Module 03

FOR B1 & B2 CERTIFICATION

ELECTRICAL FUNDAMENTALS

Aviation Maintenance Technician Certification Series

- Electron Theory
- Static Electricity and Conduction
- Electrical Terminology
- Generation of Electricity
- DC Sources of Electricity
- DC Circuits
- Restistance/Resistor
- Power
- Capacitance/Capacitor
- Magnetism
- Inductance/Inductor
- DC Motor/Generator Theory
- AC Theory

- Resistive (R), Capacitive (C) and, Inductive (L) Circuits
- Transformers
- Filters
- AC Generators
- AC Motors

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ELECTRICAL FUNDAMENTALS

Aviation Maintenance Technician Certification Series

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WELCOME

The publishers of this Aviation Maintenance Technician Certification Series welcome you to the world of aviation maintenance. As you move towards EASA certification, you are required to gain suitable knowledge and experience in your chosen area. Qualification on basic subjects for each aircraft maintenance license category or subcategory is accomplished in accordance with the following matrix. Where applicable, subjects are indicated by an "X" in the column below the license heading.

For other educational tools created to prepare candidates for licensure, contact Aircraft Technical Book Company.

We wish you good luck and success in your studies and in your aviation career!

REVISION LOG

VERSION	EFFECTIVE DATE	DESCRIPTION OF CHANGE
001	2014 08	Original Issue
002	2016 10	Format Update

FORWARD

PART-66 and the Acceptable Means of Compliance (AMC) and Guidance Material (GM) of the European Aviation Safety Agency (EASA) Regulation (EC) No. 1321/2014, Appendix 1 to the Implementing Rules establishes the Basic Knowledge Requirements for those seeking an aircraft maintenance license. The information in this Module of the Aviation Maintenance Technical Certification Series published by the Aircraft Technical Book Company meets or exceeds the breadth and depth of knowledge subject matter referenced in Appendix 1 of the Implementing Rules. However, the order of the material presented is at the discretion of the editor in an effort to convey the required knowledge in the most sequential and comprehensible manner. Knowledge levels required for Category A1, B1, B2, and B3 aircraft maintenance licenses remain unchanged from those listed in Appendix 1 Basic Knowledge Requirements. Tables from Appendix 1 Basic Knowledge Requirements are reproduced at the beginning of each module in the series and again at the beginning of each Sub-Module.

How numbers are written in this book:
This book uses the International Civil Aviation Organization (ICAO) standard of writing numbers. This method displays large numbers by adding a space between each group of 3 digits. This is opposed to the American method which uses commas and the European method which uses periods. For example, the number one million is expressed as so:

ICAO Standard	1 000 000
European Standard	1.000.000
American Standard	1,000,000

SI Units:
The International System of Units (SI) developed and maintained by the General Conference of Weights and Measures (CGPM) shall be used as the standard system of units of measurement for all aspects of international civil aviation air and ground operations.

Prefixes:
The prefixes and symbols listed in the table below shall be used to form names and symbols of the decimal multiples and submultiples of International System of Units (SI) units.

MULTIPLICATION FACTOR	PREFIX	SYMBOL
1 000 000 000 000 000 000 $= 10^{18}$	exa	E
1 000 000 000 000 000 $= 10^{15}$	peta	P
1 000 000 000 000 $= 10^{12}$	tera	T
1 000 000 000 $= 10^{9}$	giga	G
1 000 000 $= 10^{6}$	mega	M
1 000 $= 10^{3}$	kilo	k
100 $= 10^{2}$	hecto	h
10 $= 10^{1}$	deca	da
0.1 $= 10^{-1}$	deci	d
0.01 $= 10^{-2}$	centi	c
0.001 $= 10^{-3}$	milli	m
0.000 001 $= 10^{-6}$	micro	μ
0.000 000 001 $= 10^{-9}$	nano	n
0.000 000 000 001 $= 10^{-12}$	pico	p
0.000 000 000 000 001 $= 10^{-15}$	femto	f
0.000 000 000 000 000 001 $= 10^{-18}$	atto	a

International System of Units (SI) Prefixes

EASA LICENSE CATEGORY CHART

	Module number and title	A1 Airplane Turbine	B1.1 Airplane Turbine	B1.2 Airplane Piston	B1.3 Helicopter Turbine	B2 Avionics
1	Mathematics	X	X	X	X	X
2	Physics	X	X	X	X	X
3	Electrical Fundamentals	X	X	X	X	X
4	Electronic Fundamentals		X	X	X	X
5	Digital Techniques / Electronic Instrument Systems	X	X	X	X	X
6	Materials and Hardware	X	X	X	X	X
7A	Maintenance Practices	X	X	X	X	X
8	Basic Aerodynamics	X	X	X	X	X
9A	Human Factors	X	X	X	X	X
10	Aviation Legislation	X	X	X	X	X
11A	Turbine Aeroplane Aerodynamics, Structures and Systems	X	X			
11B	Piston Aeroplane Aerodynamics, Structures and Systems			X		
12	Helicopter Aerodynamics, Structures and Systems				X	
13	Aircraft Aerodynamics, Structures and Systems					X
14	Propulsion					X
15	Gas Turbine Engine	X	X		X	
16	Piston Engine			X		
17A	Propeller	X	X	X		

MODULE 03 SYLLABUS AS OUTLINED IN PART-66, APPENDIX 1.

LEVELS

CERTIFICATION CATEGORY →	B1	B2

Sub-Module 01 - Electron Theory

Structure and distribution of electrical charges within: atoms, molecules, ions, compounds; Molecular structure of conductors, semiconductors and insulators.

1   1

Sub-Module 02 - Static Electricity and Conduction

Static electricity and distribution of electrostatic charges;
Electrostatic laws of attraction and repulsion;
Units of charge, Coulomb's Law;
Conduction of electricity in solids, liquids, gases and a vacuum.

2   2

Sub-Module 03 - Electrical Terminology

The following terms, their units and factors affecting them: potential difference, electromotive force, voltage, current, resistance, conductance, charge, conventional current flow, electron flow.

2   2

Sub-Module 04 - Generation of Electricity

Production of electricity by the following methods: light, heat, friction, pressure, chemical action, magnetism and motion.

1   1

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Sub-Module 05 - DC Sources of Electricity

Construction and basic chemical action of: primary cells, secondary cells, lead acid cells, nickel cadmium cells, other alkaline cells;
Cells connected in series and parallel;
Internal resistance and its effect on a battery;
Construction, materials and operation of thermocouples;
Operation of photo-cells.

	2	2

Sub-Module 06 - DC Circuits

Ohms Law, Kirchoff's Voltage and Current Laws;
Calculations using the above laws to find resistance, voltage and current;
Significance of the internal resistance of a supply.

	2	2

Sub-Module 07 - Restistance/Resistor

(a) Resistance and affecting factors;
Specific resistance;
Resistor colour code, values and tolerances, preferred values, wattage ratings;
Resistors in series and parallel;
Calculation of total resistance using series, parallel and series parallel combinations;
Operation and use of potentiometers and rheostats;
Operation of Wheatstone Bridge;

	2	2

(b) Positive and negative temperature coefficient conductance;
Fixed resistors, stability, tolerance and limitations, methods of construction;
Variable resistors, thermistors, voltage dependent resistors;
Construction of potentiometers and rheostats;
Construction of Wheatstone Bridge.

	1	1

Sub-Module 08 - Power

Power, work and energy (kinetic and potential);
Dissipation of power by a resistor;
Power formula;
Calculations involving power, work and energy.

	2	2

Sub-Module 09 - Capacitance/Capacitor

Operation and function of a capacitor;
Factors affecting capacitance area of plates, distance between plates, number of plates, dielectric and dielectric constant, working voltage, voltage rating;
Capacitor types, construction and function;
Capacitor colour coding;
Calculations of capacitance and voltage in series and parallel circuits;
Exponential charge and discharge of a capacitor, time constants;
Testing of capacitors.

	2	2

Sub-Module 10 - Magnetism

		B1	B2
(a)	Theory of magnetism; Properties of a magnet; Action of a magnet suspended in the Earth's magnetic field; Magnetisation and demagnetisation; Magnetic shielding; Various types of magnetic material; Electromagnets construction and principles of operation; Hand clasp rules to determine: magnetic field around current carrying conductor;	2	2
(b)	Magnetomotive force, field strength, magnetic flux density, permeability, hysteresis loop, retentivity, coercive force reluctance, saturation point, eddy currents; Precautions for care and storage of magnets.	2	2

Sub-Module 11 - Inductance/Inductor

	B1	B2
Faraday's Law; Action of inducing a voltage in a conductor moving in a magnetic field; Induction principles; Effects of the following on the magnitude of an induced voltage: Magnetic field strength, rate of change of flux, number of conductor turns; Mutual induction; The effect the rate of change of primary current and mutual inductance has on induced voltage; Factors affecting mutual inductance: number of turns in coil, physical size of coil, permeability of coil, position of coils with respect to each other; Lenz's Law and polarity determining rules; Back emf, self induction; Saturation point; Principle uses of inductors.	2	2

Sub-Module 12 - DC Motor/Generator Theory

	B1	B2
Basic motor and generator theory; Construction and purpose of components in DC generator; Operation of, and factors affecting output and direction of current flow in DC generators; Operation of, and factors affecting output power, torque, speed and direction of rotation of DC motors; Series wound, shunt wound and compound motors; Starter Generator construction.	2	2

Sub-Module 13 - AC Theory

	B1	B2
Sinusoidal waveform: phase, period, frequency, cycle; Instantaneous, average, root mean square, peak, peak to peak current values and calculations of these values, in relation to voltage, current and power; Triangular/Square waves; Single/3 phase principles.	2	2

Sub-Module 14 - Resistive (R), Capacitive (C) and Inductive (L) Circuits

	B1	B2
Phase relationship of voltage and current in L, C and R circuits, parallel, series and series parallel; Power dissipation in L, C and R circuits; Impedance, phase angle, power factor and current calculations; True power, apparent power and reactive power calculations.	2	2

Sub-Module 15 - Transformers

	B1	B2
Transformer construction principles and operation; Transformer losses and methods for overcoming them; Transformer action under load and no-load conditions; Power transfer, efficiency, polarity markings; Calculation of line and phase voltages and currents, calculation of power in a three phase system; Primary and Secondary current, voltage, turns ratio, power, efficiency; Auto transformers.	2	2

Sub-Module 16 - Filters

	B1	B2
Operation, application and uses of the following filters: low pass, high pass, band pass, band stop.	1	1

Sub-Module 17 - AC Generators

	B1	B2
Rotation of loop in a magnetic field and waveform produced; Operation and construction of revolving armature and revolving field type AC generators; Single phase, two phase and three phase alternators; Three phase star and delta connections advantages and uses; Permanent Magnet Generators.	2	2

Sub-Module 18 - AC Motors

	B1	B2
Construction, principles of operation and characteristics of: AC synchronous and induction motors both single and polyphase; Methods of speed control and direction of rotation; Methods of producing a rotating field: capacitor, inductor, shaded or split pole.	2	2

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ELECTRICAL FUNDAMENTALS

SUB-MODULE 01
ELECTRON THEORY

SUB-MODULE 02
STATIC ELECTRICITY AND CONDUCTION

SUB-MODULE 03
ELECTRICAL TERMINOLOGY

SUB-MODULE 04
GENERATION OF ELECTRICITY

SUB-MODULE 05
DC SOURCES OF ELECTRICITY

SUB-MODULE 06
DC CIRCUITS

CONTENTS

CONTENTS

ELECTRICAL FUNDAMENTALS

ELECTRON THEORY

SUB-MODULE 01

PART-66 SYLLABUS LEVELS
CERTIFICATION CATEGORY → **B1 B2**

Sub-Module 01
ELECTRON THEORY
Knowledge Requirements

3.1 – Electron Theory

Structure and distribution of electrical charges within: atoms, molecules, ions, compounds;   **1   1**
Molecular structure of conductors, semiconductors and insulators.

Level 1
A familiarization with the principal elements of the subject.

Objectives:
   (a)   The applicant should be familiar with the basic elements of the subject.
   (b)   The applicant should be able to give a simple description of the whole subject, using common words and examples.
   (c)   The applicant should be able to use typical terms.

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ELECTRICITY AND ELECTRONICS

This chapter addresses the fundamental concepts that are the building blocks for advanced electrical knowledge and practical troubleshooting. Some of the questions addressed are: How does energy travel through a copper wire and through space? What is electric current, electromotive force, and what makes a landing light turn on or a hydraulic pump motor run?

Each of these questions requires an understanding of many basic principles. By developing a solid knowledge of electrical fundamentals it becomes possible to answer these practical questions and more. Understanding electrical current must begin with the nature of matter. All matter is composed of molecules. All molecules are made up of atoms, which are themselves made up of electrons, protons, and neutrons.

GENERAL COMPOSITION OF MATTER

MATTER
Matter can be defined as anything that has mass and has volume and is the substance of which physical objects are composed. Essentially, it is anything that can be touched. Mass is the amount of matter in a given object. Typically, the more matter there is in an object the more mass it will have. Weight is an indirect method of determining mass but not the same. The difference between mass and weight is that weight is determined by how much something or the fixed mass is pulled by gravity. Categories of matter are ordered by molecular activity. The four categories or states are: solids, liquids, gases, and plasma. For the purposes of the aircraft technician, only solids, liquids, and gases are considered.

ELEMENTS
An element is a substance that cannot be reduced to a simpler form by chemical means. Iron, gold, silver, copper, and oxygen are examples of elements. Beyond this point of reduction, the element ceases to be what it is.

COMPOUNDS
A compound is a chemical combination of two or more elements. Water is one of the most common compounds and is made up of two hydrogen atoms and one oxygen atom.

MOLECULES
The smallest particle of matter that can exist and still retain its identity, such as water (H_2O), is called a molecule. A molecule of water is illustrated in *Figure 1-1*. 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. It would no longer retain the characteristics of water if it were compounded of one atom of hydrogen
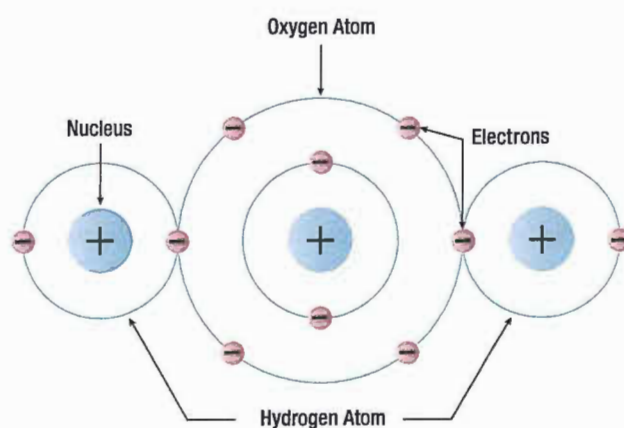
Figure 1-1. A water molecule.

and two atoms of oxygen. If a drop of water is divided in two and then divided again and again until it cannot be divided any longer, it will still be water.

ATOMS
The atom is considered to be the most basic building block of all matter. Atoms are composed of three subatomic particles. These three sub-atomic particles are: protons, neutrons, and electrons. These three particles will determine the properties of the specific atoms. Elements are substances composed of the same atoms with specific properties. Oxygen is an example of this.

The main property that defines each element is the number of neutrons, protons, and electrons. Hydrogen and helium are examples of elements. Both of these elements have neutrons, protons, and electrons but differ in the number of those items. This difference alone accounts for the variations in chemical and physical properties of these two different elements. There are over a 100 known elements in the periodic table, and

they are categorized according to their properties on that table. The kinetic theory of matter also states that the particles that make up the matter are always moving. Thermal expansion is considered in the kinetic theory and explains why matter contracts when it is cool and expands when it is hot, with the exception of water/ice.

ELECTRONS, PROTONS, AND NEUTRONS

At the center of the atom is the nucleus, which contains the protons and neutrons. The protons are positively charged particles, and the neutrons are a neutrally charged particle. The neutron has approximately the same mass as the proton. The third particle of the atom is the electron that is a negatively charged particle with a very small mass compared to the proton. The proton's mass is approximately 1 837 times greater than the electron. Due to the proton and the neutron location in the central portion of the atom (nucleus) and the electron's position at the distant periphery of the atom, it is the electron that undergoes the change during chemical reactions. Since a proton weighs approximately 1 845 times as much as an electron, the number of protons and neutrons in its nucleus determines the overall weight of an atom.

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 electron is a negative charge with no mass (weight) or a particle of matter with a negative charge.

Hydrogen represents the simplest form of an atom, as shown in *Figure 1-2*. At the nucleus of the hydrogen atom is one proton and at the outer shell is one orbiting electron. At a more complex level is the oxygen atom, as shown in *Figure 1-3*, which has eight electrons in two shells orbiting the nucleus with eight protons and eight neutrons. When the total positive charge of the protons in the nucleus equals the total negative charge of the electrons in orbit around the nucleus, the atom is said to have a neutral charge.

