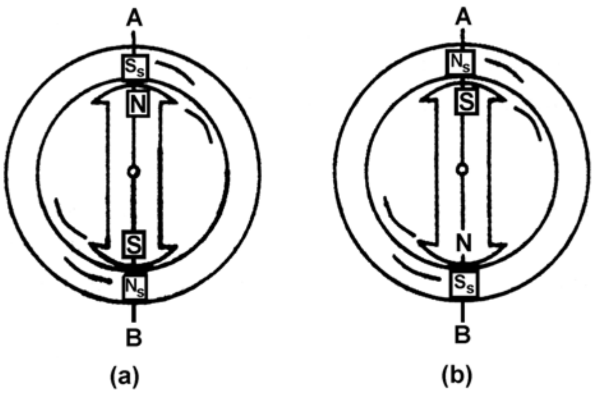


Fig. 10.35.

But half a period later, stator poles, having rotated around, interchange their positions i.e. N_S is at point B and S_S at point A. Under these conditions, N_S attracts S and S_S attracts N. Hence, rotor tends to rotate clockwise (which is just the reverse of the first direction). Hence, we find that due to continuous the rapid rotation of stator poles, the rotor is subjected to a torque which is rapidly reversing i.e. in quick succession, the rotor is subjected to torque which tends to move it first in one direction and then in the opposite direction. Owing to its large inertia, the rotor cannot instantaneously respond to such quickly-reversing torque, with the result that it remains stationary.

Now, consider the condition shown in Fig.10.35 (a). The stator and rotor poles are attracting each other. Suppose that the rotor is not stationary, but is rotating clockwise, with such a speed that it turns through one pole-pitch by the time the stator poles interchange their positions, as shown in Fig.10.35 (b). Here, again the stator and rotor poles attract each other. It means that if the rotor poles also shift their positions along with the stator poles, then they will continuously experience a unidirectional torque i.e. clockwise torque, as shown in (Fig.10.35).

Hunting or Surging or Phase Swinging

When a synchronous motor is used for driving a varying load, then a condition known as hunting is produced. Hunting may also be caused if supply frequency is pulsating (as in the case of generators driven by reciprocating internal combustion engines).

We know that when a synchronous motor is loaded (such as punch presses, compressors and pumps etc.), its rotor falls back in phase by the coupling angle α . As load is progressively increased, this angle also increases so as to produce more torque for coping with the increased load. If now, there is sudden decrease in the motor load, the motor is immediately pulled up or advanced to a new value of α corresponding to the new load. But in this process, the rotor overshoots and hence is again pulled back. In this way, the rotor starts oscillating (like a pendulum) about its new position of equilibrium corresponding to the new load. If the time period of these oscillations happens to be equal to the natural time period of the machine then mechanical resonance is set up. The amplitude of these oscillations is built up to a large value and may eventually become so great as to throw the machine out of synchronism. To stop the build-up of these oscillations, dampers or damping grids (also known as squirrel-cage winding) are employed. These dampers cosist of short-circuited Cu bars embedded in the faces of the field poles of the motor (Fig. 10.36). The oscillatory motion of the rotor sets up eddy currents in the dampers which flow in such a way as to suppress these oscillations.

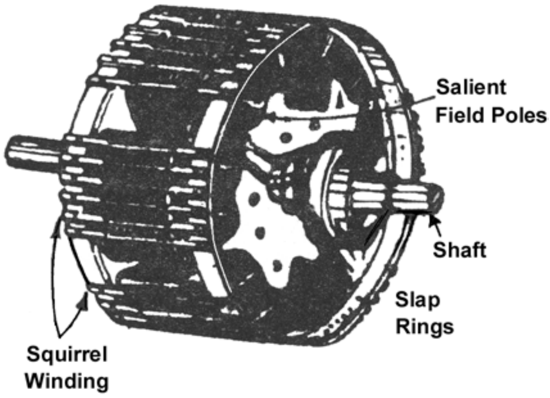


Fig. 10.36.

But it should be clearly understood that dampers do not completely prevent hunting because their operation depends upon the presence of some oscillatory motion. Howover, they serve the additional purpose of making the synchronous motor self-starting.

Methods of Starting

As said above, almost all synchronous motors are equipped with dampers or squirrel cage windings consisting of Cu bars embedded in the pole-shoes and short-circuited at both ends. Such a motor starts readily, acting as an induction motor during the starting period. The procedure is as follows :

The line voltage is applied to the armature (stator) terminals and the field circuit is left unexcited. Motor starts as an induction motor and while at reaches nearly 95% of its synchronous speed, the d.c. field is excited. At that moment the stator and rotor poles get engaged or interlocked with each other and hence pull the motor into synchronism.

However, two points should be noted :

1. At the beginning, when voltage is applied, the rotor is stationary. The rotating field of the stator winding induces a very large e.m.f. in the rotor during the starting period, though the value of this e.m.f. goes on decreasing as the rotor gathers speed. Normally, the field windings are meant for 110-V (or 250 V for large machines) but during starting period there are many thousands of volts induced in them. Hence, the rotor windings have to be highly insulated for withstanding such voltages.
2 When full line voltage is switched on to the armature at rest, a very large current, usually 5 to 7 times the full-load armature current is drawn by the motor. In some cases, this may not be objectionable but where it is, the applied by using auto-transformers (Fig. 10.37). However, the voltage should not be reduced to a very low value because the starting torque of an induction motor varies approximately as the square of the applied voltage. Usually, a value of 50% to 80% of the full-line voltage is satisfactory.

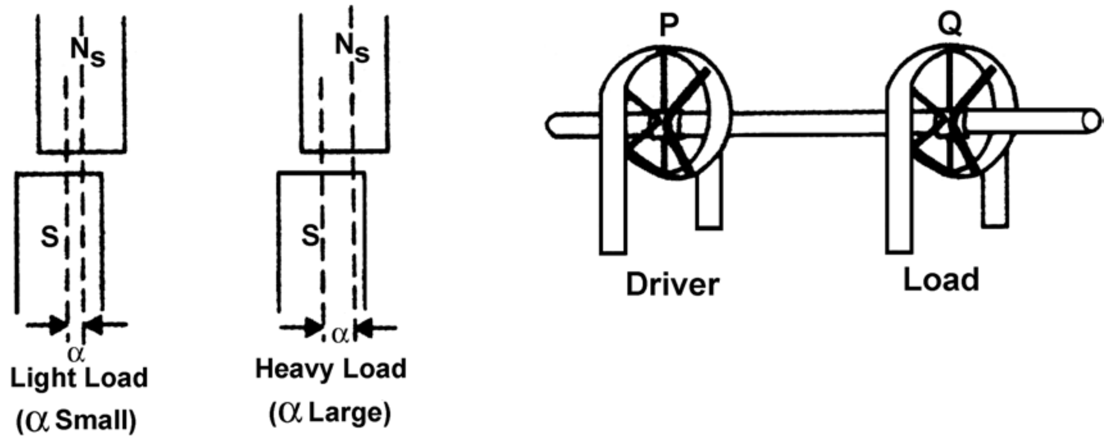


Fig. 10.37.

Auto-transformer connections are shown in (Fig. 10.38). For reducing the supply voltage, the switches S_1 are closed and S_2 are kept open. When the motor has been speeded-up, S_2 are closed and S_1 opened to cut out the transformers.

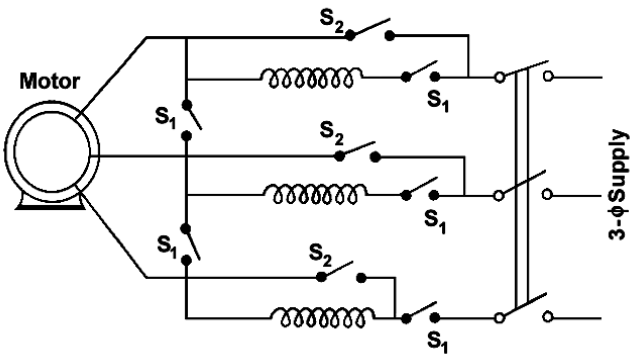


Fig. 10.38.

Motor on Load With Constant Excitation

Before considering as to what goes on inside a synchronous motor, it is worthwhile to refer briefly to the d.c. motors. We have seen that when a d.c. motor is running on a supply of, say, V volts then, on rotating, a back e.m.f. E_b is set up in its armature conductors. The resultant voltage across the armature is ($V-E_b$) and it causes an armature current $I_a = (V-E_b)/R_a$ to flow where R_a is armature circuit resistance. The value of E_b depends, among other factors, on the speed of the rotating armature. The mechanical power developed in armature depends on $E_b I_a$ (E_b and I_a being in opposition to each other).

Similarly, in a synchronous machine, a back e.m.f. E_b is set up in the armature (stator) by the rotor flux which opposes the applied voltage V. This back e.m.f. depends on rotor excitation only (and not on speed, as in d.c. motors). The net voltage in armature (stator) is the vector difference (not arithmetical, as in d.c. motors) of V and E_b. Armature current is obtained by dividing this vector difference of voltage by armature impedance (not resistance as in d.c. machines).

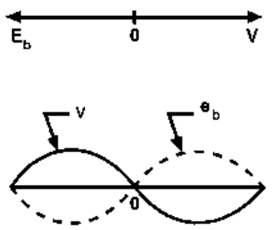


Fig. 10.39.

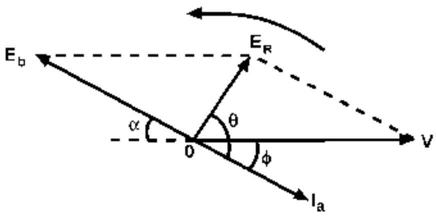


Fig. 10.40.

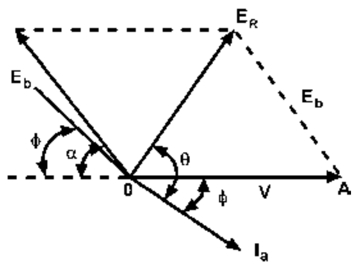


Fig. 10.41.

Fig.10.39, shows the condition when the motor (properly synchronized to the supply) is running on no-load and has no losses, and is having field excitation which makes $E_b = V$. It is seen that vector difference of E_b and V is zero and so is the armature current. Motor intake is zero, as there is neither load nor losses to be met by it. In other words, the motor just floats.

If motor is on no-load, but it has losses, then the vector for E_b falls back (vectors are rotating anti-clockwise) by a certain small angle α (Fig. 10.40), so that a resultant voltage E_R and hence current I_a is brought into existence, which supplies losses.

If, now, the motor is loaded, then its rotor will further fall back in phase by a greater value of angle α-called the load angle or coupling angle (corresponding to the twist in the shaft of the pulleys). The resultant voltage E_R is increased and motor draws an increased armature current (Fig. 10.41), though at a slightly decreased power factor.

Effect of Increased Load with Constant Excitation

We will study the effect of increased load on a synchronous motor under conditions of normal, under and over-excitation (ignoring the effects of armature reaction). With normal excitation, $E_b = V$, with under excitation, $E_b < V$ and with over-excitation, $E_b > V$. Whatever the value of excitation, it would be kept constant during out discussion. It would also be assumed that R_a is negligible as compared to X_s so that phase angle between E_R and I_a i.e. $\theta = 90^o$.

i. Normal Excitation

Fig. 10.42 (a) shows the condition when motor is running with light load so that (i) torque angle α_1 is small (ii) so E_{R1} is small (iii) hence I_{a1} is small and (iv) ϕ_1 is small so that cos ϕ_1 is large.

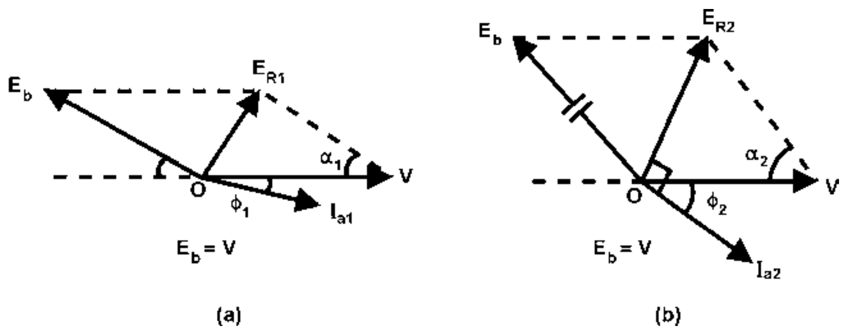


Fig. 10.42.

Now, suppose that load on the motor is increased as shown in Fig.10.42 (b) For meeting this extra load; motor must develop more torque by drawing more armature current. Unlike a d.c. motor, a synchronous motor cannot increase its I_a by decreasing its speed and hence E_b because both are constant in its case. What actually happens is as under :

1. rotor falls back in phase i.e. load angle increases to α_2 as shown in Fig.10.42 (b).
2. the resultant voltage in armature is increased considerably to new value E_{R2}.
3. as a result, I_{a1} increases to I_{a2}, thereby increasing the torque developed by the motor.
4. ϕ_1 increases to ϕ_2, so that power factor decreases from cos ϕ_1 to the new value cos ϕ_2.

Since increases in I_a is much greater that the slight decrease in power factor, the torque developed by the motor is increased (on the whole) to a new value sufficient to meet the extra load put on the motor. It will be seen that essentially it is increasing it is by increasing its I_a that the motor is able to carry the extra load put on it.

A phase summary of the effect of increased load on a synchronous motor at normal excitation is shown in (Fig. 10.43). It is seen that there is a comparatively much greater increase in I_a than in ϕ.

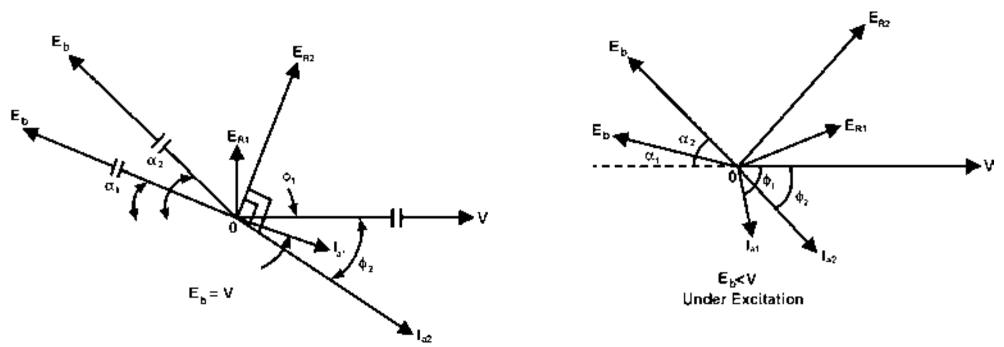


Fig. 10.43.

ii. Under-excitation

As shown in Fig. 10.43 (b), with a small load and hence, small torque angle α_1, I_{a1} lags behind V by a large phase angle ϕ_1 which means poor power factor. Unlike normal excitation, a much larger armature current must flow for developing the same power because of poor power factor. That is why I_{a1} of Fig. 10.43 (b) is larger than I_{a1} of Fig. 10.42 (a).

As load increases, E_{R1} increases to E_{R2}, consequently I_{a1} increases to I_{a2} and p.f. angle decreases from cos ϕ_1 to cos ϕ_2. Due to increase both in I_a and p.f., power generated by the armature increases to meet the increased load. As seen, in this case, change in power factor is more than the change in I_a.

iii. Over-excitation

When running on light load, α_1 is small but I_{a1} is comparatively larger and leads V by a larger angle ϕ_1. Like the under-excited motor, as more load is applied, the power factor improves and approaches unity. The armature current also increases thereby producing the necessary increased armature power to meet the increased applied load (Fig. 10.44). However, it should be noted that in this case, power factor angle ϕ decreases (or p.f. increases) at a faster rate than the armature current thereby producing the necessary increased power to meet the increased load applied to the motor.

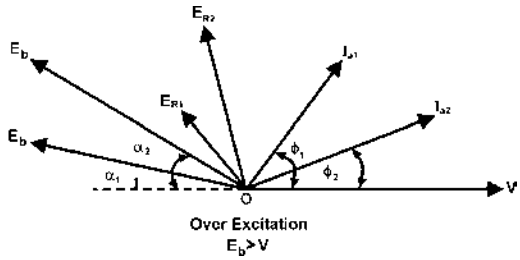


Fig. 10.44.

Summary

The main regarding the above three cases can be summarized as under :

1. As load on the motor increases, I_a increases regardless of excitation.
2. For under-and over-excited motors, p.f. tends to approach unity with increase in load.
3. Both with under-and over-excitation, change in p.f. is greater than in I_a with increase in load.
4. With normal excitation, when load is increased change in I_a is greater than in p.f. which tends to become increasingly lagging.

Effects of Changing Excitation of Constant load

As shown in (Fig. 10.45), suppose a synchronous motor is operating with normal excitation (E_b=V) at unity p.f. with a given load. If R_a is negligible as compared to X_s , then I_a lags E_R by 90° and is in phase with V because p.f. is unity. The armature is drawing a power of V. I_a per phase which is enough to meet the mechanical load on the motor. Now, let us discuss the effect of decreasing or increasing the field excitation when the load applied to the motor remains constant.

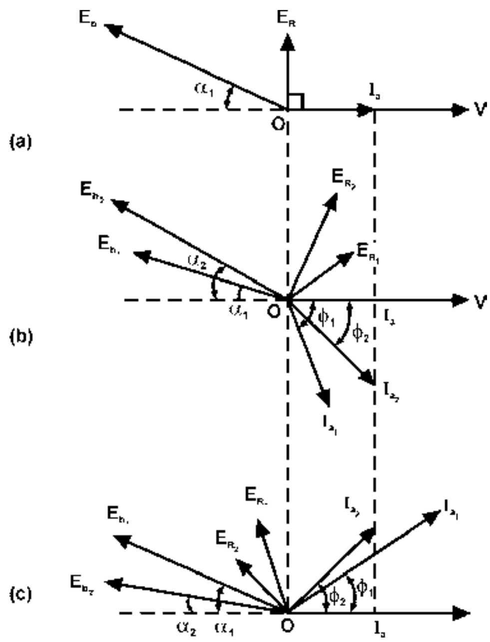


Fig. 10.45.

(a) Excitation Decreased

As shown in Fig.10.45 (b), suppose due to decrease in excitation, back e.m.f. is reduced to E_{b1} at the same load angle α_1. The resultant voltage E_{R1} causes a lagging armature current I_{a1} to flow. Even though I_{a1} is larger than I_a in magnitude it is incapable of producing necessary power VI_a for carrying the constant load because I_{a1} cos ϕ_1 component is less than I_a so that $VI_{a1} \cos \phi_1 < VI_a$.

Hence, it becomes necessary for load angle to increase from α_1 to α_2. It increases back e.m.f. from E_{b1} to E_{b2} which, in turn, increases resultant voltage from E_{R1} to E_{R2}. Consequently, armature current increases to I_{a2} whose in-phase component produces enough power ($VI_{a2} \cos \phi_2$) to meet the constant load on the motor.

(b) Excitation Increased

The effect of increasing field excitation is shown in Fig.10.45 (c) where increased E_{b1} is shown at the original load angle α_1. The resultant voltage E_{R1} causes a leading current I_{a1} whose in-phase component is larger than I_a. Hence, armature develops more power than the load on the motor. Accordingly, load angle decreases from α_1 and α_2 which decreases resultant voltage from E_{R1} to E_{R2}. Consequently, armature current decreases from I_{a1} to $I_{a2} \cos \phi_2 = I_a$. In that case, armature develops poser sufficient to carry the constant load on the motor.

Hence, we find that variations in the excitation of a synchronous motor running with a given load produce variations in its load angle only.

Different Torques of a Synchronous Motor

Various torques associated with a synchronous motor are as follows :

1. starting torque
2. running torque
3. pull-in torque and
4. pull-out torque

1. Starting Torque

It is the torque (or turning effort) developed by the motor when full voltage is applied to its stator (armature) winding. It is also sometimes called breakaway torque. Its value may be as low as 10% as in the case of centrifugal pumps and as high as 200 to 250% of full-load torque as in the case of loaded reciprocating two-cylinder compressors.

2. Running Torque

As its name indicates, it is the torque developed by the motor under running conditions. It is determined by the horse-power and speed of the driven machine. The peak horsepower determines the maximum torque that would be required by the driven machine. The motor must have a breakdown or a maximum running torque greater than this value in order to avoid stalling.

3. Pull-in Torque

A synchronous motor is started as induction motor till it urns 2 to 5% below the synchronous speed. Afterwards, excitation is switched on and the rotor pulls into step with the synchronously-rotating stator field. The amount of torque at which the motor will pull into step is called the pull-in torque.

4. Pull-out Torque

The maximum torque which the motor can develop without pulling out of step or synchronism is called the pull-out torque.

Normally, when load on the motor is increased, its rotor progressively tends to fall back in phase by some angle (called load angle) behind the synchronously-revolving stator magnetic field though it keeps running synchronously. Motor develops maximum torque when its rotor is retarded by an angle of 90° (or in other words, it has shifted backward by a distance equal to half the distance between adjacent poles). Any further increase in load will cause the motor to pull out of step (or synchronism) and stop.

Comparison Between Synchronous and Induction Motors

1. For a given frequency, the synchronous motor runs at a constant average speed whatever the load, while the speed of an induction motor falls somewhat with increase in load.
2. The synchronous motor can be operated over a wide range of power factors, both lagging and leading, but induction motor always runs with a lagging p.f. which may become very low at light loads.
3. A synchronous motor is inherently not self-starting.
4. The changes in applied voltage do not affect synchronous motor torque as much as they affect the induction motor torque. The breakdown torque of a synchronous motor varies approximately as the first power of applied voltage that of an induction motor depends on the square of this voltage.
5. A d.c excitation is required by synchronous motor but not by induction motor.
6. Synchronous motors are usually more costly and complicated than induction motors, but they are particularly attractive for low-speed drives (below 300 r.p.m.) because their power factor can always be adjusted to 1.0 and their efficiency is high. However, induction motors are excellent for speeds above 600 r.p.m.
7. Synchronous motors can be run at ultra-low speeds by using high power electronic converters which generate very low frequencies. Such motors of 10 MW range are used for driving crushers, rotary kilns and variable-speed ball mills etc.

Synchronous Motor Applications

Synchronous motors find extensive application for the following classes of service :

1. Power factor correction
2. Constant-speed, constant-load drives
3. Voltage regulation

1. Power factor correction

Overexcited synchronous motors having leading power factor are widely used for improving power factor of those power systems which employ a large number of induction motors and other devices having lagging p.f. such as welders and fluorescent lights etc.

2. Constant-speed applications

Because of their high efficiency and high-speed, synchronous motors (above 600 r.p.m.) are well-suited for loads constant speed is required such as centrifugal pumps, belt-driven reciprocating compressors, blowers, line shafts, rubber and paper mills etc.

Low-speed synchronous motors (below 600 r.p.m.) are used for drives such as centrifugal and screw-type pumps, ball and tube mills, vacuum pumps, chippers and metal rolling mills etc.

3. Voltage regulation

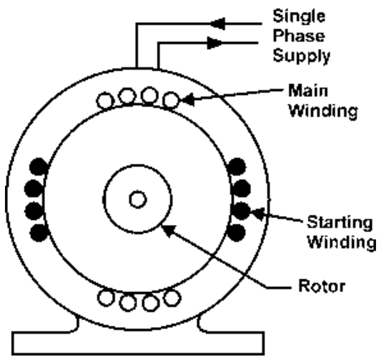
The voltage at the end of along transmission line varies greatly especially when large inductive loads are present. When an inductive load is disconnected suddenly, voltage tends to rises considerably above is normal value because of the line capacitance. By installing a synchronous motor with a field regulator (for varying its excitation), this voltage rise can be controlled.

When line voltage decreases due to inductive load, motor excitation is increased thereby raising its p.f. which compensates for the line drop. If, on the other hand, line voltage rise due to line capacitive effect, motor excitation is decreased, thereby making its p.f. lagging which helps to maintain the line voltage at its normal value.

Types of Single-phase Motors

As the name shows, such motors are designed to operate from a single-phase supply and are manufactured in a large number of types topper form a wide variety of useful services in home, offices, factories, workshops and in business establishments. These motors are classified according to their construction and method of starting :

1. Induction motors. These may be further sub-divided into split-phase, capacitor and shaded-pole type.
2. Repulsion type Motors or Single-phase Wound-rotor Motors.
3. A.C. Series Motors
4. Universal Motors
5. Unexcited Synchronous Motors (like Reluctance Motor and Hysteresis Motor).



Single-phase Induction Motor

Like 3-phase motor, a single-phase motor also consists of

i. A stator carries single-phase winding and
ii. A squirrel-cage type of rotor.

However, there is one very fundamental difference between the two : whereas a 3-phase motor is self-starting, a single-phase motor is nonself-starting. This is due to the fact that whereas the stator winding of a 3-phase motor produces a rotating (or revolving) flux, the single-phase winding produces merely a pulsating or alternating flux. A synchronously-rotating flux can be produced only by either a 2-phase or 3-phase stator winding when energised from a D-phase or 3-phase supply respectively.

An alternating flux acting on a stationary squirrel-cage rotor cannot produce rotation (only a rotating flux can).

However, if the rotor of a single-phase motor is given an initial start by hand or otherwise in either direction, then immediately a torque arises and the motor accelerates to its final speed provided it is not heavily loaded.

There are many methods to make a single-phase motor self-starting and single-phase induction motor are classified and named according to the method used as detailed below:

a. ***Split-phase motors :*** These motors are started by two -phase motor action with the help of an additional winding known as starting winding.
b. ***Capacitor motors :*** These are also started by the two -phase motor action by using a capacitor.
c. ***Shaded-pole motors :*** These are started by using shaded-pole principle.

Split-phase Induction Motor

As shown in Fig.10.46 (a), single-phase motor is temporarily converted into a 2-phase motor by providing an extra winding on the stator in addition to the main or running winding. The circuit connections are shown in Fig.10.46 (b). By

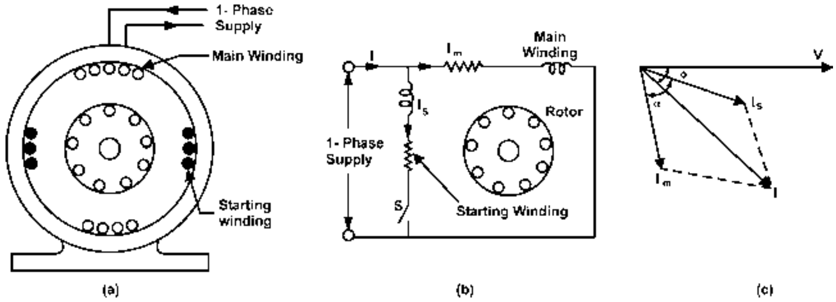


Fig. 10.46.

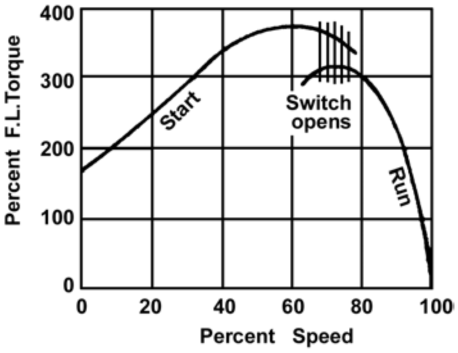


Fig. 10.47.

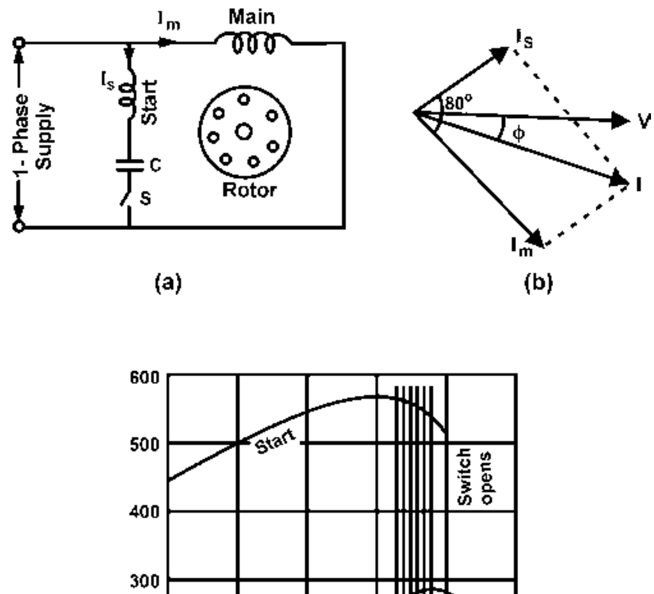
making starting winding highly resistive and main winding highly reactive, the phase difference between the current drawn by them can be made sufficiently large (the ideal value being 90°). The motor behaves like a two-phase motor for starting purposes [Fig.23-2 (c)]. The two currents produce a revolving flux and hence make the motor self-starting. The starting torque $T_{st} = k\, I_s I_m \sin \alpha$ where k is a constant governed by motor design parameters.

A centrifugal switch S is connected in series with the starting winding and is located outside the motor. Its function is to automatically disconnect the starting winding from the supply when the motor reaches 70 to 80 per cent of its full-load speed. Typical torque/speed characteristic for such a motor is shown in (Fig.10.47). As seen, the starting torque is 150 to 200 per cent of the full-load torque with a starting current of 6 to 8 times the full-load current.

The split-phase motor is widely used for such applications as washing machines, oil burners, blowers, machines, wood working tools, bottle washers, churns, buffing machines, grinders and machine tools etc. It is generally available in the 50-250 W range.

Capacitor-start Induction-run Motors

These motors have a higher starting torque because in their case angle α between currents I_s and I_m is large. The angle $\alpha$is increased by connecting a capacitor in series with the starting winding as shown in Fig. 10.48 (a). Usually, the capacitor is mounted on top of the motor frame and is generally an electrolytic capacitor. As before, the centrifugal switch cuts off both the starting winding and the capacitor when motor runs up to nearly 75 percent of its full-load speed. As seen from Fig. 10.48 (b), the current I_s drawn by starting winding leads the voltage whereas the current I_m in the main winding leads the voltage whereas the current I_m in the main winding, as before, lags V. In this way, value of α is increased to about 80^0 which increases the starting torque to twice that developed by a standard split-phase induction motor. Such motors have starting torques as high as 450 per cent of the full-load value. Typical performance curve of such a motor is shown in Fig. 10.48 (c). They are usually manufactured in the 100-500 W range.



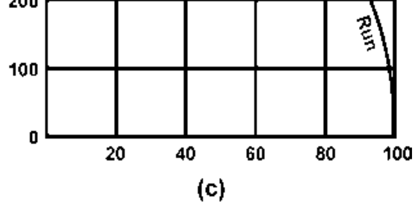


Fig. 10.48.

The capacitor-start motors are very popular for heavy-duty general-purpose application requiring high starting torques. These are generally used for such applications as compressors, jet pumps, farm and home-workshop tools, swimming pool pumps and conveyors etc.

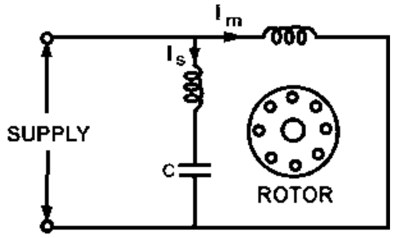


Fig. 10.49.

Capacitor-start-and-run Motors

These are similar to the capacitor-start induction-run motors except that the starting winding and capacitor are connected in the circuit at all times. In other words, the capacitor remains in the circuit permanently as shown in (Fig.10.49). That is why such motors are also known as permanent split capacitor motors. Obviously, there is no need for a centrifugal switch. The advantages of leaving the capacitor permanently in circuit are

i improvement of overload capacity of the motor
ii a higher p.f.
iii higher efficiency and
iv quieter running of the motor.

Such motors have a comparatively low starting torque which is about 50 to 100 percent of the rated torque.

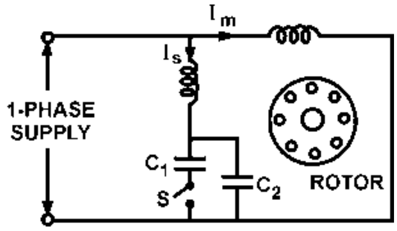


Fig. 10.50.

Such motors which start and run with one value of capacitance in the circuit are called single-value capacitor-run motors. Others which start with a high value of capacitance but run with a low value of capacitance are known as two-value capacitor-run motors (Fig. 10.50).

Such motors find applications in refrigerators, compressors, stokers, ceiling fans and blowers etc. In the smaller sizes, they often compete with shaded-pole motors. Generally, they are not suitable for belted applications or for any other continuous-duty application requiring large locked-rotor torque.

Shaded-pole Single-phase Motor

In such motor, the necessary phase-splitting is produced by induction. These motors have salient poles on the stator and a squirrel-cage type rotor (Fig. 10.51) shows a four-pole motor with the field poles connected in series for alternate polarity. One pole of such a motor is shown separately in (Fig. 10.52). The laminated pole has a slot cut across the laminations approximately one-third distance from one edge. Around the small part of the pole is placed a short-circuited Cu soil known as shading coil. This part of the pole is known as shaded part and the other as unshadded part. When an alternating current is passed through the exciting (or field) winding surrounding the whole pole, the axis of the pole shifts from the unshaded part a to the shaded part b. This shifting of the magnetic axis is, in effect, equivalent to the actual physical movement of the pole. Hence, the rotor starts rotor starts rotating in the direction of this shift i.e. from unshaded part to the shaded part.

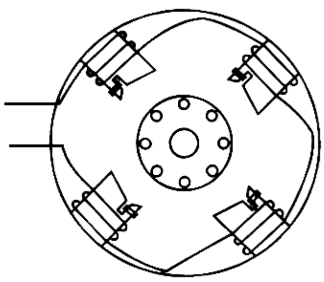


Fig. 10.51.

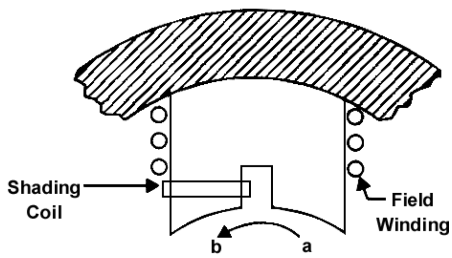


Fig. 10.52.

Let us now discuss why shifting of the magnetic axis takes place. It is helpful to remember that the shading coil is highly inductive. When the alternating current through exciting coil tends to increase, it induces a current in the shading coil by transformer action in such a direction as to oppose its growth. Hence, flux desity decreases in the shaded part when exciting current increases. However, flux density increases in the shaded part when exciting current starts decreasing (it being assumed that exciting current is sinusoidal)

In Fig 10.53 (a) exciting current is rapidly increasing along OA (shown by dots). This will produce an e.m.f. in the shading coil. As shading coil is of low resistance, a large current will be set up in such a direction (according to Len'z law) as to oppose the rise of exciting current (which is responsible for its production). Hence, the flux mostly shifts to the unshaded part and the magnetic axis lies along the middle of this part i.e. along NC.

Next, consider the moment when exciting current is near its peak value i.e. from point A to B [Fig 10.53 (b)]. Here, the change in exciting current is very slow. Hence, practically no voltage and, therefore, no current is induced in the shading coil. The flux produced by exciting current is at its maximum value and is uniformly distributed over the pole face. So the magnetic axis shifts to the centre of the pole i.e. along positions ND.

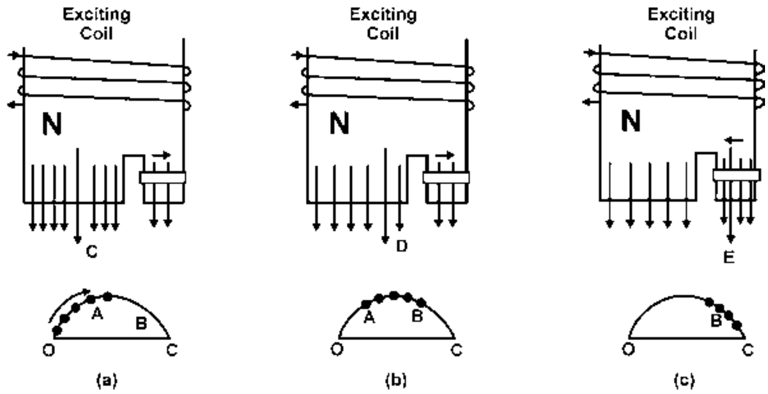


Fig. 10.53.

Fig. 10.53 (c) represents the condition when the exciting current is rapidly decreasing from B to C. This again sets up induced current in the shading coil by transformer action. This current will flow in such a direction as to oppose this decrease in exciting current, with the result that the flux is strengthened in the shaded part of the pole. Consequently, the magnetic axis shifts to the middle part of the shaded pole i.e. along NE.

From the above discussion we find that during the positive half-cycle of the exciting current, a N-pole shifts along the pole from the unshaded to the shaded part. During the next negative half-cycle of the exciting current, a S-pole trails along. The effect is as if a number of real poles were actually sweeping across the space from left to right.

Shaded pole motors are built commercially in very small sizes, varying approximately from 1/250 h.p. (3W) to 1/6 h.p. (125W). Although such motor are simple in construction, extremely rugged, reliable and cheap, they suffer from the disadvantages of (i) low starting torque (ii) very little overload capacity and (iii) low efficiency. Efficiencies vary from 5% (for tiny sizes) to 35 (for higher ratings). Because of its low starting torque, the shaded-pole motor is generally used for small fans, toys, instruments, hair dryers, ventilators, circulators and electric clocks. It is also frequently used for such devices as churns, phonograph turntables and advertising displays etc. The direction of rotation of this motor cannot be changed, because it is fixed by the position of copper rings.

Repulsion Type Motors

These can be divided into the following four distinct categories :

1. **Repulsion Motor.** It consists of (a) one stator winding (b) one rotor which is wound like a d.c. armature (c) commutator and (d) a set of brushes, which are short-circuited and remain in contact with the commutator at all times. It operates continuously on the 'repulsion' principle. No short-circuiting mechanism is required for this type.
2. **Compensated Repulsion Motor.** It is identical with repulsion motor in all respects, except that (a) it carries an additional stator winding, called compensating winding (b) there is another set of two brushes which are placed midway between the usual short-circuited brush set. The compensating winding and this added set are connected in series.
3. **Repulsion-start Induction-run Motor.** This motor starts as a repulsion motor, but normally runs as an induction motor, but normally runs as an induction motor, with constant speed characteristics. It consists of (a) one stator winding (b) one rotor which is similar to the wire-wound d.c. armature (c) a commutator and (d) a centrifugal mechanism which short circuits the commutator bars all the way round (with the help of a short-circuiting necklace) when the motor has reached nearly 75 per cent of full speed.
4. **Repulsion - start Induction - run Motor.** This motor starts as a repulsion motor, but normally runs as an induction motor, with constant speed characteristics. It consists of (a) one stator winding (b) one rotor which is similar to the wire-wound d.c. armature (c) a commutator and (d) a centrifugal mechanism which short-circuits the commutator bars all the way round (with the help of a short-circuiting necklace) when the motor has reached nearly 75 per cent of full speed.

It may be noted that repulsion motors have excellent characteristics, but are expensive and require more attention and maintenance than single-phase motors. Hence, they are being replaced by two-value capacitor motors for nearly all applications.

Repulsion Motor

Constructionally, it consists of the following :

1. Stator winding of the distributed non-salient pole type housed in the slots of a smooth-cored stator (just as in the case of split-phase motors). The stator is generally wound for four, six or eight poles.
2. A rotor (slotted core type) carrying a distributed winding (either lap or wave) which is connected to the commutator. The rotor is identical in construction to the d.c. armature.
3. A commutator, which may be one of the two types : an axial commutator with bars parallel to the shaft or a radial or vertical commutator having radial bars on which brushes press horizontally.
4. Carbon brushes (fitted in brush holders) which ride against the commutator and are used for conducting current through the armature (i.e. rotor) winding.

Repulsion Principle

To understand how torque is developed by the repulsion principle, consider (Fig. 10.54) which shows a 2-pole salient pole motor with the magnetic axis vertical. For easy understanding, the stator winding has been shown with concentrated salient-pole construction (actually it is of distributed non-salient type). The basic functioning of the machine will be the same with either type of construction. As mentioned before, the armature is of standard d.c. construction with commutator and brushes (which are short-circuited with a low-resistance jumper).

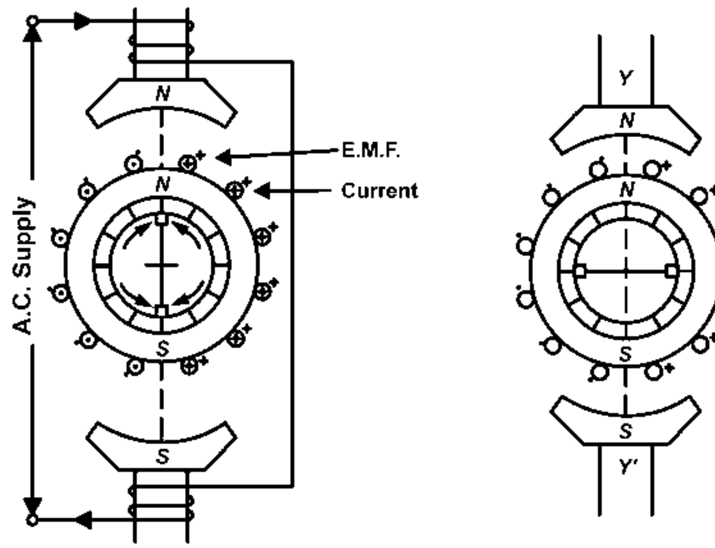


Fig. 10.54.

Suppose that the direction of flow of the alternating current in the exciting or field (stator) winding is such that it creates a N-pole at the top and a S-pole at the bottom. The alternating flux produced by the stator winding will induce e.m.f. in the armature conductors by transformer action. The direction of the induced e.m.f. can be found by using Lenz's law and is as shown in Fig. 10.54 (a). However, the direction of the induced currents in the armature conductors will depend on the positions of the short-circuited brushes. If brush axis is colinear with magnetic axis of the main poles, the directions of the induced currents (shown by dots and arrows) will be as indicated in Fig 10.54 (a). As a result, the armature will become an electromagnet with a N-pole and with a S-pole at the bottom, directly over the main S-pole. Because of this face-to-face positioning of the main and induced magnetic poles, no torque will be developed. The two forces of repulsion on top and bottom act along YY' in direct opposition to each other.

If brushes are shifted through 90^o to the position shown in Fig 10.54 (b) so that the brush axis is at right angles to the magnetic axis of the main poles, the directions of the induced voltages at any time in the respective armature conductors are exactly the same as they were for the brush position of Fig 10.54 (a). However, with brush positions of Fig. 10.54 (b), the voltages induced in the armature conductors in each path between the brush terminals will neutralize each other, hence there will be no net voltage across brushes to produce armature current. If there is no armature current, obviously, no torque will be developed.

If the brushes are set in position shown in (Fig.10.55), so that the brush axis is neither in line with nor 90^o from the magnetic axis YY' of the main poles, a net voltage will be induced between the brush terminals which will produce armature current. The armature will again act as an electromagnet and develop its own N-and S-poles which, in this case, will not directly face the respective main poles. As shown in Fig. 10.55 (a), the armature poles lie along AA' making an angle of α with YY'.

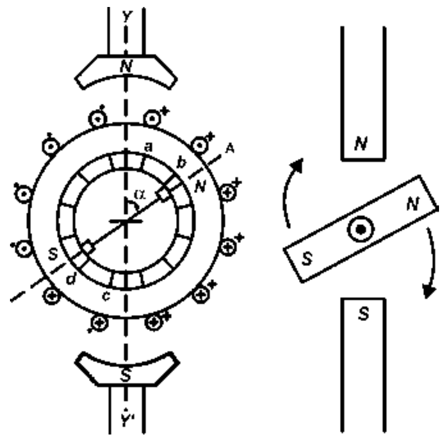


Fig. 10.55.

Hence, rotor N-pole will be repelled by the main N-pole will be repelled by the main N-pole and the rotor S-pole will, similarly, be repelled by the main S-pole . Consequently, the rotor will rotate in clockwise direction (Fig. 10.55 (b)]. Since the forces are those of repulsion, it is appropriate to call the motor as repulsion motor.

It should be noted that if the brushes are shifted counter-clockwise from YY', rotation will also be counter-clockwise. Obviously, direction of rotation of the motor is determined by the position of brushes with respect will respect to the main magnetic axis.

It is worth noting that the value of starting torque developed by such a motor will depends on the amount of brush-shift whereas direction of rotation will depend on the direction of shift Fig. 10.56 (a). Maximum starting torque is developed at some position where brush axis makes, an angle lying between 0° and 45° with the magnetic axis of main poles. Motor speed can also be controlled by means of brush shift. Variation of starting torque of a repulsion motor with brush-shift is shown in Fig.10.56 (b).

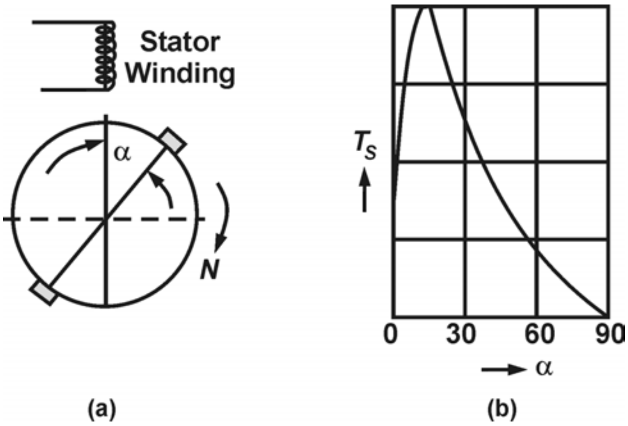


Fig. 10.56.

A straight repulsion type motor has high starting torque (about 350 per cent) and moderate starting current (about 3 to 4 times full-load value).

Principal shortcomings of such a motor are :
1. speed varies with changing load, becoming dangerously high at no load.
2. low power factor, except at high speeds.
3. tendency to spark at brushes.

Compensated Repulsion Motor
It is a modified form of the straight repulsion motor discussed above, it has an additional stator winding, called compensating winding whose purpose is (i) to improve power-factor and (ii) to provide better speed regulation. This winding is much smaller than the stator winding and is usually wound in the inner slots of each main pole and is connected in series with the armature (Fig. 10.57) though an additional set of brushes placed mid-way between the usual short-circuited brushes.

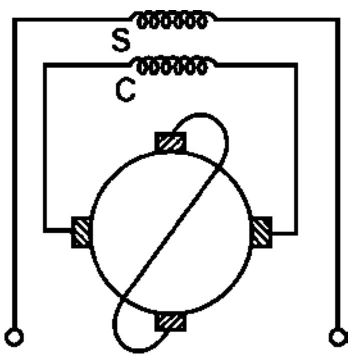


Fig. 10.57.

Repulsion-star Induction-run Motor
As mentioned earlier, this motor starts as an ordinary repulsion motor, but after it reaches about 75 per cent of its full speed, centrifugal short-circuiting device short-circuits its commutator. From then on, it runs as an induction motor, with a short-circuited squirrel-cage rotor. After the commutator is short-circuited, brushes do not carry any current, hence they may also be lifted from the commutator, in order to avoid unnecessary wear and tear and friction losses.

Repulsion-star motors are of two different designs :

1. Brush-lifting type in which the brushes are automatically lifted from the commutator when it is short-circuited. These motors generally employ radial form of commutator and are built both in small and large sizes.
2. Brush-riding type in which brushes ride on the commutator at all times. These motors use axial form of commutator and are always built in small sizes.

The starting torque of such a motor is in excess of 350 per cent with moderate starting current. It is particularly useful where starting period is of comparatively long duration, because of high inertia loads. Applications of such motors include machine tools, commercial refrigerators, compressors, pumps, hoists, floor-polishing and grinding devices etc.

Repulsion Induction Motor

In the field of repulsion motor, this type is becoming very popular, because of its good all-round characteristics which are comparable to those of a compound d.c. motor. It is particularly suitable for those applications where the load can be removed entirely by de-clutching or by a loose pulley.

This motor is a combination of the repulsion and induction types and is sometimes referred to as squirrel-cage repulsion motor. It possesses the desirable characteristics of a repulsion motor and the constant-speed characteristics of an induction motor.

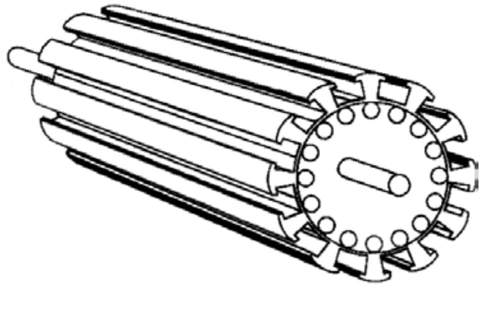


Fig. 10.58.

It has the usual stator winding as in all repulsion motors. But there are two separate and independent windings in the rotor (Fig. 10.58).

i. A squirrel-cage winding and
ii. Commutated winding similar to that of a d.c. armature.

Both these windings function during the entire period of operation of the motor. The commutated winding lies in the outer slots while squirrel-cage winding is located in the inner slots. At start, the commutated winding supplies most of the torque, the squirrel-cage winding being practically inactive because of its high reactance. When the rotor accelerates, the squirrel-cage winding takes up a larger portion of the load.

The brushes are short-circuited and ride on the commutator continuously. One of the advantages of this motor is that it requires no centrifugal short-circuiting mechanism. Sometimes such motors are also made with compensating winding for improving the power factor.

As shown in (Fig. 10.59), its starting torque is high, being in excess of 300 per cent. Moreover, it has a fairly constant speed regulation. Its field of application includes house-hold refrigerators, garage air pumps, petrol pumps, compressors, machine tools, mixing machines, lifts and hoists etc.

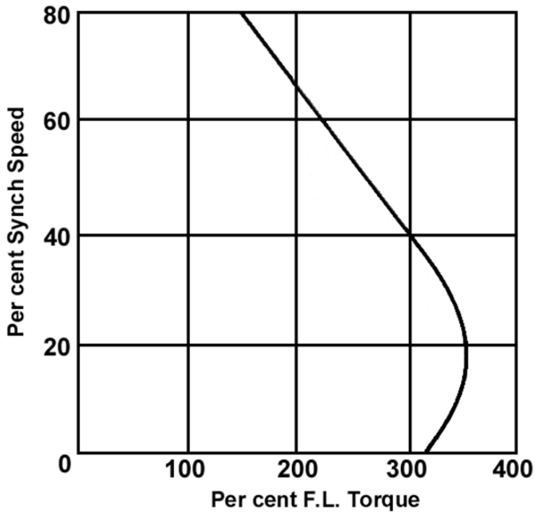


Fig. 10.59.

These motors can be reversed by the usual brush-shifting arrangement.

A.C. Series Motor

An alternating-current series motor is a single-phase motor, but is not an induction or synchronous motor. It resembles a d.c. motor in that it has brushes and a commutator. The a.c. series motor will operate on either a.c. or d.c. circuits. It will be recalled that the direction of rotation of a d.c. series motor is independent of the polarity of the applied voltage, provided the field and armature connections remain unchanged. Hence, if a d.c. series motor is connected to an a.c. source, a torque will be developed which tends to rotate the armature in one direction. However, a d.c. series motor does not operate satisfactorily from an a.c. supply for the following reasons :

1. The alternating flux sets up large eddy-current and hysteresis losses in the unlaminated portions of the magnetic circuit and causes excessive heating and reduced efficiency.
2. The self-induction of the field and armature windings causes a low power factor.
3. The alternating field flux establishes large currents in the coils, which are short-circuited by the brushes; this action causes excessive sparking at the commutator.

To design a series motor for satisfactory operation on a.c., the following changes are made:

1. The eddy-current losses are reduced by laminating the field poles, fame and armature.
2. Hysteresis losses are minimized by using high-permeability, transformer-type, silicon-steel laminations.
3. The reactance of the field windings is kept satisfactorily low by using shallow pole pieces, few turns of wire, low frequency (usually 25 cycles for large motors), low flux density, and low reluctance (a short airgap).
4. The reactance of the armature is reduced by using a compensating winding embedded in the pole pieces. If the compensating winding is connected in series with the armature, as shown in (Fig. 10.60), the armature is conductively compensated.

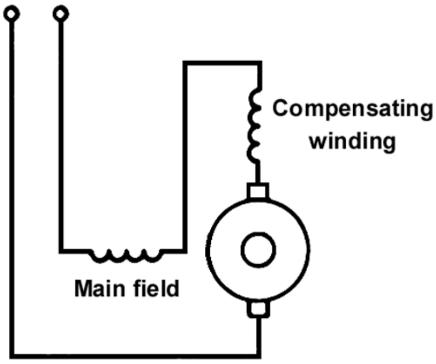


Fig. 10.60.

   If the compensating winding is designed as shown in (Fig. 10.61), the armature is inductively compensated. If the motor is designed for operation on both d.c. and a.c. circuits, the compensating winding is connected in series with the armature. The axis of the compensating winding is displaced from the main field axis by an angle of 90°. This arrangement is similar to the compensating winding used in some d.c. motors and generators to overcome armature reaction. The compensating winding establishes a counter magnetomotive force, neutralizing the effect of the armature magnetomotive force, preventing distortion of the main field flux, and reducing the armature reactance. The inductively compensated armature reactance. The inductively compensated armature acts like the primary of a transformer, the secondary of which is the shorted compensating winding. The shorted secondary receives an induced voltage by the action of the alternating armature flux, and the resulting current flowing through the turns of the compensating winding establishes the opposing magnetomotive force, neutralizing the armature reactance.

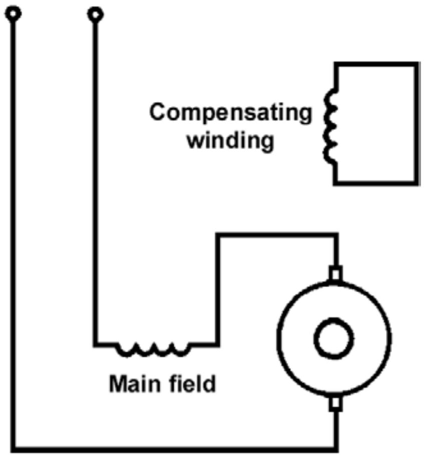


Fig. 10.61.

5. Sparking at the commutator is reduced by the use of preventive leads P_1, P_2, P_3, and so forth, as shown in (Fig. 10.62), where a ring armature is shown for simplicity. When coils at A and B are shorted by the brushes, the induced current is limited by the relatively high resistance of the leads. Sparking at the brushes is also reduced by using armature coils having only a single turn and multipolar fields. High torque is obtained by having a large number of armature conductors and a large-diameter armature. Thus, the commutator has a large number of very thin commutator bars and the armature voltage is limited to about 250 volts.

Fractional horsepower a.c. series motors are called universal motors. They do not have compensating windings or preventive leads. They are used extensively to operate fans and portable tools, such as drills, grinders, and saws.

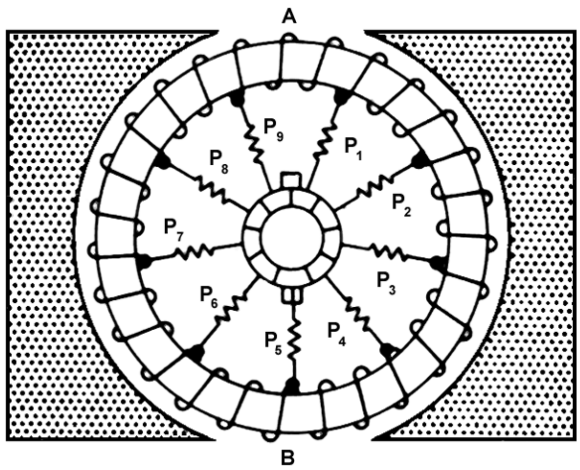


Fig. 10.62.

Universal Motor

A universal motor is defined as a motor which may be operated either on direct or single-phase a.c. supply at approximately the same speed and output.

In fact, it is a smaller version (5 to 150W) of the a.c. series motor. Being a series-wound motor, it has high starting torque and a variable speed characteristic. It turns at dangerously high speed on no-load. That is why such motors are usually built into the device they drive.

Operation

Such motors develop unidirectional torque, regardless of wheather they operate on d.c. or a.c supply. The production of unidirectional torque, when the motor runs on a.c. supply can be easily understood from (Fig. 10.63). The motor works on the same principle as a d.c. motor i.e. force between the main pole flux and the current - carrying armature conductors. This is true regardless of whether the current is alternating or direct (Fig. 10.64).

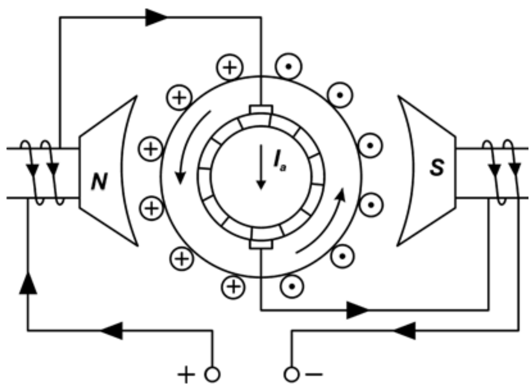


Fig. 10.63.

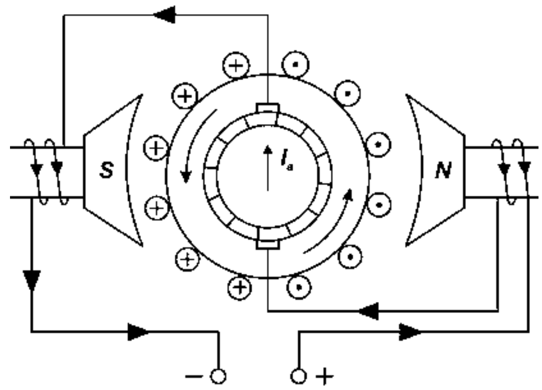


Fig. 10.64.

Applications

Universal, motors are used in vacuum cleaners where actual motor speed is the load speed. Other applications, where motor speed is reduced by a gear train are: drink and food mixers, portable drills and domestic sewing machine etc.

Reversal of Rotation

The concentrated - pole (or salient-pole) type universal motor may be reversed by reversing the flow of current through either the armature or field windings. The usual method is to interchange the leads on the brush holders. (Fig. 10.65).

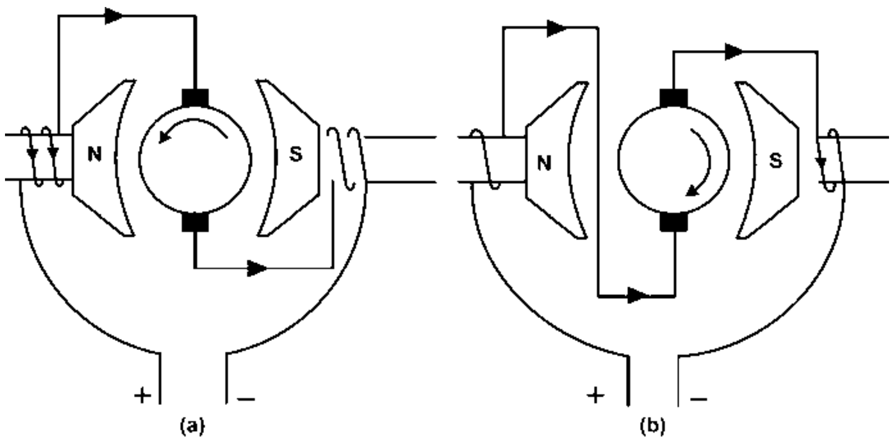


Fig. 10.65.

Speed Control of Universal Motors

The following methods are usually employed for speed - control purposes:

i. Resistance Method

As shown in (Fig.10.66), the motor speed is controlled by connecting a variable resistance R in series with the motor. This method is employed for motors used in sewing machines. The amount of resistance in the circuit is changed by means of a foot-pedal.

ii. Tapping -field Method

In this method, a field pole is tapped at various points and speed is controlled by varying the field strength (Fig. 10.67). For this purpose, either of the following two arrangements may be used:-

a. The field pole is wound in various sections with different sizes of wire and taps are brought out from each section.

b. Nichrome resistance wire is wound over one field pole and taps are brought out from this wire.

iii. Centrifugal Mechanism

Universal motors, particularly those used for home food and drink mixers, have a number of speeds. Selection is made by a centrifugal device located inside the motor and connected, as shown in (Fig. 10.68). The switch is adjustable by means of an external lever. If the motor speed rises above that set by the lever, the centrifugal device opens two contacts and inserts resistance R in the circuit, which causes the motor speed to decrease. When motor runs slow, the two contacts close and short-circuit the resistance, so that the motor speed rises. This process is repeated so rapidly that variations in speed are not noticeable.

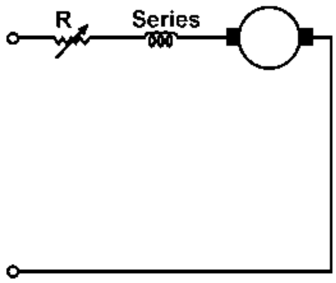


Fig. 10.66.

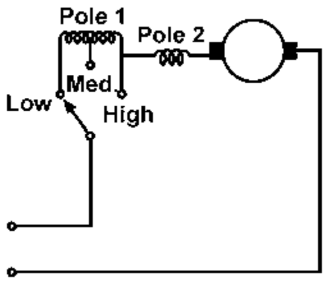


Fig. 10.67.

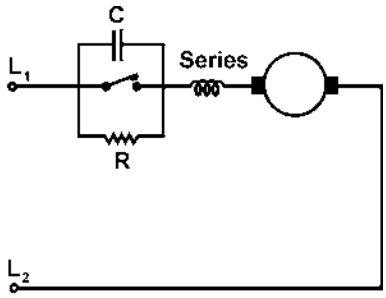


Fig. 10.68.

The resistance R is connected across the governor points as shown in (Fig.10.68). A capacitor is used across the contact points in order to reduce sparking produced due to the opening and closing of these points. Moreover, it prevents the pitting of contacts.

Reluctance Motor

It has either the conventional split-phase stator and a centrifugal switch for cutting out the auxiliary winding (split-phase type reluctance motor) or a stator similar to that of a permanent-split capacitor-run motor (capacitor-type reluctance motor). The stator produce the revolving field.

The squirrel-cage rotor is of unsymmetrical magnetic construction. This type of unsymmetrical construction can be achieved by removing some of the teeth of a symmetrical squirrel-cage rotor punching. For example, in a 48-teeth, four-pole rotor following teeth may be cut away.

1, 2, 3, 4, 5, 6, - 13, 14, 15, 16, 17, 18-25, 26, 27, 28, 29, 30-37, 38, 39, 40, 41, 42.

This would leave four projecting or salient poles (Fig.10.69) consisting of the following sets of teeth: 7.12; 19.24; 31.36 and 43-48. In this way, the rotor offers variable magnetic reluctance to the stator flux, the reluctance varying with the position of the rotor.

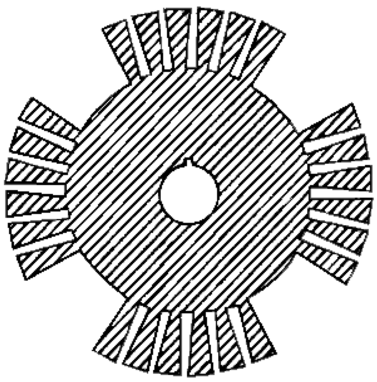


Fig. 10.69.

Working

For understanding the working of such a motor one basic fact must be kept in mind. And it is that when a piece of magnetic material is located in a magnetic field, a force acts on the material, tending to bring it into the most dense portion of the field. The force tends to align the specimen of material in such a way that the reluctance of the magnetic path that lies through the material will be minimum.

When the stator winding is energised, the revolving magnetic field exerts reluctance torque on the unsymmetrical rotor tending to align the salient pole axis of the rotor with the axis of the revolving magnetic field (because in this position, the reluctance of the magnetic path is minimum). If the reluctance torque is sufficient to start the motor and its load, the rotor will pull into step with the revolving field and continue to run at the speed of the revolving field.

However, even though the rotor revolves synchronously, its poles lag behind the stator poles by a certain angle known as torque angle, (something similar to that in a synchronous motor). The reluctance torque increases with increase in torque angle, attaining maximum value when $\alpha = 45^o$. If α increases beyond 45^o , the rotor falls out of synchronism. The average value of the reluctance torque is given by $T = K (V/f)^2 \sin 2\delta$ where K is a motor constant.

It may be noted that the amount of load which a reluctance motor could carry at its constant would only be a fraction of the load that the motor could normally carry when functioning as an induction motor. If the load is increased beyond a value under which the reluctance torque can not maintain synchronous speed, the rotor drops out of step the field, The speed, then, drops to some value at which the slip is sufficient to develop necessary torque to drive the load by induction-motor action.

The constant-speed characteristic of a reluctance motor makes it very suitable for such applications as signalling devices, recording instruments many kinds of timers and phonographs etc.

Hysteresis Motor

The operation of this motor depends on the presence of a continuously-revolving magnetic flux. Hence, for the split-phase operation, its stator has two windings which remain connected to the single-phase supply continuously both at starting as well as during the running of the motor. Usually, shaded-pole principle is employed for this purpose giving shaded-pole hysteresis motor. Alternatively, stator winding of the type used in capacitor-type motor may be used giving capacitor-type shaded-pole motor. Obviously, in either type, no centrifugal device is used.

The rotor is a smooth chrome-steel cylinder having high retentivity so that the hysteresis loss is high. It has no winding. Because of high retentivity of the rotor material, it is very difficult to change the magnetic polarities once they are induced in the rotor by the revolving flux. The rotor revolves synchronously because the rotor poles magnetically lock up with the revolving stator poles of opposite polarity. However, the rotor poles always lag behind the stator poles by an angle . Mechanical power developed by rotor is given by P_m = where P_h is hysteres loss in rotor. Also $T_h = 9.55\ P_m/N_s$. It is seen that hysteresis torque depends solely on the area or rotor's hysteresis loop.

The fact that the rotor has no teeth or winding of any sort, results in making the motor extremely quiet in operation and free from mechanical and magnetic vibrations. This makes the motor particularly useful for driving tape-decks, tape-dec, turn-tables and other precision audio equipment. Since, commercial motors usually have two poles, they run at 3,000 r.p.m. at 50-Hz single-phase supply. In order to adopt such a motor for driving an electric clock and other indicating devices, gear train is connected to the motor shaft for reducing the load speed. The unit accelerates rapidly, changing from rest to full speed almost instantaneously. It must do so because it cannot accelerate gradually as an ordinary motor it is either operating at synchronous speed or not at all.

Some unique features of a hysteresis motor are as under :-

i. since its hysteresis torque remains practically constant from locked rotor to synchronous speed, a hysteresis motor is able to synchronise any load it can accelerate-something no other motor does.
ii. due to its smooth rotor, the motor operates quietly and does not suffer from magnetic pulsations caused by slots/ salient-poles shaded-pole that are present in the rotors of other motors.

In (Fig. 10.70), is shown a two-pole shaded-pole type hysteresis motor used for driving ordinary household electric clocks. The rotor is a thin metal cylinder and the shaft drives a gear train.

Maintenance of A.C. Motors

The inspection and maintenance of a.c. motors is very simple. The bearings may or may not need frequent lubrication. If they are the sealed type, lubricated at the factory, they require no further attention. Be sure the coils are kept dry and free from oil or other abuse.

The temperature of a motor is usually its only limiting operating factor. A good rule of thumb is that a temperature too hot for the hand is too high for safety.

Next to the temperature, the sound of a motor or generator is the best trouble indicator. When operating properly, it should hum evenly. If it is overloaded it will "grunt". A three-phase motor with one lead disconnected will refuce to turn and will "growl". A knocking sound generally indicates a loose armature coil, a shaft out of alignment, or armature dragging because of worn bearings.

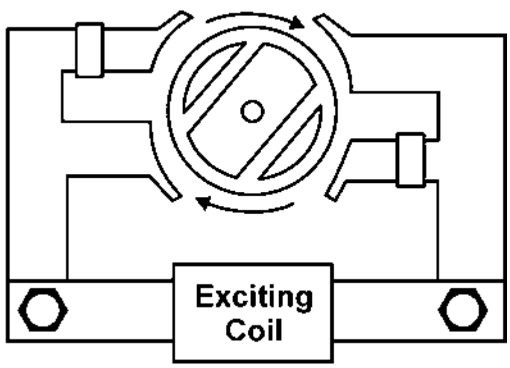


Fig. 10.70.

The inspection and maintenance of all a.c. motors should be performed in accordance with the applicable manufacturer's instructions.

Troubleshooting

The following troubleshooting procedures are not applicable to a particular a.c. motor, but are included as examples of the general troubleshooting procedures provided by various manufacturers of a.c. motors.

TROUBLE	POSSIBLE CAUSE	CORRECTION
Motor speed slow.	No lubrication. Applied voltage low. Motor wiring defective.	Lubricate as necessary. Check motor source voltage. Per form voltage continuity test of motor wiring
Motor speed fast.	Excessive supply voltage. Motor field windings shorted.	Check and adjust level of motor supply voltage. Repair shorted windings or replace or overhaul motor.
Motor will not operate. No voltage applied to motor.	Loose or broken wiring inside motor.	Perform continuity test of motor circuit.
	Defective motor switch.	Check switch and switch wiring using a continuity tester.
	Armature or field winding open-circuited.	Repair open winding or replace motor.
	Brushes worn excessively.	Replace brushes.
	Brush springs broken or too weak,	Replace brush springs.
	Brushes sticking in brush holders.	Replace or clean and adjust brushes.
Motor vibrates.	Loose or broken motor mountings.	Repair or replace motor mountings.
	Motor shaft bent.	Replace shaft or overhaul or replace motor.
	Motor bearings worn excessively	Replace bearings or overhaul motor.
Motor arcing excessively at brushes.	Brushes worn excessively.	Replace brushes.
	Brush springs weak.	Replace brush springs.
	Brushes sticking in holders.	Replace or clean brushes.
	Brushes incorrectly located.	Position brushes properly.
	Commutator dirty or excessively worn or pitted.	Clean or repair commutator as necessary.
	Open-circuited armature coil.	Repair open circuit or overhaul or replace motor.
Motor runs but overheats.	Motor bearings improperly lubricated.	Lubricate bearings.
	Excessive applied voltage.	Check voltage and adjust to proper level.
		Repair short circuit or overhaul or replace.
		Replace and adjust brushes.
Motor will not operate but draws high current.		Locate and repair short circuit.
		Repair or overhaul or replace motor.
		Repair short circuit or overhaul or replace motor.
		Check for seized motor bearings or binding of mechanism driven by motor. Repair or replace seized components.
		Reduce load or install motor capable of carrying greater load.

■■■

CHAPTER - 11
KNOWLEDGE OF CONSTRUCTION AND PRINCIPLES OF AUTO TRANSFORMERS, SINGLE AND THREE PHASE TRANSFORMERS

WORKING PRINCIPLE OF A TRANSFORMER

A transformer is a static (or stationary) piece of apparatus by means of which electric power in one circuit is transformed into electric power of the same frequency in another circuit. It can raise or lower the voltage in a circuit but with a corresponding decrease or increase in current. The physical basis of a transformer is mutual induction between two circuits linked by a common magnetic flux. In its simplest form, it consists of two inductive coils which are electrically separated but magnetically linked (Fig. 11.1). The two coils possess high mutual inductance. If one coil is connected to a source of alternating voltage, an alternating flux is set up in the laminated core, most of which is linked with the other coil in which it produces mutually-induced e.m.f. (according to Faraday's Laws of Electromagnetic Induction e = MdI/dt). If the second coil circuit is closed, a current flows in it and so electric energy is transferred (entirely magnetically) from the first coil to the second coil. The first coil, in which electric energy is fed from the a.c. supply mains, is called primary winding and the other from which energy is drawn out, is called secondary winding. In brief, a transformer is a device that

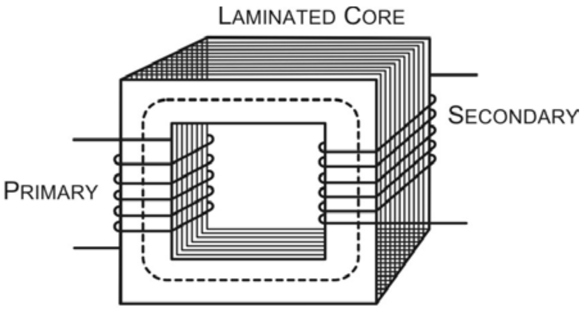
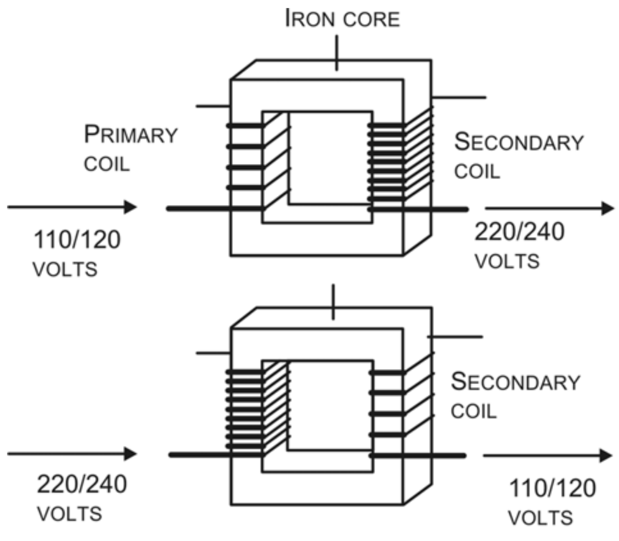


Fig. 11.1.

1. Transfers electric power from one circuit to another
2. It does so without a change of frequency
3. It accomplishes this by electromagnetic induction and
4. Where the two electric circuit are in mutual inductive influence of each other.

Transformer Construction

The simple elements of a transformer consist of two coils having mutual inductance and a laminated steel core. The two coils are insulated from each other and from the steel core. Other necessary parts are : some suitable container for assembled core and windings; a suitable medium for insulating the core and its windings from its container; suitable bushings (either of porcelain, oil-filled or capacitor-type) for insulating and bringing out the terminals of windings from the tank.



Principle of transformer

In all types of transformers, the core is constructed of transformer sheet steel laminations assembled to provide a continuous magnetic path with a minimum of air-gap included. The steel used is of high silicon content, sometimes heat treated to produce a high permeability and a low hysteresis loss at the usual operating flux densities. The eddy current loss is minimised by laminating the core, the laminations being insulated from each other by a light coat of core-plate varnish or by an oxide layer on the surface. The thickness of laminations varies from 0.35 mm for a frequency of 50 Hz to 0.5 mm for a frequency of 25 Hz. The core laminations (in the form of strips) are joined as shown in (Fig. 11.2). It is seen that the joints in the alternate layers are staggered in order to avoid the presence of narrow gaps right through the cross-section of the core. Such staggered joints are said to be 'imbricated'.

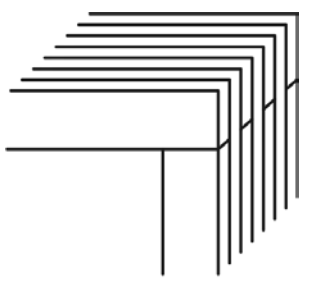
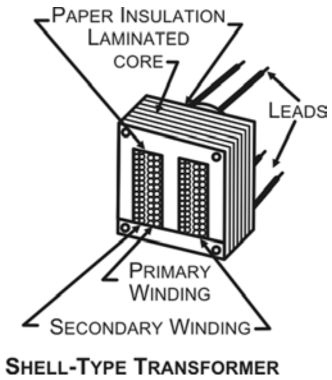
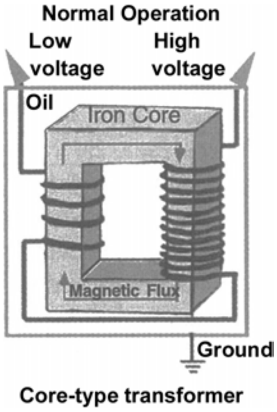


Fig. 11.2.

Constructionally, the transformers are of two general types, distinguished from each other merely by the manner in which the primary and secondary coils are placed around the laminated core. The two types are known as (i) **core-type** and (ii) **shell-type**. Another recent developments is **spiral-core or wound-core type**, the trade name being spirakore transformer.





In the so-called core type transformers, the **windings surround a considerable part of the core** whereas in shell-type transformers, the core **surrounds a considerable portion of the windings** as shown schematically in Fig. 11.3 (a) and (b) respectively.

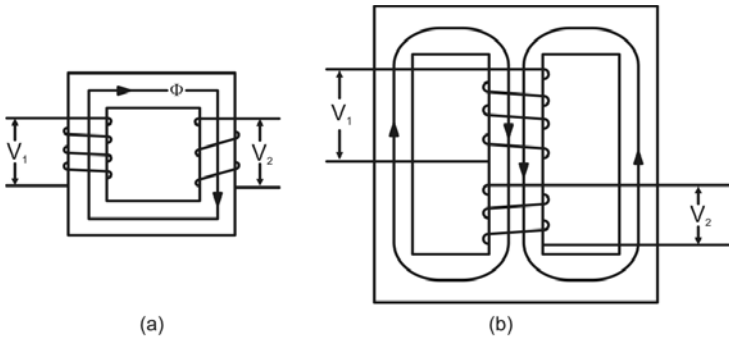


Fig. 11.3.

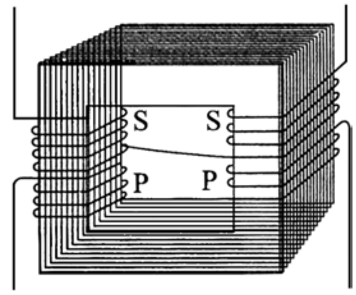


Fig. 11.4.

In the simplified diagram for the core type transformers [Fig. 11.3 (a)], the primary and secondary winding are shown located on the opposite legs (or limbs) of the core, but in actual construction, these are always interleaved to reduce leakage flux. As shown in (Fig. 11.4), half the primary and half the secondary winding have been placed side by side or concentrically on each limb, not primary on one limb (or leg) and the secondary on the other.

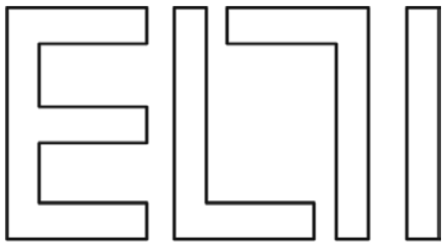


Fig. 11.5.

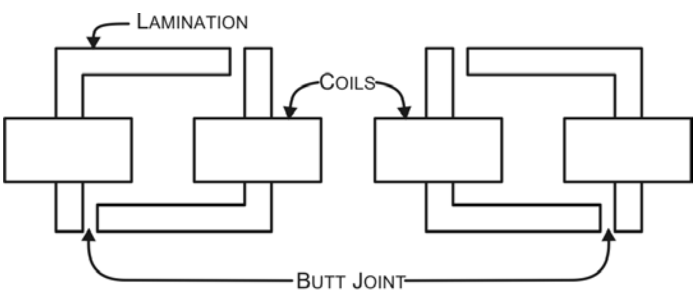


Fig. 11.6.

In both core and shell-type transformers, the individual laminations are cut in the form of long strips of L's, E's and I's as shown in (Fig. 11.5). The assembly of the complete core for the two types of transformers is shown in (Fig. 11.6) and (Fig. 11.7).

As said above, in order to avoid high reluctance at the joints where the laminations are butted against each other, the alternate layers are stacked differently to eliminate these joints a shown in (Fig. 11.6) and (Fig. 11.7).

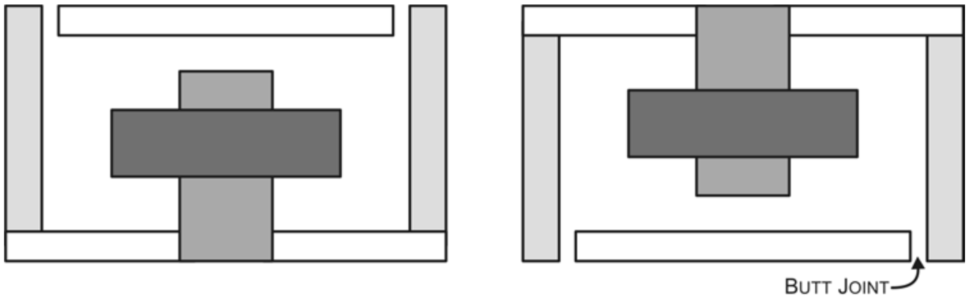
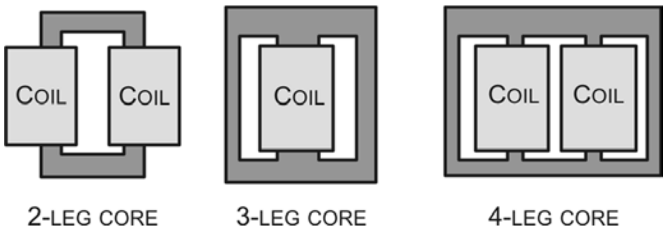


Fig. 11.7.

Core-type Transformers

The coils used are form-wound and are of the cylindrical type. The general form of these coils may be circular or oval or rectangular. In small size core-type transformers, a simple rectangular core is used with cylindrical coils which are either circular or rectangular in form. But for large-size core-type transformers, round or circular cylindrical coils are used



Single-Phase Transformer Cores.

which are so wound as to fit over a crusiform core section as shown in Fig. 11.8 (a). The circular cylindrical coils are used in most of the core-type transformers because of their mechanical strength. Such cylindrical coils are wound in helical

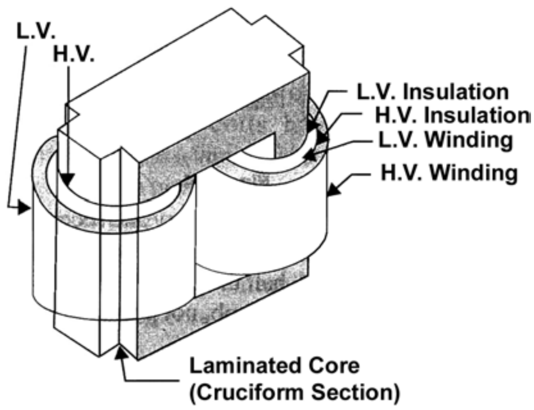


Fig. 11.8. (a)

layers with the different layers insulated from each other by paper, cloth, micarta board of cooling ducts. Fig. 11.8 (c) shows the general arrangement of these coils with respect to the core. Insulating cylinders of fuller board are used to separate the cylindrical windings from the core and from each other. Since the low-voltage (LV) winding is easiest to insulate, it is placed nearest to the core (Fig. 11.8).

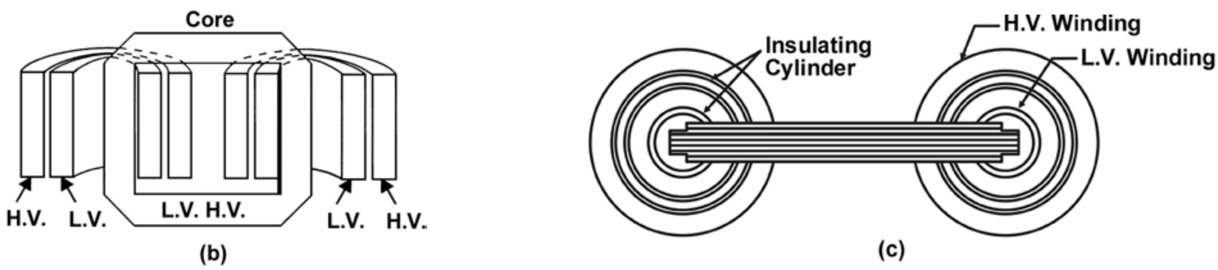


Fig. 11.8.

Because of laminations and insulation, the net or effective core area is reduced, due allowance for which has to be made. It is found that, in general, the reduction in core sectional area due to the presence of paper, surface oxide etc. is of the order of 10% approximately.

As pointed out above, rectangular cores with rectangular cylindrical coils can be used for small-size core-type transformers as shown in Fig. 11.9 (a) but for large - sized transformers, it becomes wasteful to rectangular cylindrical coils and so circular cylindrical coils are preferred. For such purposes, square cores may be used as shown in Fig. 11.9 (b) where circles represent the tubular former carrying the coils. Obviously, a considerable amount of useful space is still wasted. A common improvement on square core is to employ cruciform core as in Fig. 11.9 (c) which demands, at least, two sizes of core strips. For very large transformers, further core-stepping is done as in Fig. 11.9 (d) where at least three sizes of core plates are necessary. Core-stepping not only gives high space factor but also results in reduced length of the mean turn and the consequent I^2R loss. Three stepped core is the one most commonly used although more steps may be used for very large transformers as in Fig.11.9 (e). From the geometry of (Fig. 11.9), it can be shown that maximum gross core section for Fig. 11.9 (b) is 0.5 d^2 and for Fig. 11.9 (c), it is 0.616 d^2 where d is the diameter of the cylindrical coil.

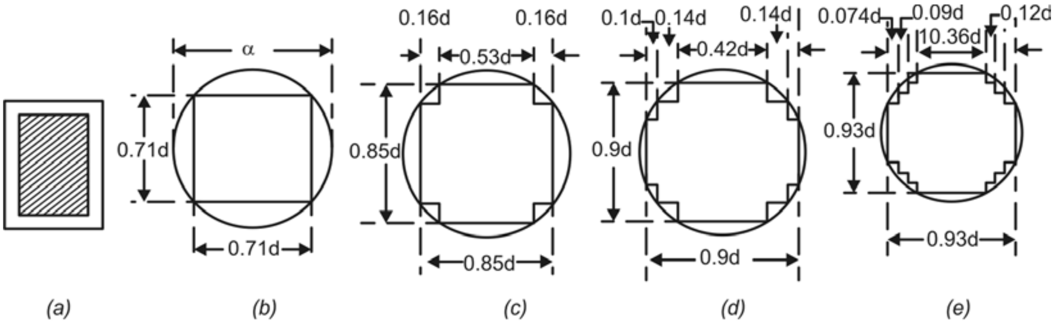


Fig. 11.9.

Shell-type Transformers

In their case also, the coils are form-would but are multi-layer disc type usually wound in the form of pancakes. The different layers of such multi-layer discs are insulated from each other by paper. The complete winding consists of stacked discs with insulation space between the coils the space forming horizontal cooling and insulating ducts. A shell-type transformer may have a simple rectangular form as shown in (Fig. 11.10), or it may have distributed form as shown in (Fig. 11.11).

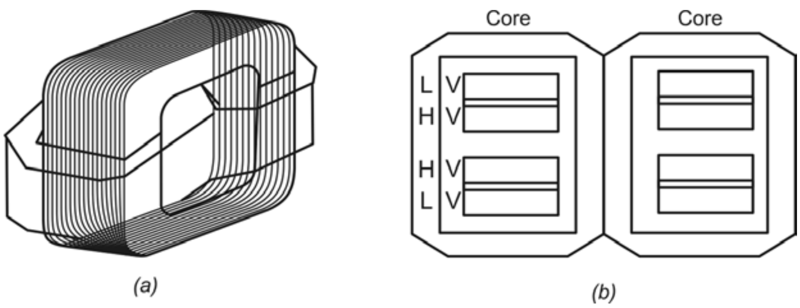


Fig. 11.10.

A very commonly-used shell-type transformer is the one known as Berry Transformer-so called after the name of its designer and is cylindrical in form. The transformer core consists of laminations arranged in groups which radiate out from the centre as shown in section in (Fig. 11.12).

It may be pointed out that cores and coils of transformers must be provided with rigid mechanical bracing in order to prevent movement and possible insulation damage. Good bracing reduces vibration and the objectionable noise- a humming sound-during operation.

The spiral-core transformer employs the newest development in core construction. The core is assembled of a continuous strip or ribbon of transformer steel wound in the form of a circular or elliptical cylinder. Such construction allows the core flux to follow the grain of the iron. Cold-rolled steel of high silicon content enables the designer to use considerably higher operating flux densities with lower loss per kg. The use of higher flux density reduces the weight per kVA. Hence, the advantages of such construction are (i) a relatively more rigid core (ii) lesser weight and size per kVA rating (iii) lower iron losses at higher operating flux densities and (iv) lower cost of manufacture.

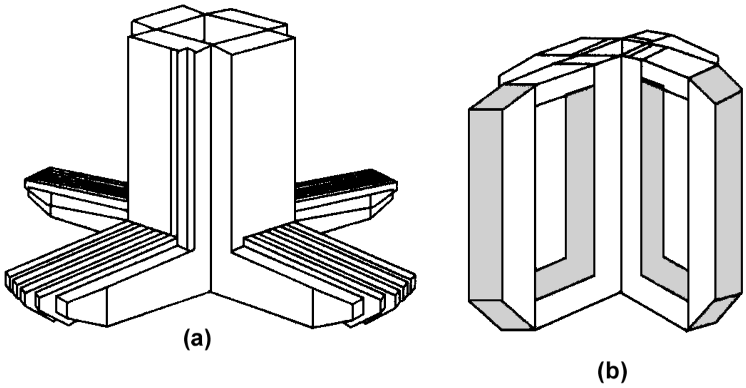


Fig. 11.11.

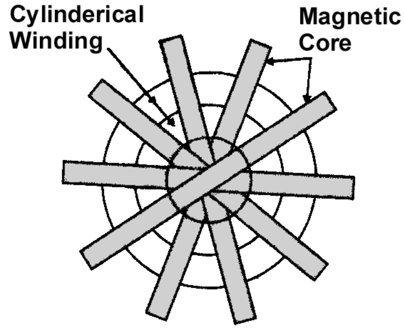


Fig. 11.12.

Transformers are generally housed in tightly-fitted sheet-metal; tanks filled with special insulating oil. This oil has been highly developed and its function is to keep cool. By circulation, it not only keeps the coils reasonably cool, but also provides the transformer with additional insulation not obtainable when the transformer is left in the air.

In cases where a smooth tank surface does not provide sufficient cooling area, the sides of the tank are corrugated or provided with radiators mounted on the sides. Good transformer oil should be absolutely free from alkalies, sulphur and particularly from moisture. The presence of even an extremely small percentage of moisture in the oil is highly detrimental from the insulation viewpoint because it lowers the dielectric strength of the oil considerably. The importance of avoiding moisture in the transformer oil is clear from the fact that even an addition of 8 parts of water in 1,000,000 reduces the insulating quality of the oil to a value generally recognized as below standard. Hence, the tanks are sealed air-tight in smaller units. In the case of large-sized transformers where complete air-tight construction is impossible, chambers known as breathers are provided to permit the oil inside the tank to expand and contract as its temperature increases or decreases. The atmospheric moisture is entrapped in these breathers and is not allowed to pass on to the oil. Another thing to avoid in the oil is sledging which is simply the decomposition of oil with long and continued use. Sledging is caused principally by exposure to oxygen during heating and results in the formation of large deposits of dark and heavy matter that eventually clogs the cooling ducts in the transformer.

No other feature in the construction of a transformer is given more attention and care than the insulating materials, because the life of the unit almost solely depends on the quality, durability and handling of these materials. All the insulating materials are selected on the basis of their high quality and ability to preserve high quality even after many years of normal use.

All the transformer leads are brought out of their cases through suitable bushings. There are many designs of these, their size and construction depending on the voltage of the leads. For moderate voltages, porcelain bushings are used to insulate the leads as they come out through the tank. In general, they look almost like the insulators used on the transmission lines. In high voltage installations, oil-filled or capacitor-type bushings are employed.

The choice of core or shell-type construction is usually determined by cost, because similar characteristics can be obtained with both types. For very high-voltage transformers or for multi winding design, shell-type construction is preferred by many manufacturers. In this type, usually the mean length of coil turn is longer than in a comparable core-type design. Both core and shell forms are used and the selection is decided by many factors such as voltage rating, kVA rating, weight, insulation stress, heat distribution etc.

Another means of classifying the transformers is according to the type of cooling employed. The following types are in common use :
(a) oil-filled self-cooled (v) oil-filled water-cooled (c) air-blast type

Small and medium size distribution transformers-so called because of their use on distribution systems as distinguished from line transmission-are of type (a). The assembled windings and cores of such transformers are mounted in a welded, oil-tight steel tank provided with steel cover. After putting the core at its proper place, the tank is filled with purified, high quality insulating oil. The oil serves to convey the heat from the core and the windings to the case from where it is radiated out to the surroundings. For small size, the tanks are usually smooth-surfaced, but for larger sizes, the cases are frequently corrugated or fluted to get greater heat radiation area without increasing the cubical capacity of the tank. Still larger sizes are provided with radiators or pipes.

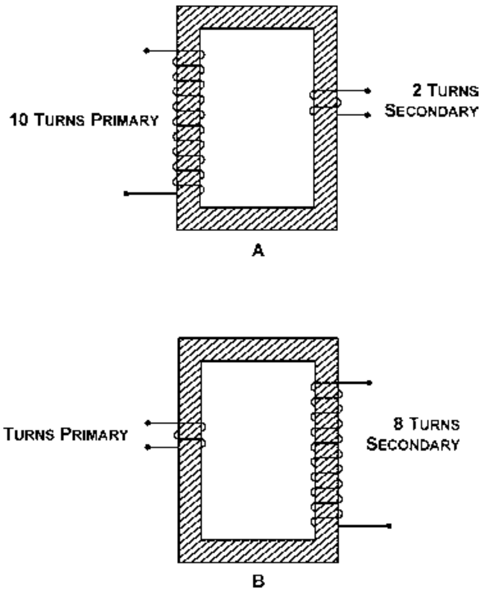


Fig. 11.13. A step-down and a step-up transformer.

Construction of very large self-cooled transformers is expensive, a more economical form of construction for such large transformers is provide in the oil-immersed, water-cooled type. As before, the windings and the core are immersed in the oil, but there is mounted near the surface of oil, a cooling coil through which cold water is kept circulating. The heat is carried away by this water. The largest transformers such as those used with high-voltage transmission lines, are constructed in this manner.

Oil-filled transformers are built for outdoor duty and as these require no housing other than their own, a great saving is thereby effected. These transformers require only periodic inspection.

For voltages below 25,000 V transformers can be built for cooling by means of an air-blast. The transformer is not immersed in oil, but is housed in a thin sheet-metal box open at both ends through which air is blown from the bottom to the means of a fan or blower.

There are many types of voltage transformers. Most of these are either step-up or step-down transformers. The factor which determines whether a transformer is a step-up or step-down whether a transformers. The factor which determines whether a transformer is a step-up or step-down type is the "turns" ratio. The turns ratio is the ratio of the number of turns in the primary winding. For example, the turns ratio of the step-down transformer shown in A of (Fig. 11.13) is 5 to 1, since there are five times as many turns in the primary as in the secondary. The step-up transformer shown in B of (Fig. 11.13) has a 1-to - 4 turns ratio.

The ratio of the transformer input voltage to the output voltage is the same as the turns ratio if the transformer is 100 percent efficient. Thus, when 10 volts are applied to the primary of the transformer shown in A of (Fig. 11.13), two volts are induced in the secondary. If 10 volts are applied to the primary of the transformer in B of (Fig. 11.13), the output voltage across the terminals of the secondary will be 40 volts.

No transformer can be constructed that is 100 percent efficient, although iron-core transformers can approach this figure. This is because of the magnetic lines of force set up in the primary do not cut across the turns of the secondary coil. A certain amount of the magnetic flux, called leakage flux, how well the flux of the primary is coupled into the secondary is called the "coefficient of coupling". For example, if it is assumed that the primary of a transformer develops 10,000 lines of force and only 9,000 cut across the secondary, the coefficient of coupling would .9 or, stated another way, the transformer would be 90 efficient.

When an a.c. voltage is connected across the primary terminals of transformer, an alternating current will flow and self-induce a voltage in the primary coil which is opposite and nearly equal to the applied voltage. The difference between these two voltages allows just enough current in the primary coil which is opposite and nearly equal to the applied voltage. The difference between these two voltages allows just enough current in the primary to magnetize its core. This is called the exciting, or magnetizing, current. The magnetic field caused by this exciting current cuts across the secondary coil and induces a voltage by mutual induction. If load is connected across the secondary coil, the load current flowing through the secondary coil will produce a magnetic field which will tend to neutralize the magnetic field produced by the primary current. This will reduce the self induced (opposition) voltage in the primary current increases as the secondary load current increases, and decreases as the secondary load current decreases. When the secondary load is removed, the primary current is again reduced to the small excising current sufficient only to magnetize the iron core of the transformer.

If a transformer steps up the voltage, it will step down the current by the same ratio. This should be evident if the power formula is considered, for the power (I × E) of the output (secondary) electrical energy is the same as the input (primary) power minus that energy loss in the transforming process. Thus, if 10 volts and 4 amps (40 watts of power) are used in the primary to produce a magnetic field, there will be 40 watts of power developed in the secondary (disregarding any loss). If the transformer has a step-up ratio of 4 to 1, the voltage across the secondary will be 40 volts and the current will be 1 amp. The voltage is 4 times greater and the current is one-fourth the primary circuit value, but the power (I × E value) is the same.

When the turns ratio and the input voltage are known, the output voltage can be determined as follows.

$$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$

Where E is the voltage of the primary, E_2 is the output voltage of the secondary, and N_1 and N_2 are the number of turns of the primary and secondary, respectively.

Transposing the equation to find the output voltage gives:

$$E_2 = \frac{K_1 N_2}{N_1}$$

AUTO-TRANSFORMERS

In circuit applications normally requiring only a small step-up or step-down of voltage, a special variant of transformer design is employed and this is known as an auto-transformer. Its circuit arrangement is shown in (Fig. 11.14) and from this it will be noted that it's most notable feature is that it consists of a single winding tapped to form primary and secondary parts. In the example illustrated the tappings provide a stepped - up voltage output, since the number of primary turns is less than that of the secondary turns.

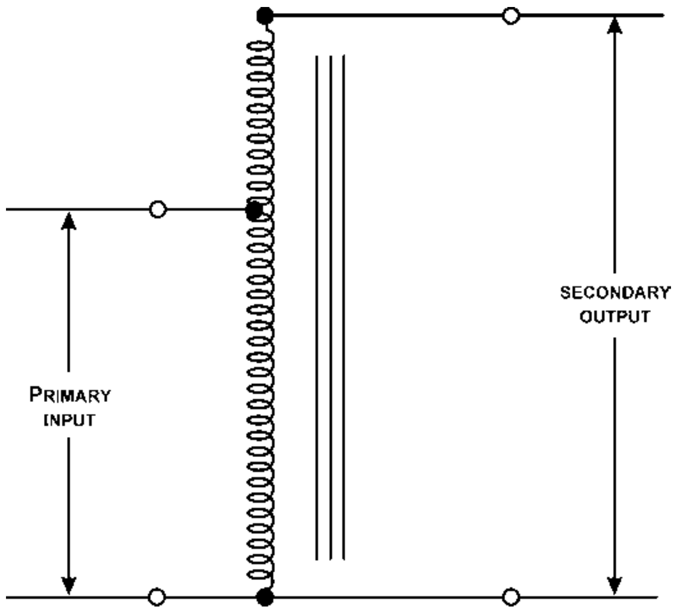


Fig. 11.14.