ELECTRON SHELLS AND ENERGY LEVELS

Electrons require a certain amount of energy to stay in an orbit. This particular quantity is called the electron's energy level. By its motion alone, the electron possesses kinetic energy, while the electron's position in orbit
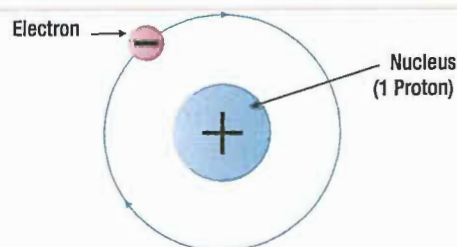
Figure 1-2. Hydrogen atom.
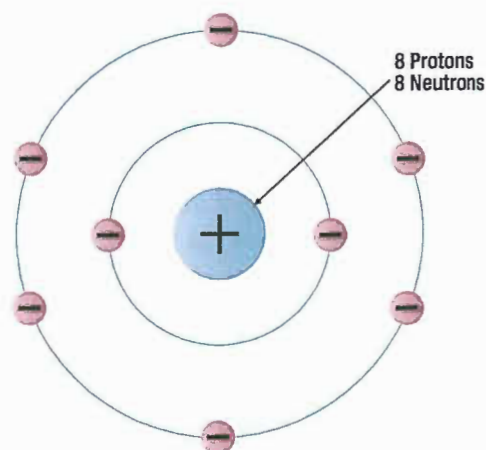
Figure 1-3. Oxygen atom.

determines its potential energy. The total energy of an electron is the main factor that determines the radius of the electron's orbit.

Electrons of an atom will appear only at certain definite energy levels (shells). The spacing between energy levels is such that when the chemical properties of the various elements are cataloged it is convenient to group several closely spaced permissible energy levels together into electron shells. The maximum number of electrons that can be contained in any shell or sub-shell is the same for all atoms and is defined as Electron Capacity $= 2n^2$. In this equation n represents the energy level in question. The first shell can only contain two electrons; the second shell can only contain eight electrons; the third, 18 and so on until we reach the seventh shell for the heaviest atoms, which have six energy levels. Because the innermost shell is the lowest energy level, the shell begins to fill up from the shell closest to the nucleus and fill outward as the atomic number of the element increases. However, an energy level does not need to be completely filled before electrons begin to fill the next level. The Periodic Table of Elements should be checked to determine an element's electron configuration.

VALENCE ELECTRONS

Valence is the number of chemical bonds an atom can form. Valence electrons are electrons that can participate in chemical bonds with other atoms. The number of electrons in the outermost shell of the atom is the determining factor in its valence. Therefore, the electrons contained in this shell are called valence electrons.

IONS

Ionization is the process by which an atom loses or gains electrons. Dislodging an electron from an atom will cause the atom to become positively charged. This net positively charged atom is called a positive ion or a cation. An atom that has gained an extra number of electrons is negatively charged and is called a negative ion or an anion. When atoms are neutral, the positively charged proton and the negatively charged electrons are equal in number.

FREE ELECTRONS

Valence electrons are found drifting midway between two nuclei. Some electrons are more tightly bound to the nucleus of their atom than others and are positioned in a shell or sphere closer to the nucleus, while others are more loosely bound and orbit at a greater distance from the nucleus. These outermost electrons are called "free" electrons because they can be easily dislodged from the positive attraction of the protons in the nucleus. Once freed from the atom, the electron can then travel from atom to atom, becoming the flow of electrons commonly called current in a practical electrical circuit.

ELECTRON MOVEMENT

The valence of an atom determines its ability to gain or lose an electron, which ultimately determines the chemical and electrical properties of the atom. These properties can be categorized as being a conductor, semiconductor or insulator, depending on the ability of the material to produce free electrons. When a material has a large number of free electrons available, a greater current can be conducted in the material.

CONDUCTORS

Elements such as gold, copper and silver possess many free electrons and make good conductors. The atoms in these materials have a few loosely bound electrons in their outer orbits. Energy in the form of heat can cause these electrons in the outer orbit to break loose and drift throughout the material. Copper and silver have one electron in their outer orbits. At room temperature, a piece of silver wire will have billions of free electrons.

INSULATORS

These are materials that do not conduct electrical current very well or not at all. Good examples of these are: glass, ceramic, and plastic. Under normal conditions, atoms in these materials do not produce free electrons. The absence of the free electrons means that electrical current cannot be conducted through the material. Only when the material is in an extremely strong electrical field will the outer electrons be dislodged. This action is called breakdown and usually causes physical damage to the insulator.

SEMICONDUCTORS

This material falls in between the characteristics of conductors and insulators, in that they are not good at conducting or insulating. Silicon and germanium are the most widely used semiconductor materials. For a more detailed explanation on this topic, refer to *Module 04 Electronic Fundamentals* in this series.

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Question: 1-1

_____ of an atom hold electrons at different energy levels.

Question: 1-2

A material that has a large number of free electrons available is known as a _____.

Question: 1-3

A material that is neither a good conductor or insulator is known as a _____.

ANSWERS

Answer: 1-1
Electron shells.

Answer: 1-3
semiconductor.

Answer: 1-2
a conductor.

ELECTRICAL FUNDAMENTALS

STATIC ELECTRICITY AND CONDUCTION

SUB-MODULE 02

PART-66 SYLLABUS LEVELS

CERTIFICATION CATEGORY → **B1** **B2**

Sub-Module 02
STATIC ELECTRICITY AND CONDUCTION
Knowledge Requirements

3.2 – *Static Electricity and Conduction*

	B1	B2
Static electricity and distribution of electrostatic charges; Electrostatic laws of attraction and repulsion; Units of charge, Coulomb's Law; Conduction of electricity in solids, liquids, gases and a vacuum.	2	2

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

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STATIC ELECTRICITY

Electricity is often described as being either static or dynamic. The difference between the two is based simply on whether the electrons are at rest (static) or in motion (dynamic). Static electricity is a build up of an electrical charge on the surface of an object. It is considered "static" due to the fact that there is no current flowing as in AC or DC electricity. Static electricity is usually caused when non-conductive materials such as rubber, plastic or glass are rubbed together, causing a transfer of electrons, which then results in an imbalance of charges between the two materials. The fact that there is an imbalance of charges between the two materials means that the objects will exhibit an attractive or repulsive force.

ATTRACTIVE AND REPULSIVE FORCES

One of the most fundamental laws of static electricity, as well as magnetics, deals with attraction and repulsion. Like charges repel each other and unlike charges attract each other. All electrons possess a negative charge and as such will repel each other. Similarly, all protons possess a positive charge and as such will repel each other. Electrons (negative) and protons (positive) are opposite in their charge and will attract each other. For example, if two pith balls are suspended, as shown in *Figure 2-1*, and each 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, repel each other as shown in part B of *Figure 2-1*. 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 charges and attract each other as shown in part C of *Figure 2-1*.

Coulomb's law further defines the relationship between charges. It states that like charges repel and opposite charges attract with a force proportional to the product of the charges and inversely proportional to the square of the distance between them. This means that objects with greater charge repel similar charges and attract opposite charges with greater force. Also, as the distance between charges becomes greater, the repulsion or attraction between the charges decreases.
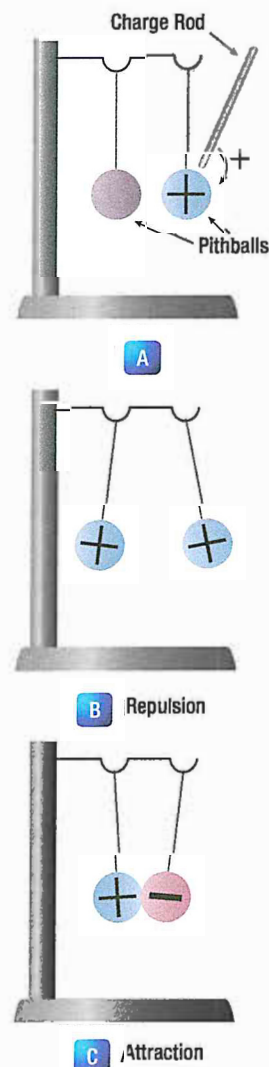
Figure 2-1. Reaction of like and unlike charges.

UNITS OF CHARGE

A single elementary charge (e) is the charge that a single proton (or electron) possesses. The coulomb (C) is an SI derived unit of electrical charge. One coulomb is equal to the charge carried by one ampere in one second. An ampere represents the flow of 6.241×10^{18} electrons.

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 *Figure 2-2*. If a positively charged rod touches an uncharged metal 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.

A method of charging a metal bar by induction is demonstrated in *Figure 2-3*. 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.
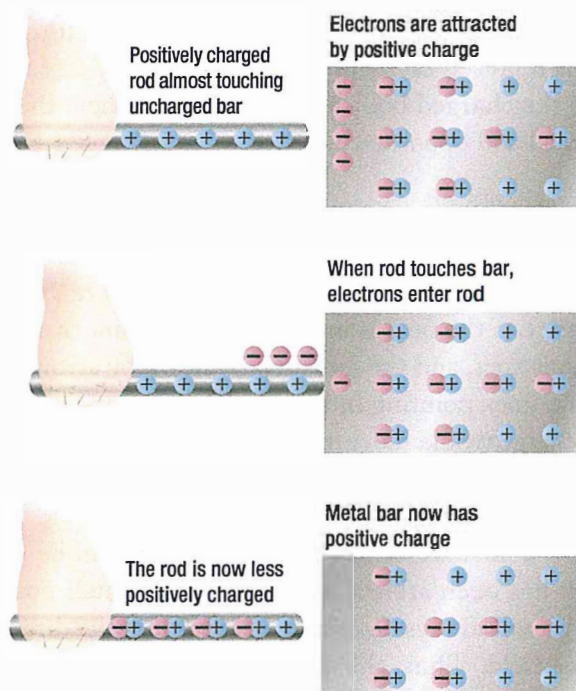
Figure 2-2. Charging by contact.
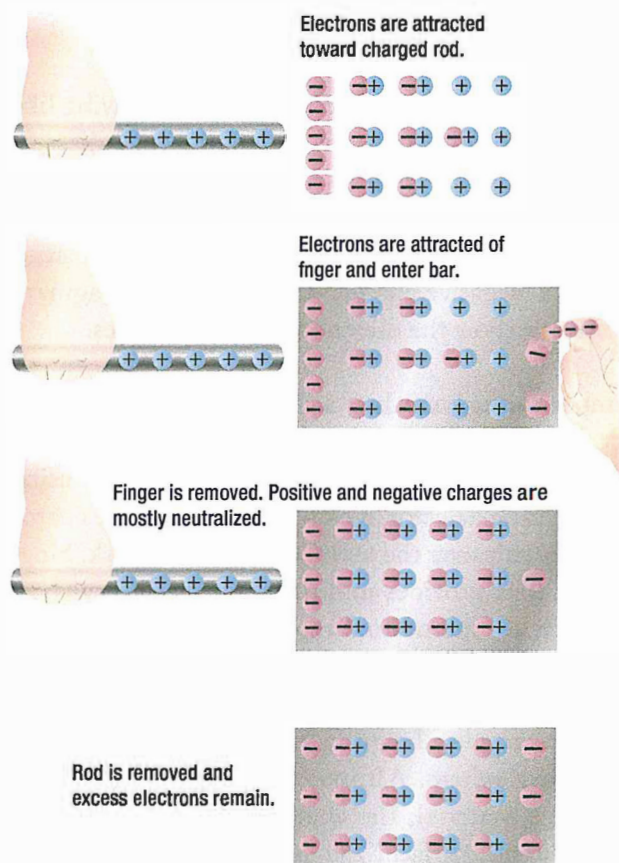
Figure 2-3. Charging a bar by induction.

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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 directions 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 *Figure 2-4*, 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.

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 *Figure 2-4*, 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.

Figure 2-5 illustrates 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.

It is important to know how a charge is distributed on an object. *Figure 2-6* shows a small metal disk on which a 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 on its surface, the mutual repulsion of electrons will result in an even distribution over the entire surface.

Another example, shown in *Figure 2-7*, 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
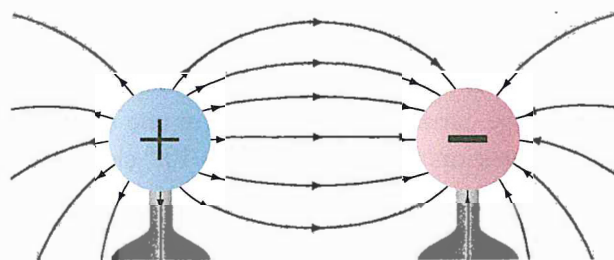
Figure 2-4. Direction of electric field around positive and negative charges.
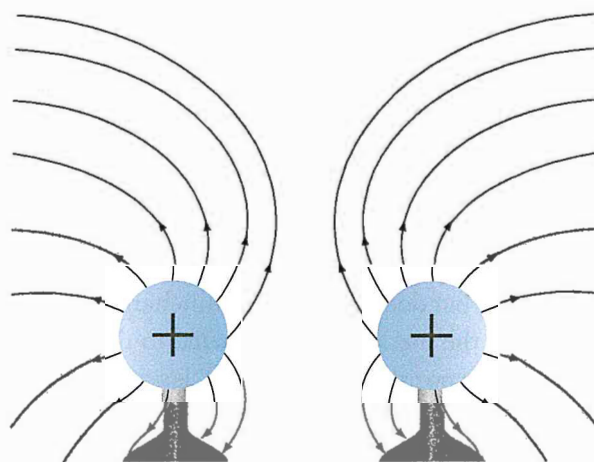
Figure 2-5. Field around two positively charged bodies.
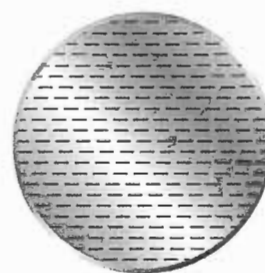
Figure 2-6. Even distribution of charge on metal disk.
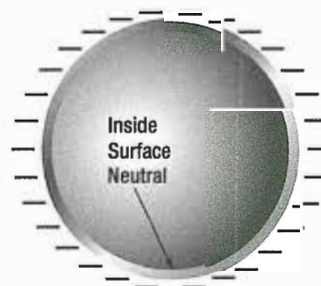
Figure 2-7. Charge on a hollow sphere.

personnel of the large Van de Graaff 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. *Figure 2-8* 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.
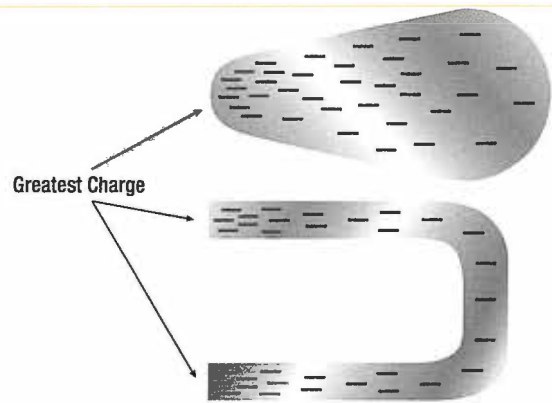
Figure 2-8. Charge on irregularly shaped objects.

ESD CONSIDERATIONS

One of the most frequent causes of damage to a solid-state component or integrated circuits is the electrostatic discharge (ESD) from the human body when one of these devices is handled. Careless handling of line replaceable units (LRUs), circuit cards, and discrete components can cause unnecessarily time consuming and expensive repairs. This damage can occur if a technician touches the mating pins for a card or box. Other sources for ESD can be the top of a toolbox that is covered with a carpet. Damage can be avoided by discharging the static electricity from your body by touching the chassis of the removed box, by wearing a grounding wrist strap, and exercising good professional handling of the components in the aircraft. This can include placing protective caps over open connectors and not placing an ESD sensitive component in an environment that will cause damage. Parts that are ESD sensitive are typically shipped in bags specially designed to protect components from electrostatic damage.

Other precautions that should be taken with working with electronic components are:
1. Always connect a ground between test equipment and circuit before attempting to inject or monitor a signal.
2. Ensure test voltages do not exceed maximum allowable voltage for the circuit components and transistors.
3. Ohmmeter ranges that require a current of more than one milliampere in the test circuit should not be used for testing transistors.
4. The heat applied to a diode or transistor, when soldering is required, should be kept to a minimum by using low-wattage soldering irons and heat-sinks.
5. Do not pry components off of a circuit board.
6. Power must be removed from a circuit before replacing a component.
7. When using test probes on equipment and the space between the test points is very close, keep the exposed portion of the leads as short as possible to prevent shorting.

CONDUCTION OF ELECTRICITY

Electricity can be conducted through solids, liquids, and gases. It can even pass through a vacuum. Electric current is the movement of valence electrons. Solids, particularly metals, that have valence electrons with weak covalent bonds are excellent conductors. Liquid metals possess the same characteristics. Some non-metallic liquids also conduct electricity by ionization of their molecules.