When a voltage is applied to the primary terminals current will flow through the portion of the winding spanned by these terminals. The magnetic flux due to this current will flow through the core and will therefore, l link with the whole of the winding. Those turns between the primary terminals act in the same way as the primary winding of a conventional transformer, and so they produce a self-induction voltage in opposition to the applied voltage the voltage induced in the remaining turns of the winding will be additive, thereby giving a secondary output voltage greater than the applied voltage. When a load circuit is connected to the secondary terminals, a current due to the induced voltage will flow through the whole winding and will be in opposition to the primary current from the input terminals. Since the turns between the primary terminals are common to input and output circuits alike they carry the different between the induced current and primary current, and they may therefore be wound with smaller gauge wire than the reminder of the winding.

Auto-transformers may also ben designed for used in consumer circuits requiring three-phase voltage at varying levels. The circuit arrangement of a typical step-up transformer applied to a windshield anticing circuit is shown in (Fig. 11.15). The three windings are star-connected and are supplied with the "primary" voltage of 208 volts from the alternator system. The secondary tappings are so arranged that up to four output voltage levels may be utilized.

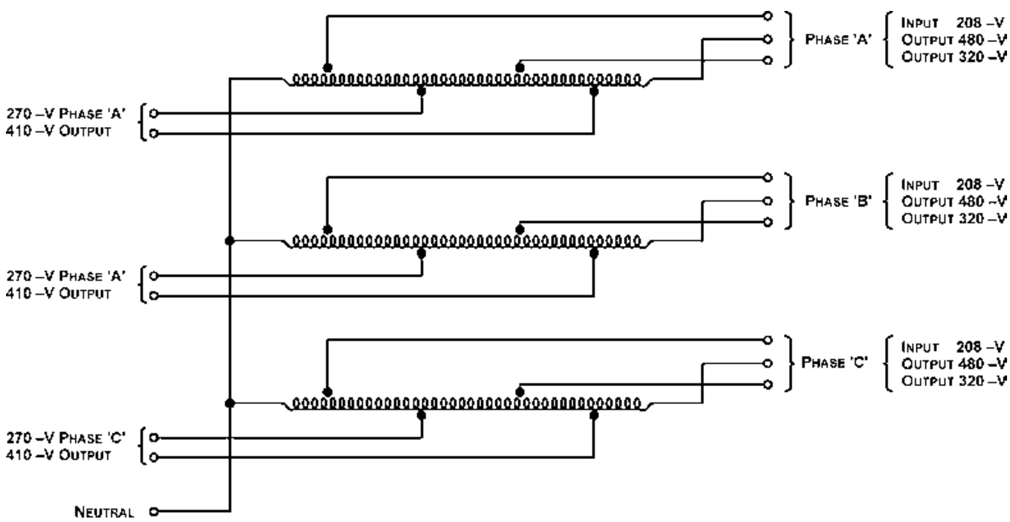


Fig. 11.15.

EFFICIENCY OF A TRANSFORMER

As is the case with other types of electrical machines, the efficiency of a transformer at a particular load and power factor is defined as the output divided by the input - the two being measured in the same units (either watts or kilowatts).

$$\text{efficiency} = \frac{\text{output}}{\text{input}}$$

But a transformer being a highly efficient piece of equipment, has very small losses, hence it is impractical to try to measure transformer efficiency by measuring its input and output. These quantities are nearly of the same size. A better method is to determine the losses and then to calculate the efficiency from

$$\text{efficiency} = \frac{\text{output}}{\text{output} + \text{losses}} = \frac{\text{output}}{\text{output} + \text{Cu Loss} + \text{Iron Loss}}$$

$$\eta = \frac{\text{input} - \text{losses}}{\text{input}} = 1 - \frac{\text{losses}}{\text{input}}$$

It may be noted here that efficiency is based on power output in watts and not on volt-amperes, although losses are proportional to VA. Hence, at any volt-ampere load, the efficiency depends on power factor, being maximum at a power factor of unity.

Efficiency can be computed by determining core loss from no-load or open-circuit test and Cu loss from the short -circuit test.

TRANSFORMER TESTS

The performance of a transformer can be calculated on the basis of its equivalent circuit which contains (Fig. 11.16) four main parameters, the equivalent resistance R_{01} as referred to primary (or secondary R_{02}), the equivalent leakage reactance X_{01} as referred to primary (or secondary X_{02}), the core-loss conductance G_0 (or resistance R_0) and the magnetising susceptance B_0 (or reactance X_0). These constants or parameters can be easily determined by two tests (i) **open-circuit test** and (ii) **short-circuit test.** These tests are very economical and convenient, because they furnish the required information without actually loading the transformer. In fact, the testing of very large a.c. machinery consists of running two tests similar to the open and short-circuit tests of a transformer.

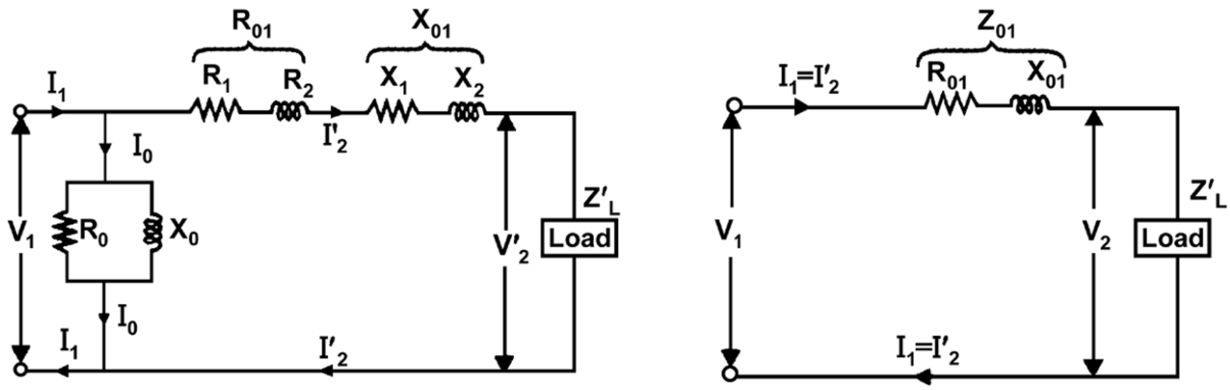


Fig. 11.16.

OPEN-CIRCUIT OR NO-LOAD TEST

The purpose of this test is to determine no-load loss or core loss and no-load I_0 which is helpful in finding X_0 and R_0.

One winding of the transformer - whichever is convenient but usually high voltage winding - is left open and the other is connected to its supply of normal voltage and frequency. A wattmeter W, voltmeter V and an ammeter A are connected in the low-voltage winding i.e. primary winding in the present case. With normal voltage applied to the primary, normal flux will be set up in the core, hence normal iron losses will occur which are recorded by the wattmeter. As the primary no-load current I_0 (as measured by ammeter) is small (usually 2 to 10% of rated load current), Cu loss is negligibly small in primary and nil in secondary (it being open). Hence, the wattmeter reading represents practically the core loss under no-load condition and which is the same for all loads.

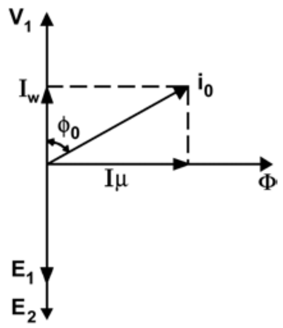


Fig. 11.17.

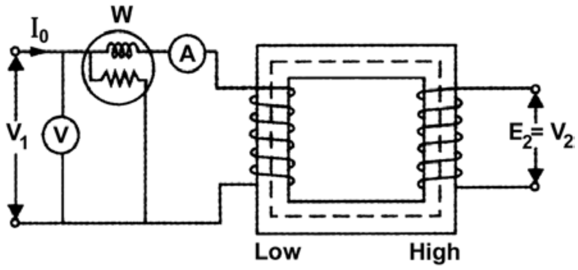


Fig. 11.18.

It should be noted that since I_0 is itself very small, the pressure coils of the wattmeter and the voltmeter are connected such that the current in them does not pass through the current coil of the wattmeter.

Sometimes, a high-resistance voltmeter is connected across the secondary. The reading of the voltmeter gives the induced emf in the secondary winding. This helps to find transformation ratio K.

The no-load vector diagram is shown in (Fig. 11.17). If W is the wattmeter reading (in Fig.11.18), then

$$W = V_1 I_0 \cos\phi_0 \quad \therefore \quad \cos\phi_0 = W / V_1 I_0$$

$$\therefore \quad I_\mu = I_0 \sin\phi_0, \ I_w = I_0 \cos\phi_0 \ \therefore \ X_0 = V_1 / I_\mu \text{ and } R_0 = V_1 / I_w$$

Or since the current is practically all-exciting current when a transformer is on no-load (i.e. $I_0 \cong I_\mu$) and as the voltage drop in primary leakage impedance is small*, hence the exciting admittance Y_0 of the transformer is given by $I_0 = V_1 Y_0$ or $Y_0 = I_0/V_1$.

The exciting conductance G is given by $W = V_1^2 G_0$ or $G_0 = W/V_1^2$

The exciting susceptance $B_0 = \sqrt{(Y_0^2 - G_0^2)}$

Short-Circuit or Impedance Test

This is an economical method for determining the following :

(i) Equivalent impedance (Z_{01} or Z_{02}), leakage reactance (X_{01} or X_{02}) (R_{01} or R_{02}) of the transformer as referred to the winding in which the measuring instruments are placed.

(ii) Cu loss at full load (and at any desired load). This loss is used in calculating the efficiency of the transformer.

(iii) Knowing Z_{01} or Z_{02}, the total voltage drop in the transformer as referred to primary or secondary can be calculated and hence regulation of the transformer determined.

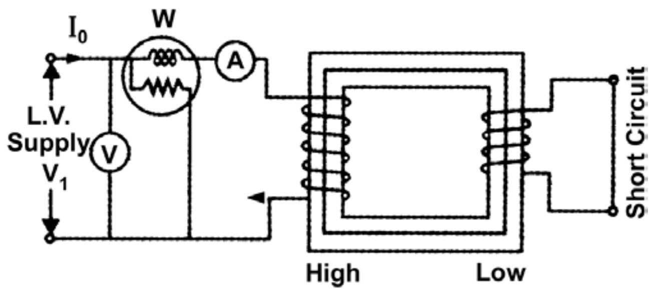


Fig. 11.19.

In this test, one winding, usually the low-voltage winding, is solidly short-circuited by a thick conductor (or through an ammeter which may serve the additional purpose of indicating rating load current) as shown in (Fig. 11.19).

A low voltage (usually 5 to 10% of normal primary voltage) at correct frequency (though for Cu losses it is not essential) is applied to the primary and is cautiously increased till full-load currents are flowing both in primary and secondary (as indicated by the respective ammeteres).

Since, in this test, the applied voltage is a small percentage of the normal voltage, the mutual flux Φ produced is also a small percentage of its normal value. Hence, core losses are very small with the result that the watt-meter reading represent the full-load Cu loss or I^2R loss for the whole transformer i.e. both primary Cu loss and secondary Cu loss. If V_{sc} is the voltage required to circulate rated load currents, then

$$Z_{01} = V_{sc}/I_1$$

Also $$W = I_1^2 R_{01}$$

$\therefore$ $$R_{01} = W/I_1$$

$\therefore$ $$X_{01} = \sqrt{(Z_{01}^2 - R_{01}^2)}$$

* *If it is not negligibly small, then* $I_0 = E_1 Y_0$ *i.e. instead of* V_1 *we will have to use* E_1.

All-day Efficiency

The ordinary or commercial efficiency of a transformer is given by the ratio

$$\eta = \frac{\text{output in watts}}{\text{input in watts}}$$

But there are certain types of transformers whose performance cannot be judged by this efficiency. Transformers used for supplying lighting and general network i.e. distribution transformers have their primaries energined all the twenty-four hours, although their secondaries supply little or no-load much of the time during the day except during the house-lighting period. It means that whereas core loss occurs throughout the day, the Cu loss occurs only when the transformer is loaded. Hence, it is considered a good practice to design such transformers so that core losses are very low. The Cu losses are relatively less important because they depend on the load. The performance of such a transformer should be judged by all-day efficiency also known as operational efficiency' which is computed on the basis of energy consumed during certain time period, usually a day of 24 hours.

$$\therefore \quad \mu_{\text{all-day}} = \frac{\text{Output in kWh}}{\text{Input in kWh}} \text{(For 24 hours)}$$

This efficiency is always less than the commercial efficiency of a transformer.

To find this all-day efficiency or (as it is also called) energy efficiency, we have to know the load cycle on the transformer i.e. how much and how long the transformer is loaded during 24 hours. Practical calculations are facilitated by making use of a load factor.

TRANSFORMER RATINGS

Transformers are usually rated in volt-amperes or kilovolt-amperes. The difference between the output terminal voltages at full-load and no-load, with a constant input voltage, is called the regulation of the transformer. As in the case of an a.c. generator, regulation is expressed as a percentage of the full-load voltage, and depends not only on actual losses (e.g. hysteresis, eddy current and magnetic leakage) but also on the power factor of the load. Thus, an inductive load, i.e. one having a lagging power factor, will give rise to a high percentage regulation, while with a capacitive load, i.e. one having a leading power factor, the regulation may be a negative quality giving a higher output voltage on full-load than on no-load.

Changes in power supply frequency, or the connection of a transformer to a supply whose frequency differs from that for which the transformer was designed, has a noticeable effect on its operation. This is due to the fact that they may be considered to be a purely inductive circuit. If, for example, the frequency is reduced at a constant value of voltage, then the current will rise. The increased current will, in turn, bring the transformer core nearer to magnetic saturation and this decreases the effective value of inductance leading to still larger current. Thus, if a transformer is used at a frequency lower than that for which it was designed, there is a risk of excessive heat generation in the primary winding and subsequent burn out. On the other hand, a transformer designed for low frequency can be used with higher frequencies, since in this case the primary current will be reduced.

Instrument Transformers

In d.c. circuit when large currents are to be measured, it is usual to use low-range ammeters with suitable shunts. For measuring high voltages, low-range voltmeters are used with a high resistance connected in series with them. But it is not convenient to use this method with alternating current and voltage instruments. For this purpose, specially constructed accurate ratio instrument transformers are employed in conjunction with standard low-range a.c. instruments. These instrument transformers are of two kinds (i) current transformers for measuring large alternating currents and (ii) potential transformers for measuring high alternating voltages.

Current Transformers

These transformers are used with low-range ammeters to measure currents in high-voltage alternating-current circuits where it is not practicable to connect instruments and meters directly to the lines. In addition to insulating the instrument from the high voltage line, they step down the current in a known ratio. The current (or series) transformer has a primary coil of one or more turns of thick wire connected in series with the line whose current is to be measured as shown in (Fig. 11.20). The secondary consists of a large number of turns of fine wire and is connected across the ammeter terminals (usually of 5-ampere or 1-ampere range).

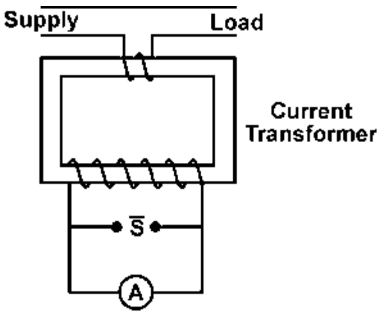


Fig. 11.20.

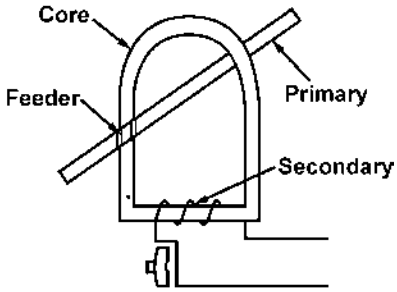


Fig. 11.21.

As regards voltage, the transformer is of step-up variety but it is obvious that current will be stepped down. Thus, if the current transformer has primary to secondary current ratio of 100:5, then it steps up the voltage 20 times whereas it steps down the current to 1/20th of its actual value. Hence, if we know current ratio (I_1/I_2) of the transformer and the reading of the a.c. ammeter, the line current can be calculated. In fact, line current is given by the current transformation ratio times the reading on the ammeter. One of the most commonly-used current transformer is the one known as clamp-on or clip-on type. It has a laminated core which is so arranged that it can be opened out at hinged section by merely pressing a trigger-like projection (Fig. 11.21). When the core is thus opened it permits the admission of very heavy current-carrying bus bars of feeders whreupon the trigger is released and the core is tightly closed by a spring. The current carrying conductor or feeder acts as a single-turn primary whereas the secondary is connected across the standard ammeter conveniently mounted in the handle.

It should be noted that, since the ammeter resistance is very low, the current transformer normally works short circuited. If for any reason, the ammeter is taken out of the secondary winding, then this winding must be short-circuited with the help of short-circuiting switch S. If this is not done, then due to the absence of counter amp-turns of the secondary, the unopposed primary m.m.f. will set up an abnormally high flux in the core which will produce excessive core loss with subsequent heating and a high voltage across the secondary terminals. This is not the case with ordinary constant-potential transformers, because their primary current is determined by the load on their secondary whereas in a current transformer, the primary current is determined entirely by the load on the system and not by the load on its own secondary.

Hence, the secondary of a current transformer should never be left open under any circumstances.

Example 1. A 100 :5 transformer is used in conjunction with a 5-amp ammeter. If the latter reads 3.5 A, find the line current.

Sol. Here, the ratio 100 : 5 stands for the ratio of primary-to-secondary currents i.e. $I_1/I_2 = 100/5$

$\therefore$ primary (or line) current $= 3.5 \times (100/5) =$ **70A**

Example 2. It is desired to measure a line current of the order of 2,000 A to 2,500 A. If a standard 5-amp ammeter is to be used along with a current transformer; what should be the turn ratio of the latter ? By what factor should the ammeter reading be multiplied to get the line current in each case?

Sol. $I_1/I_2 = 2000/5 = 400$ or $2500/5 = 500$. Since $I/I_2 = N_2/N_1 =$ hence $N_2/N_1 = 400$ in the first case and 500 in the second case. It means that $N_1 : N_2 :: 1 : 400$ or $1 : 500$.

Ratio or multiplication factor in the first case is 400 and in the second case 500.

Potential Transformers

These transformers are extremely accurate-ratio step-down transformers and are used in conjunction with standard low-range voltmeters (usually 150-V) whose deflection when divided by voltage transformation ratio, gives the true voltage on the high voltage side. In general, they are of the shell-type and do not differ much from the ordinary two-winding transformers discussed so far, except that their power rating is extremely small. Upto voltages of 5,000, potential transformers are usually of the dry type, between 5,000 and 13,800 volts, they may be either dry type or oil immersed type, although for voltages above 13,800 they are always oil immersed type. Since their secondary windings are required to operate instruments or relays or pilot lights, their ratings are usually of 40 to 100 W. For safety, the secondary should be completely insulated from the high-voltage primary and should be, in addition, grounded for affording protection to the operator. (Fig.11.22) shows the connections of such a transformer.

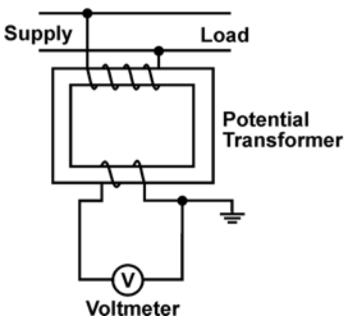


Fig. 11.22.

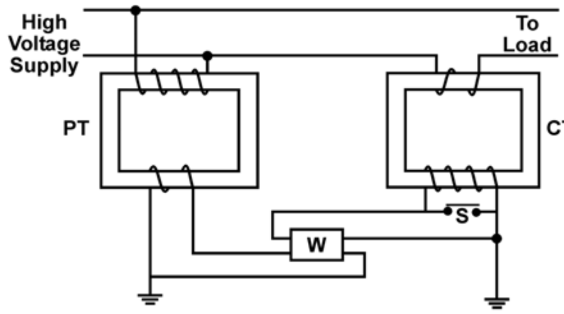
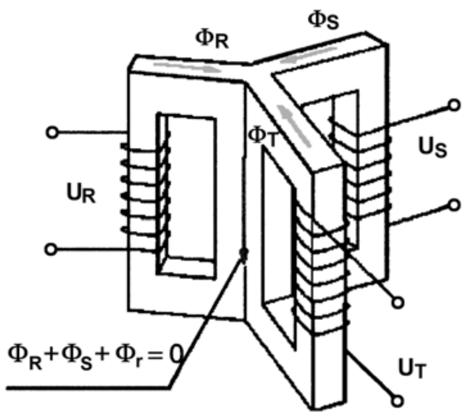


Fig. 11.23.

Fig.11.23, shows the connections of instrument transformers to a wattmeter. While connecting the wattmeter, the relative polarities of the secondary terminals of the transformers with respect to their primary terminals must be known for connections of the instruments.

Three-Phase Transformers

Large scale generation of electric power is usually 3-phase at generated voltages of 13.2 kV or somewhat higher. Transmission is generally accomplished at higher voltages of 110, 132, 275, 400 and 750 kV for which purpose 3-phase transformers are necessary to step up the generated voltage to that of the transmission line. Next, at load centres, the transmission voltages are reduced to distribution voltages of 6,600, 4,600 and 2,300 volts. Further, at most of the consumers, the distribution voltages are still reduced to utilization voltages of 440, 220 or 110 volts. Years ago, it was a common practice to use suitably interconnected three single-phase transformers instead of a single 3-phase transformer. But these days, the latter is gaining popularity because of improvement in design and manufacture but principally because of better acquaintance of operating men with the three-phase type. As compared to a bank of single-phase transformers are that it occupies less floor space for equal rating, weighs less, costs about 15% less and further, that only one unit is to be handled and connected.



Three phase transformer inner circuits

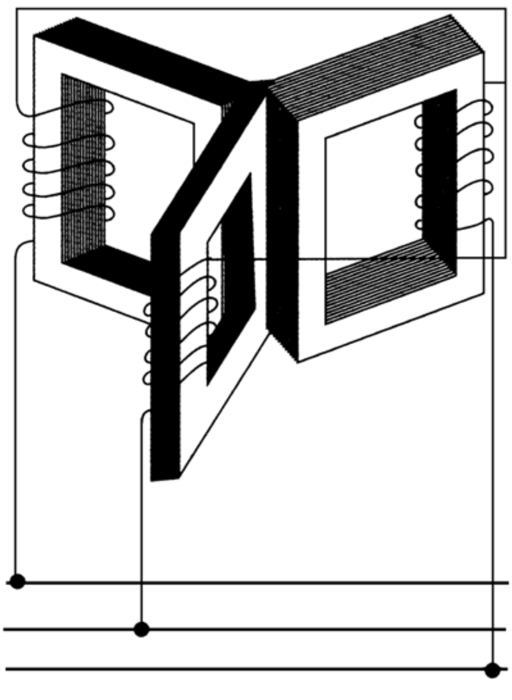


Fig. 11.24.

Like single-phase transformers, the three-phase transformers are also of the core type or shell type. The basic principle of a 3-phase transformer is illustrated in (Fig. 11.24) in which only primary windings have been shown interconnected in star and put across 3-phase supply. The three cores are 120^0 apart and their empty legs are shown in contact with each other. The centre leg, formed by these three, carries the flux produced by the three-phase currents I_R, I_Y and I_B. As at any instant $I_R + I_Y + I_B = 0$, hence the sum of three fluxes is also zero. Therefore, it will make no difference if the common leg is removed. In that case any two legs will act as the return for the third just as in a 3-phase system any two conductors act as the return for the current in the third conductor. This improved design is shown in [Fig. 11.25 (a)] where dotted rectangles indicate the three windings and numbers in the cores and yokes represent the directions and magnitudes of fluxes at a particular instant. It will be seen that at any instant, the amount of 'up' flux in any leg is equal to the sum of 'down' fluxes in the other two legs. The core type transformers are usually wound with circular cylindrical coils.

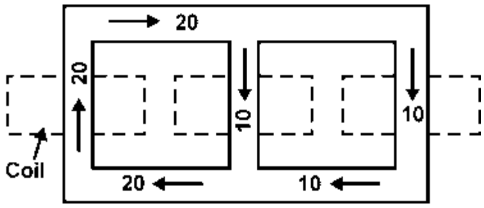
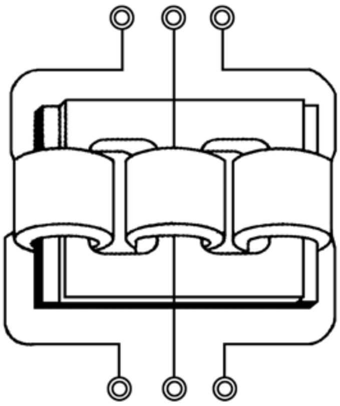


Fig. 11.25 (a).



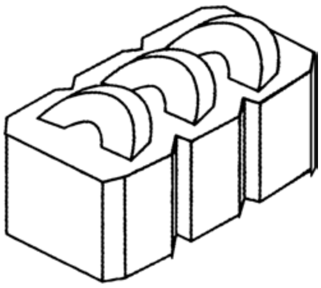
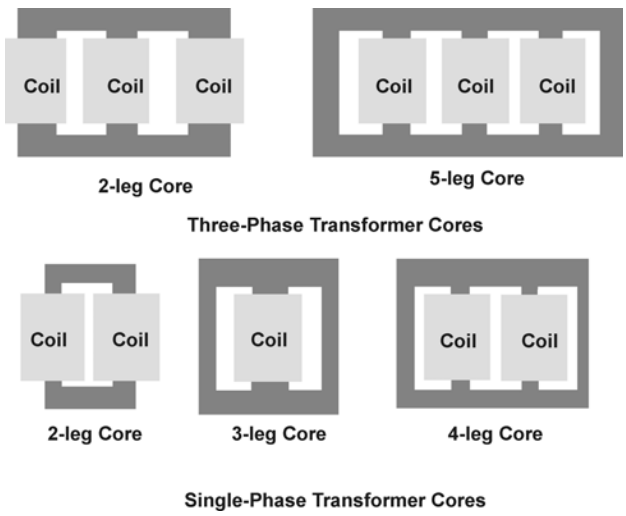


Fig. 11.25 (b). *Fig. 11.26.*

In a similar way, three single-phase shell type transformers can be combined together to form a 3-phase shell type unit as shown in [Fig. 11.25 (b)]. But some saving in iron can be achieved in constructing a single 3-phase transformer as shown in (Fig. 11.26). It does not differ from three single-phase transformers put side by side. Saving in iron is due to the joint use of the magnetic paths between the coils. The three phases, in this case, are more independent than they are in the core type transformers, because each phase has a magnetic circuit independent than they are in the core type transformers, because each phase has a magnetic circuit independent of the other.



One main drawback in a 3-phase transformer is that if any one phase becomes disabled, then the whole transformer has to be ordinarily removed from service for repairs (the shell type may be operated openΔ or Vee but this is not always feasible). However, in the case of a 3-phase bank of single-phase transformers, if one transformer goes out of order, the system can still be run open-Δ at reduced capacity or the faulty transformer can be readily replaced by a single spare.

Three-Phase Transformer Connections

There are various methods available for transforming 3-phase voltages to higher or lower 3-phase voltages i.e. for handling a considerable amount of power. The most common connections are (i) Y-Y (ii) Δ - Δ (iii) Y - Δ (iv) Δ-Y (v) open-delta or V-V (vi) Scott connection or T-T connection.

Star/Star or Y/Y Connection

This connection is most economical for small, high-voltage transformers because the number of turns/phase and the amount of insulation required is minimum (as phase voltage is only $1/\sqrt{3}$ of line voltage). In (Fig.11.27) is shown a bank of 3 transformers connected in Y on both the primary and the secondary sides. The ratio of line voltages on the primary and secondary sides is the same as the transformation ratio of each transformer. However, there is a phase shift of 30^o between the phase voltages and line voltages both on the primary and secondary sides. Of course, line voltages on both sides as well as primary voltages are respectively in phase with each other. This connection works satisfactorily only if the load is balanced. With the unbalanced load to the neutral, the neutral point shifts thereby making the three line-to-neutral (i.e.phase) voltages unequal.

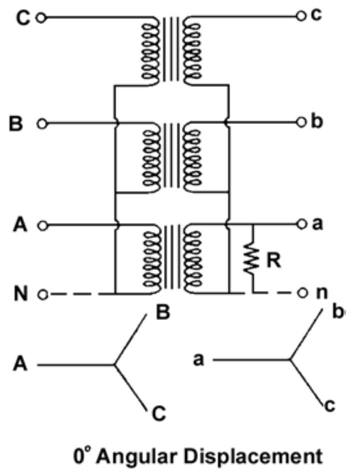


Fig. 11.27.

Delta-Delta or Δ - Δ Connection

This connections is economical for large, low-voltage transformers in which insulation problem is not so urgent, because it increases the number of turns/phase. The transformer connections and voltage triangles are shown in (Fig.11.28). The ratio of transformation between primary and secondary line voltage is exactly the same as that of each transformer. Further, the secondary voltage triangle abc occupies the same relative position as the primary voltage triangle ABC i.e. there is no angular displacement between the two. Moreover, there is no internal phase shift between phase and line voltages on either side as was the case in Y-Y connection. This connection has the following advantages:

1. As explained above, in order that the output voltage be sinusoidal, it is necessary that the magnetising current of the transformer must contain a third harmonic component. In this case, the third harmonic component of the magnetising current can flow in the Δ - connected transformer primaries without flowing in the line wires. The three phases are 120^o apart which is $3\times120 = 360^o$ with respect to the third harmonic, hence it merely circulates in the Δ. Therefore, the flux is sinusoidal which results in sinusodial voltages.

2. No difficulty is experienced from unbalanced loading as was the case in Y-Y connection. The three-phase voltages remain practically constant regardless of load imbalance.

3. An added advantage of this connection is that if one transformer becomes disabled, the system can continue to operate in open-delta or in V-V although with reduced available capacity. The reduced capacity is 58% and not 66.7% of the normal value.

Wye/Delta or Y/Δ Connection

The main use of this connection is at the substation end of the transmission line where the voltage is to be stepped down. The primary winding is Y-connected with grounded neutral as shown in (Fig.11.29). The ratio between the secondary and primary line voltage is $1/\sqrt{3}$ times the transformation ratio of each transformer. There is a 30^o shift between the primary and secondary line voltages which means that a Y-Δ transformer bank cannot be paralleled with either a Y-Y or a Δ - Δ bank. Also third harmonic currents flows in the Δ to provide a sinusoidal flux.

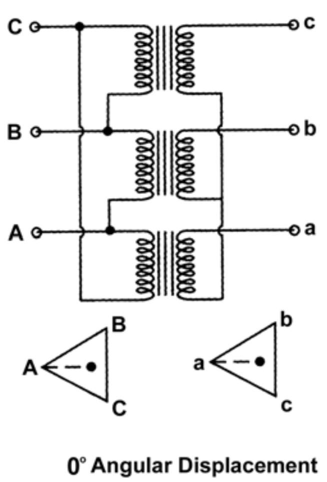


Fig. 11.28.

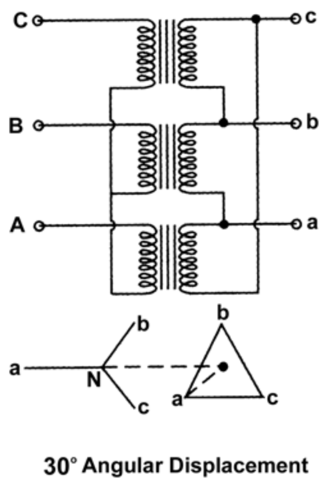


Fig. 11.29.

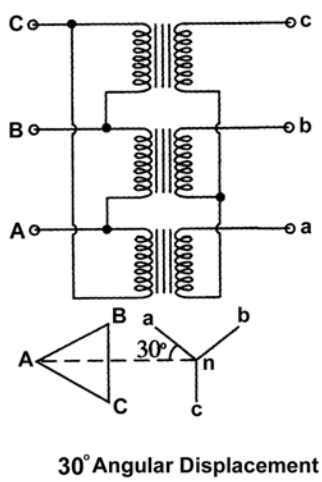


Fig. 11.30.

Delta/Wye or Δ /Y Connection

This connection is generally employed where it is necessary to step up the voltage as for example, at the beginning of high tension transmission system. The connection is shown in (Fig.11.30). The neutral of the secondary is grounded for providing 3-phase 4-wire service. In recent years, this connection has gained considerable popularity because it can be used to serve both the 3-phase power equipment and single-phase lighting circuits.

This connection is not open to the objection of a floating neutral and voltage distortion because the existence of a Δ-connection allows a path for the third-harmonic currents. It would be observed that the primary and secondary line voltages and line current are out of phase with each other by 30°. Because of this 30° shift, it is impossible to parallel such a bank with a Δ - Δ or Y-Y bank of transformers even though the voltage ratios are correctly adjusted. The ratio of secondary of primary voltage is $\sqrt{3}$ times the transformation ratio of each transformer.

Open-Delta or V-V connection

If one of the transformers of a Δ - Δ is removed and 3-phase supply is connected to the primaries as shown in (Fig.11.31), then three equal 3-phase voltages will be available at the secondary terminals on no-load. This method of transforming 3-phase power by means of only two transformers is called the open -Δ or V - V connection.

It is employed :

1. when the three-phase load is too small to warrant the installation of full three-phase transformer bank.
2. when one of the transformers in a Δ - Δ bank is disabled, so that service is continued although at reduced capacity, till the faulty transformer is repaired or a new one is substituted.
3. when it is anticipated that in future the load will increase necessitating the closing of open delta.

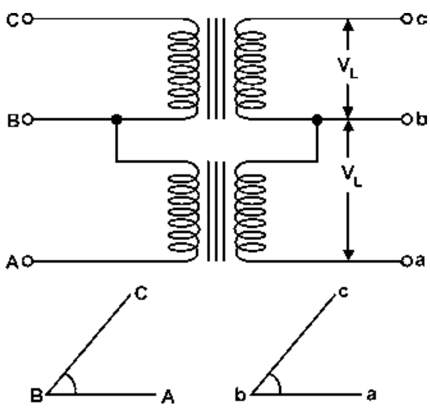


Fig. 11.31.

One important point to note is that the total load that can be carried by a V-V bank is not two-third of the capacity of a Δ - Δ bank but it is only 57.7% of it. That is a reduction of 15% (strictly, 15.5%) from its normal rating. Suppose there is Δ - Δ bank of three 10-kVA transformers. When one transformer is removed, then it runs in V-V. The total rating of the two transformers is 20kVA.

Scott Connection or T-T Connection

This is a connection by which 3-phase to 3-phase transformation is accomplished with the help of two transformers as shown in (Fig. 11.32). Since it was first proposed by Charles F. Scott, it is frequently referred to as Scott connection. This connection can also be used for 3-phase to 2-phase transformation.

One of the transformers has centre taps both on the primary and secondary windings (Fig. 11.32) and is known as the main transformer. It forms the horizontal member of the connection (Fig. 11.33).

The other transformer has a 0.866 tap and is known as teaser transformer. One end of both the primary and secondary of the teaser transformer is joined to the centre taps on both primary and secondary of the main transformer is joined to the centre taps on both primary and secondary of the main transformer respectively as shown in Fig. 11.33 (a). The other end A of the teaser primary and the two ends B and C of the main transformer primary are connected to the 3-phase supply.

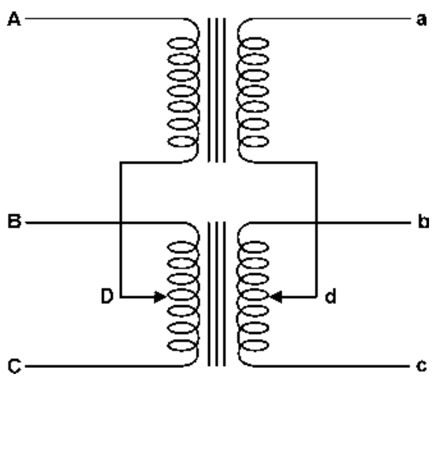


Fig. 11.32.

Connecting Transformers in A.C. Circuits

Before studying the various means of connecting transformers in a.c. circuits, the differences between single-phase and three-phase and three-phase circuits must be clearly understood. In a single-phase circuit the voltage is generated by one alternator coil. This single-phase voltage may be taken from a single-phase alternator, or from one phase of a three-phase alternator, as explained later in the study of a.c. generators.

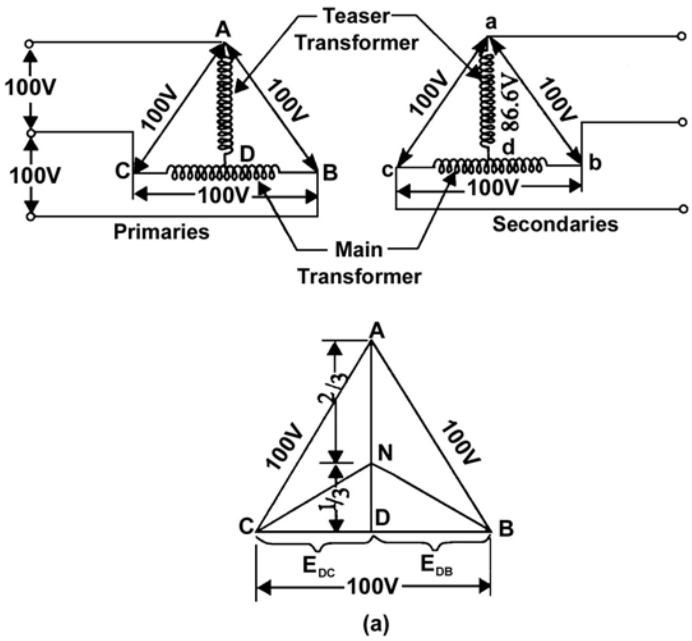


Fig. 11.33.

In a three-phase circuit three voltages are generated by an alternator with three coils so spaced within the alternator that the three voltages generated are equal but reach their maximum values at different times. In each phase of a 400-cycle, three-phase generator, a cycle is generated every 1_{400} second.

In its rotation, the magnetic pole passes one coil and generated a maximum voltage; one-third cycle (1/1200 second) later, this same pole passes another coil and generates a maximum voltage in it; and the next one-third cycle later, it passes still another coil and generates a maximum voltage in it. This causes the maximum voltages generated in the three coils always to be one-third cycle (1/1200 second) apart.

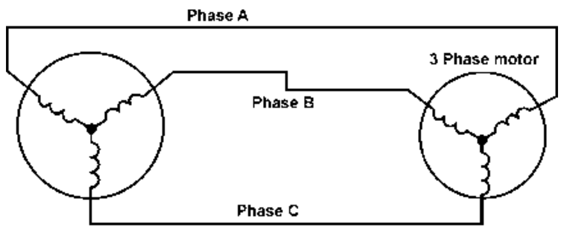


Fig. 11.34. Three-phase generator using a three conductors.

The early three-phase generators were connected to their loads with six wires and all six leads in the circuit carried the current. Later, experiments proved that the generator would furnish as much power with the coils connected so that only three wires were needed for all three phases as shown in (Fig. 11.34). The use of three wires is standard for the transmission of three-phase power today. The return current from any one alternator coil always flows back through the other two wires in the three-phase circuit.

Three-phase motors and other three-phase loads are connected with their coils or load elements arranged so that three transmission lines are required for delivery of power. Transformers that are used for stepping the voltage up or down in a three-phase circuit are electrically connected so that power is delivered to the primary and taken from the secondary by the standard three-wire system.

However, single-phase transformers and single-phase lights and motors may be connected across any one phase of a three-phase circuit, as shown in (Fig. 11.35). When single-phase loads are connected to three-phase circuits, the loads are distributed equally among the three phases in order to balance the loads on the three generator coils.

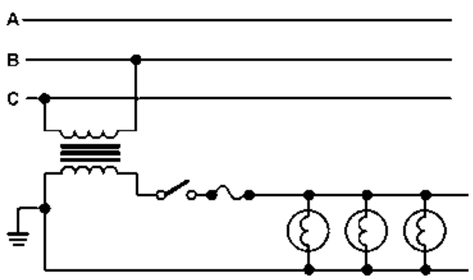


Fig. 11.35. Step-down transformer using two-wire system.

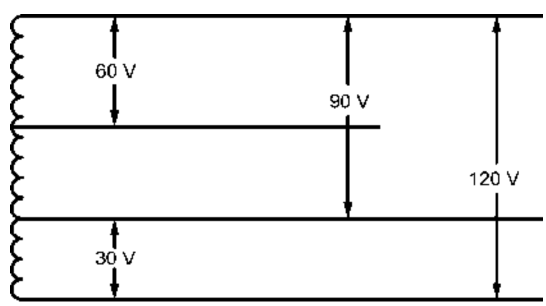


Fig. 11.36. Tapped transformer secondary.

Another use of the transformer is the single-phase transformer with several taps in the secondary. With this type of transformer, the voltage can be lowered to provide several working voltages, as shown in (Fig. 11.36).

A center tapped transformer, powering a motor requiring 220 volts along with four lights requiring 110 volts, is shown in (Fig. 11.37). The motor is connected across the entire transformer output, and the lights are connected from the center tap to one end of the transformer. With this connection only half of the secondary output is used.

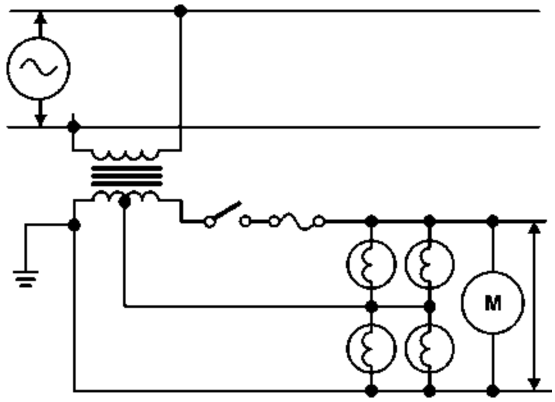


Fig. 11.37. Step-down transformer using a three-wire system.

This type of transformer connection is used extensively on aircraft because of the combinations of voltages that can be taken from one transformer. Various voltages can be picked off the secondary winding of the transformer by inserting taps (during manufacture) at various points along the secondary windings.

The various amounts of voltage are obtained by connecting to any two taps or to one tap and either end.

Transformers fro three-phase circuits can be connected in any one of several combinations of the wye (y) and delta (Δ) connections. The connection used depends on the requirements for the transformer.

When the wye connection is used in three-phase transformers, a fourth or neutral wire may be used. The neutral wire connects single-phase equipment to the transformer. Voltages (115 V) between any one of the three-phase lines and the neutral wire can be used for power for device such as lights or single-phase motors.

In combination, all four wires can furnish power at 208 volts, three-phase, for operating three-phase equipment, such as three-phase motors or rectifiers when only 3 phase equipment is used, the ground wire may be omitted. This leaves a three-phase, three-wire system as illustrated in (Fig. 11.38).

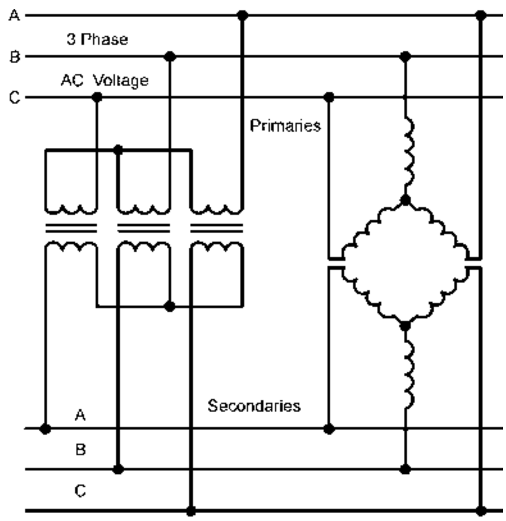


Fig. 11.38. Wye-to-wye connection.

Fig. 11.39 shows the primary and secondary with a delta connection. With this type of connection the transformer has the same voltage output as the line voltage. Between any two phases the voltage is 240 volts. In this type of connection, wires A, B, and C can furnish 240-volt, three-phase power for the operation of three-phase equipment.

The type of connection used for the primary coils may or may not be the same as the type of connection used for the secondary coils. For example, the primary may be a delta connection and the secondary a wye connection. Other combinations are delta-delta, wye-delta, and wye-wye.

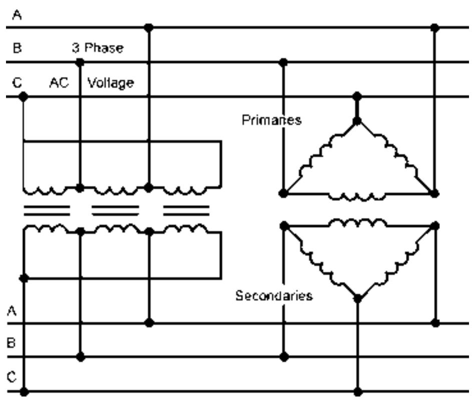


Fig. 11.39. Delta-to-delta connection.

Troubleshooting Transformers

There are occasions when a transformer must be checked for opens or shorts, and it is often necessary to determine that a transformer is a step-up or step-down transformer.

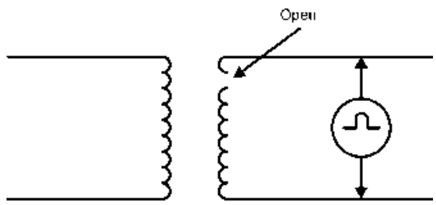


Fig. 11.40. Checking for an open in a transformer winding.

An open winding in a transformer can be located by connecting an ohmmeter as shown in (Fig. 11.40). Connected as shown, the ohmmeter would read infinity. If there were no open in the coil, the ohmmeter would indicate the resistance of wire in the coil, Both primary and secondary can be checked in the same manner.

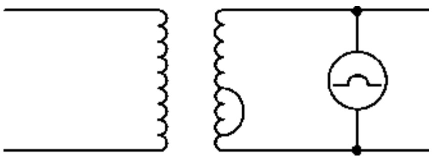


Fig. 11.41. Checking for shorted transformer windings.

The ohmmeter may also be used to check for shorted windings, as shown in (Fig. 11.41), however, this method is not always accurate. If, for example, the transformer had 500 turns and a resistance of 2 ohms, and 5 turns were shorted out, the resistance would be reduced to approximately 1.98 ohms, which is not enough of a change to be read on the ohmmeter. In this case, the rated input voltage can be applied to the primary to permit measurement of the secondary output voltage. If the secondary voltage is low, it can be assumed that the transformer has some shorted windings and the transformer should be replaced. If the output voltage is then normal, the original transformer can be considered defective.

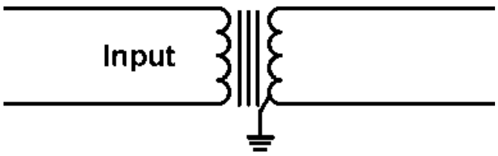


Fig. 11.42. Part of a transformer winding grounded.

An ohmmeter can be used to determine whether a transformer is a step-up or step-down transformer. In a step-down transformer, the resistance of the secondary will be less than that of the primary, and the opposite will be true in the case of a step-up transformer. Still another method involves applying a voltage to the primary and measuring the secondary output. The voltages used should not exceed the rated input voltage of the primary.

If a winding is completely shorted, it usually becomes overheated because of the high value of current flow. In many cases, the high heat will melt the wax in the transformer, and this can be detected by the resulting odor. Also, a voltmeter reading across the secondary will read zero. If the circuit contains a fuse, the heavy current may cause the fuse to blow before the transformer is heavily damaged.

In a (Fig. 11.42) one point on a transformer winding is shown connected to ground. If the external circuit of the transformer circuit is grounded, a part of the winding is effectively shorted. A megger connected between one side of the winding and the transformer case (ground) will verify this condition with a low or zero reading. In such a case, the transformer must be replaced.

All transformers discussed in this section are designed with one primary winding. They operate on a single source of a.c. transformers which operate from three voltages from an alternator or ac generator, are called three-phase or poly-phase transformers. These transformers will be discussed in the study of generators and motors.

■■■

CHAPTER - 12
KNOWLEDGE OF CONSTRUCTION, PRINCIPLES OF OPERATION OF SATURABLE REACTORS AND MAGNETIC AMPLIFIERS, BIAS, PHASE SENSITIVE HALF WAVE AND INPUTS AND OUTPUTS, POLARITY SENSITIVE INPUTS AND OUTPUTS, PUSH PULL OUTPUTS AND EFFECT OF STAGE GAINS AND CASCADING ON TIME RESPONSE.

MAGNETIC AMPLIFIERS

The magnetic amplifier is a control device being employed at an increasing rate in many aircraft electrical and electronic systems. This is because of its ruggedness, stability, and safety in comparison to vacuum tubes.

The principles on which the magnetic amplifier operates can best be explained by reviewing the operation of a simple transformer. If an a.c. voltage is applied to the primary of an iron core transformer, the iron core will be magnetized and demagnetized at the same frequency as that of the applied voltage. This, in turn, will induce a voltage in the transformer secondary. The output voltage across the terminals of the secondary will depend on the relationship of the number of turns in the primary and the secondary of the transformer.

The iron core of the transformer has a saturation point after which the application of a greater magnetic force will produce no change in the intensity of magnetization. Hence, there will be no change in transformer output, even if the input is greatly increased.

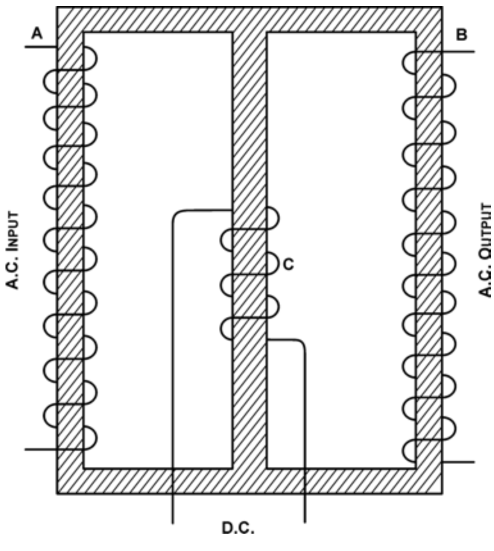


Fig. 12.1. Magnetic amplifier circuit.

The magnetic amplifier circuit in (Fig. 12.1) will be used to explain how a simple magnetic amplifier functions. Assume that there is 1 ampere of current in coil A, which has 10 turns of wire. If coil B has 10 turns of wire, an output of 1 ampere will be obtained if coil B is properly loaded. By applying direct current to coil C, the core of the magnetic amplifier coil can be further magnetized. Assume that coil C has the proper number of turns and, upon the application of 30 milli amperes, that the core is magnetized to the point where 1 ampere on coil A results in only 0.24 ampere output from the coil B.

By making the d.c. input to coil C continuously variable from 0 to 30 milliamperes and maintaining an input of 1 ampere on coil A, it is possible to control the output of coil B to any point between 0.24 ampere and 1 ampere in this example. The term "amplifier" is used for this arrangement because, by use of a few milliamperes, control of an output of 1 or more amperes is obtained.

The same procedure can be used with the circuit shown in (Fig. 12.2).

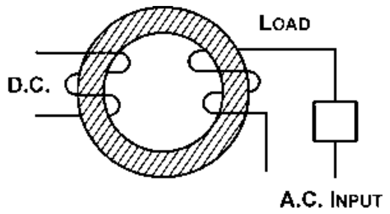


Fig. 12.2. Saturable reactor circuit.

By controlling the extent of magnetization of the iron ring, it is possible to control the amount of current flowing to the load, since the amount of magnetization controls the impedance of the a.c. input winding. This type of magnetic amplifier is called a simple saturable reactor circuit.

Adding a rectifier to such a circuit would remove half the cycle of the a.c. input and permit a direct current to flow to the load. The amount of d.c. flowing in the load circuit is controlled by a d.c. control winding (sometimes referred to as bias). This type of magnetic amplifier is referred to as being self-saturating.

In order to use the full a.c. input power, a circuit such as that shown in (Fig. 12.3) may be used. This circuit uses full-wave bridge rectifier. The load will receive a controlled direct current by using the full a.c. input. This type of circuit is known as a self-saturating, full-wave magnetic amplifier.

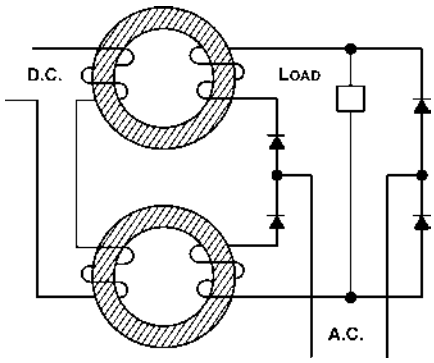


Fig. 12.3. Self-saturating, full-wave magnetic amplifier.

In (Fig. 12.4) it is assumed that the d.c. control winding is supplied by a variable source, such as a sensing circuit. In order to control such a source and use its variations to control the a.c. output, it is necessary to include another d.c. winding that has a constant value. This winding, referred to as the reference winding, magnetizes the magnetic core in one direction.

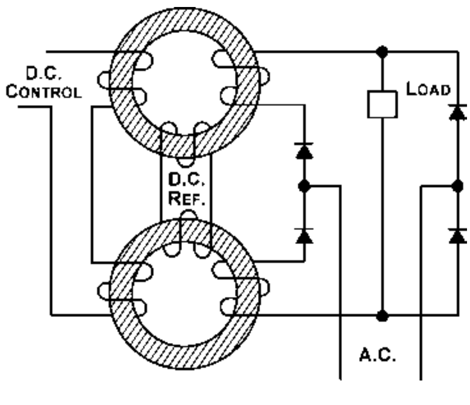


Fig. 12.4. Basic preamplifier circuit.

The d.c. control winding, acting in opposition to the reference winding, either increases (degenerative) or decreases (regenerative) the magnetization of the core to change the amount of current flowing through the load. This is essentially a basic preamplifier.

SINGLE STAGE TRANSISTOR AMPLIFIER

When only one transistor with associated circuitry is used for amplifying a weak signal, the circuit is known as single stage transistor amplifier.

A single stage transistor amplifier has one transistor, bias circuit and other auxiliary components. Although a practical amplifier consists of a number of stages, yet such a complex circuit can be conveniently split up into separate single stages. By analysing carefully only a single stage and using this single stage analysis repeatedly, we can effectively analyse the complex circuit. It follows, therefore, that single stage amplifier analysis is of great value in understanding the practical amplifier circuits.

HOW TRANSISTOR AMPLIFIES?

Fig 12.5 shows a single stage transistor amplifier. When a weak a.c. signal is given to the base of transistor, a small base current (which is a.c.) starts flowing. Due to transistor action, a much larger (β times the base current) a.c. current flows through the collector load R_C . As the value of R_C is quite high (usually 4-10 k Ω), therefore, a large voltage appears across R_C. Thus, a weak signal applied in the base circuit appears in amplified form in the collector circuit. It is in this way that a transistor acts as an amplifier.

The action of transistor amplifier can be beautifully explained by referring to (Fig. 12.5). Suppose a change of 0.1 V in signal voltage produces a change of 2 mA in the collector current. Obviously, a signal of only 0.1 V applied to the base will give an output voltage = 2mA x 5 k Ω =10V. Thus, the transistor has been able to raise the voltage level of the signal from 0.1V to 10V i.e. voltage amplification or stage gain is 100.

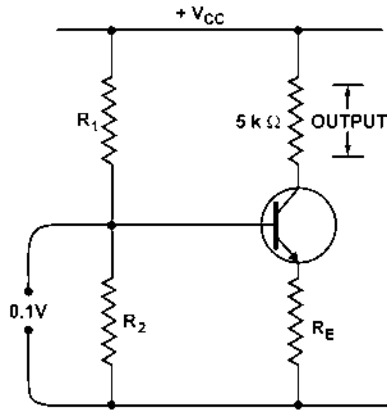


Fig. 12.5.

PRACTICAL CIRCUIT OF TRANSISTOR AMPLIFIER

It is important to note that a transistor can accomplish faithful amplification only if proper associated circuitry is used with it. (Fig. 12.6) shows a practical single stage transistor amplifier. The various circuit elements and their functions are described below:

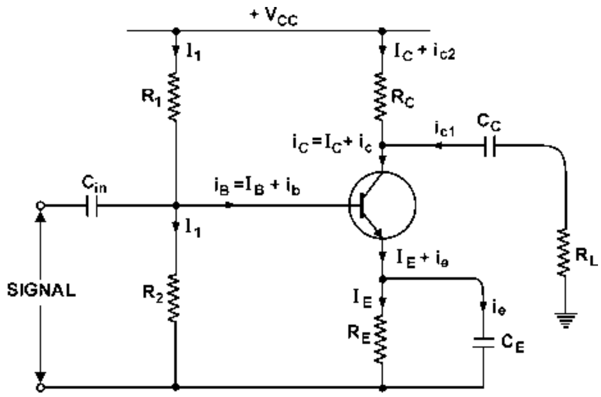


Fig. 12.6.

(I) BIASING CIRCUIT

The resistances R_1 R_2 and R_3 form the biasing and stabilisation circuit. The biasing circuit must establish a proper operating point otherwise a part of the negative half-cycle of the signal may be cut off in the output.

(II) INPUT CAPACITOR C_{in}

An electrolytic capacitor C_{in} ($\simeq$ 10 μ F) is used to couple the signal to the base of the transistor. If it is not used, the signal source resistance will come across R_2 and thus change the bias. The capacitor C_{in} allows only a.c. signal to flow but isolates the signal source from R_2.

(III) EMITTER BYPASS CAPACITOR C_E

An emitter bypass capacitor C_E ($\simeq$ 100 μ F) is used in parallel with R_E to provide a low reactance path to the amplified a.c. signal. If it is not used, then amplified a.c. signal flowing through R_E will cause a voltage drop across it, thereby reducing the output voltage.

(IV) COUPLING CAPACITOR C_C

The coupling capacitor C_C ($\simeq 10\ \mu$ F) couples one stage of amplification to the next stage. If it is not used, the bias conditions of the next stage will be drastically changed due to the shunting effect of R_C. This is because R_C will come in parallel with the upper resistance R_1 of the biasing network of the next stage, thereby altering the biasing conditions of the latter. In short, the coupling capacitor C_C isolated the d.c. of one stage from the next stage, but allows the passage of a.c. signal.

VARIOUS CIRCUIT CURRENTS

It is useful to mention the various currents in the complete amplifier circuit. These are shown in the circuit of (Fig. 12.6).

I BASE CURRENT

When no signal is applied in the base circuit, d.c. base current I_B flows due to biasing circuit. When a.c. signal is applied, a.c. base current i_c is flows. Therefore, with the application of signal, total base current i_B is given by.

$i_B = I_B + i_b$

II COLLECTOR CURRENT

When no signal is applied, a d.c. collector current I_C flows due to biasing circuit. When a.c. signal is applied, a.c. collector current i_c also flows. Therefore, the total collector current i_C is given by.

where $i_C = I_C + i_c$

$I_C = \beta I_B =$ zero signal collector current

$i_c = \beta i_b =$ collector current due to signal.

III EMITTER CURRENT

When no signal is applied, a d.c. emitter current I_E flows. With the application of signal, total emitter current i_E is given by;

$i_E = I_E + i_e$

It is useful to keep in mind that :

$I_E = I_B + I_C$

$i_e = i_b + i_c$

Now base current is usually very small, therefore, as a reasonable approximation,

$I_E \simeq I_C$ and $i_e \simeq i_c$

Phase Reversal

In common emitter connection, when the input signal voltage increases in the positive sense, the output voltage increases in the negative direction and vice-versa. In other words, there is a phase difference of $180°$ between the input and output voltage in CE connection. This is called phase reversal.

Consider a common emitter amplifier circuit shown in (Fig. 12.7). The signal is fed at the input terminals (i.e. between base and emitter) and output is taken from collector and emitter end of supply. The total instantaneous output voltage v_{CE} is given by;

$v_{CE} = V_{CC} - i_C R_C$

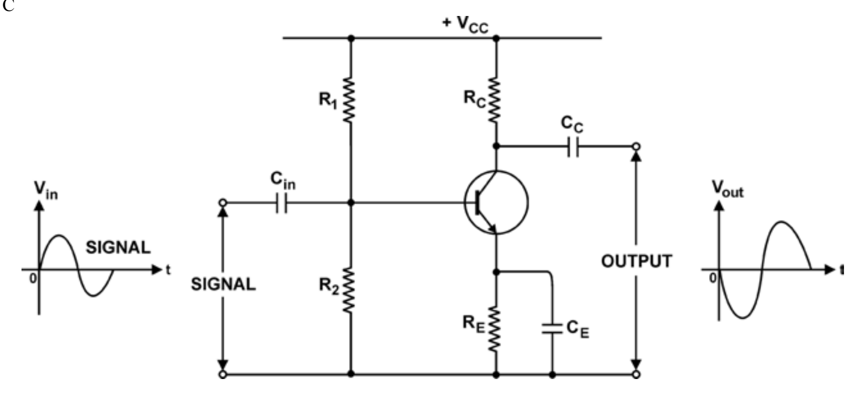


Fig. 12.7.

When the signal voltage increases in the positive half-cycle, the base current also increases. The result is that collector current and hence voltage drop $i_C R_C$ increases. As V_{CC} is constant, therefore, output voltage v_{CE} decreases. In other words, as the signal voltage is increasing in the positive half cycle, the output voltage is increasing in the negative sense i.e. output is 180^o out of phase with the input. It follows, therefore, that in a common emitter amplifier, the positive half-cycle of the signal appears as amplified negative half-cycle in the output and vice-versa. It may be noted that amplification is not affected by this phase reversal.

Classification of Amplifiers

The transistor amplifiers may be classified as to their usage, frequency capabilities, coupling methods and mode of operation.

(i) **According to use.** The classifications of amplifiers as to usage are basically voltage amplifiers and power amplifiers. The former primarily increases the voltage level of the signal whereas the latter mainly increases the power level of the signal.

(ii) **According to frequency capabilities.** According to frequency capabilities, amplifiers are classified as audio amplifiers, radio frequency amplifiers etc. The former are used to amplify the signals lying in the audio range i.e. 20 Hz to 20 kHz whereas the latter are used to amplify signals having very high frequency.

(iii) **According to coupling methods.** The output from a single stage amplifier is usually insufficient to meet the practical requirements. Additional amplification is often necessary. To do this, the output of one stage is coupled to the next stage. Depending upon the coupling device used, the amplifiers are classified as R-C coupled amplifiers, transformer coupled amplifiers etc.

(iv) **According to mode of operation.** The amplifiers are frequently classified according to their mode of operation as class A, class B and class C amplifiers. This classification depends on the portion of the input signal cycle during which collector current is expected to flow. Thus, class A amplifier is one in which collector current flows for the entire a.c. signal. Class B amplifier is one in which collector current flows for half-cycle of input a.c. signal. Finally, class C amplifier is one in which collector current flows for less than half-cycle of a.c. signal.

Multistage Transistor Amplifier

A transistor circuit containing more than one stage of amplification is known as multistage transistor amplifier.

In a multistage amplifier, a number of single amplifiers are connected in cascade arrangement i.e. output of first stage is connected to the input of the second stage through a suitable coupling device and so on. The purpose of coupling device (e.g. a capacitor, transformer etc.) is (i) to transfer a.c. output of one stage to the input of the next stage and (ii) to isolate the d.c. conditions of one stage from the next stage. (Fig. 12.8) shows the block diagram of a 3-stage amplifier. Each stage consists of one transistor and associated circuitry and is coupled to the next stage through a coupling device.

The name of the amplifier is usually given after the type of coupling used. e.g.

Name of coupling	**Name of multistage amplifier**
RC coupling	R-C coupled amplifier
Transformer coupling	Transformer coupled
Direct coupling	Direct coupled amplifier

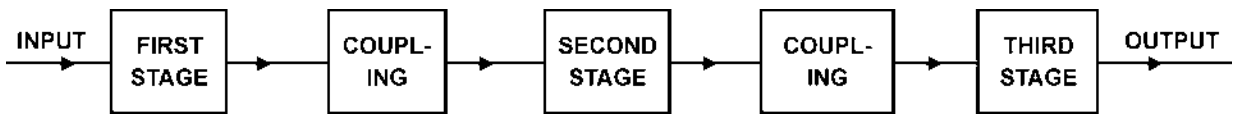


Fig. 12.8.

(i) In RC coupling, a capacitor is used as the coupling device. The capacitor connects the output of one stage to the input of the next stage in order to pass the a.c. signal on while blocking the d.c. bias voltages.

(ii) In transformer coupling, transformer is used as the coupling device. The transformer coupling provides the same two functions (viz. to pass the signal on and blocking d.c.) but permits in addition impedance matching.

(iii) In direct coupling or d.c. coupling, the individual amplifier stage bias conditions are so designed that the two stages may be directly connected without the necessity for d.c. isolation.

Important Terms

In the study of multistage amplifiers, we shall frequently come across the terms gain, frequency response, decibel gain and bandwidth. The terms stand discussed below :

(i) **Gain**

The ratio of the output electrical quantity to the input one of the amplifier is called its**gain**.

The gain of a multistage amplifier is equal to the product of gains of individual stages. For instance, if G_1, G_2, and G_3 are the individual voltage gains of a three-stage amplifier, then total voltage gain G is given by;

$$G = G_1 \times G_2 \times G_3$$

It is worthwhile to mention here that in practice, total gain G is less than $G_1 \times G_2 \times G_3$ due to the loading effect of next stages.

(ii) **Frequency response**

The voltage gain of an amplifier varies with signal frequency. It is because reactance of the capacitors in the circuit changes with signal frequency and hence affect the output voltage. The curve between voltage gain and signal frequency of an amplifier is known as frequency response. (Fig. 12.9) shows the frequency response of a typical amplifier. The gain of the amplifier increases as the frequency increases from zero till it becomes maximum at f_r, called resonant frequency. If the frequency of signal increases beyond f_r, the gain decreases.

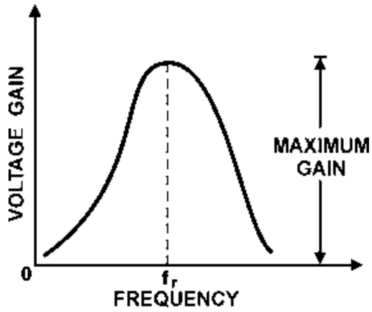


Fig. 12.9.

The performance of an amplifier depends to a considerable extent upon its frequency response. While designing an amplifier, appropriate steps must be taken to ensure that gain is essentially uniform over some specified frequency range. For instance, in case of an audio amplifier, which is used to amplify speech or music, it is necessary that all the frequencies in the sound spectrum (i.e. 20 Hz to 20 kHz) should be uniformly amplified other wise speaker will give a distorted sound output.

(iii) **Decibel gain**

Although the gain of an amplifier can be expressed as a number, yet it is of great practical importance to assign it a unit. The unit assigned is bel or decibel (db). Shown in (Fig. 12.10).

The common logarithm (log to the base 10) of power gain is known as **bel power gain** i.e.

$$\text{Power gain} = \log_{10} \frac{P_{out}}{P_{in}} \text{ bel}$$

1 bel = 10 db

$$\therefore \text{ Power gain } = 10 \log_{10} \frac{P_{out}}{P_{in}} \text{ db}$$

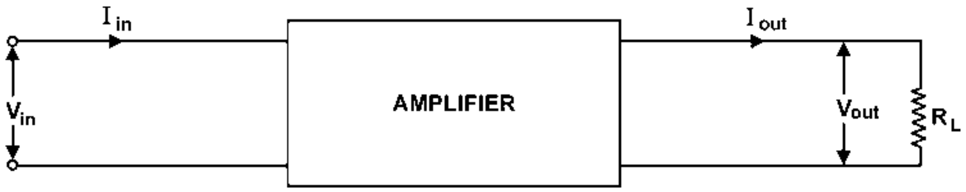


Fig. 12.10.

If the two powers are developed in the same resistance or equal resistances, then,

$$P_1 = \frac{V_{in}^2}{R} = I_{in}^2 R$$

$$P_2 = \frac{V_{out}^2}{R} = I_{out}^2 R$$

$$\therefore \text{ Voltage gain in db} = 10 \log_{10} \frac{V_{out}^2 / R}{V_{in}^2 / R} = 20 \log_{10} \frac{V_{out}}{V_{in}}$$

$$\text{Current gain in db } = 10 \log_{10} \frac{I_{out}^2 R}{I_{in}^2 R} = 20 \log_{10} \frac{I_{out}}{I_{in}}$$

Advantages

The following are the advantages of expressing the gain in db :

a. The unit db is a logarithmic unit. Out ear response is also logarithmic i.e. loudness of sound heard by ear is not according to the intensity of sound but according to the log of intensity of sound. Thus if the intensity of sound given by speaker (i.e. power) is increased 100 times, our ears hear a doubling effect ($\log_{10} 100 = 2$) i.e. as if loudness were doubled instead of made 100 times. Hence, this unit tallies with the natural response of our ears.

b. When the gains are expressed in db, the overall gain of a multistage amplifier is the sum of gains of individual stages in db. Thus referring to (Fig. 12.11).

$$\text{Gain as number} = \frac{V_2}{V_1} \times \frac{V_3}{V_2}$$

$$\text{Gain in db} = 20\log_{10}\frac{V_2}{V_1} \times \frac{V_3}{V_2}$$

$$= 20\log_{10}\frac{V_2}{V_1} + 20\log_{10}\frac{V_3}{V_2}$$

= 1st stage gain in db + 2nd stage gain in db

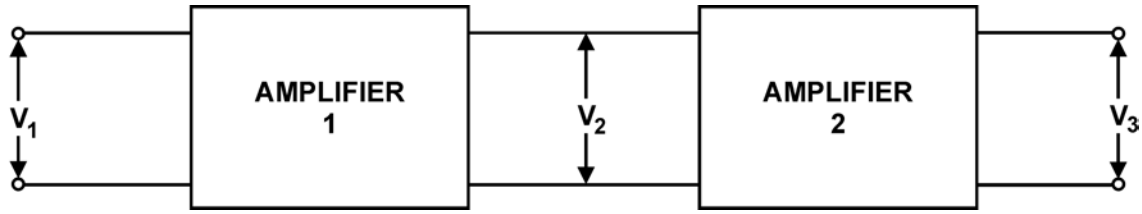


Fig. 12.11.

However, absolute gain is obtained by multiplying the gains of individual stages. Obviously, it is easier to add than to multiply.

(iv) **Bandwidth.** The range of frequency over which the gain is equal to or greater than 70.7% of the maximum gain is known as **bandwidth.**

The voltage gain of an amplifier changes with frequency. Referring to the frequency response in (Fig. 12.12), it is clear that for any frequency lying between f_1 and f_2 , the gain is equal to or greater than 70.7% of the maximum gain. Therefore, f_1-f_2 is the bandwidth. It may be seen that f_1 and f_2 are the limiting frequencies. The former (f_1) is called lower cut-off frequency and the latter (f_2) is known as upper cut-off frequency. For distortionless amplification, it is important that signal frequency range must be within the bandwidth of the amplifier.

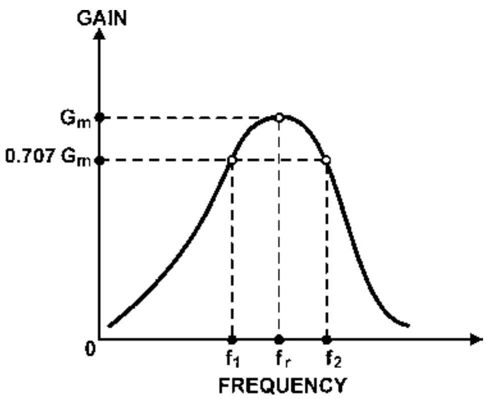


Fig. 12.12.

The bandwidth of an amplifier can also be defined in terms of db. Suppose the maximum voltage gain of an amplifier is 100. Then 70.7% of it is 70.7.

$\therefore$ Fall in voltage gain from maximum gain

$$= 20\log_{10} 100 - 20\log_{10} 70.7$$

$$= 20\log_{10}\frac{100}{70.7}\text{db}$$

$$= 20\log_{10} 1.4142\text{db} = 3\text{db}$$

Hence **bandwidth** of an amplifier is the range of frequency at the limits of which its voltage gain falls by 3 db from the maximum gain.

The frequency f_1 or f_2 is also called 3-db frequency or half-power frequency.

The 3-db designation comes from the fact that voltage gain at these frequencies is 3db below the maximum value. The term half-power is used because when voltage is down to 0.707 of its maximum value, the power (proportional to V^2) is down to $(0.707)^2$ or one-half of its maximum value.

RC Coupled Transistor Amplifier

This is the most popular type of coupling because it is cheap and provides excellent audio fidelity over a wide range of frequency. It is usually employed for voltage amplification. (Fig. 12.13) shows two stages of an RC coupled amplifier. A coupling capacitor C_C is used to connect the output of first stage to the base (i.e. input) of the second stage and so on. As the coupling from one stage to next is achieved by a coupling capacitor followed by connection to a shunt resistor, therefore, such amlifiers are called resistance - capacitance coupled amplifiers.

The resistances R_1, R_2 and R_E form the biasing and stabilisation network. The emitter bypass capacitor offers low reactance path to the signal. Without it, the voltage gain of each stage would be lost. The coupling capacitor C_C transmits a.c. signal but blocks d.c. This prevents d.c. interference between various stages and the shifting of operating point.

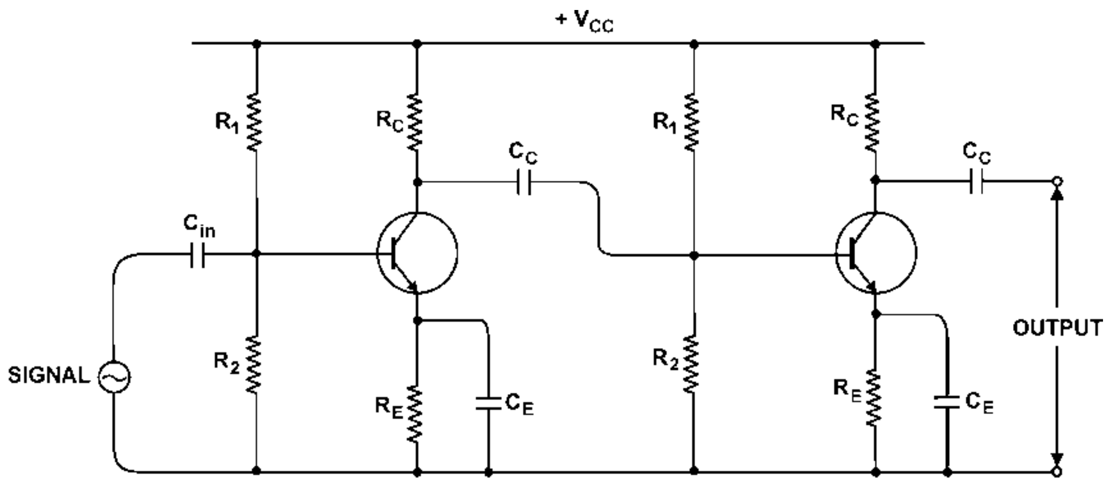


Fig. 12.13.

Operation

When a.c. signal is applied to the base of the first transistor, it appears in the amplified form across its collector load R_C. The amplified signal developed across R_C is given to base of next stage through coupling capacitor C_C. The second stage does further amplification of the signal. In this way, the cascaded (one after another) stages amplify the signal and the overall gain in considerably increased.

It may be mentioned here that total gain is less than the product of the gains of individual stages. It is because when a second stage is made to follow the first stage, the effective load resistance of first stage is reduced due to the shunting effect of the input resistance of second stage. This reduces the gain of the stage which is loaded by the next stage. For instance, in a 3-stage amplifier, the gain of first and second stages will be reduced due to loading effect of next stage. However, the gain of the third stage which has no loading effect of subsequent stage, remains unchanged. The overall gain shall be equal to the product of the gains of three stages.

Advantages

(i) It has excellent frequency response. The gain is constant over the audio frequency range which is the region of most importance for speech, music etc.

(ii) It has lower cost since it employs resistors and capacitors which are cheap.

(iii) The circuit is very compact as the modern resistors and capacitors are small and extremely light.

Disadvantages

(i) The RC coupled amplifiers have low voltage and power gain. It is because the low resistance presented by the input of each stage to the preceding stage decreases the effective load resistance (R_{AC}) and hence the gain.

(ii) They have the tendency to become noisy with age, particularly in moist climates.

(iii) Impedance matching is poor. It is because the output impedance of RC coupled amplifier s several hundred ohms whereas the input impedance of a speaker is only a few ohms. Hence, little power will be transferred to the speaker.

Applications

The RC coupled amplifiers have excellent audio fidelity over a wide range of frequency. Therefore, they are widely used as voltage amplifiers e.g. in the initial stages of public address system. If other type of coupling (e.g. transformer coupling) is employed in the initial stages, this results in frequency distortion which may be amplified in next stages. However, because of poor impedance matching, RC coupling is rarely used in the final stages.

Transformer-Coupled Amplifier

The main reason for low voltage and power gain of RC coupled amplifier is that the effective load (R_{AC}) of each stage is decreased due to the low resistance presented by the input of each stage to the preceding stage. If the effective load resistance of each stage could be increased, the voltage and power gain could be increased. This can be achieved by transformer coupling. By the use of impedance-changing properties of transformer, the low resistance of a stage (or load) can be reflected as a high load resistance to the previous stage.

Transformer coupling is generally employed when the load is small. It is mostly used for power amplification. (Fig. 12.14) shows two stages of transformer coupled amplifier. A coupling transformer is used to feed the output of one stage to the input of the next stage. The primary P of this transformer is made the collector load and its secondary S gives input to the next stage.

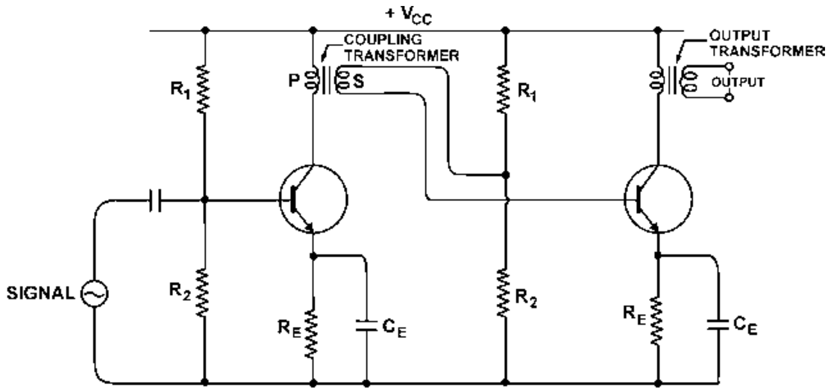


Fig. 12.14.

Operation

When an a.c. signal is applied to the base of first transistor, it appears in the amplified form across primary P of the coupling transformer. The voltage developed across primary is transferred to the input of the next stage by the transformer secondary as shown in (Fig. 12.14). The second stage renders amplification in an exactly similar manner.

Advantages

(i) No signal power is lost in the collector or base resistors.

(ii) An excellent impedance mathching can be achieved in a transformer coupled amplifier. It is easy to make the inductive reactance of primary equal to the output impedance of the transistor and inductive reactance of secondary equal to the input impedance of next stage.

(iii) Due to excellent impedance matching, transformer coupling provides higher gain. As a matter of fact, a single stage of properly designed transformer coupling can provide the gain of two stages of RC coupling.

Disadvantages

(i) It has a poor frequency response i.e. the gain varies considerably with frequency.

(ii) The coupling transformers are bulky and fairly expensive at audio frequencies.

(iii) Frequency distortion is higher i.e. low frequency signals are less amplified as compared to the high frequency signals.

(iv) Transformer coupling tends to introduce hum in the output.

Applications

Transformer coupling is mostly employed for impedance matching. In general, the last stage of a multistage amplifier is the power stage. Here, a concentrated effort is made to transfer maximum power to the output device e.g. a loudspeaker. For maximum power transfer, the impedance of power source should be equal to that of load. Usually, the impedance of an output device is a few ohms whereas the output impedance of transistor is several hundred times this value. In order to match the impedance, a step-down transformer of proper turn ratio is used. The impedance of secondary of the transformer is made equal to the load impedance and primary impedance equal to the output impedance of transistor.

Direct-Coupled Amplifier

There are many applications in which extremely low frequency (<10 Hz) signals are to be amplified e.g. amplifying photo-electric current, thermo-couple current etc. The coupling devices such as capacitors and transformers cannot be used because the electrical sizes of these components become very large at extremely low frequencies. Under such situations, one stage is directly connected to the next stage without any intervening coupling device. This type of coupling is known as direct coupling.

Circuit details

Fig. 12.15 shows the circuit of a three-stage direct-coupled amplifier. It uses complementary transistor. Thus, the first stage uses npn transistor, the second stage uses pnp transistor and so on. This arragnement makes the design very simple. The output from the collector of first transistor T_1 is fed to the input of the second transistor T_2 and so on.

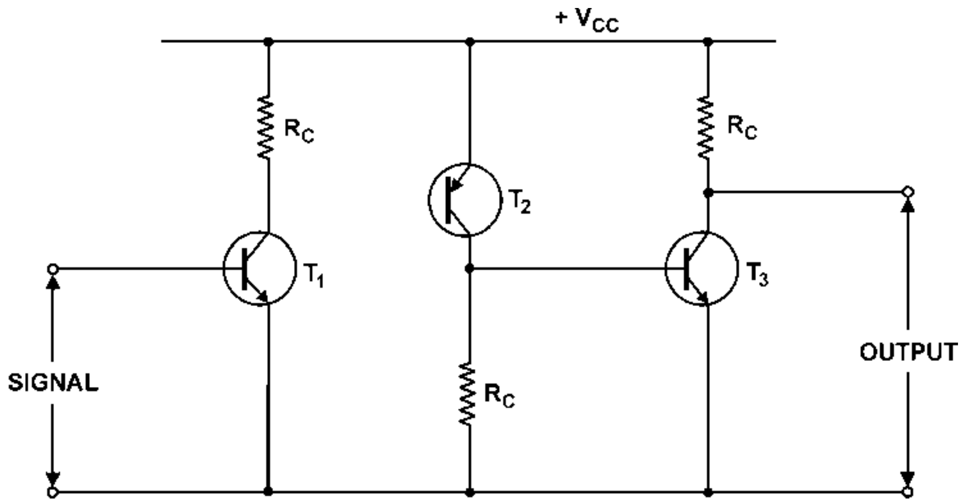


Fig. 12.15.

The weak signal is applied to the input of first transistor T_1. Due to transistor action, an amplified output is obtained across the collector load R_C of transistor T_1. This voltage drives the base of the second transistor and amplified output is obtained across its collector load. In this way, direct coupled amplifier raises the strength of weak signal.

Advantages

(i) The circuit arrangement is simple because of minimum use of resistors.

(ii) The circuit has low cost because of the absence of expensive coupling devices.

Disvantages

(i) It cannot be used for amplifying high frequencies.

(ii) The operating point is shifted due to temperature variations.

Comparison of Different Types of Coupling

S. No.	Particular	R_C coupling	Transformer coupling coupling	Direct
1.	Frequency response	Excellent in the audio frequency range	Poor	Best
2.	Cost	Less	More	Least
3.	Space and weight	Less	More	Least
4.	Impedance matching	Not good	Excellent	Good
5.	Use	For voltage amplification	For poweramplification	For amplifying extremely low frequencies

Difference Between Transistor And Tube Amplifiers

Although both transistors and grid-controlled tubes (e.g. triode, tetrode and pentode) can render the job of amplification, they differ in the following respects :

(i) The electron tube is a voltage driven device while transistor is a current operated device.

(ii) The input and output impedances of the electron tubes are generally quite large. On the other hand, input and output impedances of transistors are relatively small.

(iii) Voltages for transistor amplifiers are much smaller than those of tube amplifiers.

(iv) Resistances of the components of a transistor amplifier are generally smaller than the resistances of the corresponding components of the tube amplifier.

(v) The capacitances of the components of a transistor amplifier are usually larger than the corresponding components of the tube amplifier.

TRANSISTOR AUDIO POWER AMPLIFIERS

Introduction

A practical amplifier always consists of a number of stages that amplify a weak signal until sufficient power is available to operate a loudspeaker or other output device. The first few stages in this multistage amplifier have the function of only voltage amplification. However, the last stage is designed to provide maximum power. This final stage is known as power stage.

The term audio means the range of frequencies which our ears can hear. The range of human hearing extends from 20 Hz to 20 kHz. Therefore, audio amplifiers amplify electrical signals that have a frequency range corresponding to the range of human hearing i.e. 20 Hz to 20 kHz. (Fig. 12.16) shows the block diagram of an audio amplifier. The early stages build up the voltage level of the signal while the last stage builds up power to a level sufficient to operate the loudspeaker. In this chapter, we shall talk about the final stage in a multistage amplifier-the power amplifier.

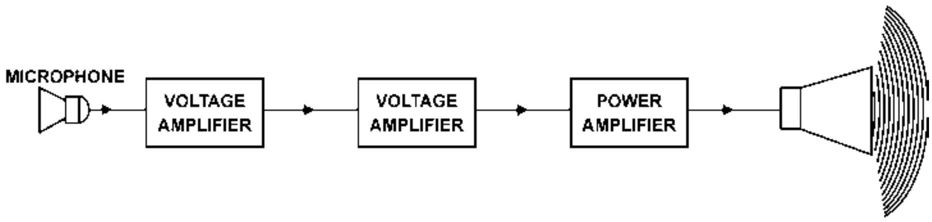


Fig. 12.16.

Performance Quantities of Power Amplifiers

As mentioned previously, the prime objective for a power amplifier is to obtain maximum output power. Since a transistor, like any other electronic device has voltage, current and power dissipation limits, therefore, the criteria for a power amplifier are : collector efficiency, distortion and power dissipation capability.

(i) **Collector efficiency**

The main criterion for a power amplifier is not the power gain rather it is the maximum a.c. power output. Now, an amplifier converts d.c. power from supply into a.c. power output. Therefore, the ability of a power amplifier to convert d.c. power from supply into a.c. output power is a measure of its effectiveness. This is known as collector efficiency and may be defined as under :

The ratio of a.c. output power to the zero signal power (i.e. d.c. power) supplied by the battery of a power amplifier is known as **collector efficiency.**

Collector efficiency means as to how well an amplifier converts d.c. power from the battery into a.c. output power. For instance, if the d.c. power supplied by the battery is 10W and a.c. output power is 2W, then collector efficiency is 20%. The greater the collector efficiency, the larger is the a.c. power output. It is obvious that for power amplifiers, maximum collector efficiency is the desired goal.

(ii) **Distortion**

The change of output wave shape from the input wave shape of an amplifier is known as **distortion.**

A transistor like other electronic devices, is essentially a nonlinear device. Therefore, whenever a signal is applied to the input of the transistor, the output signal is not exactly like the input signal i.e. distortion occurs. Distortion is not a problem for small signals (i.e. voltage amplifiers) since transistor is a linear device for small variation about the operating point. However, a power amplifier handles large signals and, therefore, the problem of distortion immediately arises. For the comparison of two power amplifiers, the one which has the less distortion is the better. We shall discuss the method of reducing distortion in amplifiers in the chapter of negative feedback in amplifiers.

(iii) **Power dissipation capability**

The ability of a power transistor to dissipate heat is known as **power dissipation capability.**

As stated before, a power transistor handles large currents and heats up during operation. As any temperature change influences the operation of transistor, therefore, the transistor must dissipate this heat to its surroundings. To achieve this, generally a heat sink (a metal case) is attached to a power transistor case. The increased surface area allows heat to escape easily and keeps the case temperature of the transistor within permissible limits.

Classification of Power Amplifiers

Transistor power amplifiers handle large signals. Many of them are driven so hard by the input large signal that collector current is either cut-off or is in the saturation region during a large portion of the input cycle. Therefore, such amplifiers

are generally classified according to their mode of operation i.e. the portion of the input cycle during which the collector current is expected to flow. On this basis, they are classified as :
(i) class A power amplifier (ii) class B power amplifier (iii) class C power amplifier

(i) **Class A power amplifier**
If the collector current flows at all times during the full cycle of the signal, the power amplifier is known as **class A power amplifier.**

Obviously, for this to happen, the power amplifier must be biased in such a way that no part of the signal is cut off. Fig. 12.17 (i) shows circuit of class A power amplifier. Note that collector has a transformer as the load which is most common for all classes of power amplifiers. The use of transformer permits impedance matching, resulting in the transference of maximum power to the load e.g. loudspeaker.

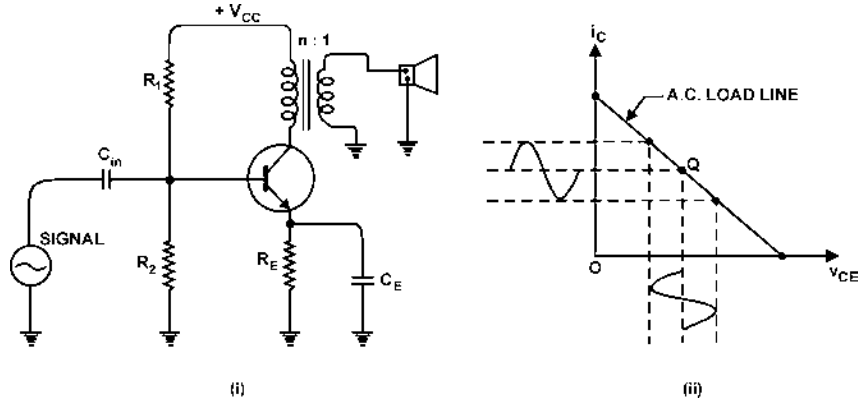


Fig. 12.17.

Fig. 12.17 (ii) shows the class A operation in terms of a.c. load line. The operating point Q is so selected that collector current flows at all times throughout the full cycle of the applied signal. As the output wave shape is exactly similar to the input wave shape, therefore, such amplifiers have least distortion. However, they have the disadvantage of low power output and low collector efficiency (about 35%).

(ii) **Class B power amplifier**
If the collector current flows only during the positive half-cycle of the input signal, it is called a **class B power amplifier.** In class B operation, the transistor bias is so adjusted that zero signal collector current is zero i.e. no baising circuit is needed at all. During the positive half-cycle of the signal, the input circuit is forward biased and hence collector current flows. However, during the negative half-cycle of the signal, the input circuit is reverse biased and no collector current flows. (Fig.12.18) shows the class B operation in terms of a.c. load line. Obviously, the operating point Q shall be located at collector cut off voltage. It is easy to see that output from a class B amplifier is amplified half-wave rectification.

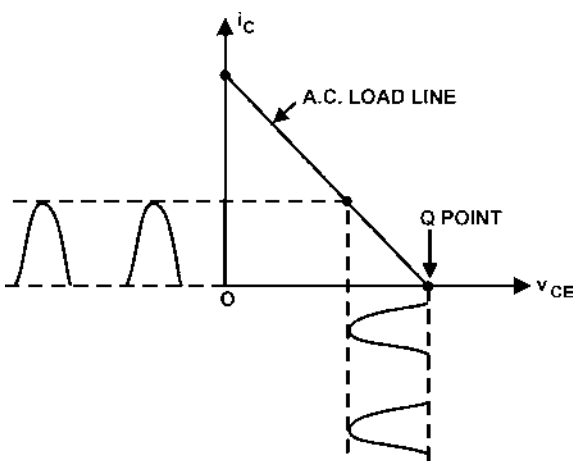


Fig. 12.18.

In a class B amplifier, the negative half-cycle of the signal is cut off and hence a severe distortion occurs. However, class B amplifiers provide higher power output and collector efficiency (50-60%). Such amplifiers are mostly used for power amplification in pust-pull arrangement. In such an arrangement, 2 transistors are used in class B operation. One transistor amplifies the positive half-cycle of the signal while the other amplifies the negative half-cycle.

(iii) **Class C power amplifier**
If the collector current flows for less than half-cycle of the input signal, it is called**class C power amplifier.**

In class C amplifier, the base is given some negative bias so that collector current does not flow just when the positive half-cycle of the signal starts. Such amplifiers are never used for power amplification. However, they are used as tuned amplifiers i.e. to amplify a narrow band of frequencies near the resonant frequency.

Stages of a Practical Power Amplifier

The function of a practical power amplifier is to amplify a weak signal until sufficient power is available to operate a loudspeaker or other output device. To achieve this goal, a power amplifier has generally three stages viz. voltage amplification stage, driver stage and output stage. (Fig. 12.19) shows the block diagram of a practical power amplifier.

Fig. 12.19.

(i) Voltage amplification stage. The signals found in practice have extremely low voltage level (<10 mV). Therefore, the voltage level of the weak signal is raised by two or more voltage amplifiers. Generally, RC coupling is employed for this purpose.

(ii) Driver stage. The output from the last voltage amplification stage is fed to the driver stage. It supplies the necessary power to the output stage. The driver stage generally employs class A transformer coupled power amplifier. Here, concentrated effort is made to obtain maximum power gain.

(iii) Output stage. The output power from the driver stage is fed to the output stage. It is the final stage and feeds power directly to the speaker or other output device. The output stage is invariably transformer coupled and employs class B amplifiers in push-pull arrangement. Here, concentrated effort is made to obtain maximum power output.

Driver Stage

The stage that immediately precedes the output stage is called the driver stage. It operates as a class A power amplifier and supplies the drive for the output stage. (Fig. 12.20) shows the driver stage. Note that transformer coupling is employed. The primary of this transformer is the collector load. The secondary is almost always centre-tapped so as to provide equal and opposite voltages to the input of push-pull amplifier (i.e. output stage). The driver transformer is usually a step-down transformer and facilitates impedance matching.

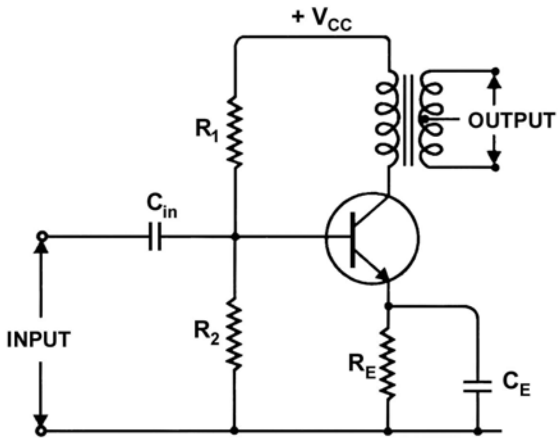


Fig. 12.20.

The output from the last voltage amplification stage forms the input to the driver stage. The driver stage renders power amplification in the usual way. If may be added that main consideration here is the maximum power gain. The output of the driver stage is taken from the centre-tapped secondary and is fed to the output stage.

Output Stage

The output stage essentially consists of a power amplifier and its purpose is to transfer maximum power to the output device. If a single transistor is used in the output stage, it can only be employed as class A amplifier for faithful amplification. Unfortunately, the power efficiency of a class A amplifier is very low ($\approx$ 35%). As transistor amplifiers are operated from batteries, which is a costly source of power, therefore, such a low efficiency cannot be tolerated.

In order to obtain high output power at high efficiency, pushpull arrangement is used in the output stage. In this arrangment, we employ two transistors in class B operation. One transistor amplifies the positive half-cycle of the signal while the other transistor amplifies the negative half-cycle of the signal . In this way, output voltage is a complete sine wave. At the same time, the circuit delivers high output power to the load due to class B operation.

Push-Pull Amplifier

The push-pull amplifier is a power amplifier and is frequently employed in the output stages of electronic circuits. It is used whenever high output power at high efficiency is required. (Fig. 12.21) shows the circuit of a push-pull amplifier. Two transisitors T_{r1} and T_{r2} placed back to back are employed. Both transistors are operated in class B operation i.e. collector current is nearly zero in the absence of the signal. The centre-tapped secondary of driver transformer T_1 supplies equal and opposite voltages to the base circuits of two transistors.

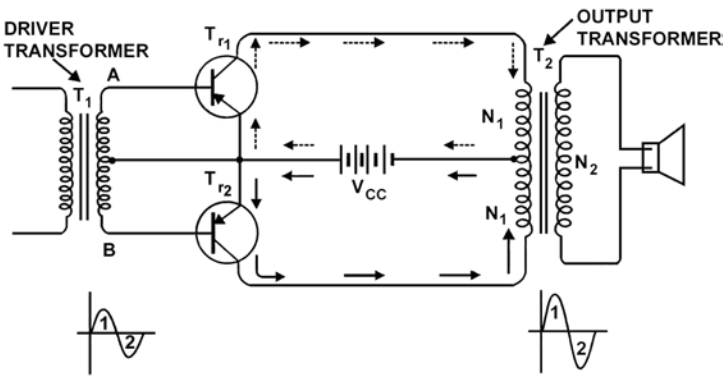


Fig. 12.21.

The output transformer T_2 has the centre-tapped primary winding. The supply voltage V_{CC} is connected between the bases and this centre tap. The loudspeaker is connected across the secondary of this transformer.

Circuit operation

The input signal appears across the secondary AB of driver transformer. Suppose during the first half-cycle (marked 1) of the signal, end A becomes positive and end B negative. This will make the base-emitter junction of T_{r1} reverse biased and that of T_{r2} forward biased. The circuit will conduct current due to T_{r2} only and is shown by solid arrows. Therefore, this half-cycle of the signal is amplified by T_{r2} and appears in the lower half of the primary of output transformer. In the next half-cycle of the signal, T_{r1} is forward biased whereas T_{r2} is reverse biased. Therefore, T_{r1} conducts and is shown by dotted arrows. Consequently, this half-cycle of the signal is amplified by T_{r1} and appears in the upper half of the output transformer primary. The centre-tapped primary of the output transformer combines two collector currents to form a sine wave output in the secondary.

It may be noted here that push-pull arrangement also permits a maximum transfer of power to the load through impedence matching. If R_L is the resistance appearing across secondary of output transformer, then resistance R'_L of primary shall become :

$$R'_L = \left[\frac{2N_1}{N_2}\right]^2 R_L$$

where N_1 = Number of turns between either end of primary winding and centre-tap
N_2 = Number of secondary turns.

Advantages

(i) The efficiency of the circuit is quite high ($\simeq$75%) due to class B operation.
(ii) A high a.c. output power is obtained.

Disadvantages

(i) Two transistors have to be used.
(ii) It requires two equal and opposite voltages at the input. Therefore, push-pull circuit requires the use of driver stage to furnish these signals.
(iii) If the parameters of the two transistors are not the same, there will be unequal amplification of the two halves of the signal.
(iv) The circuit gives more distortion.
(v) Transformers used are bulky and expensive.