Water, for example, ionizes when electricity is applied and the ions carry the electric current. Gases are typically good insulators but some gases also ionize and carry current, especially in the presence of a large electromotive force such as lightening. There are no electrons to carry current in a vacuum, however, should electrons be injected into a vacuum, there is nothing to inhibit their movement. As such a vacuum is an ideal conductor.

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Question: 2-1

The buildup of an electrical charge on the surface of an object is known as _____.

Question: 2-2

A sphere made of conductive material has electric charge on the outer surface. The charge on the inside is

_____.

Question: 2-3

To prevent damage to electronic equipment when handling, the technician must take precautions to prevent EDS which stands for _____.

ANSWERS

Answer: 2-1
static electricity.

Answer: 2-3
electrostatic discharge.

Answer: 2-2
neutral.

ELECTRICAL FUNDAMENTALS

ELECTRICAL TERMINOLOGY

SUB-MODULE 03

	B1	B2

Sub-Module 03
ELECTRICAL TERMINOLOGY
Knowledge Requirements

3.3 – Electrical Terminology

	B1	B2
The following terms, their units and factors affecting them: potential difference, electromotive force, voltage, current, resistance, conductance, charge, conventional current flow, electron flow.	2	2

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

SI PREFIXES USED FOR ELECTRICAL CALCULATIONS

In any system of measurements, a single set of units is usually not sufficient for all the computations involved in electrical repair and maintenance. Small distances, for example, can usually be measured in inches, but larger distances are more meaningfully expressed in feet, yards, or miles. Since electrical values often vary from numbers that are a millionth part of a basic unit of measurement to very large values, it is often necessary to use a wide range of numbers to represent the values of such units as volts, amperes, or ohms. A series of prefixes which appear with the name of the unit have been devised for the various multiples or sub multiples of the basic units. There are 12 of these prefixes, which are also known as conversion factors.

Four of the most commonly used prefixes used in electrical work with a short definition of each are as follows:

Mega (M) means one million (1 000 000)
Kilo (k) means one thousand (1 000)
Milli (m) means one-thousandth (1/1 000)
Micro (μ) means one-millionth (1/1 000 000)

One of the most extensively used conversion factors, kilo, can be used to explain the use of prefixes with basic units of measurement. Kilo means 1 000, and when used with volts, is expressed as kilovolt, meaning 1 000 volts.

The symbol for kilo is the letter "k". Thus, 1 000 volts is one kilovolt or 1kV. Conversely, one volt would equal one-thousandth of a kV, or 1/1 000 kV. This could also be written 0.001 kV.

Similarly, the word "milli" means one-thousandth, and thus, 1 millivolt equals one-thousandth (1/1 000) of a volt. *Figure 3-1* contains a complete list of the multiples used to express electrical quantities, together with the prefixes and symbols used to represent each number.

Number	Prefix	Symbol
1 000 000 000 000	tera	t
1 000 000 000	giga	g
1 000 000	mega	M
1 000	kilo	k
100	hecto	h
10	deka	dk
0.1	deci	d
0.01	centi	c
0.001	milli	m
0.000 001	micro	μ
0.000 000 001	nano	n
0.000 000 000 001	pico	p

Figure 3-1. Prefixes and symbols for multiples of basic quantities.

CONVENTIONAL FLOW AND ELECTRON FLOW

Today's technician will find that there are two competing schools of thought and analytical practices regarding the flow of electricity. The two are called the conventional current theory and the electron theory.

CONVENTIONAL FLOW
Of the two, the conventional current theory was the first to be developed and, through many years of use, this method has become ingrained in electrical texts. The theory was initially advanced by Benjamin Franklin who reasoned that current flowed out of a positive source into a negative source or an area that lacked an abundance of charge. The notation assigned to the electric charges was positive (+) for the abundance of charge and negative (–) for a lack of charge. It then seemed natural to visualize the flow of current as being from the positive (+) to the negative (–).

ELECTRON FLOW
Later discoveries were made that proved that just the opposite is true. Electron flow is what actually happens where an abundance of electrons flow out of the negative (–) source to an area that lacks electrons or the positive (+) source. Both conventional flow and electron flow are used in industry. Many textbooks in current use employ both electron flow and conventional flow methods. From the practical standpoint of the technician, troubleshooting a system, it makes little to no difference which way current is flowing as long as it is used consistently in the analysis.

ELECTROMOTIVE FORCE (VOLTAGE)

Unlike current, which is easy to visualize as a flow, voltage is a variable that is determined between two points. Often we refer to voltage as a value across two points. It is the electromotive force (emf) or the push or pressure felt in a conductor that ultimately moves the electrons in a flow. The symbol for emf is the capital letter "$\mathcal{E}$."

Across the terminals of the typical aircraft battery, voltage can be measured as the potential difference of 12 volts or 24 volts. That is to say that between the two terminal posts of the battery, there is an electromotive force of 12 or 24 volts available to push current through a circuit. Relatively free electrons in the negative terminal will move toward the excessive number of positive charges in the positive terminal. Recall from the discussion on static electricity that like charges repel each other but opposite charges attract each other. The net result is a flow or current through a conductor. There cannot be a flow in a conductor unless there is an applied voltage from a battery, generator, or ground power unit. The potential difference, or the voltage across any two points in an electrical system, can be determined by:

$$E = \frac{\mathcal{E}}{Q}$$

Where:
  E = potential difference in volts
  $\mathcal{E}$ = energy expanded or absorbed in joules (J)
  Q = Charge measured in coulombs

Figure 3-2 illustrates the flow of electrons of electric current. Two interconnected water tanks demonstrate that when a difference of pressure exists between the two tanks, water will flow until the two tanks are equalized. The illustration shows the level of water in tank A to be at a higher level, reading 10 psi (higher potential energy) than the water level in tank B, reading 2 psi (lower potential energy). Between the two tanks, there is 8-psi potential difference. If the valve in the interconnecting line between the tanks is opened, water will flow from tank A into tank B until the level of water (potential energy) of both tanks is equalized.

It is important to note that it was not the pressure in tank A that caused the water to flow; rather, it was the difference in pressure between tank A and tank B that caused the flow.

This comparison illustrates the principle that electrons move, when a path is available, from a point of excess electrons (higher potential energy) to a point deficient in electrons (lower potential energy). The force that causes this movement is the potential difference in electrical energy between the two points. This force is called the electrical pressure or the potential difference or the electromotive force (electron moving force).
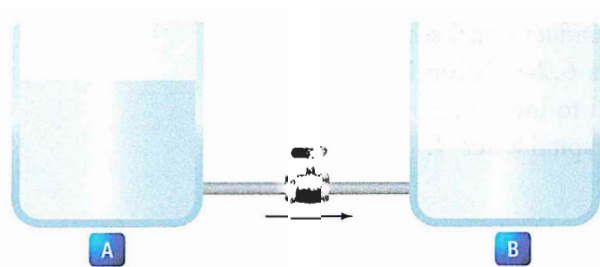
Figure 3-2. Difference of pressure.

CURRENT

Electrons in motion make up an electric current. This electric current is usually referred to as "current" or "current flow," no matter how many electrons are moving. Current is a measurement of a rate at which a charge flows through some region of space or a conductor. The moving charges are the free electrons found in conductors, such as copper, silver, aluminum, and gold. The term "free electron" describes a condition in some atoms where the outer electrons are loosely bound to their parent atom. These loosely bound electrons can be easily motivated to move in a given direction when an external source, such as a battery, is applied to the circuit. These electrons are attracted to the positive terminal of the battery, while the negative terminal is the source of the electrons. The greater amount of charge moving through the conductor in a given amount of time translates into a current.

$$Current = \frac{Charge}{Time}$$

or

$$I = \frac{Q}{t}$$

Where:
  I = Current in Amperes (A)
  Q = Charge in Coulombs (C)
  t = time

The System International (SI) unit for current is the Ampere (A), where:

$$1\,A = 1\,\frac{C}{s}$$

That is 1 ampere (A) of current is equivalent to 1 coulomb (C) of charge passing through a conductor in 1 second(s). One coulomb of charge equals 6.24 billion billion (10^{18}) electrons. The symbol used to indicate current in formulas or on schematics is the capital letter "I."

When current flow is one direction, it is called direct current (DC). Later in the text, we will discuss the form of current that periodically oscillates back and forth within the circuit. The present discussion will only be concerned with the use of direct current. The velocity of the charge is actually an average velocity and is called drift velocity. To understand the idea of drift velocity, think of a conductor in which the charge carriers are free electrons. These electrons are always in a state of random motion similar to that of gas molecules. When a voltage is applied across the conductor, an electromotive force creates an electric field within the conductor and a current is established. The electrons do not move in a straight direction but undergo repeated collisions with other nearby atoms. These collisions usually knock other free electrons from their atoms, and these electrons move on toward the positive end of the conductor with an average velocity called the drift velocity, which is relatively a slow speed. To understand the nearly instantaneous speed of the effect of the current, it is helpful to visualize a long tube filled with steel balls as shown in *Figure 3-3*.

It can be seen that a ball introduced in one end of the tube, which represents the conductor, will immediately cause a ball to be emitted at the opposite end of the tube. Thus, electric current can be viewed as instantaneous, even though it is the result of a relatively slow drift of electrons.
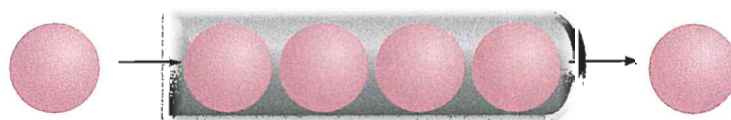
Figure 3-3. Electron movement.

RESISTANCE

The two fundamental properties of current and voltage are related by a third property known as resistance. In any electrical circuit, when voltage is applied to it, a current will result. The resistance of the conductor determines the amount of current that flows under the given voltage. In most cases, the greater the circuit resistance, the less the current. If the resistance is reduced, then the current will increase. This relation is linear in nature and is known as Ohm's law. Ohm's law will be discussed in detail in *Sub-Module 07*, DC Circuits.

Question: 3-1

Arrange the following SI prefixes from largest to smallest: pico. milli, micro, deci, nano, centi.

Question: 3-3

The amount of current that will flow through a conductor when voltage is applied is determined by the _____ of the conductor.

Question: 3-2

In electron flow theory, electrons flow form _____ to _____.

Question: 3-4

The rate at which an electrical charge flows through a conductor is called _____.

ANSWERS

Answer: 3-1
deci, centi, milli, micro, nano, pico.

Answer: 3-3
resistance.

Answer: 3-2
negative.
positive.

Answer: 3-4
amperage.

PART-66 SYLLABUS LEVELS
CERTIFICATION CATEGORY → B1 B2

Sub-Module 04
GENERATION OF ELECTRICITY

Knowledge Requirements

3.4 – Generation of Electricity

Production of electricity by the following methods: light, heat, friction, pressure, chemical action, magnetism and motion.

B1	B2
1	1

GENERATION OF ELECTRICITY

Level 1

A familiarization with the principal elements of the subject.

Objectives:
  (a) The applicant should be familiar with the basic elements of the subject.
  (b) The applicant should be able to give a simple description of the whole subject, using common words and examples.
  (c) The applicant should be able to use typical terms.

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SOURCES OF ELECTRICITY

Electrical energy can be produced in a number of methods. The four most common are pressure, chemical, thermal, and light.

PRESSURE SOURCE

This form of electrical generation is commonly known as piezoelectric (piezo or piez taken from Greek: to press; pressure; to squeeze) is a result of the application of mechanical pressure on a dielectric or nonconducting crystal. The most common piezoelectric materials used today are crystalline quartz and Rochelle salt. However, Rochelle salt is being superseded by other materials, such as barium titanate.

The application of a mechanical stress produces an electric polarization, which is proportional to this stress. This polarization establishes a voltage across the crystal. If a circuit is connected across the crystal a flow of current can be observed when the crystal is loaded (pressure is applied). An opposite condition can occur, where an application of a voltage between certain faces of the crystal can produce a mechanical distortion. This effect is commonly referred to as the piezoelectric effect.

Piezoelectric materials are used extensively in transducers for converting a mechanical strain into an electrical signal. Such devices include microphones, phonograph pickups and vibration-sensing elements. The opposite effect, in which a mechanical output is derived from an electrical signal input, is also widely used in headphones and loudspeakers.

CHEMICAL SOURCE

Chemical energy can be converted into electricity; the most common form of this is the battery. A primary battery produces electricity using two different metals in a chemical solution like alkaline electrolyte, where a chemical reaction between the metals and the chemicals frees more electrons in one metal than in the other. One terminal of the battery is attached to one of the metals such as zinc; the other terminal is attached to the other metal such as manganese oxide. The end that frees more electrons develops a positive charge and the other end develops a negative charge. If a wire is attached from one end of the battery to the other, electrons flow through the wire to balance the electrical charge.

THERMAL SOURCES

The most common source of thermal electricity found in the aviation industry comes from thermocouples. Thermocouples are widely used as temperature sensors. They are cheap and interchangeable, have standard connectors, and can measure a wide range of temperatures. Thermocouples are pairs of dissimilar metal wires joined at least at one end, which generate a voltage between the two wires that is proportional to the temperature at the junction. This is called the Seebeck effect, in honor of Thomas Seebeck who first noticed the phenomena in 1821. It was also noticed that different metal combinations have a different voltage difference. Thermocouples are utilized in aviation as ways to measure cylinder head temperatures, inter-turbine temperature and exhaust gas temperature.

LIGHT SOURCES

A solar cell or a photovoltaic cell is a device that converts light energy into electricity. Fundamentally, the device contains certain chemical elements that when exposed to light energy, they release electrons. Photons in sunlight are taken in by the solar panel or cell, where they are then absorbed by semi conducting materials, such as silicon. Electrons in the cell are broken loose from their atoms, allowing them to flow through the material to produce electricity. The complementary positive charges that are also created are called holes (absence of electron) and flow in the direction opposite of the electrons in a silicon solar panel. Solar cells have many applications and have historically been used in earth orbiting satellites or space probes, hand held calculators, and wrist watches.

FRICTION

The production of electricity by friction refers to the build up of static electricity when non-conductive materials are rubbed together. A transfer of electrons occurs resulting in an imbalance of charges between the materials. Static electricity is discussed in *Sub-Module 02*.

MAGNETISM AND MOTION

When a conductor is moved through the magnetic lines of flux created by a magnet or electromagnet, electromotive force is created and current flow produced for use by various electrically operated devices and components. This generation of electricity via magnetism and motion is discussed in subsequent *Sub-Modules* in this module.

Question: 4-1

Electrical energy produced from mechanical pressure on a dielectric or non-conducting crystal is known as

_____.

Question: 4-2

Name a chemical source of electricity.

Question: 4-3

What happens when a conductor is moved through the magnetic lines of flux of a magnet or electromagnet?

ANSWERS

Answer: 4-1

piezoelectric.

Answer: 4-3

An electromotive force is created and current flows in the conductor.

Answer: 4-2

A battery.

PART-66 SYLLABUS **LEVELS**
CERTIFICATION CATEGORY → **B1 B2**

Sub-Module 05
DC SOURCES OF ELECTRICITY
Knowledge Requirements

3.5 - DC Sources of Electricity

Construction and basic chemical action of: primary cells, secondary cells, lead acid cells, nickel cadmium cells, other alkaline cells;

Cells connected in series and parallel;

Internal resistance and its effect on a battery;

Construction, materials and operation of thermocouples;

Operation of photo-cells.

2   2

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

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BATTERIES

PRIMARY CELL

The dry cell is the most common type of primary cell battery and is similar in its characteristics to that of an electrolytic cell. This type of a battery is basically designed with a metal electrode or graphite rod acting as the cathode (+) terminal, immersed in an electrolytic paste. This electrode/electrolytic build-up is then encased in a metal container, usually made of zinc, which itself acts as the anode (–) terminal. When the battery is in a discharge condition an electrochemical reaction takes place resulting in one of the metals being consumed. Because of this consumption, the charging process is not reversible. Attempting to reverse the chemical reaction in a primary cell by way of recharging is usually dangerous and can lead to a battery explosion.

These batteries are commonly used to power items such as flashlights. The most common primary cells today are found in alkaline batteries, silver-oxide and lithium batteries. The earlier carbon-zinc cells, with a carbon post as cathode and a zinc shell as anode were once prevalent but are not as common.

SECONDARY CELL

A secondary cell is any kind of electrolytic cell in which the electrochemical reaction that releases energy is reversible. The lead-acid car battery is a secondary cell battery. The electrolyte is sulphuric acid (battery acid), the positive electrode is lead peroxide, and the negative electrode is lead. A typical lead-acid battery consists of six lead-acid cells in a case. Each cell produces 2 volts, so the whole battery produces a total of 12 volts.

Other commonly used secondary cell chemistry types are nickel cadmium (NiCd), nickel metal hydride (NiMH), lithium ion (Li-ion), and Lithium ion polymer (Li-ion polymer).