■■■

CHAPTER - 13
KNOWLEDGE OF CONSTRUCTION, PRINCIPLE OF OPERATION OF SERVOMOTORS AND RATE GENERATORS, SYSTEM RESPONSE TO DISPLACEMENT (POSITION) AND RATE (VELOCITY) COMMAND SIGNALS, PURPOSE OF PULLUP AND RATE FEEDBACK SIGNALS, CAUSES OF HUNTING AND METHODS OF DAMPING, TROUBLE SHOOTING OF SERVOMECHANISM.

SERVOMECHANISMS

A servomechanism may be broadly defined as a closed - loop control system in which a small power input controls a much larger power output in a strictly proportionate manner. In applying such a mechanism to the automatic control of an aircraft, the system must be capable of continuous operation and have the ability to (i) detect the difference between an input and an output (error detection): (ii) amplify the error signals and (iii) control the closing of the servo loop by providing the feedback.

There are two main classes of servomechanism: (i) position control and (ii) speed control; both classes may be independently applied to automatic flight control systems depending respectively on whether they are of the displacement type or the rate sensing type. In some control systems they may also be used in conduction with each other.

POSITION CONTROL SERVOMECHANISM

A block schematic diagram of a position control servomechanism is illustrated in (Fig. 13.1), and from this it will be noted that it is one in which a load has to be rotated through an output angle θ_0 corresponding to an input angle θ_i of a controlling shaft. The controlling shaft is, in this example, mechanically coupled to the wiper arm of a potentiometer, the signal output of which is fed to a servomotor via an amplifier. The output angle of the load is measured by a second potentiometer whose wiper arm is mechanically coupled to an output shaft. The potentiometers are electrically connected in such a way that when their wiper arms occupy corresponding angular positions the servomechanism is in a 'null' or zero signal condition. When it is required to move the load to a particular angular position (θ_0) the controlling shaft is rotated through the appropriate number of degrees; thus the mechanism is no longer at 'null' and an error signal corresponding to angle θ_i is produced and fed to the amplifier.

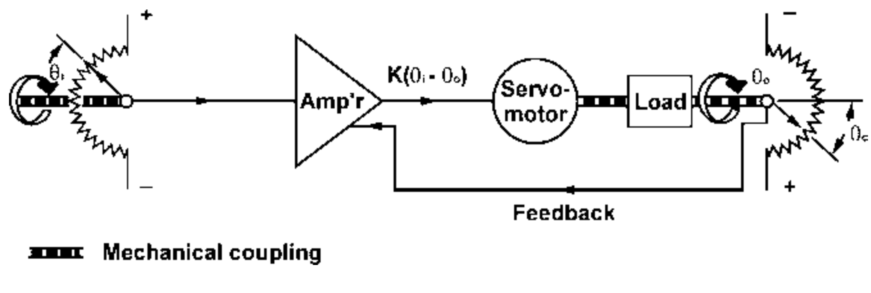


Fig. 13.1. Position control servomechanism.

The amplifier has an amplification factor of K, and therefore the input to the servomotor is increased to K $\theta_{i.}$ As the motor positions the load, the output shaft rotates the wiper arm of the second potintiometer to produce a signal corresponding to an angle $\theta_{0.}$ This signal is fed back to the amplifier thereby reducing the input error signal to the amplifier so that the real output from this unit to the servomoter is K(θ_i - θ_0). When the load finally reaches the position required, the servomechanism will then be at a new 'null' condition.

SPEED CONTROL SERVOMECHANISM

A speed control servomechanism is one in which error signals are produced as a result of a difference between voltages corresponding to input and output speeds, such signals being used to control the speed of the servomotor and load.

Referring to (Fig. 13.2), it will be noted that the system differs from that used for position control in that the servomotor also drives a device known as a tachogenerator. When it is required to operate the load, the servomotor is driven by an amplified input error voltage, V_i and the motor accelerates the load towards the required speed. At the same time, the motor drives the tachogenerator which produces an output voltage, V_0, in proportion to its speed of rotation. The output voltage is fed back to the amplifier thereby reducing the input error voltage and so producing a real output from the amplifier equal to $K(V_i - V_0)$. The servomotor in this class of servomechanism (sometimes called a velodyne) is therefore controlled by differences in voltages, and will speed up or slow down until the difference is zero.

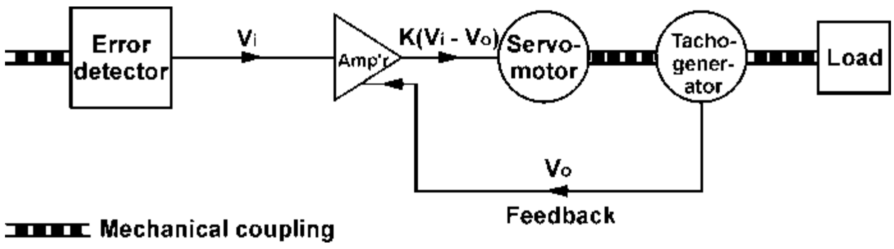


Fig. 13.2. Speed control servomechanism.

RESPONSE OF SERVOMECHANISM

The response to servomechanism is the pattern of behaviour of the load when a change is made to the input condition the most important factors being the form which the input change takes and the various restraints, friction, etc., which act on the output. There are two types of input change to be considered and these are referred to as step input, and ramp input, the names being derived from the shape of the curves of input against time as shown in (Fig.13.3).

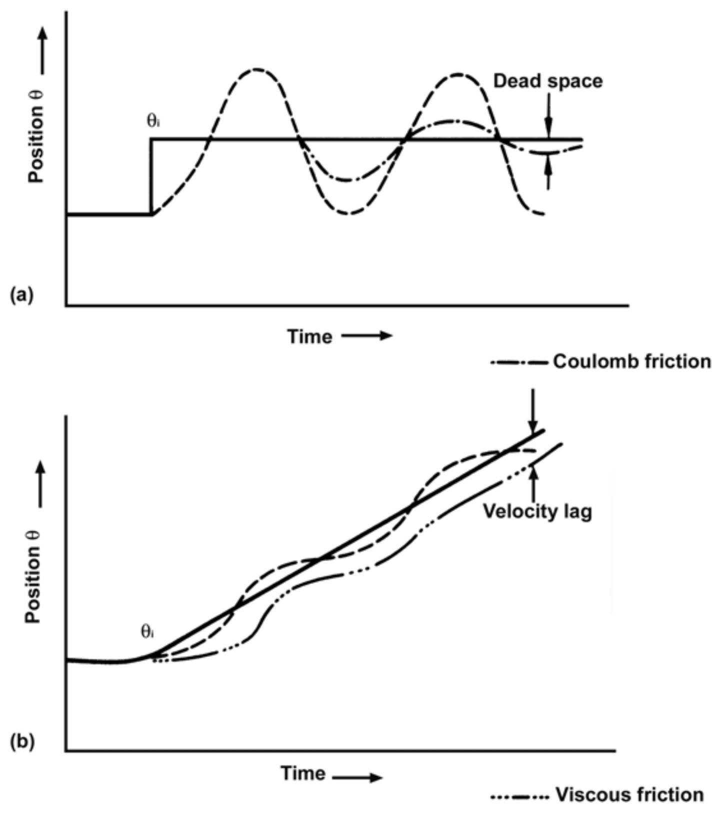


Fig. 13.3. Response of servomechanisms : (a) Step input (b) Ramp Input.

A step input is one whereby the input (e.g. the controlling shaft of the system shown in Fig. 13.1) is suddenly changed to a new angular position θ_i, from a null position. Because of the inertia of the load an angular change at the servomechanism output will not be able to follow exactly that at the input, with the result that a large error signal is produced initially. This reduces the error to zero. At this point however and although the acceleration is zero, the load has reached a steady rate of change and so it overshoots resulting in an increase of error in the opposite sense to decelerate the load until it comes to rest in the opposite direction. By this time the error signal is equal to the original error signal but of opposite polarity, and so the load is accelerated back towards the required position and produces another overshoot. If the frictional losses in the system are negligible, a continuous oscillation is produced.

A ramp input is one whereby the input is suddenly moved at a constant speed. In the early stages of the input and while the error signal is small, the load accelerates slowly and lags behind the input. The signal increases as the lag increases, thereby building up the acceleration. Eventually the input and load speeds are equal, but since a substantial position error exists, the load continues to accelerate, the acceleration is reduced and the load attains a constant speed at zero position error with no error signal. Thus, as in the case of a step input, a continuous oscillation is produced.

DAMPING

Oscillatory or transient responses of a servomechanism from whatever cause are obviously undesirable, and so it is necessary to provide some from of damping by which a load can be brought to rest in its required position with the minimum of overshoot.

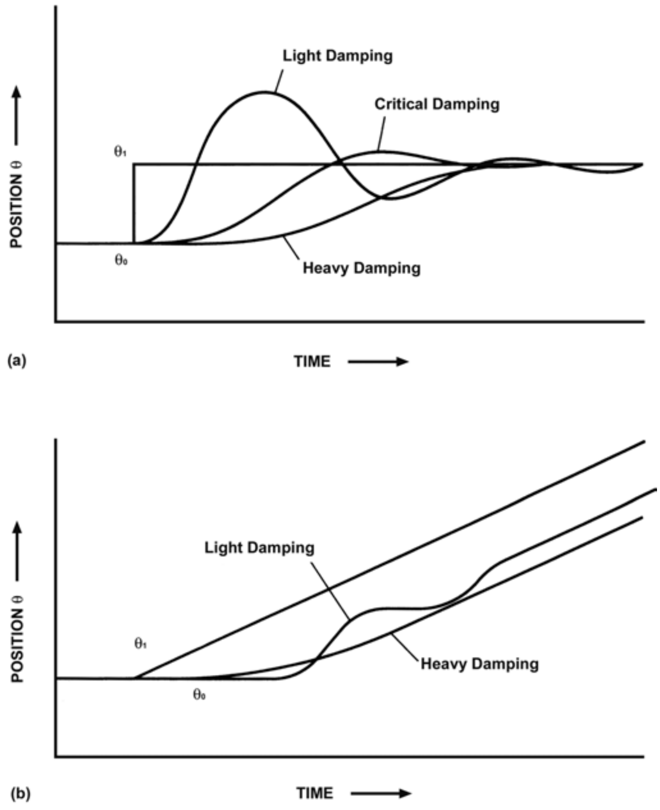


Fig. 13.4. Degrees of damping: (a) step input (b) ramp input.

Varying degrees of damping can be applied (see Fig. 13.4). Using only inherent friction light damping is achieved. If there is too much extra viscous friction, the system is heavily damped and a very sluggish response is produced. The degdree of damping which just prevents any overshoot is known as critical damping. Damping which allows one small overshoot and gives the smallest settling time is known as optimum damping.

Servomechanisms possess various inherent factors which, together, have the general effect of reducing the amplitude of each successive oscillation; such factors includes static friction, kinetic friction, eddy current, lurbicant viscosity, etc. and while contributing to damping requirements they do have certain detrimental effects, e.g. power is wasted, and errors can be introduced with the servomechanism operating in the steady state. The effects are partly due to a small force of constant magnitude known as coulomb friction, and to viscous friction which increases with speed.

Coulomb friction relates particularly to the response to a step input and this is illustrated in Fig. 13.3 (a). It has the tendency to downgrade the sensitivity of a servomechanism, since the torque required to overcome the friction must be generated before any movement of the load takes place. To provide this torque the load error must reach some finite size and any errors less than this will not be corrected. The load comes to rest somewhere within a band of error (the dead space), the width of the band depending on the amount of coulomb friction. The friction is, however, very small in most current types of servomechanism so that its effect can neglected.

Viscous friction Fig. 13.3 (b) produces a similar dead space effect, but as the friction varies with speed, the effect is associated with a ramp input. In the steady state the load moves with constant speed, and is therefore resisted by viscous friction. An error signal must be produced to overcome this and so a steady state error must exist, the error bieng known as velocity lag. Coulomb friction also contributes to velocity lag, but is considered small in comparison with viscous friction.

The transient responses just described are generally adequate in applications requiring the use of small position servomechanisms, but when large loads are involved it is desirable to further reduce the number of oscillations, and the response time. Two methods commonly employed are viscous damping and velocity feedback damping.

VISCOUS DAMPING

A device commonly used for viscous damping is one in which a disc is free to rotate between the pole faces of an electromagnet. The disc is coupled to the servomechanism output shaft so that, as it rotates, eddy currents are induced in the disc. The eddy currents are of a magnitude proportional to the field strength, and to the disc velocity, and they establish magnetic fields and forces which oppose rotation of the disc and output shaft. The damping effect is produced by absorpition of the servomotor torque in the desired proportion.

The response achieved by additional viscous damping can be made adequate for the particular servomechanism function, but since it absorbs servomotor torque it has the disadvantage of wasting energy; furthermore, where a ramp input is concerned the velocity lag is increased.

VELOCITY FEEDBACK DAMPING

Velocity feedback damping overcomes the wasting of energy by feeding back a voltage from a tachogenerator (see Fig. 13.2), the voltage being proportional to the load velocity and in opposition to the error signal applied to the amplifier unit of the servomechanism. Thus, the net input to the amplifier is the error signal voltae (i.e. the difference between input and out put voltages) minus the velocity feedback voltage and since the overall effect will result in a lowering of the amplifier output, the servomotor torque will also be lowered so that less energy will be expended. Velocity feedback also increases velocity lag in response to ramp input, but for a different physical reason. In this case, the stready state velocity of the load imposes a signal at the amplifier input which must be cancelled in some way if the steady state velocity is to be maintained. The cancellation can only be made by an equal error signal, which means that an error must exist. By suitably adjusting the feedback voltage it can be arranged that the error signal is reduced to zero and then reversed before the load reaches its new position. In this manner the momentum of the load acting against the reversed servomotor torque will bring the load to rest just as it reaches its new position, thereby reducing overshoots and subsequent instability. The principle of this form of damping is shown in (Fig. 13.5).

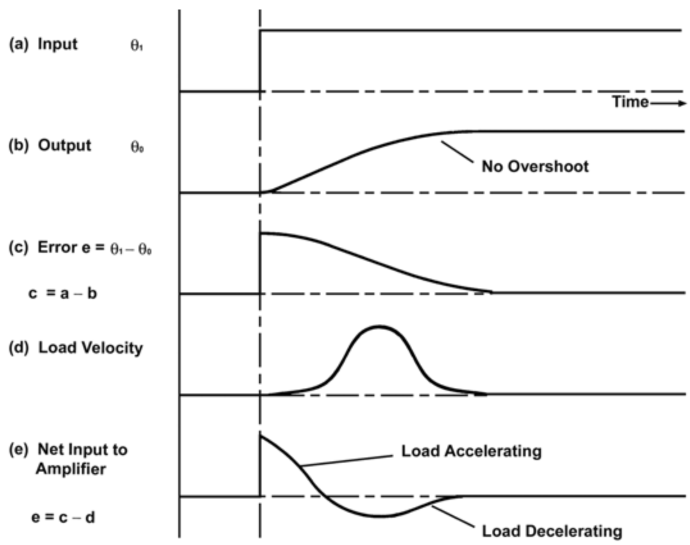


Fig. 13.5. Principle of velocity feedback damping.

ERROR RATE DAMPING

As already noted, in velocity control servomechanisms (ramp input) employing velocity feedback damping the transient response is improved but velocity lag is increased. This can be tolerated in certain applications, but where requirements for rotating a load at constant speed are to be met the lag must be reduced to zero in the steady condition. This may be achieved by adopting either of two methods which in each case produce the same result, i.e. cancelling the velocity feedback signal when the input and output velocities are equal. One method [see Fig. 13.6 (a)] is to fit a second tachogenerator at the input so that it feeds a signal forward into the amplifier, thus making the net input an error voltage plus a voltage proportional to input shaft speed minus the velocity feedback voltage. During a ramp input a steady state is eventually reached in which the tachogenerators apply equal and opposite voltages to the amplifier; the net input is therefore zero. If any velocity lag exists at this stage, the position error signal will establish torques at the servomotor to reduce it.

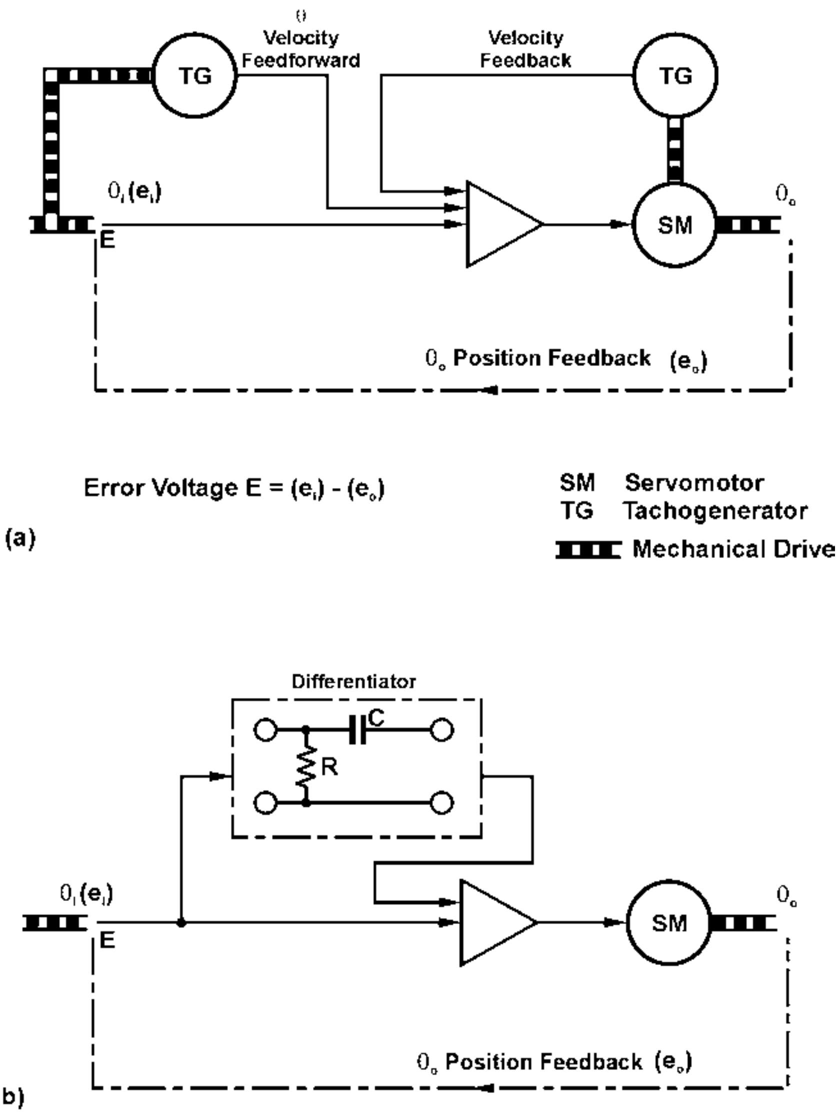


Fig. 13.6. Error-rate damping: (a) feedforward of input velocity (b) feedforward of error rate.

The foregoing method, although eliminating velocity lag, presents the difficulty of ensuring that the voltage outputs of both tachogenerators will remain constant over a long period of time. Since the velocity of an error is equal to its rate of change, with respect to time, i.e. the differential of the error, then by combining a differential signal with the actual error signal at the amplifier input, the same final result will be obtained as when using two tachogenerators. In the second method, therefore, the tachogenerators are dispensed with and are replaced by a resistance - capacitance differentiating network as shown in [see Fig. 13.6 (b)].

TRANSIENT VELOCITY DAMPING

This type of damping also known as acceleration feedback, utilises a differentiating network connected in the velocity feedback signal line as shown in (Fig. 13.7). Thus, only the derivative of the load velocity reaches the amplifier, with the result that damping is effective only during the transient response period, i.e. when a rate of change of load velocity exists. Once the steady state is reached there is no further rate of change, the derivative is zero, and the feedback ceases thereby reducing velocity lag.

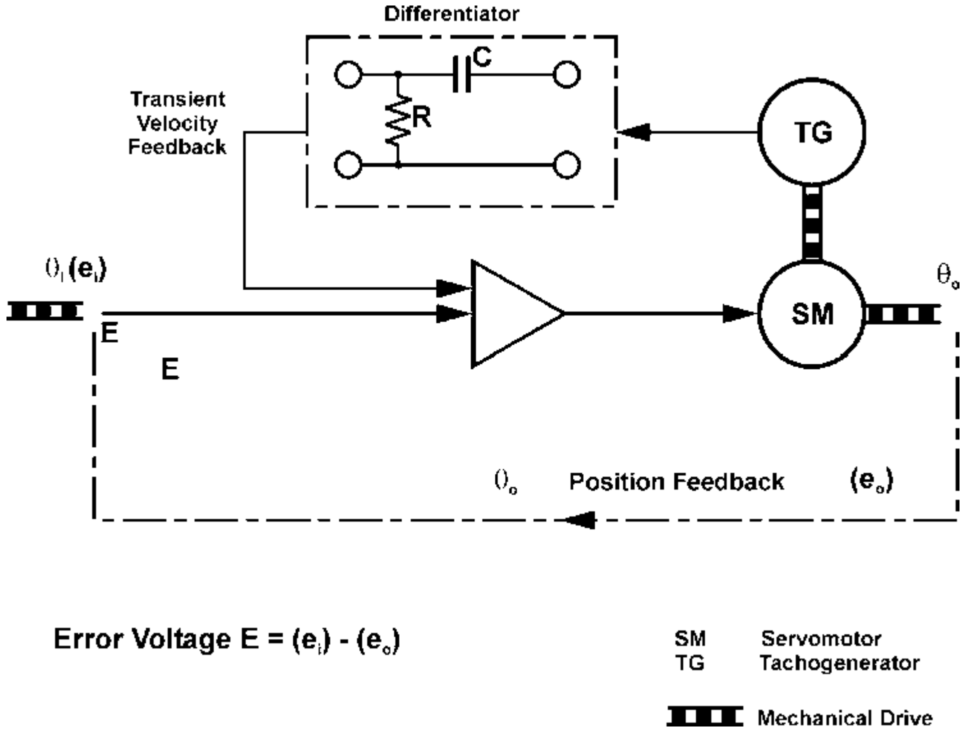


Fig. 13.7. Transient velocity damping.

PHASE ADVANCE DAMPING

A suitable transient response in a remote position control system and a good steady state response in a velocity system can be obtined by inserting a resistance - capacitance network in the input to the amplifier, as shown in (Fig. 13.8). With this arrangement, the output signal is θ degrees in advance of the input signal.

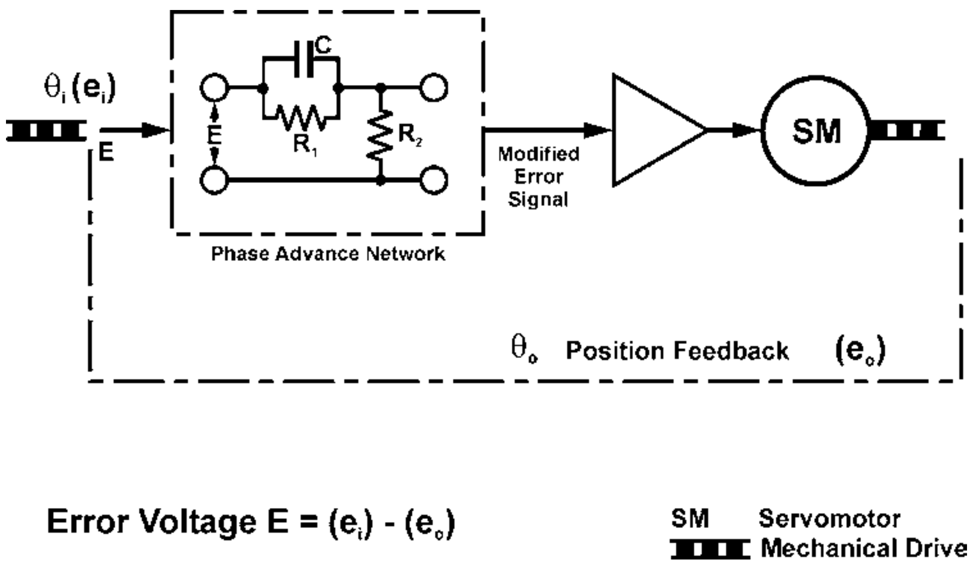


Fig. 13.8. Phase advance damping.

When a position control system is subjected to a step function input, the error rises immediately to its maximum value because of the inertia of the system. Initially, therefore, since the capacitor 'C' cannot charge instantaneously (due to its time constant) the full error voltage is developed across R_2 and is applied to the amplifier, causing the motor to accelerate rapidly. As the capacitor is charged the voltage acsross it rises and the input to the amplifier falls, thus reducing the motor torque. As the load reaches the required position, the error voltage falls. However, if the values of the components of the phase advance network have been carefully chosen, the charge acquired by the capacitor during the initial period will cause the voltage across it to exceed the error voltage. Thus the voltage applied to the amplifier is now negative despite the slightly positive error voltage. This means that a retarding torque is applied to the load before it reaches its required position; overshooting is therefore prevented and stability during the transient period is improved.

For a ramp function input the phase advance network gives an almost zero error in the steady state, i.e. it virtually eliminates velocity lag. In the steady state there is neither acceleration nor deceleration and zero torque is required. For this condition to be satisfied, the input to the amplifier must be zero, i.e. zero error.

INTEGRAL CONTROL

The methods so far described reduce velocity lag, but have no effect on lag and 'dead space' caused by inherent friction. A commonly used method of dealing with these residual steady state errors is known as integral control. The arrangement as used in conjunction with feed forward of error rate is shown in (Fig. 13.9).

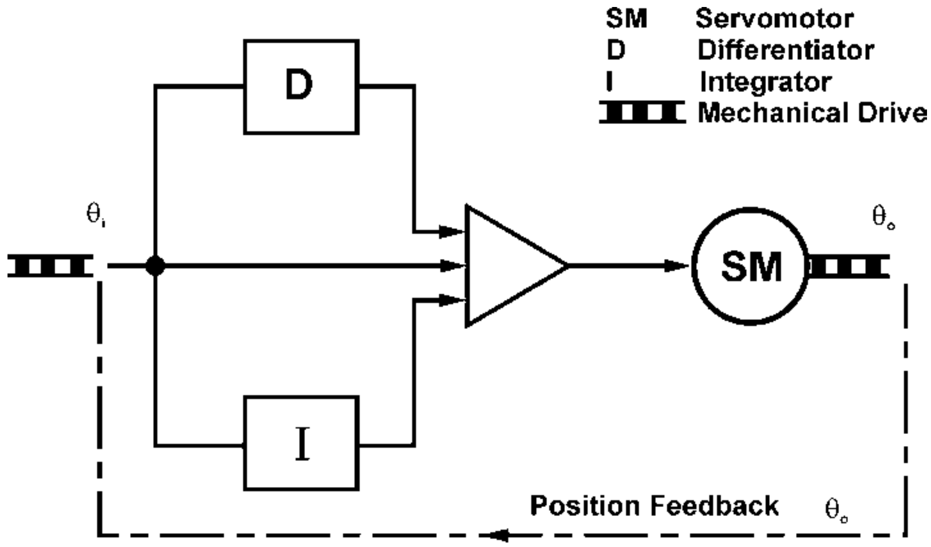


Fig. 13.9. Integral control.

The diffentiator operates in the same manner as that used for error rate and transient velocity damping, but the conditions are modified by the inclusion of an integrator which feeds the time integral of the error signal into the amplifier. The effect on the transient response is negligible, but as the error settles to its steady state so its integral increases, superimposing on the amplifier a signal which provides additional torque at the load. The load is moved by this torque towards the correct position.

Adjustment of the proportion of the integrator output can be made to ensure, when the error signal is zero, that the subsequent constant integrator output is just sufficient to counter the inherent friction. Thus, velocity lag is zero. For a step input the dead space error signal is integrated until large enough to zero the error, and adjustment of the damping differentiator out put ensures stability.

SERVOMOTORS

They are also called control motors and have high-torque capabilities. Unlike large industrial motors, they are not used for continuous energy conversion but only for precise speed and precise position control at high torques. Of course, their basic principle of operation is the same as that of other eletromagnetic motors. However, their construction, design and mode of operation are different. Their power ratings vary from a fraction of a watt upto a few 100 W. Due to their low-inertia, they have high speed of response. That is why they are smaller in diameter but longer in length. They generally operate at very low speeds or sometime zero speed. They find wide applications in radar, tracking and guidance systems, process controllers, computers and machine tools. Both dc and ac (2 phase and 3 phase) servomotors are used at present.

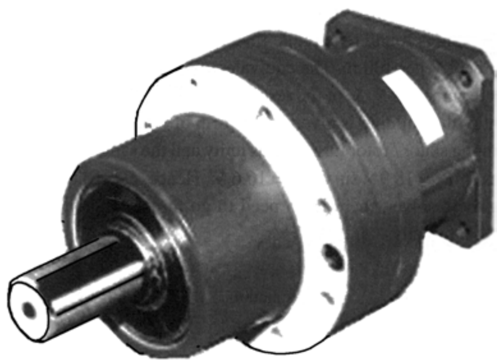
Servomotors differ in application capabilities from large industrial motors in the following respects:

1. they produce high torque at all speeds including zero speed
2. they are capable of holding a static (i.e. no motion) position
3. they do not overheat at standstill or lower speeds
4. due to low-inertia, they are able to reverse directions quickly
5. they are able to accelerate and deaccelerate quickly
6. they are able to return to a given position time after time without any drift

These motors look like the usual electric motors. Their main difference from industrial motors is that more electric wires come out of them for power as well as for control. The servomotor wires go to a controller and not to the electrical line through contactors. Usually, a tachometer (speed-indicating device) is mechanically connected to the motor shaft. Sometimes, blower or fans may also be attached for motor cooling at low speeds.

DC SERVOMOTORS

These motors are either separately-excited dc motors or permanent-magnet dc motors. The schematic diagram of a separately-excited dc motor alongwith its armature and field MMFs and torque/speed characteristics is shown in (Fig.13.10). The speed of dc servomotors is normally controlled by varying the armature voltage. Their armature is



DC servo motor

deliberately designed to have large resistance so that torque-speed characteristics are linear and have a large negative slope as shown in Fig. 13.10 (c). The negative slope serves the purpose of providing the viscous damping for servo drive system.

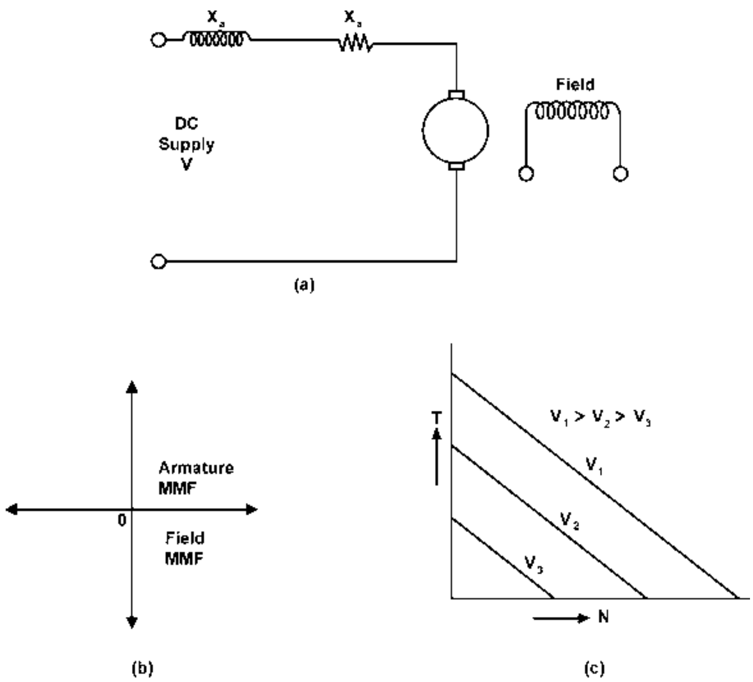
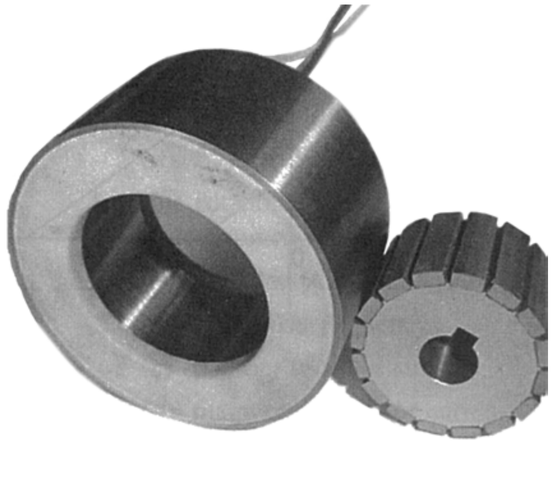


Fig. 13.10.

As shown in Fig. 13.10 (b), the armature mmf and excitation field mmf are in quadrature. This fact provides a fast torque response because torque and flux become decoupled. Accordingly, a step change in the armature voltage or current produces a quick change in the position or speed of the rotor.

AC SERVOMOTORS

Presently, most of the ac servomotors are of the two-phase squirrel-cage induction type and are used for low power applications. However, recently three-phase induction motors have been modified for high power servo systems which had so far been using high power dc servomotors.



Permanent magnet stepper motor

a. Two-phase AC Servomotor

Such motors normally run on a frequency of 60 Hz or 400 Hz (for airborne systems). The stator has two distributed windings which are displaced from each other by 90° (electrical). The main winding (also called the reference or fixed phase) is supplied from a constant voltage source, $V_m \angle 0°$ (Fig. 13.11). The other winding (also called the control phase) is supplied with a variable voltage of the same frequency as the reference phase but is phase-displaced by 90° (electrical). The control - phase voltage is controlled by an electronic controller. The speed and torque of the rotor are controlled by the phase difference between the main and control windings. Reversing the phase difference from leading to lagging (or vice versa) reverses the motor direction.

Since the rotor bars have high resistance, the torque-speed characteristics for various armature voltages are almost linear over a wide speed range particularly near the zero speed. The motor operation can be controlled by varying the voltage of the main phase while keeping that of the reference phase constant.

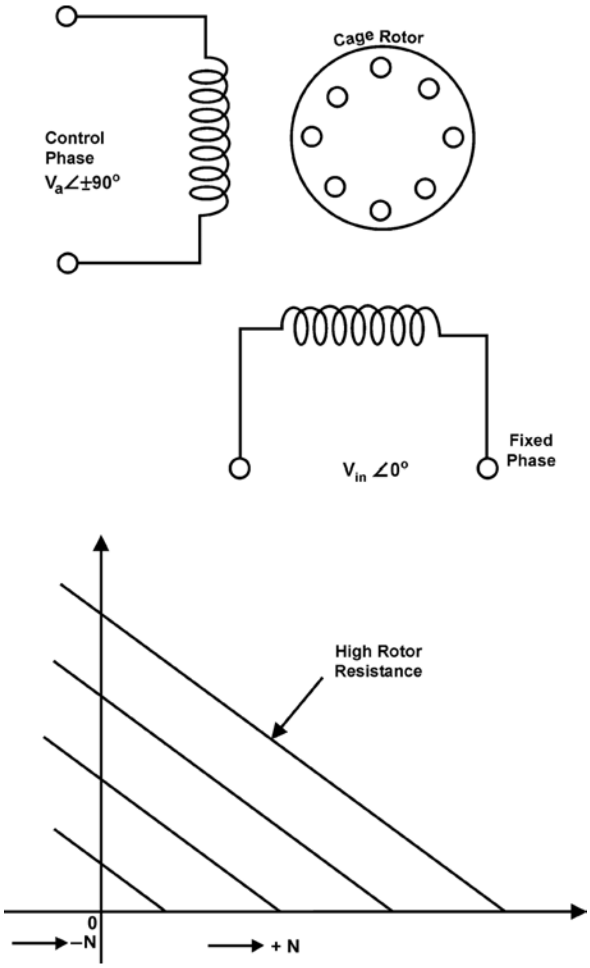


Fig. 13.11.

b. Three-phase AC Servomotors

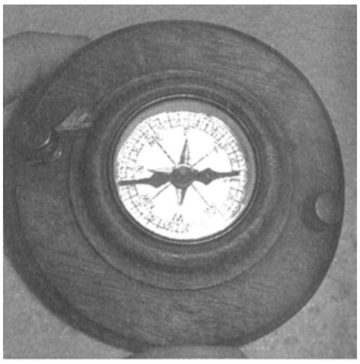
A great deal of research has been to modify a three-phase squirrel - case induction motor for use in high power servo systems. Normally, such a motor is a highly non-linear coupled-circuit device. Recently, this machine has been operated successfully as a linear decoupled machine (like a dc machine) by using a control method called vector control or field oriented control. In this method, the currents fed to the machine are controlled in such a way that its torque and flux become decoupled as in a dc machine. This results in a high speed and a high torque response.

■■■

CHAPTER - 14
KNOWLEDGE OF CONSTRUCTION, PRINCIPLE OF OPERATION USE AND PRECAUTIONS TO BE OBSERVED ON AIRCRAFT TEST EQUIPMENT

ABSOLUTE AND SECONDARY INSTRUMENTS

The various electrical instruments may, in a very broad sense, be divided into (i) absolute instruments and (ii) secondary instruments. Absolute instruments are those which give the value of the quantity to be measured in terms of the constant of the instruments and their deflection only. No previous calibration or comparison is necessary in thier case. The example of such an instrument is tangent galvanometer which gives the value of current in terms of the tangent of deflection produced by the current and of the radius and number of turns of wire used and the horizontal component of earth's field.



An absolute instrument

Secondary instruments are those in which the value of electrical quantity to be measured can be determined from the deflection of the instruments only when they have been pre-calibrated by comparison with an absolute instrument. Without calibration, the deflection of such instruments is meaningless.

It is the secondary instruments which are most generally used in everyday work, the use of the absolute instruments being merely confined within laboratories as standardizing instruments.

Electrical Principles of Operation

All electrical measuring instruments depend for their action on one of the many physical effects of an electric current or potential and are generally classified according to which of these effects is utilized in their operation. The effects generally utilized are :

1. Magnetic effect - for ammeters and voltmeters usually.
2. Electrodynamic effect - for ammeters and voltmeters usually.
3. Electromagnetic effect - for ammeters, voltmeters, wattmeters and watthour meters.
4. Thermal effect - for ammeters and voltmeters.
5. Chemical effect - for d.c. ampere-hour meters.
6. Electrostatic effect - for voltmeters only.

Another way to classify secondary instruments is to divide them into (i) indicating instruments (ii) recording instruments and (iii) integrating instruments.

Indicating instruments are those which indicate the instantaneous value of the electrical quantity being measured at the time at which it is being measured. Their indications, are given by pointers moving over calibrated dials. Ordinary ammeters, voltmeters and wattmeters belong to this class.

Recording instruments are those which, instead of indicating by means of a pointer and a scale the instantaneous value of an electrical quantity, give a continuous record of the variations of such a quantity over a selected period of time. The moving system of the instrument carries an inked-pen which rests lightly on a chart or graph that is moved at a uniform and low speed, in a direction perpendicular to that of the deflection of the pen. The path traced out by the pen presents a continuous record of the variations in the deflection of the instruments.

Integrating instruments are those which measure and register by a set of dials and pointer either the total quantity of electricity (in ampere-hours) or the total amount of electrical energy (in watt-hours or kWh) supplied to a circuit in a given time. Their summation gives the product of time and the electrical quantity but gives no direct indication as to the rate at which the quantity or energy is being supplied because their registrations are independent of this rate provided the current flowing through the instrument is sufficient to operate it.

Essential of Indicating Instruments

As defined above, indicating instruments are those which indicate the value of the quantity that is being measured at the time at which it is measured. Such instruments consist essentially of a pointer which moves over a calibrated scale and which is attached to a moving system pivoted in jewelled bearings. The moving system is subjected to the following three torques :

1. A deflecting (or operating) torque
2. A controlling (or restoring) torque
3. A damping torque

Deflecting Torque

The deflecting or operating torque (T_d) is produced by utilizing one or other effects mentioned in para 4 as Electrical principle of operation i.e. magnetic, electrostatic, electrodynamic, thermal or chemical etc. The actual method of torque production depends on the type of instrument and will be discussed in the succeeding paragraphs. This deflecting torque cause the moving system (and hence the pointer attached to it) to move from its 'zero' position i.e. its position when the instrument is disconnected from the supply.

Controlling Torque

The deflection of the moving system would be indefinite if there were no controlling or restoring torque. This torque opposes the deflecting torque and increases with the deflection of the moving system. The pointer is brought to rest at a position where the two opposing torques are numerically equal. The deflecting torque ensures that currents of different magnitudes shall produce deflections of the moving system in proportion to their size. Without such a torque, the pointer would swing over to the maximum deflected position irrespective of the magnitude of the current to be measured. Moreover, in the absence of a restoring torque, the pointer once deflected, would not return to its zero position on removing the current. The controlling or restoring or balancing torque in indicating instruments is either obtained by a spring or by gravity as described below.

a. Spring Control

A hair-spring, usually of phosphor-bronze, is attached to the moving system of the instrument as shown in Fig. 14.1 (a). With the deflection of the pointer, the spring is twisted in the opposite direction. This twist in the spring produces restoring torque which is directly proportional to the angle of deflection of the moving system. The pointer comes to a position of rest (or equilibrium) when the deflecting torque (T_d) and controlling torque (T_c) are equal. For example, in permanent-magnet moving-coil type of instruments, the deflecting torque is proportional to the current passing through them.

$\therefore T_d \alpha I$ and for spring control $\mathbf{T}_c \alpha \theta$

As $T_c = T_d$ $\quad\quad \therefore \theta \alpha I$

Since deflection θ is directly proportional to current I, the spring-controlled instruments have a uniform or equally-spaced scales over the whole of their ranges as shown in Fig. 14.1 (b).

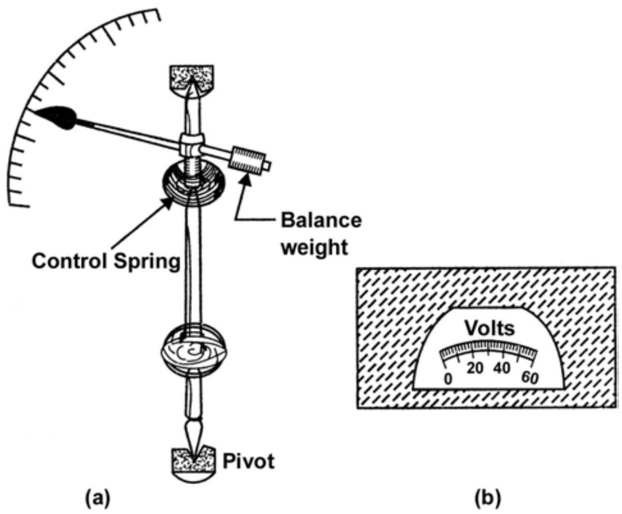


Fig. 14.1.

To ensure that controlling torque is proportional to the angle of deflection, the spring should have a fairly large number of turns so that angular deformation per unit length, on full-scale deflection, is small. Moreover, the stress in the spring should be restricted to such a value that it does not produce a permanent set in it.

Springs are made of such materials which
1. are non-magnetic.
2. are not subject to much fatigue.
3. have low specific resistance-especially in cases where they are used for leading the current in or out of the instrument.
4. have low temperature-resistance coefficient.

b. Gravity Control

Gravity control is obtained by attaching a small adjustable weight to some part of the moving system such that the two exert torques are in the opposite directions. The usual arrangement is shown in Fig. 14.2 (a).

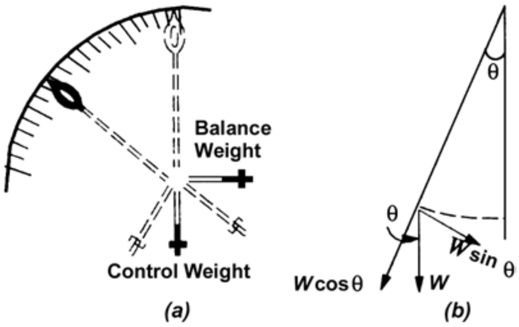


Fig. 14.2.

It is seen from Fig. 14.2 (b) that the controlling or restoring torque is proportional to the sine of the angle of deflection i.e. $T_e \alpha \sin\theta$. The degree of control is adjusted by screwing the weight up or down the carrying system.

As compared to spring control, the disadvantages of gravity control are :
i. it gives cramped scale
ii. the instrument has to be kept vertical.

However, gravity control has the following advantages :
i. it is cheap
ii. it is unaffected by temperature
iii. it is not subjected to fatigue or deterioration with time
iv. have low temperature - resistance co - efficient.

The exact expression for controlling torque is $T_C = CQ$

where C is spring constant. Its value is given by $C = \frac{Ebt^3}{L}$ N - m/rad. The angle 'Q' is in radians.

Damping Torque

A damping force is one which acts on the moving system of the instrument only when it is moving and always opposes its motion. Such a stabilizing or damping force is necessary to bring the pointer to rest quickly, otherwise due to inertia of the moving system, the pointer will oscillate about its final deflected position quite for sometime before coming to rest in the steady position. The degree of damping should be adjusted to a value which is sufficient to enable the pointer to rise quickly to its deflected position without overshooting. In that case, the instrument is said to be dead-beat. Any increase of damping above this limit i.e. overdamping will make the instrument slow and lethargic. In (Fig. 14.3) is shown the effect of damping on the variation of position, with time, of the moving system of an instrument.

The damping force can be provided by (i) air friction (ii) eddy currents and (iii) fluid-friction (used occasionally).

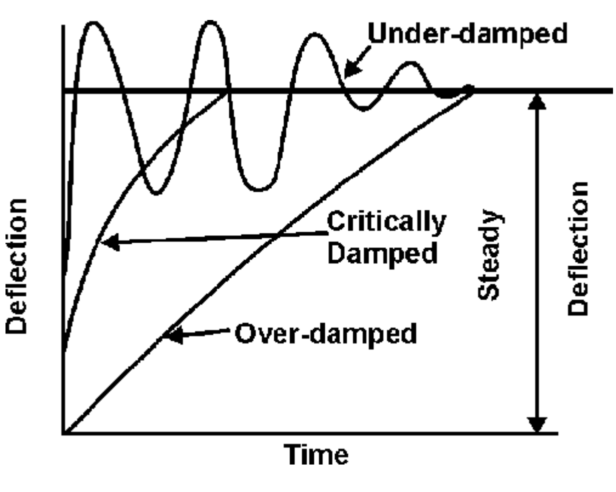


Fig. 14.3.

Two methods of air-friction damping are shown in Fig. 14.4 (a) and Fig. 14.4 (b). In Fig. 14.4 (a), the light aluminium piston attached to the moving system of the instrument is arranged to travel with a very small clearance, in a fixed air chamber closed at one end. The cross-section of the chamber is either circular or rectangular. Damping of the oscillations is affected by the compression and suction actions of the piston on the air enclosed in the chamber. Such a system of damping is not much favoured these days, those shown in Fig. 14.4 (b) and Fig. 14.4 (c) being preferred. In the latter method, one or two light aluminium vanes are mounted on the spindle of the moving system which moves in a closed sector-shaped box as shown.

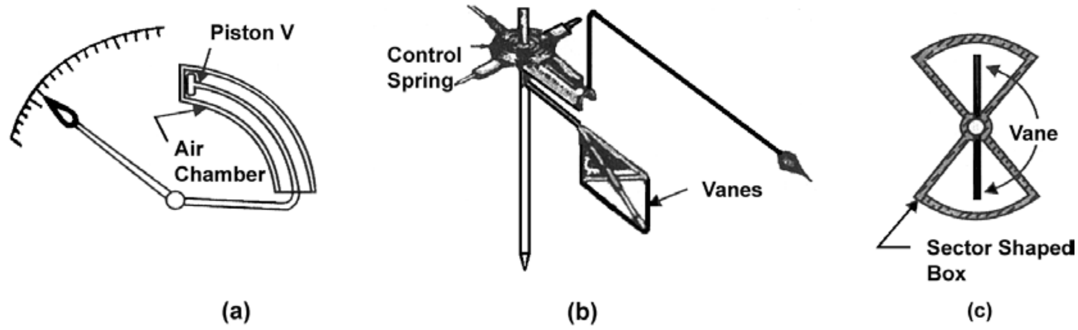


Fig. 14.4.

Fluid friction is similar in action to the air friction. Due to greater viscosity of oil, the damping is more effective. However, oil damping is not much used because of several disadvantages such as objectionable creeping of oil, the necessity of using the instrument always in the vertical position and its obvious unsuitability for use in portable instruments.

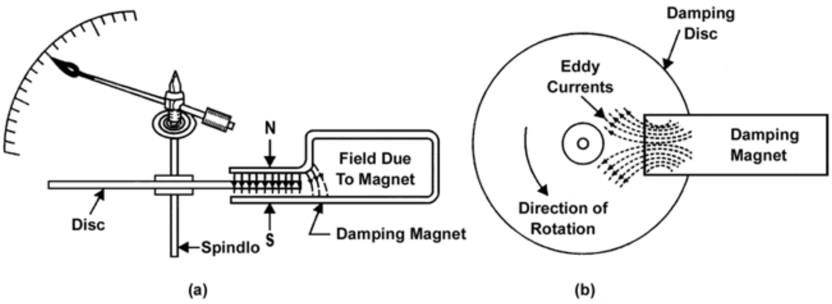


Fig. 14.5.

The eddy-current form of damping is the most efficient of the three. The two forms of such a damping are shown in (Fig. 14.5) and (Fig. 14.6). In Fig. 14.5 (a) is shown a thin disc of a conducting but nonmagnetic material like copper or aluminium mounted on the spindle which carries the moving system and the pointer of the instrument. The disc is so positioned that its edge, when in rotation, cuts the magnetic flux between the poles of a permanent magnet. Hence, eddy currents are produced in the disc which flow and so produce a damping force in such a direction as to oppose the very cause producing them as per (Lenz's Law Art). Since the cause producing them is the rotation of the disc, these eddy currents retard the motion of the disc and the moving system as a whole.

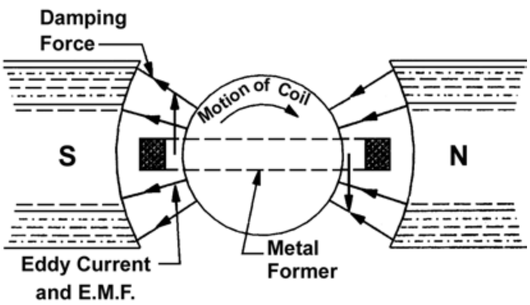


Fig. 14.6.

In (Fig. 14.6) is shown the second type of eddy-current damping generally employed in permanent-magnet moving-coil instruments. The coil is wound on a thin light aluminium former in which eddy currents are produced when the coil moves in the field of the permanent magnet. The directions of the induced currents and of the damping force produced by them are shown in the figure given above.

D'Arsonval Meter

The basic d.c. meter movement is known as the D'Arsonval meter movement because it was first employed by the French scientist, D' Arsonval, in making electrical measurement. This type of meter movement is a current-measuring device which is used in the ammeter, voltmeter, and ohmmeter. Basically, both the ammeter and the voltmeter are current-measuring instruments, the principal difference being the method in which they are connected in a circuit. While an ohmmeter is also basically a current-measuring instrument, it differs from the ammeter and voltmeter in that it provides its own source of power and contains auxiliary circuits.

Ammeter

The D'Arsonval ammeter is an instrument designed for measuring direct current flowing in an electrical circuit and consists of the following parts : a permanent magnet, a moving element mounting, bearings, and a case which includes terminals, a dial, and screws. Each part and its function are described in the discussion which follows.

The permanent magnet furnishes a magnetic field which will react with the magnetic field set up by the moving element.

The moving element is mounted so that it is free to rotate when energized by the current to be measured. A pointer which moves across a calibrated scale is attached to this element. A moving-coil mechanism is shown in (Fig. 14.7). The controlling element is a spring, or springs, whose main function is to provide a counter or restoring force. The strength of this force increases with the turning of the moving element and brings the pointer to rest at some point on the scale. Two springs are generally used; they are wound in opposite directions to compensate for the expansion and contraction of the spring material due to temperature variation. The springs are made of nonmagnetic material and conduct current to and from the moving coil in some meters.

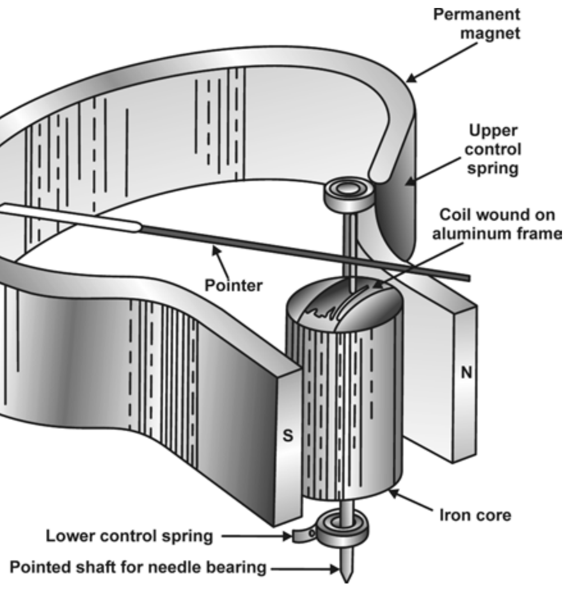


Fig. 14.7. Moving-coil element with pointer and springs.

The moving element consists of a shaft with very hard pivot points to carry the moving coil or other movable element (Fig. 14.7). The pivot points are so fitted into highly polished jewels or very hard glass bearings that the moving element can rotate with very little friction. Another type of mounting has been designed in which the pivot points are reversed and the bearings are inside the moving-coil assembly. A method of mounting moving elements is shown in (Fig. 14.8).

The bearings are highly polished jewels such as sapphire, synthetic jewels, or very hard glass. These are usually round and have a conical depression in which the pivots rotate. They are set in threaded nuts which allow adjustment. The radius of the depression in the jewel is greater than the radius of the pivot point. This limits the area of contact surfaces and provides a bearing which, when operated dry, probably has the lowest constant friction value of any known type of bearing.

The case houses the instrument movement and protects it from mechanical injury and exposure. It also has a window for viewing the movement of the pointer across a calibrated scale. The dial has printed on it pertinent information such as the scale, units of measurement, and meter uses. The terminals are made of materials having very low electrical resistance. Their function is to conduct the required current into and away from the meter.

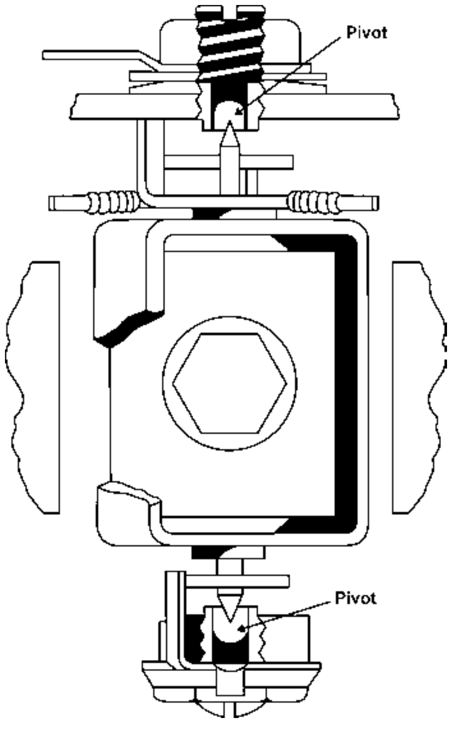


Fig. 14.8. Method of mounting moving elements.

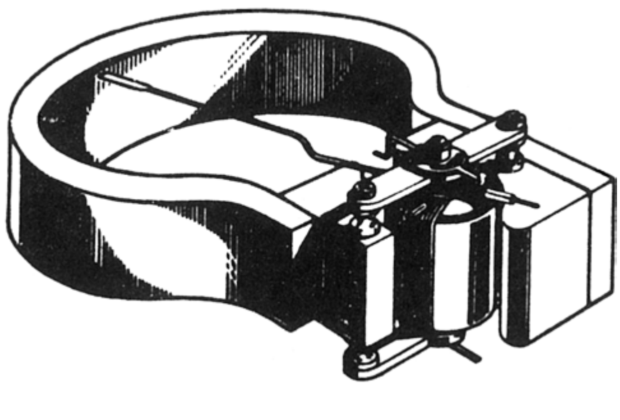


Fig. 14.9. D'Arsonval meter movement.

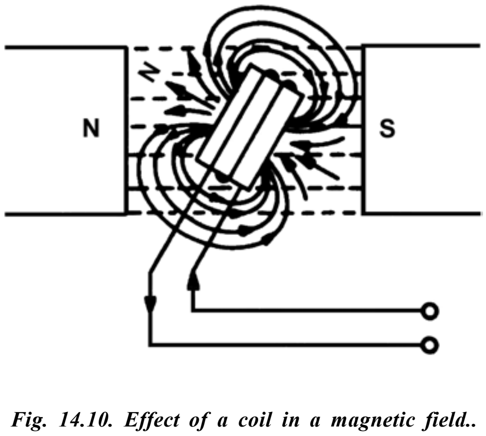


Fig. 14.10. Effect of a coil in a magnetic field..

Operation of the Meter Movement

The major units are mounted in their relationship to one another (Fig. 14.9). Note that the coil portion of the moving element is in the magnetic field of the permanent magnet.

In order to understand how the meter works, assume that the coil of the moving element is placed in a magnetic field as shown in (Fig. 14.10).

The coil is pivoted so that it is able to rotate back and forth within the magnetic field set up by the magnet. When the coil is connected in a circuit, current flows through the coil in the direction indicated by the arrows and sets up a magnetic field within the coil. This field has the same polarity as the adjacent poles of the magnet. The interaction of the two fields causes the coil to rotate to a position so that the two magnetic fields are aligned. This force of rotation (torque) is proportional to the interaction between the like poles of the coil and the magnet and, therefore, to the amount of current flow in the coil. As a result, a pointer attached to the coil will indicate the amount of current flowing in the circuit as it moves across a graduated scale.

In the arrangement just discussed, note that any torque sufficient to overcome the inertia and friction of moving parts causes the coil to rotate until the fields align. This uncontrolled movement would cause inaccurate current readings. There fore, the turning motion of the coil is opposed by two springs. The value of the current flowing through the coil determines the turning force of the coil. When the turning force is equal to the opposition of the springs, the coil stops moving and the pointer indicates the current reading on a calibrated scale. In some meters the springs are made of conducting material and conduct current to and from the coil. The pole pieces of the magnet form a circular air gap within which the coil is pivoted.

To obtain a clockwise rotation, the north pole of the permanent magnet and that of the coil must be adjacent. The current flowing through the coil must, therefore, always be in the same direction. The D'Arsonval movement can be used only for d.c. measurements and the correct polarity must be observed. If the current is allowed to flow in the wrong direction through the coil, the coil will rotate counterclock wise and the pointer will be damaged. Since the movement of the coil is directly proportional to the current through the coil, the scale is normally a linear scale.

Meter Sensitivity

The sensitivity of a meter movement is usually expressed as the amount of current required to give full-scale deflection. In addition, the sensitivity may be expressed as the number of millivolts across the meter when full-scale current flows through it. This voltage drop is obtained by multiplying the full-scale current by the resistance of the meter movement. A meter movement, whose resistance is 50 ohms and which requires 1 milliampere (ma.) for full-scale reading, may be described as a 50-milli volt 0-1 milli ammeter.

Extending the Range of an Ammeter

A 0-1 milli ammeter movement may be used to measure currents greater than 1 ma. by connecting a resistor is called a shunt because it bypasses a portion of the current around the movement, extending the range of the ammeter. A schematic drawing of a meter movement with a shunt connected across it to extend its range is shown in (Fig. 14.11).

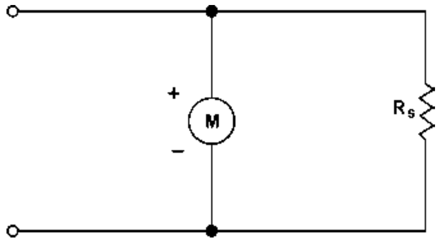


Fig. 14.11. Meter movement with shunt.

Determining the Value of a Shunt

The value of a shunt resistor can be computed by applying the basic rules for parallel circuits. If a 50 millivolt 0-1 milliammeter is to be used to measure values of current up to 10 ma., the following procedure can be used : The first step involves drawing a schematic of the meter shunted by a resistor labelled R_S (shunt resistor), as shown in (Fig. 14.12).

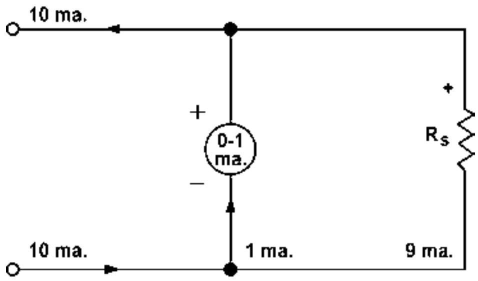


Fig. 14.12. Circuit schematic for shunt resistor.

Since the sensitivity of the meter is known, the meter resistance can be computed. The circuit is then redrawn as shown in (Fig. 14.13), and the branch currents can be computed, since a maximum of 1 ma. can flow through the meter. The voltage drop across R_S is the same as that across the meter, R_m :

E = I R

= 0.001 × 50

= 0.050 volt.

R_s can be found by applying Ohm's law :

$$R_s = \frac{E_{rs}}{I_{rs}}$$

$$= \frac{0.050}{0.009}$$

= 5.55 ohms.

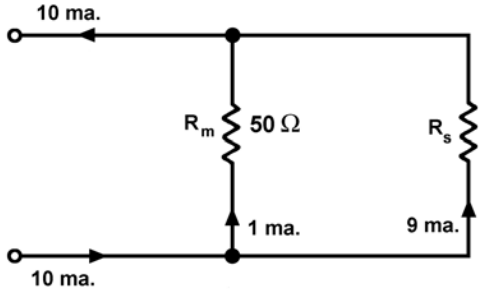


Fig. 14.13. Equivalent meter circuit.

The value of the shunt resistor (5.55 Ω) is very small, but this value is critical. Resistors used as shunts musts have close tolerances, usually 1 percent.

Universal Ammeter Shunt

The schematic drawing in (Fig. 14.14), the universal shunt, shows an arrangement whereby two or more ranges are provided by tapping the shunt resistor at the proper points. In this arrangement, a 0-5 ma. movement with a resistance of 20 ohms is shunted to provide a 0-25 ma. range and a 0-50 ma. range.

Ammeters having a number of internal shunts are called multirange ammeters. A scale for each range is provided on the meter face (Fig. 14.15). Some multimeters avoid internal switching through the use of external shunts. Changing ammeter ranges involves the selection and installation on the meter case of the proper size shunt.

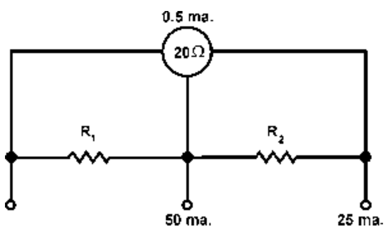


Fig. 14.14. Universal ammeter shunt.

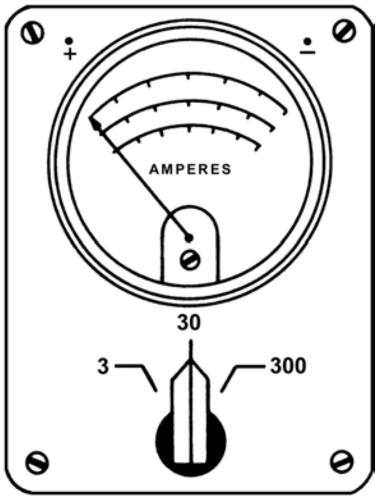


Fig. 14.15. A multirange ammeter.

MULTIMETERS

Ammeters are commonly incorporated in multiple-purpose instruments such as multimeter or volt-ohm-milliammeters. These instruments vary somewhat according to the design used by different manufacturers, but most incorporate the functions of an ammeter, a voltmeter, and an ohmmeter in one unit. A typical multimeter is shown in (Fig. 14.16). This multimeter has two selector switches : a function switch and a range switch. Since a multimeter is actually three meters in one case, the function switch must be placed in proper position for the type of measurement to be made. In (Fig. 14.16), the function swhich is shown in the ammeter position to measure d.c. milliamperes and the range switch is set at 1000. Set in this manner, the ammeter can measure up to 1,000 milliamperes or 1 ampere.

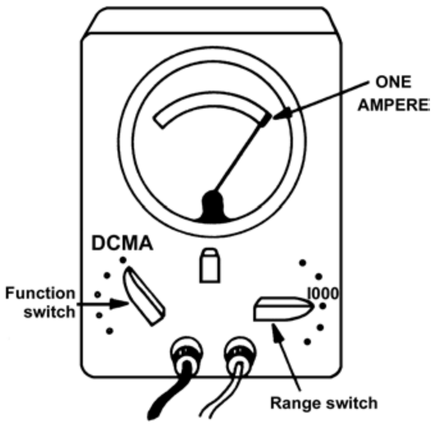


Fig. 14.16. A multimeter set to measure one ampere.

Multimeters have several scales, and the one used should correspond properly to the position of the range switch. If current of unknown value is to be measured, always select the highest possible range to avoid damage to the meter. The test leads should always be connected to the meter in the manner prescribed by the manufacturer. Usually the red lead is positive and the black lead is negative, or common. Many multimeters employ color coded jacks as an aid in connecting the meter into the circuit to be tested. In (Fig. 14.17), a multimeter properly set to measure current flow is connected into a circuit.

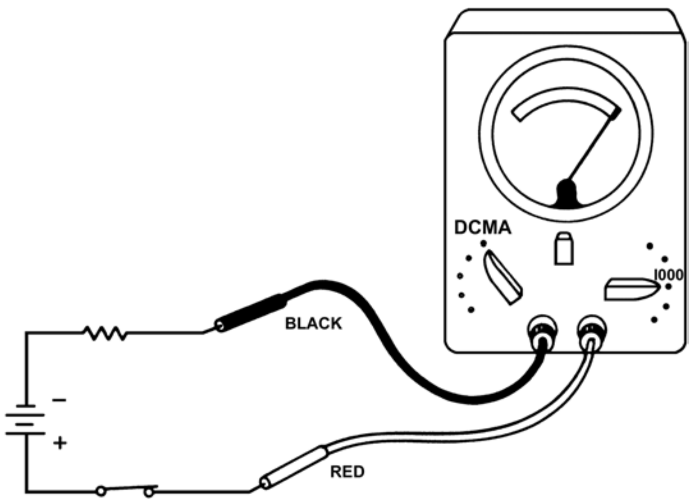


Fig. 14.17. A multimeter set to measure current flow.

The precautions to be observed when using all ammeter are summarized as follows :

1. Always connect an ammeter in series with the element through which the current flow is to be measured.
2. Never connect an ammeter across a source of voltage, such as a battery or generator. Remember that the resistance of an ammeter, particularly on the higher ranges, is extremely low and that any voltage, even a volt or so, can cause very high current to flow through the meter, causing damage to it.
3. Use a range large enough to keep the deflection less than full scale. Before measuring a current, form some idea of its magnitude. Then switch to a large enough scale or start with the highest range and work down until the appropriate scale is reached. The most accurate readings are obtained at approximately scale is reached. The most accurate readings are obtained at approximately half-scale deflection. Many milliammeters have been ruined by attempts to measure amperes. Therefore, be sure to read the lettering either on the dial or on the switch positions and choose proper scale before connecting the meter in the circuit.
4. Observe proper polarity in connecting the meter in the circuit. Current must flow through the coil in a definite direction in order to move the indicator needle up-scale. Current reversal because of incorrect connection in the circuit results in a reversed meter deflection and frequently causes bending of the meter needle. Avoid improper meter connections by observing the polarity markings on the meter.

VOLTMETER

The D' Arsonval meter movement can be used either as an ammeter or a voltmeter (Fig. 14.18). Thus, an ammeter can be converted to a voltmeter by placing a resistance in series with the meter coil and measuring the current flowing through it. In other words, a voltmeter is a current-measuring instrument, designed to indicate voltage by measuring the current flow through a resistance of known value. Various voltage ranges can be obtained by adding resistors in series with the meter coil. For low-range instruments, this resistance is mounted inside the case with the D' Arsonval movement and usually consists of resistance wire having a low temperature coefficient which is wound either on spools or card frames. For higher voltage ranges, the series resistance may be connected externally. When this is done, the unit containing the resistance is commonly called a multiplier.

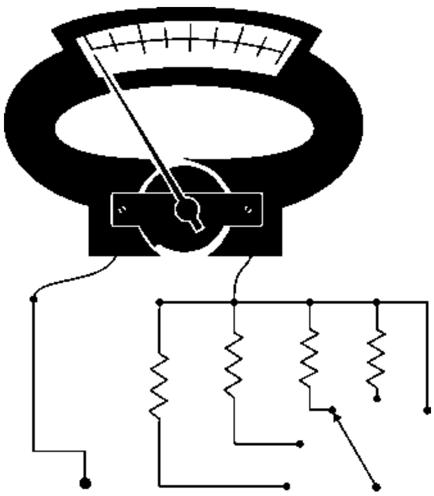


Fig. 14.18. Simplified diagram of a voltmeter.

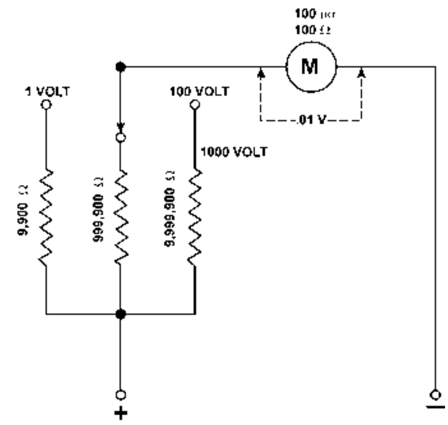


Fig. 14.19. Multirange voltmeter schematic.

Extending the Voltmeter Range

The value of the necessary series resistance is determined by the current required for full-scale deflection of the meter and by the range of voltage to be measured. Because the current through the meter circuit is directly proportional to the applied voltage, the meter scale can be calibrated directly in volts for a fixed series resistance.

For example, assume that the basic meter (microammeter) is to be made into a voltmeter with a full-scale reading of 1 volt. The coil resistance of the basic meter is 100 ohms, and 0.0001 ampere (100 microamperes) cause a full-scale deflection. The total resistance, R, of the meter coil and the series resistance is

$$R = \frac{E}{I} = \frac{1}{0.0001} = 10{,}000 \text{ ohms},$$

and the series resistance alone is

$R_s = 10{,}000 - 100 = 9{,}900$ ohms.

Multirange voltmeters utilize one meter movement with the required resistances connected in series with the meter by a convenient switching arrangement. A multirange voltmeter circuit with three ranges is shown in (Fig. 14.19). The total circuit resistance for each of the three ranges beginning with the 1-volt range is :

$$R = \frac{E}{I} = \frac{1}{100} = 0.01 \text{ megohm}$$

$$\frac{100}{100} = 1 \text{ megohm}$$

$$\frac{1{,}000}{100} = 10 \text{ megohms.}$$

Multirange voltmeters, like multirange a meters, meters are used frequently. They are physically very similar to ammeters, and their multipliers are usually located inside the meter with suitable switches or sets of terminals on the outside of the meter for selecting ranges (see Fig. 14.20).

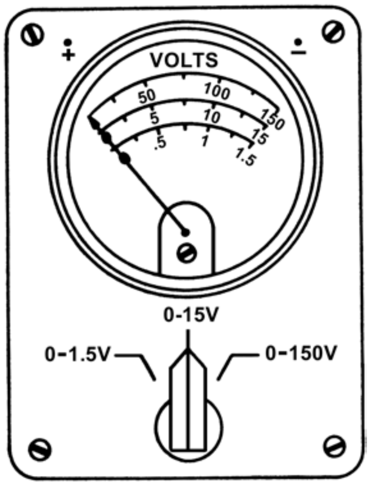


Fig. 14.20. Typical multirange voltmeter.

Voltage-measuring instruments are connected across (in parallel with) a circuit. If the approximate value of the voltage to be measured is not known, it is best, as in using the ammeter, to start with the highest range of the voltmeter and progressively lower the range until a suitable reading is obtained.

In many cases, the voltmeter is not a central-zero indicating instrument. Thus, it is necessary to observe the proper polarity when connecting the instrument to the circuit, as is the case when connecting the d.c. ammeter. The positive terminal of the voltmeter is always connected to the positive terminal of the source, and the negative terminal to the negative terminal of the source, when the source voltage is being measured. In any case, the voltmeter is connected so that electrons will flow into the negative terminal and out of the positive terminal of the meter. In (Fig. 14.21) a multimeter is properly connected to a circuit to measure the voltage drop across a resistor. The function switch is set at the d.c. volts position and the range switch is placed in the 50-volt position and the range switch is placed in the 50-volt position.

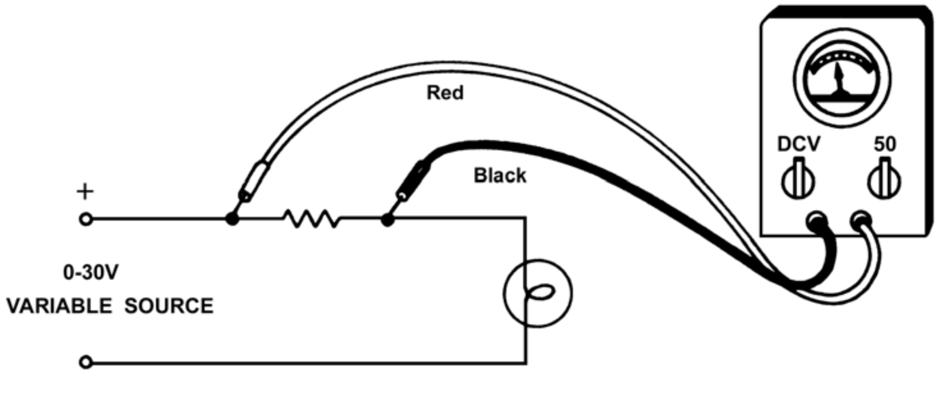


Fig. 14.21. A multimeter connected to measure a circuit voltage drop.

The function of a voltmeter is to indicate the potential difference between two points in a circuit. When the voltmeter is connected across a circuit, it shunts the circuit. If the voltmeter has low resistance, it will draw an appreciable amount of current. The effective resistance of the circuit will be lowered, and the voltage reading will consequently be lowered.

When voltage measurements are made in high-resistance circuits, it is necessary to use a high-resistance voltmeter to prevent the shunting action of the meter. The effect is less noticeable in low-resistance circuits because the shunting effect is less.

Voltmeter Sensitivity

The sensitivity of a voltmeter is given in ohms per volt (Ω/E) and is determined by dividing the resistance (R_m) of the meter plus the series resistance (R_s) by the full-scale reading in volts.
Thus,

$$\text{sensitivity} = \frac{R_m + R_s}{E}$$

This is the same as saying that the sensitivity is equal to the reciprocal of the current (in amperes); that is

$$\text{Sensitivity} = \frac{\text{ohms}}{\text{volts}} = \frac{1}{\frac{\text{volts}}{\text{ohms}}} = \frac{1}{\text{amperes}}$$

Thus, the sensitivity of a 100-microampere movement is the reciprocal of 0.0001 ampere, or 10,000 ohms per volt.
The sensitivity of a voltmeter can be increased by increasing the strength of the permanent magnet, by using lighter weight materials for the moving element (consistent with increased number of turns on the coil), and by using sapphire jewel bearings to support the moving coil.

Voltmeter Accuracy

The accuracy of a meter is generally expressed in percent. For example, a meter with an accuracy of 1 percent will indicate a value within a percent of the correct value. The statement means that, if the correct value is 100 units, the meter indication may be anywhere within the range of 99 to 101 units.

OHMMETERS

Two instruments are commonly used to check the continuity or to measure the resistance of a circuit or circuit element. These instruments are the ohmmeter and the megger, or megohmmeter. The ohmmeter is widely used to measure resistance and to check the continuity of electrical circuits and devices. Its range usually extends to a few megohms. The megger is widely used for measuring insulation resistance, such as the resistance between the windings and the frame of electric machinery, and for measuring the insulation resistance of cables, insulators, and bushings. Its range may extend to more than 1,000 megohms. When measuring very high resistances of this nature, it is not necessary to find the exact value of resistance, but rather to know that the insulation is either above or below a certain standard. When precision measurements are required, some type of bridge circuit is used. Ohmmeters may be of the series or shunt type.

Series-type Ohmmeters

A simplified schematic of an ohmmeter is shown in (Fig. 14.22). E is a source of EMF; R_1 is a variable resistor used to zero the meter; R_2 is a fixed resistor used to limit the current in the meter movement; and A and B are test terminals across which the resistance to be measured is placed.

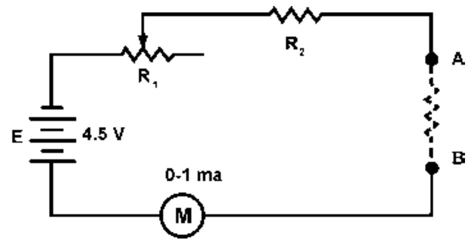


Fig. 14.22. Ohmmeter circuit.

If A and B are connected together (short-circuited), the meter, the battery, and resistors R_1 and R_2 form a simple series circuit. With R_1 adjusted so that the total resistance in the circuit is 4,500 ohms, the current through the meter is 1 ma. and the needle deflects full scale. Since there is no resistance between A and B, this position of the needle is labelled zero (Fig. 14.23). If a resistance equal to 4,500 ohms is placed between terminals A and B, the total resistance is 9,000 ohms and the current is .5 ma.

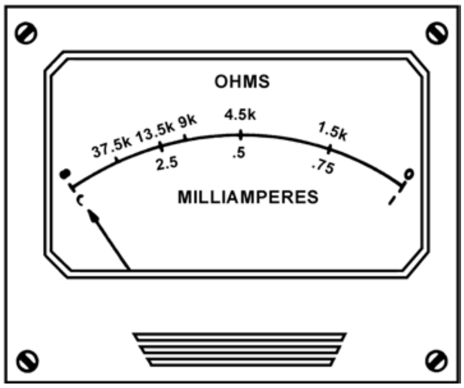


Fig. 14.23. A typical ohmmeter scale.

This causes the needle to deflect half scale. This half-scale reading, labelled 4.5 K ohms, is equal to the internal resistance of the meter, in this instance 4,500 ohms. If a resistance of 9,000 ohms is placed between terminals A and B, the needle deflects one-third scale. Resistances of 13.5 K and 1.5 K placed between terminals A and B will cause a deflection of one-fourth and three-fourths scale, respectively.

If terminals A and B are not connected (open-circuited), no current flows and the needle does not move. The left side of the scale is, therefore, labelled infinity to indicate an infinite resistance.

A typical ohmmeter scale is shown in (Fig. 14.23). Note that the scale is not linear and is crowded at the high resistance end. For this reason, it is good practice to use an ohmmeter range in which the readings are not too far from mid-scale. A good rule is to use a range in which the reading obtained does not exceed ten times, or is not less than one-tenth, the mid-scale reading.

The useful range of the scale shown is, by this rule, from 450 ohms to 45,000 ohms.

Most ohmmeters have more than one scale. Additional scales are made possible by using various values of limiting resistors and battery voltage. Some ohmmeters have a special scale called a low-ohm scale for reading low resistances. A shunt-type ohmmeter circuit is used for this scale.

Shunt-Type Ohmmeter

Shunt-type ohmmeters are used to measure small values of resistance. In the circuit shown in (Fig. 14.24), E (voltage) is applied across a limiting resistor R and a meter movement in series. Resistance and battery values are chosen so that the meter movement deflects full scale when terminals A and B are open. When the terminals are short-circuited, the meter reads zero; the short circuit conducts all the current around the meter. The unknown resistance R_x is placed between terminals A and B in parallel with the meter movement. The smaller the resistance value being measured, the less current flows through the meter movement.

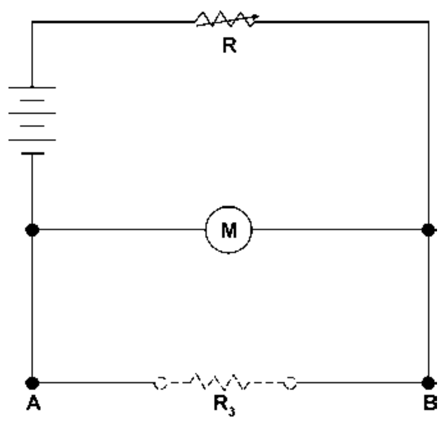


Fig. 14.24. Shunt-type ohmmeter circuit.

The value of the limiting resistor R is usually made large compared to the resistance of the meter movement. This keeps the current drawn from the battery practically constant. Thus, the value of R_x determines how much of this constant current flows through the meter and how much through R_x.

Note that in a shunt-type ohmmeter, current is always flowing from the battery through the meter movement and the limiting resistor. Therefore, when using an ohmmeter with a low-ohm scale, do not leave the switch in low-ohm position.

Use of the Ohmmeter

The ohmmeter is not as accurate a measuring device as the ammeter or the voltmeter because of the associated circuitry. Thus, resistance values cannot be read with greater than 5 to 10 percent accuracy. While there are instruments which read the resistance of an element with very great accuracy, they usually are more complicated to use.

In addition to measuring the resistance, the ohmmeter is a very useful instrument for checking continuity in a circuit. Often, when troubleshooting electronic circuits or wiring a circuit, visual inspections of all parts of the current path cannot be readily accomplished. Therefore, it is not always apparent whether a circuit is complete or whether current might be flowing in the wrong part of the circuit because of contact with adjacent circuits. The best method of checking a circuit under these conditions is to send a current through the circuit. The ohmmeter is the ideal instrument for checking circuits in this manner. It provides the power and the meter to indicate whether the current is flowing.

Observe the following precautions when using an ohmmeter :

1. Choose a scale which will contain the resistance of the element to be measured. In general, use a scale in which the reading will fall in the upper half of the scale (near full-scale deflection).
2. Short the leads together and set the meter to read zero ohms by setting the zero adjustment. If the scale is changed, readjust to zero ohms.
3. Connect the unknown resistance between the test leads and read its resistance from the scale. Never attempt to measure resistance in a circuit while it is connected to a source of voltage. Disconnect at least one end of the element being measured to avoid reading the resistance of parallel paths.

Megger (Megohmmeter)

The megger, or megohmmeter, is a high-range ohmmeter containing a hand-operated generator. It is used to measure insulation resistance and other high resistance values. It is also used for ground, continuity, and short-circuit testing of electrical power systems. The chief advantage of the megger over an ohmmeter is its capacity to measure resistance with a high potential, or "breakdown" voltage. This type of testing ensures that insulation or a dielectric material will not short or leak under potential electrical stress.

The megger (Fig. 14.25) consists of two primary elements, both of which are provided with individual magnetic fields from a common permanent magnet : (1) A hand-driven d.c. generator, G, which supplies the necessary current for making the measurement and (2) the instrument portion, which indicates the value of the resistance being measured. The instrument portion is of the opposed-coil type. Coils A and B are mounted on the movable member with a fixed angular relationship to each other and are free to turn as a unit in a magnetic field. Coil B tends to move the pointer counterclockwise and coil A, clockwise. The coils are mounted on a light, movable frame that is pivoted in jewel bearings and free to move about axis 0.

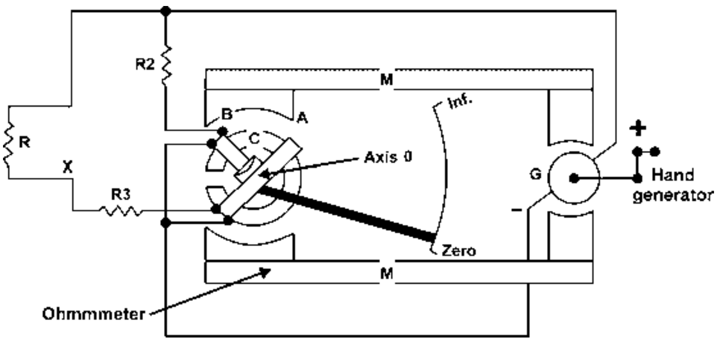


Fig. 14.25. Simplified megger circuit.

Coil A is connected in series with R3 and the unknown resistance, R_x, to be measured. The series combination of coil A, R3 and R_x is connected between the + and - brushes of the d.c. generator. Coil B is connected in series with R2 and this combination is also connected across the generator. There are no restraining springs on the movable member of the instrument portion of the megger. When the generator is not in operation, the pointer floats freely and may come to rest at any position on the scale.

If the terminals are open-circuited, no current flows in coil A, and the current in coil B alone controls the movement of the moving element. Coil B takes a position opposite the gap in the core (since the core cannot move and coil B can), and the pointer indicates infinity on the scale. When a resistance is connected between the terminals, current flows in coil A, tending to move the pointer clockwise. At the same time, coil B tends to move the pointer counterclockwise. Therefore, the moving element, composed of both coils and the pointer, comes to rest at a position at which the two forces are balanced. This position depends upon the value of the external resistance, which controls the relative magnitude of current of coil A. Because changes in voltage affect both coil A and B in the same proportion, the position of the moving element is independent of the voltage. If the terminals are short-circuited, the pointer rests at zero because the current in A is relatively large. The instrument is not damaged under these circumstances because the current is limited by R3.

There are two types of hand-driven megger: the variable type and the constant-pressure type. The speed of the variable-pressure type. The speed of the variable-pressure megger is dependent on how fast the hand crank is turned. The constant-pressure megger utilizes a centrifugal governor, or slip clutch. The governor becomes effective only when the megger is operated at a speed above its slip speed, at which speed its voltage remains constant.

A.C. MEASURING INSTRUMENTS

A d.c. meter, such as an ammeter, connected in an a.c. circuit will indicate zero, because the moving ammeter coil that carries the current to be measured is located in a permanent magnet field. Since the field of a permanent magnet remains constant and in the same direction at all times, the moving coil follows the polarity of the current. The coil attempts to move in one direction during half of the a.c. cycle and in the reverse direction during the other half when the current reverses.

The current reverses direction too rapidly for the coil to follow, causing the coil to assume an average position. Since the current is equal and opposite during each half of the a.c. cycle, the direct current meter indicates zero, which is the average value. Thus, a meter with a permanent magnet cannot be used to measure alternating voltage and current. However, the permanent magnet D' Arsonval meter may be used to measure alternating current or voltage if the current that passes through the meter is first rectified - that is, changed from alternating current to direct current.

Rectifier A.C. Meters

Copper-oxide rectifiers are generally used with D' Arsonval d.c. meter movements to measure alternating currents and voltages; however, there are many types of rectifiers which may be used, some of which are included in the discussion of alternator systems.

A copper-oxide rectifier allows current to flow through a meter in only one direction. A shown in (Fig. 14.26), the copper-oxide rectifier consists of copper-oxide disks separated alternately by copper disks and fastened together as a single unit. Current flows more readily from copper to copper oxide than from copper to copper. When a.c. is applied, therefore, current flows in only one direction, yielding a pulsating d.c. output as shown by the output wave shapes in (Fig. 14.27). This current can then be measured as it flows through the meter movement.

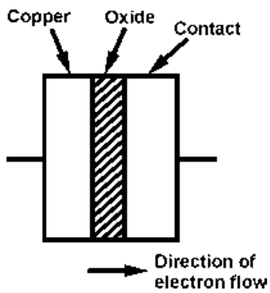


Fig. 14.26. Copper-oxide rectifier.

In some a.c. meters, selenium or vacuum tube rectifiers are used in place of the copper-oxide rectifier. The principle of operation, however, is the same in all meters employing rectifiers.

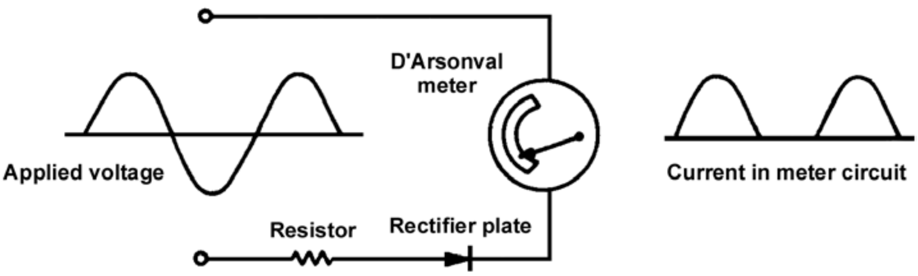


Fig. 14.27. A half-wave rectifier circuit.

Electrodynamometer Meter Movement

The electrodynamometer meter can be used to measure alternating or direct voltage and current. It operates on the same principles as the permanent magnet moving-coil meter, except that the permanent magnet is replaced by an air-core electromagnet. The field of the electrodynamometer meter is developed by the same current that flows through the moving coil (see Fig. 14.28).

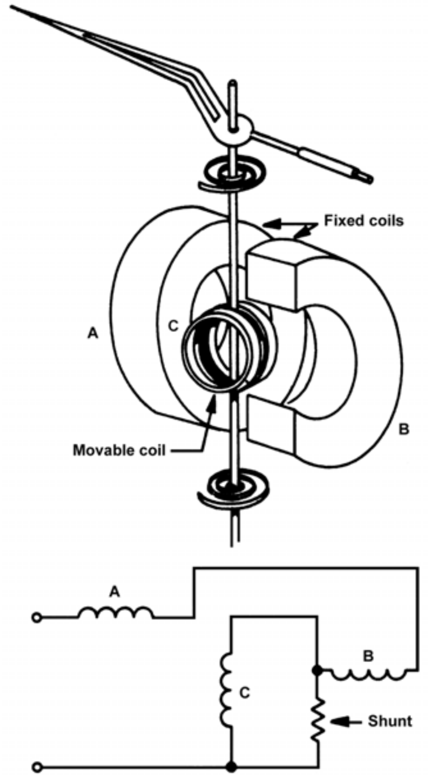


Fig. 14.28. Simplified diagram of an electrodynamometer movement.

In the electrodynamometer meter, two stationary field coils are connected in series with the movable coil. The movable coil is attached to the central shaft and rotates inside the two stationary field coils. The spiral springs provide the restraining force for the meter and also a means of introducing current to the movable coil.

When current flows through field coils A and B and movable coil C, coil C rotates in opposition to the springs and places itself parallel to the field coils. The more current flowing through the coils, the more the moving coil overcomes the opposition of the springs and the farther the pointer moves across the scale. If the scale is properly calibrated and the proper shunts or multipliers are used, the dynamometer movement will indicate current or voltage.

Although electrodynamometer meters are very accurate, they do not have the sensitivity of D'Arsonval meters and, for this reason, are not widely used outside the laboratory.

Electrodynamometer Ammeter

In the electrodynamometer ammeter, low resistance coils produce only a small voltage drop in the circuit measured. An inductive shunt is connected in series with the field coils. This shunt, similar to the resistor shunt used in d.c. ammeters, permits only part of the current being measured to flow through the coils. As in the d.c. ammeter, most of the current in the circuit flows through the shunt; but the scale is calibrated accordingly, and the meter the total current. An a.c. ammeter, like a d.c. ammeter, is connected in series with the circuit in which current is measured. Effective values are indicated by the meter. A schematic diagram of an electrodynamometer ammeter circuit is shown in (Fig. 14.29).

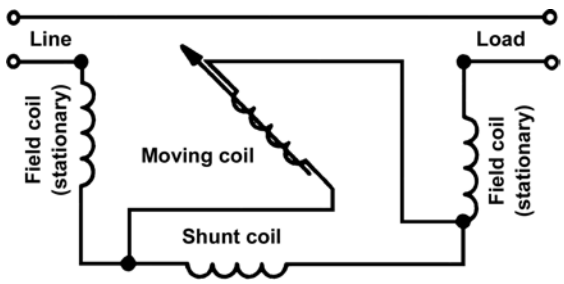


Fig. 14.29. Electrodynamometer ammeter circuit.

Electrodynamometer Voltmeter

In the electrodynamometer voltmeter, field coils are wound with many turns of small wire. Approximately 0.01 ampere of current flow through both coils is required to operate the meter. Resistors of a non-inductive material, connected in series with the coils, provide for different voltage ranges. Voltmeters are connected in parallel across the unit in which voltage is to be measured. The values of voltages indicated are effective values. A schematic diagram of an electrodynamometer voltmeter is shown in (Fig. 14.30).

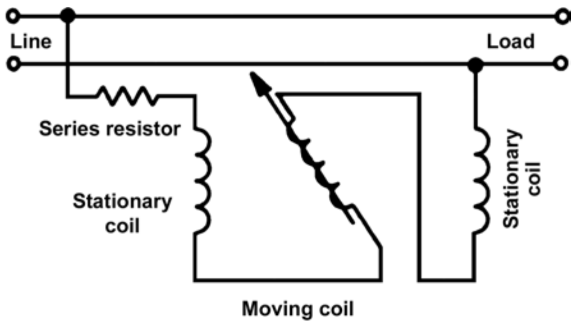


Fig. 14.30. Electrodynamometer voltmeter circuit.

Moving Iron-Vane Meter

The moving iron-vane meter is another basic type of meter. It can be used to measure either a.c. or d.c. Unlike the D'Arsonval meter, which employs permanent magnets, it depends on induced magnetism for its operation. It depends on induced magnetism for its operation. It utilizes the principle of repulsion between two concentric iron vanes, one fixed and one movable, placed inside a solenoid, as shown in (Fig. 14.31). A pointer is attached to the movable vane.

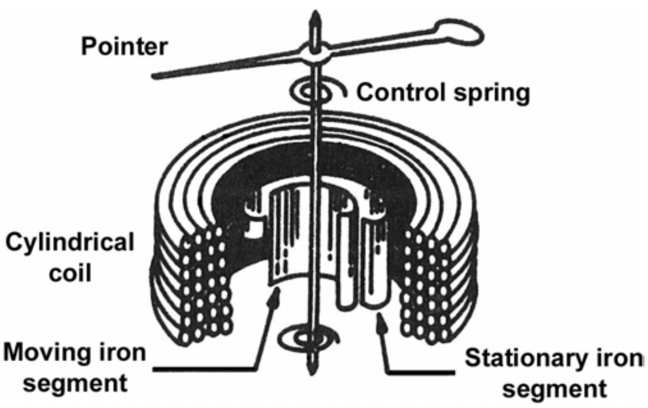


Fig. 14.31. Moving iron-vane meter.

When current flows through the coil, the two iron vanes become magnetized with north poles at their upper ends and south poles at their lower ends for one direction of current through the coil. Because like poles repel, the unbalanced component of force, tangent to the movable element, causes it to turn against the force exerted by the springs.

The movable vane is rectangular in shape and the fixed vane is tapered. The design permits the use of a relatively uniform scale.

When no current flows through the coil, the movable vane is positioned so that it is opposite the larger portion of the tapered fixed vane, and the scale reading is zero. The amount of magnetization of the vanes depends on the strength of the field, which, in turn, depends on the amount of current flowing through the coil. The force of repulsion is greater opposite the large end of the fixed vane than it is nearer the smaller end. Therefore, the movable vane moves toward the smaller end through an angle that is proportional to the magnitude of the coil current. The movement ceases when the force of repulsion is balanced by the restraining force of the spring.

Because the repulsion is always in the same direction (toward the smaller end of the fixed vane), regardless of the direction of current flow through the coil, the moving iron-vane instrument operates on either d.c. or a.c. circuits.

Mechanical damping in this type of instrument can be obtained by the use of an aluminium vane attached to the shaft so that, as the shaft moves, the vane moves in a restricted air space.

When the moving iron-vane meter is designed to be used as an ammeter, the coil is wound with relatively few turns of large wire in order to carry the rated current.

When the moving iron-vane meter is designed to be used as a voltmeter, the solenoid is wound with many turns of small wire. Portable voltmeters are made with self-contained series resistance for ranges up to 750 volts. Higher ranges are obtained by the use of additional external multipliers.

The moving iron-vane instrument may be used to measure direct current but has an error due to residual magnetism in the vanes. The error may be minimized by reversing the meter connections and averaging the readings. When used on a.c. circuits the instrument has an accuracy of 0.5 percent. Because of its simplicity, its relatively low cost, and the fact that no current is conducted to the moving element, this type of movement is used extensively to measure current and voltage in a.c. power circuits. However, because the reluctance of the magnetic circuit is high, the moving iron-vane meter requires much more power to produce full-scale deflection than is required by a D' Arsonval meter of the same range. Therefore, the moving iron-vane meter is seldom used in high-resistance low-power circuits.

Inclined-Coil Iron-Vane Meter

The principle of the moving iron-vane mechanism is applied to the inclined-coil type of meter, which can be used to measure both a.c. and d.c. The inclined-coil, iron-vane meter has a coil mounted at an angle to the shaft. Attached obliquely to the shaft, and located inside the coil, are two soft-iron vanes. When no current flows through the coil, a control spring holds the pointer at zero, and the iron vanes lie in planes parallel to the plane of the coil. When current flows through the coil, the vanes tend to line up with magnetic lines passing through the center of the coil at right angles to the plane of the coil. Thus, the vanes rotate against the spring action to move the pointer over the scale.

The iron vanes tend to line up with the magnetic lines regardless of the direction of current flow through the coil. Therefore, the inclined-coil, iron-vane meter can be used to measure either alternating current or direct current. The aluminium disk and the drag magnets provide electromagnetic damping.

Like the moving iron-vane meter, the inclined coil type requires a relatively large amount of current for full-scale deflection and is seldom used in high-resistance low-power circuits.

As in the moving iron-vane instruments, the inclined-coil instrument is wound with few turns of relatively large wire when use as an ammeter and with many turns of small wire when used as a voltmeter.

Thermocouple Meter

If the ends of two dissimilar metals are welded together and this junction is heated, a d.c. voltage is developed across the two open ends. The voltage developed depends on the material of which the wires are made and on the difference in temperature between the heated junction and the open ends.

In one type of instrument, the junction is heated electrically by the flow of current through a heater element. It does not matter whether the current is alternating or direct because the heating effect is independent of current direction. The maximum current that can be measured depends on the current rating of the heater, the heat that the thermocouple can stand without being damaged, and on the current rating of the meter used with the thermocouple. Voltage can also be measured if a suitable resistor is placed in series with the heater. In meter applications, a D' Arsonval meter is used with a resistance wire heater, as shown in (Fig. 14.32).

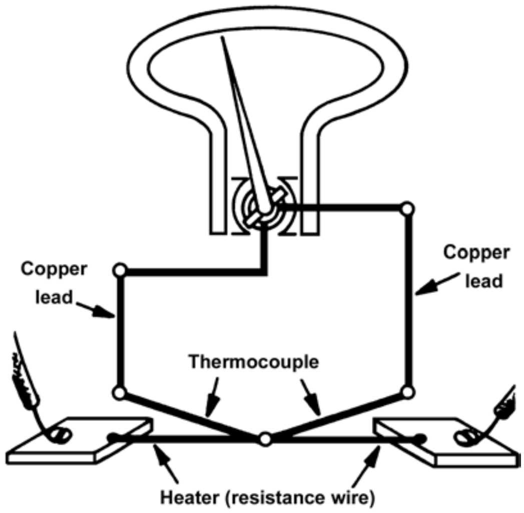


Fig. 14.32. Simplified diagram of a thermocouple meter.