Lead-acid batteries used in aircraft are similar to automobile batteries. The lead acid battery is made up of a series of identical cells each containing sets of positive and negative plates. *Figure 5-1* illustrates each cell contains positive plates of lead dioxide (PbO2), negative plates of spongy lead, and electrolyte (sulfuric acid and water). A practical cell is constructed with many more plates than just two in order to get the required current output. All positive plates are connected together as well
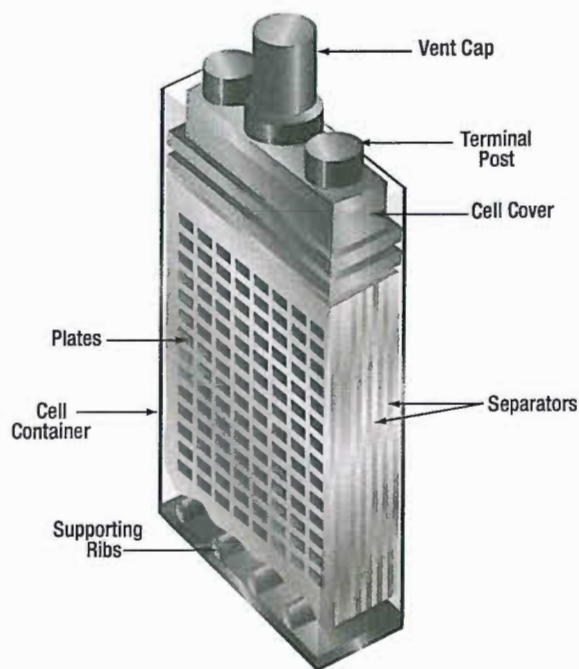
Figure 5-1. Lead-acid cell construction.

as all the negatives. Because each positive plate is always positioned between two negative plates, there are always one or more negative plates than positive plates.

Between the plates are porous separators that keep the positive and negative plates from touching each other and shorting out the cell. The separators have vertical ribs on the side facing the positive plate. This construction permits the electrolyte to circulate freely around the plates. In addition, it provides a path for sediment to settle to the bottom of the cell.

Each cell is seated in a hard rubber casing through the top of which are terminal posts and a hole into which is screwed a non-spill vent cap. The hole provides access for testing the strength of the electrolyte and adding water. The vent plug permits gases to escape from the cell with a minimum of leakage of electrolyte, regardless of the position the airplane might assume. *Figure 5-2* shows the construction of the vent plug. In level flight, the lead weight permits venting of gases through a small hole. In inverted flight, this hole is covered by the lead weight.

The individual cells of the battery are connected in series by means of cell straps. (*Figure 5-3*) The complete assembly is enclosed in an acid resisting metal container
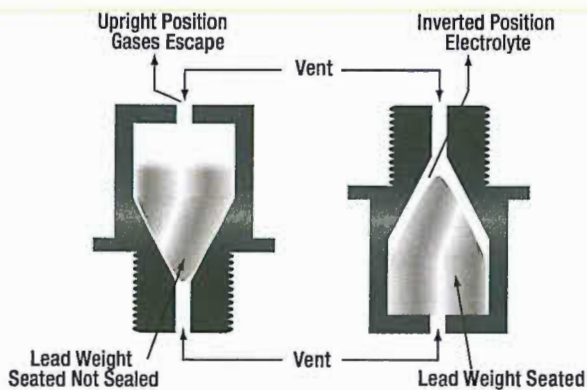
Figure 5-2. Non-spill battery vent plug.
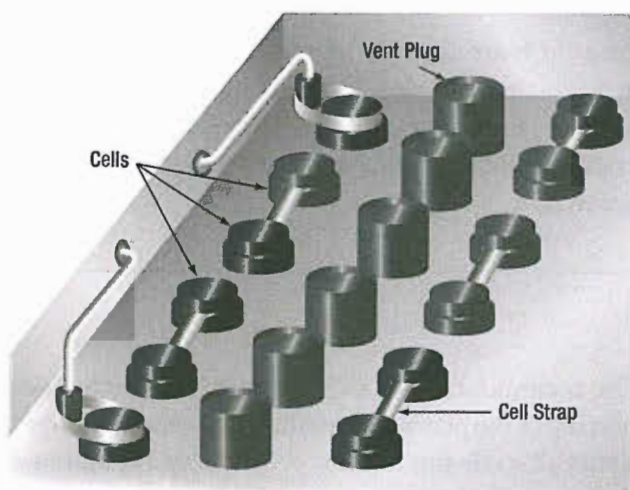
Figure 5-3. Connection of storage battery.

(battery box), which serves as electrical shielding and mechanical protection. The battery box has a removable top. It also has a vent tube nipple at each end. When the battery is installed in an airplane, a vent tube is attached to each nipple. One tube is the intake tube and is exposed to the slipstream. The other is the exhaust vent tube and is attached to the battery drain sump, which is a glass jar containing a felt pad moistened with a concentrated solution of sodium bicarbonate (baking soda). With this arrangement, the airstream is directed through the battery case where battery gases are picked up, neutralized in the sump, and then expelled overboard without damage to the airplane.

To facilitate installation and removal of the battery in some aircraft, a quick disconnect assembly is used to connect the power leads to the battery. This assembly attaches the battery leads in the aircraft to a receptacle mounted on the side of the battery. (*Figure 5-4*)

The receptacle covers the battery terminal posts and prevents accidental shorting during the installation and removal of the battery. The plug consists of a socket and a hand wheel with a course pitch thread. It can be readily connected to the receptacle by the hand wheel. Another advantage of this assembly is that the plug can be installed in only one position, eliminating the possibility of reversing the battery leads.

The voltage of lead acid cell is approximately 2 volts in order to attain the voltage required for the application. Each cell is then connected in series with heavy gage metal straps to form a battery. In a typical battery, such as that used in a aircraft for starting, the voltage required is 12 or 24 volts. This voltage is achieved by connecting six cells or twelve cells respectively together in series and enclosing them in one plastic box.

Each cell containing the plates are filled with an electrolyte composed of sulphuric acid and distilled water with a specific gravity of 1.270 at 60 °F. This solution contains positive hydrogen ions and negative sulfate (SO_4) ions that are free to combine with other ions and form a new chemical compound. When the cell is discharged, electrons leave the negative plate and flow to the positive plates where they cause the lead dioxide (PbO_2) to break down into negative oxygen ions and positive lead ions. The negative oxygen ions join with positive hydrogen ions from the sulfuric acid and form water (H_2O). The negative sulfate ions join with the lead ions in both plates and form lead sulfate ($PbSO_4$). After the discharge, the specific gravity changes to about 1.150.

Figure 5-4. A battery quick-disconnect assembly.

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BATTERY RATINGS

The voltage of a battery is determined by the number of cells connected in series to form the battery. Although the voltage of one lead acid cell just removed from a charger is approximately 2.2 volts, a lead acid cell is normally rated at approximately 2 volts. A battery rated at 12 volts consists of 6 lead acid cells connected in series, and a battery rated at 24 volts is composed of 12 cells.
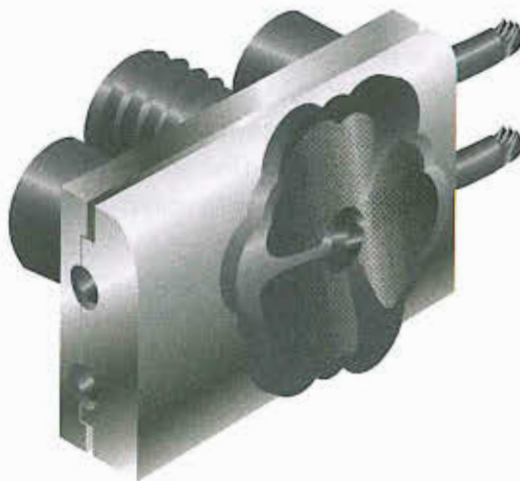
The most common battery rating is the amp-hour rating. This is a unit of measurement for battery capacity. It is determined by multiplying a current flow in amperes by the time in hours that the battery is being discharged.

A battery with a capacity of 1 amp-hour should be able to continuously supply a current of 1 amp to a load for exactly 1 hour, or 2 amps for ½ hour, or ⅓ amp for 3 hours, etc., before becoming completely discharged. Actually, the amp-hour output of a particular battery depends on the rate at which it is discharged. Heavy discharge current heats the battery and decreases its efficiency and total ampere hour output. For airplane batteries, a period of 5 hours has been established as the discharge time in rating battery capacity. However, this time of 5 hours is only a basis for rating and does not necessarily mean the length of time during which the battery is expected to furnish current. Under actual service conditions, the battery can be completely discharged within a few minutes, or it may never be discharged if the generator provides sufficient charge.

The amp-hour capacity of a battery depends upon its total effective plate area. Connecting batteries in parallel increases amp-hour capacity. Connecting batteries in series increases the total voltage but not the amp-hour capacity.

LIFE CYCLE OF A BATTERY

Battery life cycle is defined as the number of complete charge/discharge cycles a battery can perform before its normal charge capacity falls below 80% of its initial rated capacity. Battery life can vary anywhere from 500 to 1 300 cycles. Various factors can cause deterioration of a battery and shorten its service life. The first is over-discharging, which causes excess sulphation; second, too rapid charging or discharging which can result in overheating of the plates and shedding of active material.

The accumulation of shed material, in turn, causes shorting of the plates and results in internal discharge. A battery that remains in a low or discharged condition for a long period of time may be permanently damaged. The deterioration can continue to a point where cell capacity can drop to 80% after 1 000 cycles. In a lot of cases the cell can continue working to nearly 2 000 cycles but with a diminished capacity of 60% of its original state.

LEAD-ACID BATTERY TESTING METHODS

The state of charge of a storage battery depends upon the condition of its active materials, primarily the plates. However, the state of charge of a battery is indicated by the density of the electrolyte and is checked by a hydrometer, an instrument that measures the specific gravity (weight as compared with water) of liquids.

The most commonly used hydrometer consists of a small sealed glass tube weighted at its lower end so it will float upright. (*Figure 5-5*) Within the narrow stem of the tube is a paper scale with a range of 1.100 to 1.300. When a hydrometer is used, a quantity of electrolyte sufficient to float the hydrometer is drawn up into the syringe. The depth to which the hydrometer sinks into the electrolyte is determined by the density of the electrolyte, and the scale value indicated at the level of the electrolyte is its specific gravity. The more dense the electrolyte, the higher the hydrometer will float; therefore, the highest number on the scale (1.300) is at the lower end of the hydrometer scale.

In a new, fully charged aircraft storage battery, the electrolyte is approximately 30 percent acid and 70 percent water (by volume) and is 1.300 times as heavy as pure water. During discharge, the solution (electrolyte) becomes less dense and its specific gravity drops below 1.300. A specific gravity reading between 1.300 and 1.275 indicates a high state of charge; between 1.275
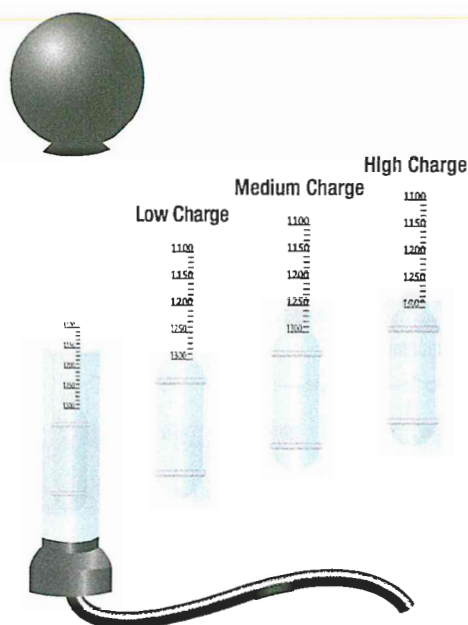
Figure 5-5. Hydrometer (specific gravity readings).

and 1.240, a medium state of charge; and between 1.240 and 1.200, a low state of charge. Aircraft batteries are generally of small capacity but are subject to heavy loads. The values specified for state of charge are therefore rather high. Hydrometer tests are made periodically on all storage batteries installed in aircraft. An aircraft battery in a low state of charge may have perhaps 50 percent charge remaining, but is nevertheless considered low in the face of heavy demands that would soon exhaust it. A battery in such a state of charge is considered in need of immediate recharging.

When a battery is tested using a hydrometer, the temperature of the electrolyte must be taken into consideration. The specific gravity readings on the hydrometer will vary from the actual specific gravity as the temperature changes. No correction is necessary when the temperature is between 70 °F and 90 °F, since the variation is not great enough to consider. When temperatures are greater than 90 °F or less than 70 °F, it is necessary to apply a correction factor. Some hydrometers are equipped with a correction scale inside the tube. With other hydrometers, it is necessary to refer to a chart provided by the manufacturer. In both cases, the corrections should be added to, or subtracted from the reading shown on the hydrometer.

The specific gravity of a cell is reliable only if nothing has been added to the electrolyte except occasional small amounts of distilled water to replace that lost as a result of normal evaporation. Always take hydrometer readings before adding distilled water, never after. This is necessary to allow time for the water to mix thoroughly with the electrolyte and to avoid drawing up into the hydrometer syringe a sample that does not represent the true strength of the solution.

Exercise extreme care when making the hydrometer test of a lead-acid cell. Handle the electrolyte carefully because sulfuric acid will burn clothing and skin. If the acid does contact the skin, wash the area thoroughly with water and then apply bicarbonate of soda.

LEAD-ACID BATTERY CHARGING METHODS

Passing direct current through the battery in a direction opposite to that of the discharge current may charge a storage battery. Because of the internal resistance (IR) in the battery, the voltage of the external charging source must be greater than the open circuit voltage. For example, the open circuit voltage of a fully charged 12 cell, lead-acid battery is approximately 26.4 volts (12 × 2.2 volts), but approximately 28 volts are required to charge it. This larger voltage is needed for charging because of the voltage drop in the battery caused by the internal resistance. Hence, the charging voltage of a lead acid battery must equal the open circuit voltage plus the IR drop within the battery (product of the charging current and the internal resistance).

The internal resistance of a battery increases over time. The active material inside the battery converts to lead sulfate when a load is placed on the battery. The lead sulfate builds up and as it does, resistance increases. The internal resistance can be calculated using the difference between the no load voltage and the load voltage for a particular circuit. This voltage drop is caused by the internal resistance. Using Ohm's law, the value of the resistance can be calculated. Theoretical discussions and circuit diagrams assume a battery has zero resistance. The technician in the field must be aware that this is not the case.

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Batteries are charged by either the constant voltage or constant current method. In the constant voltage method (*Figure 5-6A*), a motor generator set with a constant, regulated voltage forces the current through the battery. In this method, the current at the start of the process is high but automatically tapers off, reaching a value of approximately 1 ampere when the battery is fully charged. The constant voltage method requires less time and supervision than does the constant current method. In the constant current method (*Figure 5-6B*), the current remains almost constant during the entire charging process.

This method requires a longer time to charge a battery fully and, toward the end of the process, presents the danger of overcharging, if care is not exercised. In the aircraft, the storage battery is charged by direct current from the aircraft generator system. This method of charging is the constant voltage method, since the generator voltage is held constant by use of a voltage regulator.

When a storage battery is being charged, it generates a certain amount of hydrogen and oxygen. Since this is an explosive mixture, it is important to take steps to prevent ignition of the gas mixture. Loosen the vent caps and leave in place. Do not permit open flames, sparks, or other sources of ignition in the vicinity. Before disconnecting or connecting a battery to the charge, always turn off the power by means of a remote switch.
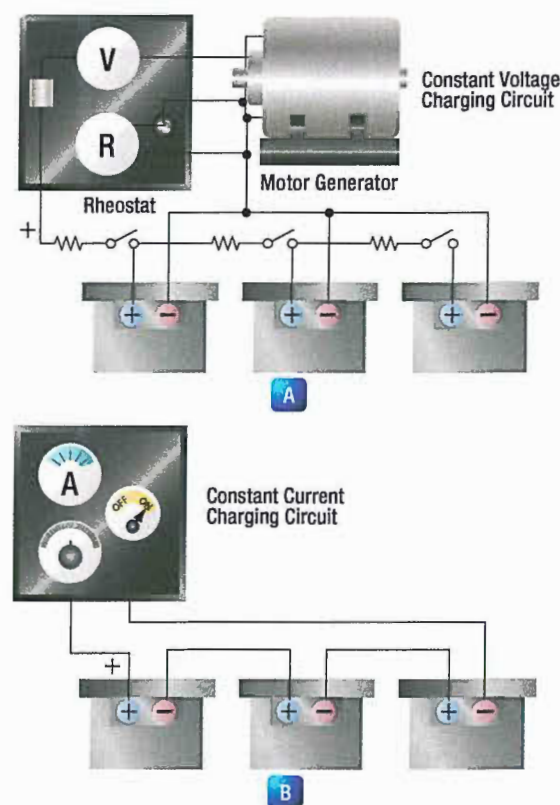
Figure 5-6. Battery charging methods.

NICKEL-CADMIUM BATTERIES

CHEMISTRY AND CONSTRUCTION

Active materials in nickel-cadmium cells (Ni-Cad) are nickel hydrate (NiOOH) in the charged positive plate (Anode) and sponge cadmium (Cd) in the charged negative plate (Cathode). The electrolyte is a potassium hydroxide (KOH) solution in concentration of 20-34 percent by weight pure KOH in distilled water.

Sintered nickel-cadmium cells have relatively thin sintered nickel matrices forming a plate grid structure. The grid structure is highly porous and is impregnated with the active positive material (nickel-hydroxide) and the negative material (cadmium-hydroxide). The plates are then formed by sintering nickel powder to fine-mesh wire screen. In other variations of the process the active material in the sintered matrix is converted

chemically, or thermally, to an active state and then formed. In general, there are many steps to these cycles of impregnation and formation.

Thin sintered plate cells are ideally suited for very high rate charge and discharge service. Pocket plate nickel-cadmium cells have the positive or negative active material, pressed into pockets of perforated nickel plated steel plates or into tubes. The active material is trapped securely in contact with a metal current collector so active material shedding is largely eliminated. Plate designs vary in thickness depending upon cycling service requirements. The typical open circuit cell voltage of a nickel-cadmium battery is about 1.25 volts.

OPERATION OF NICKEL-CADMIUM CELLS

When a charging current is applied to a nickel-cadmium battery, the negative plates lose oxygen and begin forming metallic cadmium. The active material of the positive plates, nickel-hydroxide, becomes more highly oxidized. This process continues while the charging current is applied or until all the oxygen is removed from the negative plates and only cadmium remains.

Toward the end of the charging cycle, the cells emit gas. This will also occur if the cells are overcharged. This gas is caused by decomposition of the water in the electrolyte into hydrogen at the negative plates and oxygen at the positive plates. The voltage used during charging, as well as the temperature, determines when gassing will occur. To completely charge a nickel-cadmium battery, some gassing, however slight, must take place; thus, some water will be used.

The chemical action is reversed during discharge. The positive plates slowly give up oxygen, which is regained by the negative plates. This process results in the conversion of the chemical energy into electrical energy. During discharge, the plates absorb a quantity of the electrolyte. On recharge, the level of the electrolyte rises and, at full charge, the electrolyte will be at its highest level. Therefore, water should be added only when the battery is fully charged.

The nickel-cadmium battery is usually interchangeable with the lead-acid type. When replacing a lead acid battery with a nickel-cadmium battery, the battery compartment must be clean, dry, and free of all traces of acid from the old battery. The compartment must be washed out and neutralized with ammonia or boric acid solution, allowed to dry thoroughly, and then painted with an alkali resisting varnish.

The pad in the battery sump jar should be saturated with a three percent (by weight) solution of boric acid and water before connecting the battery vent system.

GENERAL MAINTENANCE AND SAFETY PRECAUTIONS

Refer to the battery manufacturer for detailed service instructions. Below are general recommendations for maintenance and safety precautions. For vent nickel cadmium cells, general maintenance requirements are:

1. Hydrate cells to supply water lost during overcharging.
2. Maintain inter-cell connectors at proper torque values.
3. Keep cell tops and exposed sides clean and dry.

Electrolyte spillage can form grounding paths. White moss around vent cap seals is potassium carbonate (K_2CO_3). Clean up these surfaces with distilled water and dry. While handling the caustic potassium hydroxide electrolyte, wear safety goggles to protect the eyes. The technician should also wear plastic gloves and an apron to protect skin and clothes. In case of spillage on hands or clothes, neutralize the alkali immediately with vinegar or dilute boric acid solution (one pound per gallon of water); then rinse with clear water.

During overcharging conditions, explosive mixtures of hydrogen and oxygen develop in nickel-cadmium cells. When this occurs, the cell relief valves vent these gases to the atmosphere, creating a potentially explosive hazard. Additionally, room ventilation should be such as to prevent a hydrogen build up in closed spaces from exceeding one percent by volume. Explosions can occur at concentrations above four percent by volume in air.

SEALED LEAD ACID BATTERIES

In many applications, sealed lead acid (SLA) batteries are gaining in use over the Ni-Cad batteries. One leading characteristic of Ni-Cad batteries is that they perform well in low voltage, full-discharge, high cycle applications. However, they do not perform as well in extended standby applications, such as auxiliary or as emergency battery packs used to power inertial reference units or stand-by equipment (attitude gyro).

It is typical during the servicing of a Ni-Cad battery to match as many as twenty individual cells in order to prevent unbalance and thus cell reversal during end of discharge. When a Ni-Cad does reverse, very high pressure and heat can result. The result is often pressure seal rupture, and in the worst case, a cell explosion. With SLA batteries, cell matching is inherent in each battery. Ni-Cads also have an undesirable characteristic caused

DC SOURCES OF ELECTRICITY

by constant overcharge and infrequent discharges, as in standby applications. It is technically known as "voltage depression" and commonly but erroneously called "memory effect." This characteristic is only detectable when a full discharge is attempted. Thus, it is possible to believe a full charge exists, while in fact it does not. SLA batteries do not have this characteristic voltage depression (memory) phenomenon, and therefore do not require scheduled deep cycle maintenance as do Ni-Cads.

The Ni-Cad emergency battery pack requires relatively complicated test equipment due to the complex characteristics of the Ni-Cad. Sealed lead acid batteries do not have these temperamental characteristics and therefore it is not necessary to purchase special battery maintenance equipment. Some manufactures of SLA batteries have included in the battery packs a means by which the battery can be tested while still installed on the aircraft. Ni-Cads must have a scheduled energy test performed on the bench due to the inability to measure their energy level on the aircraft, and because of their notable "memory" shortcoming.

The SLA battery can be designed to alert the technician if a battery is failing. Furthermore, it may be possible to test the failure detection circuits by activating a Built in Test (BITE) button. This practice significantly reduces regulatory paperwork and maintenance workload.

THERMOCOUPLES

Mentioned in *Sub-Module 04* as a thermal means for generation of electricity, thermocouples have significant application in aviation. They are most often used in fire detection systems and in high-temperature engine indicating systems.

A thermocouple is a circuit or connection of two unlike metals. The metals are touching at two separate junctions. One of the junctions is placed in an area where temperature needs to be monitored. The other junction is remotely located in a flight deck instrument or in an area where voltage can be forwarded to a data computer. When the temperature rises at the "hot junction", an electromotive force is produced in the circuit. This voltage is directly proportional to the temperature. By measuring the amount of electromotive force, temperature can be determined.

As stated, thermocouples are used to measure high temperatures. Two common applications are the measurement of cylinder head temperature (CHT) in reciprocating engines and exhaust gas temperature (EGT) in turbine engines. Thermocouple junctions are made from a variety of metals, depending on the temperature range required to be measured and the maximum temperature to which they are exposed. Iron and constantan, or copper and constantan, are common materials for CHT measurement. Chromel and alumel are used for turbine EGT thermocouples. The unique and consistent voltages produced by these combinations of metals are measured in millivolts. This limits the use of the electricity produced.

When thermocouples are used in fire detection systems, the temperature difference between the two junctions of metals will remain negligible in normal conditions. When a fire or overheat condition exists at one of the junctions, electricity is produced and amplified to set off an alarm.

PHOTO-CELLS

Photo-cells are a source of electricity with applications in electronics and electronic control of mechanical systems. Light contains electromagnetic energy that is carried by photons. The amount of energy depends on the frequency of light of the photon. All semiconductors are affected by light energy. When a photon strikes a semiconductor atom, it raises the energy level above what is needed to hold its electrons in orbit. The extra energy frees an electron enabling it to flow as current. This current can be used in a circuit to initiate any number of actions such as energizing a coil to close a circuit enabling its operation.

Question: 5-1

A battery where the electrochemical reaction that releases energy is reversible is known as a

_____.

Question: 5-2

The individual cells of a battery are connected in

_____.

Question: 5-3

Name 2 ways to shorten the battery life of a lead-acid battery.

Question: 5-4

The two methods of charging a lead acid battery are _____ and _____ methods.

Question: 5-5

Can a Nicad battery replace a lead acid battery?

Question: 5-6

When a light photon strikes a semiconductor atom in a photo cell, the extra energy frees an _____ allowing it to flow as current.

ANSWERS

Answer: 5-1
secondary cell.

Answer: 5-4
constant voltage.
constant current.

Answer: 5-2
series.

Answer: 5-5
Yes, but the battery compartment must be cleaned and neutralized.

Answer: 5-3
1. Over-discharging which causes sulfating.
2. Too rapid charging or discharging which overheats the plates resulting in shedding of active material.

Answer: 5-6
electron.

PART-66 SYLLABUS LEVELS

CERTIFICATION CATEGORY → **B1 B2**

Sub-Module 06
DC CIRCUITS
Knowledge Requirements

3.6 – DC Circuits

Ohms Law, Kirchoff's Voltage and Current Laws;

Calculations using the above laws to find resistance, voltage and current;

Significance of the internal resistance of a supply.

2   2

Level 2

A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:

(a) The applicant should be able to understand the theoretical fundamentals of the subject.

(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.

(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.

(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.

(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

DC CIRCUITS

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SERIES DC CIRCUITS

INTRODUCTION

The series circuit is the most basic electrical circuit and provides a good introduction to basic circuit analysis. The series circuit represents the first building block for all of the circuits to be studied and analyzed. *Figure 6-1* shows this simple circuit with nothing more than a voltage source or battery, a conductor, and a resistor. This is classified as a series circuit because the components are connected end-to-end, so that the same current flows through each component equally. There is only one path for the current to take and the battery and resistor are in series with each other. Next is to make a few additions to the simple circuit in *Figure 6-1*.

Figure 6-2 shows an additional resistor and a little more detail regarding the values. With these values, we can now begin to learn more about the nature of the circuit. In this configuration, there is a 12 volt DC source in series with two resistors, $R_1 = 10\ \Omega$ and $R_2 = 30\ \Omega$. For resistors in a series configuration, the total resistance of the circuit is equal to the sum of the individual resistors. The basic formula is:

$$R_T = R_1 + R_2 + R_3 + \ldots\ldots R_N$$

For *Figure 6-2*, this will be:
$$R_T = 10\Omega + 30\Omega$$
$$R_T = 40\ \Omega$$

Now that the total resistance of the circuit is known, the current for the circuit can be determined. In a series circuit, the current cannot be different at different points within the circuit. The current through a series circuit will always be the same through each element and at any point. Therefore, the current in the simple circuit can now be determined using Ohm's law:
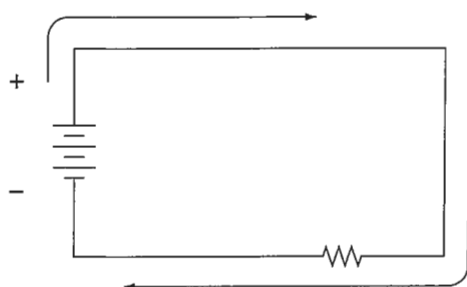
Formula, $E = I\ (R)$

Solve for current, $I = \dfrac{E}{R}$

The variables, $E = 12V$ and $R_T = 40\ \Omega$

Solve for current, $I = \dfrac{12\ V}{40\ \Omega}$

Current in circuits, $I = 0.3A$

Ohm's law describes a relationship between the variables of voltage, current, and resistance that is linear and easy to illustrate with a few extra calculations. First will be the act of changing the total resistance of the circuit while the other two remain constant. In this example, the R_T of the circuit in *Figure 6-2* will be doubled. The effects on the total current in the circuit are:

Formula, $E = I\ (R)$

Solve for current, $I = \dfrac{E}{R}$

The variables, $E = 12V$ and $R_T = 80\ \Omega$

Solve for current, $I = \dfrac{12\ V}{80\ \Omega}$

Current in circuits, $I = 0.15A$

It can be seen quantitatively and intuitively that when the resistance of the circuit is doubled, the current is reduced by half the original value.

Next, reduce the R_T of the circuit in *Figure 6-2* to half of its original value. The effects on the total current are:

Formula, $E = I\ (R)$

Solve for current, $I = \dfrac{E}{R}$

The variables, $E = 12V$ and $R_T = 20\ \Omega$

Solve for current, $I = \dfrac{12\ V}{20\ \Omega}$

Current in circuits, $I = 0.6A$
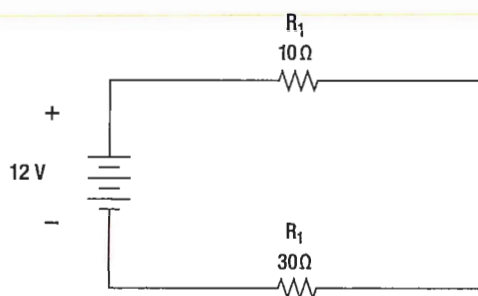

Figure 6-1. Simple DC circuit.

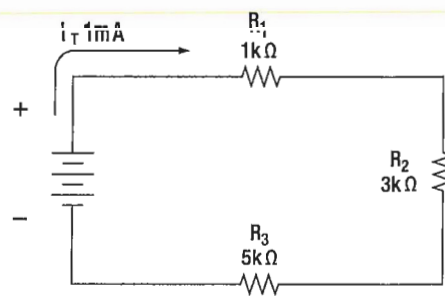Figure 6-2. Inducing minimum voltage in an elementary generator.

Figure 6-3. Example of three resistors in series.

VOLTAGE DROPS AND FURTHER APPLICATION OF OHM'S LAW

The example circuit in *Figure 6-3* will be used to illustrate the idea of voltage drop. It is important to differentiate between voltage and voltage drop when discussing series circuits. Voltage drop refers to the loss in electrical pressure or EMF caused by forcing electrons through a resistor. Because there are two resistors in the example, there will be separate voltage drops. Each drop is associated with each individual resistor. The amount of electrical pressure required to force a given number of electrons through a resistance is proportional to the size of the resistor.

In *Figure 6-3*, the values used to illustrate the idea of voltage drop are:

Current, $I = 1mA$
$R_1 = 1\,k\,\Omega$
$R_2 = 3\,k\,\Omega$
$R_3 = 5\,k\,\Omega$

The voltage drop across each resistor will be calculated using Ohm's law. The drop for each resistor is the product of each resistance and the total current in the circuit. Keep in mind that the same current flows through series resistor.

Formula, $E = I\,(R)$
Voltage across R_1: $E_1 = I_T\,(R_1)$
$E_1 = 1\,mA\,(1\,k\,\Omega) = 1$ volt
Voltage across R_2: $E_2 = I_T\,(R_2)$
$E_2 = 1\,mA\,(3\,k\,\Omega) = 3$ volt
Voltage across R_3: $E_3 = I_T\,(R_3)$
$E_3 = 1\,mA\,(5\,k\,\Omega) = 5$ volt

The source voltage can now be determined, which can then be used to confirm the calculations for each voltage drop.

Using Ohm's law:

Formula: $E = I\,(R)$
Source voltage = current times the total resistance
$E_S = I\,(R_T)$

$R_T = 1\,k\,\Omega + 3\,k\,\Omega + 5\,k\,\Omega$
$R_T = 9\,k\,\Omega$
Now: $E_S = I\,(R_T)$
Substitute $E_S = 1\,mA\,(9\,k\,\Omega)$
$E_S = 9$ volts

Simple checks to confirm the calculation and to illustrate the concept of the voltage drop add up the individual values of the voltage drops and compare them to the results of the above calculation.

1 volt + 3 volts + 5 volts = 9 volts

VOLTAGE SOURCES IN SERIES

A voltage source is an energy source that provides a constant voltage to a load. Two or more of these sources in series will equal the algebraic sum of all the sources connected in series. The significance of pointing out the algebraic sum is to indicate that the polarity of the sources must be considered when adding up the sources. The polarity will be indicated by a plus or minus sign depending on the source's position in the circuit.

In *Figure 6-4* all of the sources are in the same direction in terms of their polarity. All of the voltages have the same sign when added up. In the case of *Figure 6-4*, three cells of a value of 1.5 volts are in series with the polarity in the same direction.

The addition is simple enough:

$E_T = 1.5v + 1.5v + 1.5v = + 4.5$ volts

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However, in *Figure 6-5*, one of the three sources has been turned around, and the polarity opposes the other two sources. Again the addition is simple:

$$E_T = + 1.5v - 1.5v + 1.5v = +1.5 \text{ volts}$$

KIRCHHOFF'S VOLTAGE LAW

A law of basic importance to the analysis of an electrical circuit is Kirchhoff's voltage law. This law simply states that the algebraic sum of all voltages around a closed path or loop is zero. Another way of saying it: The sum of all the voltage drops equals the total source voltage. A simplified formula showing this law is shown below:

With three resistors in the circuit:
$$E_S - E_1 - E_2 - E_3 \ldots -E_N = 0 \text{ volts}$$

Notice that the sign of the source is opposite that of the individual voltage drops. Therefore, the algebraic sum equals zero.