As current flows through the resistance wire, the heat developed is transferred to the contact point and develops an e.m.f. which causes current to flow through the meter. The coil rotates and causes the pointer to move over a calibrated scale. The amount of coil movement is dependent on the amount of heat, which varies as the square of the current. Thermocouple meters are used extensively in a.c. measurements.

Disc Ammeter with Split-phase Windings

In this arrangement, the windings on the two laminated a.c. magnets P_1 and P_2 are connected in series. But the winding of P_2 is shunted by a resistance R with the result that the current in this winding lags with respect to the total line current. In this way, the necessary phase angle α is produced between two fluxes Φ_1 produced by P_1 and P_2 respectively. This angle is of the order of 60^o. If the hysteresis effects etc. are neglected, then each flux will be proportional to the current to be measured i.e. line current I.

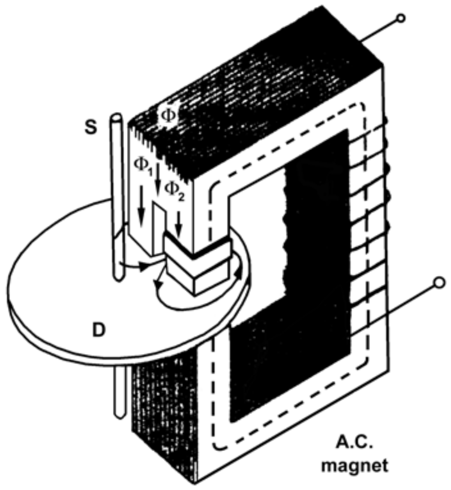


Fig. 14.33.

Shaded-pole Induction Ammeters

In the shaded-pole type induction ammeter (Fig.14.33) only one single flux-producing winding is used. The flux Φ produced by this winding is split up into two fluxes Φ_1 and Φ_2 which are made to have the necessary phase difference of α by the device shown in (Fig. 14.33). The portions of the upper and lower poles near the disc D are divided by a slot into two halves, one of which carries a closed 'shading' winding or ring. This shading winding or ring acts as a short-circuited secondary and the main winding as the primary. The current induced in the ring by transformer action retards the phase of flux Φ_2 with respect to that of Φ_1 by about 50° or so. The fluxes Φ_1 and Φ_2 passing through the unshaded and the shaded parts respectively, react with eddy currents i_2 and i_1 respectively and so produce the driving torque whose value is

$$T_d \alpha \Phi_{1m} \Phi_{2m} \sin \alpha$$

Assuming that both Φ_1 and Φ_2 are proportional to the current I, we have

$$T_d \alpha I^2$$

This torque is balanced by the controlling torque provided by the springs.

The actual shaded-pole type induction instrument is shown in (Fig. 14.34). It consists of a suitably -shaped aluminium or copper disc mounted on a spindle which is supported by jewelled bearings. The spindle carries a pointer and has a control spring attached to it. The edge or periphery of the disc moves in the air-gap of a laminated a.c. electromagnet which is energised either by the current to be measured (as ammeter) or by the current proportional to the voltage to be measured (as a voltmeter). Damping is by eddy currents induced by a permanent magnet embracing another portion of the same disc. As seen, the disc serves both for damping as well as operating purposes. The main flux is split into two component fluxes by shading one-half of each pole. These two fluxes have a phase difference of 40° to 50° between them and they induce two eddy currents in the disc. The fluxes and eddy currents produce a resultant torque which deflects the disc- continuous rotation being prevented by the control spring and the deflection produced is proportional to the square of the current or voltage being measured.

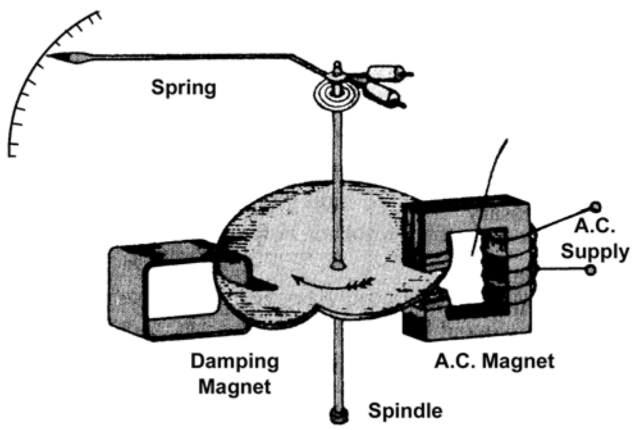


Fig. 14.34.

Induction Voltmeters

Their construction is similar to that of the ammeters except for this difference that their winding are wound with a large number of turns of fine wire. Since they are connected across the lines, they carry very small currents (5-10 mA), the number of turns of wire has to be large for producing an adequate amount of m.m.f. Splitphase winding are obtained by connecting a high resistance R in series with the winding of one magnet and an inductive coil in series with the winding of the other magnet as shown in (Fig. 14.35).

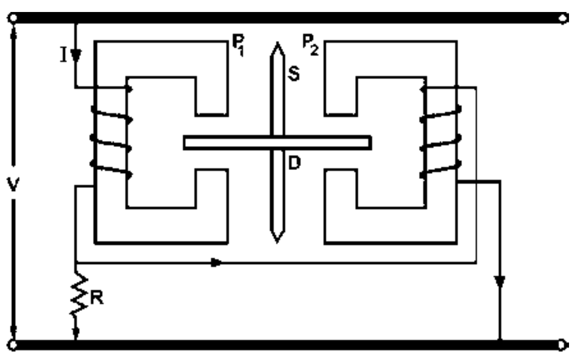


Fig. 14.35.

Wattmeter

Electric power is measured by means of a wattmeter. Because electric power is the product of current and voltage, a wattmeter must have two elements, one for current and the other for voltage, as indicated in (Fig. 14.36). For this reason, wattmeters are usually of the electrodynamometer type.

The movable coil with a series resistance forms the voltage element, and the stationary coils constitute the current element. The strength of the field around the potential coil depends on the amount of current that flows through it. The current, in turn, depends on the load voltage applied across the coil and the high resistance in series with it. The strength of the field around the current coils depends on the amount of current flowing through the load. Thus, the meter deflection is proportional to the product of the voltage across the potential coil and the current through the current coils. The effect is almost the same (if the scale is properly calibrated) as if the voltage applied across the load and the current through the load were multiplied together.

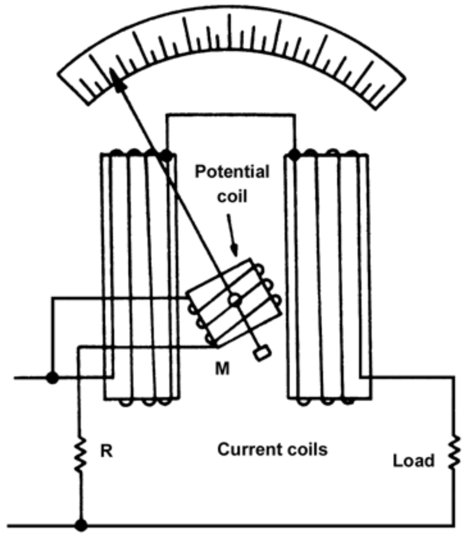


Fig. 14.36. Simplified electrodynamometer wattmeter circuit.

If the current in the line is reversed, the direction of current in both coils and the potential coil is reversed, the net result is that the pointer continues to read up-scale . Therefore, this type of wattmeter can be used to measure either a.c. or d.c. power.

Power Meters

In some a.c. power generating systems it is usual to provide an indication of the total power generated and/or the total reactive power. Separate instruments may be employed; one calibrated to read directly in watts and the other calibrate to read in var's (volt amperes reactive) or, as in the case of the instrument illustrated in (Fig. 14.37), both functions may be combined in what is termed a watt/var meter.

The construction and operation of the meter, not unlike the frequency meter described earlier, is based on the conventional electrodynamometer pattern and its scale, which is common to both units of measurement, is calibrated for use with a current transformer and an external resistor. A selector switch mounted adjacent to the meter provides for it to be operated as either a wattmeter or as a varmeter.

When selected to read in watts the field coil is supplied from the current transformer which as will be noted from (Fig. 14.37) senses the load conditions at phase "B" of the supply. The magnetic field produced around the field coil is proportional to the load. The moving coil is supplied at 115 volts from phase B to ground and this field is constant under all conditions. The currents in both coils are in phase with each other and the torque resulting from both magnetic fields deflects the moving coil and pointer until balance between it and controlling spring torque is attained.

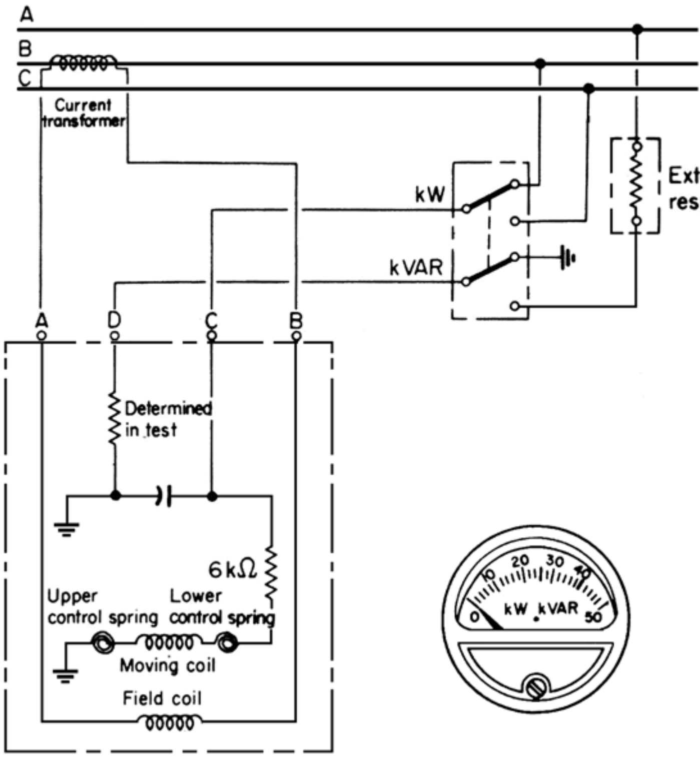


Fig. 14.37. Circuit arrangements of a watt/VAR meter.

In the "var" position of the selector switch the field coil is again supplied from the current transformer sensing load conditions at phase "B". The moving coil, however, is now connected across phases "A" and "C" and in order to obtain the correct coil current, a calibrated resistor is connected in the circuit and mounted external to the instrument. The current in the moving coil is then the magnetic fields of both coils bear the same angular relationship and no torque is produced.

For power factors less than unity there is interaction of the coil fields and a torque proportional to the load current and phase angle error is produced. Thus, the moving coil and pointer are rotated to a balanced position at which the reactive power is indicated.

Frequency Meters

Alternating-current electrical equipment is designed to operate within a given frequency range. In some instances the equipment is designed to operate at one particular frequency, as are electric clocks and time switches. For example, electric clocks are commonly designed to operate at 60 c.p.s. If the supply frequency is reduced 59 c.p.s., the clock will lose one minute every hour.

Transformers and a.c. machinery are designed to operate at a specified frequency. If the supply frequency falls more than 10 percent from the rated value, the equipment may draw excessive current, and dangerous overheating will result. It is, therefore, necessary to control the frequency of electric power systems. Frequency meters are employed to indicate the frequency so that corrective measures can be taken if the frequency varies beyond the prescribed limits.

Frequency meters are designed so that they will not be affected by changes in voltage. Because a.c. systems are designed to operate normally at one particular frequency, the range of the frequency meter may be restricted to a few cycles on either side of the normal frequency. There are several types of frequency meters, including the vibrating-reed type, and the resonant-circuit type. Of these types, the vibrating-reed frequency meter is used most often in aircraft systems, and is discussed in some detail.

Vibrating-Reed Frequency Meter

The vibrating-reed type of frequency meter is one of the simplest devices for indicating the frequency of an a.c. source. A simplified diagram of one type of vibrating-reed frequency meter is shown in (Fig. 14.38).

The current whose frequency is to be measured flows through the coil and exerts maximum attraction on the soft-iron armature twice during each cycle (A of Fig. 14.38). The armature is attached to the bar, which is mounted on a flexible support. Reeds of suitable dimensions to have natural vibration frequencies of 110, 112, 114, and so forth up to 130 c.p.s. are mounted on the bar (B of Fig. 14.38). The reed having a frequency of 110 c.p.s. is marked "55" cycles; the one having a frequency of 130 c.p.s. is marked "65" c.p.s.; the one having a frequency of 120 c.p.s. is marked "60" c.p.s., and so forth.

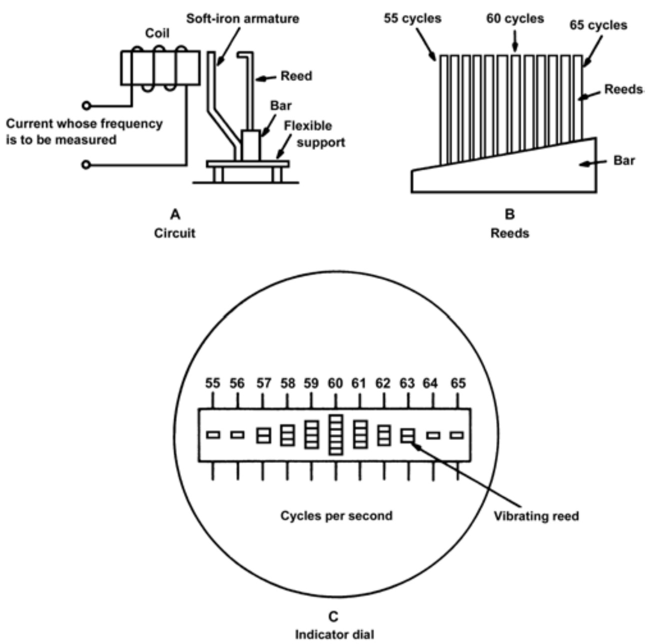


Fig. 14.38. Simplified diagram of a vibrating-reed frequency meter.

In some instruments the reeds are the same lengths, but are weighted by different amounts at the top so that they will have different natural rates of vibration.

When the coil is energized with a current having a frequency between 55 and 65 c.p.s., all the reeds are vibrated slightly; but the reed having a natural frequency closest to that of the energizing current (whose frequency is to be measured) vibrates through a larger amplitude. The frequency is read from the scale value opposite the reed having the greatest amplitude of vibration.

An end view of the reeds is shown in the indicator dial (C of Fig. 14.38). If the energizing current has a frequency of 60 c.p.s., the reed marked "60" c.ps. will vibrate the greatest amount, as shown.

FREQUENCY METERS

These instruments form part of the metering system required for main a.c. power generating systems, and in some aircraft, they may also be employed in secondary a.c. generating systems utilizing inverters. The dial presentation and circuit diagram of a typical meter are shown in (Fig. 14.39). The indicating element, which is used in a mutual inductance circuit, is of the standard electrodynamometer pattern consisting essentially of a moving coil and a fixed field coil. The inductor circuit includes a nickel-iron core loading inductance, a dual fixed capacitor unit, four current-limiting resistors connected in series-parallel, and two other parallel-connected resistors which provide for temperature compensation. The electrical values of all the inductor circuit components are fixed.

The instrument also incorporates a circuit which is used for the initial calibration of the scale. The circuit is comprised of a resistor, used to govern the total length of the arc over which the pointer travels between the minimum and maximum frequencies, and a variable inductor system which governs the position of the centre of the arc of pointer travel relative to the mid-point of the instrument scale.

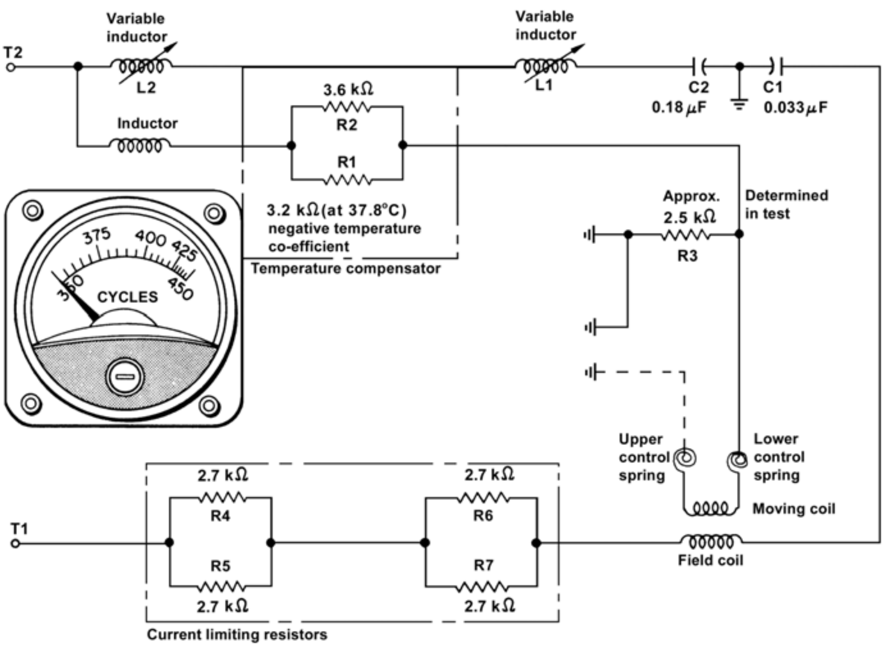


Fig. 14.39. Circuit arrangements of a frequency meter.

In operation the potential determined by the supply voltage and frequency is impressed on the field coil, which in turn sets up a main magnetic field in the area occupied by the moving coil. A second potential, whose value is also dependent on the supply voltage and frequency, is impressed on the moving coil, via the controlling springs. Thus, a second magnetic field is produced which interacts with the main magnetic field and also produces a torque causing the moving coil to rotate in the same manner as a conventional moving coil indicator. Rotation of the coil continues until the voltage produced in this winding by the main field is equal and opposite to the impressed potential at the given frequency. The total current in the moving coil and the resulting torque are therefore reduced to zero and the coil and pointer remain stationary at the point on the scale which corresponds to the frequency impressed on the two coils.

Ampere-hour Mercury Motor Meter

It is one of the best and most popular form of mercury Ammeter used for d.c. work.

Construction

It consists of a thin Copper disc D, mounted at the base of a spindle working in jewelled cup bearing and revolving between a pair of permanent magnets M_1 and M_2. One of the two magnets i.e. M_2 is used for driving purpose whereas M_1 is used for braking. In between the poles of M_1 and M_2 is a hollow circular box B in which rotates the Cu disc and the rest of the space is filled up with mercury which exerts a considerable upward thrust on the disc, thereby reducing the pressure on the bearings. The spindle is so weighted that it just sinks in the mercury bath. A worm cut in the spindle at its top engages the gear wheels of the recording mechanism as shown in (Fig. 14.40) and (Fig. 14.41).

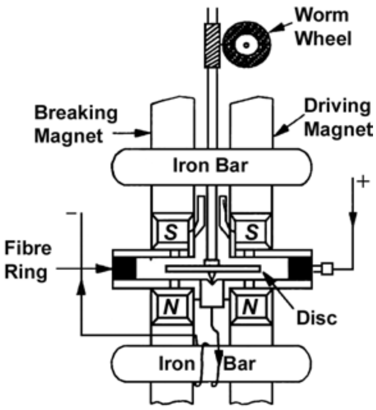


Fig. 14.40.

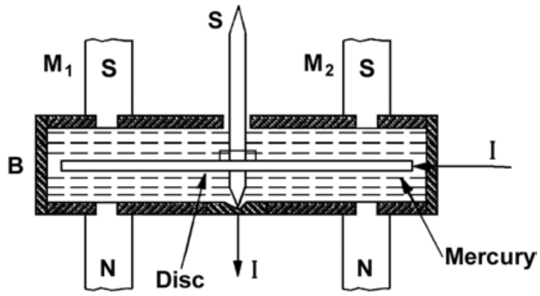


Fig. 14.41.

Principle of Action

Its principle of action can be understood from (Fig. 14.42) which shows a separate line drawing of the motor element. The current to be measured is led in the disc through the mercury, at a point at its circumference on the right-hand side. As shown by arrows, it flows radially to the centre of the disc where it passes out to the external circuit through the spindle and its bearings. It is worth noting that current flow takes place only under the right-hand side magnet M_2 and not under the left-hand side magnet M_1. The field of M_2 will, therefore, exert a force on the right-side portion of the disc which carries the current (motor action). The direction of the force, as found by Fleming's Left-hand rule, is as shown by the arrow. The magnitude of the force depends on the flux density and current ($\because$ F=BIl). The driving or motoring torque T_d so produced is given by the product of the force and the distance from the spindle at which this force acts. When the disc rotates under the influence of this torque, it cuts through the field of left-hand side magnet M_1 and hence eddy currents are produced in it which results in the production of braking torque. The magnitude of the retarding or braking torque is proportional to the speed of rotation of the disc.

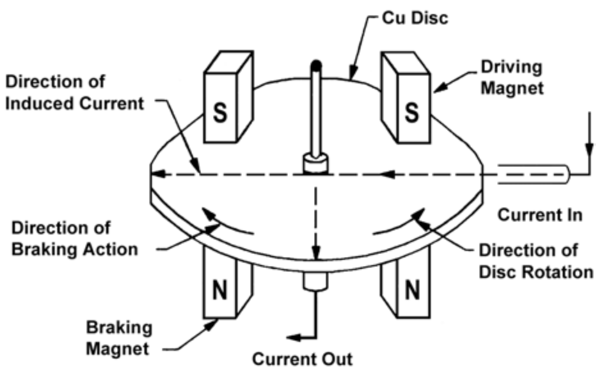


Fig. 14.42.

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CHAPTER - 15
KNOWLEDGE AND PURPOSE OF BONDING & SHIELDING AND DIFFERENCE BETWEEN THEM, PRECAUTION, METHODS EMPLOYED, MINIMUM ACCEPTABLE STANDARDS FOR INSULATION AND BONDING AND TESTING

BONDING

Bonding is the electrical interconnection of metallic aircraft parts (normally at earth potential) for the safe distribution of electrical charges and currents.

FUNCTION OF BONDING

Bonding provides a means of protection against charges as a result of the build-up of precipitation, static, and electrostatic induction as a result of lightening strikes so that the safety of the aircraft or its occupants is not endangered. The means provided are such as to (a) minimise damage to the aircraft structure or components, (b) prevent the passage of such electrical currents as would cause dangerous malfunctioning of the aircraft or its equipment, and (c) prevent the occurrence of high potential differences within the aircraft. Bonding also reduces the possibility of electric shock from the electrical supply system reduces interference with the functioning of essential services (e.g. radio communications and navigational aids) and provides a low resistance electrical return path for electric current in each return systems.

PRIMARY AND SECONDARY CONDUCTORS

Primary conductors are those required to carry lightening strikes, whilst secondary conductors are provided for other forms of bonding. The current British Civil Airworthiness Requirements (BCAR) for bonding paths are as follows:-

A BCAR Section D D4-6 and Section K K4-6

(i) The cross sectional area of Primary Conductors made from copper shall be not less than 0.0045 sq in. i.e. 0.25 in by 26 swg, except that, where a single conductor is likely to carry the whole discharge from an isolated section, the cross sectional area shall be not less than 0.009 sq in, i.e. 0.5 in by 26 swg. Aluminium Primary Conductors shall have a cross sectional area giving an equivalent surge carrying capacity.

(ii) The cross sectional area of secondary conductors made from copper must not be less than 0.001 sq in which corresponds to 44 strands of 39 swg form braided conductors. Where a single wire is used its size must be not less than 18 swg.

B BCAR 23 ACB 23.867 and JAR -25 ACJ 25 X 899 (4.2)

(i) Where additional conductors are required to provide or supplement the inherent primary bonding paths provided by the structure or equipment, then the cross sectional area of such primary conductors made from copper should not be less than 3 mm^2 except that, where a single conductor is likely to carry the whole discharge from an isolated section, the cross sectional area would be not less than 6 mm^2. Aluminium primary conductors should have a cross sectional area giving an equivalent surge carrying capacity.

(ii) Where additional conductors are required to provide or supplement the inherent secondary bonding paths provided by the structure or equipment, the cross sectional area of such secondary conductors made from copper should be not less than 1mm^2. Where a single wire is used its size should be not less than 1-2 mm dia.

BONDING OF AIRCRAFT OF METALLIC AND NON-METALLIC CONSTRUCTION

The skin of an all-metal aircraft is considered adequate to ensure protection against lightning discharge provided that the method of construction is such that it produces satisfactory electrical construction is such that it produces satisfactory electrical contact at the joints.

NOTE: An electrical contact with a resistance less than 0.05 ohm is considered satisfactory.

With regard to aircraft of non-metallic or composite construction, a cage, consisting of metallic conductors having a surge carrying capacity at least carrying capacity at least equal to that required for primary conductors and to which metal parts are bonded, forms part of the configuration of the structure and must conform to the requirements of chapter D4 - 6 of BCAR.

The earth system which in the case of aircraft of metallic construction is normally the aircraft structure and for aircraft of nonmetallic construction is the complete bonding system, must be automatically connected to the ground on landing. This is normally achieved through the nose or tail wheel tyre, which is impregnated with an electrically conducting compound, to provide a low resistance path.

NOTE: On some aircraft, a static discharge wick or similar device trailed from a landing gear assembly is used to provide ground contact on landing.

The reduction or removal of electrostatic charges which build up on such surfaces as glass figure reinforced plastic, can be achieved by the application of a paint, e.g. PR 934, which produces a conductive surface.

BONDING CONNECTIONS

When a bonding connection is to be made or renewed, it is essential that the conductor has the specified current - carrying capacity, since the bond may have been designed to carry relatively high electrical loads, e.g. under circuit fault conditions.

The manufacturers of solid bonding strip and braided bonding cord usually quote the cross-sectional area on the relevant data sheet. However, in the case of renewal or repair, if the original conductor cannot be matched exactly, a replacement manufactured of the same type of material, but of greater cross-sectional area, should be selected.

Braided copper or aluminium cords fitted at each end with connecting tags or lugs (usually referred to as 'bonding jumpers), should be used for bonding connections between moving parts or parts subjected to vibration, and these are suitable both as primary and secondary conductors.

The tags or lugs on bonding jumpers are generally fitted by the "crimping method', see Leaflet (EEL /3-1 and only the correction. During assembly of the connections to aluminium cords, anti-oxidant (crimping) compound consisting of 50% by weight of zinc oxide in white petroleum jelly, and complying with DTD 5503, should be applied to the connections.

Where applicable, the soldering of tags or lugs fitted to braided copper cord should be in accordance, with Leaflet BL / 6-1, using a resin flux. Special care is necessary because over beating and cooling of conductors will cause brittleness, while a loss of flexibility up to 25.4 mm (1 inch) from the lug may occur as a result of the capillary action of the molten solder.

NOTE: Primary flexible conductors are often made of 600 strands of copper wire, 0-0048 inch in diameter, and formed in a flat braid approximately 0.625 inch wide.

All bonding connection should be properly locked to prevent intermittent contact which may be caused by vibration.

NOTE: Intermittent contact is worse than no contact at all.

Bonding connections should not interfere mechanically or electrically with any associated or adjacent equipment, and bonding jumpers should not be excessively tight or slack.

The run of all primary conductors should be as straight as possible; sharp bends must be avoided.

The number of location of bonding connections to the various components is important and this should be checked and verified by reference to the relevant drawing e.g. where an engine is not in direct electrical contact with its mounting it should be bonded with at least two primary conductors, one on each side of the engine.

In most instances the following joints are considered self-bonding, provided that all insulating materials (e.g. anoetic finish, paint storage compounds etc.) are removed from the contact faces before assembly, but if any doubt exists regarding the correctness of the bonds, a bonding test should be carried out:-

a. Metal-to-metal joints held together by threaded devices, reverted joints, structural wires under appreciable tension and bolted or clamped fittings.
b. Most cowling fasteners, locking and latching mechanisms.
c. Metal-to-metal hinges for doors and panels and metal-to-metal bearings (including ball bearings).

(i) In the case of bearings for control surface hinges it should be ascertained which bearings are classified as self bonding, e.g. metal-to-metal, nylon with conducting grease.

(ii) Where applicable, bonding jumpers for control surfaces should be as flexible and as short as possible, of as low impedance as is practicable and should not be tinned. The possibility of a jumper jamming the controls must be avoided.

FLEXIBLE BONDING CONNECTIONS

Flexible hose connections used for joining rigid pipes should be bonded by fitting clips around the pipes approximately 13 mm (1/2 inch) away from the hose, and bridging with a corrupted bonding strip or jumper; the practice of tucking the ends of bonding strips between the hose and the pipe is not recommended. To obtain good electrical contact the area under each clip should be cleaned and, after the clip has been fitted, protection should be restored.

Not only must the flexible hose connection be bridged, but each pipe run should be bonded to earth at each end, particularly within a radius of 2.42 metres (8 feet) of any unscrewed radio equipment or aerial lead, where earthing bonds should not be more than 1.5 metres (5 feet apart), or less distance apart, if called for by the manufacturer.

If bridging strips or bonding cords are fractured a new conductor should be fitted. The soldering of broken ends is prohibited.

High -pressure flexible pipe assemblies are usually self-bonding, but a bonding test should be made between the assembly end-couplings to prove the integrity of the bonding.

NOTE: The provisions of paragraph (3.6.2) above also apply to any long electrically-conducting parts (including metallic conduits and metal braiding) which are not insulated from earth.

When any bonding or earth connection is made to the structure or equipment, the specified standard of protection again corrosion should be provided.

After a non-conducting protective coating has been removed from the connecting area, the preferred sealing and anti-oxidant treatment as specified on the relevant drawing and specification should be carried out.

NOTE: Non-conducting protective treatments include all generally used priming and finishing paints, varnishes and temporary protectives, chromic, anoetic and phosphate coatings. Metallic coatings, such as cadmium and tin, are satisfactory conductors and should not be removed. If a polysulphide compound is used for sealing the earth or bonding point, it must be ensured that the anti-oxidant to be subsequently applied will not have a detrimental effect on the sealing. e.g. DTD 5503 should not be used.

When the connection has been made any excess compound should be wiped off, using a rag damped in methyl ethyl ketone (MEK) and the connection and adjacent area re-protected by the specified method, this depending on the materials concerned and the position of the connection.

When a 'corrosion washer' forms part of the connecting assembly, it should be correctly fitted and be of the correct material for the type of connection concerned.

NOTE: A corrosion washer is plated, or manufactured of a material having a potential such that when placed between materials of widely differing potential it reduces the risk of corrosion caused by electrolytic action.

EARTH TERMINALS

When earth-return terminal assemblies are fitted or replaced, the correct method of fitting to the structure, the corrosion protection required and the exact location on the structure should be carefully checked. The procedure for fitting and the number of terminations to be attached will vary with the design of the terminal assembly and the type of structure, therefore reference should be made to the relevant drawings and instructions to ensure both electrical and structural integrity.

(i) All earth terminal assemblies should be checked for resistance between the lug attachment point(s) and the surrounding structure and this must not exceed the figure specified for the aircraft concern (e.g. 0.025 ohm). When earth terminal assemblies are also used to carry electrical supplies, a milivolt drop test, as outlined in paragraph 4.3 must be carried out.

(ii) If the resistance in either case is unsatisfactory, the terminal assembly should be removed, the contacting faces cleared with a fine abrasive (e.g. aluminium wool) and reassembled using, where applicable, new corrosion washers. The connecting area should be sealed and treated with anti-oxidant compound as specified in the relevant drawing and specification.

NOTE: Leads connected to earth terminal assemblies should be of insulated cable with terminal tags fitted by the crimping method. It is important that the cable is of the specified gauge for the service concerned and is kept as short as possible.

BONDING CARRYING THE MAIN ELECTRICAL SUPPLY

(i) The cross-sectional area of the main earth system, or any connection to it, must be such that without over-heating or causing excessive voltage drop, it will carry any electrical currents which may pass through it normally or under fault conditions.

(ii) If, under fault conditions, it should form part of a short-circuit, not provided against by a protective device, it should be capable of carrying the full short-circuit current which can pass, without risk of fire or damage to the bonding system.

NOTE: For example, paragraph (ii) may apply to bonding which under fault conditions becomes part of a starter or other heavy current circuit. Particular attention should be given to non-metallic aircraft fitted with a double-pole wiring system to which single-pole wiring system to which single- pole equipments has subsequently been added.

During refuelling of an aircraft, stringent precautions are necessary to minimize the risk of fire or explosion due to the presence of static charges. The aircraft itself may be charged, the fuel flowing through the hose generates electrical potentials, and the fuel tanker may be charged. Thus potential differences must be prevented from occurring and which could otherwise result in the generation of sparks and ignition of flammable vapours. The equalizing of potentials is achieved by providing a bonding connection between the aircraft and tanker which themselves are bonded to the ground, and by bonding the hose nozzle to a point specially provided on the aircraft. During the refuelling operation physical contact between the hose nozzle and tank filler is always maintained.

In a number of current " new technology" aircraft, high-performance non-metallic composite materials are used in major structural areas. Although they obviously have advantages from the structural point of view, the reduction in what may be termed the "metallic content" of the airframe does, unfortunately, reduce the effectiveness of shielding the aircraft, and electrical and electronic systems from the effects of lightening strikes.

BOND TESTING

Special test equipment, comprising a meter and two cables each of specific length, is required for checking the resistance of an ohmmeter operating on the current ratio principle, and a single 1.2 volt nickel alkaline cell housed in a wooden carrying case. The associated cables are 60 feet and 6 feet in length, and are fitted with a single-spike probe and a double-spike probe respectively. Plug and socket connectors provide for quick-action connection of the cables to the instrument.

Prior to carrying out a bonding test, a check should be made on the state of the nickel-alkaline cell of the tester by observing.

a. that a full-scale deflection of pointer of the meter is obtained when the two spikes of the 6-foot cable probe are shorted by a suitable conductor; and
b. that the meter reads zero when the two spikes of the 6-foot cable probe are shorted with the single spike cable probe.

The 60-feet lead of the test equipment should be connected to the main earth (also known as the bond datum point) at the terminal points which are usually shown diagrammatically in the relevant Aircraft Maintenance Manual. Since the length of a standard bonding tester lead is 60 feet, the measurement between extremities of the larger types of aircraft may have to be done by selecting one or more main earth points successively, in which event the resistance value between the maim earth points chosen should be checked before proceeding to check the remote point.

NOTE: When connecting the 60-feet lead to an earthing point, any protective treatment (e.g. strippable lacquer) should be removed at the point of contact.

The 6-foot test lead should be used to check the resistance between selected points ; these are usually specified in the bonding test schedule or the Maintenance Manual for the aircraft concerned. When the two spikes of the test lead probe are brought into contact with the aircraft part, the test-meter will indicate, in ohms, the resistance of the bond.

As an alternative to the above, the four terminal method of resistance measurement may be adopted with the appropriate milliammeter (see Fig.15.1). With this type of instrument, a test current (approximately 2 amps) is supplied by the internal batteries and passed through the resistance via cables C1 and C2. The voltage drop across the resistance is measured (P1 and P2) and compared with the current flowing. The resultant value is then displayed (normally digitally) on the meter. The test leads may be in the form of duplex spikes (see Fig.15.2) or when used in association with crocodile type test leads, single spikes. In order to check that the instrument is functioning correctly, the two hand spikes should be placed on a low resistance conductor with the potential spikes (P1 and P2) closely together (see Fig.15.3). The result of this test should be a zero reading on the meter.

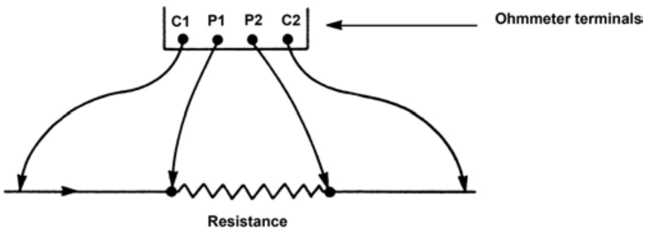

Fig. 15.1. Four terminal resistance measurement.

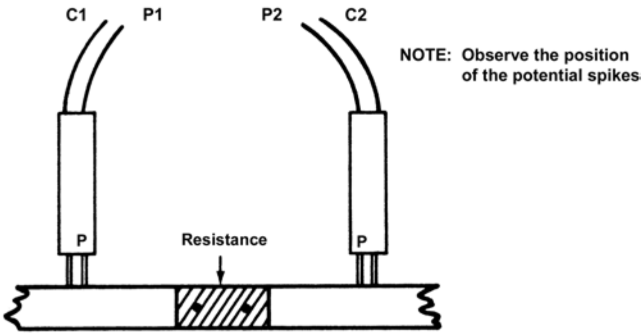

Fig. 15.2. Duplex hand spikes.

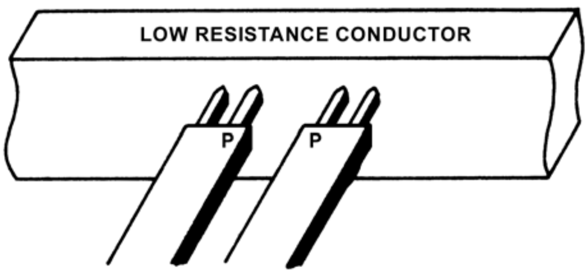

Fig. 15.3. Test position of hand spikes.

To ensure good electrical contact at the probe spikes, it may be necessary to penetrate or remove a small area of a non-conducting protective coating. Therefore, after test, any damage to the protective coating must be restored.

If the resistance at a bond connection is excessive, rectification action will depend on the type of connection. The following action should be taken for the more common types of connections:-

a. In the case of bonding jumpers, the connecting tag or lug should be removed and the contacting faces thoroughly cleaned, using a slight abrasive if necessary. The bare metal thus exposed should be only just large enough to accept the palm of the tag or lug. The connecting area should be sealed and treated with antioxidant as specified in the relevant drawing and specification.

NOTE: When an abrasive has been used it is important to ensure that all traces of it are removed.

b. Where equipment is bonded through a holding bolt, the bolt should be removed and the area under the bolt-head, or nut, thoroughly cleaned and protected as recommended in paragraph 3.10.7 (a). The correct washer (both with regard to size and material) should be fitted before the bolt is replaced and tightened.

c. Where the required bond value cannot be obtained at a structural joint the advice of the manufacturer should be sought.

NOTE: Corrosion tends to form at a bonding or earth connection and is often the cause of excessive resistance.

The resistance between the man in earth system and a metal plate on which the earthing device (e.g. tyre) is resting should be measured and should not exceed 10 megohms when measured with a 250 volt or 500 volt resistance tester, as specified in the test schedule.

NOTE: After carrying out tests, all areas where the protective coating has been removed should be re-protected using the appropriate scheme.

BONDING TESTER SERVICING

A tester requires little in the way of servicing, a part from periodic attention to the alkaline cell, which should be removed at prescribed intervals for routine servicing. When replacing the cell, it is most important that the polarity of connection is correct. The ohmmeter is normally sealed in its case and no attempt should be made to open it; if a fault should develop, then the complete instrument should be withdrawn from use and overhauled.

The leads are an integral part of the tester, and being carefully matched to the meter unit must not be modified or altered in any way. All contact surfaces of plug pins and probes must be kept scrupulously clean, and the points of the probe spikes should be reasonably sharp to give effective penetration of protective finishes, etc., on metal surfaces.

The accuracy of the tester should be checked periodically by using it to measure the resistance of standard test resistors. Normally, three such resistors are supplied for testing purposes and the readings obtained should be within 10% of the standard ohmic values.

STATIC DISCHARGE WICKS

As noted earlier, the discharge of static takes place continuously in order to equalize the potentials of the charges in the atmosphere and the aircraft. However, it is often the case that the rate of discharge is lower than the actual charging rate, with the result that the aircraft that the aircraft's charge potential raches such a value it permits what is termed a corona discharge, a discharge which if of sufficient magnitude, will glow in poor visibility or at night. Corona discharge occurs more rapidly at curves and sections of an aircraft having minimum radii such as wing tips, trailing edges, propeller tips, horizontal and vertical stabilizers, radio antennae, pitot tubes, etc.

Corona discharge can cause serious interference with radio frequency signals and means must therefore be provided to ensure that the discharges occur at points where interference will be minimized. This is accomplished by devices called static discharge wicks or more simply, static dischargers. They provide a relatively easy exit for the charge so that the corona breaks out at predetermined points rather than haphazardly at points favourable to its ocurrence. Static dischargers are fitted to the trailing edges of ailerons, elevators and rudder of an aircraft. A typical static discharger consists of nichrome wires formed in the manner of a "brush" or wick thereby providing a number of discharge points. In some instances, static dischargers may also take the form of small metal rods for trailing edge fitting at the tips of wings, horizontal and vertical stabilizers. Sharp tungsten needles extend at right angles to the discharger tips to keep corona voltage low and to ensure that discharge will occur only at these points.

SCREENING

Screening performs a similar function to bonding in that it provides a low resistance path for voltages producing unwanted radio frequency interference. However, whereas a bonding system is a conducting link for voltages produced by the build up of static charges, the voltages to be conducted by a screening system are those stray ones due to the coupling of external fields originating from certain items of electrical equipment, and circuits when in operation. Typical examples are " d.c.generator, engine ignition systems, d.c. motors, time switches and similar apparatus designed for making and breaking circuits at a controlled rate.

The methods adopted for screening are generally of three main types governed principally by the equipment or circuit radiating the interference fields. In equipment such as generators, motors and time switches several capacitors, which provide a low resistance path, are interconnected across the interference source, i.e. brushes, commutators and contacts, to form a self-contained unit known as a suppressor. The other methods adopted are the enclosing of equipment and circuits in metal cases and the enclosure of cables in a metal braided sheath, a method used for screening the cables of ignition systems. The suppressors and metal screens are connected to the main earth or ground system of an aircraft.

EARTHING OR GROUNDING

In the literal sense, earthing or grounding as it is often termed, refers to the return of current to the conducting mass of the earth, or ground, itself. If considered as a single body, the earth is so large that any transfer of electrons between it and another body fails to produce any perceptible change in its state of electrification. It can therefore be regarded as electrically neutral and as a zero reference point for judging the state of electrification of other bodies. For example, if two charged bodies, A and B, both have positive potentials relative to earth, but the potential of A is more positive than that of B, then the potential of B may be described as negative to that of A by the appropriate amount.

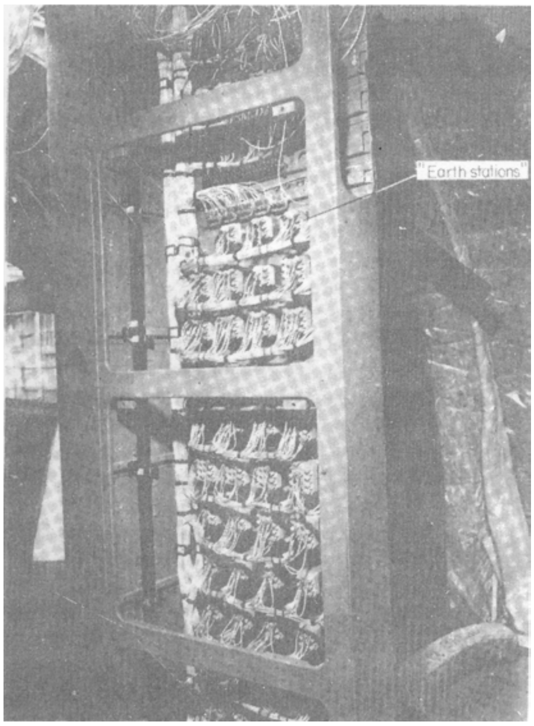

Fig. 15.4. Open looms.

As we have already learned, the positive outputs of aircraft power supplies and the positive input terminals of consumer components are all connected to busbars which are insulated from the aircraft structure. Since in most aircraft the structure is of metal and of sufficient mass to remain electrically neutral, then it too can function as an earth or " negative busbar' and so provide the return path of current. Thus, power supply and consumer circuits can be completed by coupling all negative connections to the structure at various 'earth stations', the number and locations of which are predicted in a manner appropriate to the particular type of aircraft. As this results in the bulk of cable required for the circuits being on the positive side only, then such an electrical installation is designated as a 'single' wire, or single-pole, earth-return system", For a.c. power supply circuits the airframe also services as a connection for the neutral point.

The selection of types of connection for earth return cables is based on such important factors as mechanical strength, current to be carried, corrosive effects, and ease with which connections can be made. As a result, they can vary in form; some typical arrangements being a single bolt passing through and secured directly to a structural member, and either a single bolt or a cluster of bolts secured to an earthing plate designed for riveting or bolting to a structural member. In order to ensure good electrical contact and minimum resistance between an earthing bolt or plate and the structure, protective film is removed from the contacting surfacing before assembly. Protection against corrosion is provided by coating the surfaces with an anti-corrosion and solvent resistant compound to the edges of the joint. An example of a cluster arrangement with a corrosion plate is illustration in (Fig.15.4).

Earth-return cables are connected to earthing bolts by means of crimped ring type connectors, each bolt accommodating cables from several circuits. For some circuits, however, it is necessary to connect cables separately and this applies particularly to those of the sensitive low current-carrying type, e.g. resistance type temperature indicators in which erros can arise from varying earth return currents of other circuits.

In aircraft in which the primary structure is of non-metallic construction, a separate continuous main earth and bonding system is provided. It consists of four or more soft copper strip-type conductors extending the whole length of the fuselage and disposed so that they are not more than six feet apart as measured around the periphery of the fuselage at the position of greatest cross-sectional area. The fuselage earthing strips are connected to further strips which follow the leading and trailing edges from root to tip of each wing and horizontal stabilizer, and also to strip located on or near the leading edge of the vertical stabilizer. Earthing strips are provided in the trailing edges of the rudder, elevators and ailerons, and are connected to the fuselage and wing systems via the outer hinges of the control surfaces. The strips are arranged to run with as few bends as possible and are connected to each other by means of screwed or riveted joints.

Lightning strike plates, extending round the tips of each wing, horizontal and vertical stabilizers, fuselage nose and tail, are also provided. They consist of copper strips and are mounted on the exterior of the structure.

INSPECTION AND TESTING OF CIRCUITS

Inspection of Wiring System

Before carrying out tests, or when inspection is specified in the Approval Maintenance Schedule, all aircraft circuits, together with plugs, sockets, terminal blocks and equipment terminals, should be examined, as approciated, for signs of damage, deterioration, chafing, poor workmanship and security of attachments and connections. It is not intended, for the purpose of this examination, that electrical apparatus should be removed from its mountings or that cables should be unduly disturbed, but if modifications or repairs, for example, have been carried out in the vicinity, looms should be closely inspected for ingress of metallic swarf between cables. Whenever a structure is opened over wiring which is not normally visible through available inspection panels, circuits so exposed should lbe thoroughly inspected.

The primary purpose of the inspection is to determine the physical state of the wiring system, especially at bends, points of support, duct entries, etc., or where high temperature or contamination could cause local deterioration. Where cables are grouped together, the state of the outer cables is generally indicative of the condition of the remainder.

Cables completely enclosed in ducts obviously cannot be examined along their length, but should be checked for continuity and insulation, especially if oil or water ingress is suspected. Where there is evidence of damage to the ducts, the cables should be exposed to ascertain their condition.

Terminations must be secure and good electrical contact obtained without strain on the threads of terminal pillars or studs. Torque loadings, where apropriate, should be within the limits specified.

CONTINUITY TESTING

A concealed break in a cable core or at a connection may be found by using a continuity tester which normally consists of a low voltage battery (2.5 volts is satisfactory) and a test lamp or low reading voltmeter.

NOTE: In some testers incorportating a test lamp, semiconductors are included in the test lamp circuit and, to prevent damage, the currents should be limited to 120 milliamps.

Before testing, the main electrical supply should be switched off or disconnected. A check should be made that all fuses are intact and that the circuit to be tested is not disconnected at any intermediate point. All switches and circuit breakers, as appropriate, should be closed to completed the circuit.

When carrying out a low voltage continuity check, it is essential to work progressively through the circuit, commencing from the relevant fuse or circuit breaker and terminated at the equipment. Large circuits will probably have several parallel paths and these should be progressed systematically, breaking down as little as possible at plug and socket or terminal block connections. In testing of this nature, it is valueless to check several low resistance paths in parallel.

MILLIVOLT DROP TEST

Excessive resistance in high-current carrying circuits can be caused by loose terminal connections, poorly swaged lead ends, etc. Faults of this kind are indicated by low terminal voltage at the connections to the service load and by heating at a conductor joint. If such faults are suspected, a millivolt drop test as described below is recommended, but it is also acceptable to check along progressive sections of the system with an accurately calibrated voltmeter :-

a. For continuously-rated circuits, the test should, whenever possible, be made with the normal operating current flowing, the power being derived from an external source. For short-rated circuits, a suitable resistance or other dummy load should be used in lieu of the normal load and the current should be scaled down to avoid overheating.

NOTE: The test voltage may be reduced for safety reasons.

b. The millivolt-meter should be connected to each side of the suspected joint and a note mode of the volt drop indicated. The indicated reading should be compared with the figures quoted in the relevant publication (an approximate guide is 5 mV/10 amps flowing).

INSULATION RESISTANCE TESTING

In the following paragraphs general test procedures are outlined; however, as a result of the wide variation in electrical installation and equipment which exists with different aircraft, the routing charts and Approved Test Schedule for the aircraft concerned must be consulted. All ancillary equipment should be tested separately in accordance with the appropriate manufacturers' publications.

After installation and where specified in the Approved Maintenance Schedule or Test Schedule, aircraft circuits should be tested by means of a 250-volt insulation tester which should have its output controlled so that the testing voltage cannot exceed 300 volts. In all systems having normal voltages over 30 volts, cables forming circuits essential to the safety of the aircraft should be tested individually. Other circuits may be connected in groups for test. However, the number of circuits which may be grouped for test is governed by the test results; where the insulation resistance so measured is found to be less than the appropriate minimum value stated in second paragraph of Test Results, the number of circuits grouped together should be reduced.

NOTE: Information on the testing of magneto earthing circuits is given in Leaflet EL / 3-9 of CAIP.

Immediately after an insulation test, functioning checks should be made on all the services subjected to the test. If the insulation test or subsequent functioning tests should reveal a fault, the fault should be rectified and the insulation and functioning tests should be repeated in that sequence on the affected circuits.

PREPARATIONS PRIOR TO TEST

Before beginning an insulation test on a system, the following preparations should be made, details of which will depend on the installation concerned:-

a. The aircraft battery and any external supply should be disconnected

b. Where applicable, circuit breakers should be closed.

c. The power selector switch should be switched to the position appropriate to that required for normal in-flight operation.

d. All switches in the circuit concerned should be 'ON', dimmer - switches should be set at the minimum resistance position and micro-switches operated to the 'ON' position.

e. All items of ancillary equipment which are supplied by the system concerned should be disconnected. This includes all rotary equipment (e.g. generators, motors, actuator units, etc.) radio equipment, capacitors, semiconductors, voltage regulator coils, electrical instruments, fire extinguishers etc.

f. In cases where the insulation resistance with the items connected is not less than 2 megohms, the disconnection my be made by the earth lead, leaving the item connected to the circuit.

NOTE: Bonded earth connections to the airframe structure should, if possible, remain undisturbed for the purpose of these tests.

g. Components such as cut-outs and relays which are normally open should have their terminals bridged to ensure continuity of the circuit, and disconnected leads from suppressors should also be bridged for similar reasons. Where a suppressor cannot be bridged, and plug and socket connections are used, the capacitors should be discharged before the circuit is re-connected, otherwise arcing and burning of the pins may occur. Items in series which are disconnected should also be bridged so that part of the circuit is not omitted.

TESTING THE SYSTEM

Double-pole systems on some older types of aircraft can be tested by connecting the leads of the insulation tester to each of the battery leads and measuring the resistance between them and, afterwards, checking the resistance between them and earth; fuses should be left in position for this test. On some large aircraft with double-pole systems, cables may be grouped as for single-pole systems, the easrthing checks being made between bunched positive and earth and bunched negative and earth.

To test single-pole systems, one lead of the tester should be connected to earth and the other to the cable or bunch of cables to be tested. When cables are bunched together, it is advisable to ,limit the number to the smallest convenient figure. If the insulation resistance is less than the appropriate value quoted in second paragraph of Test Result, the number of circuits should be reduced. Testing should continue until, by process of elimination, any defective cables have been identified.

TEST RESULTS

The result of insulation tests are of little significance unless they are related to test results obtained on other occasions. The insulation resistance values are likely to vary with changes in the temperature and humidity of the local atmosphere, e.g. if the aircraft has been in damp conditions for some time before the test, low readings can be expected. Results of tests and the temperature and humidity conditions at the time of the test should be recorded, so that any pronounced drop in resistance found on subsequent tests can be checked and rectified as necessary.

Section J of British Civil Airworthiness Requirements does not specify minimum values of insulation resistance, but gives guidance on values that may be expected during maintenance testing. These values can be, and frequently are, exceeded considerably on new installations. The values given are as follows:-

a. Wiring (including accessories for jointing and terminating):-

In engine nacelles, undercarriage wheel wells and other situations exposed to weather or extremes of temperature ..	2 megohms
Galley and other non-essential services, lighting, signalling and indication services. ..	5 megohms
Other services	10 megohms

NOTE: The above values relate to single circuits or small groups of circuits.

b. Wiring accessories alone (e.g. terminal blocks, connectors, plugs and sockets, etc.):-
Between terminals .. .. 100 megohms

Between terminals bunched together and earth $\frac{200}{\text{number of terminals}}$ megohms

c. Rotating machinery whichever is the greater of $\frac{\text{rated voltage}}{150}$ or 0.5 megohms

d. All other equipment (including indicating instruments) .. .. 5 megohms

FUNCTIONING TESTS

Before conducting any tests, all precautions for aircraft and personnel safety should be taken. Whenever possible, functioning tests should be carried out using an external supply coupled to the ground supply connector. Tests must ensure proper functioning of individual and integrated sections of circuits, and should be in accordance with schedules established by reference to details in the relevant Maintenance Manual. Wiring Diagram Manual or, where appropriate, instructions relating to the incorporation of a modification or any susbstancial rewiring.

NOTE: Where applicable, when one or more engines are running, the power supply can be obtained from the associated generators, due reference being made to the functioning of any isolating relays.

For certain circuits (e.g. stand by lighting), functioning tests can only be carried out using the aircraft battery system, but this battery should be used as little as possible.

After the normal functioning test of an individual circuit has been completed and the circuit switched off, the fuse should be removed or the circuit breaker tripped and the circuit again switched on to check the isolation of the circuut concerned.

When the operation of a circuit (e.g. generator equaliser circuit) depends on the inherent resistance value of the circuit, the resistance should be measured with a low reading ohm-meter (such as that used in a bonding tester) to determine that the resistance is within the specified limits.

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CHAPTER - 16
DETAIL KNOWLEDGE OF AIRCRAFT WIRING SYSTEM PROCEDURE OF LAYING OF ELECTRICAL CABLES AND PRECAUTIONS TO BE TAKEN THEREOF

WIRES AND CABLES

Wires and cables constitute the framework of power distribution systems conducting power in its various forms and controlled quantities, between sections contained within consumer equipment (known as "equipment" wires and cables), and also between equipment located in the relevant areas of an aircraft (known as "airframe" wires and cables). The differences between a wire and a cable relate principally to their constructional features (and indirectly to their applications also) and may be understood from the following broad definitions.

A wire is single solid rod or filament of drawn metal enclosed in a suitable insulating material and outer protective covering. Although the term properly refers to the metal conductor, it is generally understood to include the insulation and covering. Specific applications of single wires are to be found in consumer equipment; for example, between the supply connections and the brush gear of a motor, and also between the various components which together make up the stages of an electronic amplifier.

A cable is usually made up of a conductor composed of a group of single solid wires stranded together to provide greater flexibility, and enclosed by insulating material and outer protective covering. A cable may be either of the single core type, i.e., with cores stranded together as a single conductor, or of the multicore type having a number of single core cables in a common outer protective covering.

Having highlighted the above definitions, it is interesting to note that with the present lack of international standardization of terminology, they may not be used in the same context. For example, in the U.S. and some other countries, the term "wire" is used as an all embracing one.

In connection with power distribution systems in their various forms, such terms as "wiring systems", "wiring of components", "circuit wiring" are commonly used. These are of a general nature and apply equally to systems incorporating either wires, cables or both.

TYPES OF WIRES AND CABLES

Wires and cables are designed and manufactured for duties under specific environmental conditions and are selected on this basis. This ensures functioning of distribution and consumer systems, and also helps to minimize risk for fire and structural damage in the event of failure of any kind. Table 16.1 gives details of some commonly used general service wires and cables of U.K. manufacture, while typical constructional features are illustrated in (Fig 16.1).

The names adopted for the various types are derived from contractions of the names of the various insulating materials used. For example, "NYVIN" is derived from "NYlon" and from poly VINyl-chloride (P.V.C.); and "TERSIL" is derived from polyesTER and SILicone. Cables may also be further classified by prefixes and suffixes relating to the number of cores and any additional protective covering. For example, "TRINYVIN" would denote a cable made up of three single Nyvin cables, and if suffixed by "METSGEATH" the name would further denote that the cable is enclosed in a metal braided sheath.

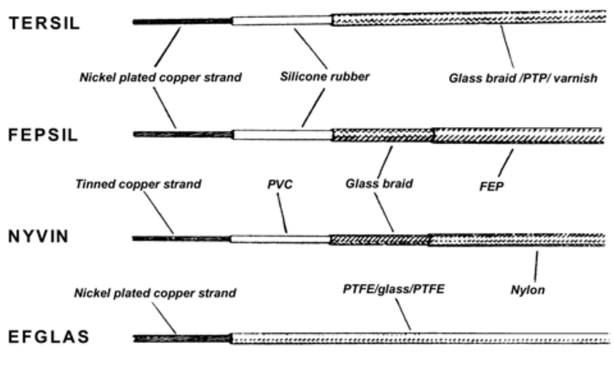

Fig. 16.1. Constructional features of some typical cables.

It will be noted from the Table that only two metals are used for conductors, i.e. copper (which may also be tinned, nickel-plated or silver-plated depending on cable application) and aluminium. Copper has a very low specific resistance and is adopted for all but cables of large cross-sectional areas. An aluminium conductor having the same resistance as a copper conductor, has only two-thirds of the weight but twice the cross-sectional area of the copper conductor. This has an advantage where low-resistance short-term circuits are concerned; for example, in power supply circuits of engine starter motor systems.

The insulation materials used for wires and cables must conform to a number of rigid requirements such as, toughness and flexibility over a fairly wide temperature range, resistance to fuels, lubricants and hydraulic fluids, ease of stripping for terminating, non-flammability and minimum weight. These requirements, which are set out in standard specifications, are met by the materials listed in Table 16.1 and in the selection of the correct cable for a specific duty and environmental condition.

To ensure proper identification of cables, standard specification also require that cable manufacturers comply with a code and mark outer protective coverings accordingly. Such a coding scheme usually signifies, in sequence, the type of cable, country of origin ("G" for U.K. manufacturers) manufacturer's code letter, year of manufacture also by a letter, and its wire gauge size, thus, NYVIN G-AN 22. A colour code scheme is also adopted particularly as a means of tracing the individual cores of multicore cables to and from their respective terminal points. In such cases it is usual for the insulation of each core to be produced in a different colour and in accordance with the appropriate specification. Another method of coding, and one used for cables in three-phase circuits of some types of aircraft, is the weaving of a coloured trace into the outer covering of each core; thus red-(phase A); yellow - (phase B); blue - (phase C). The code may also be applied to certain single-core cables by using a coloured outer covering.

ROUTING OF WIRES AND CABLES

As noted earlier in this chapter, the quantity of wires and cables required for a distribution system depends on the size and complexity of the systems. However, regardless of quantity, it is important that wires and cables be routed through an aircraft in a manner which, is safe, avoids interference with the reception and transmission of signals by such equipment as radio and compass systems, and which also permits a systematic approach to their identification, installation and removal, and to circuit testing. Various methods, dependent also on size and complexity, are adopted but in general, they may be grouped under three principal headings : (i) open loom, (ii) ducted loom, and (iii) conduit.

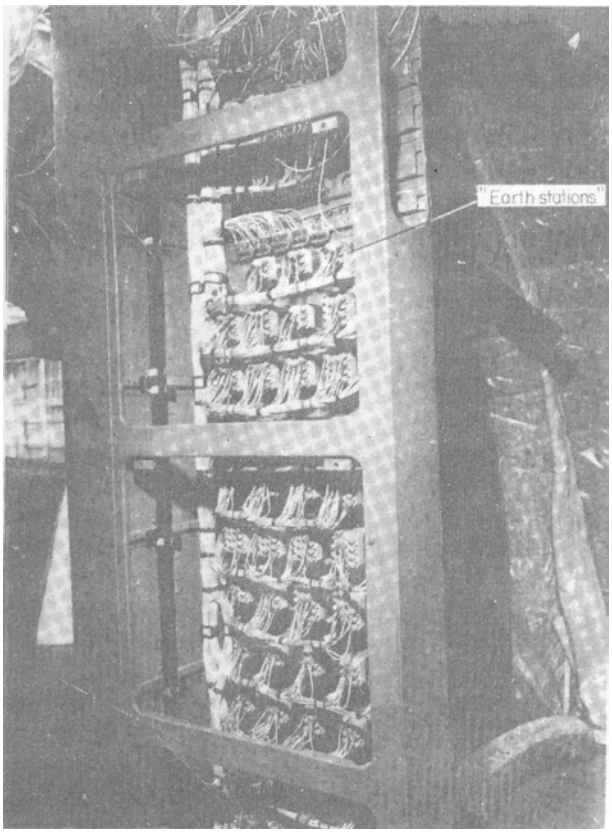

Fig. 16.2. Open looms.

Open Loom

In this method, wires or cables to be routed to and from consumer equipment in the specific zones of the aircraft, are grouped parallel to each other in a bundle and bound together with waxed cording or p.v.c. strapping. A loom is supported at intervals throughout its run usually by means of clips secured at relevant parts of the aircraft structure. An application of the method to an aircraft junction box is shown in (Fig. 16.2).

The composition of a cable loom is dictated by such factors as (i) overall diameter, (ii) temperature conditions, i.e. temperature rise in cables when operating at their maximum current-carrying capacity in varying ambient temperature conditions, (iii) type of current, i.e. whether alternating, direct, heavy-duty or light-duty, (iv) interference resulting from inductive or magnetic effects, (v) type of circuit with which cables are associated; this applies particularly to circuits in the essential category, the cables of which must be safe-guarded against damage in the event of short circuits developing in adjoining cables.

Magnetic fields exist around cables carrying direct current and where these cables must interconnect equipment in the vicinity of a compass magnetic detector element, it is necessary for the fields to be cancelled out. This is achieved by routing the positive and earth-return cables together and connecting the earth-return cable at an earthing point located at a specific safe distance from the magnetic detector element of a compass system.

TABLE 16.1

Type	Specification		Materials			
	British B.S.G.	American MIL-W-	Conductor	Insulation & Covering	Ambient temperature range	Application
NYVIN	177	5086 A (Type 2)	Tinned Copper or Aluminium	P.V.C. Compound Glass braid Nylon	-75°C to + 65°C	General services wiring except where ambient temperatures are high and/or extended.
PREN			Tinned Copper or Aluminium	Glass braid polychloroprene Compound	-75°C to + 50°C	Properties of flexibility are required.
TERSIL	189	8777 B (ASG)	Nicke-plated Copper; or Aluminium	Silicone Rubber Polyester tapes Glass braid Polyester fiber Varnish	-75°C to + 150°C	
EFGLAS	192	7129 B	Nickel-plated Copper	Glass braid P.T.F.E. +	-75°C to + 220°C	In high operating temperatures and in areas where resistance to aircraft fluids necessary. Also where severe flexing under low-temperature conditions is encountered e.g., landing m,gear shock strut switch circuits.
UNIFIRE - "F"			Nickel-plated Copper	Glass braid P.T.F.E. Asbestos felt impregnated with silicone varnish	Up to 240°C	In circuits required to function during or after a fire.
NYVINMETSHEATH			Tinned Copper or Aluminium	As for NYVIN plus an overall tinned-copper braid overlaid with polyester tape, nylon braid and lacquer	-75°C to + 65°C	In areas where screening required
FEPSIL	206		Nickel-plated Copper	Silicone Rubber Glass braid and Varnish F.E.P.	-75°C to + 190°C	

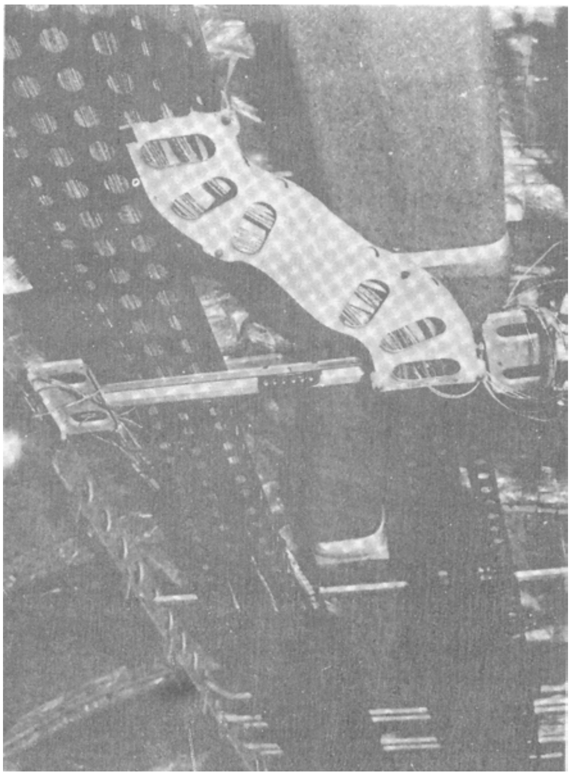

Fig. 16.3. Ducted looms.

Ducted Loom

This method is basically the same as that of the open loom except that the bundles are supported in ducts which are routed through the aircraft and secured to the aircraft structure (see Fig. 16.3). Ducts may be of aluminium alloy, resinimprenated asbestos or moulded fibre-glass-reinforced plastic. In some applications of this method, a main duct containing several channels may be used, each channel supporting a cable loom corresponding to a specific consumer system. For identification purposes, each loom is bound with appropriately coloured waxed cording.

Conduits are generally used for conveying cables in areas where there is the possibility of exposure to oil, hydraulic or other fluids. Depending on the particular application, conduits may take the form of either plastic, flexible metal or rigid metal sheaths. In cases where shielding against signal interference is necessary the appropriate cables are conveyed by metal conduits in contact with metal structural members to ensure good bonding.

Cable Seals

In pressurized cabin aircraft it is essential for many cables to pass through pressure bulkheads without a "break" in them and without causing leakage of cabin air. This is accomplished by sealing the necessary apertures with either pressure bungs or pressure-proof plugs and sockets. An example of a pressure bung assembly is shown in (Fig. 16.4). It consists of a housing, perforated synthetic rubber bung, antifriction washer and knurled clamping nuts; the housing is flanged and threaded, having a tapered bore to accept the bung. The holes in the bung vary in size to accommodate cables of various diameters, each hole being sealed by a thin covering of synthetic rubber at the smaller diameter end of the bung. The covering is pierced by a special tool when loading the bung with cables.

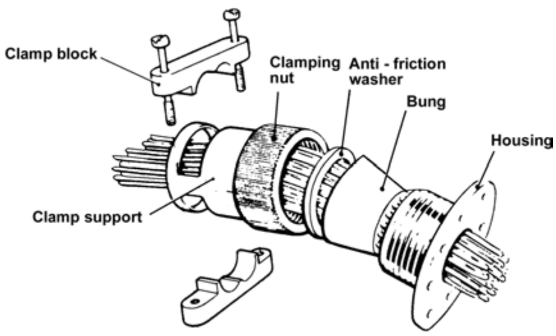

Fig. 16.4. Pressure bung assembly.

The cables are a tight fit in the holes of the bung which, when fully loaded and forced into the housing by the clamping nut, is compressed tightly into the housing and around the cables. The anti-friction washer prevents damage to the face of the bung when the clamping nut is turned. On assembly, holes not occupied by cables are plunged with plastic plugs.

In instances where cable "breaks" are required at a pressure bulkhead, the cables at each side of the bulkhead are terminated by specially-sealed plug or socket assemblies of a type similar to those shown in (Fig. 16.5).

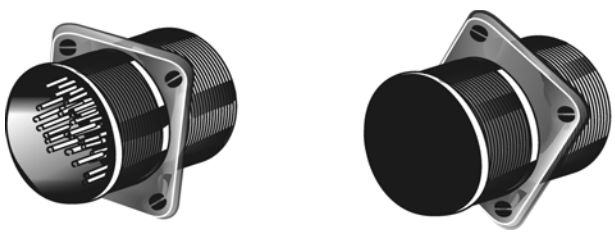

Fig. 16.5. Fixed through-type (bulkhead).

SPECIAL PURPOSE CABLES

For certain of electrical systems, cables are required to perform a more specialized function than that of the cables already referred to. Some examples of what are generally termed, special purpose cables, are described in the following paragraphs.

Ignition Cables

These cables are used for the transmission of high tension voltages in both piston engine and turbine engine ignition systems, and are of the single-core stranded type suitably insulated, and screened by metal braided sheathing to prevent interference. The number of cables required for a system corresponds to that of the sparking plugs or igniter plugs as appropriate, and they are generally made up into a complete ignition cable harness. Depending on the type of engine installation, the cables may be enclosed in a metal conduit, which also forms part of a harness, or they may be routed openly. Cables are connected to the relevant system components by special end fitting comprising either small springs or contact caps secured to the cable conductor, insulation, and a threaded coupling assembly.

Thermocouple Cables

These cables are used for the connection of cylinder head temperature indicators and turbine engine exhaust gas temperature indicators to their respective thermocouple sensing elements. The conducting materials are normally the same as those selected for the sensing element combinations , namely, iron and constantan or copper and constantan for cylinder head thermocouples, chromel (an alloy of chromium and nickel) and alumel (an alloy of aluminium and nickel) for exhaust gas thermocouples.

In the case of cylinder head temperature indicating systems only one thermocouple sensing element is used and the cables between it and a firewall connector are normally asbestos covered. For exhaust gas temperature measurement a number of thermocouples are required to be radially disposed in the gas stream, and it is the usual practice therefore, to arrange the cables in the form of a harness tailored to suit a specific engine installation. The insulating material of the harness cables is either silicone rubber or P.T.F.E. impregnated fibre glass. The cables terminate at an engine or firewall junction box from which cables extend to the indicator. The insulating material of extension cables is normally of the polyvinyl type, since they are subject to lower ambient temperatures than the engine harness. In some applications extension cables are encased in silicone paste within metalbraided flexible conduit.

Co-axial Cables

Co-axial cables contain two or more separate conductors. The innermost conductor may be of the solid, or stranded copper wire type, and may be plain, tinned, silver-plated or even gold-plated in some applications, depending on the degree of conductivity required. The remaining conductors are in the form of tubes, usually of fine wire braid. The insulation is usually of polyethylene or Teflon. Outer coverings or jackets serve to weatherproof the cables and protect them from fluid, mechanical and electrical damage. The materials used for the covering are manufactured to suit operations under varying environmental conditions.

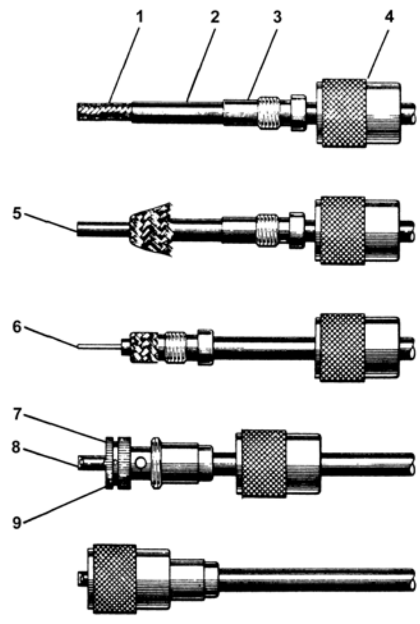

Fig. 16.6. Typical coaxial cable and end fitting

1. *Outer braid conductor*
2. *Outer covering*
3. *Adapter*
4. *Coupling ring*
5. *Insulation*
6. *Inner conductor*
7. *Plug sub-assembly*
8. *Contact*
9. *Solder holes*

Co-axial cables have several main advantages. First, they are shielded against electrostatic and magnetic fields; an electrostatic field does not extend beyond the outer conductor and the fields due to current flow in inner and outer conductors cancel each other.

Secondly, since co-axial cables do not radiate, then likewise they will not pick up any energy, or be influenced by other strong fields. The installations in which coaxial cables are most commonly employed are radio, for the connection of antennae, and capacitance type fuel quantity in indicating systems for the interconnection of tank units and amplifiers. The construction of a typical coaxial cable and also the sequence adopted for attaching the end fitting are shown in (Fig. 16.6). The outer covering is cut back to expose the braided outer conductor (step "A") which is then fanned out and folded back over the adapter (step "B" and "C"). At the same time, the insulation is cut back to expose the inner conductor. The next step (D) is to screw the sub-assembly to the adapter thereby clamping the outer conductor firmly between the two components. Although not applicable to all cables the outer conductor may also be soldered to the sub-assembly through solder holes. The assembly is completed by soldering a contact on to the inner conductor may also be soldered to the sub-assembly through solder holes. The assembly is completed by soldering a contact on to the inner conductor and screwing the coupling ring on to the sub-assembly.

Factor Affecting Selection of Conductor Material

Although silver is the best conductor, its cost limits its use to special circuits where a substance with high conductivity is needed.

The two most generally used conductors are copper and aluminum. Each has characteristics that make its use advantageous under certain circumstances; also, each has certain disadvantages.

Copper has a higher conductivity; it is more ductile (can be drawn out), has relatively high tensile strength, and can be easily soldered. It is more expensive and heavier than aluminum.

Current-carrying capacity of wire (in amperes)

Size	Rubber or Thermoplastic	Thermoplastic asbestors, varcam, or	Impregnoted asbestos	Asbestos weatherproof	Slow-burning or asbestos var-cam
0000	300	385	475	510	370
000	260	330	410	430	320
00	225	285	355	370	275
0	195	245	305	325	235
1	165	210	265	280	205
2	140	180	225	240	175
3	120	155	195	210	150
4	105	135	170	180	130
6	80	100	125	135	100
8	55	70	90	100	70
10	40	55	70	75	55
12	25	40	50	55	40
14	20	30	40	45	30

Although aluminum has only about 60% of the conductivity of copper, it is used extensively. Its lightness makes possible long spans, and its relatively large diameter for a given conductivity reduces corona, the discharge of electricity from the wire when it has a high potential. The discharge is greater when smaller diameter wire is used. Some bus bars are made of aluminum instead of copper, where there is a greater radiating surface for the same conductance. The characteristics of copper and aluminum are compared in Table 16.2.

Table 16.2 Characteristics of copper and aluminum

Characteristic	Copper	Aluminum
Tensile strength (lb./in.^{2})...........	55,000	25,000
Tensile strength for same conductivity (lb.)..................	55,000	40,000
Weight for same conductivity (lb.)..	100	48
Cross section for same conductivity (C.M.)..................	100	160
Specific resistance (Ω /mil ft.)...	10.6	17

Voltage Drop in Aircraft Wire and Cable

It is recommended that the voltage drop in the main power cables from the aircraft generation source or the battery to the bus should not exceed 2% of the regulated voltage when the generator is carrying rated current or the battery is being discharged at a 5-minute rate. Table 16.3 shows the recommended maximum voltage drop in the load circuits between the bus and the utilization equipment.

Table 16.3 Recommended maximum voltage drop in load circuits

Nominal system voltage	Allowable voltage drop	
	Continuous operation	**Intermittent operation**
14	0.5	1
28	1	2
115	4	8
200	7	14

The resistance of the current return path through the aircraft structure is always considered negligible. However, this is based on the assumption that adequate bonding of the structure or a special electric current return path has been provided which is capable of carrying the required electric current with a negligible voltage drop. A resistance measurement of 0.005 ohms from ground point of the generator or battery to ground terminal of any electrical device is considered satisfactory. Another satisfactory method of determining circuit resistance is to check the voltage drop across the circuit. If the voltage drop does not exceed the limit established by the aircraft or product manufacturer, the resistance value for the circuit is considered satisfactory. When using the voltage drop method of checking a circuit, the input voltage must be maintained at a constant value.

The chart in (Fig. 16.7) applies to copper conductors carrying direct current. Curve 1, 2. and 3 are plotted to show the maximum ampere rating for the specified conductor under the specified conditions shown. To select the correct size of conductor, two major requirements must be met. First, the size must be sufficient to prevent an excessive voltage drop while carrying the required current over the required distance. Secondly, the size must be sufficient to prevent overheating of the cable while carrying the required current. The charts in (Figures 16.7 and 16.8) can simplify these determination. To use this chart to select the proper size of conductor, the following must be known :

1. The conductor length in feet.
2. The number of amperes of current to be carried.
3. The amount of voltage drop permitted.
4. Whether the current to be carried will be intermittent or continuous, and if continuous, whether it is a single conductor in free air, in a conduit, or in a bundle.

Assume that it is desired to install a 50-foot conductor from the aircraft bus to the equipment in a 28-volt system. For this length, a 1-volt drop is permissible for contiuous operation. By referring to the chart in (Fig. 16.8) the maximum number of feet a conductor may be run carrying a specified current with a 1-volt drop can be determined. In this example the number 50 is selected.

Assuming the current required by the equipment is 20 amperes, the line indicating the value of 20 amperes should be selected from the diagonal lines. Follow this diagonal line downward until it intersects the horizontal line number 50. From this point, drop straight down to the bottom of the chart to find that a conductor between size No. 8 and 10 is required to prevent a greater drop than 1 volt. Since the indicated value is between two numbers, the larger size, No. 8, should be selected. This is the smallest size which should be used to avoid an excessive voltage drop.

To determine that the conductor size is sufficient to preclude overheating, disregard both the numbers along the left side of the chart and the horizontal lines. Assume that the conductor is to be a single wire in free air carrying continuous current. Place a pointer at the top of the table on the diagonal line numbered 20 amperes. Follow this line until the pointer intersects the diagonal line marked "curve 2". Drop the pointer straight down to the bottom of the chart. This point is between numbers 16 and 18. The larger size, No.16, should be selected. This is the smallest-size conductor acceptable for carrying 20-ampere current in a single wire in free air without overheating.

If the installation is for equipment having only an intermittent (Max, 2 min.) requirement for power, the chart in (Fig. 16.7) is used in the same manner.

DIMENSIONS

For most conductors, the amount of resistance varies directly with the conductor's length. That is, as length increases for a given conductor, its resistance increases.

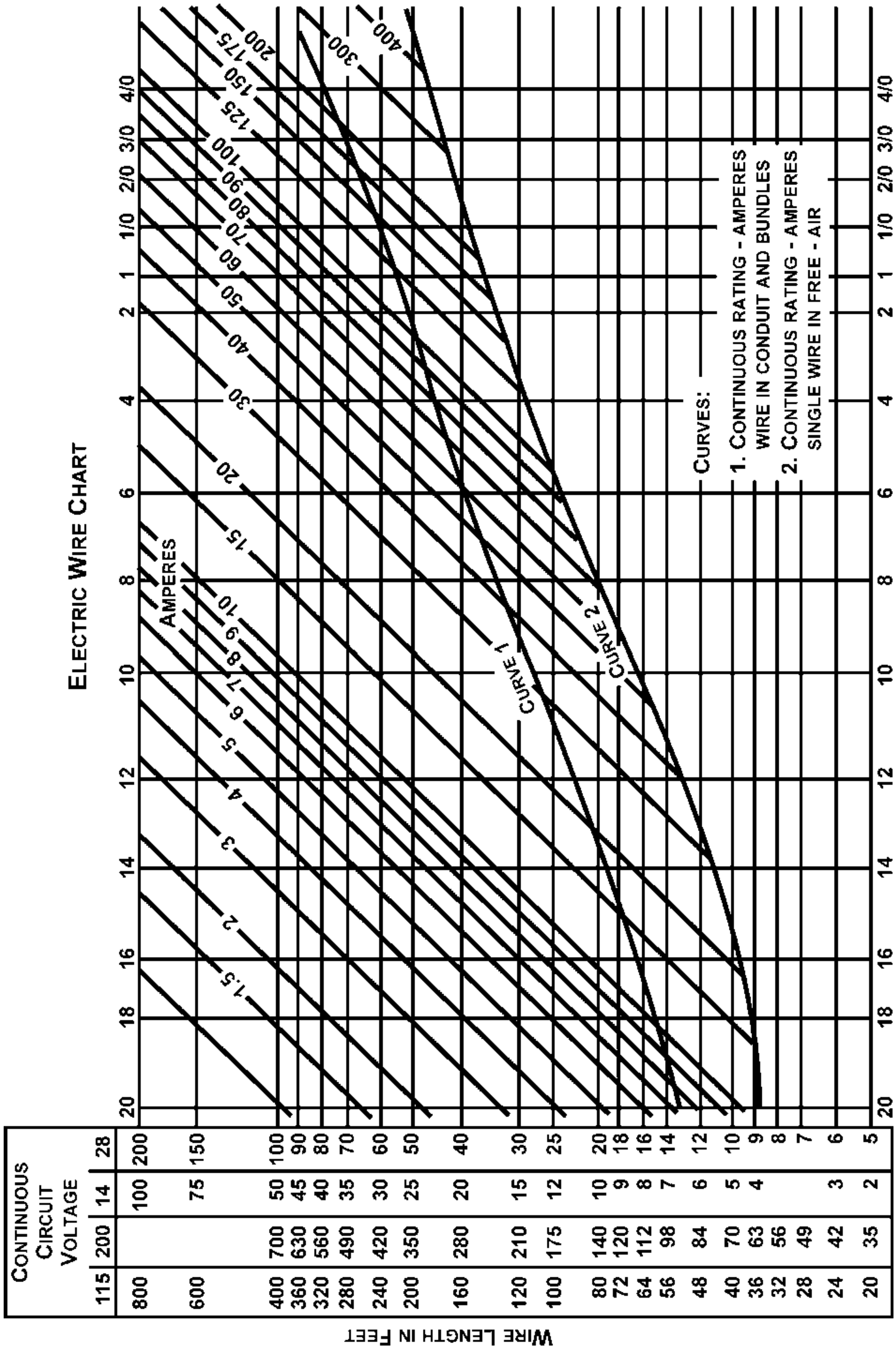

Fig. 16.7. Conductor chart, continuous rating. (Applicable to copper conductors)

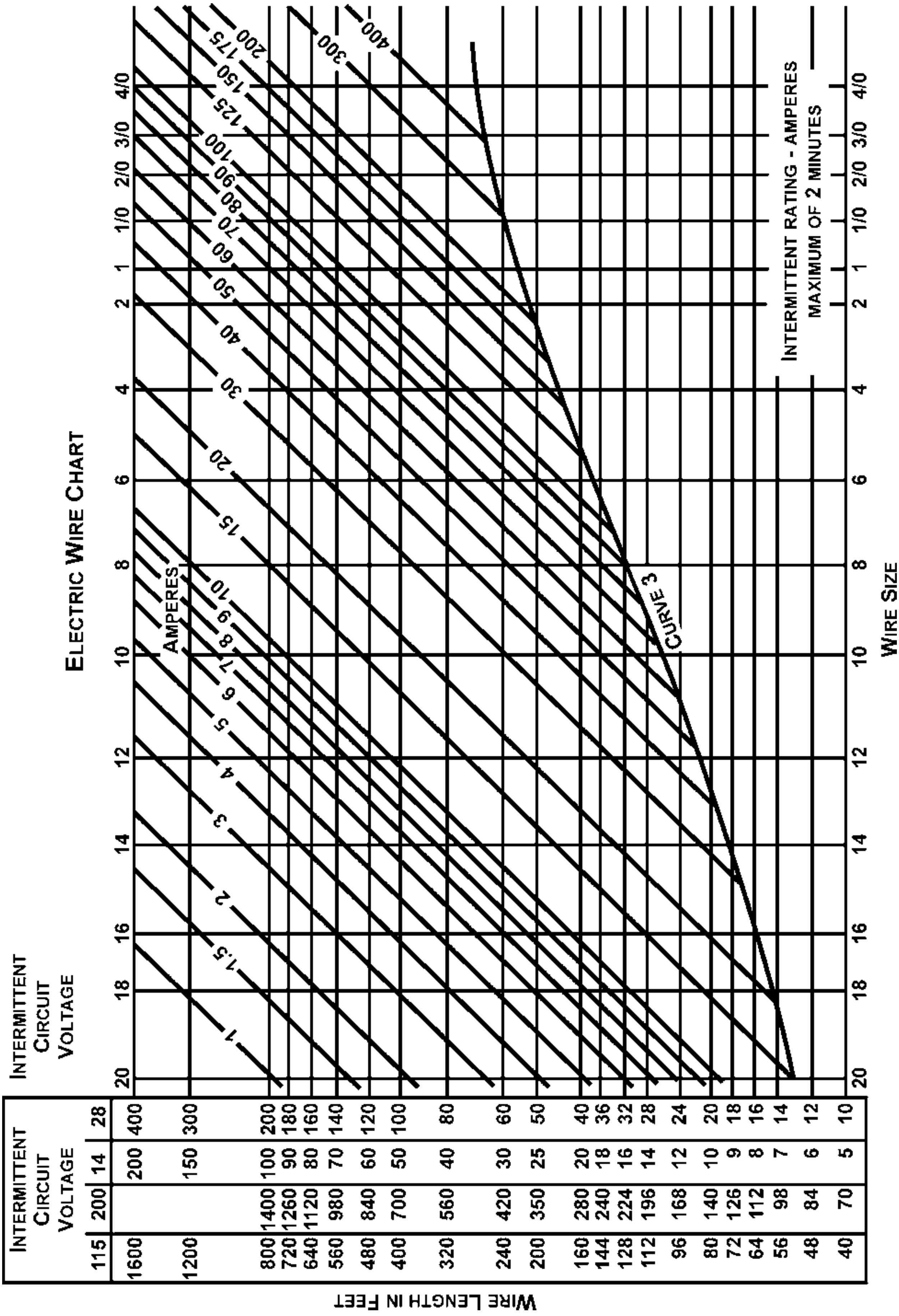

Fig. 16.8. Conductor chart, intermittent rating. (Applicable to copper conductors)

On the other hand, the resistance of a conductor varies inversely with its cross-sectional area. In other words, as a conductor's cross-sectional area increases, resistance decreases. Aircraft wire is measured by the**American Wire Gage (AWG)** system, with the larger numbers representing the smaller wires. The smallest size wire normally used in aircraft is 22-gauge wire, which has a diameter of about 0.025 inch. However, conductors carrying large amounts of current are typically of the 0000, or four aught size, and have a diameter of about 0.52 inch.

A **circular mil** is the standard measurement of a round conductor's cross-sectional area. One mil is equivalent to .001 inches. Thus, a wire that has a diameter of .125 is expressed as 125 mils. To find the cross-sectional area of a conductor in circular mils, square the conductor's diameter. For example, if a round wire has a diameter of 3/8 inch. or 375 mils, its circular area is 1,40,625 circular mils (375×345=1,40,625).

The **square mil** is the unit of measure for square or rectangular conductors such as bus bars. To determine the cross-sectional area of a conductor in square mils, multiply the conductor's length by its width. For example, the cross-sectional area of a strip of copper that is 400 mils thick and 500 mils wide is 2,00,000 square mils.

It should be noted that one circular mil is .7854 of one square mil. Therefore, to convert a circular mil area to a square mil area, multiply the area in circular mils by .7854 mil. Conversely, to convert a square mil area to a circular area, divide the area in aqure mils by .7854 (Fig. 16.9).

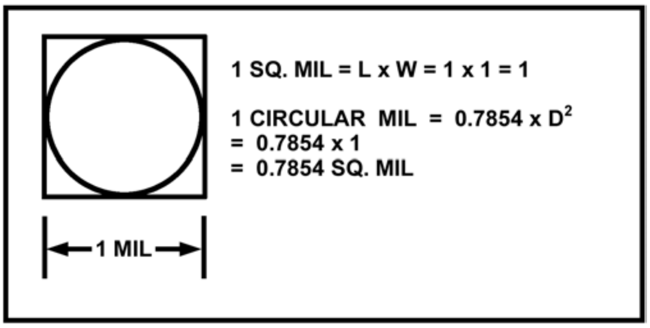

Fig. 16.9. The area of a round conductor is measured in circular mils.

Coding Schemes

As an aid to the correlation of the details illustrated in any particular diagram with the actual physical conditions, i.e. where items are located, sizes of cables used, etc., aircraft manufacturers also adopt an identification coding scheme apart from those adopted by cable manufacturers. Such a scheme may either be to the manufacturer's own specification, or to one devised as a standard coding scheme. In order to illustrate the principle of schemes generally, some example applications of one of the more widely adopted coding standards will be described .

In this scheme, deviced by the Air Transport Association of America under Specification No. 100, the coding for cable installations consists of a six-position combination of letters and numbers which is quoted on all relevant wiring diagrams and routing charts and is imprinted on the outer covering of cables. In cases where the code cannot be affixed to a cable it is printed on non-metallic sleeves placed over the ends of the cable.

The code is printed at specified intervals along the length of a cable by feeding it through a special printing machine. The following example serves to illustrate the significance of each position of the code:

1 P 1 A 22 N

Position 1. The number in this position is called the unit number and is only used where components have identical circuits, e.g., the components of a twin generator system. In this case number 1 refers to the cables interconnecting the components of the first system. The number is omitted from cables used singly.

Position 2. In this position, a letter is used to indicate the function of the circuit i.e., it designates the circuit or system with which the cable is connected. Each system has its own letter. When the circuit is part of radar, radio, special electronic equipment, a second letter is used to further define the circuit.

Position 3. The number in this position is that of the cable and is used to differentiate between cables which do not have a common terminal in the same circuit. In this respect, contacts of switches, relays, etc. are not classified as common terminals. Beginning with the lowest number and progressing in numerical order as far as is practicable, a different number is given to each cable.

Position 4. The letter used in this position, signifies the segments of cable (i.e., that portion of cable between two terminals or connections) and differentiates between segments in a particular circuit when the same cable number is used throughout. When practicable, segments are lettered in alphabetical sequence (excluding the letter "I" and "O") the letter "A" identifying the first segment of each cable, beginning at the power source. A different letter is use for each of the cable segments having a common terminal or connection.

Position 5. In this position, the number used indicates the cable size and corresponds to the American Wire Gauge (AWG) range of sizes. This does not apply to coaxial cables for which the number is omitted, or to thermocouple cables for which a dash (-) is used as a substitute.

Position 6. In this position, a letter indicates whether a cable is used as a connection to a neutral or earth point, an a.c. phase cable, or as a thermocouple cable, the letter "V" indicates a supply cable in a single-phase circuit, while in three-phase circuit, while in three-phase circuits the cables are identified by the letters "A", "B" and "C". Thermocouple cables are identified by letters which indicate the type of conductor material, thus: AL (Alumel); CH (Chromel); CU (Copper); CN (Constantan).

The practical application of the coding scheme may be understood from (Fig. 16.10) which shows the wiring of a very simple temperature sensing switch and warning lamp system.

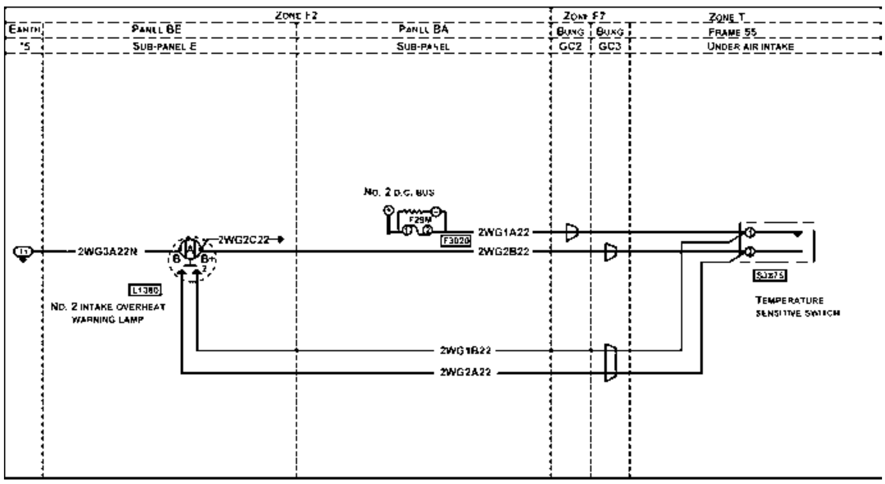

Fig. 16.10. Routing chart.

The system is related to the No.2 engine air intake, its circuit function is designated by the letters "WG", and it uses cables of wire size 22 throughout. Starting from the power source i.e., from the No. 2 d.c. busbar, the first cable is run from the fuse connection 2, through a pressure bung to terminal 1 of the switch; thus, the code for this cable is 2 WG 1 A 22. Terminal 1 also serves as a common power supply connection to the contact 2 of the press-to-test facility in the warning lamp; therefore, the interconnecting cable which also passes through a press-to-test facility in the warning lamp; therefore, the interconnecting cable which also passes through a pressure bung, is a second segment cable and as the cables are the second pair in the circuit and respectively first and second segments, their code numbers are 2 WG 2 A 22 and 2 WG 2 B 22. The cable shown going away from the B+ terminal of the lamp, is a third segment connecting a supply to a lamp in a centralized warning system and so accordingly carries the code 2 WG 2 C 22. The circuit is completed via cable number 3 and since it connects to earth it carries the full six-position code; thus, 2 WG 2 A 22 N.

The coding schemes adopted for items of electrical equipment, control panels, connector groups, junction boxes, etc. are related to physical locations within the aircraft and for this purpose aircraft are divided into electrical zones. A reference letter and number are allocated to each zone and also to equipment, connectors, panels etc., so that they can be identified within the zones. The reference letters and numbers are given in the appropriate wiring diagrams and are correlated to the diagrammatic representations of all items. In the aircraft itself, references are marked on or near the related items.

Electrical Wiring Installation

The following recommended procedures for installing aircraft electrical wiring are typical of those used on most types of aircraft. For purposes of this discussion, the following definitions are applicable :

1. Open wiring-- any wire, wire group, or wire bundle not enclosed in conduit.
2. Wire group-- two or more wires going to the same location, tied together to retain identity of the group.

3. Wire bundle-- two or more wire groups tied together because they are going in the same direction at the point where the tie is located.
4. Electrically protected wiring-- wires which include (in the circuit) protections against overloading, such as fuses, circuit breakers, or other limiting devices.
5. Electrically unprotected wiring-- wires (generally from generators to main bus distribution points) which do not have protection, such as fuses, circuit breakers, or other current-limiting devices.

Wire Groups and Bundles

Grouping or bundling certain wires, such as electrically unproptected power wiring and wiring to duplicate vital equipment, should be avoided.

Wire bundles should generally be limited in size to a bundles of 75 wires, or 2 in. in diameter where practicable. When several wires are grouped at junction boxes, terminal blocks, panels, etc., identity of the group within a bundle can be retained as shown in (Fig. 16.11).

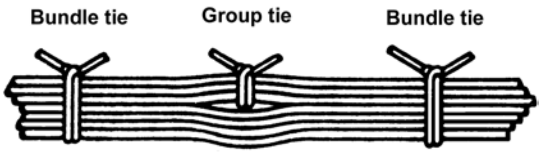

Fig. 16.11. Group and bundle ties.

Twisting Wires

When specified on the engineering drawing, parallel wires must be twisted. The following are the most common examples:
1. Wiring in the vicinity of magnetic compass or flux valve.
2. Three-phase distribution wiring.
3. Certain other wires (usually radio wiring).

Twist the wires so that they will lie snugly against each other, making approximately the number of twists per foot shown in table 16.4. Always check wire insulation for damage after twisting. If the insulation is torn or frayed, replace the wire.

Table 16.4. Recommended number of twists per foot.

	Wire Size									
	# 22	# 20	# 18	# 16	# 14	# 12	#10	# 8	# 6	# 4
2 Wires	10	10	9	8	7½	7	6½	6	5	4
3 Wires	10	10	8½	7	6½	6	5½	5	4	3

Spliced Connections in Wire Bundles

Spliced connections in wire groups or bundles should be located so that they can be easily inspected. Splices should also be staggered (Fig. 16.12) so that the bundle does not become excessively enlarged. All noninsulated splices should be covered with plastic, securely tied at both ends.

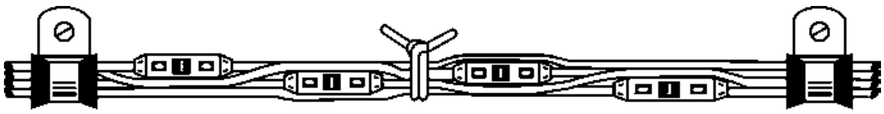

Fig. 16.12. Staggered splices in wire bundle.

Slack in Wiring Bundles

Single wires or wire bundles should not be installed with excessive slack. Slack between supports should normally not exceed 1/2 in. This is the maximum it should be possible to deflec the wire with normal hand force. However, this may

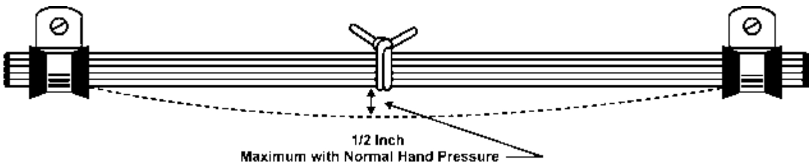

Fig. 16.13. Slack in wire bundle between supports.

be exceeded if the wire bundle is thin and the clamps are far apart. But the slack should never be so great that the wire bundle can abrade against any surface it touches. (Fig. 16.13) illustrates the proper slack for wires in bundles. A sufficient amount of slack should be allowed near each end of a bundle to:

1. Permit easy maintenance.
2. Allow replacement of terminals.
3. Prevent mechanical strain on the wires, wire junctions, or supports.
4. Permit free movement of shock and vibration mounted equipment.
5. Permit shifting of equipment for purposes of maintenance.

Blend Radii

Bends in wire groups or bundles should not be less than 10 times the outside diameter of the wire group or bundle. However, at terminal strips, where wire is suitably supported at each end of the bend, a minimum radius of three times the outside diameter of the wire, or wire bundle, is normally acceptable. There are, of course, exceptions to these guidelines in the case of certain types of cable; for example, coaxial cable should never be bent to a smaller radius than six times the outside diameter.

Bend Radii

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Routing and Installation

All wiring should be installed so that it is mechanically and electrically sound and neat in appearance. Whenever practicable, wires and bundles should be routed parallel with, or at right angles to, the stringers or ribs of the area involved. An exception to this general rule is the coaxial cables, which are routed as directly as possible.

The wiring must be adequately supported throughout its length. A sufficient number of supports must be provided to prevent undue vibration of the unsupported lengths. All wires and wire groups should be routed and installed to protect them from:

1. Chafing or abrasion.
2. High temperature.
3. Being used as handholds, or as support for personal belongings and equipment.
4. Damage by personnel moving within the aircraft.
5. Damage from cargo stowage or shifting.
6. Damage from battery acid fumes, spray or spillage.
7. Damage from solvents and fluids.

Protection Against Chafing

Wires and wire groups should be installed so that they are protected against chafing or abrasion in those locations where contact with sharp surfaces or other wires would damage the insulation. Damage to the insulation can cause short circuits, malfunctions, or inadvertent operation of equipment. Cable clamps should be used to support wire bundles (Fig. 16.14) at each hole through a bulkhead. If wires come closer than 1/4 in. to the edge of the hole, a suitable grommet is used in the hole, as shown in (Fig. 16.15).

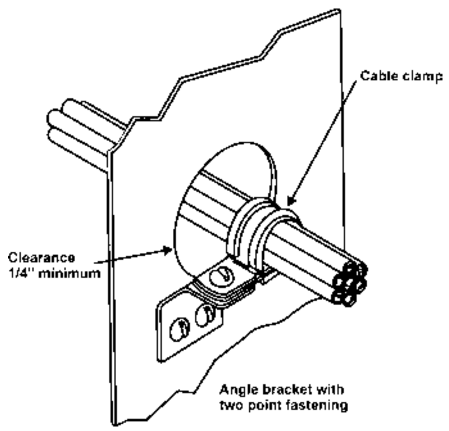

Fig. 16.14. Cable clamp at bulkhead hole.

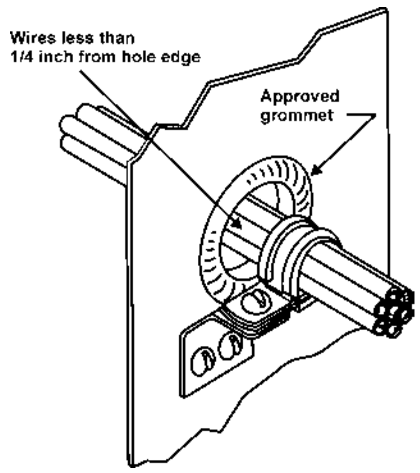

Fig. 16.15. Cable clamp and grommet at bulkhead hole.

Sometimes it is necessary to cut nylon or rubber grommets to facilitate installation. In these instances, after insertion, the grommet can be secured in place with general-purpose cement. The slot should be at the top of the hole, and the cut should be made at an angle of 45^0 to the axis of the wire bundle hole.

Protection Against High Temperature

To prevent insulation deterioration, wires should be kept separate from high-temperature equipment, such as resistors, exhaust stacks, heating ducts, etc. The amount of separation is normally specified by engineering drawings. Some wires must invariably be run through hot areas. Some wires must invariably be run through hot areas. These wires must be insulated with high-temperature material such as asbestos, fibre glass, or Teflon. Additional protection is also often required in the form of conduits. A low-temperature insulated wire should never be used to replace a high-temperature insulated wire.

Many coaxial cables have soft plastic insulation, such as polyethylene, which is especially subject to deformation and deterioration at elevated temperatures. All high-temperature areas should be avoided when installing these cables.

Additional abrasion protection should be given to asbestos wires enclosed in conduit. Either conduit with a high-temperature rubber linear should be used, or asbestos wires can be enclosed individually in high-temperature plastic tubes before being installed in the conduit.

Protection Against Solvents and Fluids

Avoid installing wires in areas where they will be subjected to damage from fluids. Wires should not be placed in the lowest 4 inches of the aircraft fuselage, except those that must terminate in that area. If there is a possibility that wiring without a protective nylon outer jacket may be soaked with fluids, plastic tubing should be used to protect it. This tubing should extend past the exposure area in both directions and should be tied at each end. If the wire has a low point between the tubing ends, provide a 1/8 in. drainage hole, as shown in in (Fig. 16.16). This hole should be punched into the tubing after the installation is complete and the low point definitely established by using a hole punch to cut a half circle. Care should be taken not to damage any wires inside the tubing when using the punch.

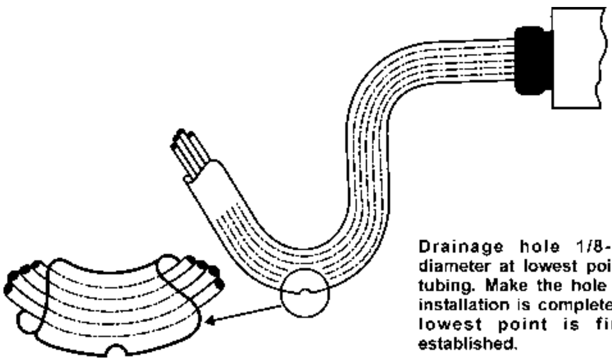

Fig. 16.16. Drainage hole in low point of tubing.

Wire also should never be routed below a battery. All wires in the vicinity of a battery should be inspected frequently. Wires discolored by battery fumes should be replaced.

Protection of Wires in Wheel Well Area

Wires located in wheel wells are subject to many additional hazards, such as exposure to fluids, pinching, and severe flexing in service. All wire bundles should be protected by sleeves of flexible tubing securely held at each end. There should be no relative movement at points where flexible tubing is secured. These wires and the insulating tubing should be inspected carefully at very frequent intervals, and wires or tubing should be replaced at the first sign of wear. There should be no strain on attachments when parts are fully extended, but slack should not be excessive.

Routing Precautions

When wiring must be routed parallel to combustible fluid or oxygen lines for short distances, as much separation as possible should be maintained. The wires should be on a level with, or above, the plumbing lines. Clamps should be spaced so that if a wire is broken at a clamp, it will not contact the line. Where a 6 in. separation is not possible , both the wire bundle and the plumbing line can be clamped to the same structure to prevent any relative motion. If the separation is less than 2 in. but more than 1/2 in., two cable clamps back-to-back (Fig. 16.17) can be used to maintain a rigid separation only, and not for support of the bundle. No wire should be routed so that it is located nearer than 1/2 in. to a plumbing line. Neither should a wire or wire bundle be supported from a plumbing line that carries flammable fluids or oxygen.

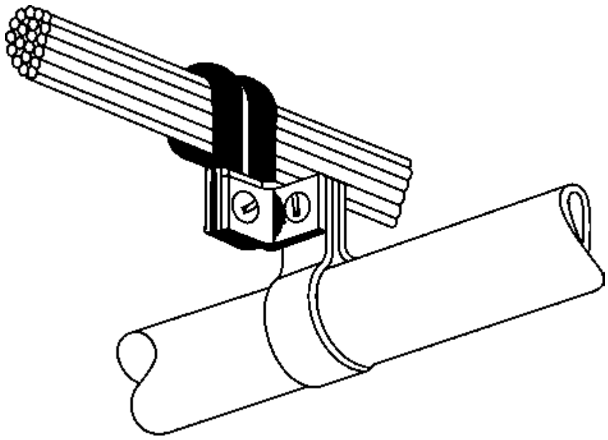

Fig. 16.17. Separation of wires from plumbing lines.

Wiring should be routed to maintain a minimum clearance of at least 3 in. from control cables. If this cannot be accomplished, mechanical guards should be installed to prevent contact between wiring and control cables.

Installation of Cable Clamps

Cable clamps should be installed with regard to the proper mounting angle (Fig. 16.18). The mounting screw should be above the sire bundle. It is also desirable that the back of the cable clamp rest against a structural member where practicable.

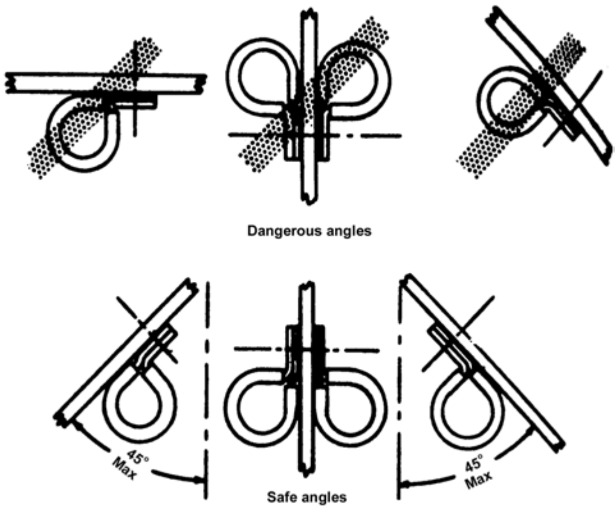

Fig. 16.18. Proper mounting angle for cable clamps.

Fig. 16.19 shows some typical mounting hardware used in installing cable clamps.

Be sure that wires are not pinched in cable clamps. Where possible, mount them directly to structural members, as shown in (Fig. 16.20).

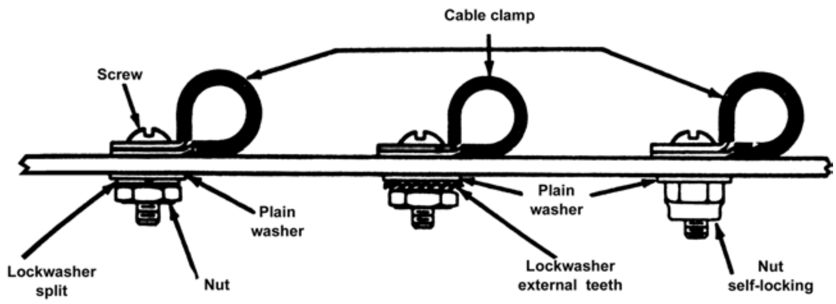

Fig. 16.19. Typical mounting hardware for cable clamps.

Clamps can be used with rubber cushions to secure wire bundles to tubular structures as shown in (Fig. 16.21). Such clamps must fit tightly but should not be deformed when locked in place.

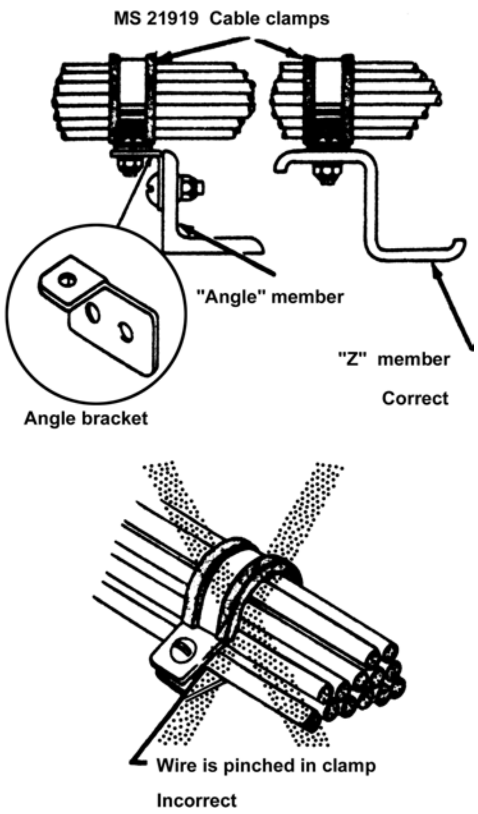

Fig. 16.20. Mounting cable clamp to structure.

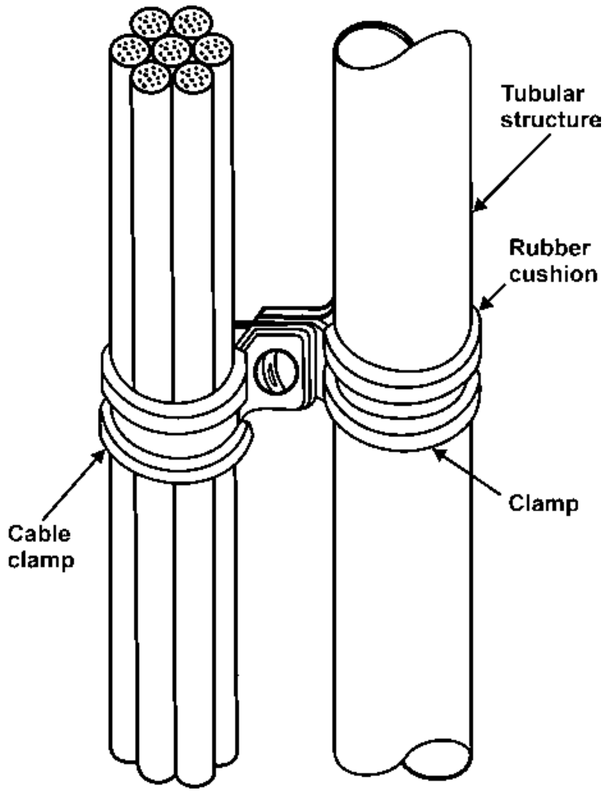

Fig. 16.21. Installing cable clamp to tubular structure.

LACING AND TYING WIRE BUNDLES

Wire groups and bundles are laced or tied with cord to provide ease of installation, maintenance, and inspection. This section describes and illustrates recommended procedures for lacing and tying wires with knots which will hold tightly under all conditions. For the purposes of this discussion, the following terms are defined:

1. Tying is the securing together of a group or bundle of wires by individual pieces of cord tied around the group or bundle at regular intervals.
2. Lacing is the securing together of a group or bundle of wires by a continuous piece of cord forming loops at regular intervals around the group or bundle.
3. A wire group is two or more wires tied or laced together to give identity to an individual system.
4. A wire bundle is two or more wires or groups tied or laced together to facilitate maintenance.

The material used for lacing and tying is either cotton or nylon cord. Nylon cord is moisture and fungus-resistant, but cotton cord must be waxed before using to give it these necessary protective characteristics.

Single-Cord Lacing

Fig. 16.22 shows the steps in lacing a wire bundle with a single cord. The lacing procedure is started at the thick end of the group or bundle with a knot consisting of a clove hitch with an extra loop. The lacing is then continued at regular intervals with half hitches along the wire group or bundle and at each point where a wire or wire group that the bundle is neat and secure. The lacing is ended by tying a knot consisting of a clovehitch with an extra loop. After the knot is tied, the free ends of the lacing cord should be trimmed to approximately 3/8 in.

Double-Cord Lacing

Fig. 16.23 illustrates the procedure for double-cord lacing. The lacing is started at the thick end of the wire group or bundle with a bowline-on-a-bight knot (A of Fig. 16.23). At regular intervals along the wire group or bundle and at each point where a wire group or bundle, and at each point where a wire branches off, the lacing is firmly together. The half hitches should be spaced so that the group or bundle is neat and secure. The lacing is ended with a knot consisting of a half hitch, continuing one of the cords clockwise and the other counterclockwise and then tying the cord ends with a square knot. The free ends of the lacing cord should be trimmed to approximately 3/8 in.

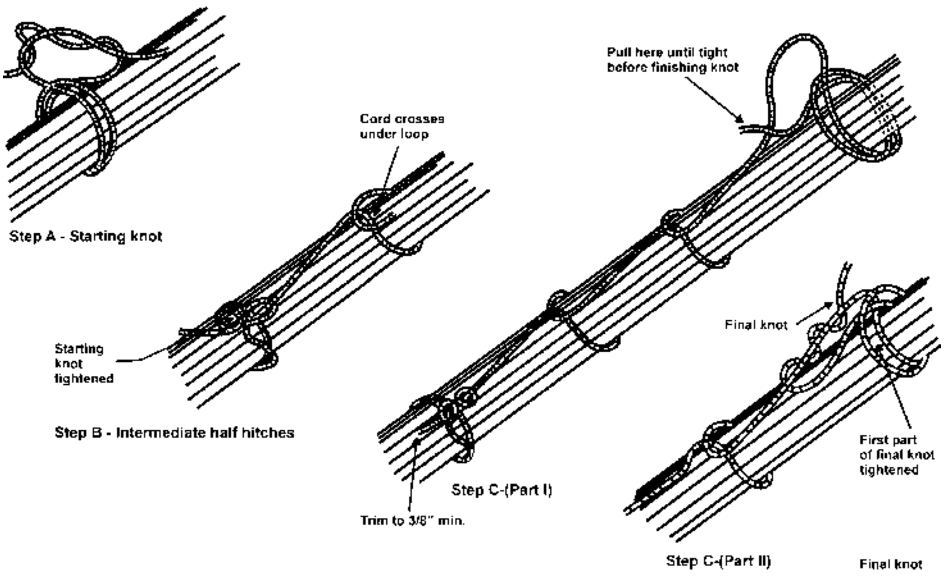

Fig. 16.22. Single-cord lacing.

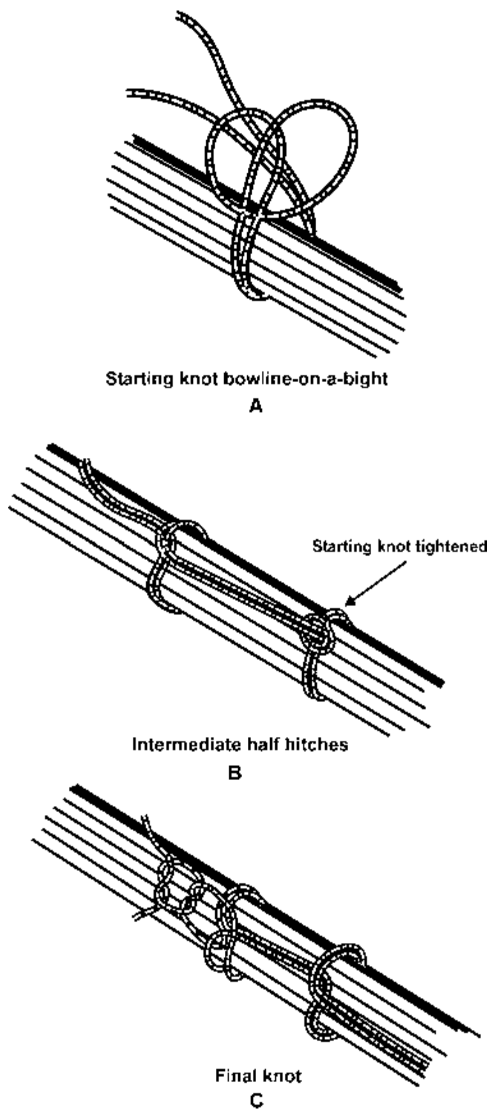

Fig. 16.23. Double-cord lacing.

Lacing Branch-Offs

Fig. 16.24 illustrates a recommended procedure for lacing a wire group that branches off the main wire bundle. The branch-off point. Continue the lacing along the branched-off point. Continue the lacing along the branched-off wire group, using regularly spaced half hitches. If a double cord is used, both cords should be held snugly together. The half hitches should be spaced to lace the bundle neatly and securely. End the lacing with the regular terminal knot used in single or double-cord lacing, as applicable, and trim the free ends of the lacing cord neatly.

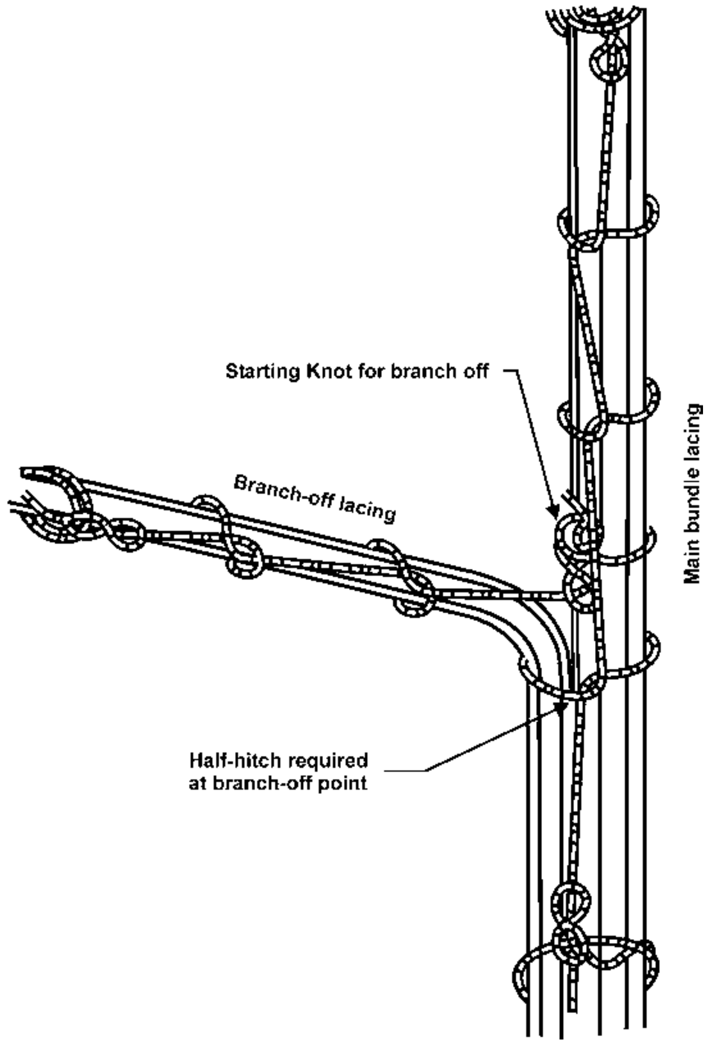

Fig. 16.24. Lacing a branch-off.

Tying

All wire groups or bundles should be tied where supports are more than 12 in. apart. Ties are made using waxed cotton cord, nylon cord, or fibre glass cord. Some manufacturers permit the use of pressure-sensitive vinyl electrical tape. When permitted, the tape should be wrapped three turns around the bundle and the ends heat sealed to prevent unwinding of the tape. (Fig. 16.25) illustrates a recommended procedure for tying a wire group or bundle. The tie is started by wrapping the cord around the wire group to tie a clove-hitch knot. Then a square knot with an extra loop is tied and the free ends of the cord trimmed.

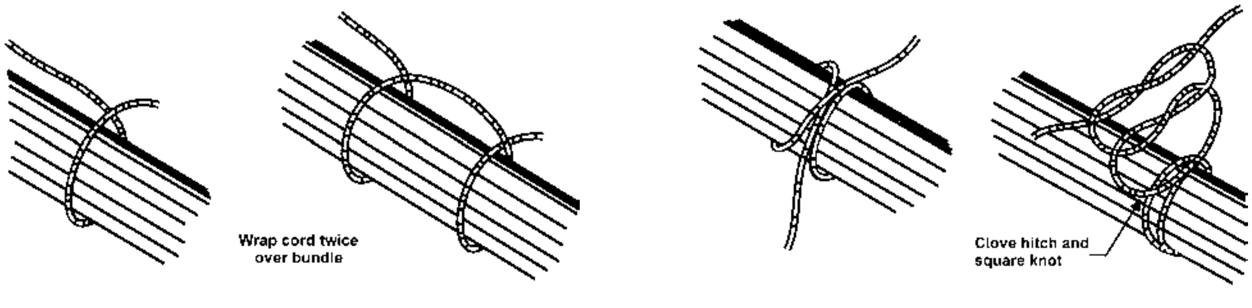

Fig. 16.25. Tying a wire group or bundle.

Temporary ties are sometimes used in making up and installing wire group and bundles. Colored cord is normally used to make temporary ties, since they are removed when the installation is complete.

Whether lacing or tying, bundles should be secured tightly enough to prevent slipping, but not so tightly that the cord cuts into or deforms the insulation. This applies especially to coaxial cable, which has a soft dielectric insulation between the inner and outer conductor. Coaxial cables have been damaged by the use of lacing materials or by methods of lacing or tying wire bundles which cause a concentrated force on the cable insulation. Elastic lacing materials, small diameter lacing cord, and excessive tightening deform the interconductor insulation and result in short circuits or impedance changes. Flat nylon braided waxed lacing tape should be used for lacing or tying any wire bundles containing coaxial cables. The part of a wire group or bundle located inside a conduit is not tied or laced, but wire groups or bundles inside enclosures, such as junction boxes, should be laced only.

Cutting Wire And Cable

To make installation, maintenance, and repair easier, runs of wire and cable in aircraft are broken at specified locations by junctions, such as connectors, terminal blocks, or buses. Before assembly to these junctions, wires and cables must be cut to length.

All wires and cables should be cut to the lengths specified on drawings and wiring diagrams. The cut should be made clean and square, and the wire or cable should not be deformed. If necessary, large-diameter wire should be re-shaped after cutting. Good cuts can be made only if the blades of cutting tools are sharp and free from nicks. A dull blade will deform and extrude wire ends.

Stripping Wire And Cable

Nearly all wire and cable used as electrical conductors are covered with some type of insulation. In order to make electrical connections with the wire, a part of this insulation must be removed to expose the bare conductor.

Copper wire can be stripped in a number of ways depending on the size and insulation. Table 16.5 lists some types of tripping tools recommended for various wire sizes and types of insulation.

Table 16.5 Wire strippers for copper wire.

Stripper	Wire Size	Insulations
Hot-blade	#26-#4	All except asbestos
Rotary, electric	#26-#4	All
Bench	#20-#6	All
Hand pliers	#26-#8	All
Knife	#2-#0000	All

Aluminum wire must be stripped using extreme care, since individual strands will break very easily after being nicked.

The following general precautions are recommended when stripping any type of wire:

1. When using any type of wire stripper, hold the wire so that it is perpendicular to the cutting blades.
2. Adjust automatic stripping tools carefully; follow the manufacturer's instructions to avoid nicking, cutting, or otherwise damaging strands. This is especially important for aluminum wires and for copper wires smaller than No.10. Examine stripped wires for damage. Cut off and re-strip (if length is sufficient), or reject and replace any wires with more than the allowable number of nicked or broken strands listed in the manufacturer's instructions.
3. Make sure insulation is clean-out with no frayed or ragged edges. Trim if necessary.
4. Make sure all insulation is removed from stripped area. Some types of wires are supplied with a transparent layer of insulation between the conductor and the primary insulation. If this is present, remove it.
5. When using hand-plier strippers to remove lengths of insulation longer than 3/4 in., it is easier to accomplish in two or more operations.
6. Re-twist copper strands by hand or with pliers if necessary to restore natural lay and tightness of strands.

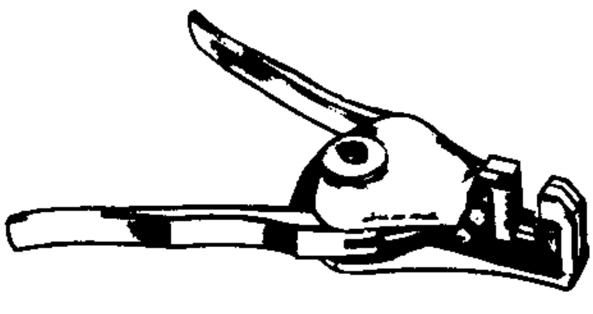

Fig. 16.26. Light-duty hand wire strippers.

A pair of hand wire strippers is shown in (Fig. 16.26). This tool is commonly used to strip most types of wire.

The following general procedures describe the steps for stripping wire with a hand stripper. (refer to Fig. 16.27).

1. Insert wire into exact center of correct cutting slot for wire size to be stripped. Each slot is marked with wire size.
2. Close handles together as far as they will go.
3. Release handles, allowing wire holder to return to the "open" position.
4. Remove stripped wire.

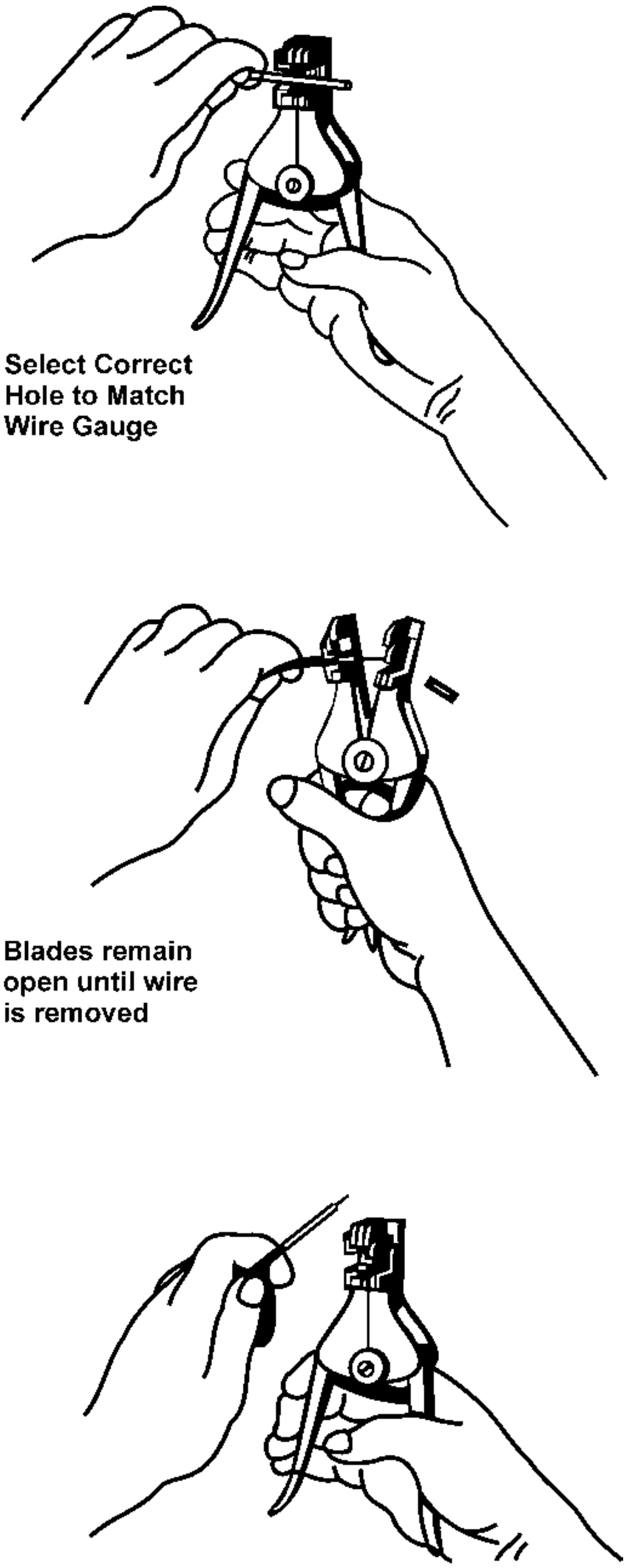

Fig. 16.27. Stripping wire with hand stripper.

Solderless Terminals and Splices

Splicing of electrical cable should be kept to a minimum and avoided entirely in locations subject to extreme vibrations. Individual wires in a group or bundle can usually be spliced, provided the completed splice is located so that it can be inspected periodically. The splices should be staggered so that the bundle does not become excessively enlarged. Many types of aircraft splice connectors are available for splicing individual wires. Self-insulated splice connectors are usually preferred; however, a noninsulated splice connector can be used if the splice is covered with plastic sleeving secured at both ends. Solder splices may be used, but they are particularly brittle and not recommended.

Electric wires are terminated with solderless terminal lugs to permit easy and efficient connection to and disconnection from terminal blocks, bus bars, or other electrical equipment. Solderless splices join electric wires to form permanent continuous runs. Solderless terminal lugs and splices are made of copper or aluminum and are preinsulated or uninsulated, depending on the desired application.

Terminal lugs are generally available in there types for use in different space conditions. These are the flag, straight, and right-angle lugs. Terminal lugs are "crimped" (sometimes called "staked" or "swaged") to the wires by means of hand or power crimping tools.

The following discussion describes recommended methods for terminating copper and aluminum wires using solderless terminal lugs. It also describes the method for splicing copper wires using solderless splices.

Copper Wire Terminals

Copper wire are terminated with solderless, perinsulated straight copper terminal lugs. The insulation is part of the terminal lug and extends beyond its barrel so that it will cover a portion of the wire insulation, making the use of an insulation sleeve unnecessary (Fig. 16.28).

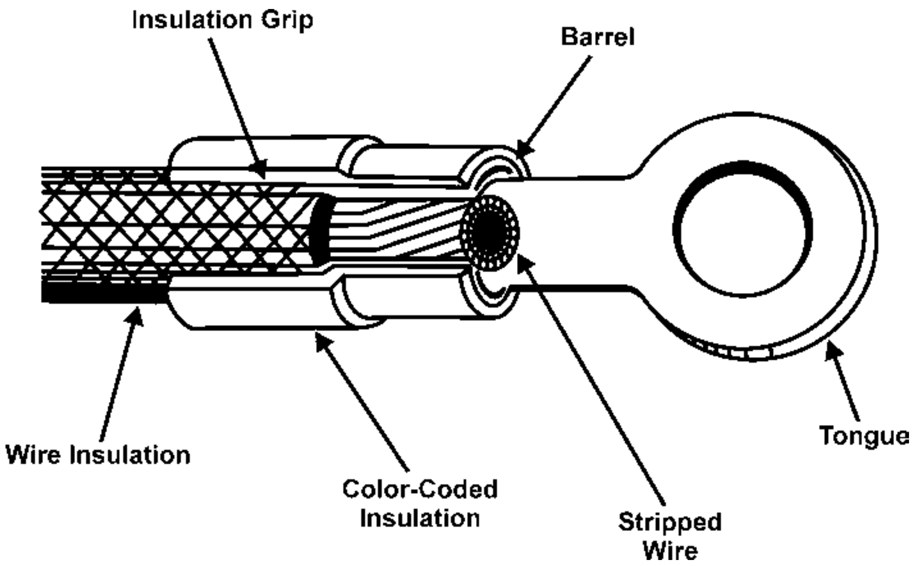

Fig. 16.28. Preinsulated terminal lug.

In addition, preinsulated terminal lugs contain an insulation grip (a metal reinforcing sleeve) beneath the insulation for extra gripping strength on the wire insulation. Preinsulated terminals accommodate more than one size of wire; the insulation is usually color-coded to identify the wire sizes that can be terminated with each of the terminal lug sizes.

Crimping Tools

Hand, portable power, and stationary power tools are available for crimping terminal lugs. These tools crimp the barrel of the terminal lug to the conductor and simultaneously crimp the insulation grip to the wire insulation.

Hand crimping tools all have a self-locking ratchet that prevents opening the tool until the crimp is complete. Some hand crimping tools are equipped with a nest of various size inserts to fit different size terminal lugs. Others are used on one terminal lug size only. All types of hand crimping tools are checked by gages for proper adjustment of crimping jaws.

Fig. 16.29 shows a terminal lug inserted into a hand tool. The following general guidelines outline the crimping procedure:

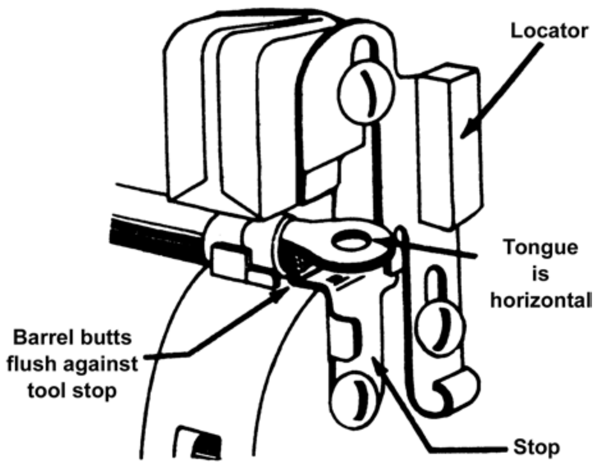

Fig. 16.29. Inserting terminal lug into hand tool.

1. Strip the wire insulation to proper length.
2. Insert the terminal lug, tongue first, into the hand tool barrel crimping jaws until the terminal lug barrel butts flush against the tool stop.
3. Insert the stripped wire into the terminal lug barrel until the wire insulation butts flush against the end of the barrel.
4. Squeeze the tool handles until the ratchet releases.
5. Remove the completed assembly and examineit for proper crimp.

Some types of uninsulated terminal lugs are insulated after assembly to a wire by means of pieces of transparent flexible tubing called "sleeves." The sleeve provides electrical and mechanical protection at the connection. When the size of the sleeving used is such that it will tightly over the terminal lug, the sleeving need not be tied; otherwise, it should be tied with lacing cord (Fig. 16.30).

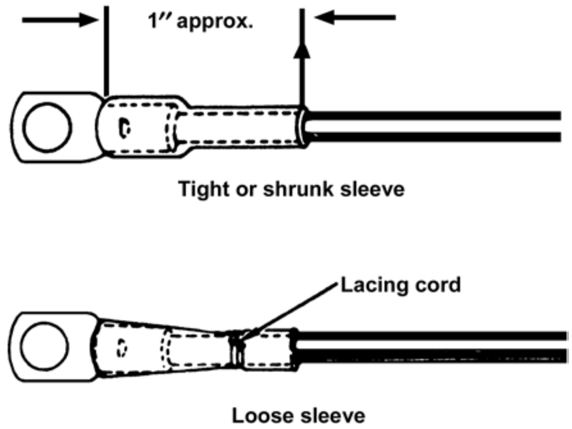

Fig. 16.30. Insulating sleeves.

Aluminum Wire Terminals

Aluminium wire is being used increasingly in aircraft systems because of its weight advantage over copper. However, bending aluminium will cause "work hardening" of the metal, making it brittle. This results in failure or breakage of strands much sooner than in a similar case with copper wire. Aluminum also forms a high-resistant oxide film immediately upon exposure to air. To compensate for these disadvantages, it is important to use the most reliable installation procedures.

Only aluminum terminal lugs are used to terminate aluminum wires. They are generally available in three types: (1) Straight, (2) right-angle, and (3) flag. All aluminum terminals incorporate an inspection hole (Fig. 16.30) which permits checking the depth of wire insertion. The barrel of aluminum terminal lugs is filled with a petrolatumzinc dust compound. This compound removes the oxide film from the aluminum by a grinding process during the crimping operation. The compound will also minimize latter oxidation of the completed connection by excluding moisture and air. The compound is retained inside the terminal lug barrel by a plastic or foil seal at the end of the barrel.

Splicing Copper Wires Using Preinsulated Wires

Preinsulated permanent copper splices join small wires of sizes 22 through 10. Each splice size can be used for more than one wire size. Splices are usually color-coded in the same manner as preinsulated, small copper terminal lugs. Some splices are insulated with white plastic. Splices are also used to reduce wire sizes as shown in (Fig. 16.31).

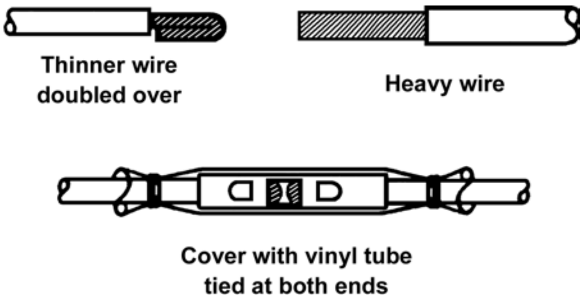

Fig. 16.31. Reducing wire size with a permanent splice.

Crimping tools are used to accomplish this type of splice. The crimping procedures are the same as those sued for terminal lugs, except that the crimping operation must be done twice, one for each end of the splice.

Emergency Splicing Repairs

Broken wires can be repaired by means of crimped splices, by using terminal lugs from which the tongue has been cut off, or by soldering together and potting broken strands. These repairs are applicable to copper strands. These repairs are applicable to copper wire. Damaged aluminum wire must not be temporarily spliced. These repairs are for temporary emergency use only and should be replaced as soon as possible with permanent repairs. Since some manufacturers prohibit splicing, the applicable manufacturer's instructions should always be consulted.

Splicing with Solder and Potting Compound

When neither a permanent splice nor a terminal lug is available, a broken wire can be repaired as follows (see Fig. 16.32):

1. Install a piece of plastic sleeving about 3 in. long, and of the proper diameter to fit loosely over the insulation, on one piece of the broken wire.

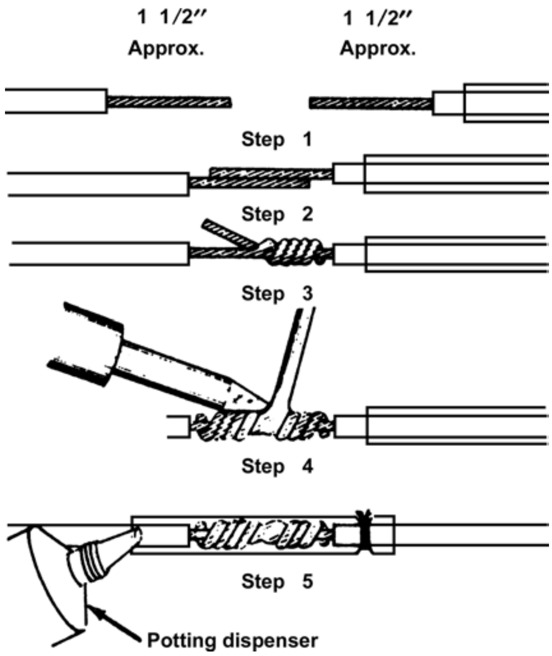

Fig. 16.32. Repairing broken wire by soldering and potting.

2. Strip approximately 1-1/2 in. from each broken end of the wire.
3. Lay the stripped ends side by side and twist one wire around the other with approximately four turns.
4. Twist the free end of the second wire around the first wire with approximately four turns. Solder the wire turns together, using 60/40 tin-lead resin-core solder.

5. When solder is cool, draw the sleeve over the soldered wires and tie at one end. If potting compound is available, fill the sleeve with potting material and tied securely.
6. Allow the potting compound to set without touching for 4 hrs. Full cure and electrical characteristics are achieved in 24 hrs.

CONNECTING TERMINAL LUGS TO TERMINAL BLOCKS

Terminal lugs should be installed on terminal blocks in such a manner that they are locked against movement in the direction of loosening (Fig. 16.33).

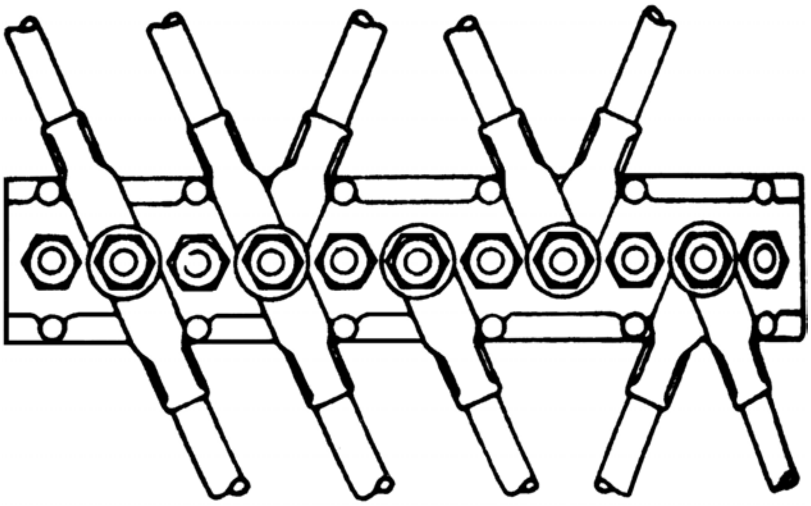

Fig. 16.33. Connecting terminals to terminal block.

Terminal blocks are normally supplied with studs secured in place by a plain washer, an external tooth lockwasher, and a nut. In connecting terminals, a recommended practice is to place-copper terminal lugs directly on top of the nut, followed with a plain washer and elastic stop nut, or with a plain washer, split steel lockwasher, and plain nut.

Aluminum terminal lugs should be placed over a plated brass plain washer, followed with another plated brass plain washer, split steel lockwasher, and plain nut or elastic stop nut. The plated brass washer should have diameter equal to the tongue width of the aluminum terminal lug. Consult the manufacturer's instructions for recommended dimensions of these plated brass washers. Do not place any washer in the current path between two aluminum terminal lugs or between two copper terminal lugs. Also, do not place a lockwasher directly against the tongue or pad of the aluminum terminal.

To join a copper terminal lug to an aluminum terminal lug, place a plated brass plain washer over the nut which holds the stud in place; follow with the aluminum terminal lug, a plated brass plain washer, the copper terminal lug, plain washer, split steel lockwasher and plain nut or self-locking, all metal nut. As a general rule use a torque wrench to tighten nuts to ensure sufficient contact pressure. Manufacturer's instructions provide installation torques for all types of terminals.

CONNECTORS

Connectors (plugs and receptacles) facilitate maintenance when frequent disconnection is required. Since the cable is soldered to the connector inserts, the joints should be individually installed and the cable bundle firmly supported to avoid damage by vibration. Connectors have been particularly vulnerable to corrosion in the past, due to condensation within the shell. Special connectors with waterproof features have been developed which may replace nonwaterproof plugs in areas where moisture causes a problem. A connector of the same basic type and design should be used when replacing a connector. Connectors that are susceptible to corrosion difficulties may be treated with a chemically inert waterproof jelly. When replacing connector assemblies, the socket-type insert should be used on the half which is "live" or "hot" after the connector is disconnected to prevent unintentional grounding.

Types of Connectors

Connectors are identified by AN numbers and are divided into classes with the manufacturer's variations in each class. The manufacturer's variations are differences in appearance and in the method of meeting a specification. Some commonly used connectors are shown in (Fig. 16.34). There are five basic classes of AN connectors used in most aircraft. Each class of connector has slightly different construction characteristics. Classes A, B, C, and D are made of aluminum, and class K is made of steel.

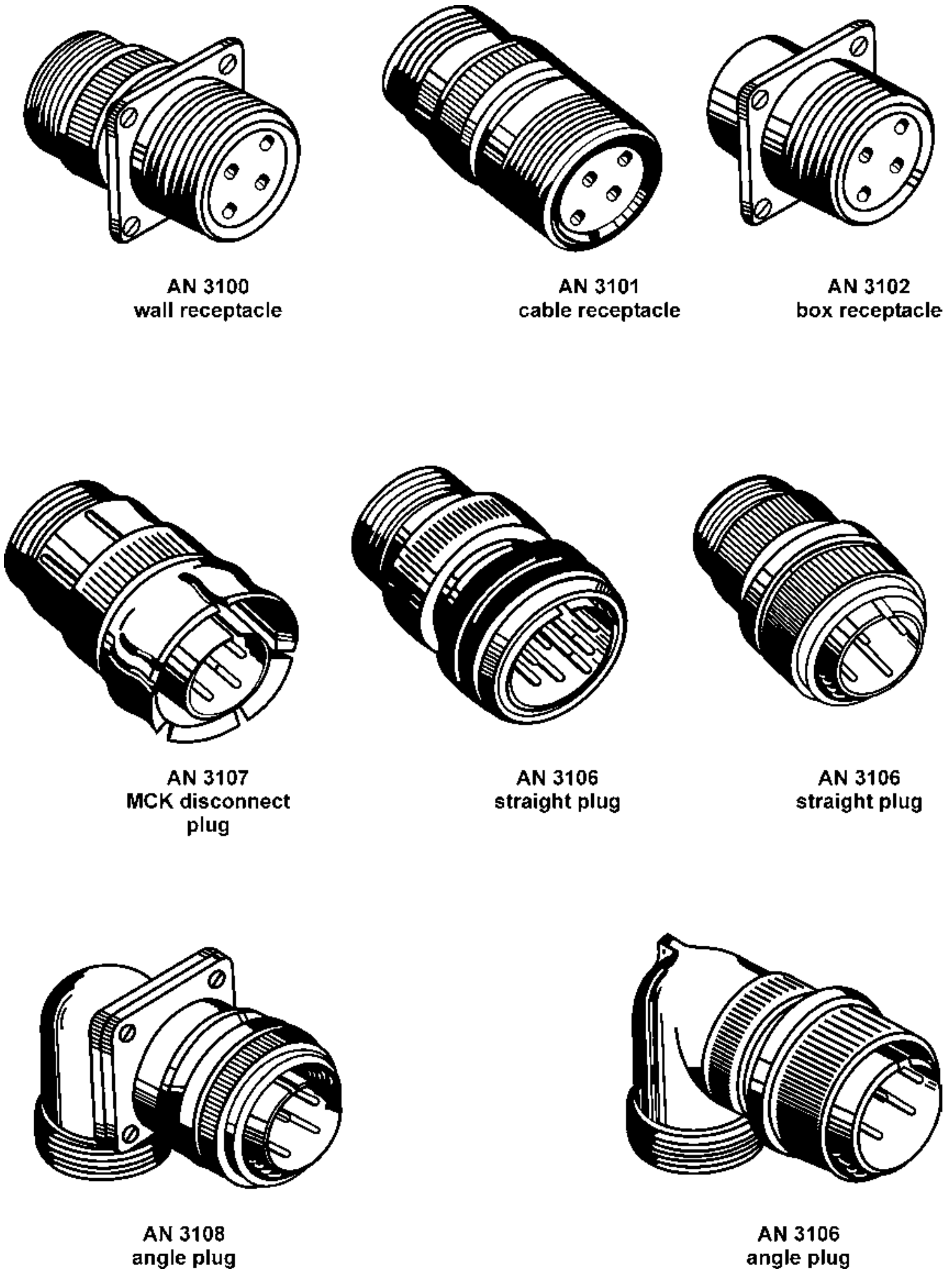

Fig. 16.34. AN connectors.

1. Class A-- Solid, one-piece back shell general-purpose connector.
2. Class B-- Connector back shell separates into two parts lengthwise. Used primarily where it is important that the soldered connectors are readily accessible. The back shell is held together by a threaded ring or by screws.
3. Class C--A pressurized connector with inserts that are not removable. Similar to a class A connector in appearance, but the inside sealing arrangement is sometimes different. It is used on walls or bulkheads of pressurized equipment.
4. Class D-- Moisture and vibration-resistant connector which has a sealing grommet in the back shell. Wires are threaded through tight-fitting holes in the grommet, thus sealing against moisture.
5. Class K--A fireproof connector used in areas where it is vital that the electric current is not interrupted, even though the connector may be exposed to continuous open flame. Wires are crimped to the pin or socket contacts and the shells are made of steel. This class of connector is normally longer than other connectors.

Connector Identification

Code letters and numbers are marked on the coupling ring shell to identify a connector. This code (Fig. 16.35) provides all the information necessary to obtain the correct replacement for a defective or damaged part.

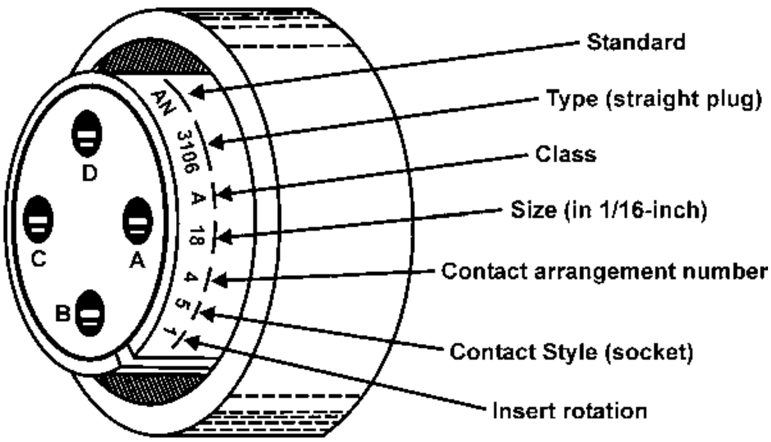

Fig. 16.35. AN connector marking.

Many special-purpose connectors have been designed for use in aircraft applications. These include subminiature and rectangular shell connectors, and connectors with short body shells, or of split-shell construction.

Installation of Connectors

The following procedures outline one recommended method of assembling connectors to receptacles :

1. Locate the proper position of the plug in relation to the receptacle by aligning the key of one part with the groove or keyway of the other part.
2. Start the plug into the receptacle with a slight forward pressure and engage the thread of coupling ring and receptacle.
3. Alternately push in the plug and tighten the coupling ring until the plug is completely seated.
4. Use connector pliers to tighten coupling rings one-sixteenth to one-eighth of a turn beyond finger tight if space around the connector is too small to obtain a good finger grip.
5. Never use force to mate connectors to receptacles. Do not hammer a plug into its receptacle, and never use a torque wrench or pliers to lock coupling rings.

A connector is generally disassembled from a receptacle in the following manner :

1. Use connector pliers to loosen coupling rings which are too tight to be loosened by hand.
2. Alternately pull on the plug body and unscrew the coupling ring until the connector is separated.
3. Protect disconnected plugs and receptacles with caps or plastic bags to keep debris from entering and causing faults.
4. Do not use excessive force, and do not pull on attached wires.

"POTTING"

This is a technique usually applied to plugs and sockets which are to be employed in situations where there is the possibility of water or other liquids passing through the cable entry. It eliminates elaborate cable ferrules, gland nuts, etc., by providing a simple plastic shroud with sufficient height to cover the terminations, and filling the cavity with a special compound which though semi-fluid in its initial condition, rapidly hardens into a rubbery state to form a fairly efficient seal. In addition to sealing it provides reinforcement for the cable connections.

The potting compound consists of a basic material and an alkaline or acid base material (known as an "accelerator") which are thoroughly mixed in the correct proportion to give the desired consistency and hardness of the compound. Once mixed, the compound is injected into a special mould and allowed to set. When the mould is removed, the resilient hemispherically-shaped insulation extends well into the plug or socket, bonding itself to the back of the insulant around the contact and conductor joints and partly out along the conductor insulation.

■■■

CHAPTER - 17
KNOWLEDGE OF PRINCIPLE OF OPERATION, INSPECTION AND TROUBLE SHOOTING OF AIRCRAFT GALLEY EQUIPMENT, AIRCRAFT LIGHTS, AND ELECTRICAL COMPONENTS AND INDICATING CIRCUITS FOR LANDING GEAR, FLAP SYSTEM AND AIR CONDITIONING SYSTEM ETC. KNOWLEDGE OF OPERATION AND INSPECTION OF AIRCRAFT FIRE AND SMOKE DETECTION AND PROTECTION SYSTEM.

GENERAL

Lighting plays an important role in the safe operation of an aircraft and in the control of many of its systems. In the main, lighting falls into two groups-external lighting and internal lighting. The main functions of such lighting are :

a. External Lighting

1. The marking of some of the aircraft's extremities by means of navigation lights.
2. The attracting of attention by means of flashing lights.
3. Forward and lateral illumination for aircraft landing and taxying.
4. Illumination of parts of the aircraft, to enable visual checks for ice formation.
5. Illumination to facilitate evacuation of passengers and crew following an emergency landing.

b. Internal Lighting

1. Illumination of flight deck instrumentation and control consoles.
2. Illumination of passenger compartment and passenger information signs.
3. Emergency lighting.

In general, white incandescent and fluorescent lamps, electro-luminescent (electrically actvated phosphor) and self-illuminating signs are used to provide aircraft lighting. Coloured lighting used for warning lights, indicator lights on instrument panels, navigation and anti-collision lights is normally achieved by the use of coloured lenses. Emergency lights are used to illuminate both internal and external emergency egress paths.

Primary power supplies required for the individual lights and lighting systems described in this leaflet will vary according to the size and complexity of the aircraft and may be either a.c. or d.c. Reference should, therefore, be made to the relevant aircraft Maintenance Manual for precise details. Individual circuit protection is normally provided by panel mounted circuit breakers whilst lighting controls are conveniently located throughout the aircraft.

Requirements for the minimum intensities, dihedral angles, effective flash frequency and colours which are applicable to the external lights provided in order to comply with the Rules of the Air and Air Traffic Control Regulations are contained in JAR-25 and BCAR Chapter D6-7 for large aeroplanes, G6-7 for rotorcraft and K6-7 for light aeroplanes.

EXTERNAL LIGHTING

Navigation Lights

The requirements and characteristics for navigation lights have been agreed internationally, and for UK registered aircraft are set out in the statutory Rules of the Air and Air Traffic Control Regulations and the Air Navigation Order. Briefly, the requirement is that every aircraft in flight or moving on the ground during the hours of darkness shall display:

a. A green light at near the starboard wing tip, visible in the horizontal plane from a point directly ahead through an arc of 110^{o} to starboard (dihedral angle R of Fig. 17.1).

b. A red light at or near the port wing tip, with an arc of visibility to port similar to that in (a) (dihedral angle L of Fig. 17.1).

c. White light visible from the rear of the aircraft in the horizontal plane through an arc of 140^{o}. The conventional location of this light is on the tail of the aircraft, but in some cases, notably such aircraft as the wide bodied types, a white light meeting the specification is mounted on the trailing edge section of each wing up (dihedral angle A of Fig. 17.1).

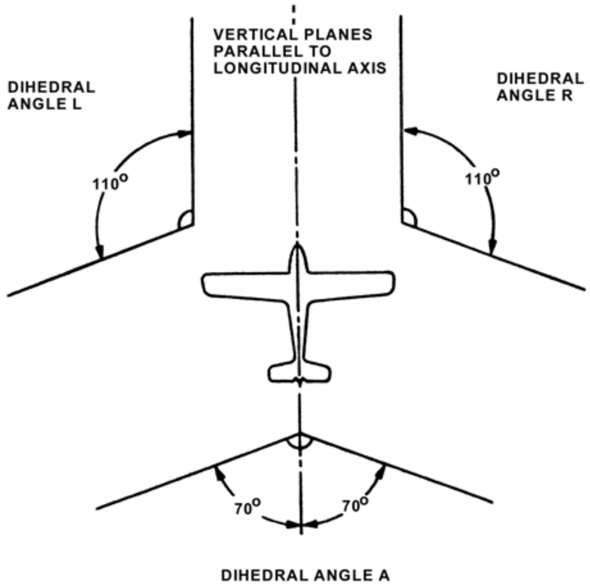

Fig. 17.1. External Lighting Angles.

Construction of the light fittings varies in order to meet the installation requirements for different types of aircraft. In general, however, they consist of a filament type lamp, an appropriate fitting and a transparent coloured screen or cap. To obtain a sharp cut-off of light at the required angle of visibility, the screen and the filament of the lamp are shaped and arranged accordingly.

Originally, navigation lights were required to emit a steady light, but in order to improve the attention attracting function, subsequent legislation required the lights to flash in a controlled sequence. However, following the introduction of flashing anti-collision beacons the requirement for flashing navigation lights was discontinued, and the steady lighting requirement was re-introduced. It is, therefore, possible for some aircraft, which are below a certain weight criterion and registered before current regulations became effective, to be still equipped with flashing navigation lights.

Anti-Collision Lights

Anti-collision lights complement the navigation lights and by emitting a flashing light attract attention and thus enable the presence of an aircraft to be more readily identified. The lights may be of the type which emits a rotating beam of light or of the strobe type, from which short-duration flashes of high intensity light are emitted. In some current types of aircraft both types are used in combination, the strobe lighting forming supplementary lighting.

Rotating Beam Lights

These lights, or beacons as they are often called, consist of a filament lamp unit and a motor. In some cases the motor drives a reflector see (a) and in others the actual lamp unit see (b). The drive transmission system is usually contained within a mounting enclosed by a red glass cover. The motor speed and gear drive ratios of beacons are such that the reflector or lamp unit, as the case may be, is operated to establish a beam of light which rotates at constant frequency. Typical speeds are 40-45 rev/mn giving a flash frequency of 80-90 Hz/min. There are variations of design, but the two types described in (a) and (b) usefully illustrate how the rotating reflector and rotating lamp techniques are applied.

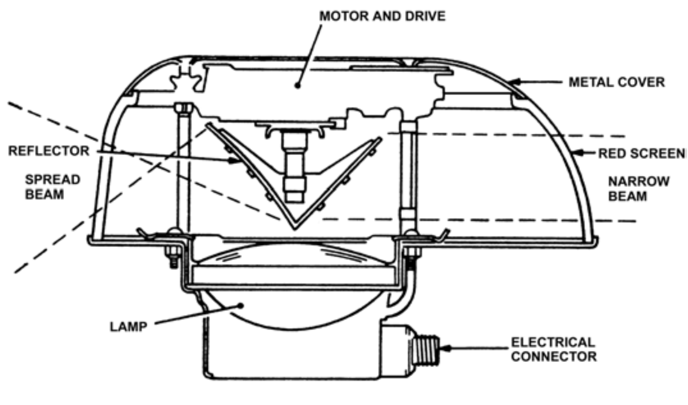

Fig. 17.2. Rotating Reflector Beacon.

a. The beacon illustrated in (Fig. 17.2) employs a V-shaped reflector which is rotated at approximately 45 rev/min by a motor, over and about the axis of a sealed beam lamp. One half of the reflector is flat and emits a narrow high-intensity beam of light near the horizontal, while the other half is curved half is curved to increase the up and down spread of its emitted beam to 30^o above and below the horizontal, there by effectively reducing the light intensity.
b. The beacon illustrated in (Fig. 17.3) is one employing two filament lamps, mounted in tandem, each of which is pivoted on its own axis. One half of each lamp forms a reflector by being silvered, and the drive from the motor is so arranged that the lamps oscillate through 180^o and, as can be seen from the inset diagram, the light beams are 180^o apart at any instant.

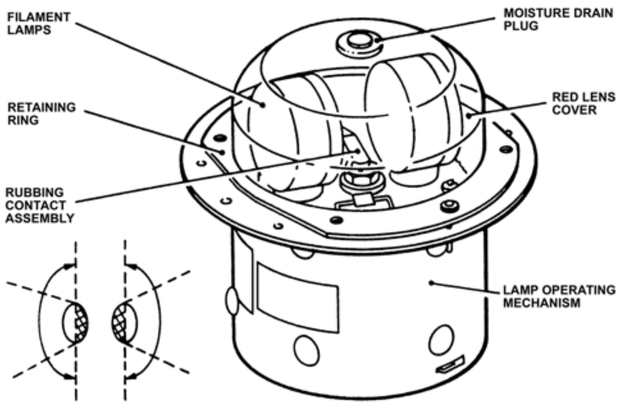

Fig. 17.3. Rotating Lamp Beacon.

Strobe Lighting
This type of lighting system is based on the principle of a capacitor-discharge flash tube. The light unit takes the form of a quartz or glass tube filled with xenon gas which is connected to a power supply unit made up essentially of a capacitor, and which converts an input power of either 28 V d.c. or 115 V a.c. into a high d.c. output, usually around 450 V. The capacitor is charged to that voltage and periodically discharged between two electrodes in the xenon-filled tube, the energy producing an effective high-intensity flash of light having a characteristic blue-white colour.

Supplemental Lighting
Depending on the size of the aircraft, strobe lighting may be installed in the wing tips to supplement the conventional red beacons, or may be used in combination as a complete strobe type anti-collision high-intensity lighting system controlled in a flashing sequence by controllers and flasher timing unit.

LANDING LIGHTS AND TAXI LIGHTS
As their names indicate these lights provide essential illumination for the landing of an aircraft and for taxi-ing it to and from runways and terminal areas at night and at other times when visibility conditions are poor. Landing lights are so arranged that they illuminate the runway immediately ahead of the aircraft from such positions as wing leading gear structure. The lights are of the sealed beam type and in some air craft are mounted to direct beams of light at predetermined and fixed angles. In other types of aircraft, the lights may be extended to preselected angles, and retracted, by an electric motor and gear mechanism, or by a linear actuator. Micro-type limit switches are incorporated in the motor circuit and are actuated at the extreme limits of travel to interrupt motor operation.

A typical power rating for lights is 600 watts, and depending on the design the power supply required for operation may be either d.c. or a.c. at 28 volts, the latter being derived from a 115-volts supply via a step-down transformer. In lights of the retractable type which require a.c. for their operation, the motor is driven directly from the 115-volts supply. The supplies to the light and motor are controlled by switches on the appropriate control panel in the cockpit. An example of a retractable type landing light is shown in (Fig. 17.4).

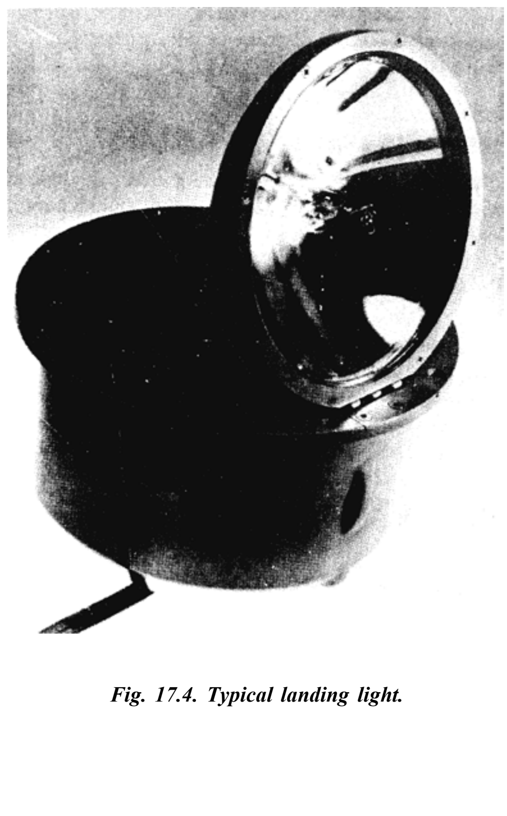

Fig. 17.4. Typical landing light.

The circuit of an extending/retracting light system is shown in (Fig. 17.5). It is drawn to indicate the retracted position, and so the "retract" and "extend" limit switches controlling the motor, are open and closed respectively. The supply circuit to the light itself is automatically interrupted when it is retracted. When the control switch is placed in the "extend" position, the 115-volt supply passes through the corresponding field winding of the motor until interrupted by the opening of the extend limit switch. The retract limit switch closes soon after the motor starts extending the light. The switch in the supply circuit to the light also closes but the light is not illuminated until it is fully extended and the control switch placed in the "on" position. The power supply to the light is reduced from 115 to 15 volts by a step-down transformer.

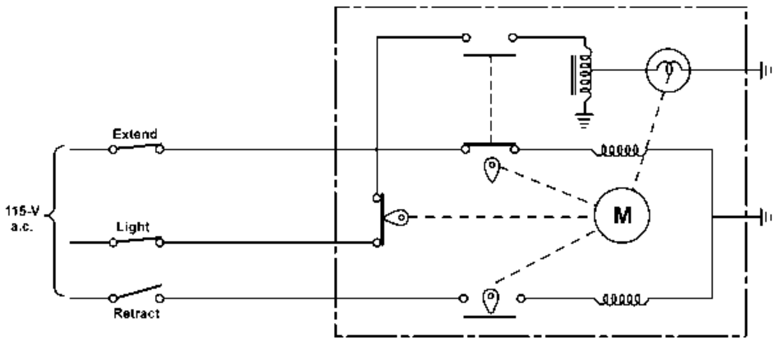

Fig. 17.5. Extending/retracting light circuit.

In some aircraft, a fixed-type landing light is located in the leading edge of each wing near the fuselage, and extending/ retracting type is located in the fairing of each outboard landing flap track. In lights located in flap track fairings, additional switches are included in the "retract" and "extend" circuits. The switches are actuated by a mechanical coupling between the wing and flaps are lowered, and the landing lights extended, the circuits of the motor will be signalled to adjust the positions of the lights so that their beams remain parallel to a known fore and aft datum regardless of flap positions.

Taxi lights are also of the sealed beam type and are located in the fuselage nose section, in most cases on the nose landing gear assembly. The power rating of the lights is normally lower than that of landing lights either d.c. or a.c. at 28 volts 250 watts.

In certain cases the function of a taxi light is combined with that of a landing light. For example, in the unit illustrated in (Fig. 17.4), the light has two filaments, one rated at 600 watts and the other at 400 watts; both filaments provide the illumination for landing, while for taxi-ing only the 400 watt filament is used.

In addition to taxi lights some of the larger types of transport aircraft are equipped with lights which direct beams of light to the sides of the runway (see Fig. 17.6). These are known as runway turn-off lights, their primary function being to illuminate the points along the runway at which an aircraft must turn to leave the runway after landing.

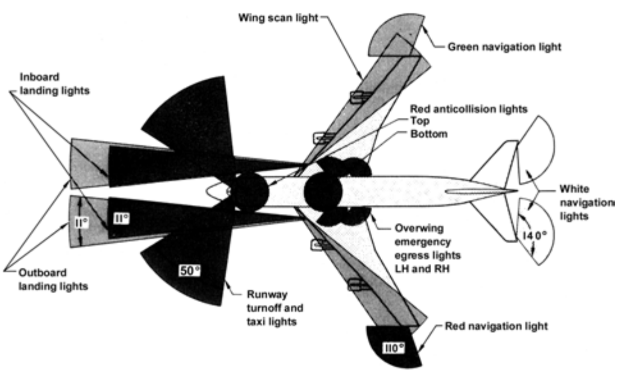

Fig. 17.6. Disposition of external lighting.

Ice Inspection Lamps

Ice inspection lamps, or wing-scan lamps as they are sometimes called, are fitted to transport aircraft to allow for the visual inspection on the wing leading edges and air intakes of turbine engines, for the formation of ice. Further information on ice inspection lamps is given in Leaflet AL/11-6. The lamps are generally of the sealed beam type with power ratings ranging from 60 to 250 W depending on the light intensity required for the particular aircraft type.

Service Lighting

Service lighting is fitted to some aircraft to provide general illumination for routine inspection and servicing in such areas as wheel wells, air conditioning compartments, tail cone, APU compartments, electrical/electronic equipment centres and fuelling panels. The lights are generally of the explosion-proof dome or bulkhead type with conveniently located control switches.

Exterior Emergency Lighting

Exterior emergency lighting is normally provided by white incandescent lights at each overwing emergency exit to illuminate the area where an evacuee is likely to make the first step outside the passenger cabin, along a portion of the overwing escape route to an area where first contact with the ground would be made.

At each non-overwing emergency exit not having an escape assist means, similar illumination is provided which is capable of lighting the ground surface where an evacuee is likely to make first contact with the ground outside the passenger compartment.

Where an emergency exit has an escape assist means, illumination is provided to ensure that it is visible from the relevant emergency exit and to illuminate the area of the ground with which an avacuee would first make contact. In some such installations the light units may form part of the escape assist means and are, therefore, automatically activated when the assist means is erected.

INTERNAL LIGHTING

An important requirement of internal lighting is that there should be adequate illumination of the aircraft interior for all conditions of flight. To achieve this, most passenger transport aircraft have flight deck and passenger compartment lighting divided into three groups :-

a. **Main.** Main lighting is usually equally distributed and connected to the various busbars, so ensuring that single power failures do not result in the loss of all main lighting.

b. **Standby.** In the event of a total electrical power failure, illumination, at a considerably lower level, would be provided by standby lighting normally powered from the aircraft batteries.

c. **Emergency.** Emergency lighting is normally provided for the illumination of emergency exit paths and exits throughout the aircraft. Such lighting is, in some aircraft, arranged and connected in groups to the aircraft batteries, capable of being automatically transferred to emergency battery packs when the main battery voltage level has fallen to a pre-determined value. On other aircraft these are of the self-contained battery operated type.

The internal lighting can also be further divided into four categories-flight deck or operational lighting, passenger compartment lighting, service lighting (which includes galleys, toilet and cargo/baggage compartments) and emergency lighting to assist egress and survival independently of passenger compartment lighting.

Flight Deck Lighting

General

a. To ensure adequate illumination of all instruments, switches, controls, etc., and of the panels to which these items are fitted, the following types of lighting are used :

(i) Integral lighting, in which the light source is contained within the instrument.

(ii) Pillar and bridge lighting, in which a number of lights are positioned on an instrument panel to illuminate small adjacent areas, and to provide the dial lighting of individual instruments.

(iii) Trans-illuminated panels, which are used to allow engraved marks on various controls, notices and instructions to be read under night conditions.

(iv) Flood-lighting, whereby lamps are positioned around the flight deck so as to illuminate an entire instrument panel or general area.

(v) Electro-luminescent lighting for control-position indicators and passenger information signs.

b. The choice of colour for the lighting of aircraft flight decks has been the subject of many tests and studies, and as far as the contribution to the safe and efficient operation of aircraft at night is concerned the choice has been between red and white. Red lighting was introduced during the second world war, was subsequently carried over to civil aviation, and for some time was universally adopted as the principal lighting scheme, supplemented by a certain amount of white lighting. However, from continued tests and studies of the comparative merits of red and white lighting, it was generally concluded that at the brightness levels adopted, the advantages of white light were very significant.

c. White light is superior to red for several reasons which can be listed as follow :

(i) The amount of electrical power required is reduced since red filters, which absorb about 80% of the light, are eliminated.

(ii) Heat dissipation problems are reduced.

(iii) White lighting permits colour coding of displays use of red warning flags and other similar indications.

(iv) Contrasts between instrument displays and readability are improved.

(v) Eye fatigue is reduced.

(vi) Better illumination is provided in thunderstorm conditions.

d. There are a few disadvantages, of course, but they are so outweighed by the advantages that white lighting has become standard for instrument and panel lighting and is used in many aircraft currently in service.

Integral Lighting

a. A common form of integral lighting for instruments is that known as 'wedge' or 'front' lighting; a form deriving its name form deriving its name from the shape of the two wedge shaped portions of glass which together make up the instrument cover. This type of lighting relies for its operation upon the physical law that the angle at which light leaves a reflecting surface equals the angle at which it strikes that surface. The two wedges, which have polished surfaces, are mounted opposite to each other with a narrow air space separating them, as illustrated in (Fig.17.7). Light is introduced into inner wedge (A) from lamps set into recesses in its wide end. A certain amount of light passes directly through the wedge and on to the face of the dial while the remainder is reflected back into the wedge from the polished surfaces. The angle at which the light rays strike the wedge surfaces governs the amount of light reflected back; the lower the angle, the more the light is reflected back.

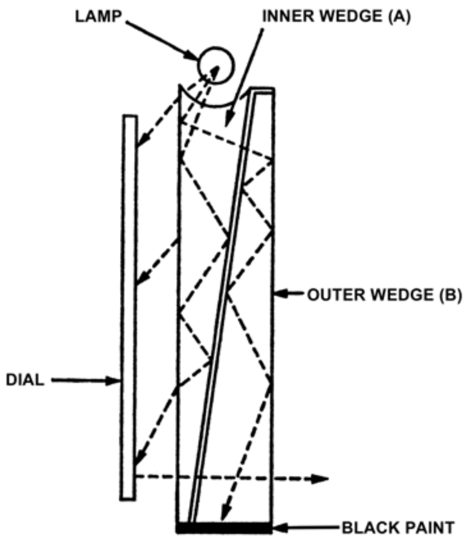

Fig. 17.7. Wedge - type lighting.

b. The double wedge mechanically changes the angle at which the light rays strike one of the reflecting surfaces of each wedge, so distributing the light evenly across the dial and also limiting the amount of light given off by the dial face. Since the source of light is a radial one, the initial angle of some light rays with respect to the polished surfaces of inner wedge (A) is less than that of others. The initially low angle light rays progress further down the wedge before they leave and spread light across the entire dial. Light escaping into outer wedge (B) is confronted with constantly decreasing angles and this has the effect of trapping light within the wedge and directing it to its wide end. Absorption of light reflected into the wide end of outed wedge (B) is ensured by painting its outer park black.

c. A further form of integral lighting has 'festoons' of micro-miniature lamps mounted in clusters around the inside of the instrument casing, which can have a significant lamp moratality without unduly reducing the satisfactory level of illumination and the need for instrument removal for lamp replacement.

Pillar and Bridge Lighting

a. **Pillar Lighting.** Pillar lighting, so called after the method of construction of the attachment which carries the lamp, is used to provide illumination for individual instruments and controls. A typical assembly, illustrated in Fig. 17.8 (a), consists of a miniature centre contact filament lamp (commonly known as a pea lamp) inside a housing, which is a push fit into the body of the assembly. The body is threaded externally for attachment to the instrument panel and has a hole running throught its length to accommodate a cable which connects the positive supply to the centre contact. The circuit through the lamp is completed by a ground tag connected to the negative cable. Light is distributed through a filter and aperture in the lamp housing. The shape of the aperture distributes a sector of light which extends downwards over an arc of approximately 90° to a depth slightly less than 50 mm (2 in) from the mounting point.

b. **Bridge Lighting.** Bridge lighting, as illustrated in Fig. 17.8 (b), is a multi-lamp development of the individual pillar lamp described in (a). Two or four lamp housings are fitted to a bridge structure designed to fit over a variety of standardised instrument cases. The bridge fitting is made up of two light alloy pressings fixed together by rivets and spacers, and carrying the requisite number of centre contact assemblies above which the lamp housings are mounted.

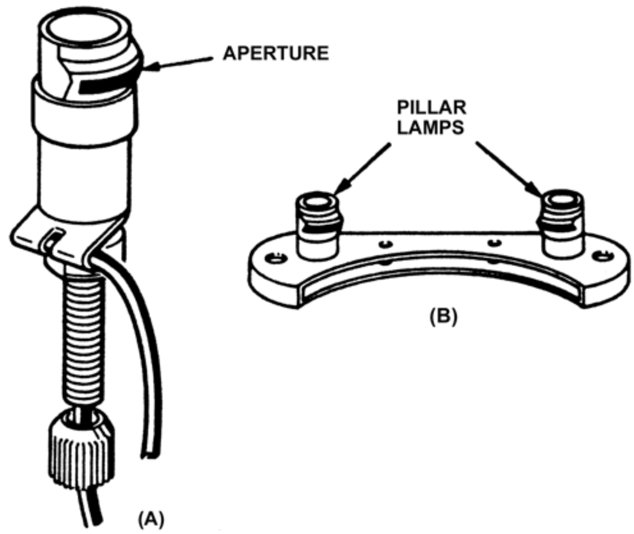

Fig. 17.8. Pillar and bridge lighting.

Trans-illuminated Panels

a. Trans-illuminated panels are designed to suit the relevant metal panel on which instruments or controls are mounted and are formed from clear sheet acrylic plastics, faces on the upper and lower surfaces by a thin sheet of translucent white plastics and faced again by a sheet of black or grey plastics. The layers are them bonded together to form the panel (see Fig. 17.9). Where necessary, numerals and inscriptions are then engraved through the outer layer to the white layer. Where components are required to be illuminated, facets are cut and angled in the surface surrounding the component. The light, transmitted by the panel clear core, originates at lamps suitable positioned in the panel. Direct emission of light is prevented by caps fitted to the lamp holders. The overall effect is to provide a clear white engraving legible during the day and illuminated by light conducted through the panel during darkness.

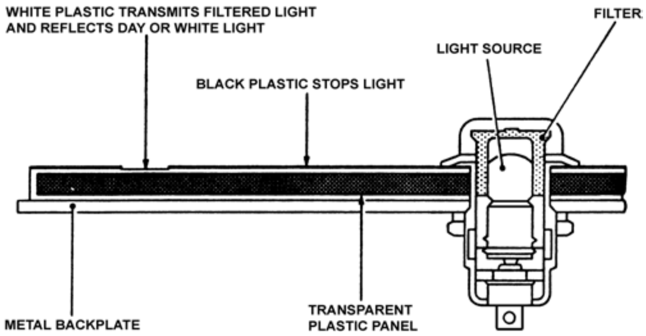

Fig. 17.9. Trans-illuminated panel.

b. Illumination for standard trans-illuminated panels is provided by lampholders mounted on the metal panel back plate, with the trans-illuminated panel being held in position by rubber skirted lamp caps which scres into lamp holders.

c. Printed circuit trans-illuminated panels use a double-faced copper laminate applied to the rear of the layered plastics panel, the lamp holders being a part of the plastics panel. Power supplies to the circuit board are introduced by a captive connector fixing screw which locates in a connector mounted on the metal panel back plate. The trans-illuminated panels are held in position by the captive connector fixing screw and fixing screws.

Flood-lighting.

Flood-lighting is normally used for the general illumination of instruments, control panels, pedestals, side consoles and areas of the flight deck flooring. The lights usually take the form of incandescent lamp or fluorescent tube units, and, depending on the size and type of aircraft, both forms may be used in combination.

Electro-Luminescent Lighting

a. Electro-luminescent lighting is employed in a number of aircraft for the illumination of passenger information signs and may also be used for the illumination of instrument dials and selective position marking of control valves and switches.

b. Electro-luminescent light consists of a thin laminate structure in which a layer of phosphor is sandwiched between two electrodes, one of which is transparent. The lighting requires an a.c. power supply for its operation, and when this is applied to the electrodes the phosphor particles become luminescent, that is to say, visible light is emitted through the transparent electrode. The luminescent intensity is proportional to the voltage and frequency of the a.c. supply.

c. The area of the phosphor layer which becomes luminescent when the power supply is applied is that actually sandwiched between the electrodes; consequently, if the back, non-transparent electrode is so shaped as to form a letter or figure, the pattern of the emitted light through the transparent electrode will be an image of that back electrode.

Central Warning System

A central warning system is as automatic signalling system which provides an 'attention getting' display in response to fault signals from specified systems. Urgency of crew action is normally indicated by the colour of the display, and/or audio tone, indicators for "Alert" signals (those demanding instant action) generally being coloured red, and "Caution" signals (those requiring less urgent action) being coloured amber.

Origination of a fault signal will cause flashing of the relevant alert or caution lamps mounted on the main instrument panels, illumination of the relevant inscription of the display unit and, in certain cases, lighting of warning lamps incorporated in, or adjacent to, control levers. Complete identification of the indicated fault will generally necessitate reference to warning indicators and instruments associated with the system at fault, as more than one fault condition can usually cause illumination of any one display unit inscription. Response to alert warnings should, however, normally be instinctive and should generally result in cessation of operation of the fault source.

Display signals other than major failure warning lamps, can usually be cancelled by operating a cancel switch. Integral self-test equipment is normally provided for in-flight testing of the system and may also provide an altitude inhibit control system which extinguishes and inhibits certain centralised warning captions during automatic landings, approach, and go-round procedures.

In addition some central warning systems are also equipped with advisory lights, normally coloured blue, that advise when a system which is operated intermittently has been activated.

Passenger Compartment Lighting

The extent to which lighting is used in a passenger compartment is dependent to some extent upon the size, but largely on the decor used for that aircraft, and can vary from a small number of roof mounted incadescent lamp fittings to a large number of fluorescent fittings located in the ceiling and hat racks so as to combine concealed, pleasing, and functional lighting effects.

Each fluorescent tube fitting requires a ballast unit to provide the momentary high voltage which enables the tube to strike and become fully illuminating. In all commercial passenger transport aircraft the lights are controlled from panels at the cabin attendants' stations.

In addition to the passenger compartment general lighting, lights are also provided at passenger service units and for the illumination of essential passenger information signs, such as "Fasten Seat Belts/No Smoking" and "Return to Cabin". The lights for these signs may be of the incandescent type or, as in a number of aircraft types, of the electro-luminescent type described. Lights for signs conveying essential passenger information are usually controlled from the flight deck.

Cargo and Baggage Compartment Lighting

Dome lights are evenly distributed throughout the cargo and baggage compartments to provide the basic illumination for the handling of cargo and baggage. Lights located adjacent to the doors also provide the lighting for the entry areas.

Each dome light is usually provided with a protective guard both to prevent damage to the unit during cargo handling and to minimise the risk of fire by preventing the cargo or baggage from coming into direct contact with a hot lens unit.

Internal Emergency Lighting

It is essential that adequate illumination of the flight deck, and the various sections of the passenger compartment containing exits, escape hatches, chutes, etc., which must be deployed under emergency conditions, is maintained following failure or disconnection of the normal lighting systems. The lighting intensity is normally or disconnection of the normal lighting systems. The lighting intensity is normally acceptable at a lower level than that provided by the standard lighting systems, since the lighting is strictly for the purpose of evacuation of the aircraft. Such lighting is normally of the white incandescent type receiving electrical power supplies as described, while self-illuminating lights, as described, are often used for emergency exit signs and hatch release handles.

In some aircraft the lighting is connected directly to an emergency battery (generally of the nickel-cadmium type, but sometimes of the silver-zinc type) which, under normal operating conditions of the aircraft, is maintained in a fully-charged state by a trickle charge from the aircraft main busbar system. Primary control of the emergency lights is in some aircraft main busbar system. Primary control of the emergency lights is in some aircraft by means of acceleration sensitive ('g) switches is also employed for their automatic operation.

Self-illuminating Signs.

Self-illuminating signs are entirely self-powered and require no period of daylight exposure to operate. Their brightness is such that they are instantly seen in dark areas by persons that are not dark-adapted, and present no direct radiation hazard.

Self-powered lights consist of a small sealed glass envelope internally coated with a layer of phosphor and containing tritium gas. Tritium is an isotope of hydrogen and emits beta-particles (electrons) of low energy which, on striking the layer of phosphor powder, cause it to emit visible light, the colour of the emitted light being controlled by the selection of the phosphor coating. Placing the light element behind a suitable silk-screened diffusing panel provides a ready means of conveying instructions or notices in darkened areas.

Control of Lighting Intensity

Certain internal lighting circuits must have a means of varying the light intensity and so they are provided with an intensity control system. The methods of control, and their application, depends largely on the extent of the lighting required, this in turn, being dependent on the type of aircraft. The fundamental operating principles of each method are shown in (Fig. 17.10).

The most basic of dimming circuit is the one utilizing a panel-mounted rheostat which is connected in series with the lights whose intensity is to be controlled [diagram (a)]. Power from the d.c. busbar is fed to the rheostat wiper which, at contact position "A" isolates the lights from the supply. When moved to contact position "B", the circuit is switched on but as current must flow through the whole of the rheostat resistance, the lights will be dimly illuminated. As the wiper is moved towards contact position "C" the

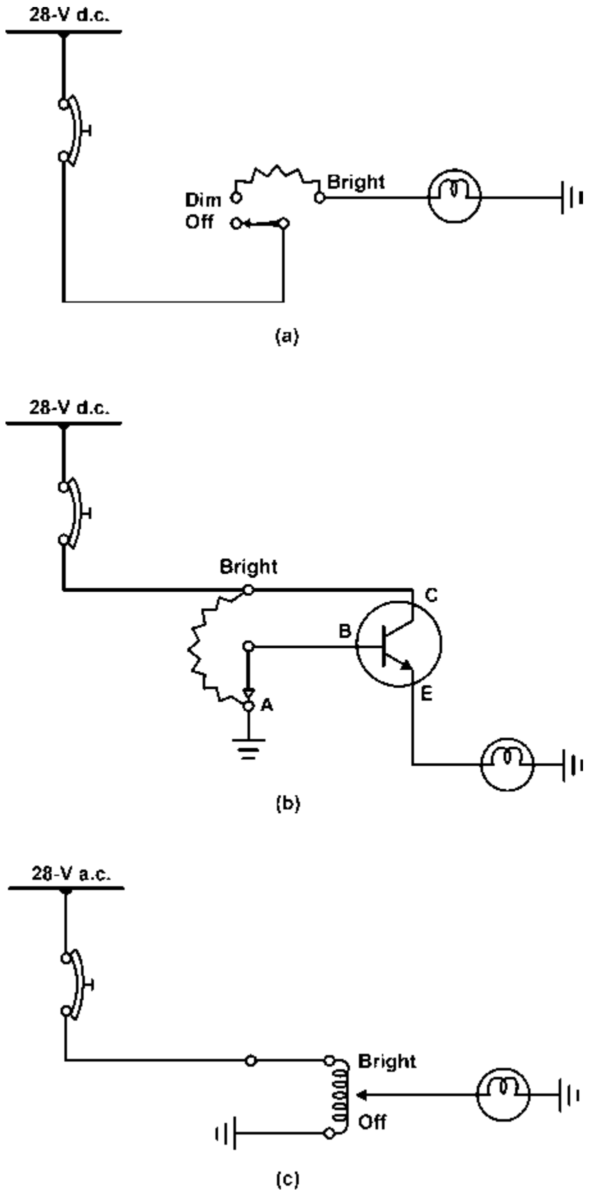

Fig. 17.10. Control of lighting intensity.

resistance in the circuit becomes less and so the lighting intensity increases. At position "C" maximum current flows through the circuit to provide maximum lighting intensity.

Diagram (b) illustrates a circuit development of the basic rheostat method and is one which is widely adopted in many aircraft since it permits the use of less "bulky" rheostats, and control of an increased number of lights in any one circuit. The circuit utilizes an NPN transistor which functions as a remotely controlled resistor unit. A rheostat is still required to vary the voltage input to the transistor, but because a transistor requires only very low voltage levels over its conducting range, the rheostat can be smaller from the point of view of electrical characteristics and physical dimensions.

D.c. power is supplied to the rheostat and also to the collector "C" of the transistor. When the rheostat wiper is at contact position "A", the voltage at the base of the transistor is zero, and no current flows through the collector to the emitter "E" or out to the lights. Movement of the wiper from contact position "A", causes a positive voltage to be applied to the base of the collector, and through the emitter to the lights as a result of a reduction in resistance of the collector-emitter junction. Further movement of the wiper increases the positive voltage at the transistor base, and the resulting decrease in collector-emitter junction resistance increases the current flow to the lights and therefore, their intensity.

Diagram (c) of Fig. 17.10, shows a method in which lighting intensity may be controlled by means of a variable transformer. This is commonly adopted in aircraft whose main power generating systems are a.c.

MAINTENANCE PRACTICES

General

Most light units and components can be maintained without the use of special tools. However, then special equipment or procedures are required to remove or install a light or component, detailed instructions will be found in the relevant aircraft Maintenance Manual. When defective filaments, lights or components are replaced, identical parts should always be used unless substitutes have been authorised. Identification details of the recommended filament and the acceptable substitutes are usually found in the relevant aircraft Maintenance Manuals. Particular attention should be paid to these manuals when maintenance Manuals. Particular attention should be paid to these manuals when maintenance is carried out on retractable landing or taxying lamps, so ensuring that the correct angular settings have been maintained. A spare filament storage area is often located within the flight deck for in-flight use. Operational check procedures for the lighting systems will be detailed in the relevant aircraft Maintenance Manual, to which reference should be made, and the information given in the following paragraphs

Checking of Lighting Components

At the specified inspection periods, or whenever the serviceability of a light or lighting system is suspect, the checks (a) to (d) should be carried out:

a. Check the component for proper installation, security of mounting, physical damage, and any evidence of overheating.
b. Check that terminal connections are secure and free from foreign matter, moisture and corrosion.
c. Check bonding connections for proper electrical contact and security.
d. Check wiring for physical damage such as chafing, fraying, damaged insulation, or contamination by harmful fluids such as hydraulic fluids, etc.

Removal and Installation of Lighting Components

Should it be necessary to remove a component of a lighting system, either as a result of a check or for the purpose of bench testing, and should special tools or equipment be require, full details will normally be found in the relevant aircraft Maintenance Manual. In the absence of such information it is recommended that the procedure of removal and installation be adopted.

Removal

a. Trip the applicable circuit breaker, or remove the appropriate fuse, to ensure electrical safety.
b. Gain access to the component.
c. Disengage from or remove the attachment parts.
   NOTE : Attachment parts are sometimes removed after disconnecting electrical connections or wiring terminals.
d. Disconnect electrical connections or wiring terminals from the component.
e. Install dust covers on plugs and receptacles, and install identification tags and insulating boots on wiring terminals.
f. Remove the component.

Installation

a. Ensure that the appropriate fuse or circuit breaker is still electrically safe.

b. Connect electrical connections or wiring terminals to component.

NOTE : Connection of electrical connections or wiring terminals is sometimes accomplished after installation of the component.

c. Position the component on its counting and install attachment parts.

d. Carry out check (by operating the appropriate switch, after re-setting of the circuit breaker or replacement of the fuse) for correct electrical operation of the circuit.

Filament Replacement

Replacement filaments should be restricted to those recommended by the aircraft manufacturer, so as to ensure the satisfactory operation of the light and to prevent damage to the circuit and circuit components.

Fluorescent Lighting

Fluorescent lighting has three general removal/replacement methods which cover the main types of light units in use. The first method is used when a fluorescent tube is retained at each end by a butt-on type tube holder which has a movable centre tab. The second method is used when the tube is retained by a spring loaded tube holder at one end and a stationary tube holder at the other end. The third method is used when the tube is rotated in the tube holder for removal and installation. With all methods, precautions are necessary to avoid damage to the tube, tube holder, and the associated ballast unit by subsequently overheating.

a. Butt-on type holders have a movable centre tube which retains the tube base pins against spring contacts. When the top of the centre tab is pressed outwards, the pins can be removed from the tube holders (see Fig. 17.11). The tube should not be rotated as this may cause damage to the pins, tube holders, and, subsequently, the ballast unit. To replace the tube, firstly check the spring contacts are in position and then press the pins at each end of the tube into the tube holders until they are secure in the contact detents.

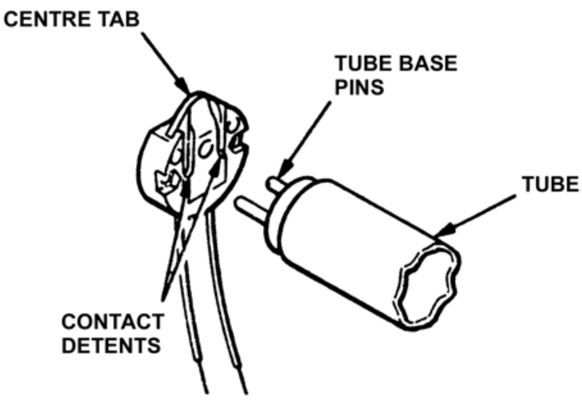

Fig. 17.11. Butt-on type tube holder.

b. To withdraw the tube from a spring-loaded tube holder opposing a stationary tube holder, apply gentle pressure with the tube towards the spring-loaded tube holder until the tube base pins on the opposite end of the tube are released from the stationary tube holder, and can be withdrawn. The tube should not be rotated during this operation, or damage may result in the same way as for the butt-on type of tube holder. To replace the tube, position the base pins in the spring-loaded tube holder (ensuring that it is not rotated) and gently apply pressure toward the spring-loaded tube holder with the tube until the pins on the opposite end of the tube can be inserted into the stationary tube holder (see Fig. 17.12).

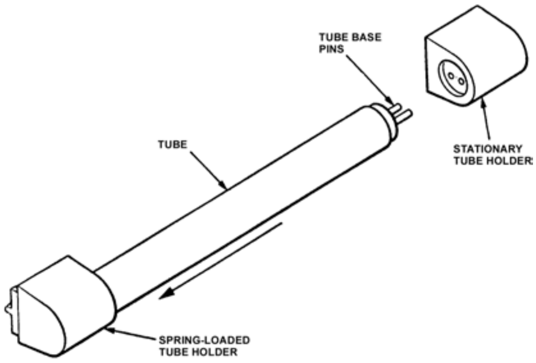

Fig. 17.12. Spring-loaded tube holder.

c. To withdraw the tube from a rotation-type tube holder, carefully rotate the tube (in either direction) until the tube base pins release from the contact detents in both tube holders, and remove the tube. To replace the tube, place the tube base pins in the tube holders and carefully rotate the tube (in either direction) until the pins engage with the contact detents.

d. When a fluorescent light ballast unit has been replaced following a failure, it is recommended that the contacts in the tube holders be checked and that the tube or tubes be replaced, so as to avoid the possibility of faulty contacts or faulty tubes causing a further of the ballast unit as a result of overheating.

Strobe Lighting

Stobe high intensity lighting can be dangerous to servicing personnel, as the energy storage capacitors are charged to voltages which can be lethal. Accordingly, a minimum of two minutes should be allowed for the capacitors to discharge after the circuit has been de-energised. In addition, it should be borne in mind that damage to the eyes may result from looking directly into high intensity light.

Plastics Fittings and Fixtures

Plastics fittings and fixtures are used extensively in aircraft lighting systems and also in the interior, trim, therefore, extreme care should be taken when handling such parts. Where possible, the use of tools should be kept to a minimum, and only gentle hand pressures should be applied when removing plastics-based trim panels, light lenses and lens covers.

Self-illuminating Signs

The only possible hazard attendant upon the use of such signs is that due to inhalation or absorption into the body of gas released in the event of breakage of the glass envelope. Tritium gas is mildly radioactive, therefore, the signs should be handled carefully to avoid breakage. Should breakage occur, the aircraft should be evacuted and all doors left open to allow maximum ventilation. Disposal of broken signs are subject to the Radioactive Substances Act 1960 and the Radioactive Substances (Luminuous Articles) Exemption Order 1962 and should, therefore, be returned to the manufacturer for disposal. All self-illuminating signs should be checked for luminosity level on initial fitting and at periods specified in the relevant maintenance schedule. Such signs usually have a scrap life of 5 years and should then be returned to the manufacturer for disposal.

Engine Starting Systems

Throughout the development of aircraft engines a number of methods of starting them have been used and the prime movers involved have varied from a mechanic manually swinging a propeller, to electric motors and electric control of sophisticated turbostarter units. Although there are still one or two types of light aircraft in service requiring the manual swinging technique, the most widely adopted starting method for reciprocating engines utilizes electric motors, while for the starting of gas turbine engines either electric motors or turbo-starter units may be utilized as the prime movers.

ELECTRIC STARTER MOTOR SYSTEMS

In basic form, these systems consist of a motor, an engaging gear, a relay and a starter switch; in some engaging gear, a relay and a starter switch; in some systems a clutch mechanism is also incorporated in the engaging gear mechanism. The motors employed may be of the plain series-field type or may be compounded with a strong bias.

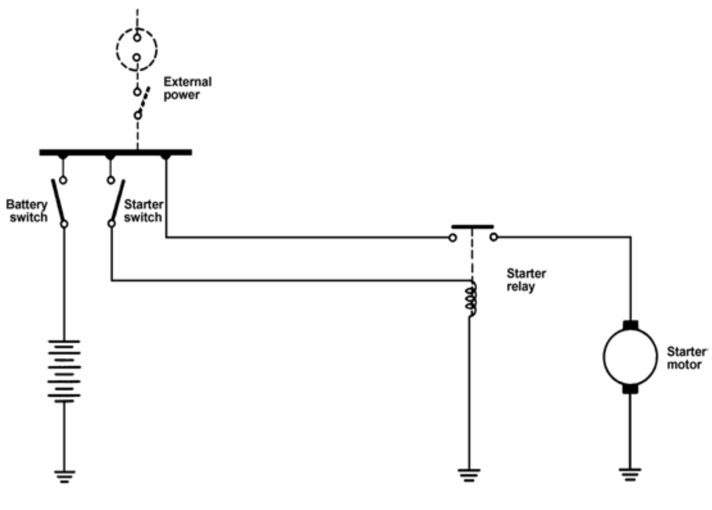

Fig. 17.13. Simple engine starting system.

Fig. 17.13 shows the interconnection of the principal electrical components typical of those required for the starting of reciprocating engines installed in many types of light aircraft. When the starter switch is closed, direct current from the battery and busbar energizes the starter relay, the closed contacts of which connect the motor to the battery. The relay contacts are of the heavy-duty type to carry the high current drawn by the motor during the period of cranking over the engine.

The method of engaging a motor with an engine varies according to the particular engine design. For most types of light aircraft engines, a pinion is engaged with a starter gear ring secured to the engine crank-shaft in a manner similar to that employed for starting automobile engines. When the engine starts, it over runs the starter motor and the pinion gets "kicked out" of engagement. In other versions used for starting more powerful engines, a jaw engages with a similar member on the engine and the drive is transmitted via a clutch and reduction gear train in the starter motor and in an accessories gearbox in the engine.