Written another way:
$$E_S = E_1 + E_2 + E_3 \ldots +E_N$$

The source voltage equals the sum of the voltage drops. The polarity of the voltage drop is determined by the direction of the current flow. When going around the circuit, notice that the polarity of the resistor is opposite that of the source voltage. The positive on the resistor is facing the positive on the source and the negative towards the negative.

Figure 6-6 illustrates the very basic idea of Kirchhoff's voltage law. There are two resistors in this example. One has a drop of 14 volts and the other has a drop of 10 volts. The source voltage must equal the sum of the voltage drops around the circuit. By inspection it is easy to determine the source voltage as 24 volts.

Figure 6-7 shows a series circuit with three voltage drops and one voltage source rated at 50 volts. Two of the voltage drops are known. However, the third is not known. Using Kirchhoff's voltage law, the third voltage drop can be determined.

With three resistors in the circuit:

$$E_S - E_1 - E_2 - E_3 = 0 \text{ volts}$$

Figure 6-4. Voltage sources in series add algebraically.
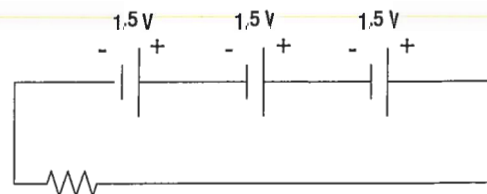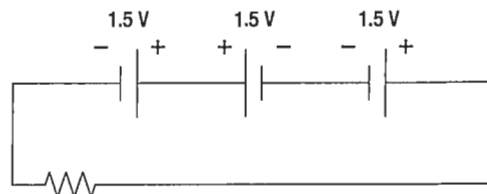

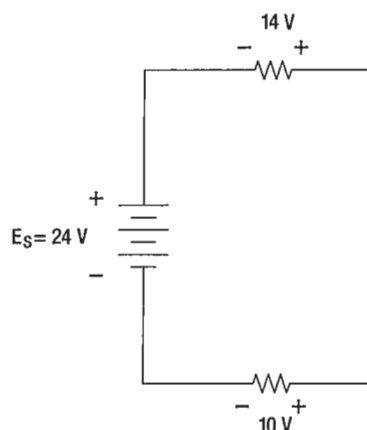Figure 6-5. Voltage sources add algebraically; one source reversed.

Figure 6-6. Kirchhoff's voltage law.
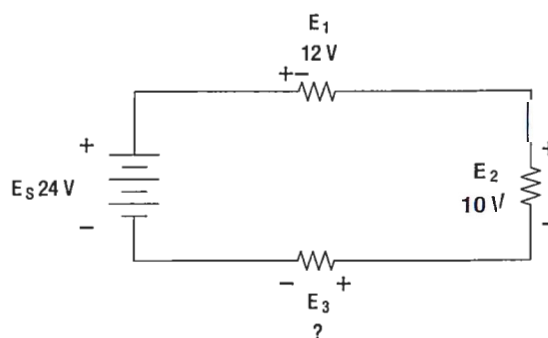

Figure 6-7. Determine the unknown voltage drop.

Substitute the known values:

$24v - 12v - 10v - E_3 = 0$
Collect known values: $2v - E_3 = 0$

Solve for the unknown: $E_3 = 2$ volts

Determine the value of E4 in *Figure 6-8*. For this example, I = 200 mA.

First, the voltage drop across each of the individual resistors must be determined.

$$E_1 = I\,(R_1)$$
$$E_1 = (200\text{ mA})\,(10\ \Omega)$$
Voltage drop across R_1 $E_1 = 2$ volts

$$E_2 = I\,(R_2)$$
$$E_2 = (200\text{ mA})\,(50\ \Omega)$$
Voltage drop across R_2 $E_2 = 10$ volts

$$E_3 = I\,(R_3)$$
$$E_3 = (200\text{ mA})\,(100\ \Omega)$$
Voltage drop across R_3 $E_3 = 20$ volts

Kirchhoff's voltage law is now employed to determine the voltage drop across E_4.

With four resistors in the circuit:
$$E_S - E_1 - E_2 - E_3 - E_4 = 0 \text{ volts}$$

Substituting values: $100v - 2v - 10v - 20\,v - E_4 = 0$

Combine: $68\,v - E_4 = 0$

Solve for unknown: $E_4 = 68\,v$

Using Ohm's law and substituting in E_4, the value for R_4 can now be determined.

Ohm's law: $R = \dfrac{E}{I}$

Specific application: $R_4 = \dfrac{E_4}{I}$

Substitute values: $R_4 = \dfrac{68V}{200\text{ mA}}$

Value for R_4: $R_4 = 340\ \Omega$

VOLTAGE DIVIDERS

Voltage dividers are devices that make it possible to obtain more than one voltage from a single power source. A voltage divider usually consists of a resistor, or resistors connected in series, with fixed or movable contacts and two fixed terminal contacts. As current flows through the resistor, different voltages can be obtained between the contacts.

Series circuits are used for voltage dividers. The voltage divider rule allows the technician to calculate the voltage across one or a combination of series resistors without having to first calculate the current in the circuit.

Because the current flows through each resistor, the voltage drops are proportional to the ohmic values of the constituent resistors. A typical voltage divider is shown in *Figure 6-9*.

To understand how a voltage divider works, examine *Figure 6-10* carefully and observe the following.

Each load draws a given amount of current: I_1, I_2, I_3. In addition to the load currents, some bleeder current (I_B) flows. The current (I_T) is drawn from the power source and is equal to the sum of all currents.
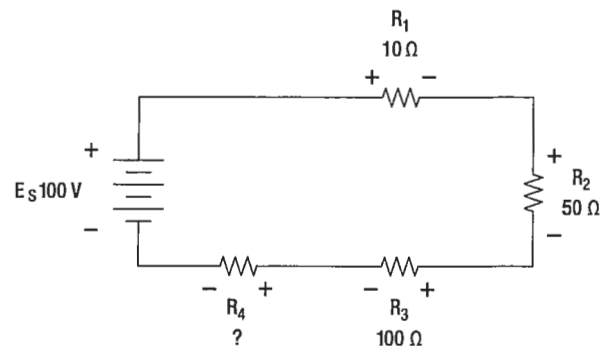

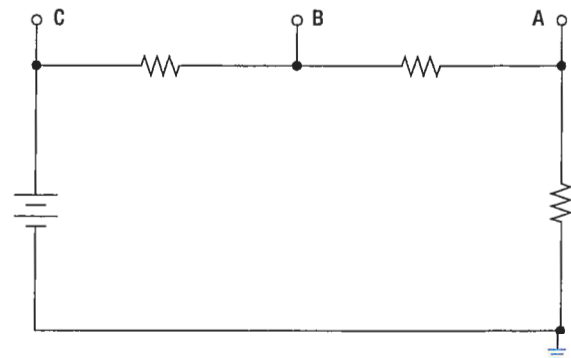Figure 6-8. Determine the unknown voltage drop.
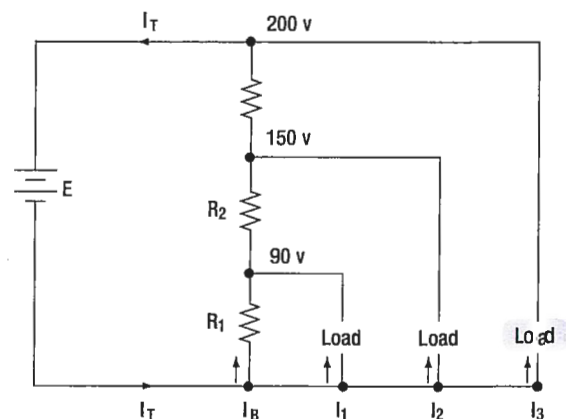

Figure 6-9. A voltage divider circuit.

Figure 6-10. A typical voltage divider.

The voltage at each point is measured with respect to a common point. Note that the common point is the point at which the total current (I_T) divides into separate currents (I_1, I_2, I_3).

Each part of the voltage divider has a different current flowing in it. The current distribution is as follows:

Through R_1 — bleeder current (I_B)
Through R_2 — I_B plus I_1
Through R_3 — I_B plus I_1, plus I_2

The voltage across each resistor of the voltage divider is:

90 volts across R_1
60 volts across R_2
50 volts across R_3

The voltage divider circuit discussed up to this point has had one side of the power supply (battery) at ground potential. In *Figure 6-11* the common reference point (ground symbol) has been moved to a different point on the voltage divider. The voltage drop across R_1 is 20 volts; however, since tap A is connected to a point in the circuit that is at the same potential as the negative side of the battery, the voltage between tap A and the reference point is a negative (–) 20 volts. Since resistors R_2 and R_3 are connected to the positive side of the battery, the voltages between the reference point and tap B or C are positive.

The following rules provide a simple method of determining negative and positive voltages: (1) If current enters a resistance flowing away from the reference point, the voltage drop across that resistance is positive in respect to the reference point; (2) if current flows out of a resistance toward the reference point, the voltage drop across that resistance is negative in respect to the reference point. It is the location of the reference point that determines whether a voltage is negative or positive.

Tracing the current flow provides a means for determining the voltage polarity. *Figure 6-12* shows the same circuit with the polarities of the voltage drops and the direction of current flow indicated. The current flows from the negative side of the battery to R_1. Tap A is at the same potential as the negative terminal of the battery since the slight voltage drop caused by the resistance of the conductor is disregarded; however, 20 volts of the

source voltage are required to force the current through R_1 and this 20-volt drop has the polarity indicated. Stated another way, there are only 80 volts of electrical pressure left in the circuit on the ground side of R_1.

When the current reaches tap B, 30 more volts have been used to move the electrons through R_2, and in a similar manner the remaining 50 volts are used for R3. But the voltages across R_2 and R_3 are positive voltages, since they are above ground potential.

Figure 6-13 shows the voltage divider used previously. The voltage drops across the resistances are the same;
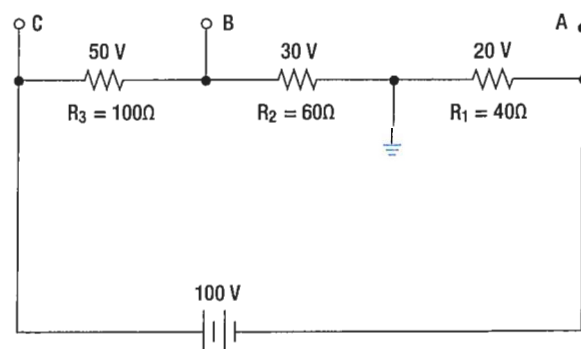

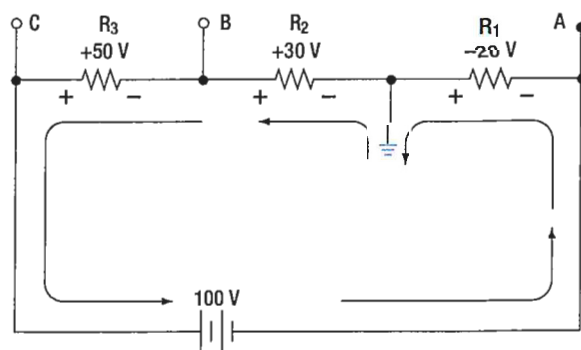Figure 6-11. Positive and negative voltage on a voltage divider.

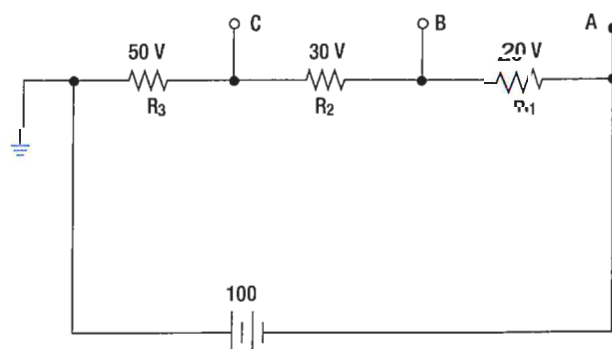Figure 6-12. Current flow through a voltage divider.

Figure 6-13. Voltage divider with changed ground.

however, the reference point (ground) has been changed. The voltage between ground and tap A is now a negative 100 volts, or the applied voltage. The voltage between ground and tap B is a negative 80 volts, and the voltage between ground and tap C is a negative 50 volts.

DETERMINING THE VOLTAGE DIVIDER FORMULA

Figure 6-14 shows the example network of four resistors and a voltage source. With a few simple calculations, a formula for determining the voltage divisions in a series circuit can be determined. The voltage drop across any particular resistor shall be called E_X, where the subscript x is the value of a particular resistor (1, 2, 3, or 4). Using Ohm's law, the voltage drop across any resistor can be determined.

Ohm's law: $E_X = I(R_X)$

As seen earlier in the text, the current is equal to the source voltage divided by the total resistance of the series circuit.

Current: $I = \dfrac{E_S}{R_T}$

The current equation can now be substituted into the equation for Ohm's law.

Substitute: $E_X = \left(\dfrac{E_S}{R_T}\right)\left(R_X\right)$

Algebraic rearrange: $E_X = \left(\dfrac{R_X}{R_T}\right)\left(E_S\right)$

This equation is the general voltage divider formula. The explanation of this formula is that the voltage drop across any resistor or combination of resistors in a series circuit is equal to the ratio of the resistance value to the total resistance, divided by the value of the source voltage. *Figure 6-15* illustrates this with a network of three resistors and one voltage source.

$$E_X = \left(\frac{R_X}{R_T}\right)E_S$$

$R_T = 100 + 300 + 600 = 1\ 000$
$E_S = 100$ volts

Voltage drop over 100 Ω resistor is:

$$E_X = \left(\frac{100\ \Omega}{1\ 000\ \Omega}\right)100\ V$$

$E_{100\ \Omega} = 10\ V$

Voltage drop over 300 Ω resistor is:

$$E_X = \left(\frac{300\ \Omega}{1\ 000\ \Omega}\right)100\ V$$

$E_{100\ \Omega} = 30\ V$

Voltage drop over 600 Ω resistor is:

$$E_X = \left(\frac{600\ \Omega}{1\ 000\ \Omega}\right)100\ V$$

$E_{100\ \Omega} = 60\ V$

Checking work:
$E_T = 10\ V + 30\ V + 60\ V = 100\ V$

<div style="text-align: right;">DC CIRCUITS</div>

Figure 6-14. Network of three resistors and one voltage source.
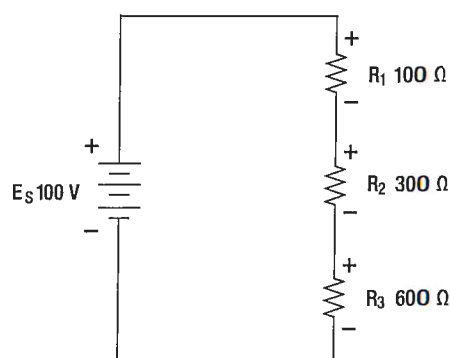
Figure 6-15. Kirchhoff's current law.

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PARALLEL DC CIRCUITS

OVERVIEW

A circuit in which two of more electrical resistances or loads are connected across the same voltage source is called a parallel circuit. The primary difference between the series circuit and the parallel circuit is that more than one path is provided for the current in the parallel circuit. Each of these parallel paths is called a branch. The minimum requirements for a parallel circuit are the following:

- A power source.
- Conductors.
- A resistance or load for each current path.
- Two or more paths for current flow.

Figure 6-16 depicts the most basic parallel circuit. Current flowing out of the source divides at point A in the diagram and goes through R_1 and R_2. As more branches are added to the circuit, more paths for the source current are provided.

VOLTAGE DROPS

The first point to understand is that the voltage across any branch is equal to the voltage across all of the other branches.

TOTAL PARALLEL RESISTANCE

The voltage across any branch is equal to the voltage across all of the other branches.

The parallel circuit consists of two or more resistors connected in such a way as to allow current flow to pass through all of the resistors at once. This eliminates the need for current to pass one resistor before passing through the next. When resistors are connected in parallel, the total resistance of the circuit decreases. The total resistance of a parallel combination is always less than the value of the smallest resistor in the circuit. In the series circuit, the current has to pass through the resistors one at a time. This gave a resistance to the current equal the sum of all the resistors. In the parallel circuit, the current has several resistors that it can pass through, actually reducing the total resistance of the circuit in relation to any one resistor value.