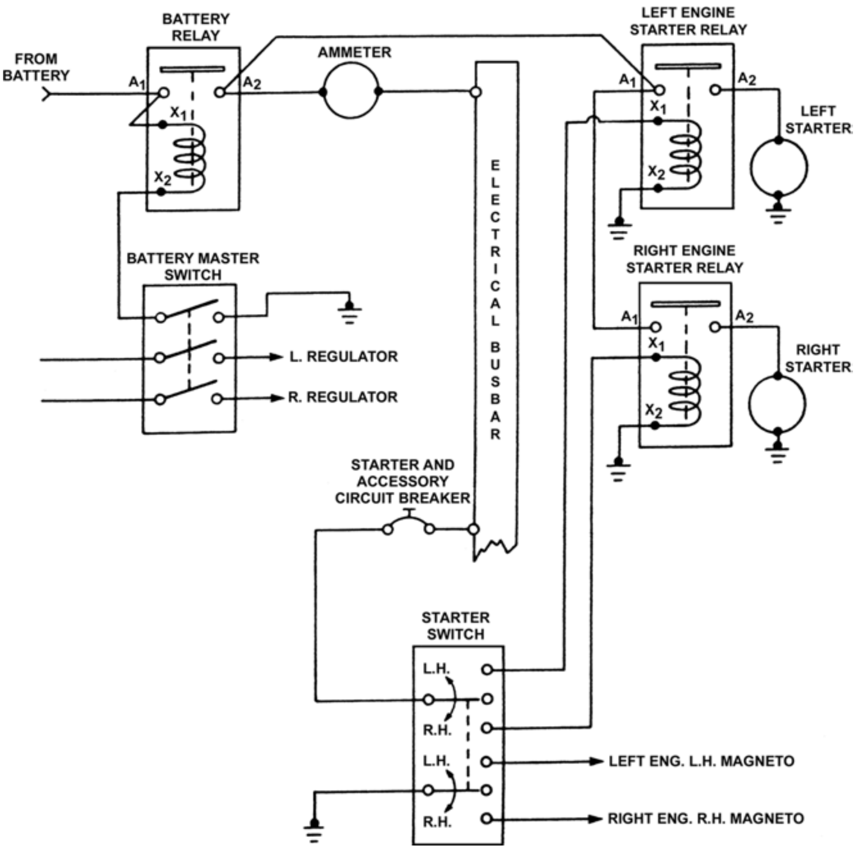

Fig. 17.14. Piper Seneca II starter system.

The gear ratio between a starter motor and a reciprocating engine is such that it provides a low cranking speed of the engine; a typical reduction ratio is about 100:1. Cranking speed is not critical because of the fuel priming provisions made in the starting drill, and also because there is a good stream of sparks available at the plug points for the power stoke. Thus, once the engine has "fired" and gets away under its own power further assistance from the starter motor is rendered unnecessary. Although the moment of inertia of an engine's moving parts is comparatively light during cranking, a starter motor has to overcome some heavy frictional loads, i.e. loads of pistons and bearings, and also loads due to compression.

Starter control systems on twin engined aircraft can vary from very simple functional systems to fairly complex fully integrated starter and ancilliary systems such as boosted magneto inputs and fuel priming systems.

Light twin aircraft, such as the Piper Aztec, have a relatively simple system, while the Cessna 421 has a much more complex type of arrangement. See (Fig. 17.14).

Operation

Power is applied from the battery to terminal A_1 on the battery relay.

The battery master switch is selected to "on". Current flows for terminal A_1 through link to X_1, through relay coil to X_2 and through the battery switch to ground. The battery relay energizes, closing contacts A_1 and A_2.

Battery power is applied through the battery relay contacts to the A_1 terminals on both starter relays and through the ammeter to the electrical busbar. Power on the busbar is available at the starter and accessory circuit breaker and through to the center terminal of the top portion of the starter switch.

Selecting starter switch to left hand position applies power to the left engine starter relay coil energizing the relay. The relay contacts close allowing power through to the left starter motor turning the engine.

During this operation, the lower portion of the starter switch is also moved to the left hand position, causing the left engines right hand magneto to be grounded through the switch. This kills the right hand magneto and only allows the left hand magneto which has the impulse coupling fitted to provide a correctly retarded spark for starting.

When the engine starts, the starter switch is released and it springs back to its centre positions de-energizing the left engine starter relay and removing the ground from the right hand magneto.

The starter motor stops, and the engine is now running on both magnetos. Operation of the starter switch to the right hand position causes the same series of events, but this time from the right engine.

Starting System Maintenance Practices

Most starting system maintenance practices include replacing the starter brushes and brush springs, cleaning dirty commutators, and turning down burned or out-of-round starter commutators.

As a rule, starter brushes should be replaced when worn down to approximately one-half of their original length. Brush spring tension should be sufficient to give brushes a good firm contact with the commutator. Brush leads should be unbroken and lead terminal screws tight.

A glazed or dirty starter commutator can be cleaned by holding a strip of double-0 sandpaper or a brush seating stone against the commutator as it is turned. The sandpaper or stone should be moved back and forth across the commutator to avoid wearing a groove. Emery paper or carborundum should never be used for this purpose because of their possible shorting action.

Roughness, out-of-roudness, or high-mica conditions are reasons for turning down the commutator. In the case of a high-mica condition, the mica should be undercut after the turning operation is accomplished.

Table 17.1 Small Aircraft Troubleshooting Procedures

PROBABLE CAUSE	ISOLATION PROCEDURE	REMEDY
Starter will not Operate :		
Defective master switch or circuit	Check master circuit.	Repair circuit
Defective starter switch or switch circuit	Check switch circuit continuity.	Replace switch or wires.
Starter lever does not activate switch.	Check starter lever adjustment.	Adjust starter lever in accordance with manufacturer's instructions.
Defective starter.	Check through items above. If another cause is not apparent, starter is defective.	Remove and repair or replace starter.
Starter Motor Runs, But Does Not Turn Crankshaft:		
Starter lever adjusted to activate switch without engaging pinion with crankshaft gear.	Check starter lever adjustment.	Adjust starter lever in accordance with manufacturer's instructions.
Defective overrunning clutch or drive.	Remove starter and check starter drive and overrunning clutch.	Replace defective parts.
Damaged starter pinion gear or crankshaft gear.	Remove and check pinion gear and crankshaft gear.	Replace defective parts.
Starter Drags :		
Low battery.	Check battery.	Charge or replace battery.
Starter switch or relay contacts burned or dirty.	Check contacts.	Replace with serviceable unit.
Defective starter.	Check starter brushes, brush spring tension for solder thrown on brush cover.	Repair or replace starter.
Dirty, worn commutator.	Clean, and check visually.	Turn down commutator.
Starter Excessively Noisy :		
Worn starter pinion.	Remove and examine pinion.	Replace starter drive.
Worn or broken teeth on crankshaft gears	Remove starter and turn over engine by hand to examine crankshaft gear.	Replace crankshaft gear.

GAS TURBINE ENGINE STARTERS

Gas turbine engines are started by rotating the compressor. On dual-axial-compressor engines, the high-pressure compressor is the only one rotated by the starter. To start a gas turbine engine it is necessary to accelerate the compressor to provide sufficient air to support combustion in the burners. Once fuel has been introduced and the engine has fired, the starter must continue to assist the engine to reach a speed above the self-accelerating speed of the engine. The torque supplied by the starter must be in excess of the torque required to overcome compressor inertia and the friction loads of the engine.

The basic types of starters which have been developed for gas turbine engines are d.c. electric motor, air turbine, and combustion. An impingement starting system is sometimes used on small engines. An impingement starter consists of jets of compressed air piped to the inside of the compressor or turbine case so that the jet air-blast is directed onto the compressor or turbine rotor blades, causing them to rotate.

The graph in (Fig. 17.15) illustrates a typical starting sequence for a gas turbine engine, regardless of the type of starter employed.

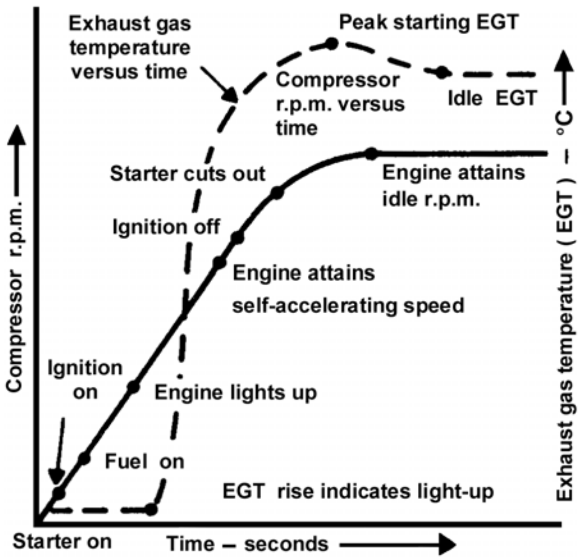

Fig. 17.15. Typical gas turbine engine starting sequence.

As soon as the starter has accelerated the compressor sufficiently to establish airflow through the engine, the ignition is turned on, and then the fuel. The exact-sequence of the starting procedure is important since there must be sufficient airflow through the engine to support combustion before the fuel/air mixture is ignited. At low engine cranking speeds, the fuel rate is not sufficient to enable the engine to accelerate, and for this reason the starter continues to crank the engine until after self-accelerating speed has been attained. If assistance from the starter were cut off below the self-accelerating speed, the engine would either fail to accelerate to idle speed, or might even decelerate because it could not produce sufficient energy to sustain rotation or to accelerate during the initial phase of the starting cycle. The starter must continue to assist the engine considerably above the self-accelerating speed to avoid a delay in the starting cycle, which would result in a hot or hung (false) start, or a combination of both. At the proper points in the sequence, the starter and usually the ignition will be automatically cut off.

Electric Starting Systems
Electric starting systems for gas turbine aircraft are of two general types:
1. Direct-cranking electrical systems and
2. Starter-generator systems.

Direct-cranking electric starting systems are similar to those used on reciprocating engines. Starter-generator starting systems are also similar to direct-cranking electrical systems. Electrically, the two systems may be identical, but the starter-generator is permanently engaged with the engine shaft through the necessary drive gears, while the direct-cranking starter must employ some means of disengaging the starter from the shaft after the engine has started.

Direct-Cranking Gas Turbine Starters
On some direct-cranking starters used on gas turbine engines no overload release clutch or gear reduction mechanism is used. This is because of the low torque and high speed requirement for starting gas turbine engines. A reduced voltage mechanism is utilized, however, in the starting systems to prevent damage to the engaging assembly during starting.

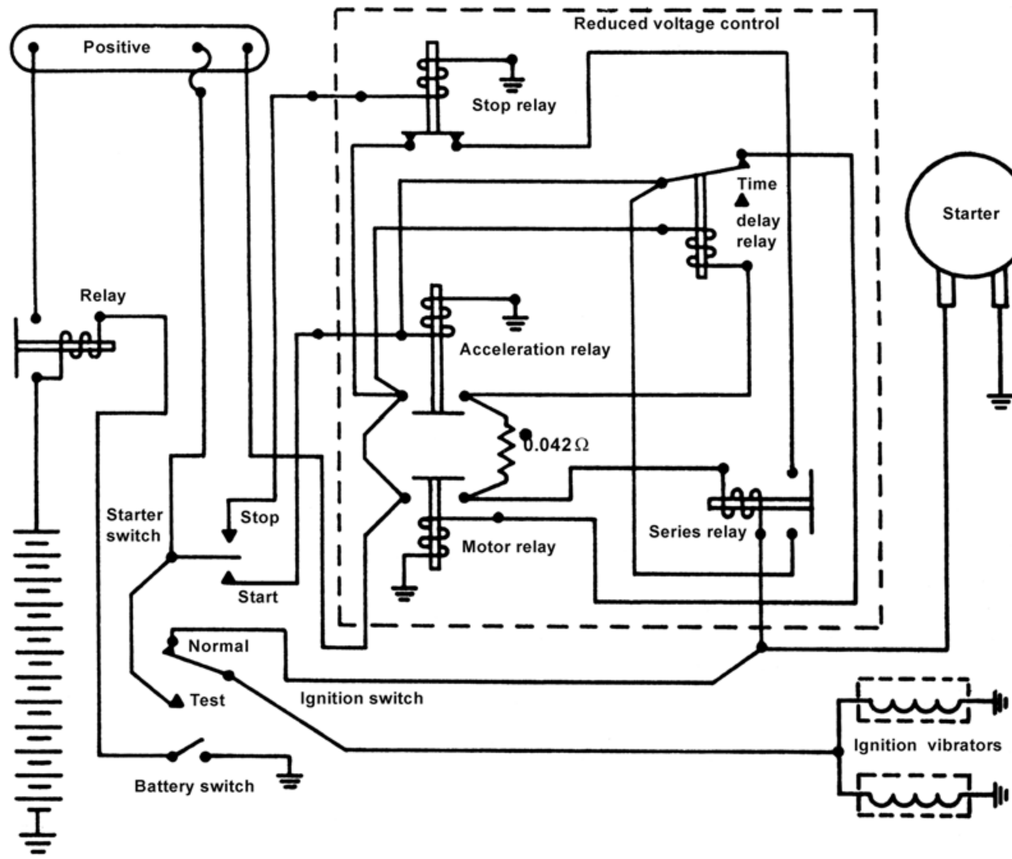

Fig. 17.16. Reduced voltage control circuit for gas turbine, direct-cranking starting system.

Fig. 17.16 shows the circuit os a reduced voltage control. The mechanism is mounted in an explosion-proof housing which contains five relays and a 0.042-ohm resistor. When the battery switch is closed, the time-delay relay coil is energized. The ground circuit for the coil of this relay is completed through the starter.

When the starter switch is moved to the start position, a circuit is completed to the coil of the acceleration relay. The closed relay contacts complete a circuit from the bus through the closed contacts, the 0.042-ohm resistor, the series relay coil, and finally through the starter motor to ground. Since the 0.042-ohm resistor causes a voltage drop, low voltage is applied to the starter motor and damage from an otherwise high torque is prevented. The time-delay relay returns to its normal "closed" position since no difference in potential exists between the time-delay relay coil terminals with the acceleration relay contacts closed.

The closed time-delay relay completes a circuit to the motor relay coil (Fig. 17.16). With the motor relay energized, a complete circuit exists through the relay and the series relay coil to the starter, by passing the 0.042-ohm resistor.

When current of 200 amperes or more flows to the starter, the series relay coil is energized sufficiently to close the series relay contacts. The starter switch may then be allowed to return to its normal "off" position because the starter circuit is complete through the stop relay and the series relay contacts to the motor relay coil.

As the starter motor increases in r.p.m., a counter-electromotive force builds up enough to allow the series relay to open and break the circuit to the motor relay. Therefore, the starting period is controlled automatically by the speed of the starter motor.

Starter-Generator Starting System

Many gas turbine aircraft are equipped with starter-generator systems. These starting systems use a combination starter-generator which operates as a starter motor to drive the engine during starting; and, after the engine has reached a self-sustaining speed, operates as a generator to supply the electrical system power.

The starter-generator unit, shown pictorially and schematically in (Fig. 17.17), is basically a shunt generator with an additional heavy series winding. This series winding is electrically connected to produce a strong field and a resulting high torque for starting.

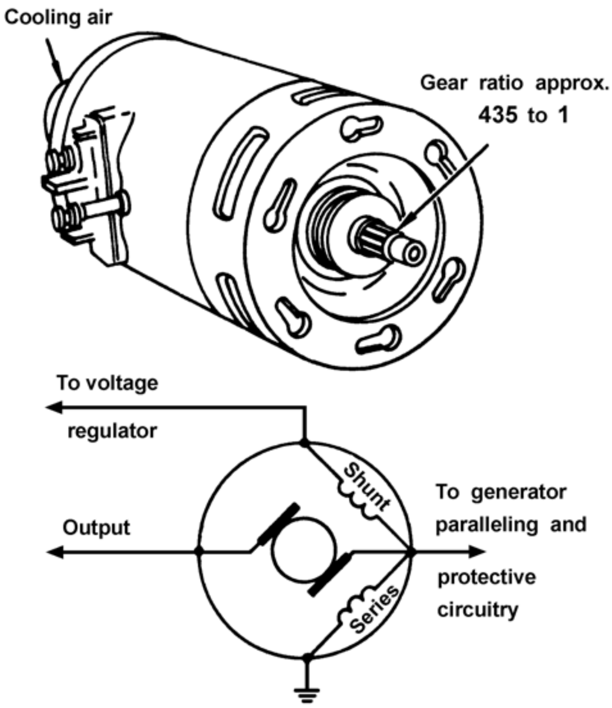

Fig. 17.17. Typical starter-generator.

Starter-generator units are desirable from an economical standpoint, since one unit performs the functions of both starter and generator. Additionally, the total weight of starting system components is reduced, and fewer spare parts are required.

The starter-generator internal circuit shown in (Fig. 17.18) has four field windings: (1) A series field ("C" field), (2) a shunt field, (3) a compensating field, and (4) an interpole or commutating winding. During starting, the series (C" field), compensating, and commutating windings are used. The unit is similar to a direct-cranking starter since all of the windings used during starting are in series with the source. While acting as a starter, the unit makes no practical use of its shunt field. A source of 24 volts and 1,500 amperes is usually required for starting.

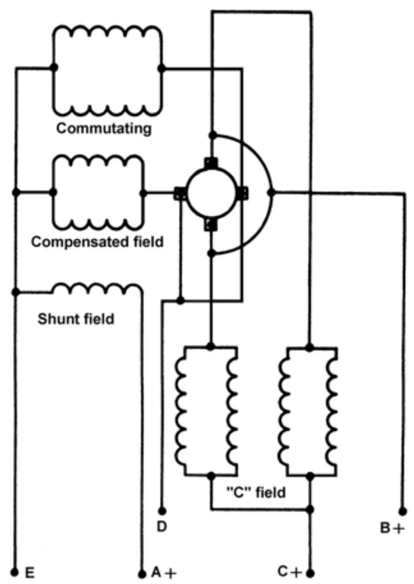

Fig. 17.18. Starter-generator internal circuit.

When operating as a generator, the shunt, compensating and commutating windings are used. The "C" field is used only for starting purposes. The shunt field is connected in the conventional voltage control circuit for the generator. Compensating and commutating (interpoles) windings provide almost sparkless commutation from no load to full load.

Fig. 17.19 illustrates the external circuit of a starter-generator with an undercurrent controller. This unit controls the starter-generator when it is used as a starter. Its purpose is to assure positive action of the starter and to kept it operating until the engine is rotating fast enough to sustain combustion. The control block of the undercurrent controller contains two relays; one is the motor relay, which controls the input to the starter. The other, the undercurrent relay, controls the operation of the motor relay.

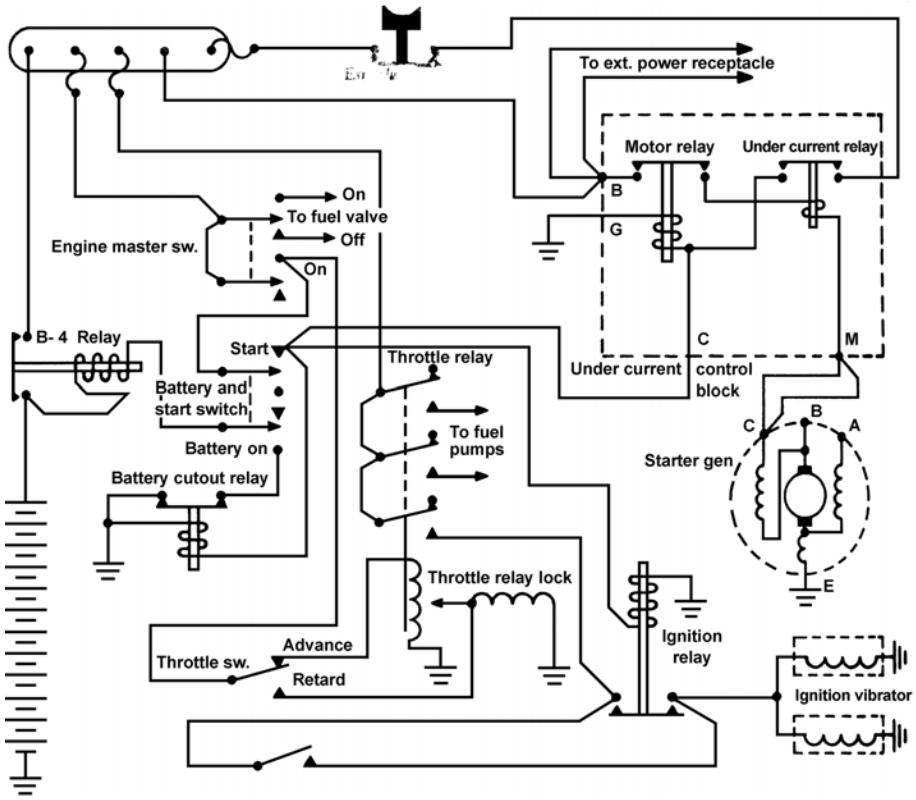

Fig. 17.19. Starter-generator circuit.

The sequence of operation for the starting system shown in (Fig. 17.19) is discussed in the following paragraphs.

To start an engine equipped with an undercurrent relay, it is first necessary to close the engine master switch. This completes the circuit from the aircraft's bus to the start switch, to the fuel valves, and to the throttle relay. Energizing the throttle relay starts the fuel pumps, and completing the fuel valve circuit gives the necessary fuel pressure for starting the engine.

As the battery and start switch is turned on, three relays close. They are the motor relay, the ignition relay, and the battery cutout relay. The motor relay closes the circuit from the power source to the starter motor; the ignition relay closes the circuit to the ignition units; (Opening the battery circuit is necessary because the heavy drain of the starter motor would damage the battery).

Closing the motor relay allows a very high current to flow to the motor. Since this current flows through the coil of the undercurrent relay, it closes. Closing the undercurrent relay complete a circuit from the positive bus to the motor relay coil, ignition relay coil, and battery cutout relay coil. The start switch is allowed to return to its normal "off" position, and all units continue to operate.

As the motor builds up speed, the current draw of the motor begins to decrease, and as it decreases to less than 200 amps, the undercurrent relay opens. This action breaks the circuit from the positive bus to the coils of the motor, ignition, and battery cutout relays. The de-energizing of these relay coils halts the start operation.

After the procedures described are completed, the engine should be operating efficiently and ignition should be self-sustaining. If, however, the engine fails to reach sufficient speed to halt the starter operation, the stop switch may be used to break the circuit from the positive bus to the main contacts of the undercurrent relay.

On a typical installation, one starter-generator is mounted on each engine gearbox. During starting, the starter-generator unit functions as a d.c. starter motor until the engine has reached a predetermined self-sustaining speed. Aircraft equipped with two 24-volt batteries can supply the electrical load required for starting by operating the batteries in a series configuration.

The following description of the starting procedure used on a four-engine turbojet aircraft equipped with starter - generator starting systems.

Starting power, which can be applied to only one starter-generator at a time, is connected to a terminal of the selected starter-generator through a corresponding starter relay. Engine starting is controlled from an engine start panel. A typical start panel contains the following switches: an engine selector switch, a power selector switch, an air start switch, and a start switch.

The engine selector switch shown in (Fig. 17.20) has five positions ("1," "2," "3," "4," and "OFF") and is turned to the position corresponding to the engine to be started. The power selector switch is used to select the electrical circuit applicable to the power source (ground power unit or battery) being used. The air-start switch, when placed in the "NORMAL" position, arms the ground starting circuit. When placed in the "AIR START" position, the igniters can be energized independently of the throttle ignition switch. The start switch when in the "START" position completes the circuit to the starter-generator of the engine selected to be started, and causes the engine to-rotate. The engine start panel shown also includes battery switch. When an engine is selected with the engine selector switch, and the start switch is held in the "START" position, the starter relay corresponding to the selected-engine is energized and connects that engine's starter-generator to the starter bus. When the start switch is placed in the "START" position, a start lock-in relay is also emergized. Once energized, the start lock-in relay provides its own holding circuit and remains energized providing closed circuits for various start functions.

An overvoltage lockout relay is provided for each starter-generator. During ground starting, the overvoltage lockout relay for the selected starter-generator is energized through the starting control circuits. When an overvoltage lockout relay is energized, overvoltage protection for the selected starter-generator is suspended. A bypass of the voltage regulator for the selected starter-generator is also provided to remove undesirable control and resistance from the starting shunt field.

On some aircraft a battery lockout switch is installed in the external power receptacle compartment. When the door is closed, activating the switch, the ground starting control circuits function for battery starting only. When the door is open, only external power ground starts can be accomplished.

A battery series relay is also a necessary unit in this starting system. When energized, the battery series relay connects the two 24-volt batteries in series to the starter bus, providing an initial starting voltage of 48 volts. The large voltage drop which occurs in delivering the current needed for starting reduces the voltage to approximately 20 volts at the instant of starting. The voltage gradually increases as starter current decreases with engine acceleration and the voltage on the starter bus eventually approaches its original maximum of 48 volts.

Some multi-engine aircraft equipped with starter generators include a parallel start relay in their starting system. After the first two engines of a four-engine aircraft are started, current flow for starting each of the last two engines passes through a parallel start relay which shifts the battery output from series to parallel. When starting the first two engines, the starting power requirement necessitates connecting the two batteries in series. After two or more engine generators are providing power, the combined power of the batteries in series is not required. Thus, the battery circuit is shifted from series to parallel when the parallel start relay is energized.

To start an engine with the aircraft batteries, the start switch is placed in the "START" position (Fig.17.20). This completes a circuit through a circuit breaker, the throttle ignition switch, and the engine selector switch to energize the start lock-in relay. Power then has a path from the start switch through the "BAT START" position of the power selector switch to energize the battery series relay, which connects the aircraft batteries in series to the starter bus.

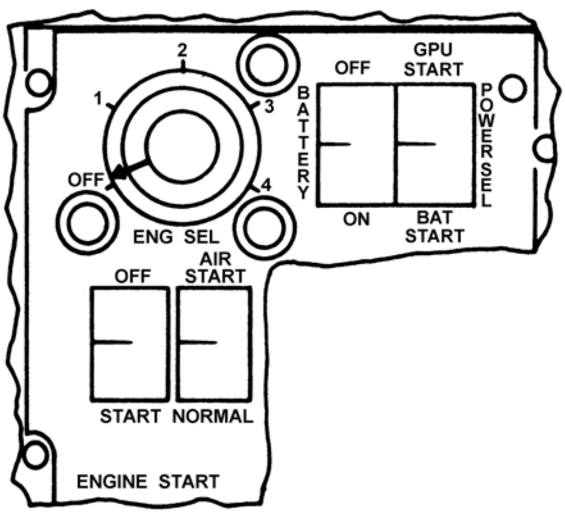

Fig. 17.20. Engine start panel.

Energizing the No.1 engine's starter relay directs power from the starter bus to the No.1 starter-generator, which then cranks the engine.

At the time the batteries are connected to the starter bus, power is also routed to the appropriate bus for the throttle ignition switch. The ignition system is connected to the starter bus through an overvoltage relay which does not become energized until the engine begins accelerating and the starter bus voltage reaches about 30 volts.

As the engine is turned by the starter to approximately 10% r.p.m., the throttle is advanced to the "IDLE" position. This action actuates the throttle ignition switch, energizing the igniter relay. When the igniter relay is closed, power is provided to excite the igniters and fire the engine.

When the engine reaches about 25 to 30% r.p.m., the start switch is released to the "OFF" position.

This removes the start and ignition circuits from the engine start cycle, and the engine accelerates under its own power.

Troubleshooting a Starter-Generator Starting System

The procedures listed in Table 17.2 are typical of those used to repair malfunctions in a starter-generator starting system similar to the system described in this section. These procedures are presented as a guide only. The appropriate manufacturer's instructions and approved maintenance directives should always be consulted for the aircraft involved.

Table 17.2 Starter-Generator Starting System Troubleshooting Procedures

PROBABLE CAUSE	ISOLATION PROCEDURE	REMEDY
Engine Does Not Rotate During Start Attempt		
Low supply voltage to the starter.	Check voltage of the battery or external power source.	Adjust voltage of the external power source or charge batteries.
Power switch is defective.	Check switch for continuity.	Replace switch.
Ignition switch in throttle quadrant.	Check switch for continuity.	Replace switch.
Sart-lockout relay energized.	Check position of generator control switch.	Place switch in "OFF" position.
Battery series relay is defective.	With start circuit energized, check for 48 volts d.c. across battery series relay coil.	Replace relay if no voltage is present.
Starter relay is defective.	With start circuit energized, check for 48 volts d.c. across starter relay coil.	Replace relay if no voltage is present.
Defective starter.	With start circuit energized, check for proper voltage at the starter.	If voltage is present, replace the starter.
Start lock-in relay defective	With start circuit energized, check for 28 volts d.c. across the relay coil.	Replace relay if voltage is not present.
Starter drive shaft in component drive gearbox is sheared.	Listen for sounds of starter rotation during an attempted start. If the starter rotates but the engine does not, the drive shaft is sheared.	Replace the engine.
Engine Starts But Does Not Accelerate To Idle		
Insufficient starter voltage.	Check starter terminal voltage	Use larger capacity ground power unit or charge batteries.
Engine Fails To Start When Throttle Is Placed In Idle		
Defective ignition system.	Turn on system and listen for spark-igniter operation.	Clean or replace spark igniters, or replace exciters, or leads to igniters.

Fig. 17.21 illustrates the circuit diagram of a system based on that employed in a current type of twin turbopropeller aircraft for the starting of its engines. The starter motor is a 28-volt d.c. four-pole compound-wound machine having a torque output of 16.5 1bf.ft (22.37 Newton metre) at a speed of 3800 rev/min and a time rating of 90 seconds. It drives the engine through a clutch, pawl mechanism and reduction gear. The clutch is held in the driving position until the engine has accelerated above the starter motor speed and until the centrifugal force acting on the pawl mechanism is sufficient to release the pawls. The starter motor is disengaged by the action of an overspeed relay.

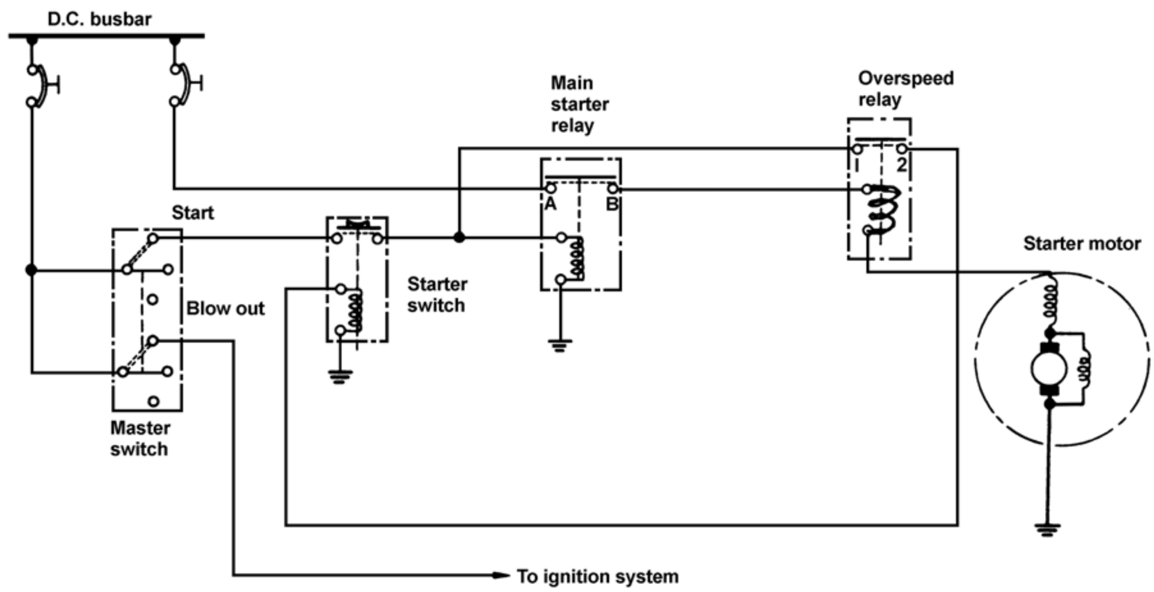

Fig. 17.21. Basic circuit of a turboprop engine starting system.

When the master switch is set to the "start" position, and the starter push switch is depressed, direct current flows through the coil of the main starter relay thereby energizing it. At the same time current also flows to contacts "A" and "B" of the starter relay completes a circuit from the main busbar to the starter motor via the coil of the over speed relay, which on being energized, allows current to flow across its contacts to the coil of the push switch thereby holding this switch closed. During initial stages of starting the current drawn by the starter motor is high, and as this is carried by the coil of the overspeed relay continued cranking of the engine is assured. As the engine accelerates, the starter motor draws less current until, at a value predetermined by the speed at which the engine becomes self-sustaining, the overspeed relay is de-energized, this in turn de-energizing the starter switch and main starter relay. The overspeed relay therefore prevents the starter motor from overspeeding ensuring that the power supply is disconnected before the starter drive is disengaged from the engine.

The purpose of the "blow out" position of the master switch is to permil the engine to be cranked over in order to blow out unburnt fuel resulting from an unsuccessful start or "light up". When the position is selected, the circuit is operated in a similar manner to normal starting except that the starter switch must be pulled to the "off" position after the motor has been running for 30 seconds. The reason for this is that since the ignition system is isolated, the starter motor is still heavily the overspeed relay remains too high for the relay to be-energize of its own accord.

TURBO-STARTER SYSTEMS

With the development of more powerful turbine engines ever-increasing power output from starter systems was required for effective starting action. As far as electrical methods of starting were concerned this presented incresingly difficult problems associated notably with high current demand, increased size and weight of motors and cables. These problems therefore led to the discontinuance of electric motors for the starting of powerful engines, and their functions were taken over by turbo-starter systems requiring a simpler control circuit consuming only a few amperes.

There are three principal types of turbo-starter systems; air, cartridge and monofuel, the application of each being governed largely by the operational role of the aircraft, i.e. civil or military. The basic principle is the same for each system, that is, a gas is made to impinge on the blades of a turbine rotor within the starter unit, thereby producing the power required to tun the engine shaft via an appropriate form of coupling.

The gas may be (i) compressed air supplied to a turbine air motor from either an external supply unit, an A.P.U. in the aircraft or the compressor of a running engine; (ii) the cordite discharge from an electrically fired cartridge or (iii) the result of igniting a monofuel, in other words a fuel which burns freely without an oxidant such as air; typical fuel is isoprophylnitrate.

The electrical control circuits normally require d.c. for their operation, their function being to energize solenoid-operated air control valves to fire cartridge units and to energize a fuel pump motor and ignition systems as appropriate to the type of turbo-starter unit.

Ignition Systems

All types of aircraft engines are dependent on electrical ignition systems. In reciprocating-type engines, the charges of fuel vapour and air which are induced and compressed in the cylinders, are ignited through the medium of sparks produced by electric discharges across the gaps between the electrodes of a spark plug fitted in each cylinder, and continuous series of high-voltage electrical impulses, separated by inervals which are related to engine speed, must be made available to each of the plugs throughout the period the engine is running. A basically similar electrical ignition system is also used to initiate combustion of the fuel/air mixture in the combustion chambers of gas turbine engines. It is, however, of much simpler form for the reasons that impulse intervals are not related to engine speed, and as combustion is continuous after "light up", the ignition system is only required during the starting period.

Reciprocating-type engine ignition systems fall into one or other of two main categories; coil ignition and magneto ignition. The former derives its power from an external source, e.g. the main power supply, while the magneto is a self-contained unit driven by the engine and supplying power from its own generator. In aircraft engine applications, magneto ignition is the system most commonly adopted.

BASIC PRINCIPLES OF A MAGNETO

A magneto consists basically of two parts, i.e. a generator and a transformer. It is based on the principles of electromagnetic induction summarised below.

When a conductor is moved through a magnetic field in such a way as to cut the lines of magnetic force, an electro-motive force (e.m.f.) is induced in that conductor. If the conductor circuit is closed then an electric current will flow.

Any conductor carrying an electric current generates a magnetic field concentric with the conductor, the strength of the field depending on the strength of the current.

Any change of magnetism, no matter how caused, when acting upon a coil of wire, induces into that wire an electric current. The strength of that current will depend on :-

(i) Strength of the magnet.
(ii) Rate of change of magnetism.
(iii) Number of turns of wire in the coil.

In a normal magneto two coils of insulated wire are wound round a soft iron core. The first or "primary" coil consists of a small number of turns (approximately 200) of relatively thick wire and the second or "secondary" coil consists of a large number of turns (approximately 10,000) of very fine wire. The soft iron core is subjected to an alternating magnetic flux either by being rotated between the poles of a permanent magnet or by the rotation of a magnet between suitably shaped shoes attached to the core. As the turns are cut by the magnetic flux a low voltage is induced in the primary coil, the current and therefore the magnetic field produced by it, being greatest when the rate of change of magnetic flux is greatest. At this point the primary circuit is the rate of change of magnetic flux is greatest. At this point the primary circuit is broken and the magnetic field collapses round the secondary coil producing a high voltage current which is directed by a suitable conductor to the centre electrode of the sparking plug.

NOTE : Although an e.m.f. is built up in the secondary coil when the magnetic flux is increasing in the core, it is the rapid collapse of the magnetic field which produces the high voltage necessary to produce a spark at the sparking plug points.

CONSTRUCTION OF A MAGNETO

Although the basic principle of operation of all magnetos is similar, the construction may vary considerably. They can, however, be divided basically into two types, i.e. the rotating armature magneto and the rotating magnet magneto.

The Rotating Armature Magneto

The assembly of the primary and secondary coils on a soft iron core discussed in paragraph 2 is known as the "armature". In the rotating armature magneto this is mounted on a shaft driven from the engine and rotated between the poles of a permanent magnet (Fig. 17.22). As only two sparks are produced for each revolution of the armature, this type of magneto is normally used only on engines with up to six cylinders.

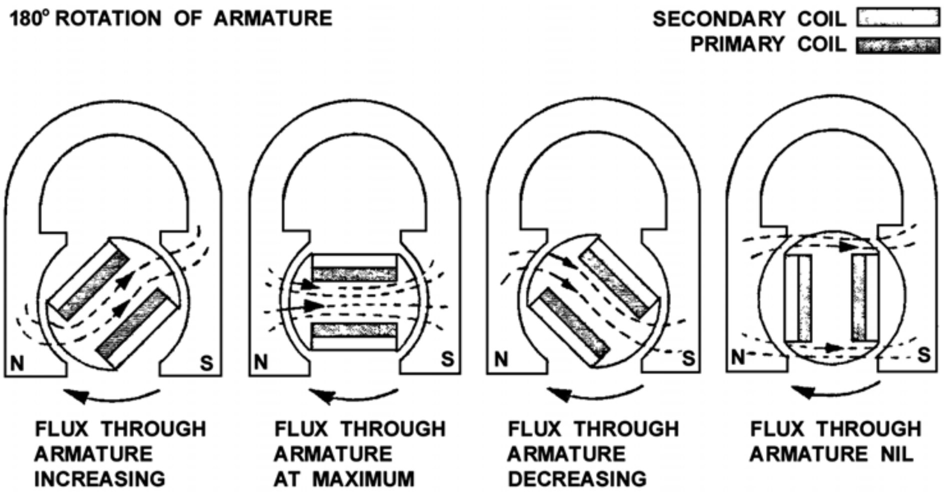

Fig. 17.22. Flux change in rotating armature magneto.

The Rotating Magnet Magneto

The most usual type of "rotating magnet magneto" is the "polar inductor magneto" where the permanent magnets are actually stationary and soft iron inductors, mounted on a non-magnetic shaft driven from the engine, are used to guide the magnetic flux through the armature (Fig. 17.23 and Fig. 17.24). Four sparks are produced for each revolution of the inductor shaft, making this type of magneto suitable for use on engines with more than six cylinders.

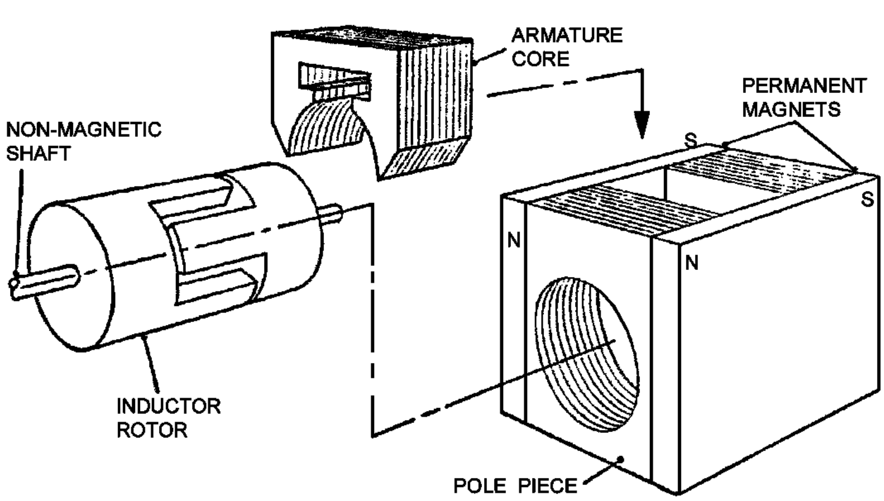

Fig. 17.23. Polar Inductor Magneto.

MAIN COMPONENT OF A MAGNETO

The Armature

The armature consists of a soft iron core around which the primary and secondary coils are wound. With a rotating armature a means of transferring the electrical current to the static part of the magneto circuit, such as carbon brushes operating in slip rings, is provided. The armature core is usually laminated to reduce the build up of heat.

The Contact-Breaker

The contact-breaker is a mechanically operated switch which is timed to break the primary circuit when induced current in the primary coil is at a maximum.

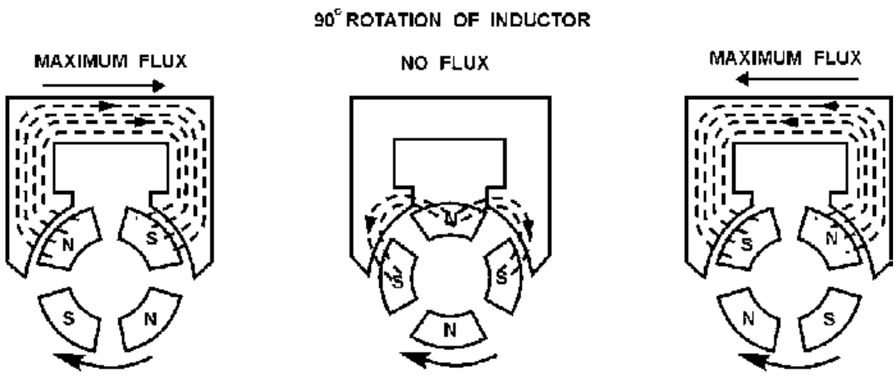

Fig. 17.24. Flux change in a polar inductor magneto.

On one type of rotating armature magneto, the contact-breaker is usually keyed on to the end of the armature shaft and rotates within a cam ring which is located concentrically round the shaft. As the contact-breaker assembly rotates, the breaker arm strikes each of the two cams is turn and breaks the primary circuit at the required moments.

On the polar inductor magneto, the contact-breaker assembly is normally stationary and the breaker arm is operated by a cam wheel attached directly to the distributior rotor. A separate cam lobe is provided for each of the engine cylinders.

The Condenser

The purpose of the condenser is to absorb the e.m.f. which tends to cause a spark to jump across the contact-breaker points as they begin to open. It ensures that the magnetic field collapses quickly and prevents rapid deterioration of the contact-breaker points due to arcing.

The Permanent Magnet

The magnet provides the necessary magnetic field to induce a current in the primary windings. Modern magnets are extremely powerful and are usually made from an alloy of aluminium, nickel and cobalt.

The Distributor

The purpose of the distributor is to ensure that the high voltage impulses produced in the secondary coil are conducted to the sparking plug in the appropriate engine cylinder in accordance with the firing order of the engine. Ignition of the gases is required in each engine cylinder once in every two revolutions of the crankshaft, thus the distributor has a segment for each cylinder arranged in firing order sequence and the rotating distributor arm is driven at half engine speed.

The distributor is usually an integral part of the magneto, the rotor being gear driven from the main magneto shaft. On some engines, however, the distributor assembly is remote from the rotor is driven from an engine gear train or from a camshaft (which also rotates a half engine speed).

As sparking between the rotor and segments in the distributor is essential, the distributor casing is vented to prevent ionisation. The vent is fitted with a flameproof wire mesh screen to prevent combustion of inflammable gases round the engine.

Impulse Starters

During an engine starting sequence the magnetos are rotating only slowly and are not producing a strong enough spark to ensure combustion. Either one or both manetos may be fitted with an impulse starter to overcome this failing. In one type of magneto fitted with an impulse starter, the drive from the engine to the armature shaft is through a spring loaded clutch device which flicks the armature through the positions at which a spark normally occurs, thus momentarily increasing the rate of rotation and the voltage generated. Once the engine is running, centrifugal weights in the impulse coupling overcome the springs and it operates as a normal "solid" drive shaft.

Safety Spark Gap

On some early magnetos a safety spark gap (see Fig. 17.25) provide a means of discharging the secondary impulse to earth. It was provided to prevent damage to the armature in the event of a plug lead becoming detached.

Booster Coils

Where no impulse starter magneto is fitted, the weak spark produced during engine starting is supplemented by means of a booster coil, which takes its power from the aircraft batteries or external power supply, and is connected either to a booster coil switch or the engine starter switch.

High tension booster coils supply a "stream" of high tension impulses to a secondary or "trailing" brush in the distributor rotor arm which, due to its position, automatically retards the ignition timing.

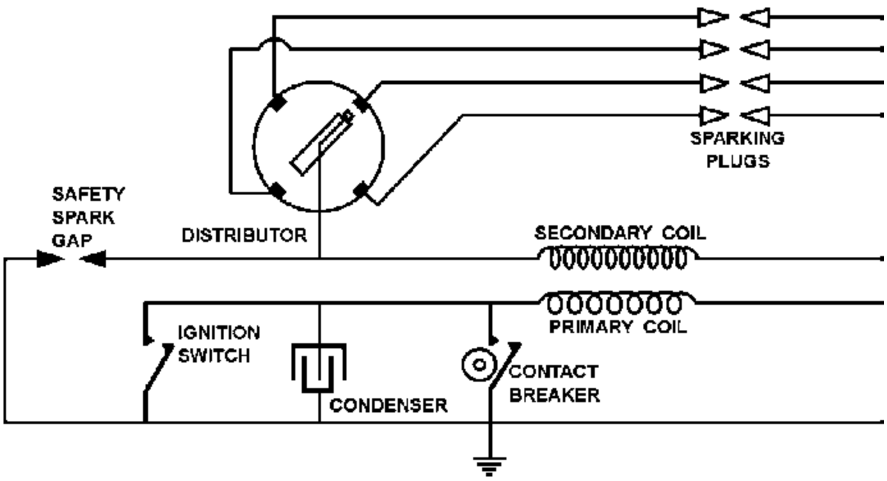

Fig. 17.25. Typical Ignition Circuit.

Low tension booster coils supply a stream of low tension impulses to the armature primary windings either to augment or replace the voltage induced in the primary windings by the magnetic flux. On one type of magneto a second contact-breaker, retarded in relation to the main contact-breaker but connected in parallel with it, controls the supply of intermittent current from a low tension booster coil to the armature primary windings. Intermittent high tension current is therefore induced in the secondary coil and a stream of high tension impulses distributed to the sparking plugs.

Ignition Switches

Whenever a magneto is rotated sufficiently to open the contact-breaker points a spark will occur. All magnetos are therefore provided with an earthing wire, which is connected to the contact-breaker end of the primary coil and through a suitable switch to earth. Since this switch is connected in parallel with the contact-breaker, with the switch closed the effect of the opening and closing of the contact-breaker is by-passed and no spark can occur.

Some aircraft are provided with a separate toggle switch to control each magneto, the primary circuit being earthed when the switch is down. Many modern aircraft however are provided with a rotary four-position switch controlling both magnetos. A spring loaded position may also be provided for engine starter operation.

The rotating portion of a magneto is driven by the engine through a coupling and an accessory gear drive shaft. As the windings are cut by the alternating magnetic flux from the appropriate source, a low voltage is induced in the primary winding to produce a current and flux of a strength directly proportional to the rate at which the main flux is cut. At this point the primary circuit is broken by the contact breaker, the contacts, or points, of which are opened by a cam driven by the rotating assembly. The primary flux therefore collapses about the secondary winding, which produces a high voltage output. The output is, low-ever, not sufficient to produce the required discharge at the spark plugs and it is necessary to speed up the rate of flux collapse. This is effected by connecting a capacitor across the contact breakers so that the capacitor is shorted out when the breaker points are closed and is charged by primary winding current when the points are open. When the potential difference across the capacitor reaches the point whereby it discharges itself, the correspondingly high current flows through the primary winding in the reverse direction and thereby rapidly suppresses the primary flux to produce the required higher secondary output voltage. In addition to this function, the capacitor also prevents arcing between the contact breaker points as they begin to open, thereby preventing rapid deterioration of the points.

The secondary winding output is supplied to the distributor, the purpose of which is to ensure that the high voltage impulses are conducted to the sparking plugs in accordance with the order in which combustion must take place in each cylinder, i.e. the "firing" order of the engine. A distributor consists of two main parts, a rotor made up of an insulating material containing conducting segments corresponding in number to the number of cylinders on the engine. The conducting segments are located circumferentially around the distributor block in the desired flring order, so that as the rotor turns a circuit is completed to a sparking plug each time there is alignment between the rotor and a segment.

Distributors usually form part of magnetos, and the rotors are rotated at the required speed by a gear driven from the main magneto shaft. In some cases, however, distributors may be separate units driven by an engine gear train and drive shaft. To prevent ionization, and to minimize "floashover", the distributor casing is vented to atmosphere, and in many types of magnet a flameproof wire mesh screen is provided to prevent combustion of any flammable vapours round the engine.

MAGNETO AND DISTRIBUTOR SPEEDS

Ignition of the combustible mixture in each cylinder once in every two revolutions of the engine crankshaft, and as a result there must be a definite relationship between such factors as the number of sparks produced by a magneto and the speeds of the magneto, distributor and engine. Magneto speed may be calculated from the relation:

$$\frac{\text{number of cylinders}}{2 \times \text{magneto sparks per rev.}}$$

A rotating armature magneto, which is normally only used on engines having up to six cylinders, produces two sparks per rev. Thus, assuming that one is fitted to a four-cylinder engine then it must be driven at the same speed as the engine. A rotating magnet or polar inductor magneto produces four sparks per rev and is normally used on engines having more than six cylinders. Thus, for a twelve-cylinder engine the magneto must be driven at one and a half times the engine speed. Distributor rotors are driven at half engine speed irrespective of magneto speed.

SPARK PLUGS

The function of the spark plug in an ignition system is to conduct a short impulse of high voltage current through the wall of the combustion chamber. Inside the combustion chamber it provides an air gap across which this impulse can produce an electric spark to ignite the fuel/air charge. While the aircraft spark plug is simple in construction and operation, it is nevertheless the direct or indirect cause of a great many malfunctions in aircraft engines. But spark plug provide a great deal of trouble-free operation, considering the adverse conditions under which they operate.

In each cylinder of an engine operating at 2,100 r.p.m., approximately 17 separate and distinct high voltage sparks bridge the air gap of a single spark plug each second. This appears to the naked eye as a continuous fire searing the spark plug electrodes at temperatures of over 3,000^{o}F. At the same time the spark plug is subjected to gas pressures as high as 2,000 p.s.i. and electrical pressure as high as 15,000 volts.

The three main components of a spark plug (Fig. 17.26) are the electrode, insulator, and outer shell. The outer shell, threaded to fit into the cylinder, is usually made of finely machined steel and is often plated to prevent corrosion from engine gases and possible thread seizure. Close-tolerance screw threads and a copper gasket prevent cylinder gas pressure from escaping around the plug. Pressure that might escape through the plug is retained by inner seals between the outer metal shell and the insulator, and between the insulator and the center electrode assembly.

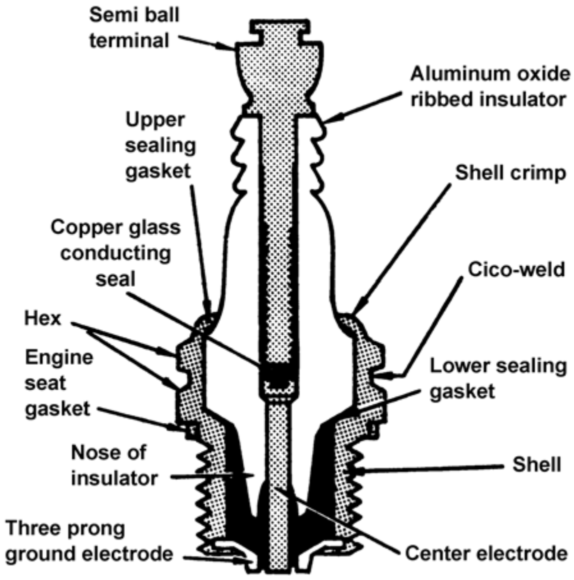

Fig. 17.26. A typical spark plug.

The insulator provides a protective core around the electrode. In addition to affording electrical insulation, the ceramic insulator core also transfers heat from the ceramic tip, or nose, to the cylinder.

The types of spark plugs used in different engines vary in respect to heat, range, reach, thread, thread size, or other characteristics of the installation requirements of different engines.

The heat range of a spark plug is a measure of its ability to transfer heat to the cylinder head. The plug must operate hot enough to burn off deposits which can cause fouling, yet remain cool enough to prevent a preignition condition. The length of the nose core is the principal factor in establishing the plug's heat range. "Hot" plugs have a long insulator nose that creates a long heat transfer path, shereas "cold" plugs have a relatively short insulator to provide a rapid transfer of heat to the cylinder head (Fig. 17.27).

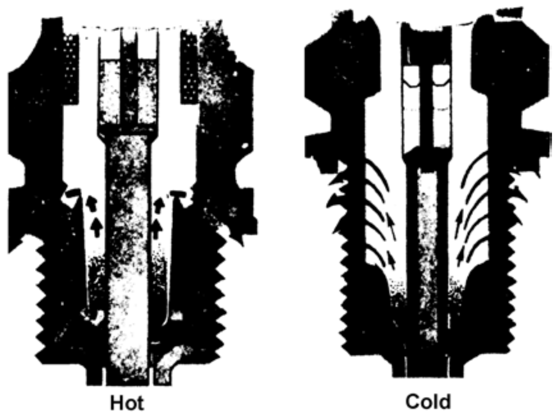

Fig. 17.27. Hot and cold spark plugs.

If an engine were operated at only one speed, spark plug design would be greatly simplified. Because flight demands impose different loads on the engine, spark plugs must be designed to operate as hot as possible at slow speeds and light loads, and as cool as possible at slow speeds and light loads, and as cool as possible at cruise and takeoff power.

The choice of spark plugs to be used in a specific aircraft engine is determined by the engine manufacturer after extensive tests. When an engine is certificated to use hot or cold spark plugs, the plug used is determined by how the engine is to be operated.

A spark plug with the proper reach (Fig. 17.28) will ensure that the electrode end inside the cylinder is in the best position to achieve ignition. The spark plug reach is the threaded portion inserted in the spark plug bushing of the cylinder. Spark plug seizure and/or improper combustion within the cylinder will probably occur if a plug with the wrong reach is used.

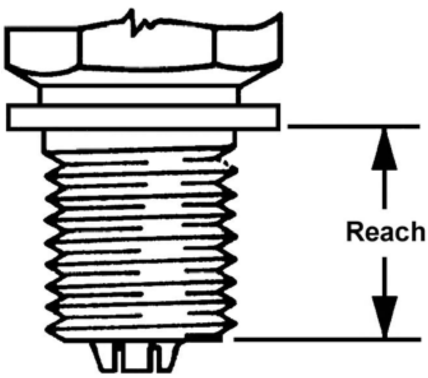

Fig. 17.28. Spark plug reach.

DUALIGNITION

Almost all piston engines employ two entirely independent ignition systems; thus each cylinder has two spark plugs, each supplied from a different magneto. The purpose of dual ignitions is to (i) reduce the possibility of engine failure because of an engine fault and (ii) reduce the time taken to burn the full charge enabling peak gas pressure to be reached and thereby increasing engine power output. Both magnetos are normally switched by a rotary switch in the manner already described.

TURBINE ENGINE IGNITION SYSTEMS

The ignition system of a turbine engine is much simpler than that of a piston engine due to the fact that fewer components are required and that electrical ignition of the air/fuel mixture is only necessary when starting an engine. Another difference is that the electrical energy developed by the system is very much higher in order to ensure ignition of atomized fuel under varying atmospheric and air mass flow condition and to meet the problems of relighting an engine in the air.

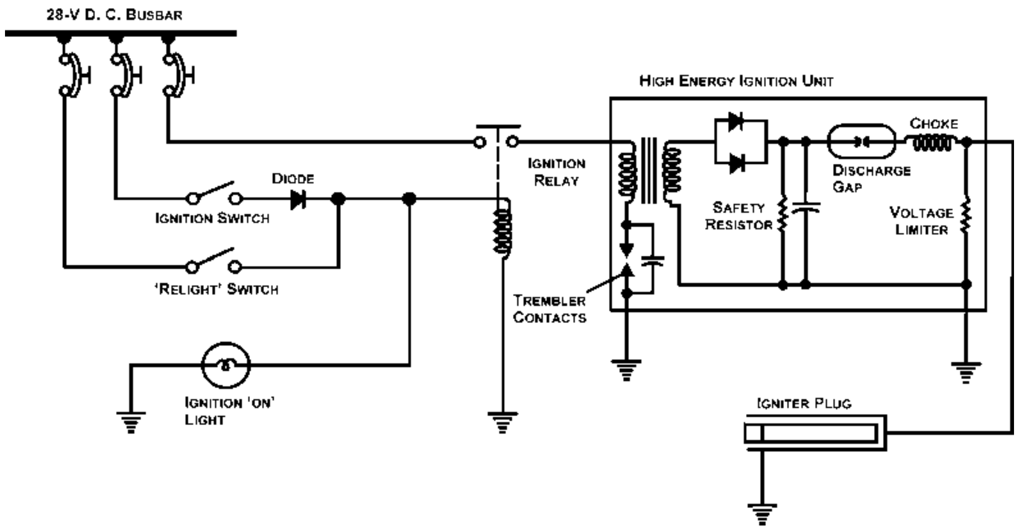

Fig. 17.29. High-energy ignition system.

The principal components of a system are a high energy ignition unit and an igniter plug interconnected as shown in (Fig. 17.29). Two such systems are normally fitted to an engine, the igniter plugs being located in diamerically-opposed combustion chambers to ensure a positive and balanced light-up during starting. Direct current from the aircraft's main busbar is supplied to an induction coil or a transistorized high tension generator within the ignition unit in conjunction with the starter, and also independently through the "relight" circuit. The coil, or generator, as appropriate, repeatedly charges a reservoir capacitor until its voltage, usually of the order of 2,000 volts, is sufficient to break down the sealed discharge gap. The gap is formed by two tungsten electrodes within a chamber exhausted of air, filled with an inert gas and sealed to prevent oxidation which would otherwise occur with the large current handled.

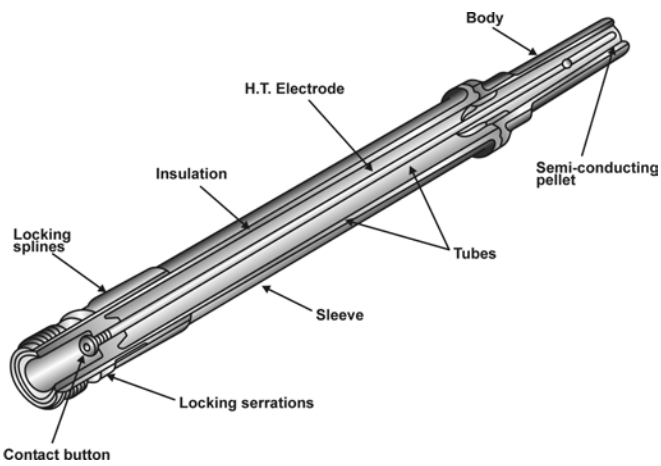

Fig. 17.30. High-energy igniter plug.

The discharge is conducted through a choke, which extends the duration of the discharge, and through a high tension lead to the igniter plug (see Fig. 17.30) at which the energy is released. A pellet at the "firing" end of the plug has a semi-conducting surface, and during operation this permits a minute electrical leakage from the centre electrode to the body, thereby heating from the centre electrode to the body, thereby heating the surface. Due to the negative temperature/resistance characteristics of the pellet a low resistance path is provided for the energy, which discharges across the surface as a high intensity flashover as opposed to a spark jumping an air gap. The capacitor recharges and the cycle is repeated approximately once every second. Once the fuel/air mixture has been ignited, the flame spreads rapidly through balance pipes which interconnect all the combustion chambers; thus combustion is self-sustaining and the ignition system can be switched off. The energy stored in the capacitors is potentially lethal, and to ensure their discharge when the d.c. supply is disconnected, the output is connected to ground via a safety resistor.

The electrical energy supplied by the ignition unit is measured in joules, and independent ignition systems normally consist of two units rated at 12 joules each.

In the event that through adverse flight conditions the flame is extinguished, the engine is "relit" by switching on the ignition system unitl the engine runs normally again. During relighting it is unnecessary to use the starter motor since the engine continues to rotate under the action of "windmilling". In some cases, relighting is automatic by having one of the two ignition units of a low rating (usually 3 joules) and keeping it in continuous operation. Where this method is not desirable a glow plug is sometimes fitted in the combustion chamber where it is heated by the combustion process and remains incandescent for a sufficient period of time to ensure automatic re-ignition.

In some types of aircraft the high energy ignition units are dependent on an initial power supply of 115 volts a.c., and the simplified circuit diagram of one such unit employed on the Boeing 747, is illustrated in (Fig. 17.31).

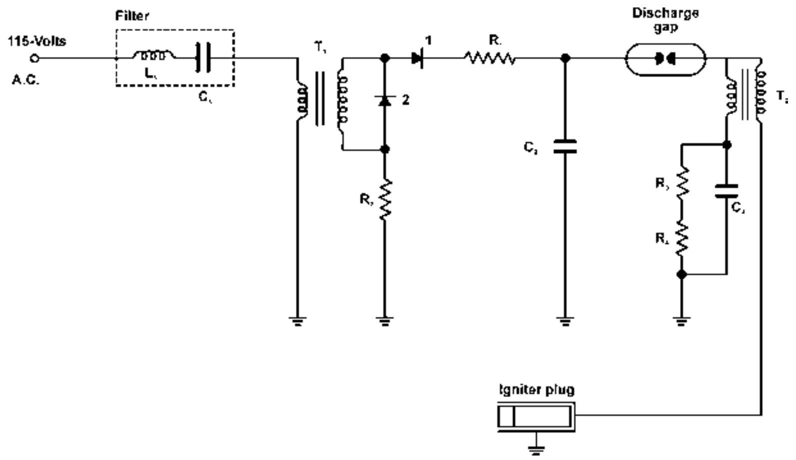

Fig. 17.31. High-energy system (a.c. powered).

The a.c. power supply is applied to the primary win ling of a step-up power transformer T1, via a radio noise filter network consisting of inductor L1 and a capacitor C1. The high voltage induced in the secondary winding of T1 is then rectified by the diodes 1 and 2, the current passing through them being limited by resistors R1 and R2. The rectified output charges the capacitor C2 until the stored voltage reaches the ionization potential of the discharge gap. The discharge flows through the primary winding of the high-tension auto-transformer T2, and is further boosted by a charge developed across capacitor C4. The voltage induced in the secondary winding is then of sufficient potential to provide the requisite discharge flashover across the igniter plug gap. Resistors R3 and R4 provide the means of dissipating the energy of the circuit in the event that the output of the igniter unit is open-circuited. In addition, they serve to "bleed-off" any residual charge on capacitor C4 between successive flashovers, and so provide a constant level of triggering voltage from the secondary winding of transformer T2.

Igniter Plugs

The igniter plug of a turbine engine ignition system differs considerably from the spark plug of a reciprocating engine ignition system. Its electrode must be capable of withstanding a current of much higher energy than the electrode of a conventional spark plug. This high-energy current can quickly cause electrode erosion, but the short periods of operation minimize this aspect of igniter maintenance. The electrode gap of the typical igniter plug is designed much larger than that of a spark plug, since the operating pressures are much lower and the spark can arc more easily than is the case for a spark plug. Finally, electrode fouling, so common to the spark plug, is minimized by the heat of the high-intensity spark.

Fig. 17.32 is a cutaway illustration of a typical annular-gap igniter plug, sometimes referred to as a "long reach" igniter because it projects slightly into the combustion-chamber liner to produce a more effective spark.

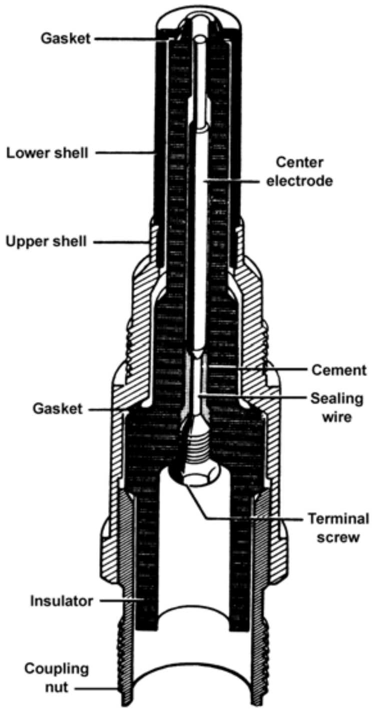

Fig. 17.32. Typical annular-gap igniter plug.

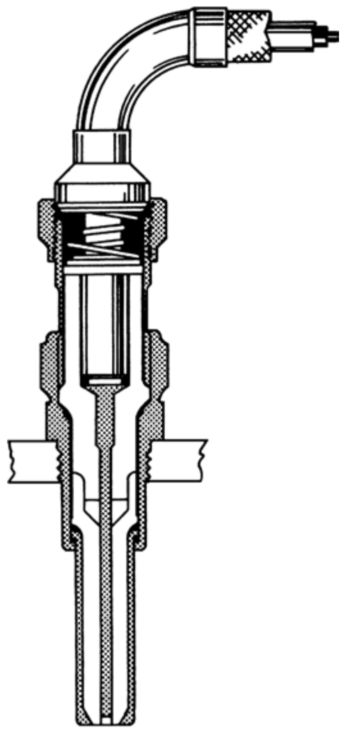

Fig. 17.33. Constrained-gap igniter plug.

Another type of igniter plug, the constrained-gap plug (Fig. 17.33) is used in some types of turbine engines. It operates at a much cooler temperature because it does not project into the combustion-chamber liner. This is possible because the spark does not remain close to the plug, but arcs beyond the face of the combustion-chamber liner.

FIRE DETECTION SYSTEMS

A fire detection system should signal the presence of a fire. Units of the system are installed in locations where there are greater possibilities of a fire. Three detector systems in common use are the thermal switch system, thermocouple system, and the continuous-loop detector system.

Thermal Switch System

A thermal switch system consists of one or more lights energized by the aircraft power system and thermal switches that control operation of the light(s). These thermal switches are heat-sensitive units that complete electrical circuits in parallel with each other but in series with the indicator lights (Fig. 17.34). If the temperature rises above a set value in any one section of the circuit, the thermal switch will close, completing the light circuit to indicate the presence of a fire or overheat condition.

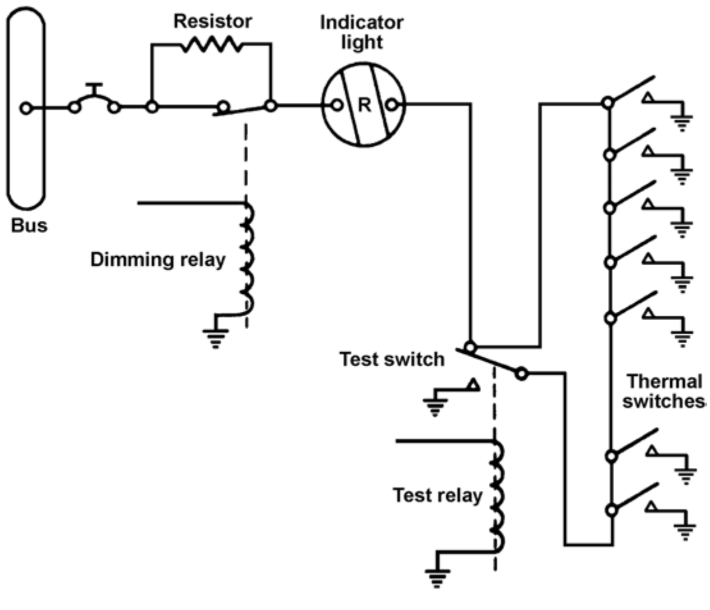

Fig. 17.34. Thermal switch fire circuit.

No set number of thermal switches is required; the exact number is usually determined by the aircraft manufacturer. On some installations several thermal detectors are connected to one light; on others there may be only one thermal switch for an indicator light.

Some warning lights are the "push-to-test" type. The bulb is tested by pushing it in to complete an auxiliary test circuit. The circuit in (Fig. 17.34) includes a test relay. With the relay contact in the position shown, there are two possible paths for current flow from the switches to the light. This is an additional safety feature. Energizing the test relay completes a series circuit and checks all the wiring and the light bulb.

Also included in the circuit shown in (Fig. 17.34) is a dimming relay. By energizing the dimming relay, the circuit is altered to include a resistor in series with the light. In some installations several circuits are wired through the dimming relay, and all the warning lights may be dimmed at the same time.

The thermal switch system uses a bimetallic thermostat switch or spot detector similar to that shown in (Fig. 17.35). Each detector unit consists of a bimetallic thermoswitch. Most spot detectors are dual-terminal thermoswitches.

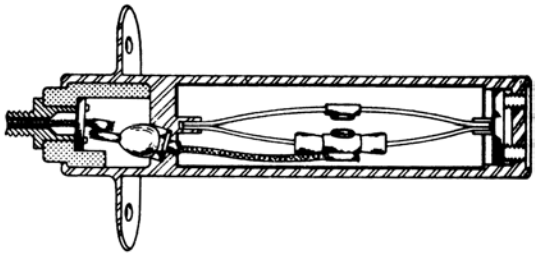

Fig. 17.35. Fenwal spot detector.

Fenwal Spot Detector

Fenwal spot detectors are wired in parallel between two complete loops of wiring, as illustrated in (Fig. 17.36). Thus, the system can withstand one fault, either an electrical open circuit or a short to ground, without sounding a false fire warning. A double fault must exist before a false fire warning can occur. In case of a fire or overheat condition, the spot-detector switch closes and completes a circuit to sound an alarm.

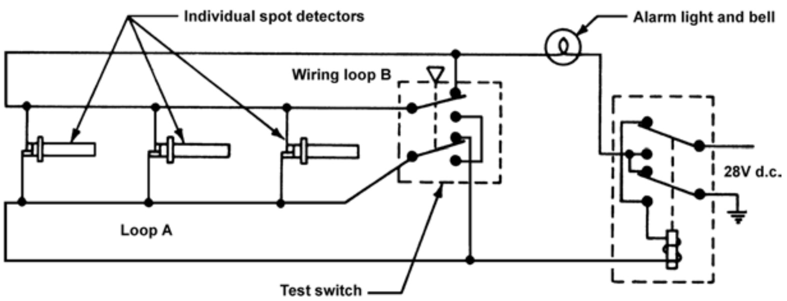

Fig. 17.36. Fenwal spot-detector circuit.

The Fenwal spot-detector system operates without a control unit. When an overheat condition or a fire causes the switch in a detector to close, the alarm bell sounds and a warning light for the affected area is lighted.

Thermocouple Systems

The thermocouple fire warning system operates on an entirely different principle than the thermal switch system. A thermocouple depends upon the rate of temperature rise and will not give a warning when an engine slowly overheats or a short circuit develops. The system consists of a relay box, warning lights, and thermocouples. The wiring system of these units may be divided into the following circuits (Fig. 17.37) : (1) The detector circuit, (2) the alarm circuit, and (3) the test circuit.

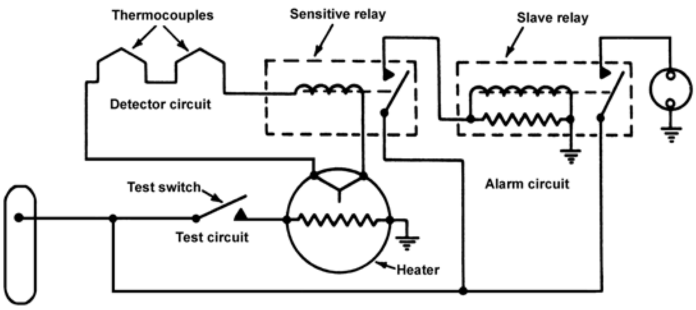

Fig. 17.37. Thermocouple fire warning circuit.

The relay box contains two relays, the sensitive relay and the slave, and the thermal test unit. Such a box may contain from one of eight identical circuits, depending on the number of potential fire zones. The relays control the warning lights. In turn, the thermocouples control the operation of the relays. The circuit consists of several thermocouples in series with each other and with the sensitive relay.

The thermocouple is constructed of two dissimilar metals such as chromel and constantan. The point where these meals are joined and will be exposed to the hea of a fire is called a hot junction. There is also a reference junction enclosed in a dead air space between two insulation blocks. A metal cage surrounds the thermocouple to give mechanical protection without hindering the free movement of air to the hot junction.

If the temperature rises rapidly, the thermocouple produces a voltage because of the temperature difference between the reference junction and the hot junction. If both junctions are heated at the same rate, no voltage will result and no warning signal is given.

If there is a fire, however, the hot junction will heat more rapidly than the reference junction. The ensuing voltage causes a current to flow within the detector circuit. Any time the current is greater than 4 milliamperes (0.004 ampere), the sensitive relay will close. This will complete a circuit from the aircraft power system to the coil of the slave relay which closes and completes the circuit to the fire-warning light.

The total number of thermocouples used in individual detector circuits depends on the size of the fire zone and the total circuit resistance. The total resistance usually does not exceed 5 ohms. As shown in (Fig. 17.37), the circuit has two resistors. The resistor connected across the terminals of the slave relay absorbs the coil's self-induced voltage. This is to prevent arcing across the points of the sensitive relay, since the contacts of the sensitive relay are so fragile they would burn or weld if arcing were permitted.

When the sensitive relay opens, the circuit to the slave relay is interrupted and the magnetic field around its coil collapses. When this happens, the coil gets a voltage through self-induction, but with the resistor across the coil terminals, there is a path for any current flow as a result of this voltage. Thus, arcing at the sensitive relay contact is eliminated.

Continuous-Loop Detector Systems

A continuous-loop detector or sensing system permits more complete coverage of a fire hazard area than any type of spot-type temperature detectors. Continuously-loop systems are versions of the thermal switch system. They are overheat systems, heat-sensitive units that complete electrical circuits at a certain temperature. There is no rate-of-heat-rise sensitively in a continuous-loop system. Two widely used types of continuous-loop systems are the Kidde and the Fenwal systems.

In the Kidde continuous-loop system (Fig. 17.38), two wires are imbedded in a special ceramic core within an Inconel tube.

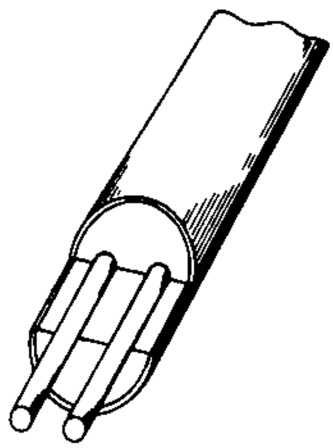

Fig. 17.38. Kidde sensing element.

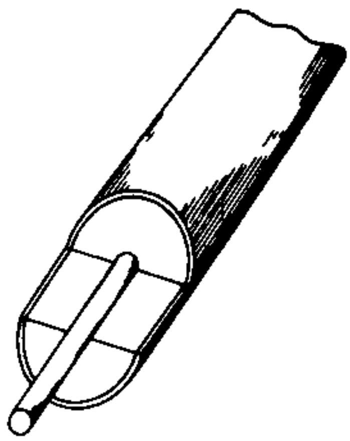

Fig. 17.39. Fenwal sensing element.

One of the two wires in the Kidde sensing system is welded to the case at each end and acts as an internal ground. The second wire is a hot lead (above ground potential) that provides a current signal when the ceramic core material changes its resistance with a change in temperature.

Another continuous-loop system, the Fenwal system (Fig. 17.39), uses a single wire surrounded by a continuous string of ceramic beads in an Inconel tube.

The beads in the Fenwal detector are wetted with a eutectic salt which possesses the characteristic of suddenly lowering its electrical resistance as the sensing element reaches its alarm temperature. In both the Kidde and the Fenwal systems, the resistance of the ceramic or eutectic salt core material prevents electrical current from flowing at normal temperatures. In case of a fire or overheat condition, the core resistance drops and current flows between the signal wire and ground, energizing the alarm system.

The Kidde sensing elements are connected to a relay control unit. This unit constantly measures the total resistance of the full sensing loop. The system senses the average temperature, as well as any single hot spot.

The Fenwal system uses a magnetic amplifier control unit. This system is non-averaging but will sound an alarm when any portion of its sensing element reaches the alarm temperature.

Both systems continuously monitor temperatures in the affected compartments, and both will automatically reset following a fire or overheat alarm after the overheat condition is removed or the fire extinguished.

Continuous Element System

The Lindberg fire detection system (Fig. 17.40) is a continuous-element type detector consisting of a stainless steel tube containing a discrete element. This element has been processed to absorb gas in proportion to the operating temperature set point. When the temperature rises (due to a fire or overheat condition) to the operating temperature set point, the heat generated causes the gas to be released from the element. Release of the gas causes the pressure in the stainless steel tube to increase. This pressure rise mechanically actuates the diaphragm switch in the responder unit, activating the warning lights and an alarm bell.

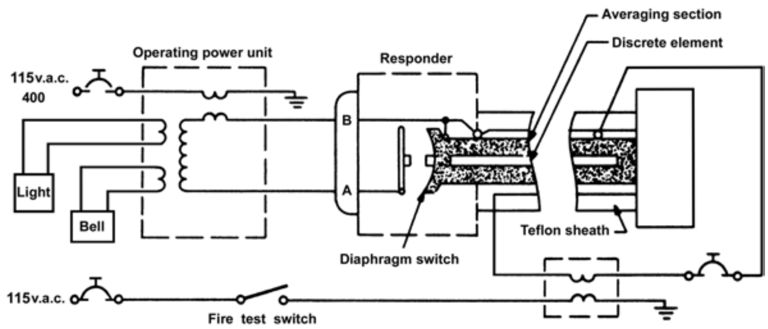

Fig. 17.40. Lindberg fire detection system schematic.

A fire test switch is used to heat the sensors, expanding the trapped gas. The pressure generated closes the diaphragm switch, activating the warning system.

Fire Wire System

In order to provide maximum coverage of an engine fire zone and to eliminate the use of a considerable number of unit detectors, a continuous wire type detector system (known as a "firewire" system) is normally used. The elements of a typical system take the form of various lengths of wire embedded in a temperature sensitive material within a small bore stainless steel or Inconel tube, and joined together by special coupling units to form a loop which may be routed round the fire zones as required. The wire and tube form centre and outer electrodes respectively and are connected to the aircraft's power supply via a control unit. The power supply requirements are 28 volts d.c. and 115 volts a.c. or, in some system, 28 volts d.c. only. Depending on the type of control unit the method of operation may be based on either variations in resistance or variations in capacitance with variations in temperature of the element filling material.

The electrical interconnection of components normally comprising a system is shown in (Fig. 17.41). The control unit in this case is of the type employed with a variable resistance system. The a.c. supply is fed to a step-down transformer,

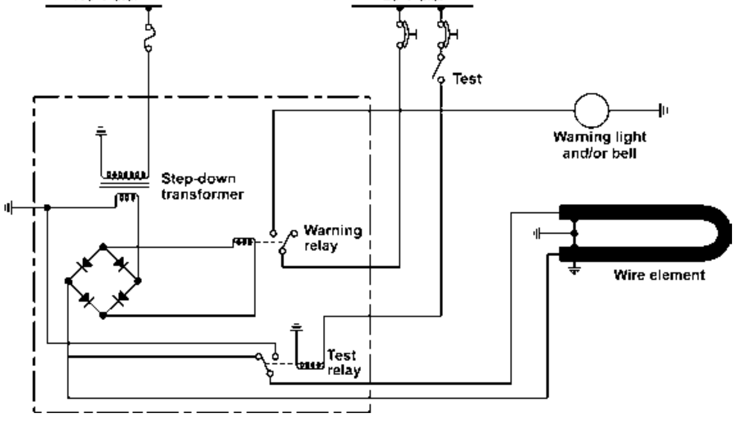

Fig. 17.41. Fire detection system.

while d.c. is supplied to the warning circuit via the contacts of a warning relay, the coil of which may be energized by the rectified output from the normal position, the ends of the centre wire electrode of the element are connected in parallel to the rectifier and to one end of the transformer secondary winding. The other end of the transformer secondary winding. The other end of the winding is connected to the outer tube or electrode so that the current path is always through the filling material, the resistance of which will govern the strength of rectified current flowing through the filling material, the resistance of which will govern the strength of rectified current flowing through the relay coil. With this arrangement the warning function is in no way affected in the event that a break should occur in the loop.

Under normal ambient temperature conditions the resistance of the filling material is such that only a small standing current flows through the material; therefore, the current flowing through the warning relay coil is insufficient to energize it. In the event of a temperature rise the resistance of the filling material will fall since it has an inverse characteristics, hence the rectified current through the relay coil will increase, and when the fire zone temperature has risen to such a value that the relay coil current is at a predetermined level the relay de-energizes and the system is automatically reset.

In a capacitance system the detector element is similar in construction to that earlier described, but in conjunction with a different type of control unit it functions as a variable capacitance system, the capacity of the element increasing as the ambient temperature increases. The element is polarized by the application of half-wave rectified a.c. from the control unit, which it stores and then discharges as a feedback current to the gate of a silicon-controlled rectifier (SCR) in the control unit during the non-charging half cycles. When the fire zone temperature rises the feedback current rises until at a pre-determined level the SCR is triggered to energize a fire warning light, or bell, relay. A principal advantage of this system is that a short circuit grounding the element or system wiring does not result in a false fire warning.

When the test switch is set to the " Test" position, the test relay is energized and its contacts change over the supply from the rectifier so that the current passes directly along the centre electrode. Thus, if there is no break in the loop there is minimum resistance and the warning relay circuit is acturated to simulate a fire warning and so indicate continuity.

Overheat Warning Systems

Overheat warning systems are used on some aircraft to indicate high area temperatures that may lead to a fire. The number of overheat warning systems varies with the aircraft. On some aircraft, they are provided for each engine turbine and each nacelle, on others they are provided for wheel well areas and for the pneumatic manifold.

When an overheat condition occurs in the detector are, the system causes a light on the fire control panel to flash.

In most systems the detector is a type of thermal switch. Each detector is operated when the heat rises to a specified temperature. This temperature depends upon the system and the type and model of the aircraft. The switch contacts of the detector are on spring structs, which close whenever the meter case is expanded by heat. One contact of each detector is grounded through the detector mounting bracket. The other contacts of all detectors connect in parallel to the closed loop of the warning light circuit. Thus, the closed contacts of any one detector can cause the warning lights to burn.

When the detector contacts close, a ground is provided for the warning light circuit. Current then flows from an electrical bus through the warning lights and a flasher or keyer to ground. Because of the flasher in the circuit, the lights flash on and off to indicate an overheat condition.

In some engine fire detection systems, detection is effected by two distinct sensing element loops; an "overheat" loop and a "fire" loop. An example of one such application based on the Lindberg Systron Donner system, is shown schematically in (Fig. 17.42). This system, unlike that of the "firewire" system described earlier, utilizes sensing elements which trigger the warning circuits as a result of the temperature effects on the pressure of a gas.

An element consists of a stainless steel tube protected throughout its length by a teflon coating. Inside the tube is a metal hydride-coated element surrounded by an inert gas (helium). One end of the type is bifurcated and joined to two diaphragm-operated pressure switches, one in the open position and the other always kept closed by the normal pressure (20 psi) of the helium acting on its diaphragm. The power required for system operation is 28 volts d.c. from the aircraft's battery busbar, and is supplied to the open switch contacts via those of the normally closed switch. Because the overall system is designed to sense two levels of temperature, then there must be two detecting elements each with a different temperature sensing level.

In the practical case, there are two pairs of elements connected as shown in (Fig. 17.42), one pair forming the "overheat" loop, and the other pair the "fire" loop. The elements are located at the bottom of an engine, and on the engine side of the firewall.

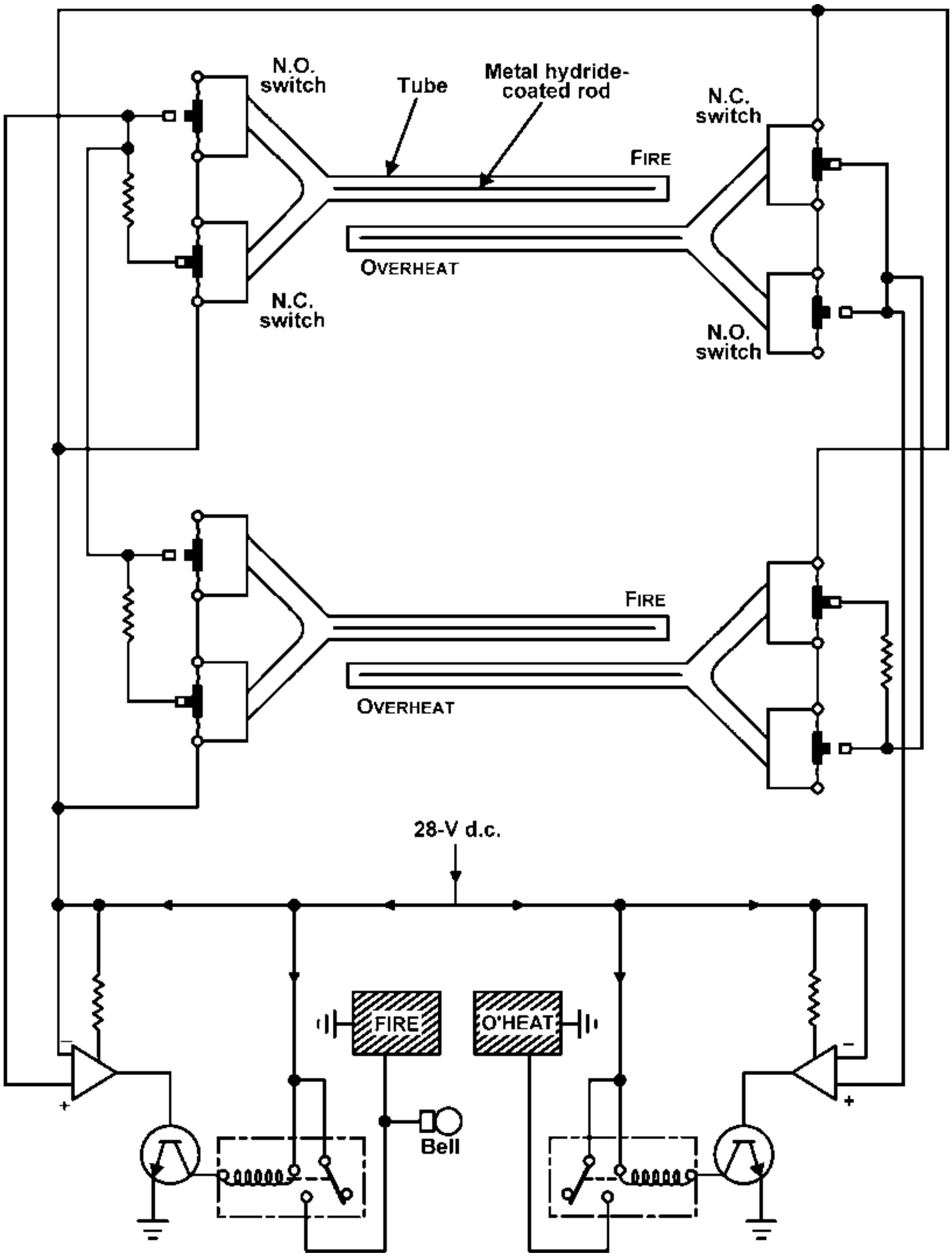

Fig. 17.42. Overheat and fire detection system.

If the local temperature rises to 205± 30ºC, the coating of the element inside an "overheat" detector will release a gas (principally hydrogen). This will increase the pressure inside the tube so that the diaphragm of the normally-open switch will be displaced and its contacts closed. The signal now flowing from the contacts closed. The signal now flowing from the contacts closed. The signal now flowing from the contacts passes through an operational amplifier the output of which biases a transistor to allow the standing 28 volt d.c. to energize a relay. The closed contacts of the relay then complete a circuit to an amber "overheat" light, and also a light on a master caution panel.

If the local temperature should continue to increase and reach 315 ± 30ºC, the pressure of the released hydrogen in a detecting element of the "fire" loop will trigger a signal to pass through a circuit similar to that of the overheat loop but, in this case, to illuminate red warning lights, and to set off an alarm bell.

In the event that the pressure of the helium inside a detector element should decrease, the normally-closed pressure switch would open to cause a "detector inoperative" light (not shown) to illuminate. Test circuits are therefore provided in the system so that the integrity of the normally-closed pressure switches can be checked.

SMOKE DETECTORS

In many of the larger types of transport aircraft, the freight holds, baggage compartments and equipment bays are often fitted with equipment designed for the detection of smoke. Detection equipment varies in construction, but in most cases the operation is based on the principle whereby air is sampled and any smoke present, causes a change of electric current within the detector circuit to trigger a warning system.

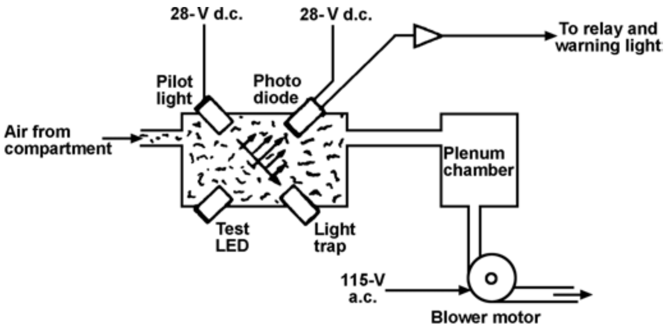

Fig. 17.43. Smoke Detector Operation.

Fig. 17.43 is a schematic arrangement of a smoke detector in use in some types of transport aircraft. The principal detecting elements are a pilot light, a light trap and a photo diode, disposed in a compartment or chamber as shown. The pilot light and photo diode are powered by 28-volt d.c.

Sampling tubes connect with the detector and plenum chambers and a blower motor powered by 115-volt a.c. When the system is armed, the blower motor draws air through the detector from the compartment in which the detector is located. The pilot light directs a beam to the light trap. If smoke is present to a level of 10 per cent, the light reflected from it as it passes through the beam will be detected by the photo diode. The current generated by the diode is then amplified to trigger a relay the contacts of which complete a circuit to the appropriate fire warning light. The light emitting diode (LED) forms part of a test circuit which activates the photo diode to simulate a smoke condition.

FIRE EXTINGUISHING

Fixed fire extinguishing systems are used mainly for the protection of engine installations, auxiliary power units, landing gear wheel bays and baggage compartments, and are designed to dilute the atmosphere of the appropriate compartments with an inert agent that will not support combustion. Typical extinguishing agents are methy1 bromide, bromochlorodifluoro-methane, freon, or halco, and these are contained within metal cylinders or "bottles" of a specified capacity. The agents are pressurized by an inert gas, usually dry nitrogen, the pressures varying between types of extinguisher, e.g. 250 $1bf/in^2$ for 4 pounds of freon. Explosive cartridge units which are fired electrically, are connected to distributor pipes and spray rings, or nozzles, located in the potential fire zones. Electrical power for cartridge unit operation is 28 volts d.c. and is supplied from an essential services busbar; the circuits are controlled by switches located in the cockpit. When the cartridge unit is fired a diaphragm is ruptured and the appropriate extinguishing agent is discharged through the distributor pipes and spray rings.

In the fire extinguisher systems of some types of aircraft, electrical indicators are provided to show when an extinguisher has been fired. An indicator consists of a special type of fuse and holder connected in the extinguisher cartridge unit circuit. The fuse takes the form of a small match-head type charge covered by a red powder and sealed within the fuse body by a disc. A transparent cover encloses the top of the fuse body and is visible through another cover screwed on to the fuse holder.

The fuse is secured in the fuse holder by a bayonet type fixing, and electrical connection to the charge is by way of terminals in the fuse holder, contact at the base of the fuse and the metal disc.

When current flows in an extinguisher cartridge circuit, the appropriate fuse charge is fired, thereby displacing the disc and interrupting the circuit. At the same time red powder is spattered on to the inside of the cover thus giving a positive visible indication of the firing of the extinguisher cartridge.

Ice and Rain Protection Systems

Icing on aircraft is caused primarily by the presence in the atmosphere of supercooled water droplets, i.e. droplets at a temperature below that at which water normally freezes. In order to freeze, water must lose heat to its surroundings, thus when it strikes, say, an aircraft wing, an engine air intake or a propeller, there is metal to conduct away the latent heat and the water freezes instantly. The subsequent build-up of ice can change the aerodynamic shape of the particular form causing such hazardous situations as decrease of lift, changes of trim due to weight changes, loss of engine power and damage to turbine engine blading. In addition, loss of forward vision can occur due to ice forming on windshield panels, and on externally mounted units such as pitot probes, obstruction of the pressure holes will result in false readings of airspeed and altitude. Therefore, for aircraft which are intended for flight in ice-forming conditions, protective systems must be incorporated to ensure their safety and that of the occupants. (Fig. 17.44) indicates the extent to which protection may be required depending on the type and size of aircraft.

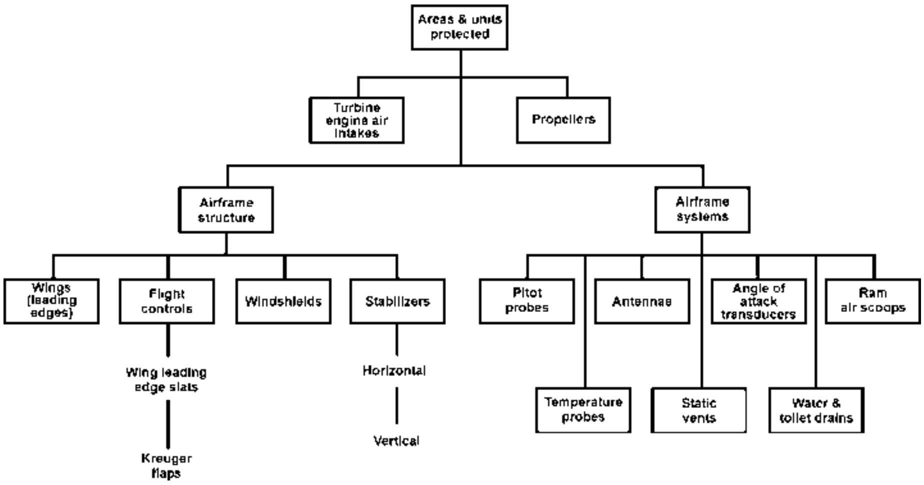

Fig. 17.44. Ice and rain protection system.

In addition to ice protection systems, some protection must also be afforded when flying in heavy rain conditions in order to improve visibility through cockpit windshields. This is accomplished by windshield wiper and rain repellent systems.

METHODS OF PROTECTION

There are three methods adopted in the systems in common use and these together with their applications and fundamental operating principles are set out in Table 17.3. They are all based on two techniques, known respectively as de-icing and anti-icing. In de-icing, ice is allowed to build up to an extent which will not seriously affect the aerodynamic shape and is then removed by operation of the system; this cycle is then continuously repeated, usually by a timing device. In anti-icing, the system is in operation continuously so that ice cannot be allowed to form.

Table 17.3

Method	**Application**	**Principle**
FLUID	Wings, stabilizers, propellers, windshields	A chemical which breaks down the bond between ice and water and can be either sprayed over the surface, e.g. a windshield, or pumped through porous panels along the leading edge of a surface, e.g. a wing.
PNEUMATIC BOOT	Wings, stabilizers	Sections of rubber boot along the leading edges are inflated and deflated causing ice to break up and, with aid of the air stream, crack off.
THERMAL		
a. Hot air bleed	Wings, stabilizers, engine air intakes	Hot air from turbojet engine compressors passed along inside of leading edge structure.
b. Combustion heating	Wings, stabilizers	Hot air from a separate combustion heater or from a heat exchanger associated with a turbine engine exhaust gas system.
c. Electrical heating	Wings, stabilizers, engine air intakes, propellers, helicopter rotor blades, windshields	Heating effects of electric current passing through wire, flat strip or film type elements.

Electrical power and certain electrical components are required in varying degrees for all the systems listed in Table 17.3. In fluid, hot air bleed and combustion heating systems the requirements are fairly simple since it is usually only necessary to operate an electrical pump, air control valves and temperature-sensing systems as appropriate. The requirements for pneumatic boot systems are also fairly simple, although the number of air control valves is increased proportionately to the number of boot sections necessary and an electronic timer is used.

In what may be termed "pure electrical heating systems", the application of electrical power and components is much wider and as a result the systems are of a more complex nature.

PNEUMATIC DE-ICING SYSTEM

The pneumatic method of de-icing the leading edges of wings, horizontal and vertical stabilizers is used in several types of small and medium-sized transport aircraft . In general, systems are similar in respect of their principal components and overall operation, and we may consider as an example the one shown in (Fig. 17.45), which is applied to the Piper "Navajo" (PA31P).

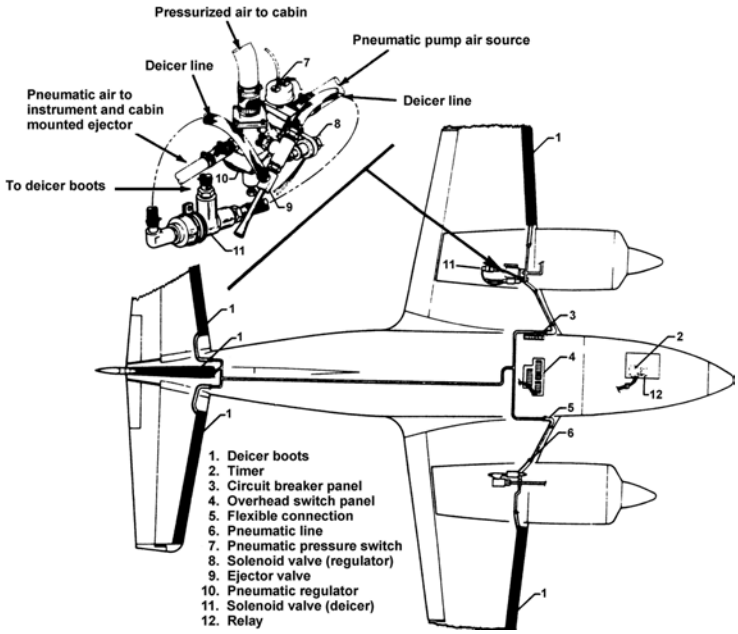

Fig. 17.45. Pneumatic de-icer boot system.

De-icing is effected by de-icer "boots" which are cemented to the leading edges of the appropriate surfaces, and which, at controlled time intervals, inflate to break up ice which has formed on them. In some systems the boots are inflated in a specific sequence, but in the example shown, all the boots inflate simultaneously for a period of 6 seconds. The boots are of fabric-reinforced rubber and contain built-in inflation tubes arranged spanwise (see Fig. 17.46) which are connected to an air supply system via solenoid-operated valves. In some types of aircraft, the tubes are arranged chordwise so that they minimize interference with the airflow over the relevant surfaces. A thin conductive coating is provided over the surfaces of the boots to dissipate static charges.

The air supply in the case of the aircraft considered is derived from engine-driven pumps and is regulated at 18 psi, but in aircraft powered by turbopropeller engines, the air is usually tapped from an engine main compressor stage and then regulated to the desired pressure. During the deflation period of the operating cycle, and also during fligh under no-icing conditions, it is necessary for the boots to be held flat against the leading edges of the appropriate surfaces, and this is achieved by connecting the boots, via their solenoid-operated valves, to a vacuum source. This is derived by passing air continuously overboard from the engine-driven pumps or, engine compressor as the case may be, through an ejector/venturi.

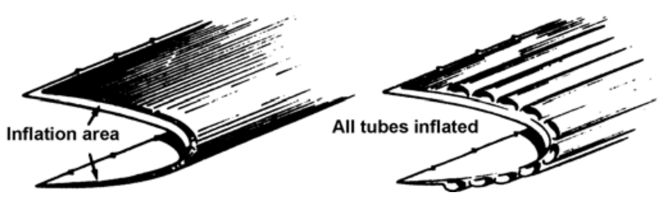

Fig. 17.46. De-icer boot operation.

ELECTRICAL DE-ICING AND ANTI-ICING SYSTEMS

It is beyond the scope of this book to go into the construction and operating detail of any one specific system, but the following details, although of a general nature only, may nevertheless, be considered as typical.

A system is made up of three principal sections: heating elements, control, protection and indicating. The power supplies normally required are 115 volts to 200 volts a.c. for heating (although the propellers for some light aircraft types and some windshield panels operate on 28 volts d.c.), 115 volts a.c. and 28 volts d.c. for control and for other sections of a system. Depending on the application, heating current may be controlled to permit de-icing, anti-icing or both.

The heating elements vary in design and construction depending on the application. For propellers they are of the fine wire type sandwiched in insulating and protective materials which form overshoes selected for maximum resistance to environmental conditions and bonded to the blade leading edges. For propeller-turbine engine air intakes, leading edges of wings, and helicopter rotor blades, the elements are of the "sheared foil" type, i.e. they are cut from thin sheets of high-grade metal to specified lengths and widths and within very close tolerances. The final resistance values of the elements which are selected from such metals as nickel, copper-nickel and nickel-chrome, are usually adjusted by chemical etching. The elements are also sandwiched between insulating and protective layers to form overshoes or mats.

Fig. 17.47 illustrates one example of a propeller and air intake de-icing system. Electrical power, at 200 volts a.c. and variable frequency, is supplied to the propeller blades and spinner, via brushes and slip rings and a cyclic time switch, so that during the de-icing part of the cycle heat is applied to all four blades simultaneously. It is unnecessary to de-ice the whole of each blade, as kinetic heating allied to centrifugal force normally keeps the outer halves free from ice.

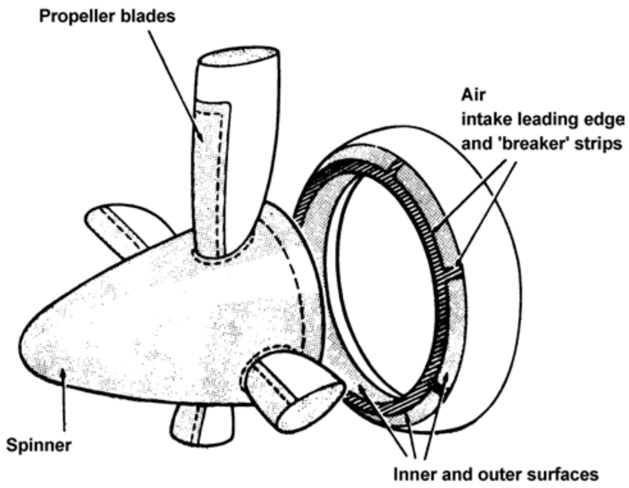

Fig. 17.47. Propeller and air intake de-icing system.

The air intake elements are arranged so that those positioned at the leading edges are continuously heated, i.e. they perform an anti-icing function, while those on the inner and outer surfaces are supplied via the cyclic time switch and so perform a de-icing function. In order that ice may be shed in reasonably-sized sections, the leading edge heating elements are extended at intervals to form "breaker" strips. The resistance of the elements is graded to provide for various heating intensities required at different parts of the air intake.

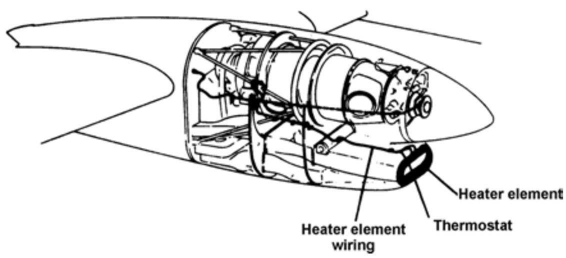

Fig. 17.48. Engine air intake anti-icing.

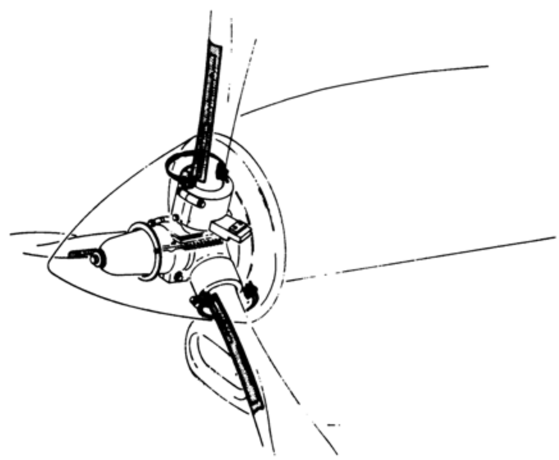

Fig. 17.49. Electrical heater elements - propeller de-icing.

The heating element arrangements adopted in another current type of turbopropeller engine, are shown in (Fig. 17.48) and (Fig. 17.49). In this case the power supply for heating is 28 volts d.c.

For windshields or other essential clear vision panels in cockpits, a transparent metal film type of element is employed in the majority of applications, the metal being either stannic oxide or gold. Panels are of laminated construction, and in order to provide rapid heat transfer the metal film is electrically deposited on the inside of the outer glass layer. It is protected from damage and completely insulated by further layers of polyvinyl butyral, glass and/or acrylic. Heating current, normally from an a.c. source, is supplied to the film by metal busbar at opposite edges of the glass layer. The power necessary to deal with the most severe icing conditions is in the order of 5-6 watts/in^2 of windshield area.

In systems applied to the windshields of some small types of aircraft, heating elements made up of fine resistance wire are used and are connected to a 28-volt d.c. power source.

Windshield systems are essentially anti-icing systems for, in addition to the protective function, the temperature of the panels must be higher than ambient during take-off, flight at low altitudes and landing, thus making them "pliable" and thereby improving their impact strength against possible collision with birds.

Temperature Control Methods
In view of the high amounts of power required for the foregoing electrical heating methods, it is essential to provide each system with appropriate controlling circuits and devices. Although there are a number of variations between systems and between designs of view of primary functions they are more or less the same, i.e. to cycle the power automatically, to detect any overloading and to isolate power supplies under specific conditions.

ENGINE AIR INTAKE AND PROPELLER SYSTEMS
Fig. 17.50 represents the supply and control circuit for the engine air intake and propeller shown in (Fig. 17.47).

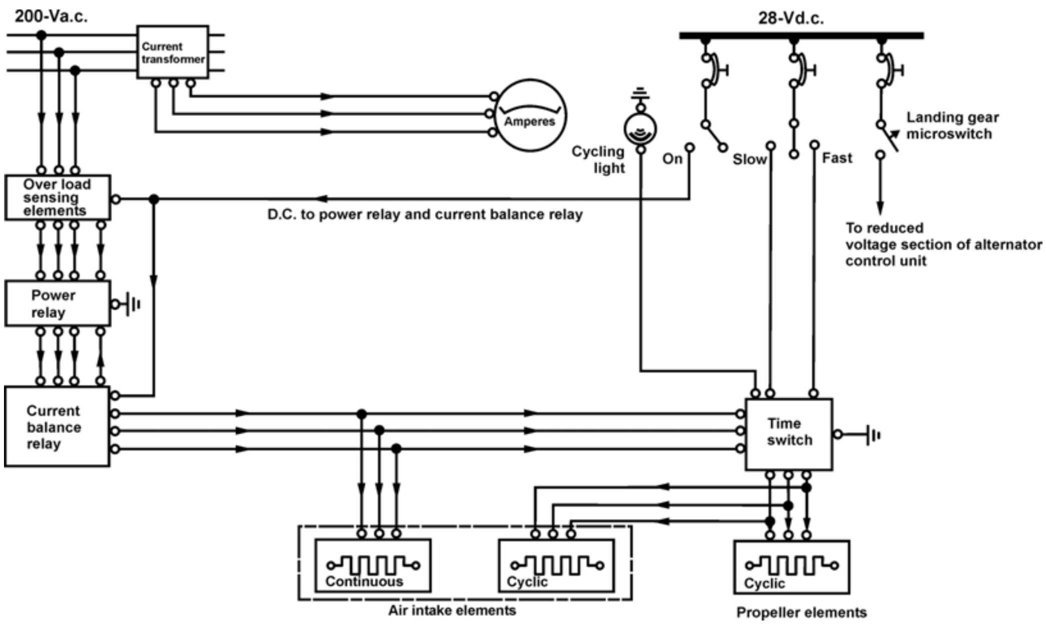

Fig. 17.50. Engine air intake and propeller de-icing and anti-icing control circuit.

When the system is switched on, direct current energizes the power relay via closed contacts in the overload sensing device, thus allowing the 200 volts a.c. flow directly through to the continuously heated elements and up to the time continuously heated elements and up to the time switch. This unit is energized to run either "fast" or "slow" by a selector switch, the settings being governed by outside air temperature and severity of icing. In this case "fast" is selected at temperatures between +10°C and -6°C and the duration of the "heat on" and "heat off" periods of the cyclic heated elements is short compared with "slow", which is selected at temperatures below -6°C. The cycling is usually controlled by cam-operated microswitches. An indication of time switch operation is provided by a flashing blue or green light on the control panel, while a general indication that the correct power is being applied to the whole system is provided by an ammeter connected to a current transformer across the generator busbar.

In the event of an a.c. overload, the heater elements are protected by the sensing device which is actuated in such a manner that it interrupts the d.c. supply to the power relay, this in turn interrupting the supply of heating current. The current balance relay fulfils a similar function and is actuated whenever there is an unbalance between phases beyond a predetermined amount.

For ground operation of the system described, it is usual for the applied voltage to be reduced in order to prevent overheating. This is effected by the automatic closing of a microswitch fitted to a landing gear shock-strut, the switch permitting direct current to flow to a reduced voltage control section within the generator voltage regulator.

The circuit of a d.c. powered system as applied to the air intake illustrated in (Fig. 17.48), is shown in (Fig. 17.51). When the system is switched on, the control relay is energized by the 28-volt supply having to pass ground through the closed contacts of a thermostat and through the contacts of the engine oil pressure switch which closes when the pressure reaches 50 psi. The supply for the heater elements which is rated at 500 watts, then passes through the energized relay contacts.

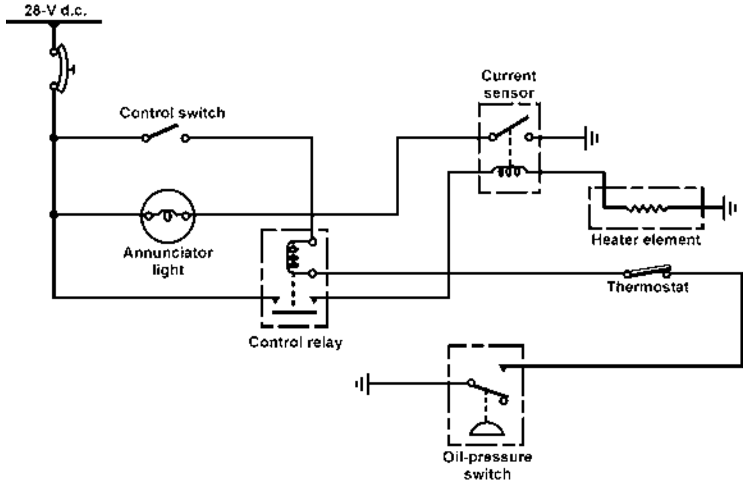

Fig. 17.51. Engine air intake anti-icing system.

The thermostat prevents overheating of the heater element by opening the circuit when the element temperature reaches 49 ± 3°C (120 ± 5°F). The oil pressure switch opens the circuit when as a result of engine shutdown the oil pressure falls below 50 ± 2 psi. Functioning of the heating circuit is indicated by an annunciator light on the system control panel. The light is illuminated by a current-sensing relay which is in series with the heater element, and energizes when heater current is above 15 amperes.

An example of a propeller de-icing system utilizing 28-volt d.c. power for heating and control is shown in (Fig. 17.52) and is one which is applied to several types of small twin-engined aircraft.

The propeller blades each have two heater elements bonded to them; one at the outboard section of a blade and the other at the inboard section. The elements are connected to the power supply via slip rings, brushes and an electrically-operated timer which is common to both propellers.

The cycling sequence of the timer is set so that (i) the outboard elements of each propeller are simultaneously heated before the inboard elements, and (ii) only one propeller is de-iced at a time. The sequence for the right-hand propeller is shown at (a) and (b) of (Fig. 17.52) respectively. The segments 3 and 4 respectively connect the supply to the outboard and inboard elements of the left-hand propeller. The timer energizes the elements for approximately 34 seconds and repeats the cycle as long as the control switch is in the "on" position. Operation of the system is indicated by the ammeter, the pointer of which registers within a shaded portion of the ammeter scale corresponding to current consumed (typically between 14 and 18 amperes) at the normal system voltage.

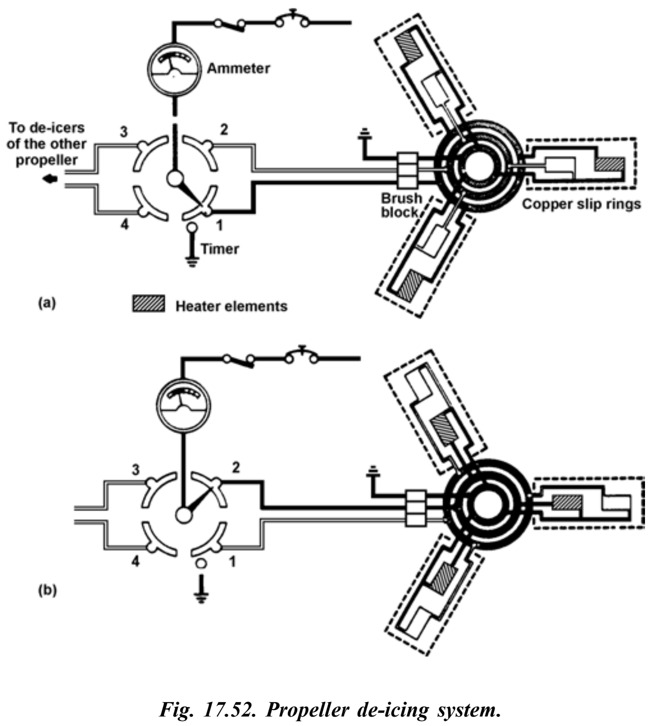

Fig. 17.52. Propeller de-icing system.

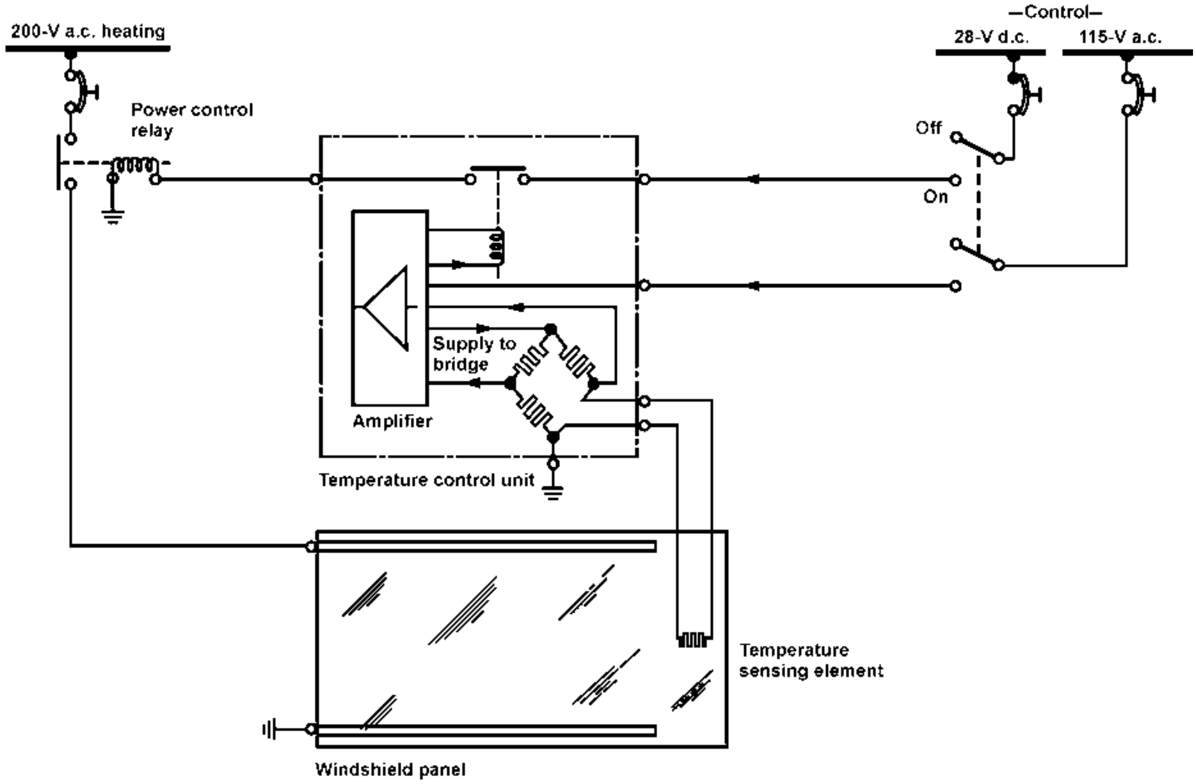

Fig. 17.53. Schematic arrangement of windshield anti-icing control system.

WINDSHIELD ANTI-ICING SYSTEMS

The control methods adopted for windshield anti-icing systems are normally thermostatic, and a typical system (Fig. 17.53) consists of a temperature-sensing element and a control unit. The element is embedded within the panel in such a way that it is electrically insulted from the main heating film and yet is capable of responding to its temperature changes without any serious lag. A control unit comprises mainly a bridge circuit, of which the sensing element forms part, an amplifier and a relay. When all the required power is switched on initially, the control unit relay is energized by an unbalanced bridge signal and the power control relay is energized to supply the windshield panel. As the panel temperature begins to increase, the sensing element resistance also increases until at a predetermined controlling temperature (a typical value is 40°C) the current flowin through the sensing element balances the bridge circuit, and the control unit and power control relays are de-energized, thereby interrupting the heating current supply. As the temperature cools the sensing element resistance decreases so as to unbalance the bridge circuit and thereby restore the heating current supply. In a number of aircraft types the windshields are each fitted with an additional overheat sensing element which in the event of failure of the normal sensing element takes over its function and controls at a suitably higher temperature; 55°C is a typical value.

Despite accurate control during manufacture slight variations in heater film resistance, and consequently glass temperature, can occur. Sensing elements are, therefore, individually embedded in each panel at one of the hotter spots but where it least affects visibility.

In some types of aircraft, windshields are heated by resistance elements of fine wire supplied with 28 volts d.c. Temperature sensing and control of heating current is carried out by a control unit operating on a similar principle to that already described.

Hot-Air Bleed Anti-Icing Systems

Systems of this type are standard principally on the larger types of public transport aircraft, for the anti-icing of engine air intake nose cowlings, wing leading edges and leading edge devices such as slats and flaps.

The hot air is bled from certain stages of main engine compressors and is then ducted through metal ducting to the air intakes and leading edges. As far as the use of electrical power is concerned, this is required solely for the operation of motorized control valves in the ducting, valve position indicating lights, and duct temperature sensing devices. The motors are limit switch controlled at the full open and closed positions, and in most applications they are of the 115-volts single-phase a.c. type. A power supply of 28 volts d.c. is used for valve control relay switching and position indicating light circuits.

The d.c. supply for valve control relay switching passes through a landing gear shock-strut micro-switch so that when an aircraft is on the ground the anti-icing system cannot be operated as in the normal in-flight situation. A ground test switch circuit is therefore provided to check the operation of valves and position indicating lights.

Ice Detection Systems

These systems consist mainly of a sensing probe located at a strategic point on an aircraft (usually the front fuselage section) and a warning light, their purpose being to give adequate warning, and an assessment of the likely severity of an impending icing hazard in sufficient time for the ice protection systems to be brought into operation. Detectors are made in a variety of forms, and in those most commonly used actuation of the warning circuit is triggered off by ice accretion at the sensing probe.

In one type of system ice accretion causes a drop in pressure sensed by the probe and a diaphragm, the deflections of which make a circuit to the warning light and to a heater within the probe. When the ice has melted the warning light and heater circuits are interrupted and the system is reset for further ice detection.

A second type of system is designed to give a warning and also automatically switch on airframe and engine de-icing systems. It consists of an a.c. motor-driven rotor which rotates in close proximity to a knife-edge cutter, a time delay unit and a warning lamp. Under icing conditions ice builds up on the rotor and closes the gap between it and the cutter. This results in substantial increase in the torque-loading on the detector motor, causing it to rotate slightly in its mounting and to trip a microswitch inside the detector. Tripping of the microswitch completes the circuit to the warning light and time delay unit which initiates operation of the de-icing systems. These conditions are maintained until the icing diminishes to the point whereby the knife-edge cutter ceases to "shave" ice, and the microswitch is returned to the open circuit condition. The detector unit is designed to provide a two minute interval between the cessation of an ice warning and shut down of a de-icing system, to prevent continuous interruption of the system during intermittent icing conditions.

In a third type of system, the fundamentals of operation are dependent on the phenomenon of magnetostriction, i.e. its sensing probe is caused to vibrate axially when subjected to a magnetic field at specific frequencies. The function of the system is shown in (Fig. 17.54).

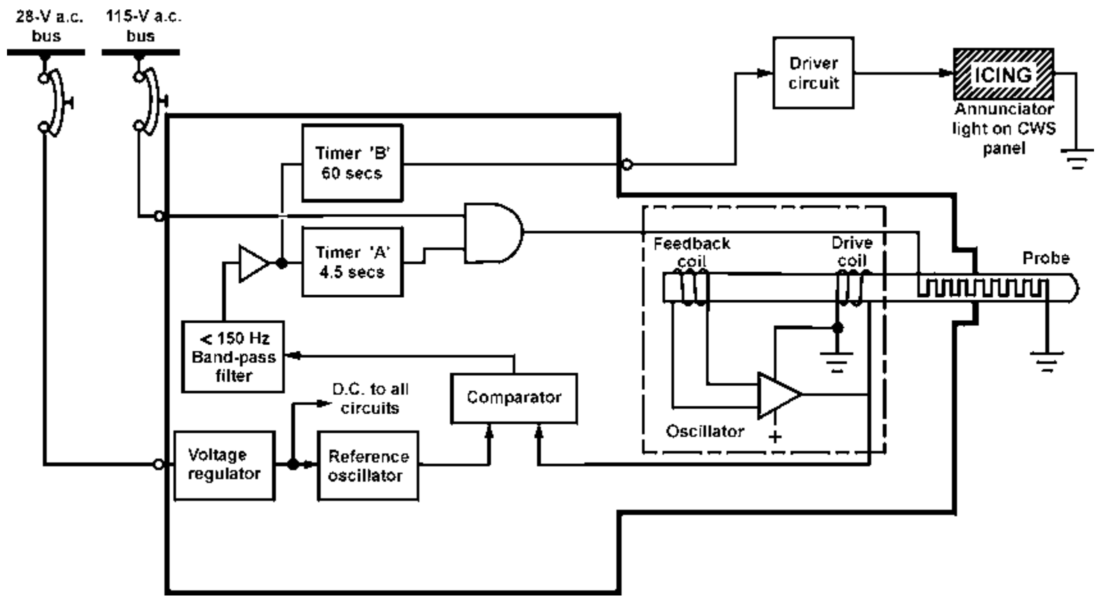

Fig. 17.54. Functional diagram of ultrasonic probe system.

The sensing probe is a ¼- inch diameter nickel alloy (Ni-Span C) tube mounted at its mechanical centre. The inherent resonant frequency of the probe is inversely proportional to its length, the simplified relationship being expressed as $f = \frac{S}{2L}$ where, f = frequency in Hz, S = 1.88 × 10^5 inches per second (the speed of sound in the tube material) and L = length of the probe in inches. Based on this expression, the tube may be cut to a specific length to achieve a desired tube length is 2.3 inches, resulting in a resonant ultrasonic frequency of 41 kHz. This frequency, however, is reduced to a nominal to kHz by the brazing of heating elements within the tube and also by capping the tip of the tube and also by capping the tip of the tube. The probe is maintained in its axial vibration by the ultrasonic frequency excitation current produced by an oscillator and passed through a drive coil wound around the probe. The frequency is controlled by a feedback coil circuit such that the drive coil will excite the probe at whatever the natural frequency of the probe might be at the time. When ice forms on the probe the natural frequency is reduced, and theoutput frequency of the oscillator drive coil is in turn reduced to match the probe frequency. By means of a comparator circuit, the lower output frequency is compared with a fixed frequency output from a reference oscillator. The frequency difference between the two oscillators relates to the ice formation on the probe, and when the difference has reached a preset level (150 Hz or less) determined by a band pass filter and a limiting amplifier, a signal is sent to a switch and delay circuit. When this occurs, two timer circuits are triggered; one controlling the a.c. supply via a logic AND gate, to the probe heater, and the other controlling the duration an icing signal is available to an annunciator light for warning the flight crew. Thus, as will be noted from Fig. (17.50), there is a standing logic 1 input to the AND gate from the 115-volt bus, so when timer "A" is triggered it will supply a second logic 1 input to the gate from the 115-volt bus, so when timer "A" is triggered it will supply a second logic 1 input to the gate causing it to switch on the heater for a period of 4.5 second. The signal from timer "B" is 28 volt d.c. and keeps the annunciator light illuminated for a period of 60 seconds. Melting of the ice from the probe increases the frequencies of the probe, and if no other icing signal is detected within 60 seconds, timer "A" automatically resets to isolate the heater from the a.c. supply. This cycle of operation is repeated while icing conditions prevail.

Failure monitoring of the detector is accomplished with unijunction oscillators which are set at both ends of the maximum difference frequency band. If the probe becomes severely damaged causing a significant change in the resonant frequency, or if an electronic component failure causes a malfunction in the reference frequency circuit, the annunciator light will be continuously illuminated.

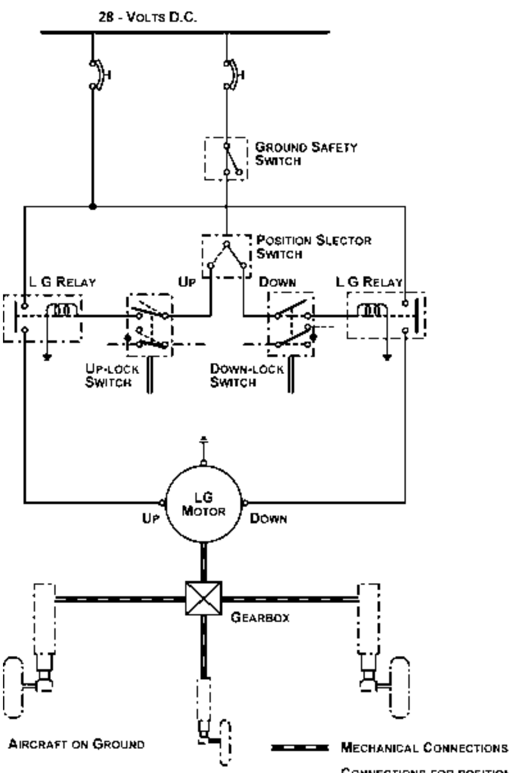

Fig. 17.55. Landing gear control system.

Landing Gear Control

In a number of the smaller types of aircraft having a retractable landing gear system, the extension and retraction of the main wheels and nose wheel, is accomplished by means of electrical power. (Fig. 17.55) is a simplified circuit diagram of a representative control system.

The motor is of the series-wound split-field type which is mechanically coupled to the three "leg" units, usually by a gearbox, torque shafts, cables, and screw jacks. The 28 volts d.c. supply to the motor is controlled by a selector switch, relay, and switches in the "down-lock" and "up-lock" circuits. A safety switch is also included in the circuit to prevent accidental retraction of the gear while the aircraft is on the ground. The switch is fitted to the shock-strut of one of the main wheel gear units, such that the compression of the strut keeps the switch contacts in the open position as shown in the diagram.

After take-off, the weight of the aircraft comes off the landing gear shock-struts, and because they have a limited amount of telescopic movement, the strut controlling the safety switch causes it to close the switch contacts. Thus, when the pilot selects "gear up", a circuit is completed via the selector switch, and closed contacts of the up-lock switch, to the coil of the relay which then completes the supply circuit to the "up" winding of the motor. When the landing gear units commence retracting, the down-lock switch is automatically actuated such that its contacts will also close, and will remain so up to and in the fully retracted position. As soon as this position is reached, the up-lock switch is also actuated so as to open its contacts, thereby interrupting the supply to the motor, and the "down" winding circuit of the motor is held in readiness for extending the landing gear. As and when the appropriate selection is made, and the landing gear units commence extending, the up-lock switch contacts now close and when the landing gear is down and locked, and the aircraft has landed, the circuit is again restored to the condition shown in (Fig. 17.55).

To prevent over-run of the motor, and hence over-travel of the landing gear units, some form of braking is necessary. This is accomplished in some cases, by incorporating a dynamic brake relay in the circuit. The relay operates in such a manner that during over-run, the motor is caused to function as a generator, the resulting electrical load on the armature stopping the motor and gear instantly.

Landing Gear Position Indication

In retractable landing gear systems, it is , of course, necessary to provide some indication that the main and nose landing gear units are locked in their retracted positions during flight, and in their extended positions safe for landing. The indication method most widely adopted is based on a system of indicating lights which are connected to microswitches actuated by the up-lock and down-lock mechanisms of each landing gear unit. To guard against landing with the landing gear unit. To guard against landing with the landing gear retracted or unlocked, a warning horn is also incorporated in the indication system. The horn is also incorporated in the indication system. The horn circuit is activated by a microswitch the contacts of which are made or broken by the engine throttle. (Fig. 17.56) illustrates a typical circuit arrangement.

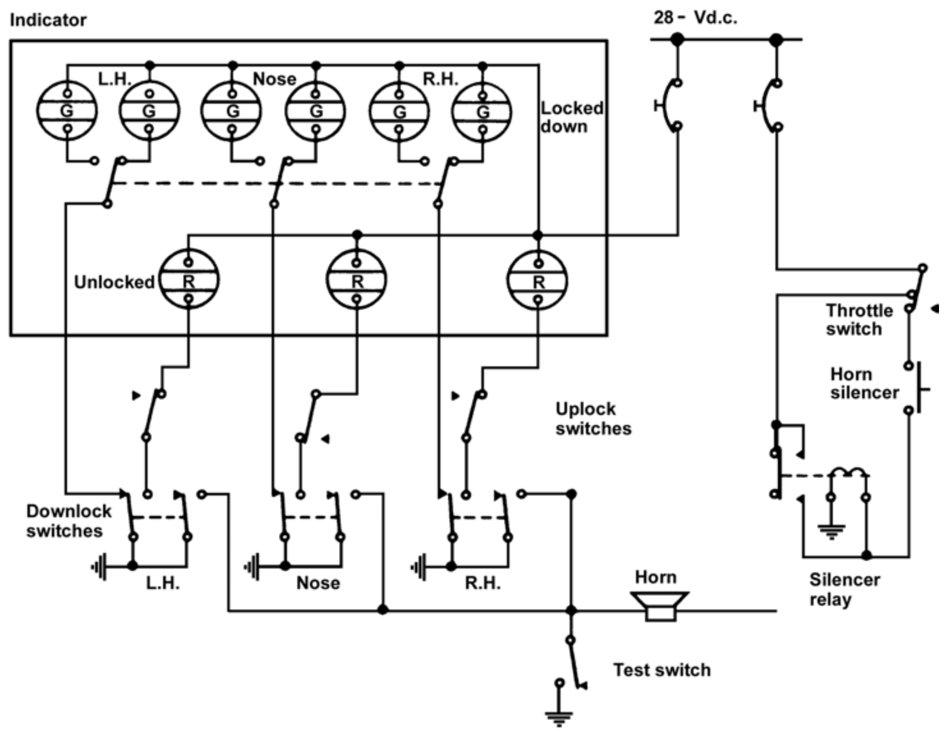

Fig. 17.56. Landing gear position indicating system.

The system operates from a 28 volts d.c. power supply which is connected to lamps within the indicator case, and also to be up-lock and down-lock micro-switches of the main and nose landing gear units. Three of the lamps are positioned behind red screens, and three behind green screens; thus, when illuminated they indicate respectively, "gear up and locked" and "gear down and locked". In the "gear up and locked" position all lights are extinguished. In the event of failure of a green lamp filament, provision is made for switching-in a standby set of lamps.

The circuit as drawn, represents the conditions when the aircraft is on the ground in a completely static condition. As soon as power goes onto the busbar, the three green lamps will illuminate because their circuits are completed to ground via the left-hand set of contacts of the corresponding down-lock micro-switches. The engine throttle is closed, and although its microswitch is also closed, the warning horn circuit is isolated since there is no path to ground for current from the busbar. Assume now that the aircraft has taken off and the pilot has selected "landing gear up"; the down-lock mechanisms of the gear units are disengaged and they cause their microswitches to change contact positions, thus interrupting the circuits to the green lamps. At the same time, the red lamps are illuminated to indicate that the gear units are unlocked, the power supply for the circuit passing to ground via the up-lock switches, and the right-hand contacts of the down-lock switches. When the landing gear units reach their retracted positions, the up-lock mechanisms are engaged and cause their microswitches to interrupt the circuits to the red lamps; thus, all lamps are extinguished. When the pilot selects "landing gear down", the up-lock mechanisms now disengage and the micro-switches again complete the circuit to the red lamps to indicate an unlocked condition. As soon as the gear units reach the fully extended position, the down-lock mechanisms engage and their microswitches revert to the original position shown in (Fig. 17.56) i.e., red lamps extinguished, and green lamps illuminated to indicate "down and locked".

As noted earlier, a warning horn is included in the system, the making and breaking of the horn circuit being controlled by a throttle-operated microswitch. In the static condition shown in (Fig. 17.56), the throttle microswitch is closed, but the warning horn will not sound since the circuit is interrupted by all three down-lock microswitches. Similarly, the circuit will be interrupted by the throttle is set for take-off and normal cruise power. In the case of an approach to land, the engine power is reduced by closing the throttle to a particular approach power setting and this action closes the throttle microswitch. If, in this flight condition, the landing gear has not been selected down in readiness for landing, then the warning horn will sound since the circuit to ground is then completed via the right-hand contacts of the down-lock microswitches. After selecting "down", the horn continues to sound, but it may be silenced by operating a push switch which, as will be noted from the diagram, energizes a relay to interrupt the horn circuit. The relay incorporates a hold-in circuit so that it will remain energized until the d.c. power supply is finally switched off. Functional testing of the horn circuit on the ground, and under engine static conditions, may be carried out by closing the throttle and its microswitch, and then operating a test switch.

Landing-Gear Control Circuits

On large aircraft-gear actuators are hydraulically operated. The electronic circuity of the system is used to provide an indication of gear position and in some cases to control the hydraulic system components. On some aircraft microswitches are tripped when the landing gear reaches its limit. These switches turn off the hydraulic pump motor and turn on the correct gear indicator in the flight compartment. These systems are very similar to those found on light aircraft.

Another means of controlling landing-gear actuator and indicator systems employs **proximity sensors.** Proximity sensors are simply inductance coils that operate in conjunction with steel targets. The inductance of a coil changes with the proximity of the steel target. As discussed earlier, the inductance of any coil is a function of the core material. If the steel target acts as the core for the proximity coil, the inductance of the coil changes as the steel target moves farther from or closer to the coil. A diagram of a proximity sensor is in (Fig. 17.57). The advantage of these sensors is that there are no moving switch contacts to fail; therefore, the reliability of the system is improved as compared with the performance of systems that employ limit switches.

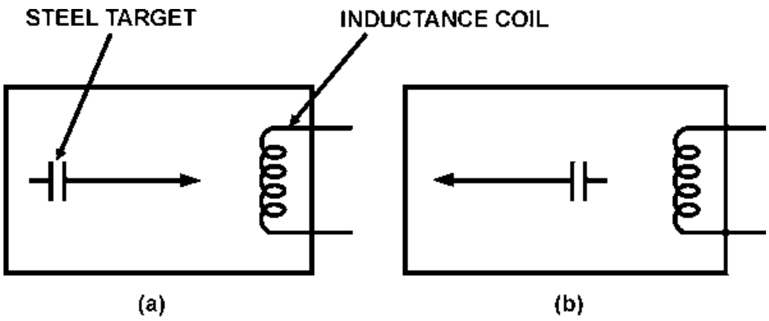

Fig. 17.57. Proximity sensor diagram. (a) Target moving toward coil; (b) Target moving away from coil.

The inductance of a proximity sensor is measured by an electronic control unit. This unit interprets the input data (some from the proximity sensor) and sends out control signals to the landing-gear actuator and indicator systems.

The Boeing 757 aircraft contains a **proximity switch electronic unit** (PSEU), which provides position sensing for landing gear, cabin doors, and thrust reversers. The system contains 70 sensors located throughout the aircraft that provide input data for the PSEU. The PSEU processes the discrete input signals and controls relays, lights, and/or other electronic components.

ANTISKID SYSTEM

The purpose of a wheel brake is to bring a rapidly moving aircraft to a stop during ground roll. It does this by changing the energy of movement into heat energy through the friction developed in the brakes. A feature found in high performance aircraft braking system is skid control or antiskid protection. This is an important system because if a wheel goes into a skid, its braking value is greatly reduced.

The skid control system performs four functions : (1) normal skid control, (2) locked wheel skid control, (3) touchdown protection, and (4) failsafe protection. The main components of the system consist of two skid control generators, a skid control box, two skid control valves, a skid control switch, a warning lamp, and an electrical control harness with a connection to the squat switch.

Normal Skid Control

Normal skid control comes into play when wheel rotation slows down but has not come to a stop. When this slowing down happens, the wheel sliding action has just begun but has not yet reached a full scale slide. In this situation the skid control valve removes some of the hydraulic pressure to the wheel. This permits the wheel to rotate a little faster and stop its sliding. The more intense the skid is, the more braking pressure is removed. The skid detection and control of each wheel is completely independent of the others. The wheel skid intensity is measured by the amount of wheel slow-down.

Skid Control Generator

The skid control generator is the unit that measures the wheel rotational speed. It also senses any changes in the speed. It is a small electrical generator, one for each wheel, mounted in the wheel axle. The generator armature is coupled to, and driven by the main wheel through the drive cap in the wheel. As it rotates, the generator develops a voltage and current signal. The signal strength indicates the wheel rotational speed. This signal is fed to the skid control box through the harness.

Skid Control Box

The box reads the signal from the generator and senses change in signal strength. It can interpret these as developing skids, locked wheels, brake applications, and brake releases. It analyses all it reads, then sends appropriate signals to solenoids in the skid control valves.

Skid Control Valves

The two skid control valves mounted on the brake control valve are solenoid operated. Electric signals from the skid control box actuate the solenoids. If there is no signal (because there is no wheel skidding), the skid control valve will have no effect on brake operation. But, if a skid develops, either slight or serious, a signal is sent to the skid control valve solenoid. This solenoids action lowers the metered pressure in the line between the metering valve and the brake cylinders. It does so by dumping fluid into the reservoir return line whenever the solenoid is energized. Naturally this immediately relaxes the brake application. The pressure flow into the brake lines from the metering valves continues as long as the pilot depresses the brake pedals. But the flow and pressure is rerouted to the reservoir instead of to the wheel brakes.

The utility system pressure enters the brake control valve where it is metered to the wheel brakes in proportion to the force applied on the pilot's foot pedal. However, before it can go to the brakes, if the solenoid is actuated, a port is opened in the line between the brake control valve and the brake. This port vents the brake application pressure to the utility system return line. This reduces the brake application, and the wheel rotates faster again. The system is designed to apply enough force to operate just below the skid point. This gives the most effective braking.

Pilot Control

The pilot can turn off the operation of the anti-skid system by a switch in the cockpit. A warning lamp lights when the system is turned off or if there is a system failure.

Locked Wheel Skid Control

The locked wheel skid control causes the brake to be fully released when its wheel locks. A locked wheel easily occurs on a patch of ice due to lack of tire friction with the surface. It will occur if the normal skid control does not prevent the wheel from reaching a full skid. To relieve a locked wheel skid. The pressure is bled off longer than in normal skid function. This is to give the wheel time to regain speed. This is locked wheel skid control is out of action during aircraft speeds of less than 15-20 mph.

Touchdown Protection

The touchdown protection circuit prevents the brakes from being applied during the landing approach even if the brake pedalsare depressed. This prevents the wheel from being locked when they contact the runway. The wheels have a chance to begin rotating before they carry the full weight of the aircraft. Two conditions must exist before the skid control valves permit brake application. Without them the skid control box will not sent the proper signal to the valve solenoids. The first is that the squat switch must signal that the weight of the aircraft is on the wheels. The second is that the wheel generators sense a wheel speed of over 15-20 mph.

Fail-Safe Protection

The fail-safe protection circuit monitors operation of the skid control system. It automatically returns the brake system to full manual in case of system failure. It also turns on a warning light.

Windshield Wiper Systems

The circuit arrangement shown in (Fig. 17.58) is typical of many of the windshield wiper systems currently in use. The wiper arms and blades for each windshield are actuated by their own 28-volt d.c. variable-speed motors coupled to converters. Each motor is supplied from different busbars and is controlled by a four-position selector switch (in some cases the switch may have six positions) and the speed variation according to selection, is accomplished by voltage dividing resistances.

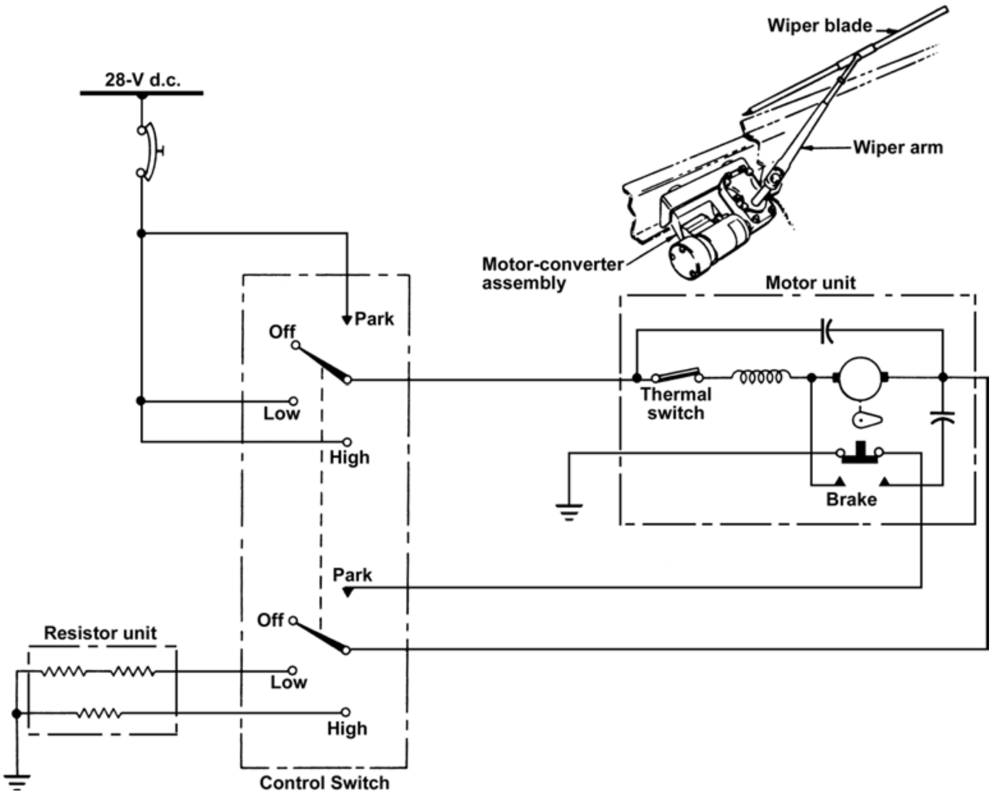

Fig. 17.58. Windshield wiper system.

In the "low" position of the switch, voltage is applied to the field and armature circuits of the motor, and then to ground via a second contact of the switch and two resistors. The voltage is there fore reduced and the motor runs at a low speed, and by means of its converter sweeps the wiper arm back and forth. When the "high" position of the switch is selected, the supply passes to ground through only one resistor and so the motor and wiper will operate at a faster speed.

When the use of the wipers is no longer required, the control switch is turned back through the "off" position to a "park" position. There is no detent in this position, and so the switch is manually held there momentarily. As will be noted from (Fig. 17.58), the supply voltage is initially applied to the motor in the normal way, but as the connection to ground is now directly through the normally-closed contacts of a brake switch within the motor, then it will run at its faster speed. As the wiper blade reaches its parked position, the motor operates a cam to change over the brake switch contacts which then short out the armature to stop the motor. The switch is then released to spring back to the "off" position.

The purpose of the thermal switch is to open the motor circuit if the field winding temperature or field current should exceed pre-determined values. Typical values are 150^0C (300^0F) and 8 to 10 amperes respectively.

Rain Repellent Systems

The purpose of these systems is to maintain a clear area on the windshields of an aircraft during take-off, approach and landing in rain conditions. A system consists of a pressurized container of repellent fluid, control switch, a solenoid valve controlling the supply of fluid to a spray nozzle mounted in the fuselage skin in front of each windshield. The fluid container is common to each windshield system and is located in the cockpit.

The operation of the system is illustrated in (Fig. 17.59). When the control switch is pushed in, a 28-volt d.c. supply is fed to the solenoid valve via the closed contacts "B" of the control relay. The spray nozzle solenoid is therefore energized to open the valve and allow fluid to flow under pressure through the spray nozzle and onto the windshield. The fluid is of a type which causes the surface tension in water to change so that the water is formed into globules which are blown off the windshield by the airstream. Through the action of a time delay circuit, approximately 5 c.c. of fluid flows through the nozzle for approximately 0.25 seconds.

At the end of this period, the time delay circuit applies power to the gate of an SCR which then energizes the control relay and in turn de-energizes the spray nozzle solenoid valve. If the control switch remains pushed in, the time delay circuit will keep the control relay energized via a hold-in circuit across the closed contacts "A". When the switch is released, the time delay circuit and SCR are returned to their original state.

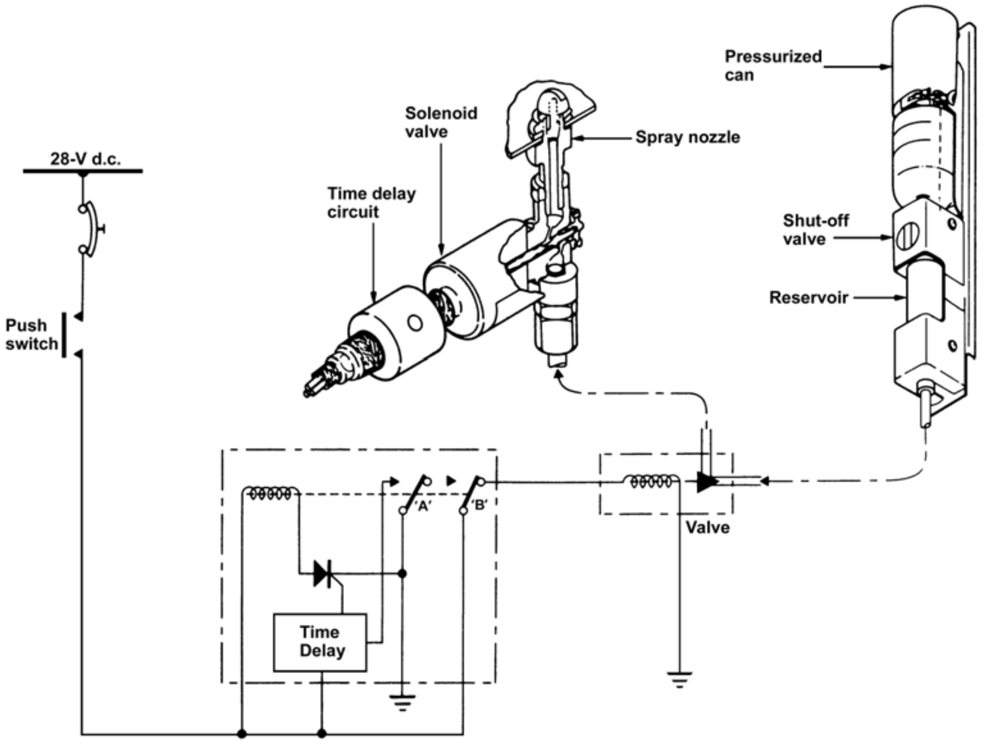

Fig. 17.59. Rain repellent system.

The fluid is contained in a can which when screwed onto the mounting bracket opens a valve to allow fluid to drain into a reservoir and the system tubing. The reservoir is a clear plastic cylinder containing a float-type contents indicator. A manually-operated shut-off valve is provided between the reservoir and can and is used during can replacement.

Airconditioning Systems

These systems are designed to maintain selected air temperature conditions within flight crew, passenger and other compartments, and in general, they are comprised of five principal sections: air supply, heating, cooling, temperature control, and distribution. The operation of systems varies depending on the size and type of aircraft for which they are designed, and space does not allow for them all to be described. However, if we take the case of most of the large transport aircraft, we find that there are a number of common features which may be represented as shown in (Fig. 17.60.)

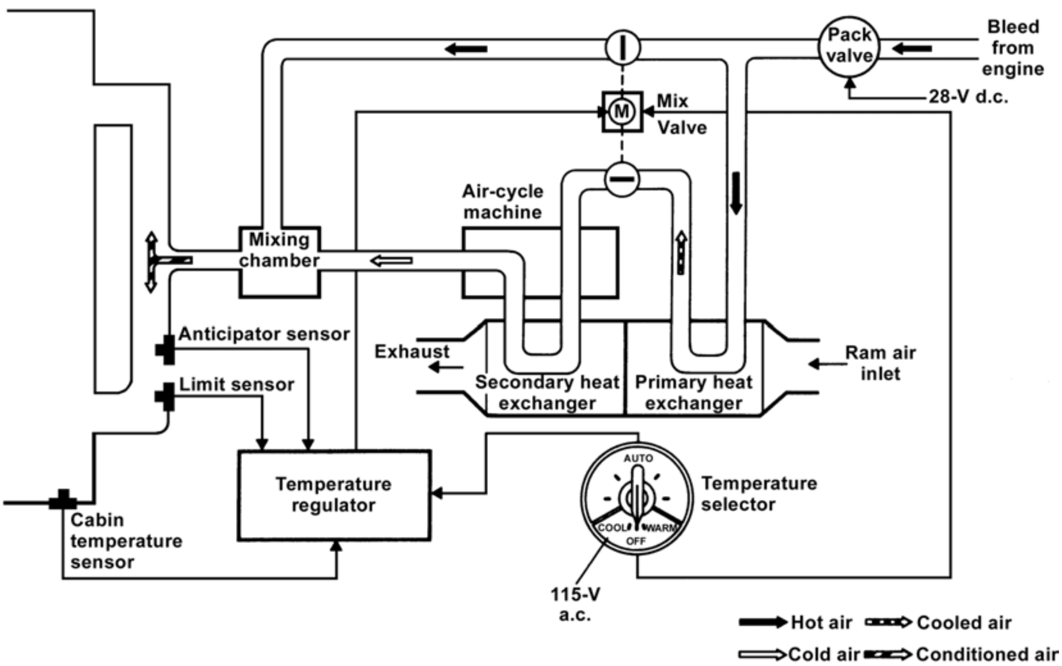

Fig. 17.60. Airconditioning system.

As in the case of hot air bleed anti-icing systems, air is supplied from stages of the main engine compressors and serves not only to provide air conditioning but also pressurization of the cabin. Since the air from the compressor stages is too warm for direct admission to the cabin, it has to be mixed with some cold air in order to attain preselected temperature conditions. This is effected by directing some of the bleed air through a cooling pack consisting of a heat exchanger system and a cooling turbine or air cycle machine. The control of the bleed air flow is accomplished by an electrically controlled pack valve, which is energized by a switch on the system control panel in the cockpit. Down-stream of the pack valve is a mox valve which has the function of proportionately dividing the hot air flow from the pack valve, and the cold air flow from the air cycle machine, into a mixing chamber. The mix valve is of the dual type; both valves being positioned by a common 115-volt a.c. actuator motor. The valves are monitored by signals from the temperature control system such that as one valve moves towards its close position, the other valve moves towards its open position.

The temperature control system is comprised principally of a selector switch, regulator, and temperature sensors located at selected points in the system. The whole system operates automatically and continuously monitors the mix valve position, but in the event of failure of the regulator, mix valve position may be carried out manually from the selector switch.

When the selector switch is in the "auto" position and at a desired cabin temperature, a potentiometer within the switch establishes a reference resistance value in an arm of a control bridge circuit of the regulator. A cabin temperature sensor is in the other arm of the control bridge circuit so that if the cabin temperature is at a level other than that selected, then the bridge will be unbalanced. As a result, a signal is developed in the circuit of the mix valve motor so that it will drive the valves to either a hot or cold position, as required, to attain the selected cabin temperature. At the same time, conditioned air is sensed by an anticipator sensor, and a limit sensor both of which are located in the ducting to the cabin, and are connected in an electrical bridge configuration. The purpose of the sensors is to modulate any rapid changes demanded by an unbalanced control bridge so that when the actuator control moves the mix valve it will produce cabin temperature changes without sudden blasts of hot or cold air, and without raising duct temperatures above limits.

To prevent the mix valve staying at a "too hot" position, a thermal switch which is set at a particular level (e.g. 90^{0}C (195^{0}F)) is located in the ducting to complete a circuit to the mix valve so that its motor will run the valve to the full cold position. At the same time a "duct overheat" light is illuminated. After the overheat condition has been corrected, the system may be returned to normal by means of a reset switch. Another thermal switch set to close at a higher level (e.g. 120^{0}C (125^{0}F)) protects against duct overheat should power control be lost. It completes a circuit which closes the pack valve and illuminates a "pack trip off" light. The system may be returned to normal after the trip condition has been corrected, by operating the reset switch referred to above.

Manual control of the system is effected by moving the selector switch to "cool" or "warm" to directly actuate the mix valve as appropriate.

Propeller Synchronizer Systems
These systems are used in some types of twin-engined aircraft, their purpose being to automatically synchronize the r.p.m. of the propellers. This is accomplished by utilizing the speed governor of one propeller as a master unit, and the governor of the second propeller as the slave unit. Both governors have magnetic pick-ups which supply electrical pulses to a control unit which detects any difference in the frequency of the pulses. The resulting output from the control unit is fed to a stepping type motor actuator mounted on the slave governor which is then "trimmed" to maintain its propeller r.p.m. at the same value as the master governor unit, and within a limited range. The limiting range of operation is built into the synchronizer system to prevent the slave governor unit fom losing more than a fixed amount of propeller r.p.m. in the event of the master engine and propeller being "feathered" when the system is in operation.

Before the system is activated, the r.p.m. of each propeller is manually synchronized as close as possible. When this has been done and the system is then activated, a maximum synchronizing r.p.m. range (typically ± 67) is effective.

Passenger Cabin Services
In passenger transport aircraft electrical power is required within the main cabin compartments for the service and convenience of the passengers, the extent of power utilization being governed of course, by the aircraft size and number of passengers it is designed to carry. Apart from the main cabin lighting referred to on page 152 it is necessary to provide such additional services as individual reading lights at each seat position, a cabin attendant call system, public address system and a galley for the preparation and serving of anything from light refreshments to several full-course meals. In-flight cinema entertainment also accounts for the utilization of electrical power in many types of aircraft.

Reading lights may be of the incandescent or fluorescent type, and are located on passenger service panels on the underside of hat racks, or in each seat headrest and are controlled individually. Cabin attendant call systems are interlinked systems comprising switches at each passenger service panel connected to an electrical chime and indicator light at the cabin attendant's panel station. The service panel switches are of the illuminating type to visually indicate to the cabin attendant the seat location from which a call has been made. In addition the system provides an interconnection between the flight crew compartment and cabin attendant's station.

A public address system is provided for giving passengers instructions and route information, and usually comprises a central amplifier unit and a number of loudspeakers concealed at various points throughout the cabin, and in toilet compartments. Information is given, as appropriate, by the aircraft's captain or cabin attendant by means of separate telephone type handsets connected to the loudspeakers. Tape-recorded music may also be relayed through the system during passenger embarkation and disembarkation.

Galley equipment has a considerable technical influence on the design of an aircraft's electrical system, in that it represents a very high percentage of the total system power requirement, and once installed it usually becomes a hard-worked section of an aircraft. The type of equipment and power loadings are governed by such factors as route distances to be flown, number of passengers to be carried and the class configurations, i.e. "economy" , "first-class" or "mixed". For aircraft in the "jumbo" and "wide-bodied" categories, galley requirements are, as may be imagined, fairly extensive. In the Boeing 747 for example, three galley complexes are installed in the cabin utilizing both 28 volts d.c. and 115 volts a.c. power and having a total power output of 140 kVA; thus, assuming that the generator output is rated with a power factor of unity, the equivalent d.c. output is 140 kilowatts or in terms of horsepower approximately 187! The galley unit of the wide-bodied Lock-heed "Tristar" is also a complex unit but is located as a central underfloor unit. It also utilizes d.c. and a.c. power not only heating purposes but also for the operation of lifts which transport service trolleys to cabin floor level.

The equipment varies, some typical units being containers and hot cups for heating of beverages, hot cupboards for the heating of pre-cooked meals and ovens for heating of cold pre-cooked meals, a number of which may have to be served, e.g. on long-distance flights. Other appliances required are water heaters for galley washing-up and toilet washbasins, and refrigerators. In most cases, the equipment is assembled as a self-contained galley unit which can be "plugged in" at the desired location within the aircraft.

It is usual for the electrical power to be supplied from the main distribution systems, via a subsidiary busbar and protection system, and also for certain galley equipment to be off-loaded in the event of failure of a generating system. The load-shedding circuit is automatic in operation and any override system provided is under the pilot's control; on some aircraft load-shedding is also controlled via a landing gear shock-strut microswitch thereby conserving electrical power on the ground. The control panel or panels, which may be mounted on or adjacent to the galley unit, incorporates the control switches, indicator lights and circuit breakers associated with each item of galley equipment, and also the indicator lights of the cabin attendant call system.

Electrically operated flap control systems are usually comprised of a reversible DC motor which drives the flap mechanism up and down through suitably designed reduction gearing. The flap mechanism has stops which operate limit switches to stop the flap travel at the extreme ends of the range. The operation of the flap motor is controlled by a flap selector switch which has three positions up, "off" and down. Quite often, the down position on the selector switch is spring-loaded to the centre off position while the up position is not. This is to allow the pilot to inch the flaps down to the desired position but to select full up when he requires it in the event of an aborted landing and go around. Most flap systems also incorporate a flap position indicator system to shown the pilot the precise amount of flap selected. See (Fig. 17.61).

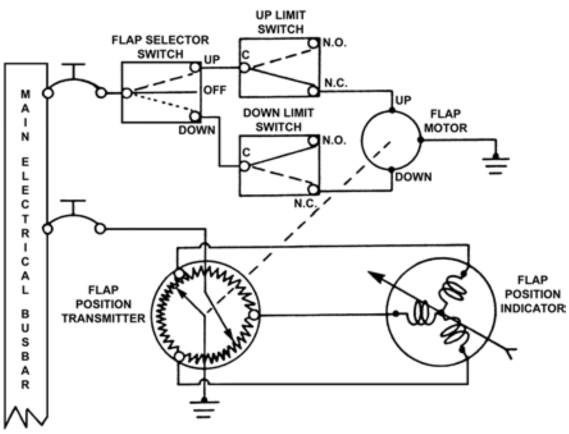

Fig. 17.61. Typical flap control and indication system.

A. OPERATION

1. Flap control, flaps selected up

Flaps are in down position as shown in circuit. Selection of flap selector switch to up allows power to be applied to the motor up terminal through the closed contacts of the up limit switch.

The motor runs in an up direction and the flaps start moving up. As soon as the flaps leave the down position the down limit switch changes over its contact preparing the circuit for a down selection as shown dotted. The flaps continue to move and when they reach the fully up position, the up limit switch changes its contacts and switches off the motor as shown dotted. The flaps are now in a fully up condition.

NOTE : At any point between up and down, both limit switches are closed. This allows the pilot to stop and start the flaps in either direction from any intermediate point.

2. Flap control, flaps selected down

The flaps are up. The limit switches are in the dotted line positions. Selection of the flap selector switch to down applies power through the down limit switch to the down terminal of the motor. The motor runs in the opposite direction to the flap control, flaps selected up, and the flaps move down. As soon as the flaps leave the up position, the up limit switch changes over to the solid line position in preparation for the next up selection.

The flaps continue down until they reach fully down and the down limit switch is operated to the solid line position. This opens up the line to the motor and the motor stops. Placing the flap selector switch to off at any time will stop the flaps at any desired position.

3. Flap position system

As the flap motor is operated there is a mechanical linkage to the flap operating shaft which turns the arrowed wipers in the flap position transmitter. This varies the ratio of electrical power applied to the three coils in the position indicator and lines up the needle in a new position.

The variation in ratio of power applied to the three coils is calibrated on a scale in degrees of flap movement. By monitoring the amount of movement on the indicator the pilot can select precisely the amount of flap required for a particular flight requirement.

Many aircraft have electrically drive fuel booster pumps installed. The purpose of these pumps is to provide fuel pressure in an emergency should the engine drive pump fail and to provide fuel priming during start.

In earlier aircraft, the fuel booster pump was simply and electrically driven pump controlled by a simple "on-off" switch. As aircraft became more sophisticated, there became a need for various speeds to be produced by fuel booster pumps to deliver various pressures under different circumtances.

a. Operation of a Simple Booster Pump Circuit

The operation of this system is very simple. Selection of the appropriate pump switch will operated that pump at one speed only. See (Fig. 17.62).

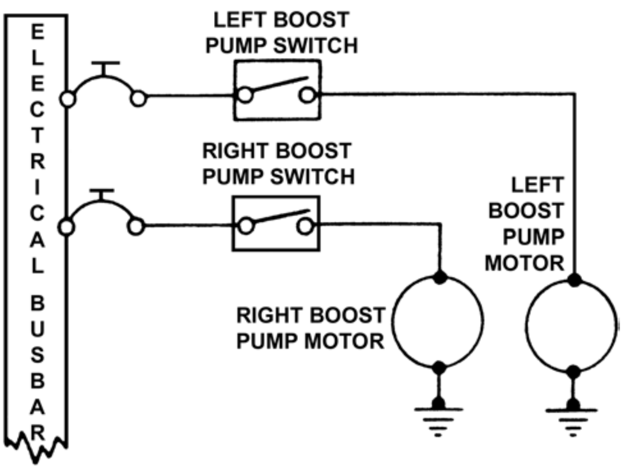

Fig. 17.62. Simple booster pump circuit.

1. Operation of a booster pump 2-stage throttle controlled

Selection of selector switch to low position ensures that power is applied through the speed control resistor to the motor making it operate at low speed.

When the engine is running, the selector switch is placed to "hi". This routes power through the throttle microswitch. If the throttle is set below 1/3 full open, the power must go through the C to N.C. contacts and the speed control resistor and the pump motor runs at low speed.

If the throttle is advanced above 1/3 full power, the C to N.O. contacts of the microswitch are connected. This applies full power to the bottom of the speed control resistor and the pump motor runs at full speed. (See Fig. 17.63).

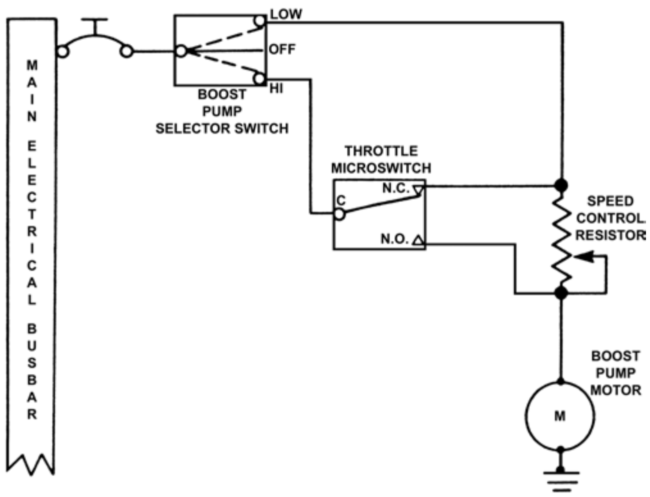

Fig. 17.63. Booster pumps 2-stage throttle controlled.

b. Functional Description of the System

Priming the engines. Selection of the prime switch to the appropriate engine connects power to the appropriate pump through the particular dropping resistor for that pump. The pump runs at low speed for priming. (See Fig. 17.64).

When the engines are started the oil pressures build up and both oil pressure switches close and apply power the two auxiliary pump switches. Selection of the auxiliary pump switches to low passes power to the pump relay and up through the dropping resistors to the pumps, running the pumps at low speed.

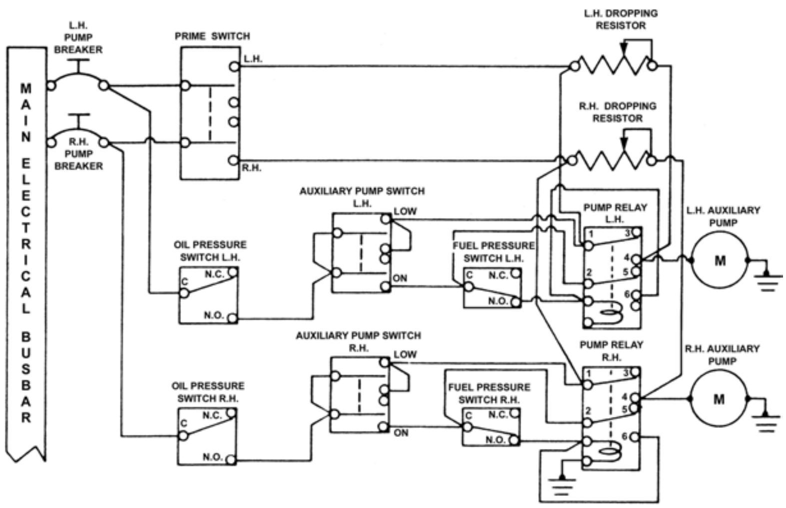

Fig. 17.64. Auxiliary fuel pumps for a Cessna 310.

Selection of the auxiliary pump switches to "on" applies power to the fuel pressure switches and contact 2 of the pump relays. Power is also applied to contact 1 of the pump relays from the low position of auxiliary pump switches. The pumps continue to run at low speed.

As long as there is fuel pressure in the system the fuel pressure switches will remain open. If the fuel pressure drops to a level which may cause problems in the transfer of fuel to the engines, the pressure switches will close from C to N.C. and energize the pump relay. This applies power across pins 1 and 4 of the relays straight to the motors and they run at full speed. At the same time, power is applied from the C terminal of the fuel pressure switch through contacts 2 and 6 of the pump relays to the relay coil which latches the pump relay on. This ensures that the pump motors continue to run at full speed.

If the fuel pressure problem comes back within normal limits. The pilot may re-position his auxiliary pump switches to off then back to on and the pumps will again run at reduced speed.

The normal position of the auxiliary pump switches for cruise would be "on" and the fuel pressure switches detect loss of pressure. By energizing the pump relay, they correct the situation automatically by increasing pump delivery pressure.

Built - In Test Equipment

Large aircraft often incorporate **built-in test equipment** (BITE) systems to monitor and detect faults in a variety of aircraft systems. The use of BITE systems reduces troubleshooting costs by eliminating the time required to connect carry-on test equipment, perform tests, and remove that equipment. The built-in test equipment continuously tests the various systems and stores all fault information so it can be recalled later by line technicians. Once the appropriate repair has been made, the BITE system can be used to retest the system for proper operation. Most BITE systems are capable of isolating system faults with at least a 95 percent probability of success on the first attempt.

The introduction of digital systems on aircraft has made BITE systems possible. Discrete digital signals are used as the code language for BITE systems. Built-in test equipment interprets the various combinations of digital signals to determine a system's status. If an incorrect input value is detected, the BITE system records the fault and displays the information upon request. As shown on this version of a BITE system illustrated in (Fig. 17.65), the fault information is displayed by light-emitting diodes on the face of the BITE unit when the appropriate button is depressed. Other BITE systems include more user-friendly displays that can be accessed from the flight deck. The proper operation and troubleshooting techniques associated with the BITE systems will be discussed later in this chapter.

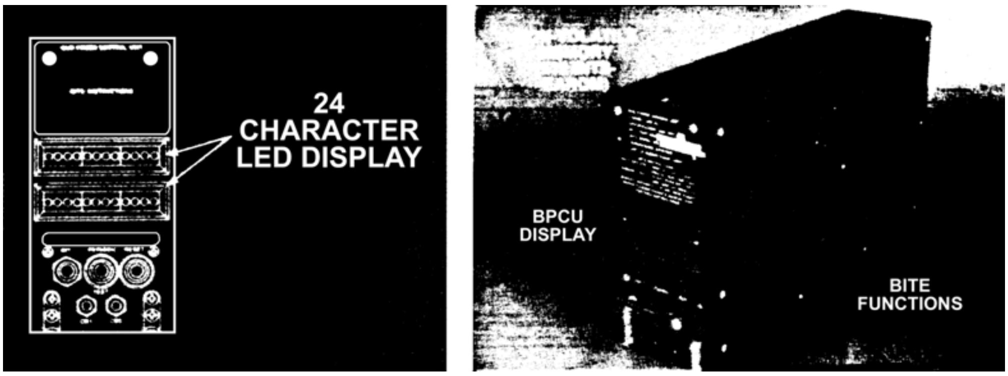

Fig. 17.65. Built-in test equipment. (a) LED display (b) bus power control unit with BITE display.

Intercom and Interphone Systems

The **intercom** system is used for communication between flight crew personnel and passengers. This system typically contains a control panel and microphone at one or more flight attendants stations and in the flight compartment. The intercom is used to inform passengers of flight details and communicate any instructions necessary to ensure a safe and comfortable flight. On most aircraft there is one central intercom amplifier, which connects to several speakers throughout the aircraft. The amplifier's volume level is automatically adjusted to compensate for varying cabin noise.

An **interphone** system provides a means of communication between flight crew members and ground service personnel. Communication during fueling, ground handling, and baggage storage is essential. On a large aircraft it is virtually impossible to communicate from the cockpit to areas outside the aircraft without some form of assistance. The interphone system contains an amplifier and several stations where a headset, containing a microphone and speaker, can be connected to the system.

The interphone system can also be used during aircraft maintenance. (Fig. 17.66) shows the interphone configuration for a typical MD-80. If communication is needed between maintenance personnel inside and outside the aircraft, the intrphone system is typically used. The system receives power from the ground service bus; thus it can be operated without use of the aircraft's generators.

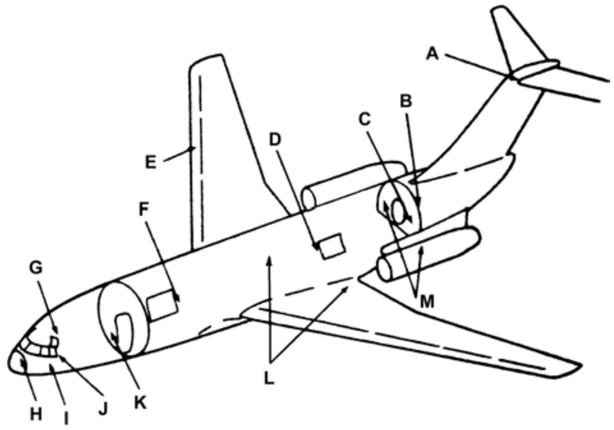

Fig. 17.66. Typical interphone connection locations. (A) Vertical stabilizer; (B) aft accessory compartment; (C) aft cabin attendant station; (D) aft lower cargo compartment; (E) fueling control panel; (F) forward lower cargo compartment; (G) flight crew cabin; (H) forward accessory compartment; (I) external power control panel; (J) electrical/electronics compartment; (K) forward cabin attendant station; (L) main gear wheel wells; (M) aft fuselage (external).

Electrical Control Units

On modern large aircraft there are several types of control units used to monitor, test, and regulate various electrical systems. These control units, commonly known as black boxes, are miniature computers designed for a specific function. Typically, black boxes are **line replaceable units** (LRUs) designed for quick removal and installation. Employing the LRU concept has helped to reduce maintenance times and improve airline productivity. Several of these control units are found on modern commercial aircraft. The **generator control unit** (GCU) and **ground power control unit** (GPCU) have already been discussed.

Other common control system include the **thrust management computer** (TMC), which is used to analyze engine parameters and power requests in order to control engine thrust, and the **flight management computer (FMC)**, which monitors flight parameters and performs autopilot functions. The FMC regulates the movement of the control surface actuators. These actuator mechanisms provide control for most primary and secondary control surface, such as stabilizers, elevators, rudders, speed brakes, and spoilers.

Engine indicating and crew alerting system (EICAS) control units monitor various electrical parameters and display system status to the flight crew. The EICAS is also responsible for alerting the crew in case of an emergency situation. As illustrated in (Fig. 17.67), the two EICAS computers receive input data from various airframe and engine sensors. Output data are sent to warning electronic units, the standby engine indicator, and the EICAS display panels. The EICAS display panels consists of two cathode-ray tubes (CRTs). Each CRT is used to display status, caution, or warning information. On Airbus Industries aircraft a similar system is used to monitor engine and flight parameters. This system is known as **electronic centralized aircraft monitoring** (ECAM). The EICAS and the ECAM system will be discussed.

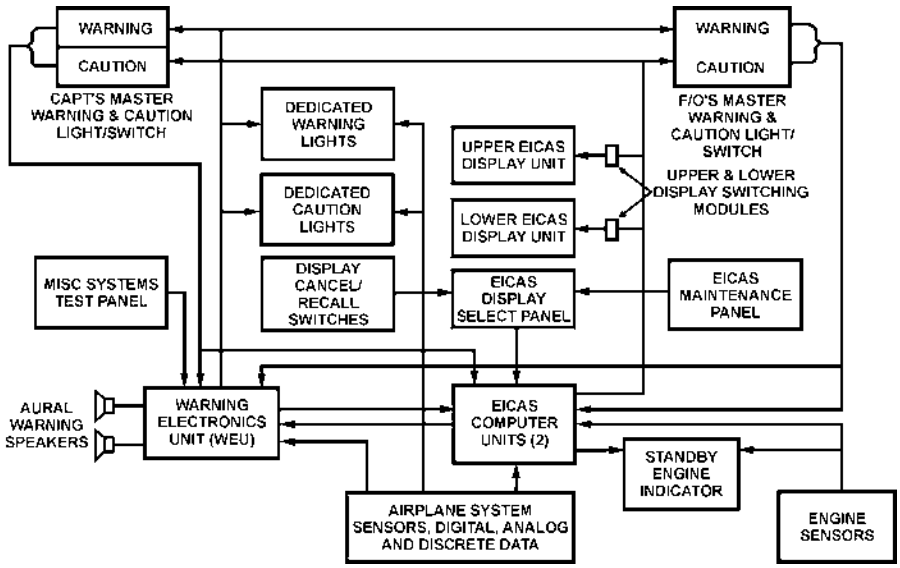

Fig. 17.67. Block diagram of engine indicating and crew alerting system.

Equipment Cooling

Heat is an electronic unit's biggest enemy; therefore, most aircraft contain some means of electronic-equipment cooling. Since large aircraft contain numerous electronic LRUs, they are, for the most part, centrally located. Typically, this equipment compartment is behind and/or below the aircraft's flight deck. The use of a centralized equipment center enables cooling with a minimum of air ducts.

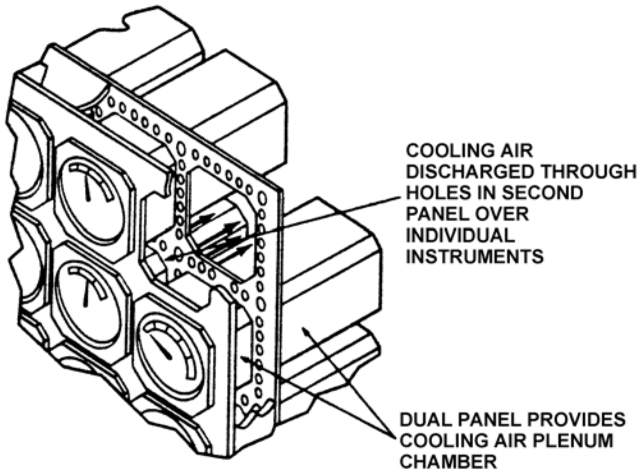

Fig. 17.68. Instrument cooling system.

Cooling fans and air ducts are commonly employed to force air over the warm equipment and dispense the heat overboard. In some cases heat exchangers are used to cool the warm air and recirculate it back over the equipment. On some aircraft separate air conditioner units are used to ensure proper equipment cooling. In this case the warm air is circulated through the air conditioner, and the cool air is returned to the equipment compartment.

Most equipment-cooling systems also employ overheat and smoke detector sensors. These sensors monitor the system and provide an appropriate indication for the flight crew. The flight crew may then take the appropriate actions to ensure proper system operations.

Pressurized air can also be used to cool electronic instruments. Cooling air is forced into a plenum chamber created by an inner and outer instrument panel. As illustrated in (Fig. 17.68), holes in the inner panel direct air over each instrument. This process improves instrument cooling and enhances the reliability of the instruments.

MAINTENANCE AND TROUBLESHOOTING OF ELECTRICAL SYSTEMS

General Requirements

To ensure safe flight operations, electrical systems must be maintained in perfect working condition. The routine inspection procedures performed on all aircraft are used to detect any potential electrical system failures. During these inspections, specific electric components are inspected and tested as dictated by the manufacturer. If a malfunction or defect is found, the proper maintenance procedures are used to correct the problem.

Electrical system failure is not always detected during inspections. Often system fail during operation and must be repaired prior to further flight. Maintenance of this type is usually more critical; that is, the aircraft downtime must be as short as possible. Unexpected maintenance causes flight delays, passenger inconvenience, and lower profit margins. Maintenance of electrical systems must be performed with both speed and accuracy. The safety of any flight often lies in the hands of the aircraft technician. Be sure to perform all maintenance procedures and electrical system inspections in accordance with the manufacturer's recommendations and to the best of your ability.

Inspection Schedules

By mandate of the FAA flight regulations, all civilian aircraft must be inspected in accordance with a schedule set forth by an approved inspection program. The **100-hour**, the **annual**, or the **periodic inspection program** can be used for light-aircraft inspections. Each of these programs is designed to instruct the aircraft technician as to which systems and components require routine maintenance and/or inspection.

Large aircraft are typically maintained according to one of the inspection programs approved by the FAA. These programs, known as **continuous airworthiness inspection programs,** include various routine service inspections and more complete maintenance procedures called checks. An A-check, B-check, C-check, and D-check are designed to fit the specific needs of a particular aircraft operator. A-checks are the simplest; routine maintenance is performed approximately every 200 hours. D-checks are typically complete air-frame overhauls performed every 4 to 5 years. Typically under this type of system, certain portions of the aircraft are inspected at given intervals of flight time. For example, the aircraft's position lights require an operational check during a preflight walkaround inspection; every 100 hours the oil level of the integrated drive generators may require visual inspection, with oil added as needed. Repair or replacement of any defective flight-critical parts must be completed prior to the aircraft's return to service. During a check any life-limited electrical parts must be replaced or overhauled according to the manufacturer's schedule.

On large aircraft the use of built-in test equipment often facilitates an inspection. The technician can quickly and easily inspect an electrical system by examining the fault data stored by the test equipment. If a fault is stored within the system's memory, the technician can make necessary repairs during the inspection. The current trend in the aircraft industry is to employ more BITE systems wherever possible. This is being done in an effort to reduce maintenance costs and aircraft downtime.

Light aircraft are often maintained on an annual or 100-hour inspection basis. During an inspection of this type, the entire aircraft is inspected, including the electrical systems. All electrical systems, their components, and related wiring should be checked in accordance with the inspection schedule. Typically, an operational check of all electrical systems is conducted. Any defects are repaired, routine maintenance is performed, and all life-limited parts are replaced.

Life-limited parts are those that deteriorate beyond use in a given length of time. For example, emergency lighting system batteries are often considered life-limited parts; that is, they must be replaced on or before specific dates. Routine maintenance of electric components may include servicing batteries, lubricating motor bearings, and replacing generator brushes. Inspections of electrical systems include an operational check and a visual inspection. While performing a visual inspection, the technician should look for loose connectors, chafed wires, poor electrical bonding, loose bundle supports, nicked or damaged wire insulation, and any other obvious defects.

Multimeter Troubleshooting

A multimeter is a combination of three basic instruments: an ohmmeter, a voltmeter, and an ammeter. This combination instrument has made it possible for the technician to reduce his or her inventory of test instruments. Each of the three instruments contained within a multimeter performs a specific function. A typical multimeter is shown in (Fig. 17.69). Of the three instruments, the voltmeter is by far the most useful tool to detect an open circuit.

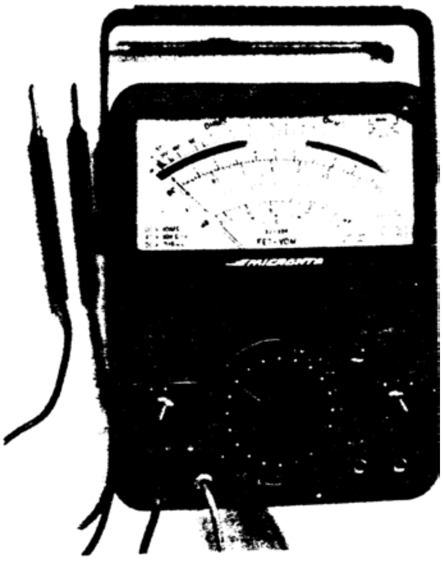

Fig. 17.69. A typical analog multimeter.

Open circuits (opens) are the most common wiring defect. Open circuits are created by broken wires, defective connectors, loose terminals, and any other condition that creates a circuit disconnection (see Fig. 17.70). Opens can also occur within components such as switches, fuses, circuit breakers, lamps, or motors.

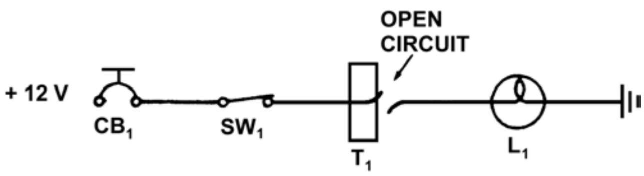

Fig. 17.70. Diagram to illustrate an open circuit.

Short circuits (shorts) are also common problems for aircraft electrical systems. There are two types of short circuits, a **short to ground** and a **cross short**. A **short to ground** from a positive wire creates an infinite current flow because of the extremely low resistance from the voltage positive to negative (see Fig. 17.71). In Fig. 17.71(a), the wire broke, forming an open circuit; the conductor exposed by the break then shorted to ground. In Fig. 17.71(b), the wire's insulation failed and exposed the conductor; the exposed conductor shorted to ground. The high current flow opens the circuit is not protected, the wiring will overheat and most likely melt into a disconnection. A **cross short** takes place when two or more circuits are accidentally connected together (see Fig. 17.72). In this situation, when one circuit is switched on, more than one circuit operates. A cross short connects power to an "extra" circuit. Short circuits are most likely created by the friction between two wires or between a wire and the airframe. The friction wears through the insulation, and the conductor is exposed, thus creating the potential for a short circuit. An ohmmeter is usually used to troubleshoot both types of short circuits.

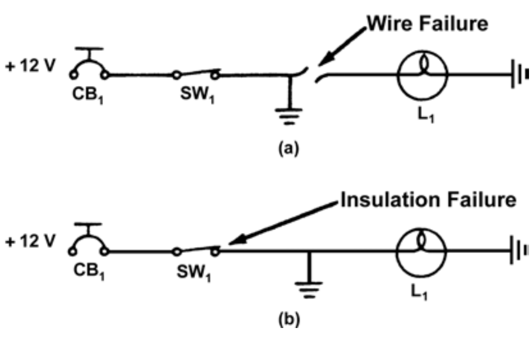

Fig. 17.71. An illustration of a short to ground
(a) created bya a broken wire and
(b) created by defective insulation.

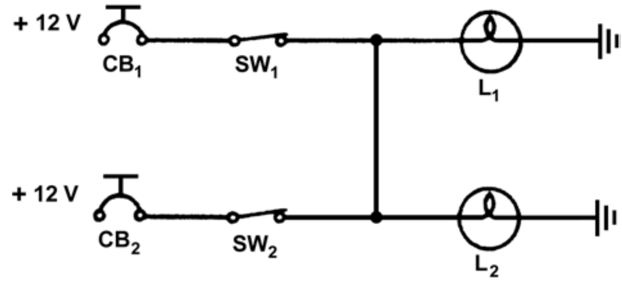

Fig. 17.72. An illustration of a cross short. Both L_1 and L_2 illuminate when SW_1 or SW_2 is closed.

Voltmeter Troubleshooting

Voltmeters are always connected in a circuit in parallel with respect to that portion of the circuit to be measured. If one probe of a voltmeter is connected to a positive voltage and the other probe to a negative voltage, the meter will indicate the voltage difference between those two points.

If one desires to measure the voltage available to the lamp represented in Fig. 17.73 (a), the voltmeter should be placed between points A and B. Point A is connected to the positive of the battery, and point B is connected to the negative of the battery. In this case the voltmeter would indicate 12V.

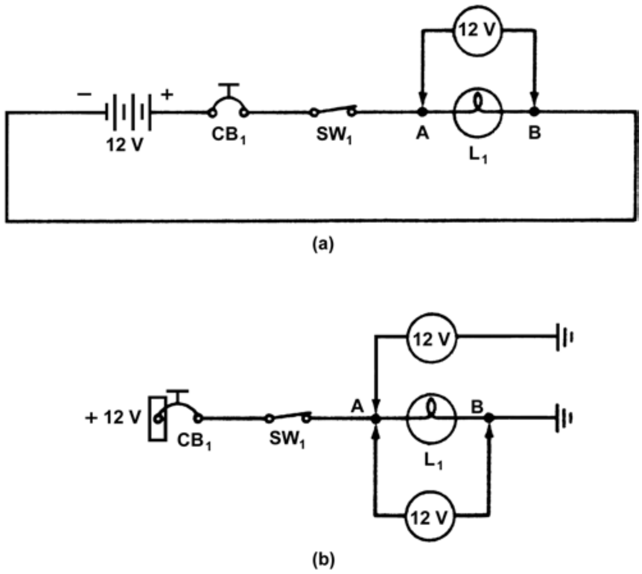

Fig. 17.73. Measuring the voltage available to a light (a) in a two-wire system and (b) in a single-wire system.

In an aircraft most circuits are connected from the positive bus through a load to the aircraft's ground, as shown in Fig. 17.73 (b). Since the negative connection of the battery is connected to the aircraft's ground, a voltmeter connected between points A and B will indicate 12V, and a voltmeter connected between point A and the aircraft's ground will indicate 12. The fact that the entire metal structure of the aircraft is connected to the battery negative makes the voltmeter a very versatile tool. As illustrated in (Fig. 17.74), a voltmeter can be connected to any convenient ground in order to find the positive voltage present in a circuit. Voltmeter V_1 indicates 12 V, V_2 indicates 12 V, and V_3 indicates 12 V. Voltmeter V_4 indicates zero volts because its probes are connected between two negative voltage points (ground to ground).

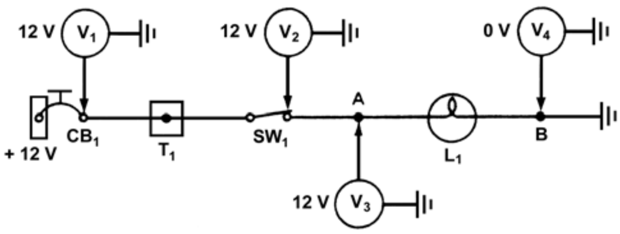

Fig. 17.74. Voltmeters used to test voltage in a circuit.

When using a voltmeter, it is important to consider voltage as consisting of two parts, a positive voltage and a negative voltage. As long as a voltmeter is connected to one positive voltage and one negative voltage, it will indicate system voltage and one negative voltage, it will indicate system voltage. As illustrated in (Fig. 17.75), if the voltmeter is connected to two equal positive voltage values or two equal negative voltage values, it will indicate zero.

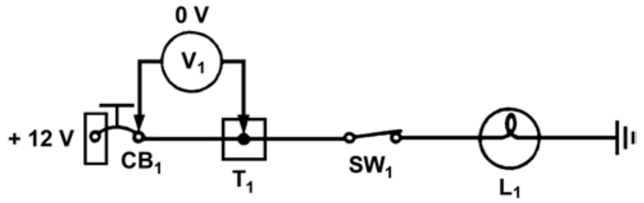

Fig. 17.75. A voltmeter connected between two points of positive voltage.

When troubleshooting a circuit with an open (disconnected) wire, the technician should place the voltmeter in various convenient places along the suspect wire. Since the positive voltage signal initiates at the aircraft bus, it is logical to first test for a positive voltage near the bus and move systematically toward the load. This concept is illustrated in (Fig. 17.76). The first test is performed as represented by voltmeter V_1; the second test, voltmeter V_2; the third test, voltmeter V_3; each measures 12 V. This indicates that the circuit's positive wire is continuous (not open) from the bus through terminal 1 and the switch. Voltmeter V_4, being connected to what should be the positive side of the lamp, should read 12 V. Since V_4 indicates zero volts, the circuit must be open between the switch and the light.

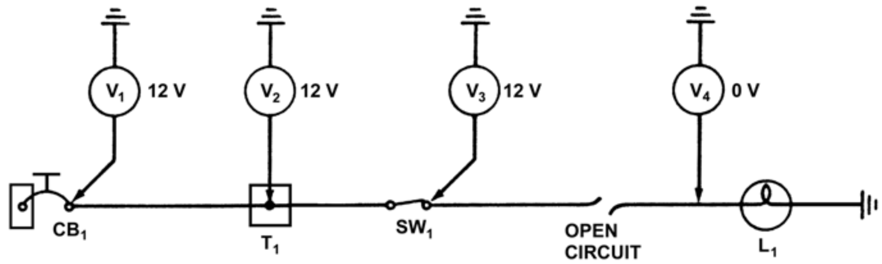

Fig. 17.76. Placement of a voltmeter to troubleshoot an open circuit.

When you are dealing with complex circuitry, the troubleshooting process becomes more difficult. When deciding where to connect the voltmeter, always consider the following :

1. A wire's insulation should never be removed to install a meter's test probe; therefore, take all measurements at open terminals, plug connectors, switches, fuses, or any other areas where the conductor is exposed.
2. Since an open in a wire can occur virtually anywhere, always connect the test meter to an easily accessible connection. If there is no positive voltage at that point (while you are referencing ground with the other meter probe), you can conclude that the open is between that test point and the positive bus. To further pin-point the defective wire or connector, move the positive voltmeter probe to the next exposed terminal nearer the aircraft bus. If the voltmeter indicates zero volts, the open is between that test point and the positive bus. If the meter indicates system voltage, the open circuit is between the first and second test points, as shown in (Fig. 17.77). The first test was performed at the switch because it was easily accessible. From this test it was easy to determine which portion of the circuit (before or after the switch) should be tested next.

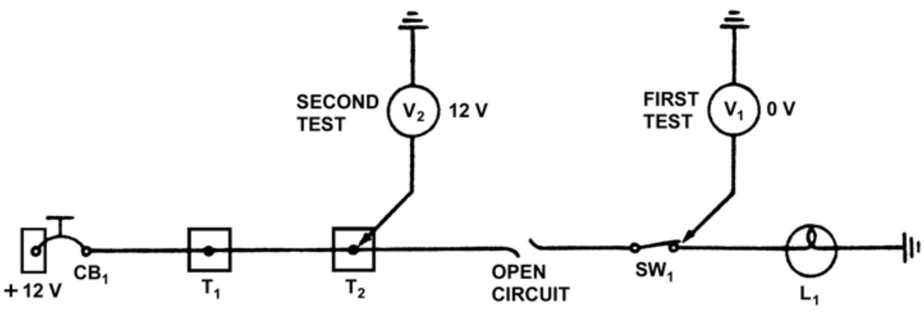

Fig. 17.77. Voltage tests of an open circuit. Since the first test indicated 0 V, the second test is made closer to the bus.

In many situations it is easiest to check voltage at the load of a circuit. In this case, if there is no voltage available to the load, the circuit is defective. If voltage is present to the input connections of the load, the load itself is defective. Be cautious: voltage consists of two parts, positive and negative, and both must be available to the load in order for it to operate.

A voltmeter may be used to determine if the negative voltage of a circuit is available to the load. As illustrated in (Fig. 17.78), the voltmeter should be referenced to a positive voltage source when testing for a negative signal. That is, the meter's red test probe should be connected to a point that is known to be a positive voltage. The aircraft's bus, or any other positive connection, may be used for this purpose. In this configuration, if the meter's negative probe is connected to a negative voltage, the meter will indicate system voltage. If no negative signal is present at the meter's black test probe, the meter will indicate zero volts.

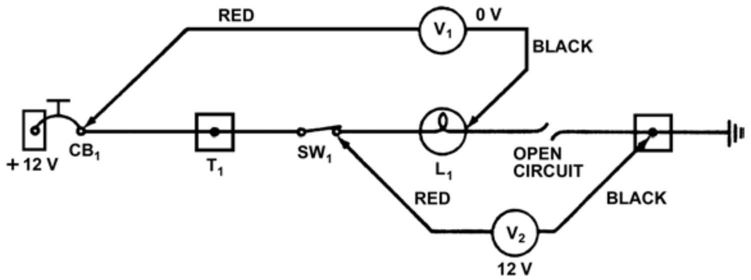

Fig. 17.78. Using a voltmeter to test for a negative voltage. If V_1 measures 0 V, there is no negative voltage present at the meter's black probe. If V_2 measures 12 V, negative voltage is present at the black probe.

Voltmeters and Composite Aircraft

It should be noted that the new breed of composited aircraft require some special procedures when voltage is checked. As with systems on metal aircraft, both the negative and positive voltage signals must be present to all electric power users. However, on composite aircraft the negative voltage cannot be transmitted through a metal structure. Some composite aircraft use a separate wire to carry the negative (ground) voltage from a ground bus to each electrical load. When checking for a positive voltage on this type of system, be sure to verify that you are connected to an uninterrupted ground source, as seen in (Fig. 17.79). To verify an uninterrupted ground circuit, place your voltmeter probes between a known voltage positive source and the ground wire in question. Never draw conclusions about voltage measured between two unverified points.

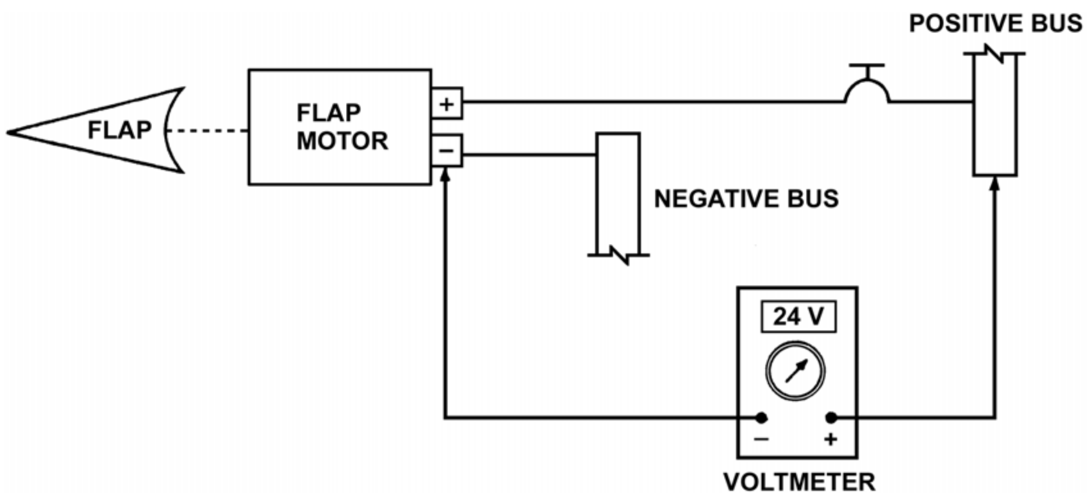

Fig. 17.79. Testing for an uninterrupted ground circuit on a composite aircraft.

Some composite aircraft incorporate a ground plane on the inside skin of the aircraft. This ground plane is used as the negative-side voltage source. When an electric component is not working because of a lack of voltage, be sure to check the ground plane. To check for a negative voltage signal on the ground plane, use a voltmeter and reference a known positive voltage. On some aircraft special low-resistance ohmmeters are used to verify continuity of the ground plane.