The amount of current passing through each resistor will vary according to its individual resistance. The total current of the circuit is the sum of the current in
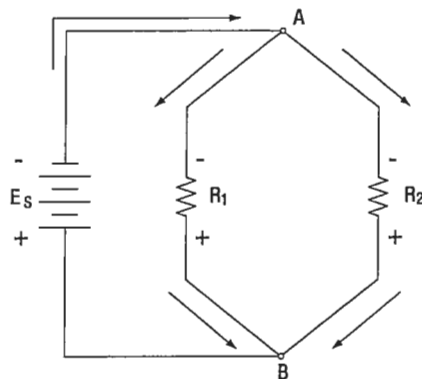
Figure 6-16. Basic parallel circuit.

all branches. It can be determined by inspection that the total current will be greater than that of any given branch. Using Ohm's law to calculate the resistance based on the applied voltage and the total current, it can be determined that the total resistance is less than any individual branch.

An example of this is if there was a circuit with a 100 Ω resistor and a 5 Ω resistor; while the exact value must be calculated, it still can be said that the combined resistance between the two will be less than the 5 Ω.

RESISTORS IN PARALLEL

The formula for the total parallel resistance is as follows:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots \frac{1}{R_N}$$

If the reciprocal of both sides is taken, then the general formula for the total parallel resistance is:

$$R_T = \frac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \dots \dfrac{1}{R_N}}$$

TWO RESISTORS IN PARALLEL

Typically, it is more convenient to consider only two resistors at a time because this setup occurs in common practice. Any number of resistors in a circuit can be broken down into pairs. Therefore, the most common method is to use the formula for two resistors in parallel.

$$R_T = \frac{1}{R_1} + \frac{1}{R_2}$$

Combining the terms in the denominator and rewriting:

$$R_T = \frac{R_1 R_2}{R_1 + R_2}$$

Put in words, this states that the total resistance for two resistors in parallel is equal to the product of both resistors divided by the sum of the two resistors. In the formula below, calculate the total resistance.

General formula: $R_T = \dfrac{R_1 R_2}{R_1 + R_2}$

Known values: $R_1 = 500\ \Omega$
                  $R_2 = 400\ \Omega$

$$R_T = \frac{500\ \Omega\ 400\ \Omega}{500\ \Omega + 400\ \Omega}$$

$$R_T = \frac{200\ 000\ \Omega}{900\ \Omega}$$

$$R_T = 222.22\ \Omega$$

CURRENT SOURCE

A current source is an energy source that provides a constant value of current to a load even when the load changes in resistive value. The general rule to remember is that the total current produced by current sources in parallel is equal to the algebraic sum of the individual sources.

KIRCHHOFF'S CURRENT LAW

Kirchhoff's current law can be stated as: The sum of the currents into a junction or node is equal to the sum of the currents flowing out of that same junction or node. A junction can be defined as a point in the circuit where two or more circuit paths come together. In the case of the parallel circuit, it is the point in the circuit where the individual branches join.

General formula: $I_T = I_1 + I_2 + I_3$

Refer to *Figure 6-17* for an illustration. Point A and point B represent two junctions or nodes in the circuit with three resistive branches in between. The voltage source provides a total current I_T into node A. At this point, the current must divide, flowing out of node A into each of the branches according to the resistive value of each branch. Kirchhoff's current law states that the current going in must equal that going out. Following the current through the three branches and back into node B, the total current I_T entering node B and leaving

node B is the same as that which entered node A. The current then continues back to the voltage source.

Figure 6-18 shows that the individual branch currents are:

$I_1 = 5\ mA$
$I_2 = 12\ mA$

The total current flow into the node A equals the sum of the branch currents, which is:
$$I_T = I_1 + I_2$$
Substitute $I_T = 5mA + 12mA$
$$I_T = 17mA$$

The total current entering node B is also the same.
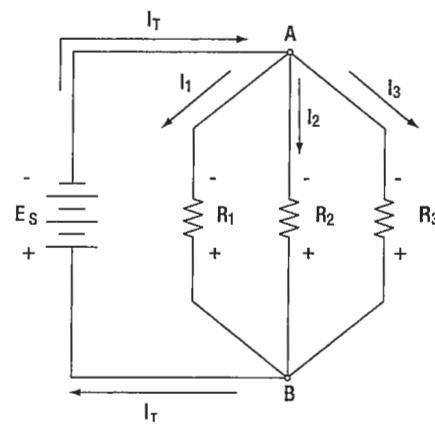

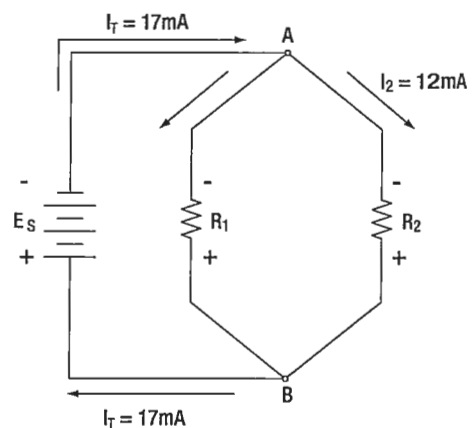Figure 6-17. Individual branch currents.

Figure 6-18. Determining an unknown circuit in branch 2.

Figure 6-19 illustrates how to determine an unknown current in one branch. Note that the total current into a junction of the three branches is known. Two of the branch currents are known. By rearranging the general formula, the current in branch two can be determined.

General formula $I_T = I_1 + I_2 + I_3$
Substitute $75mA = 30mA + I_2 + 20mA$
Solve I_2 $I_2 = 75mA - 30mA - 20mA$
                   $I_2 = 25mA$

CURRENT DIVIDERS

It can now be easily seen that the parallel circuit is a current divider. As could be seen in *Figure 6-16*, there is a current through each of the two resistors. Because the same voltage is applied across both resistors in parallel, the branch currents are inversely proportional to the ohmic values of the resistors. Branches with higher resistance have less current than those with lower resistance. For example, if the resistive value of R_2 is twice as high as that of R_1, the current in R_2 will be half of that of R_1. All of this can be determined with Ohm's law.

By Ohm's law, the current through any one of the branches can be written as:

$$I_X = E_S/R_X$$

The voltage source appears across each of the parallel resistors and R_X represents any one the resistors. The source voltage is equal to the total current times the total parallel resistance.

$I_T = 75mA$
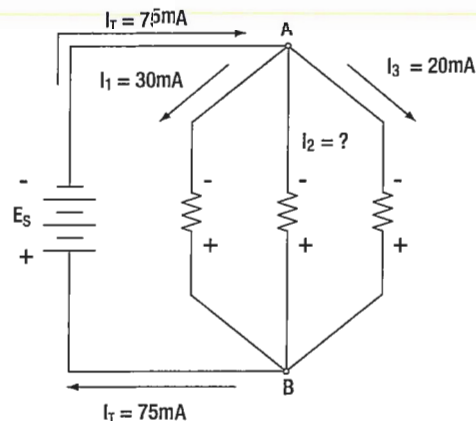
Figure 6-19. Series-parallel circuits.

	E_S	$I_T R_T$
Substituting $I_T R_T$ for E_S	I_X	$\dfrac{I_T R_T}{R_X}$
Rearranging	I_X	$\left(\dfrac{R_T}{R_X}\right)I_T$
	I_2	$\left(\dfrac{R_2}{R_T}\right)I_T$
And	I_1	$\left(\dfrac{R_1}{R_T}\right)I_T$

This formula is the general current divider formula. The current through any branch equals the total parallel resistance divided by the individual branch resistance, multiplied by the total current.

SERIES-PARALLEL DC CIRCUITS

OVERVIEW

Most of the circuits that the technician will encounter will not be a simple series or parallel circuit. Circuits are usually a combination of both, known as series-parallel circuits, which are groups consisting of resistors in parallel and in series. An example of this type of circuit can be seen in *Figure 6-20*. While the series-parallel circuit can initially appear to be complex, the same rules that have been used for the series and parallel circuits can be applied to these circuits.

The voltage source will provide a current out to resistor R_1, then to the group of resistors R_2 and R_3 and then to the next resistor R_4 before returning to the voltage source.
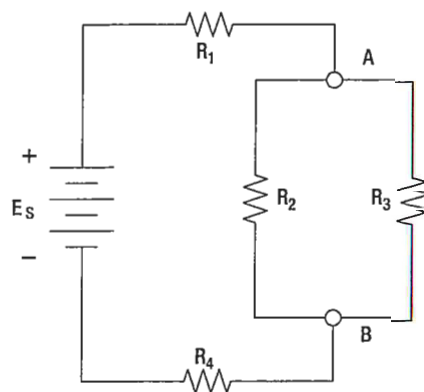
Figure 6-20. Equivalent circuit with three series connected resistors.

The first step in the simplification process is to isolate the group R_2 and R_3 and recognize that they are a parallel network that can be reduced to an equivalent resistor.

Using the formula for parallel resistance:

$$R_{23} = \frac{R_2 R_3}{R_2 + R_3}$$

R_2 and R_3 can be reduced to R_{23}. *Figure 6-21* now shows an equivalent circuit with three series connected resistors. The total resistance of the circuit can now be simply determined by adding up the values of resistors R_1, R_{23}, and R_4.
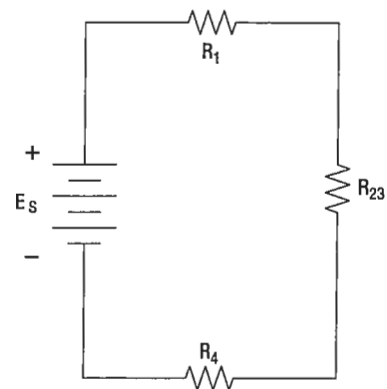
Figure 6-21. Determining total resistance.

DETERMINING THE TOTAL RESISTANCE

A more quantitative example for determining total resistance and the current in each branch in a combination circuit is shown in the following example. Also refer to *Figure 6-22*.

The first step is to determine the current at junction A, leading into the parallel branch. To determine the I_T, the total resistance R_T of the entire circuit must be known. The total resistance of the circuit is given as:

$$R_T = R_1 + R_{23}$$

Where

$$R_{23} = \left(\frac{R_2 R_3}{R_2 + R_3}\right) \text{ Parallel network}$$

Find R_{EQ}

$$R_{23} = \frac{2k\,\Omega\ 3k\,\Omega}{2k\,\Omega + 3k\,\Omega}$$

Solve for R_{EQ}

$$R_{23} = \frac{6k\,\Omega}{5k\,\Omega}$$

$$R_{23} = 1.2k\,\Omega$$

Solve for R_T

$$R_T = 1k\,\Omega + 1.2k\,\Omega$$

$$R_T = 2.2k\,\Omega$$

With the total resistance R_T now determined, the total I_T can be determined. Using Ohm's law:

$$I_T = \frac{E_S}{R_T}$$

Substitute values

$$I_T = \frac{24V}{2.2k\,\Omega}$$

$$I_T = 10.9mA$$

The current through the parallel branches of R_2 and R_3 can be determined using the current divider rule discussed earlier in the text. Recall that:

Current divider rule

$$I_2 = \left(\frac{R_2}{R_T}\right)\left(I_T\right)$$

And

$$I_3 = \left(\frac{R_3}{R_T}\right)\left(I_T\right)$$

Substitute values for I_2

$$I_2 = \left(\frac{R_3}{R_2 + R_3}\right)\left(I_T\right)$$

$$I_2 = \left(\frac{3k\,\Omega}{2k\,\Omega + 3k\,\Omega}\right)\left(10.9mA\right)$$

$$I_2 = \left(\frac{3k\,\Omega}{5k\,\Omega}\right)\left(10.9mA\right)$$

$$I_2 = 0.6\,\Omega\ (10.9mA)$$

$$I_2 = 6.54mA$$
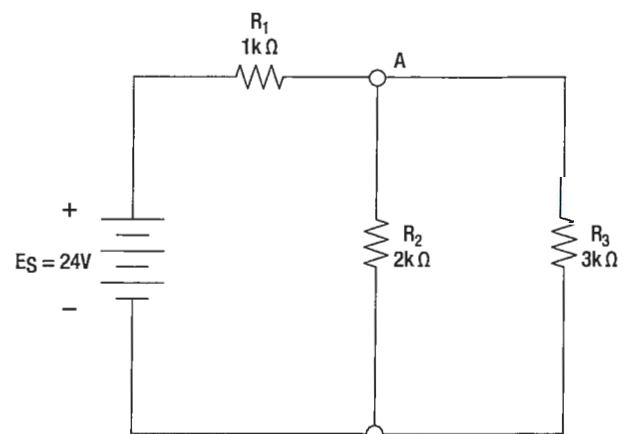
Figure 6-22. Determining total resistance.

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Now using Kirchhoff's current law, the current in branch with R_3 can be determined.

$I_T = I_2 + I_3$

$I_3 = I_T - I_2$

$I_3 = 10.9\text{mA} - 6.54\text{mA}$

$I_3 = 4.36\text{mA}$

Question: 6-1

For resistors in a series circuits, the total resistance is equal to _____.

Question: 6-2

What is Ohm's Law?

Question: 6-3

The source voltage equals the sum of the voltage drops. This is know as _____.

Question: 6-4

What is the primary difference between a series and parallel circuit?

Question: 6-5

The total resistance in a parallel circuit is always _____ than the value of the smallest resistor in the circuit.

Question: 6-6

The total current produced by current sources in parallel is equal to the algebraic _____ of the individual sources.

Question: 6-7

A circuit that is a combination of a series circuit and one or more parallel circuits is known as

_____.

ANSWERS

Answer: 6-1
the sum of the individual resisters in the circuit.

Answer: 6-5
less.

Answer: 6-2
$E = I \times R$

Answer: 6-6
sum.

Answer: 6-3
Kirchhoff's voltage law.

Answer: 6-7
a series-parallel circuit or a combination circuit.

Answer: 6-4
In a parallel circuit, more than one path is provided for current to flow. In a series circuit, there is only one path for current.

Sub-Module 07
RESISTANCE/RESISTOR
Knowledge Requirements

3.7 - Resistance/Resistor

(a) Resistance and affecting factors; Specific resistance; Resistor colour code, values and tolerances, preferred values, wattage ratings; Resistors in series and parallel; Calculation of total resistance using series, parallel and series parallel combinations; Operation and use of potentiometers and rheostats; Operation of Wheatstone Bridge;	2	2
(b) Positive and negative temperature coefficient conductance; Fixed resistors, stability, tolerance and limitations, methods of construction; Variable resistors, thermistors, voltage dependent resistors; Construction of potentiometers and rheostats; Construction of Wheatstone Bridge.	1	1

Level 1
A familiarization with the principal elements of the subject.

Objectives:
(a) The applicant should be familiar with the basic elements of the subject.
(b) The applicant should be able to give a simple description of the whole subject, using common words and examples.
(c) The applicant should be able to use typical terms.

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

OHM'S LAW (RESISTANCE)

The two fundamental properties of current and voltage are related by a third property known as resistance. In any electrical circuit, when voltage is applied to it, a current will result. The resistance of the conductor will determine the amount of current that flows under the given voltage. In most cases, the greater the circuit resistance, the less the current. If the resistance is reduced, then the current will increase. This relation is linear in nature and is known as Ohm's law.

By having a linearly proportional characteristic, it is meant that if one unit in the relationship increases or decreases by a certain percentage, the other variables in the relationship will increase or decrease by the same percentage. An example would be if the voltage across a resistor is doubled, then the current through the resistor doubles. It should be added that this relationship is true only if the resistance in the circuit remains constant. For it can be seen that if the resistance changes, current also changes. A graph of this relationship is shown in

Figure 7-1, which uses a constant resistance of 20Ω. The relationship between voltage and current in this example shows voltage plotted horizontally along the X axis in values from 0 to 120 volts, and the corresponding values of current are plotted vertically in values from 0 to 6.0 amperes along the Y axis.
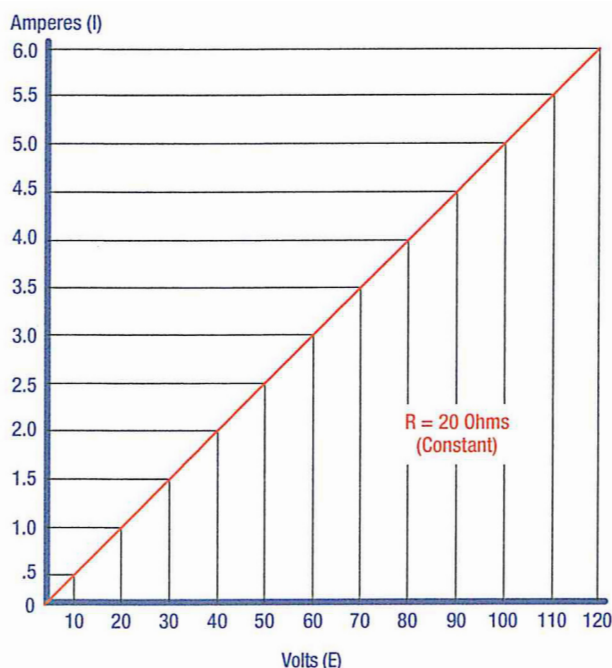
Figure 7-1. Voltage vs current in a constant-resistance circuit.