Ohmmeter Troubleshooting

Ohmmeters are best suited for two types of tests: (1) continuity checks of components removed from a circuit and (2) continuity checks of short circuits. Components such as switches, relays, lightbulbs, and transformers may all the tested with an ohmmeter. However, these components must be removed or disconnected from the circuit prior to testing.

Fig. 17.80 illustrates the use of an ohmmeter for testing components. A component such as a switch, circuit breaker, or fuse must have zero resistance (when closed) to operate properly. If the ohmmeter measures infinite resistance, the component is defective.

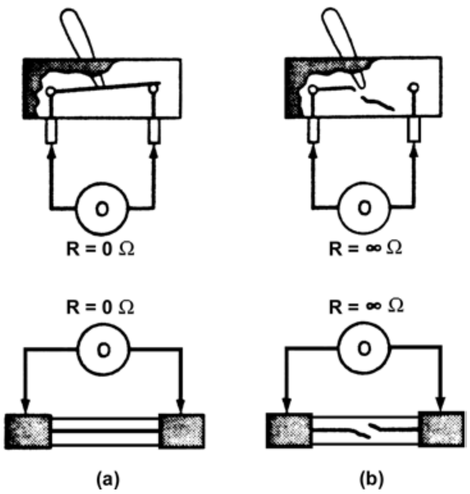

Fig. 17.80. Testing components with an ohmmeter. (a) Zero resistance measured across operable components; (b) infinite resistance measured across defective components.

An ohmmeter test is also valid for most power users as shown in (Fig. 17.81). The light tested should show relatively low resistance if it is functional. If it is defective (open), the light will show infinite resistance. In general, any power user should have a resistance equal to its rated voltage divided by its rated amperage (R=E/I). Any load that has infinite resistance is defective.

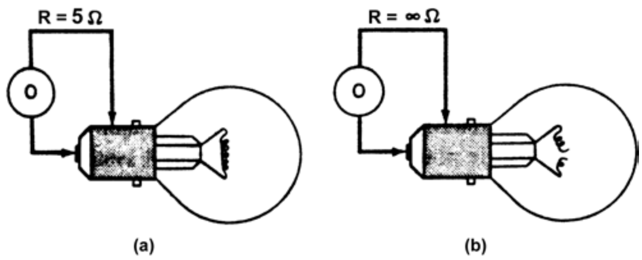

Fig. 17.81. Testing load units with an ohmmeter. (a) A good bulb indicates low resistance; (b) a defective bulb indicates infinite resistance.

Ohmmeters are often used to troubleshoot shorted circuits. For this type of troubleshooting, the circuit power must be turned off and the circuit isolated from the rest of the electrical system. In most cases this can be achieved by turning off the aircraft's battery master switch and opening the appropriate circuit breaker. (Fig. 17.82) shows the ohmmeter configuration for testing a wire shorted to ground. In Fig. 17.82 (a) the short to ground seems to appear at T_2; however, this is incorrect. The short is in wire segment C; but since wire segment C is connected to T_2, the meter indicates zero resistance from T_2 to ground. To pinpoint the location of the shorted circuit, isolate the various segments of wire. In Fig. 17.82 (b), segment C is isolated from T_2. The ohmmeter now reads infinite resistance; the short no longer appears to be at T_2.

If the meter probe is moved to the end of wire segment C, it will once again measure zero resistance to ground. Fig. 17.82 (c) illustrates the final test needed to find the defective wire. In this case wire segment C is completely isolated; the switch is open, and wire segment C is removed from T_2. Since the ohmmeter indicates zero resistance, wire segment C (a positive wire) must be shorted to ground.

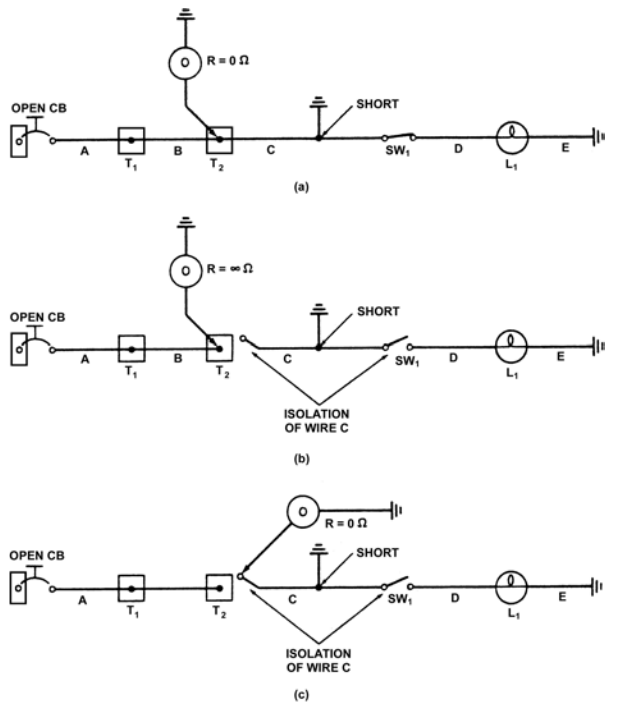

Fig. 17.82. Using an ohmmeter to find a short to ground.
(a) T_2 has zero resistance to ground when wire C is not isolated.
(b) T_2 has infinite resistance to ground with wire C isolated.
(c) Wire C has zero resistance to ground.

Ohmmeters can be used to test for open circuits; however, it is typically easier to use a voltmeter. The physical length of a meter's test leads may inhibit the use of an ohmmeter for a continuity check of open circuits. If you want to test a wire that is routed from the flight deck to the tail of the aircraft, your ohmmeter must be connected on both ends of the wire. With even a relatively small aircraft, this is impossible without extending the length of the meter's test leads. Using a voltmeter, one could simply test voltage at the tail end of the wire to ground and determine the wire's condition.

Ammeter Troubleshooting

Ammeters are typically used to test aircraft charging systems. In such cases it is often important to measure the total output amperage of an alternator or generator. Although multimeters normally incorporate an ammeter, they are not typically of high enough capacity to measure charging system current. If it becomes necessary to measure a relatively high ampereage, be sure to utilize an ammeter that is capable of measuring the anticipated current. The installation of charging system ammeters is discussed.

A Typical Troubleshooting Sequence

A typical sequence for troubleshooting a defective position-light circuit is as follows. First examine the schematic diagram, and operate the defective system. While operating the system, make note of exactly what operates correctly and what operates incorrectly. Examine the circuit protector of the system, and determine its condition. If the fuse or circuit breaker has opened, the circuit is most likely shorted to ground. If the fuse is continuous or the circuit breaker is closed, the defect is most likely an open. Study the circuit's schematic diagram, and determine which component or wire is a likely suspect. If the defect is a short circuit, as illustrated in (Fig. 17.83), an ohmmeter should be used to find the defective wire segment.

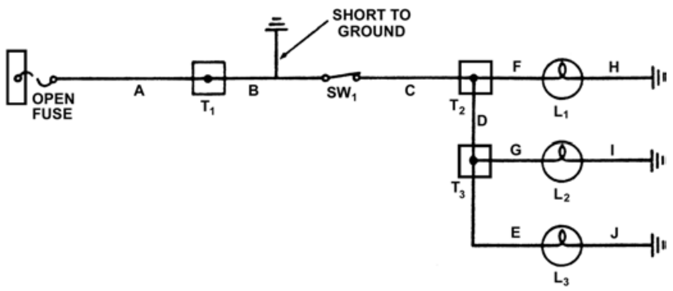

Fig. 17.83. A typical short circuit.

Before the ohmmeter is installed to troubleshoot the short, a portion of the circuit could be tested from the flight deck. For example, if switch 1 is turned off and the fuse (or circuit breaker) opens when the circuit is tried again, wire segments C through J are not the cause of the defect. This must be true, since these wire segments are disconnected from the bus when switch 1is opened. If switch 1 is turned off and the fuse remains closed (operable), the circuit defect must be located between the switch and the position lamps (wires C through J). This must be true since the circuit protector did not open while the wire segments C through J were disconnected from the circuit.

Troubleshooting from the flight deck is an important part of the pair process. As illustrated in the last paragraph, this is done by operating the flight deck controls and drawing accurate conclusions from the results. If done properly, considerable time can be saved by studying the system's schematic and operating related electrical systems. Often this process can significantly reduce the possible defect locations, therefore improving the troubleshooting process.

If the defect in the position-light circuit is an open, as in (Fig. 17.84), a voltmeter should be used to locate the fault. In this case opening switch 1 would not allow the technician to draw any significant conclusions. A voltmeter must be installed systematically throughout the circuit to determine which wire segment is defective.

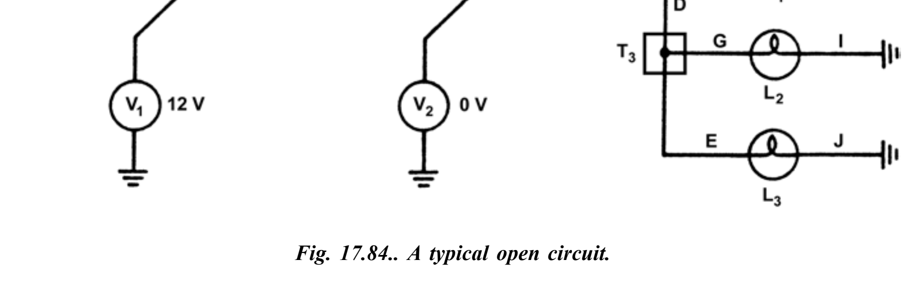

Fig. 17.84.. A typical open circuit.

Troubleshooting With Built-in Test Equipment

Built-in test equipment (BITE) systems found on modern commercial aircraft are designed to troubleshoot the electrical problems typically encountered during maintenance. System faults that occur during normal aircraft operations must be repaired swiftly and accurately. A typical aircraft may use several BITE units to monitor the major systems, such as electric power, environmental control systems, and flight control systems. BITE systems perform fault detection, fault isolation, and operational verification after system repair.

BITE systems provide fault detection continuously during aircraft operation. If a fault is detected, the BITE system stores the necessary defect information in a nonvolatile memory and sends the appropriate display signal (if any) to the flight deck. If the fault requires immediate attention, the flight crew will notify the ground technician via radio transmission or upon landing. The technician must access the appropriate BUTE system to perform the fault isolation test. Through correct operation, many BITE systems will display failure data and repair code information.

Several versions of built-in test equipment are in use today. Simple systems typically incorporate a **go/no go** red or greed LED on the equipment **black box** or **line replaceable unit** (LRU). More complex systems use a multicharacter display and monitor more than one LRU and the associated wiring. The system in (Fig. 17.85) is accessed from the equipment center of the aircraft. More advanced BITE systems incorporate displays that are activated from the flight deck and have paper printouts. In addition, advanced systems may have a means to transmit data from the aircraft to the maintenance facility during flight; this means is known as ACARS (ARINC communication addressing and reporting system).

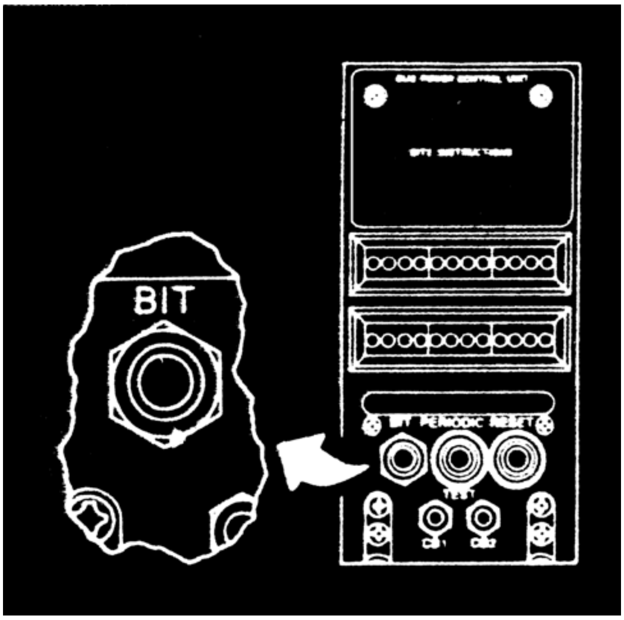

Fig. 17.85. BITE system display.

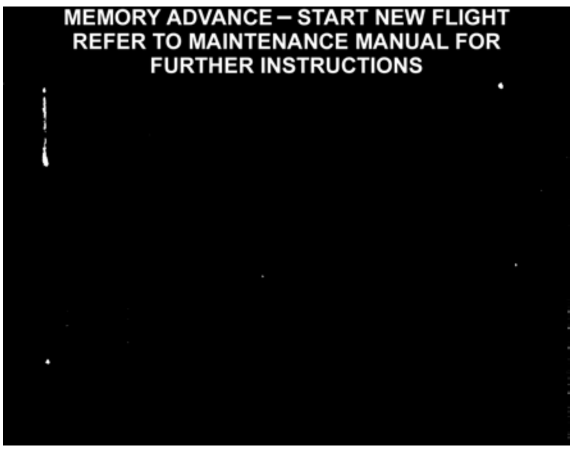

Fig. 17.86. Typical BITE display: BPCU FAILED ERROR CODE 02.

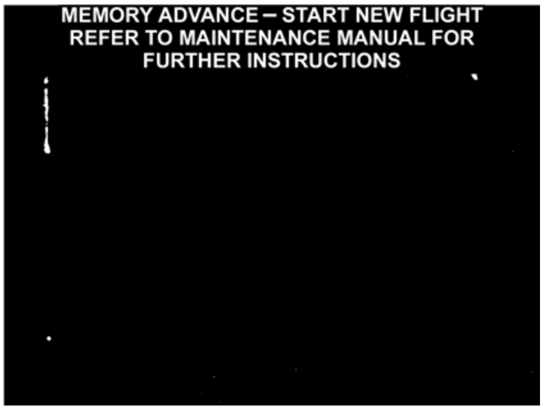

Fig. 17.87. BITE display of LAST FLT 00 END OF DATA.

The BITE system shown in (Fig. 17.85) its incorporated with the bus power control unit (BPCU). This system monitors the entire electric power generation system, including the left, right, and APU generators; the constant-speed drives; and their related control units. The BIT button is depressed on this system to activate the 24-character LED fault display. Typically a BITE system will display fault information in a coded message, as illustrated in (Fig. 17.86). The message is then decoded by the technician through the use of the aircraft's maintenance manual. The appropriate manual will inform the technician of any LRU to be replaced or circuit to be repaired and its location within the aircraft. The fault information on this system is displayed for 2s, and then the display automatically advances to the next fault. This BITE system will make an appropriate indication when all fault have been displayed, as in (Fig. 17.87).

After the system fault has been repaired, the BITE box should be reset and an operational check performed. The repaired system should be run through a complete cycle of operation. In the case of the electric power generation system, the appropriate engine and ac generator should be subjected to a variety of operating parameters. The flight deck instruments and failure indicators are monitored during the test to detect any further problems.

After the repaired system has been run, the BITE system fault display should be reactivated. This will initiate the read-out of the nonvolatile memories, and remaining operational faults will be displayed. If the system is found to be without fault, the BITE display will respond accordingly, as in (Fig. 17.88).

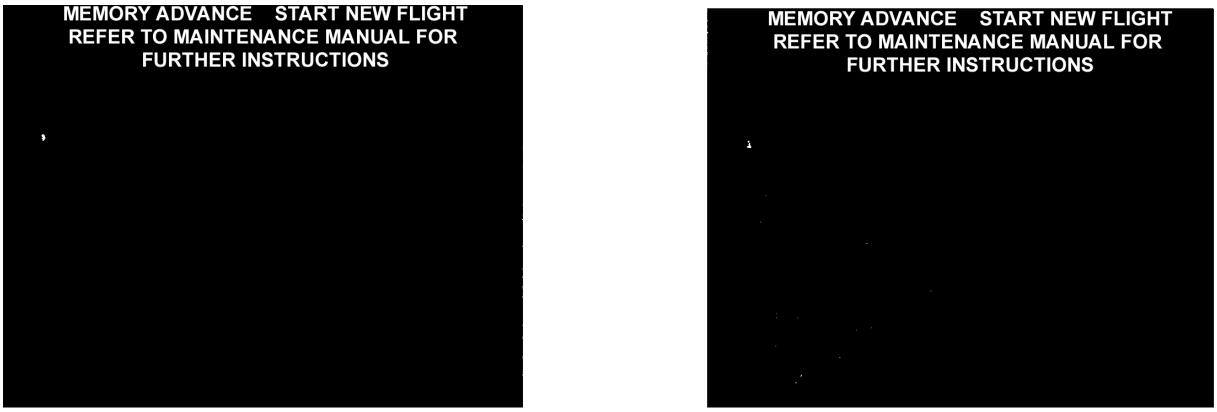

Fig. 17.88. BITE display of a system with no recorded fault data: LEFT GEN POWER SYSTEM, O.K.

Multipurpose Control Display Unit

A multipurpose control display unit (MCDU) is used to access a slightly more advanced BITE system. Some aircraft require that the MCDU be accessed from the equipment bay, while other aircraft require a carry-on MCDU controller, which is connected to the system on the flight deck. Many aircraft use a controller located on the instrument panel and display information on the EICAS display unit. The operation of the MCDU is similar to the operation of the previously described BITE system. The MCDU is typical of the system found on the Boeing 757 and 767 aircraft. The MCDU receives digital data in an ARINC 429 format from the thrust management, flight control, and flight management computers, along with EICAS inputs. The MCDU both monitors inflights are directly correlated to the various flight deck effects associated with in-flight problems. A **flight deck effect** is any EICAS display or discrete annunciator used to inform the flight crew of an in-flight fault.

Fig. 17.89. A central display unit (CDU) on a Boeing 747-400 aircraft.

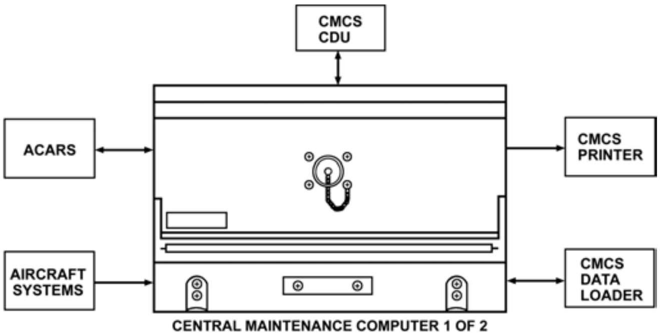

Fig. 17.90. Central maintenance computer and data links to CDU, printer, data loader, aircraft systems and ACARS.

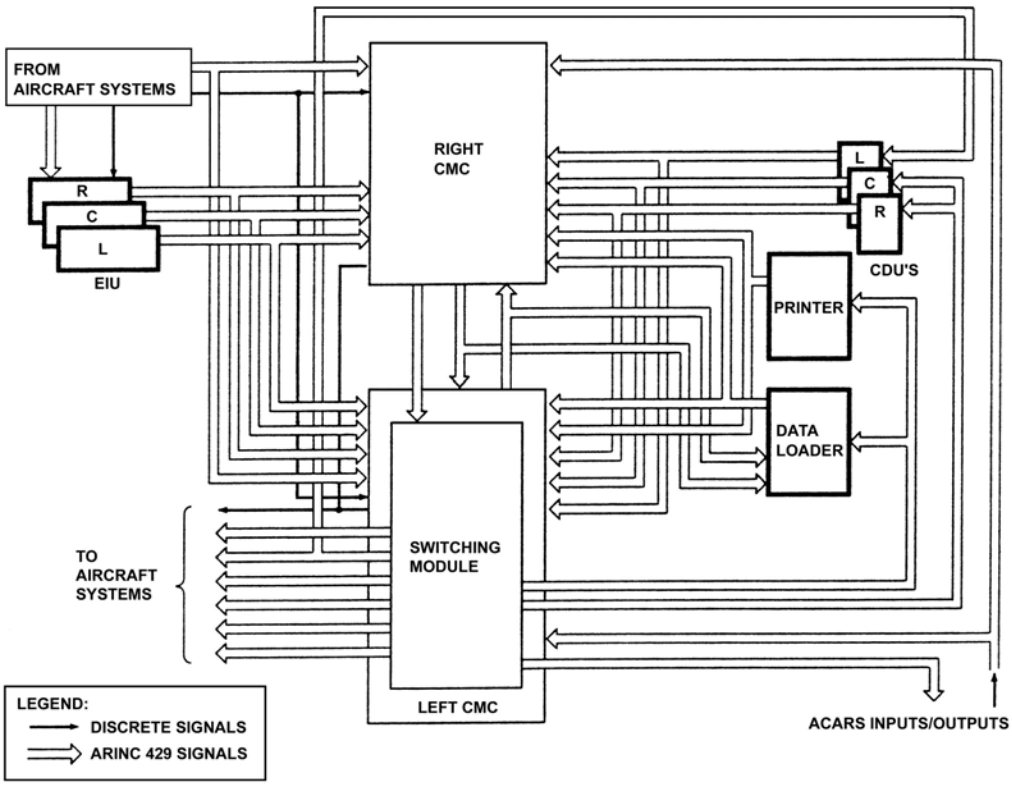

Fig. 17.91. Central maintenance computer system block diagram.

When the aircraft lands, the MCDU automatically records any in-flight faults (from the last flight) in a nonvolatile memory. To access this memory, the technician must first cycle the MCDU off and on again. This will result in an internal test of the MCDU. After the internal test has been completed and OK'd by the display, the technician should select the in-flight mode of operation. The unit will respond accordingly with faults listed in order of occurrence. At the end of the fault data, the unit will ask if it should display faults from previous flights. The MCDU will store faults from a maximum of 10 flights.

In the case of an MCDU located in the equipment bay, fault data appear on an LED display similar to that shown in (Fig. 17.86). On this type of MCDU, the top line displays the flight on which the fault occurred and the related flight deck effect; the bottom line displays the faulty LRU to be replaced. If the MCDU is accessed from the flight deck, the EICAS is used to display the message.

Central Maintenance Computer System

The latest generation of built-in test equipment is known as the **central maintenance computer system** (CMCS). This system is designed to perform in-flight and ground tests of virtually every aircraft system, each one accessed from a central location. The **control display unit** (CDU), used to access and display faults, is located in the center console of the flight deck. This type of system is found on the Boeing 747-400, a state-of-the-art four-engine transport-category aircraft. As shown in (Fig. 17.89), the CDU uses a CRT display. This type of display allows for a more descriptive message of faults, Which are directly correlated to flight deck effects created by the same faults. A CMCS printer is incorporated to provide a written report of the fault data, and a software data loader is used to store faults on a computer disk (Fig. 17.90). Aircraft equipped with ACARS are capable of transmitting fault data from the aircraft to a ground facility. ACARS will also answer all maintenance data requests from the ground facility.

There are two central maintenance computers (CMCs) located in the aircraft's equipment bay. The CMCs receive up to 50 digital ARINC 429 data inputs and various discrete inputs. Each CMC has 10 ARINC 429 data inputs and various discrete inputs. Each CMC has 10 ARINC 429 outputs; one is a crosstalk bus to the other CMC. The outputs are sent to the aircraft systems through the left CMC; therefore, if only one CMC is available, it must be installed in the left slot. If the left CMC detects internal faults, output data are automatically passed from the right CMC directly through the left CMC. (Fig. 17.91) is a block diagram of the CMC data inputs and outputs.

During flight the CMC receive fault data from the air craft's electronic interface units (EIUs) and other digital and discrete systems to record in-flight failure. The EIUs monitor system parameters and control the displays of the EICAS and EFIS (electronic flight instrument system). Once the aircraft is on the ground, the CMC can be interrogated for any history of in-flight faults stored in a nonvolatile memory. Up to 500 faults can be stored in the nonvolatile memory.

The **control display unit** (CDU) shown in (Fig. 17.92) displays two different menu pages used to initiate interrogation of the CMC. The first page is used primarily for line maintenance and operations; the second page is used for in-depth troubleshooting. A specific function is selected from the menu by pressing the button adjacent to that function. There are three basic types of faults:

1. **existing faults** (those faults active at the time of inquiry)
2. **present leg faults,** (those faults that were recorded during present leg or previous flights)
3. **fault history** (those faults that were recorded during present leg or previous flights)

Depressing the button for the **ground tests** function tells the CMC to test LRUs and various systems. The **EICAS maintenance pages** function will activate the real-time display of various systems, such as electric power. This function will also allow for access of maintenance pages recorded in memory at an earlier time, called snapshots. The **confidence tests** function allows the technician to perform tests that are typically performed before a flight.

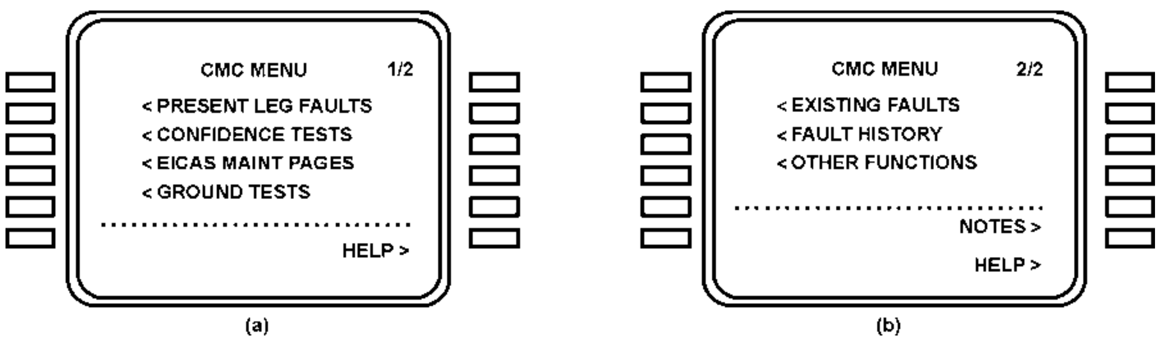

Fig. 17.92. Central maintenance computer menu display. (a) Page 1 of 2, for line maintenance; (b) Page 2 of 2, for extended maintenance troubleshooting.

Centralized Fault Display System
The Airbus A-320 employs a similar central maintenance system called the **central fault display system** (CFDS). This system classifies faults into three categories: **Class 1, Class 2, and Class 3** failures. Class 1 failures have an operational consequence on the flight. The crew is notified by a red warning or amber caution on the electronic centralized aircraft monitoring (ECAM) system or by discrete instrument flags. The pilot must report Class 1 failures in the logbook, since they require maintenance action before the next flight. Class 2 failures are displayed to the pilot by means of the ECAM system only after landing and engine shutdown. Class 2 failures must be reported by the pilot in the log because they cannot be left uncorrected until the next scheduled maintenance. Class 2 failures are categorized by the **minimum equipment list** (MEL) to determine the number of flights allowable prior to initiating repair. Class 3 failures are not reported to the pilot and can be left unattended until the next scheduled maintenance. Class 3 failures are displayed only during access of CFDS data.

There are several different types of built-in test equipment systems. The descriptions above give an overview of common equipment. Systems of the future promise to be even more accurate, cover more equipment, and be easier to use. BITE systems are here to stay and for good reason: they simplify complicated troubleshooting tasks. The operation of many BITE systems is relatively complex, so before using any particular system, the technician should become completely familiar with the operation of the equipment.

Electrostatic-Discharge-Sensitive Equipment
Some electronic units found on modern aircraft are extremely sensitive to stray current flows. Even a static electrical discharge from a technician to a sensitive component could damage that component. These extremely delicate components are known as **electrostatic-discharge-sensitive** (ESDS) parts. ESDS parts are identified by one or more of the symbols found in (Fig. 17.93). A part labeled as electro-static-discharge-sensitive may be damaged by a static discharge of as little as 100 V. A technician walking on an aircraft's carpet, removing a coat, or simply rubbing his or her hair can accumulate a static charge well over 1000 V. A static charge of this magnitude will damage ESDS parts. Most people cannot feel an electrostatic discharge below 3000 V. A visible spark from a static discharge is typically above 12,000 V. Each of these two levels is well above the tolerance of ESDS parts. A technician may become charged and damage a component without even realizing it.

Fig. 17.93. Typical symbols used to identify ESDS parts.

A technician and all of his or her equipment must be connected to the aircraft's ground prior to servicing any ESDS components. This will neutralize any electrostatic charge that may have accumulated. The most common way to ground a technician employs the use of a grounded wrist strap. The wrist strap, as shown in (Fig. 17.94), is connected around a bare wrist of the technician and connected to the aircraft's ground by means of a wire and plug. All bench technicians and equipment used to repair ESDS units that have been removed from the aircraft are also grounded to prevent component damage.

Fig. 17.94. A typical wrist strap.

If an ESDS component is removed from the aircraft, its connecting lead must by shorted together by means of wires, shorting clips, metal foil, or a conductive foam. Printed-circuit-board connections are also shorted together in order to keep all components at the same voltage potential. After this procedure has been completed, the unit should be placed in a special container to protect it from static electricity. A semiconductive plastic bag is often used for this purpose (see Fig. 17.95). The protective containers are designed to prevent a static charge from reaching the components inside. All ESDS components should be stored and/or shipped in these protective containers.

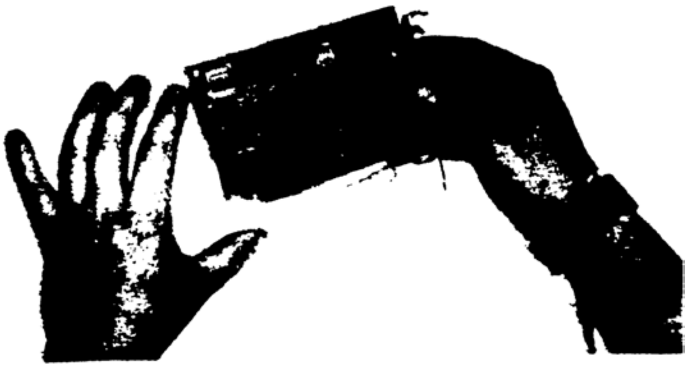

Fig. 17.95. Storage of ESDS parts in a protective package.

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CHAPTER - 18
KNOWLEDGE OF ELECTRICAL POWER DISTRIBUTION SYSTEMS, THE OPERATION AND CONSTRUCTION OF STATIC INVERTERS, ROTARY INVERTERS AND TRANSFORMER RECTIFIER UNITS

External and Auxiliary Power Supplies

Electrical power is required for the starting of engines, operation of certain services during "turn-round" servicing periods at airports, e.g. lighting, and for the testing of electrical systems during routine maintenance checks. The batteries of an aircraft are, of course, a means of supplying the necessary power, and although capable of effecting engine starts their capacity does not permit widescale use on the ground and as we have already learned from previous chapter, they are restricted to the supply of power under emergency conditions. It is necessary, therefore, to incorporate a separate circuit through which power from an external ground power unit (see Fig. 18.1) may be connected to the aircraft's distribution busbar system. In its simplest form, an external power supply system consists of a connector located in the aircraft at a conveniently accessible point (at the side of a fuselage for example) and a switch for completing the circuit between the ground power unit and the busbar system.

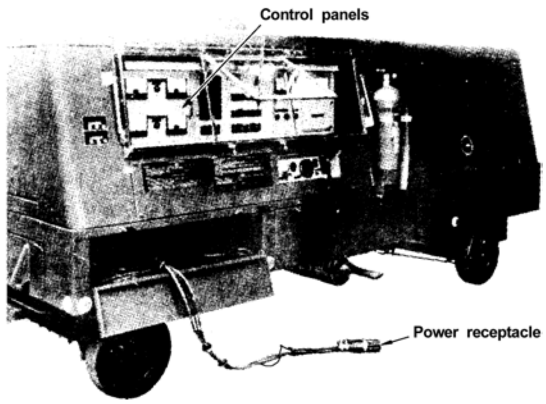

Fig. 18.1. Ground power unit.

In addition to the external power supply system, some types of aircraft carry separate batteries which can supply the ground services in the event that a ground power unit is not available in order to conserve the main batteries for engine starting.

In the majority of large public transport aircraft, complete independence of ground power units is obtained by special auxiliary power units installed within the aircraft.

D.C. Systems

A basic system for the supply of d.c. is shown in (Fig. 18.2) and from this it will also noted how, in addition to the external power supply, the battery may be connected to the main busbar by selecting the "flight" position of the switch. As the name suggests this is the position to which the switch is selected when the aircraft is in flight since under this condition the generator system supplies the main busbar and the battery is constantly supplied with charging current.

The external power connector symbol shown in the diagram represents a twin-socket type of unit which although of an obsolete type is worth noting because it established certain aspects which are basic in the design of present-day connectors or receptacles as they are also called, namely the dimensioning of pins and sockets, and the method of protecting them. The pins were of different diameters to prevent a reverse polarity condition, and the cover of the unit had to be rotated to expose the sockets.

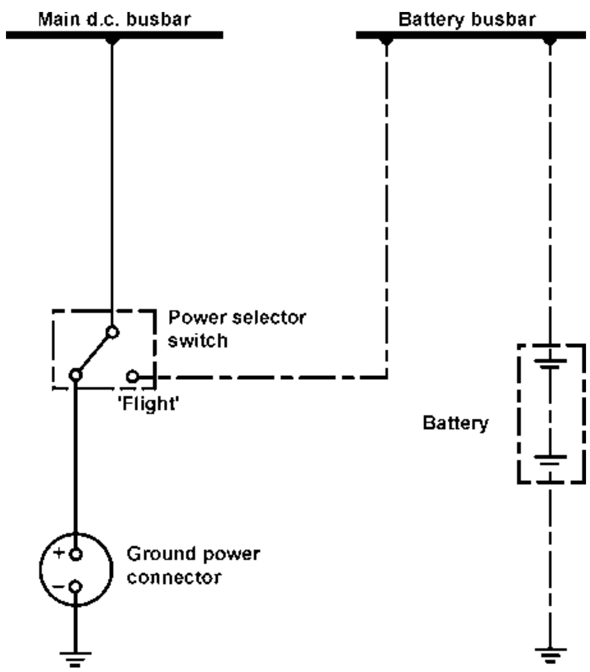

Fig. 18.2. Basic external supply system.

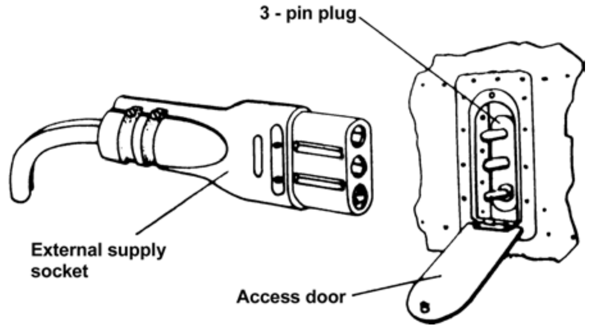

Fig. 18.3. External power supply connection.

An example of a current type of unit is shown in (Fig. 18.3). It consists of two positive pins and one negative pin; one of the positive pins is shorter and of smaller diameter than the remaining pins. The pins are enclosed by a protective shroud, and the complete unit is normally fitted in a recessed housing located at the appropriate part of the airframe structure. Access to the plug from outside the aircraft, is via a hinged flap provided with quick-release fasteners.

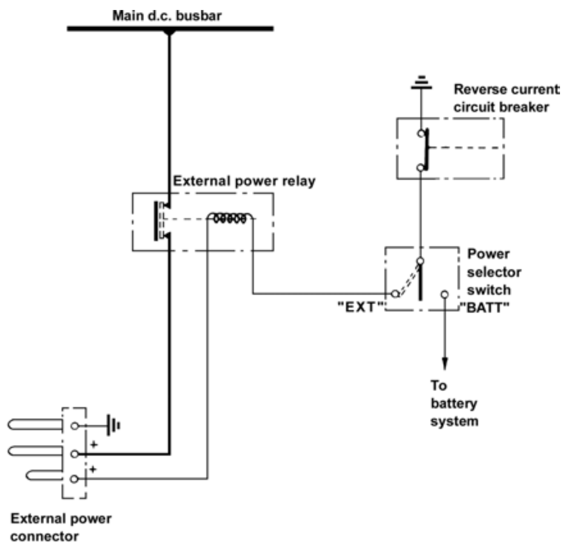

Fig. 18.4. Three - pin receptacle system.

The circuit of a three-pin receptacle system is illustrated in (Fig. 18.4) and from this it will be noted that the short positive pin is connected in the coil circuit of the external power relay. The reason for this is that in the event of the external supply socket being with drawn with the circuit "live", the external power relay will de-energize before the main pins are disengaged from the socket. This ensures that breaking of the supply takes place at the heavy-duty contacts of the relay thus preventing arcing at the main pins.

In some aircraft d.c power is distributed from a multiple busbar system and it is necessary for certain services connected to each of the busbars to be operated when the aircraft is on the ground. This requires a more sophisticated arrangement of the external power supply system and the circuit of one such arrangement is shown in (Fig. 18.5). In addition to the external supply relay or contactor, contactors for "tying" busbars together are provided, together with magnetic indicators to indicate that all connections are made.

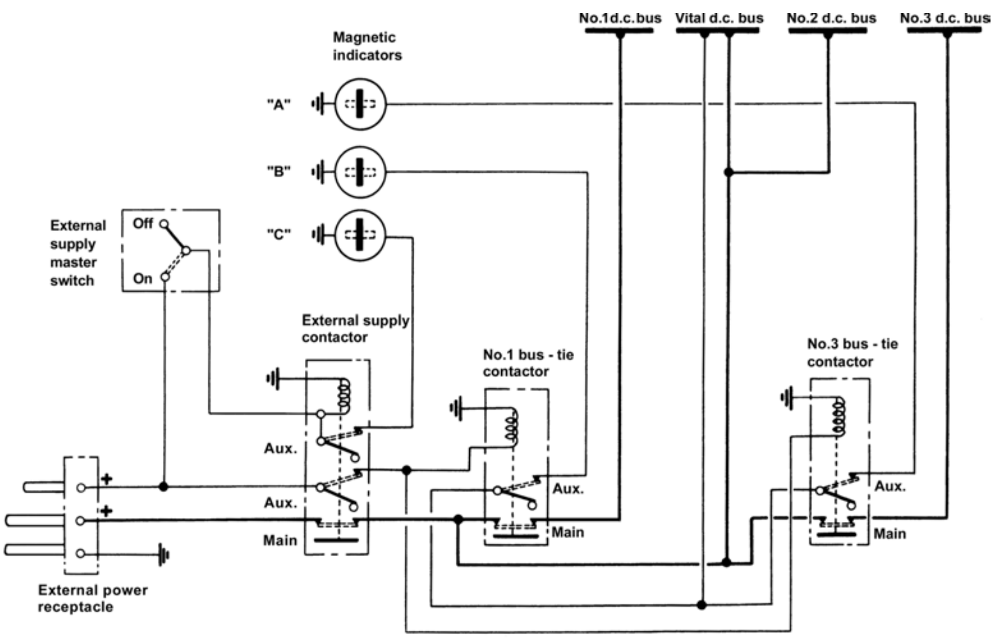

Fig. 18.5. Schematic of an external power supply - multiple d.c. busbar system.

When the external ground power unit is connected to the aircraft and the master switch is selected "on", it energizes the external supply contactor, thus closing its auxiliary and main sets of contacts. One set of auxiliary contacts complete a circuit to a magnetic indicator which then indicates that the external supply is connected and on ("C" in Fig. 18.5), a second set complete circuits to the coils of No.1 and No.3 bus-tie contractors while a third and main heavy-duty set connect the supply direct to the "vital" and No.2. busbar. When both bus-tie contactors are energized their main contacts connect the supply from the external supply contactor to their respective busbars. Indication that both busbars are also "tied" to the ground power supply is provided by magnetic indicators "A" and "B" which are energized from the vital busbar via the auxiliary contacts of the contactor.

In some aircraft, and as an example we may consider the Boeing 737, a separate external power connector is installed for starting an auxiliary power unit in the event that the aircraft's battery is in operative. The circuit arrangement is shown in (Fig. 18.6).

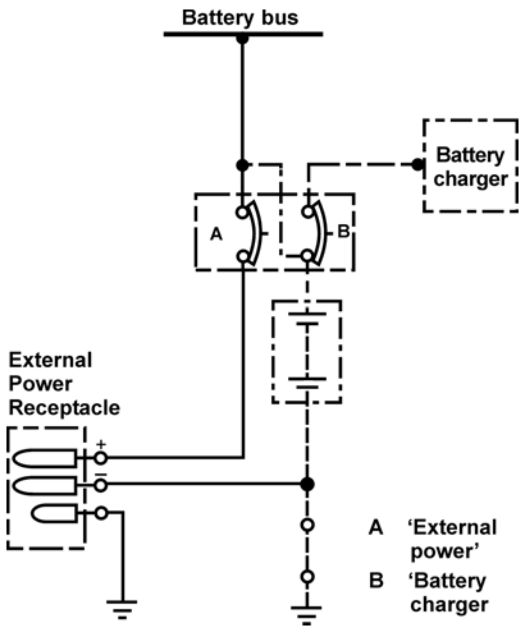

Fig. 18.6. Separate external d.c. supply for A.P.U. starting.

The receptacle is located adjacent to the battery together with two circuit breakers indicated as "A" and "B" in the diagram. The positive pin of the receptacle is coupled directly to the battery busbar via circuit breaker "A", and forms a parallel circuit with the battery. Before external power is applied, circuit breaker "B" must be tripped in order to prevent damage to the battery charger.

A.C. Systems

In aircraft which from the point of view of electrical power are principally of the "a.c.type", then it is essential for the external supply system of the installation to include a section through which an external source of a.c. power may be supplied. The circuit arrangements for the appropriate systems vary between aircraft types but in order to gain some understanding of the circuit requirements and operation generally we may consider the circuit shown in (Fig. 18.7).

When external power is coupled to the receptacle a three-phase supply is fed to the main contacts of the external power breaker, to an external power transformer/rectifier unit (T.R.U.) and to a phase sequence protection unit. The T.R.U. provides a 28 volt d.c. feedback supply to a hold-in circuit of the ground power unit. If the phase sequence is correct the protection unit completes a circuit to the control relay coil, thus energizing it. A single-phase supply is also fed to an amber light which comes on to indicate that external power is coupled, and to a voltmeter and frequency meter via a selector switch.

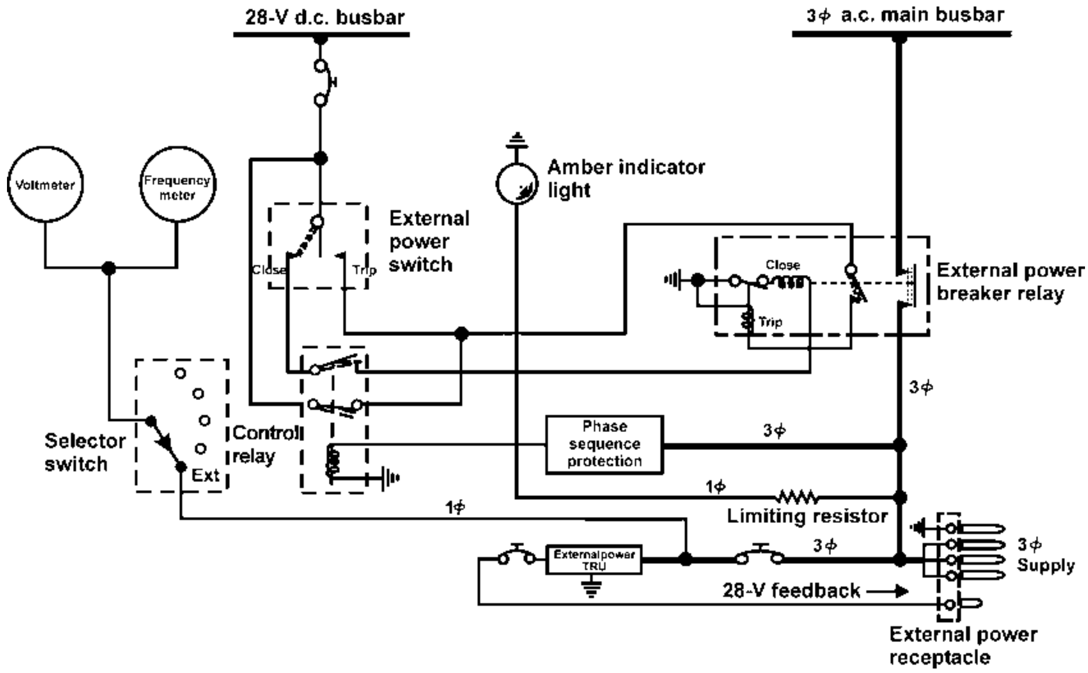

Fig. 18.7. Schematic of an external power supply - a.c. system.

The circuit is controlled by an external power switch connected to a busbar supplied with 28 volts d.c. from the aircraft battery system. When the switch is set to the "close" position current flows across the main contacts of the energized control relay, to the "close" coil of the external power breaker, thus energizing it to connect the external supply to the three-phase a.c. main busbar. The external power supply is disconnected by selecting the "trip" position on the external power switch. This action connects a d.c. supply to the trip coil of the external power breaker, thus releasing its main and auxiliary contacts and isolating the external power from the a.c. main busbar.

Fig. 18.8 illustrates an external a.c. power receptacle and control panel arrangement generally representative of that adopted in large public transport aircraft. The receptacle is of the six-prong type; three of the large prongs are for the corresponding a.c. power phases, and a fourth large prong for the ground connection between the aircraft structure and external power unit. The two small shorter prongs connect d.c. power for the operation of interlocking relays which connect the external a.c. power to the aircraft.

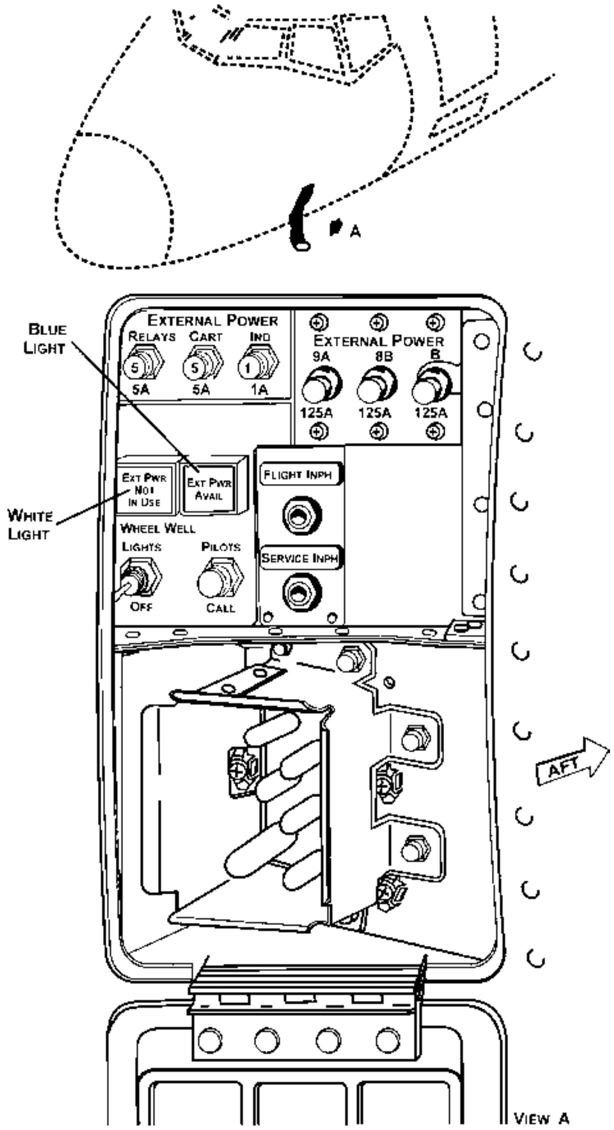

Fig. 18.8. External a.c. power receptacle and control panel.

The control panel contains three single-phase a.c. circuit breakers, and three more breakers which protect relay control and indicating light circuits within the aircraft's external power supply circuit. Indicator lights, interphone jack plug sockets, and pilot's call button switch are also contained on the panel.

The white indicator light is only illuminated whenever external a.c. power is connected but is not supplying power to any a.c. load busbar on the aircraft. The blue light is illuminated whenever a.c. power is being supplied to the load busbars.

The pilot's call button switch and interphone jack plug sockets provide for communication between ground crew and flight crew.

AUXILIARY POWER UNITS

Many of today's aircraft are designed so that if necessary, they may be independent of ground support equipment. This is achieved by the incorporation of an auxiliary power unit (A.P.U.) in the tail section which, after being started by the aircraft's battery system, provides power for engine starting, ground air conditioning and other electrical services. In some installations, the A.P.U. is also used for supplying power in flight in the event of an engine-driven generator failure and for supplementing the delivery of air to the cabin during take-off and climb.

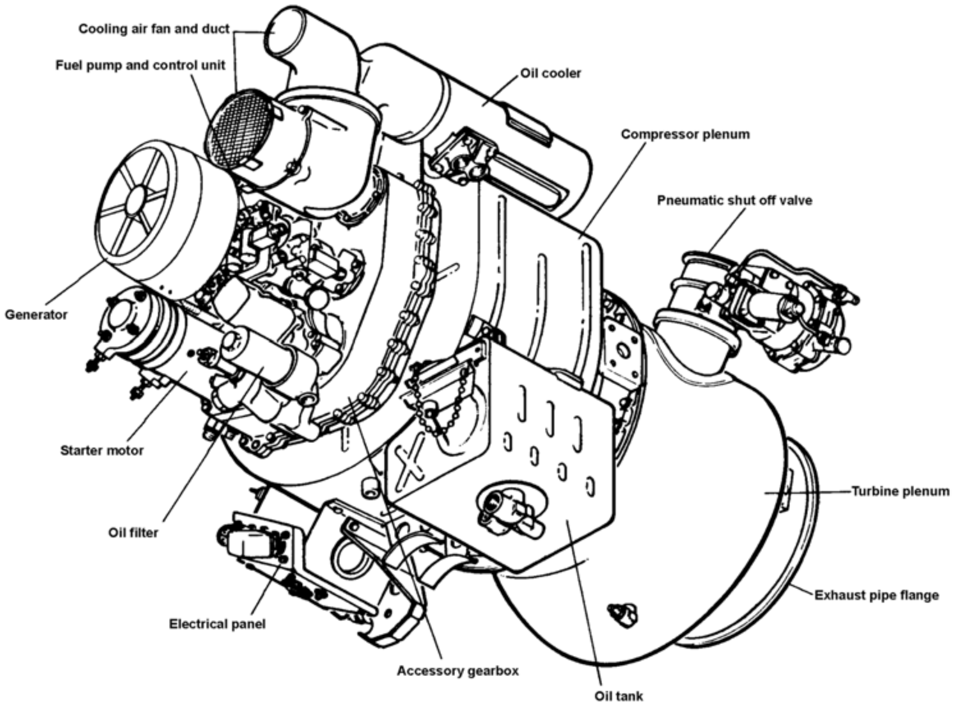

Fig. 18.9. Auxiliary power unit.

In general, an A.P.U. consists of a small gas turbine engine, a bleed-air control and supply system, and an accessory gearbox. The gas turbine comprises a two-stage centrifugal compressor connected to a single-stage turbine. The bleed-air control and supply system automatically regulates the amount of air bleed from the compressor for delivery to the cabin air conditioning system. In addition to those accessories essential for engine operation, e.g. fuel pump control unit and oil pumps, the accessory gearbox drives a generator which is of the same type as those driven by the main engines, and having the same type of control and protection unit.

A motor for starting the A.P.U. is also secured to the gearbox and is operated by the aircraft battery system or, when available, from a ground power unit. In some types of A.P.U. the functions of engine starting and power generation are combined in a starter/generator unit. In order to record the hours run, an hour meter is automatically driven by an A.P.U.

An external view of a typical unit and a typical installation, are shown in (Figs. 18.9 and 18.10) respectively.

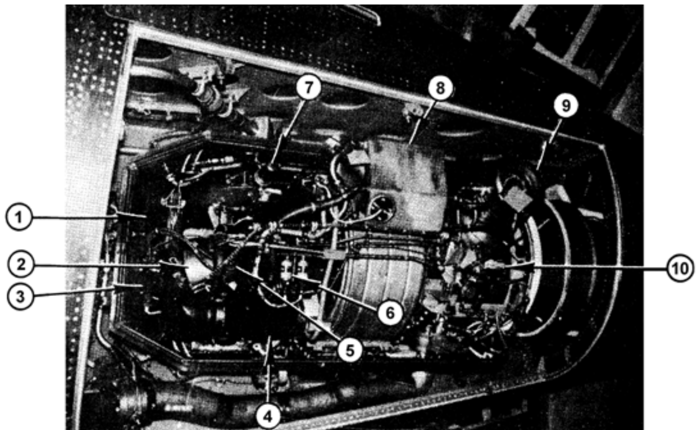

Fig. 18.10. A.P.U. installation.

Power Distribution

In order for the power available at the appropriate generating sources, to be made available at the inputs of the power-consuming equipment and system then clearly, some organized form of distribution throughout an aircraft is essential The precise manner in which this is arranged is governed principally by the type of aircraft and its electrical system, components. For example, in a small light aircraft, electrical power requirements may be limited to a few consumer services and components situated within a small area, and the power may be distributed via only a few yards of cable, some terminal blocks, circuit breakers or fuses. In a large multijet transport aircraft on the other hand, literally miles of cable are involved, together with multiple load distribution busbars, protection networks, junction boxes and control panels.

BUSBARS

In most types of aircraft, the output from the generating sources is coupled to one or more low impedance conductors referred to as busbars. These are usually situated in junction boxes or distribution panels located at central points within the aircraft, and they provide a convenient means for connecting positive supplies to the various consumer circuits; in other words, they perform a "carry-all" function. Busbars vary in form dependent on the methods to be adopted in meeting the electrical power requirements of a particular aircraft type. In a very simple system a busbar can take the form of a strip of interlinked terminals while in the more complex systems main busbars are thick metal (usually copper) strips or rods to which input and output supply connections can be made. The strips or rods are insulated from the main structure and are normally provided with some form of protective covering. Flat, flexible strips of braided copper wire are also used in some aircraft and serve as subsidiary busbars.

Busbar Systems. The function of a distribution system is primarily a simple one, but it is complicated by having to meet additional requirements which concern a power source, or a power consumer system operating either separately or collectively, under abnormal conditions. The requirements and abnormal conditions, may be considered in relation to three main areas, which may be summarized as follows:

1. Power-consuming equipment must not be deprived of power in the event of power source failures unless the total power demand exceeds the available supply.
2. Faults on the distribution system (e.g. fault currents, grounding or earthing at a busbar) should have the minimum effect on system functioning, and should constitute minimum possible fire risk.
3. Power-consuming equipment faults must not endanger the supply of power to other equipment.

These requirements are met in a combined manner by paralleling generators where appropriate, by providing adequate circuit protection devices, any by arranging for faulted generators to be isolated from the distribution system. The operating fundamentals of these methods are described elsewhere in this book, but the method with which this Chapter is concerned is the additional one of arranging busbars and distribution circuits so that they may be fed from different power sources.

In adopting this arrangement it is usual to categorize all consumer services into their order of importance and, in general, they fall into three groups: vital, essential and non-essential.

Vital services are those which would be required after an emergency wheels-up landing, e.g. emergency lighting and crash switch operation of fire extinguishers. These services are connected directly to the battery.

Essential services are those required to ensure safe flight in an in-flight emergency situation. They are connected to d.c. and a.c. busbars, as appropriate, and in such a way that they can always be supplied from a generator or from batteries.

Non-essential service are those which can be isolated in an in-flight emergency for load shedding purpose, and are connected to d.c. and a.c. busbars, as appropriate, supplied from a generator.

Fig. 18.11 illustrated in much simplified form, the principle of dividing categorized consumer services between individual busbars. In this example, the power distribution system is one in which the power supplies are 28-volt d.c. from engine-driven generators operating in parallel, 115-volts 400 Hz a.c. from rotary inverters, and 28-volt d.c. from batteries. Each generator has its own busbar to which are connected the non-essential consumer services. Both busbars are in turn connected to the battery busbar thereby ensuring that the batteries are maintained in the charged condition. In the event that one generator should fail it is automatically isolated from its respective busbar and all busbar loads are then taken over by the operative generator. Should both generators fail however, non-essential consumers can no longer be supplied, but the batteries will automatically supply power to the essential services and keep them operating for a predetermined period calculated on the basis of consumer load requirements and battery state of charge.

For the particular system represented by (Fig. 18.11) the d.c. supplies for driving the inverters are taken from busbars appropriate to the importance of the a.c. operated consumers. Thus, essential a.c. consumers are operated by No.1

inverter and so it is driven by d.c. from the essential services busbar. No. 2 and No.3 inverters supply a.c. to non-essential services and so they are powered by d.c. from the No.1 and No.2 busbars.

Fig. 18.12 illustrates a split busbar method of power distribution, and is based on an aircraft utilizing non-paralleled constant-frequency a.c. as the primary power source and d.c. via transformer-rectifier units (T.R.U.'s).

The generators supply three-phase power through separate channels, to the two main busbars and these, in turn, supply the non-essential consumer loads and T.R.U.'s. The essential a.c. loads are supplied from the essential busbar which under normal operating conditions is connected via a changeover relay to the No.1 main busbar. The main busbars are normally isolated from each other i.e., the generators are not paralleled, but if the supply from either of the generators fails, the busbar are automatically inter-connected by the energizing of the "bus-tie" breaker and serve as one, thereby maintaining supplies to all a.c. consumers and both T.R.U.'s. If, for any reason, the power supplied from both generators should fail the non-essential services will be isolated and the changeover relay between No.1 main busbar, and the essential busbar, will automatically de-energized and connect the essential busbar to an emergency static inverter.

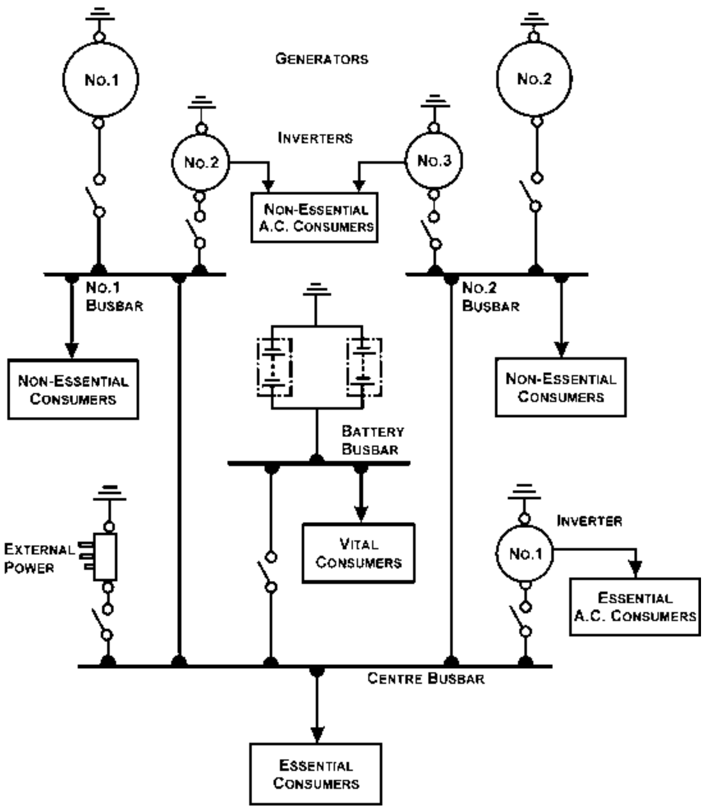

Fig. 18.11. Busbar system.

The supply of d.c. is derived from independent T.R.U. and from batteries. The No.1 T.R.U. supplies essential loads and the No.2 unit supplies non-essential loads connected to the main d.c. busbar; both busbars are automatically interconnected by an isolation relay. The batteries are directly connected to the battery busbar and this is interconnected with the essential busbar. In the event of both generators failing the main d.c. busbar will become isolated from the essential d.c. busbar which will then be automatically supplied from the batteries to maintain operation of essential d.c. and a.c. consumers.

External power supplies and supplies from an auxiliary power unit can be connected to the whole system in the manner indicated in (Fig. 18.12).

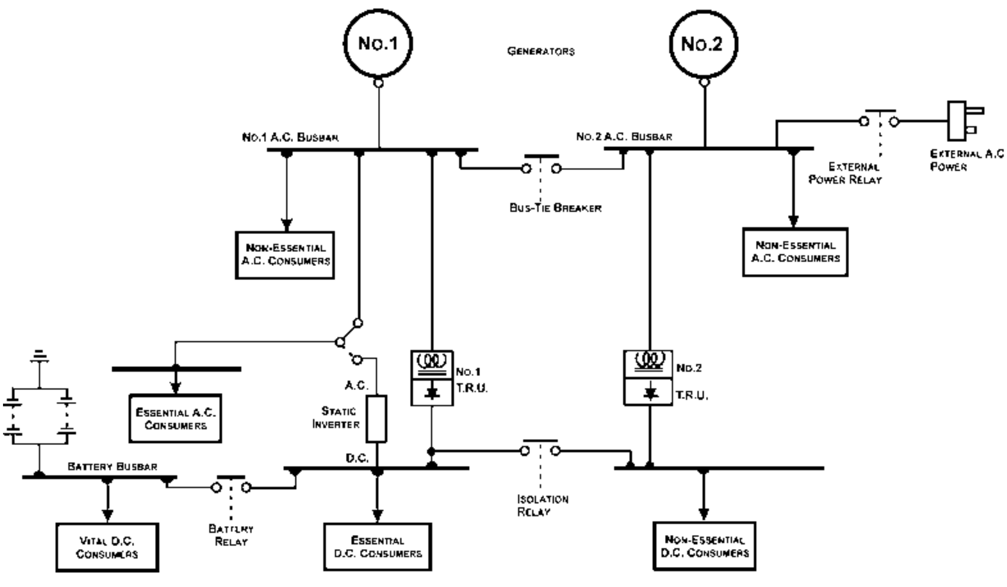

Fig. 18.12. Split busbar system (primary a.c. power source).

Another example of a split busbar system, based on that used in the B737, is shown in (Fig. 18.13). The primary power source is non-parallel 115/200-volt 3-phase a.c. from two 40 kVA generators. A source of a.c. power can be supplied from another 40 kVA generator driven by an auxiliary power unit, and also from an external power unit. Direct current is supplied via three T.R.U.'s.

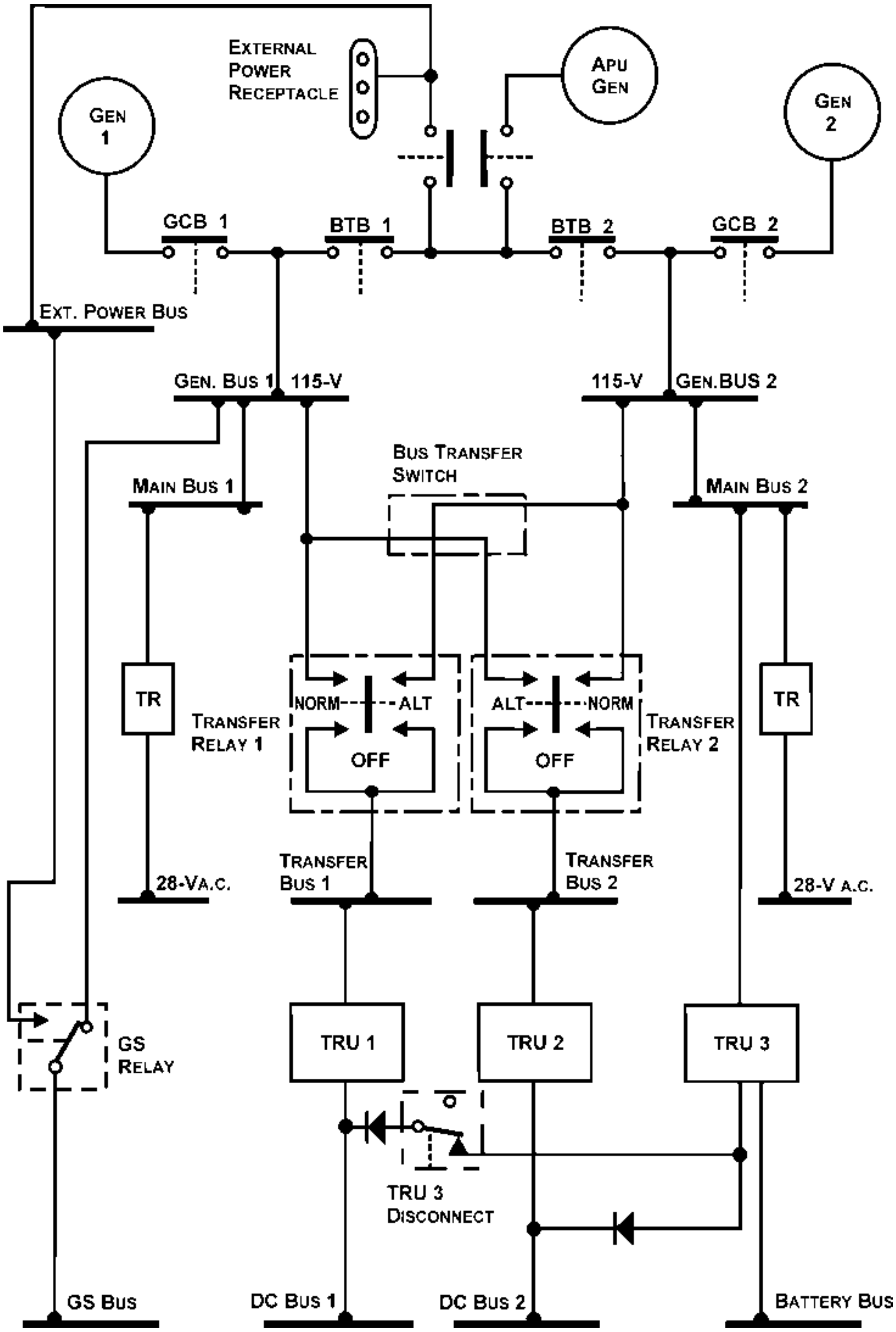

Fig. 18.13. Split busbar system.

The four power sources are connected to the busbars by six 3-phase breakers and two transfer relays, which are energized and de-energized according to the switching selections made on the system control panel shown in (Fig. 18.14). An interlocking circuit system between breakers and switches is also provided to enable proper sequencing of breaker and overall system operation. A source of power switched onto or entering the system always takes priority and so will automatically disconnect any existing power source. The switches are of the "momentary select" type in that following a selection they are returned to a neutral position by spring loading. The bus transfer switch is retained in the "auto" position by a guard cover to provide a path for signals controlling the "normal" and "alternate" positions of the transfer relays. In the "off" position the transfer relays are prevented from being energized to the "alternate" positions so that the two main generating systems are completely isolated from each other.

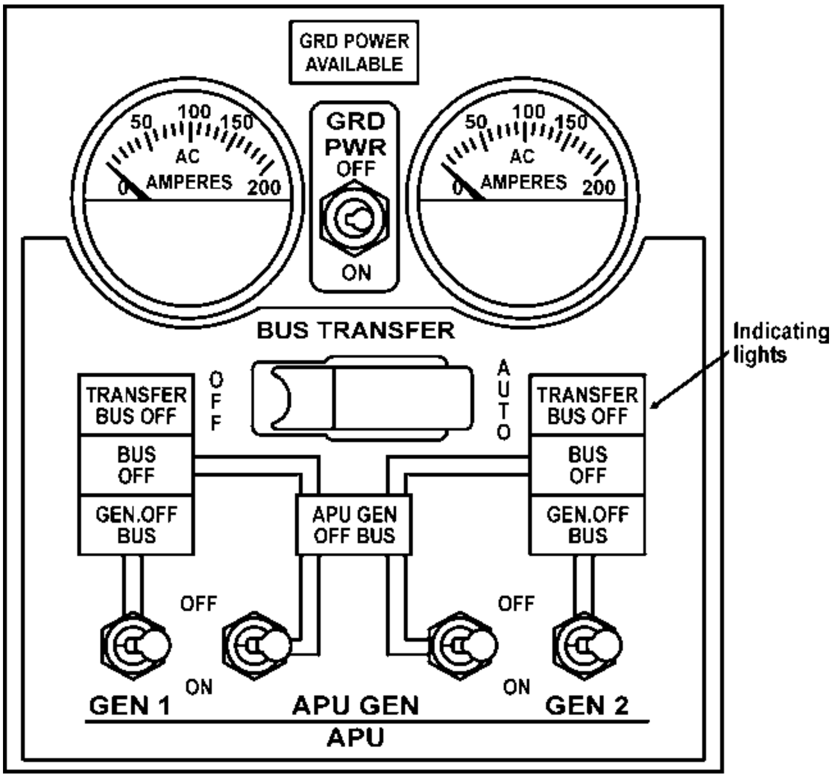

Fig. 18.14. Control panel.

The indicating lights on the control panel are illuminated as follows:

Ground Power Available (blue)	- when external power is plugged into the aircraft.
Transfer Bus Off (amber)	- when either the normal coil of a transfer relay is de-energized.
Bus Off (amber)	- if both the respective GCB and BTB are open.
Gen Bus Off (blue)	- if the respective GCB is open.
APU Gen Bus Off (blue)	- if APU engine is running and over 95% rev/min, but there is no power from the generator.

The ammeters indicate the load current of both main generators.

When external power is connected to the aircraft and is switched on, the external power contactor closes and energizes both bus-tie breakers (BTB's) to connect power to the whole busbar system. The connection between the generator busbars and transfer busbars is made via the transfer relays which are energized to the "normal" position by the BTB's.

The normal in-flight configuration of the power distribution system is for each generator to supply its respective busbars through its own breaker, i.e. GCB1 and GCB2. These breakers are then energized by the generator switches, the interlock circuits keep the BTB's 1 and 2 in the open position, so that the generator systems are always kept entirely separate. GCB 1 and GCB 2 have a set of auxiliary contacts which in the closed position energize transfer relays to their "normal" positions and so provide connections between generators and transfer busbars 1 and 2. As will be noted from the diagram, the transfer busbars supply TRU's 1 and 2, while TRU 3 is supplied direct from the main busbar 2.

In the event of loss of power from one or other generator, number 1 for example, GCB 1 will open thus isolating the corresponding busbars. When GCB 1 opens, however, another set of auxiliary contacts within the breaker permit a d.c. signal to flow from the control unit of generator 2, via a bus transfer switch, to the "alternate" coil of transfer relay 1. The contacts therefore change over so that power can then be supplied to transfer bus 1 from generator 2 which is still supplying its busbars in the normal way. A similar transfer of power takes place in the event of loss of power from generator 2.

Generator busbar 1 and main busbar 1 which carry non-essential loads, can not be supplied with loss conditions. If, however, power to these busbars is required, the APU breaker and BTB 1. At the same time, transfer relay 1 contacts would change over from "alternate" to "normal" so that the APU supplies the whole number 1 system. If a loss of power from the number 2 system should then occur, it is not possible to connect it to the APU since its number 2 switch is electrically locked out during in-flight operation.

The three TRU's are connected in such a way that the loss of any one unit will not result in the loss of a d.c. busbar. The relay between TRU 1 and TRU 3 is held closed by supplying d.c. signals from the generator control units via the bus transfer switch in its "auto" position.

A further variation of the split busbar concept, as adopted in the a.c. power generating system of the B747, is simply illustrated in (Fig. 18.15). It utilizes a system of interlocking GCB's and BTB's, but in this case various combinations of generator operation are possible.

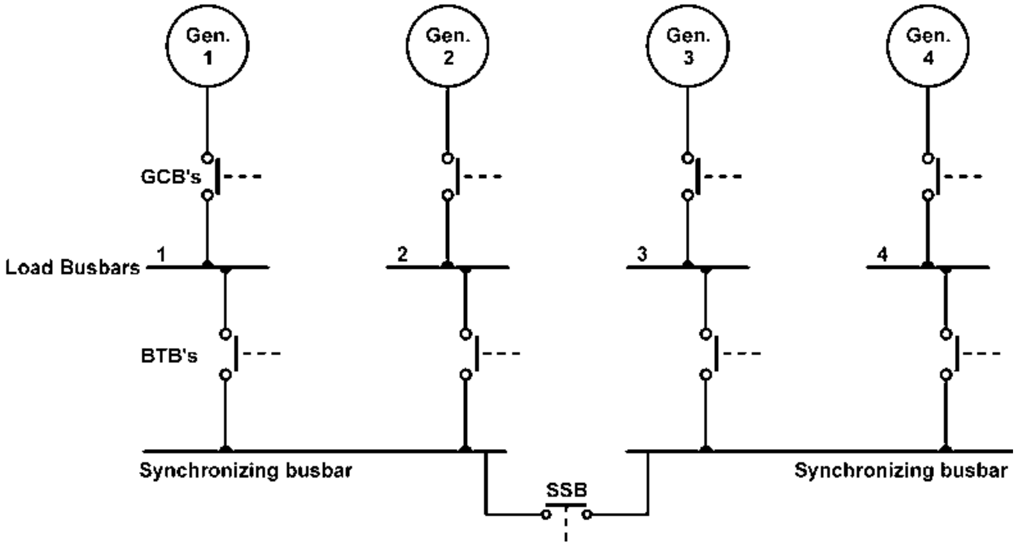

Fig. 18.15. Combinations of parallel operation.

If the GCB's only are closed, then each generator will only supply its respective load busbar; in other words, they are operated individually and unparalleled. The generators may, however, also be operated in parallel when the BTB's are closed to connect the load busbars to a synchronous busbar. As will be noted from the diagram, this busbar is split into two parts by a split system breaker (SSB) which, in the open position allows the generators to operate in two parallel pairs. Closing of the SSB connects both parts of the synchronous busbar so that all four generators can operate as a fully paralleled system. By means of the interlocking system between breakers and the manual and automatic sequencing by which they are controlled, any generator can supply power to any load busbar, and any combination of generators can be operated in parallel.

INVERTERS

An inverter is used in some aircraft systems to convert a portion of the aircraft's d.c. power to a.c. This a.c. is used mainly for instruments, radio, radar, lighting, and other accessories. These inverters are usually built to supply current at a frequency of 400 c.p.s., but some are designed to provide more than one voltage; for example, 26-volt a.c. in one winding and 115 volts in another.

There are two basic types of inverters: the rotary and the static. Either type can be single-phase or multiphase. The multiphase inverter is lighter for the same power rating than the single-phase, but there are complications in distributing multiphase power and in keeping the loads balanced.

Rotary Inverters

There are many sizes, types, and configurations of rotary inverters. Such inverters are essentially a.c. generators and d.c. motors in one housing. The generator field, or armature, and the motor field, or armature, are mounted on a common shaft which will rotate within the housing. One common type of rotary inverter is the permanent magnet inverter.

Permanent Magnet Rotary Inverter

A permanent magnet inverter is composed of a d.c. motor and a permanent magnet a.c. generator assembly. Each has a separate stator mounted within a common housing. The motor armature is mounted on a rotor and connected to the d.c. supply through a commutator and brush assembly. The motor field windings are mounted on the housing and connected directly to the d.c. supply. A permanent magnet rotor is mounted at the opposite end of the same shaft as the motor armature, and the stator windings are mounted on the housing, allowing a.c. to be taken from the inverter without the use of brushes. (Fig. 18.16) shows and internal wiring diagram for this type of rotary inverter. The generator rotor has six poles, magnetized to provide alternate north and south poles about its circumference.

When the motor field and armature are excited, the rotor will begin to turn. As the rotor turns, the permanent magnet will rotate within the a.c. stator coils, and the magnetic flux developed by the permanent magnets will be cut by the conductors in the a.c. stator coils. An a.c. voltage will be produced in the windings whose polarity will change as each pole passes the windings.

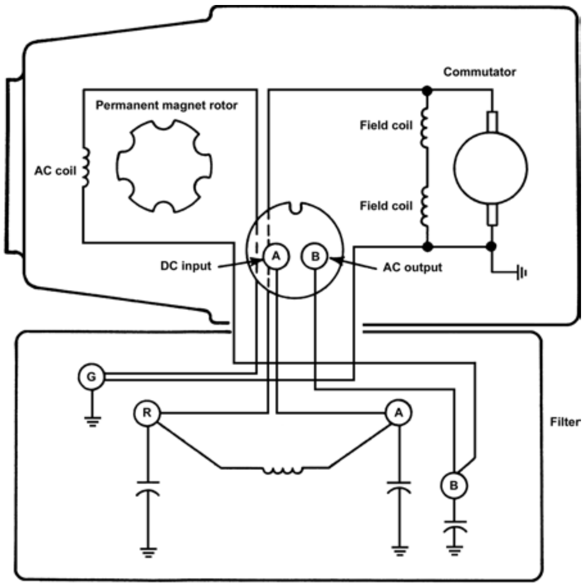

Fig. 18.16. Internal wiring diagram of single-phase permanent magnet rotary inverter.

This type inverter may be made multiphase by placing more a.c. stator coils in the housing in order to shift the phase the proper amount in each coil.

As the name of the rotary inverter indicates, it has a revolving armature in the a.c. generator section. The illustration in (Fig. 18.17) shows the diagram of a revolving-armature, three-phase inverter.

The d.c. motor in this inverter is a four-pole, compound-wound motor. The four field coils consist of many turns of fine wire, with a few turns of heavy wire placed on top. The fine wire is the shunt field, connected to the d.c. source through a filter and to ground through a centrifugal governor. The heavy wire is the series field, which is connected in series with the motor armature. The centrifugal governor controls the speed by shunting a resistor which is in series with the shunt field when the motor reaches a certain speed.

The alternator is a three-phase, four-pole, star connected a.c. generator. The d.c. input is supplied to the generator field coils and connected to ground through a carbon-pile voltage regulator. The output is taken off the armature through three slip rings to provide three-phase power.

The invertor would be a single-phase inverter if it had a single armature winding and one slip ring.

The frequency of this type unit is determined by the speed of the motor and the number of generator poles.

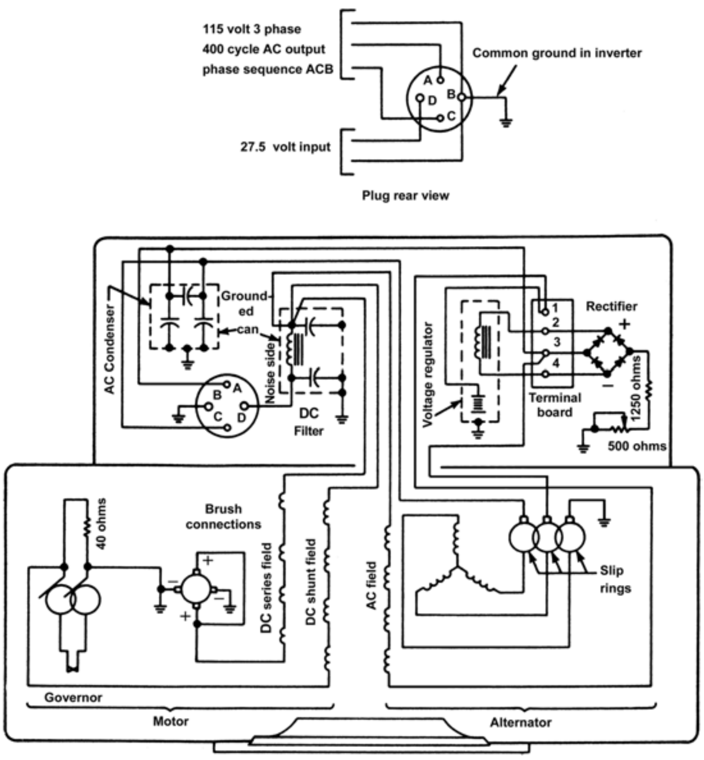

Fig. 18.17. Internal wiring diagram of three-phase, revolving-armature inverter.

Inductor-Type Rotary Inverter

Inductor-type inverters use a rotor made of soft iron laminations with grooves cut laterally across the surface to provide poles that correspond to the number of stator poles, as illustrated in (Fig. 18.18). The field coils are wound on one set of stationary poles and the a.c. armature coils on the other set of stationary poles. When d.c. is applied to the field coils, a magnetic field is produced. The rotor turns within the field coils and, as the poles on the rotor align with the stationary poles, a low reluctance path for flux is established from the field pole through the rotor poles to the a.c. armature pole and through the housing back to the field pole. In this circumstance, there will be a large amount of magnetic flux linking the a.c. coils.

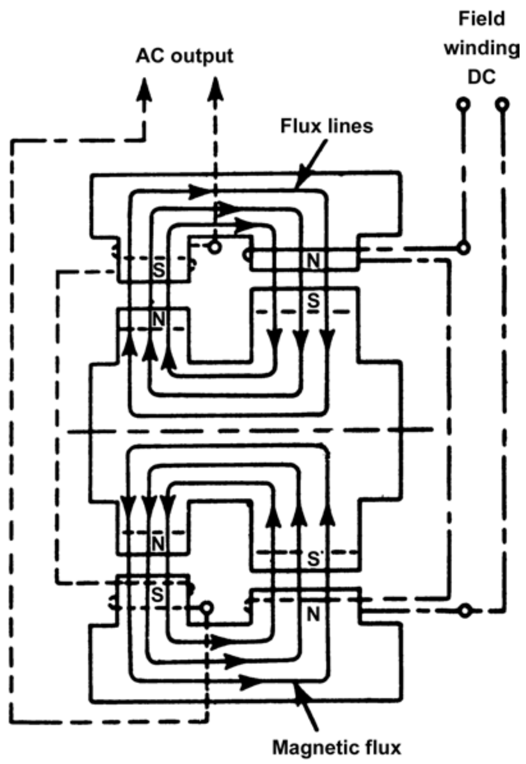

Fig. 18.18. Diagram of basic inductor-type inverter.

When the rotor poles are between the stationary poles, there is a high-reluctance path for flux, consisting mainly of air; then, will be a small amount of magnetic flux linking the a.c. coils, This increase and decrease in flux density in the stator induces an alternating current in the a.c. coils.

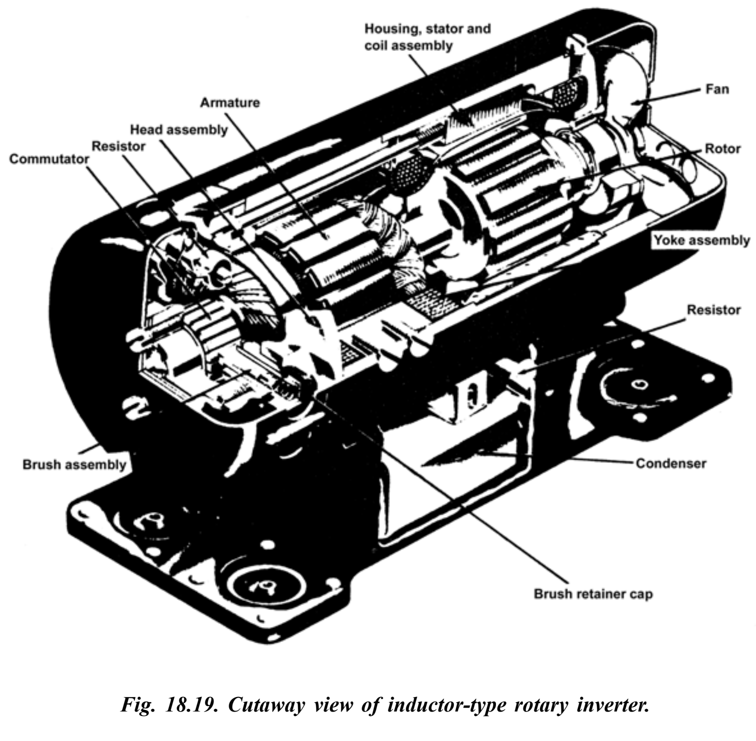

Fig. 18.19. Cutaway view of inductor-type rotary inverter.

The frequency of this type of inverter is determined by the number of poles and the speed of the motor. The voltage is controlled by d.c. stator field current. A cutaway view of an inductor-type rotary inverter is shown in (Fig. 18.19).

Fig. 18.20 is a simplified diagram of a typical aircraft a.c. power distribution system, utilizing a main and a standby rotary inverter system.

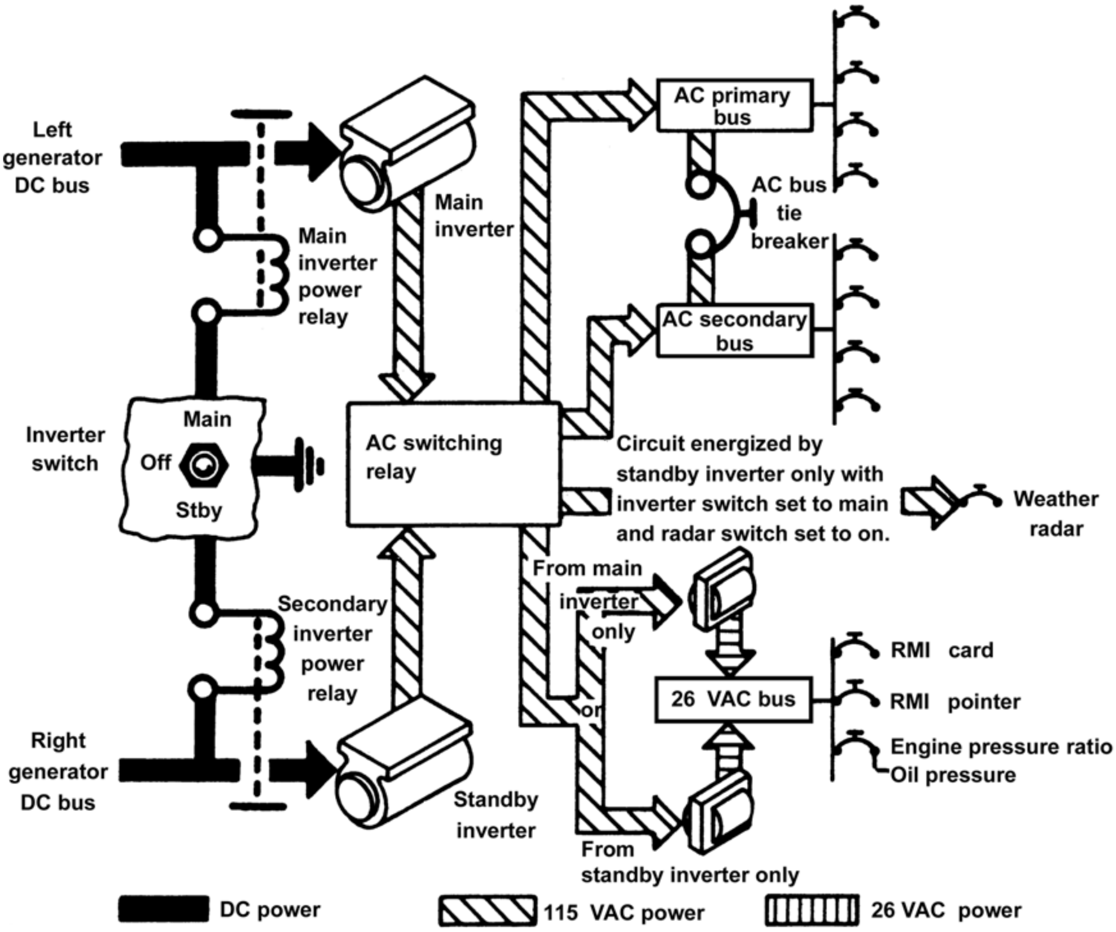

Fig. 18.20. A typical aircraft a.c. power distribution system using main and standby rotary inverters.

Static Inverters

In many applications where continuous d.c. voltage must be converted to alternating voltage, static inverters are used in place of rotary inverters or motor generator sets. The rapid progress being made by the semiconductor industry is extending the range of applications of such equipment into voltage and power ranges which would have been impractical a few years ago. Some such applications are power supplies for frequency-sensitive military and commercial a.c. equipment, aircraft emergency a.c. systems, and conversion of wide frequency range power to precise frequency power.

The use of static inverters in small aircraft also has increased rapidly in the last few years, and the technology has advanced to the point that static inverters are available for any requirement filled by rotary inverters. For example, 250 VA emergency a.c. supplies operated from aircraft batteries are in production, as are 2,500 V A main a.c. supplies operated from a varying frequency generator supply. This type of equipment has certain advantages for aircraft applications, particularly the absence of moving parts and the adaptability to conduction cooling.

Static inverters, referred to as solid-state inverters, are manufactured in a wide range of types and models, which can be classified by the shape of the a.c.output waveform and the power output capabilities. One of the most commonly used static inverters produces a regulated sine wave output.

A block diagram of a typical regulated sine wave static inverter is shown in (Fig. 18.21). This inverter converts a low d.c. voltage into higher a.c. voltage. The a.c. output voltage is held to a very small voltage tolerance, a typical variation of less than 1 percent with a full input load change. Output taps are normally provided to permit selection of various voltages; for example, taps may be provided for a 105-, 115-, and 125- volt a.c. outputs. Frequency regulation is typically within a range of one cycle for a 0-100 percent load change.

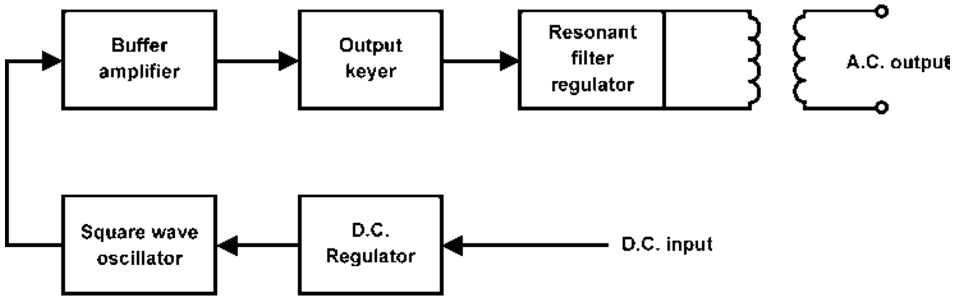

Fig. 18.21. Regulated sine wave static inverter.

Variation of this type of static inverter are available, many of which provide a square wave output.

Since static inverters use solid-state components, they are considerably smaller, more compact, and much lighter in weight than rotary inverters. Depending on the output power rating required, static inverters that are no longer than a typical airspeed indicator can be used in aircraft systems. Some of the features of static inverters are:

1. High efficiency.
2. Low maintenance, long life.
3. No warm up period required.
4. Capable of starting under load.
5. Fast response to load changes.

Static inverters are commonly used to provide power for such frequency-sensitive instruments as the attitude gyro and directional gyro. They also provide power for autosyn and magnesyn indicators and transmitters, rate gyros, radar, and other airborne applications. (Fig. 18.22) is a schematic of a typical small jet aircraft auxiliary battery system. It shows the battery as input to the inverter, and the output inverter circuits to various subsystems.

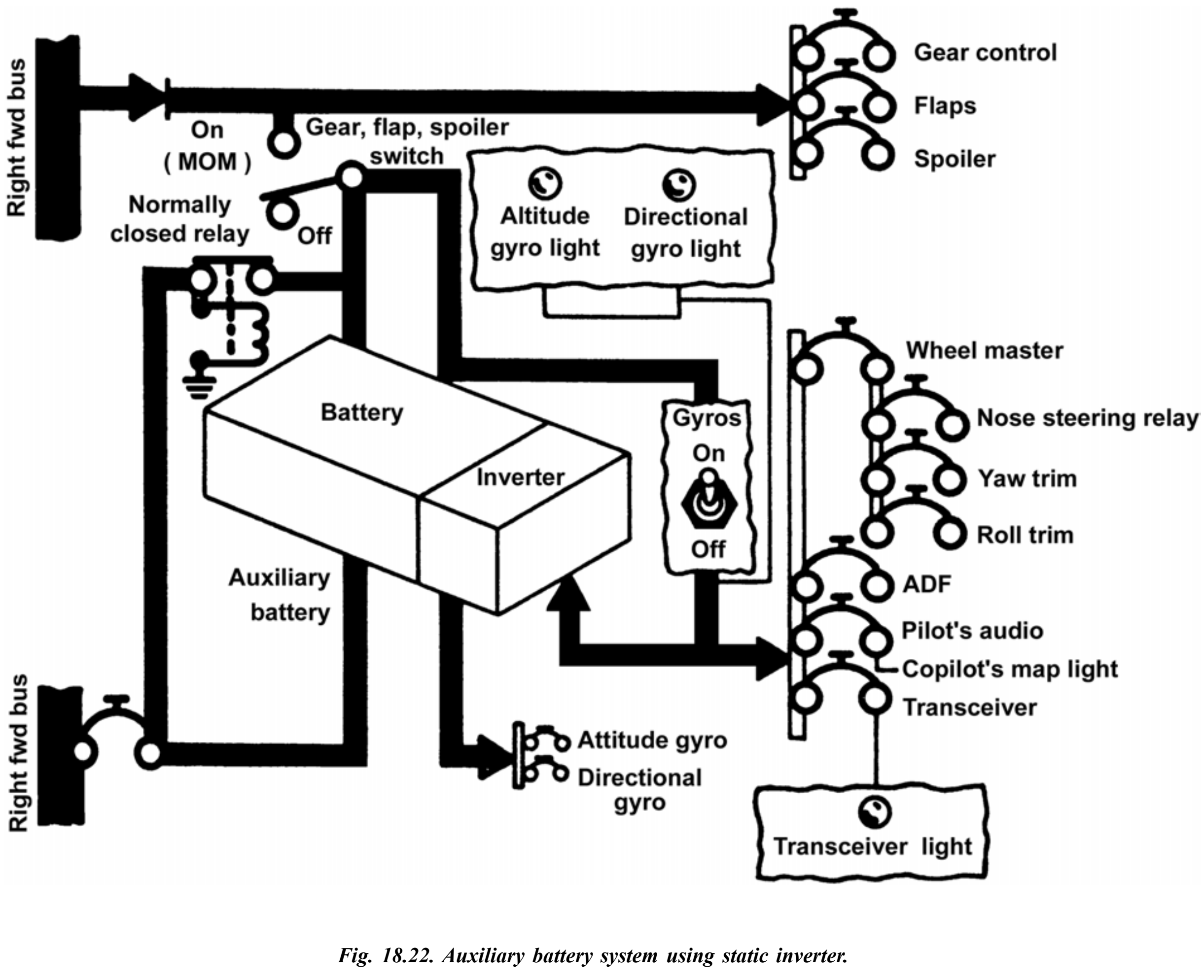

Fig. 18.22. Auxiliary battery system using static inverter.

The function of an inverter used for the conversion of battery supply to single-phase 115-volts a.c. is shown in the block diagram of (Fig. 18.22).

The d.c. is supplied to transistorized circuits of a filter network, a pulse shaper, a constant current generator, power driver stage and the output stage. After any variations in the input have been filtered or smoothed out, d.c. is supplied to a square-wave generator which provides first-stage conversion of the d.c. into square-wave form a.c. and also establishes the required operating frequency of 400 Hz. This output is then supplied to a pulse shaper circuit which controls the pulse width of the signal and changes its wave form before it is passed on to the power driver stage. It will be noted from the diagram that the d.c. required for pulse shaper operation is supplied via a turn-on delay circuit. The reason for this is to cause the pulse shaper to delay its output to the power driver stage until the voltage has stabilized. The power driver supplies a pulse-width modulated symmetrical output to control the output stage, the signal having a square-wave form. The power driver also shorts itself out each time the voltage falls to zero, i.e. during "notch time".

The output stage also produces a square-wave out-put but of variable pulse width. This output is finally fed to a filter circuit which reduces the total odd harmonics to produce a sine wave output at the voltage and frequency required for operating the systems connected to the inverter.

As in the case of other types of generators, the output of a static inverter must also be maintained within certain limits. In the example illustrated, this is done by means of a voltage sensor and a current sensor, both of which produce a rectified a.c. feedback signal which controls the "notch time" of the pulse shaper output through the medium of a regulator circuit and a notch control circuit.

TRANSFORMER - RECTIFIER UNITS

Transformer-rectifier units (T.R.U.'s) are combinations of static transformers and rectifiers, and are utilized in some a.c. systems as secondary supply units, and also as the main conversion units in aircraft having rectified a.c. power systems.

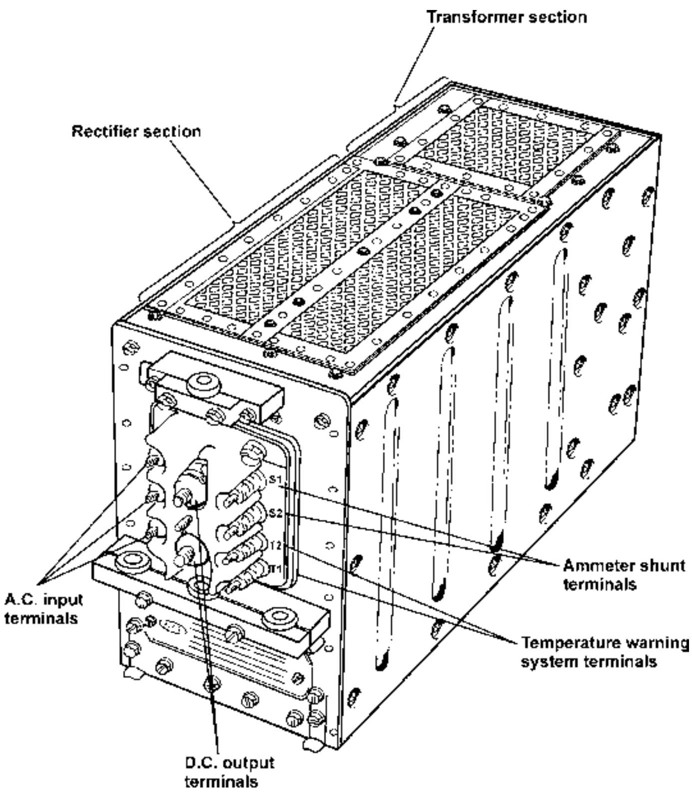

Fig. 18.23. Transformer-rectifier unit.

Fig. 18.23 illustrates a T.R.U. designed to operate on a regulated three-phase input of 200 volts at a frequency of 400 Hz and to provide a continuous d.c. output of 110 A at approximately 26 volts. The circuit is shown schematically in (Fig. 18.23). The unit consists of a transformer and two three-phase bridge rectifier assemblies mounted in separate sections of the casing. The transformer has a conventional starwound primary winding and secondary windings wound in star and delta. Each secondary winding is connected to invidual bridge rectifier assemblies made up of six silicon diodes, and connected in parallel. An ammeter shunt (dropping 50 mV at 100 A) is connected in the output side of the rectifiers to enable current taken from the main d.c. output terminals to be measured at ammeter auxiliary terminals. These terminals, together with all others associated with input and output circuits, are grouped on a panel at one end of the unit. Cooling of the unit is by natural convection through gauze-covered ventilation panels and in order to give warning of overheating conditions, thermal switches are provided at the transformer and rectifier assemblies, and are connected to independent warning lights. The switches are supplied with d.c. from an external source (normally aone of the busbars) and their contacts close when temperature conditions at their respective locations rise to approximately 150^0C and 200^0C.

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