A straight line drawn through all the points where the voltage and current lines meet represents the equation I = $^E/_{20}$ and is called a linear relationship.

$$\text{If} \quad E = 10V$$

$$\text{Then} \quad \frac{10V}{20\Omega} = 0.5A$$

$$\text{If} \quad E = 60V$$

$$\text{Then} \quad \frac{60V}{20\Omega} = 3A$$

$$\text{If} \quad E = 120V$$

$$\text{Then} \quad \frac{120V}{20\Omega} = 6A$$

Ohm's law may be expressed as an equation, as follows:

Equation: 1

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

I = Current in amperes (A)
E = Voltage (V)
R = Resistance (Ω)

Where I is current in amperes, E is the potential difference measured in volts, and R is the resistance measured in ohms. If any two of these circuit quantities are known, the third may be found by simple algebraic transposition. With this equation, we can calculate current in a circuit if the voltage and resistance are known. This same formula can be used to calculate voltage. By multiplying both sides of the equation 1 by R, we get an equivalent form of Ohm's law, which is:

Equation: 2

$$E = I\,(R)$$

Finally, if we divide equation 2 by I, we will solve for resistance:

Equation: 3

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

All three formulas presented in this section are equivalent to each other and are simply different ways of expressing Ohm's law. The various equations, which may be derived by transposing the basic law, can be easily obtained by using the triangles in *Figure 7-2*.

The triangles containing E, R, and I are divided into two parts, with E above the line and I × R below it. To determine an unknown circuit quantity when the other two are known, cover the unknown quantity with a thumb. The location of the remaining uncovered letters in the triangle will indicate the mathematical operation to be performed. For example, to find I, refer to *Figure 7-2A*, and cover I with the thumb. The uncovered letters indicate that E is to be divided by R, or I = E/R. To find R, refer to *Figure 7-2B*, and cover R with the thumb. The result indicates that E is to be divided by I, or R = E/I. To find E, refer to *Figure 7-2C*, and cover E with the thumb. The result indicates I is to be multiplied by R, or E = I × R.

This chart is useful when learning to use Ohm's law. It should be used to supplement the beginner's knowledge of the algebraic method.

A
To find I (amperes), place thumb over I and divide E by R as indicated

B
To find R (ohms), place thumb over R and divide as indicated

C
To find E (volts), place thumb over E multiply as indicated
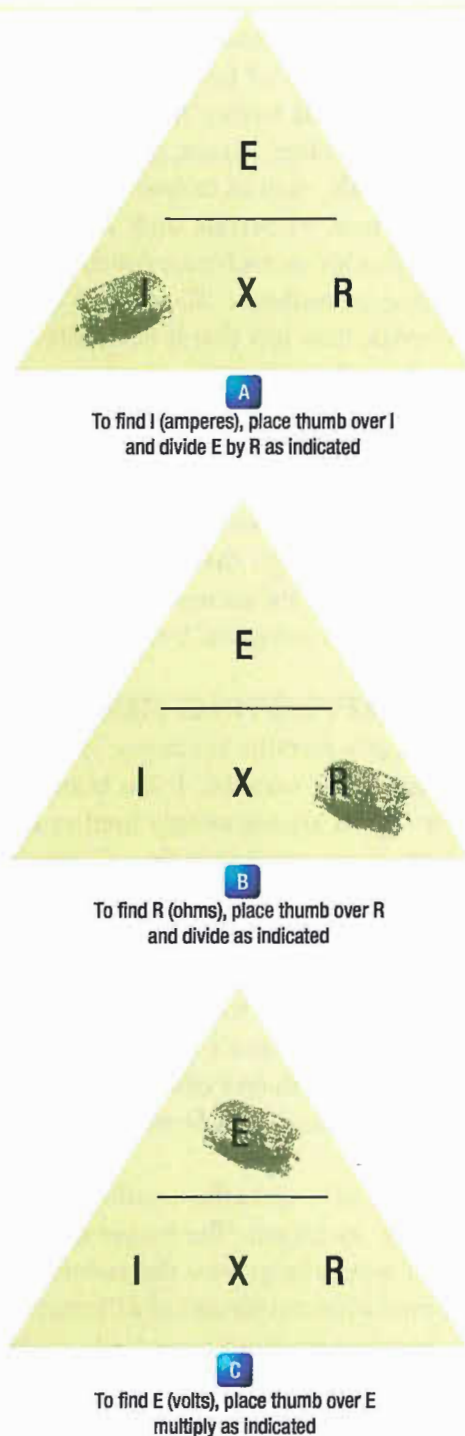
Figure 7-2. Ohm's law chart.

RESISTANCE OF A CONDUCTOR

While wire of any size or resistance value may be used, the word "conductor" usually refers to materials that offer low resistance to current flow, and the word "insulator" describes materials that offer high resistance to current. There is no distinct dividing line between conductors and insulators; under the proper conditions, all types of material conduct some current. Materials offering a resistance to current flow midway between the best conductors and the poorest conductors (insulators) are sometimes referred to as "semiconductors," and find their greatest application in the field of transistors.

The best conductors are materials, chiefly metals, which possess a large number of free electrons; conversely, insulators are materials having few free electrons. The best conductors are silver, copper, gold, and aluminum; but some nonmetals, such as carbon and water, can be used as conductors. Materials such as rubber, glass, ceramics, and plastics are such poor conductors that they are usually used as insulators. The current flow in some of these materials is so low that it is usually considered zero. The unit used to measure resistance is called the ohm. The symbol for the ohm is the Greek letter omega (Ω). In mathematical formulas, the capital letter "R" refers to resistance. The resistance of a conductor and the voltage applied to it determine the number of amperes of current flowing through the conductor. Thus, 1 ohm of resistance will limit the current flow to 1 ampere in a conductor to which a voltage of 1 volt is applied.

FACTORS AFFECTING RESISTANCE

The resistance of a metallic conductor is dependent on the type of conductor material. It has been pointed out that certain metals are commonly used as conductors because of the large number of free electrons in their outer orbits. Copper is usually considered the best available conductor material, since a copper wire of a particular diameter offers a lower resistance to current flow than an aluminum wire of the same diameter. However, aluminum is much lighter than copper, and for this reason as well as cost considerations, aluminum is often used when the weight factor is important.

The resistance of a metallic conductor is directly proportional to its length. The longer the length of a given size of wire, the greater the resistance. *Figure 7-3* shows two wire conductors of different lengths. If 1 volt of electrical pressure is applied across the two ends of the conductor that is 1 foot in length and the resistance to the movement of free electrons is assumed to be 1 ohm, the current flow is limited to 1 ampere. If the same size conductor is doubled in length, the same electrons set in motion by the 1 volt applied now find twice the resistance; consequently, the current flow will be reduced by one-half.

The resistance of a metallic conductor is inversely proportional to the cross-sectional area. This area may be triangular or even square, but is usually circular. If the cross-sectional area of a conductor is doubled, the
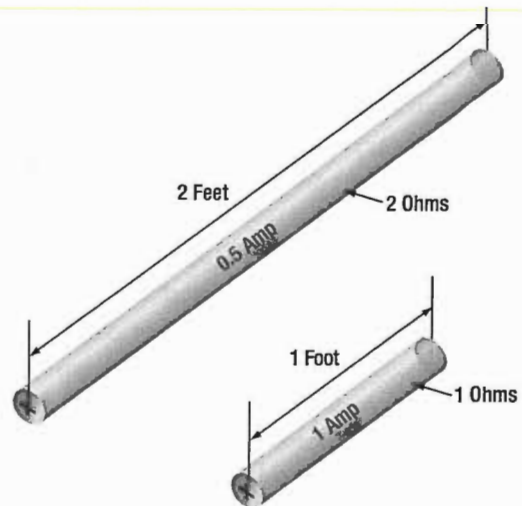

Figure 7-3. Resistance varies with length of conductor.

resistance to current flow will be reduced in half. This is true because of the increased area in which an electron can move without collision or capture by an atom. Thus, the resistance varies inversely with the cross-sectional area of a conductor.

The fourth major factor influencing the resistance of a conductor is temperature. Although some substances, such as carbon, show a decrease in resistance as the ambient (surrounding) temperature increases, most materials used as conductors increase in resistance as temperature increases. The resistance of a few alloys, such as constantan and Manganin™, change very little as the temperature changes. The amount of increase in the resistance of a 1 ohm sample of a conductor, per degree rise in temperature above 0° Celsius (C), the assumed standard, is called the temperature coefficient of resistance.

For each metal, this is a different value; for example, for copper the value is approximately 0.004 27 ohm. Thus, a copper wire having a resistance of 50 ohms at a temperature of 0°C will have an increase in resistance of 50 × 0.004 27, or 0.214 ohm, for each degree rise in temperature above 0 °C. The temperature coefficient of resistance must be considered where there is an appreciable change in temperature of a conductor during operation. Charts listing the temperature coefficient of resistance for different materials are available. *Figure 7-4* shows a table for "resistivity" of some common electric conductors.

Conductor Material	Resistivity (Ohm meters @ 20 °C)
Silver	1.64×10^{-8}
Copper	1.72×10^{-8}
Aluminum	2.83×10^{-8}
Tungsten	5.50×10^{-8}
Nickel	7.80×10^{-6}
Iron	12.0×10^{-8}
Constantan	49.0×10^{-8}
Nichrome II	110×10

Figure 7-4. Resistivity table.

The resistance of a material is determined by four properties: material, length, area, and temperature. The first three properties are related by the following equation at T = 20 °C (room temperature):

$$R = \frac{(\rho \times L)}{A}$$

Where
R = resistance in ohms
ρ = Resistivity of the material in circular mil-ohms per foot
L = Length of the sample in feet
A = area in circular mils

RESISTANCE AND ITS RELATION TO WIRE SIZING

CIRCULAR CONDUCTORS (WIRES/CABLES)

Because it is known that the resistance of a conductor is directly proportional to its length, and if we are given the resistance of the unit length of wire, we can readily calculate the resistance of any length of wire of that particular material having the same diameter. Also, because it is known that the resistance of a conductor is inversely proportional to its cross-sectional area, and if we are given the resistance of a length of wire with unit cross-sectional area, we can calculate the resistance of a similar length of wire of the same material with any cross-sectional area. Therefore, if we know the resistance of a given conductor, we can calculate the resistance for any conductor of the same material at the same temperature.

Use the following formula which basically states that the relationship between cross-sectional area, length and resistance of a certain conductor will remain the same if the size or length of the conductor is changed:

$$\frac{R_1}{\frac{L_1}{A_1}} = \frac{R_2}{\frac{L_1}{A_1}}$$

If we have a conductor that is 1 meter long with a cross-sectional area of 1 mm² and has a resistance of 0.017 ohm, what is the resistance of 50m of wire from the same material but with a cross-sectional area of 0.25 mm²?

$$\frac{R_1}{\frac{L_1}{A_1}} = \frac{R_2}{\frac{L_1}{A_1}}$$

$$R_2 = 0.017 \times \frac{50m}{1m} \times \frac{1mm^2}{0.25mm^2} = 3.4\Omega$$

System International (SI) units are commonly used in the analysis of electric circuits. However, when referencing tables and charts for conductor sizes and ohmic values, be sure denominations are for the system in which you are working. Conductors in North America are still being manufactured using the foot as the unit length and the mil (one thousandth of an inch) as the unit of diameter. Therefore, the resistance of a conductor of a given AWG size is listed on the charts with length in feet and diameter in mils. Any diameter or length in meters or cross sectional area in square meters must be converted to an Imperial denomination to reference the AWG chart. The conversion factors 1 mil = 0.025 4 mm. and 1 foot = .304 8 meter can be applied.

In the case of using copper conductors, we are spared the task of tedious calculations by using a table as shown in *Figure 7-5*. Note that cross-sectional dimensions listed on the table are such that each decrease of one gauge number equals a 25 percent increase in the cross-

RESISTANCE/RESISTOR

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sectional area. Because of this, a decrease of three gauge numbers represents an increase in cross-sectional area of approximately a 2:1 increase. Likewise, change of ten wire gauge numbers represents a 10:1 change in cross-sectional area — also, by doubling the cross-sectional area of the conductor, the resistance is cut in half. A decrease of three wire gauge numbers cuts the resistance of the conductor of a given length in half.

RECTANGULAR CONDUCTORS (BUS BARS)

To compute the cross-sectional area of a conductor in square mils, the length in mils of one side is squared. In the case of a rectangular conductor, the length of one side is multiplied by the length of the other. For example, a common rectangular bus bar (large, special conductor) is ⅜ inch thick and 4 inches wide. The ⅜-inch thickness may be expressed as 0.375 inch. Since 1 000 mils equal 1 inch, the width in inches can be converted to 4 000 mils. The cross-sectional area of the rectangular conductor is found by converting 0.375 to mils (375 mils × 4 000 mils = 1 500 000 square mils).

AWG Number	Diameter in mils	Ohms per 1 000 ft.
0000	460.0	0.049 01
000	409.6	0.061 80
00	364.8	0.077 93
0	324.9	0.098 27
1	289.3	0.123 9
2	257.6	0.156 3
3	229.4	0.197 0
4	204.3	0.248 5
5	181.9	0.313 3
6	162.0	0.395 1
8	128.5	0.628 2
10	101.9	0.998 9
12	80.81	1.588
14	64.08	2.525
16	50.82	4.016
18	40.30	6.385
20	31.96	10.15
22	25.35	16.14
24	20.10	25.67
26	15.94	40.81
28	12.64	64.9
30	10.03	103.2

Figure 7-5. Conversion table when using copper conductors.

TYPES OF RESISTORS

FIXED RESISTOR

Figure 7-6 is a schematic representation of a fixed resistor. Fixed resistors have built into the design a means of opposing current. The general use of a resistor in a circuit is to limit the amount of current flow. There are a number of methods used in construction and sizing of a resistor that control properties such as resistance value, the precision of the resistance value, and the ability to dissipate heat. While in some applications the purpose of the resistive element is used to generate heat, such as in propeller anti-ice boots, heat typically is the unwanted loss of energy.

CARBON COMPOSITION

The carbon composed resistor is constructed from a mixture of finely grouped carbon/graphite, an insulation material for filler, and a substance for binding the material together. The amount of graphite in relation to the insulation material will determine the ohmic or resistive value of the resistor. This mixture is compressed

Figure 8-6. Fixed resistor schematic.

into a rod, which is then fitted with axial leads or "pigtails." The finished product is then sealed in an insulating coating for isolation and physical protection.

There are other types of fixed resistors in common use. Included in this group are:
- Carbon film
- Metal oxide
- Metal film
- Metal glaze

The construction of a film resistor is accomplished by depositing a resistive material evenly on a ceramic rod. This resistive material can be graphite for the carbon film resistor, nickel chromium for the metal film resistor, metal and glass for the metal glaze resistor and last, metal and an insulating oxide for the metal oxide resistor.

RESISTOR RATINGS

It is very difficult to manufacture a resistor to an exact standard of ohmic values. Fortunately, most circuit requirements are not extremely critical. For many uses, the actual resistance in ohms can be 20 percent higher or lower than the value marked on the resistor without causing difficulty. The percentage variation between the marked value and the actual value of a resistor is known as the "tolerance" of a resistor. A resistor coded for a 5 percent tolerance will not be more than 5 percent higher or lower than the value indicated by the color code. The resistor color code is made up of a group of colors, numbers, and tolerance values. Each color is represented by a number, and in most cases, by a tolerance value. (*Figure 7-7*)

When the color code is used with the end-to-center band marking system, the resistor is normally marked with bands of color at one end of the resistor. The body or base color of the resistor has nothing to do with the color code, and in no way indicates a resistance value. To prevent confusion, this body will never be the same color as any of the bands indicating resistance value.

When the end-to-center band marking system is used, either three or four bands will mark the resistor.

1. The first color band (nearest the end of the resistor) will indicate the first digit in the numerical resistance value. This band will never be gold or silver in color.

2. The second color band will always indicate the second digit of ohmic value. It will never be gold or silver in color. (*Figure 7-8*)

3. The third color band indicates the number of zeros to be added to the two digits derived from the first and second bands, except in the following two cases: (A) If the third band is gold in color, the first two digits must be multiplied by 10 percent. (B) If the third band is silver in color, the first two digits must be multiplied by 1 percent.

4. If there is a fourth color band, it is used as a multiplier for percentage of tolerance, as indicated in the color code chart in *Figure 7-7*. If there is no fourth band, the tolerance is understood to be 20 percent.

Figure 7-8 provides an example, which illustrates the rules for reading the resistance value of a resistor marked with the end-to-center band system. This resistor is marked with three bands of color, which must be read from the end toward the center.

There is no fourth color band; therefore, the tolerance is understood to be 20 percent. 20 percent of 250 000 Ω, equals 50 000 Ω.

Resistor Color Code		
Color	Number	Tolerance
Black	0	—
Brown	1	1%
Red	2	2%
Orange	3	3%
Yellow	4	4%
Green	5	5%
Blue	6	6%
Violet	7	7%
Gray	8	8%
White	9	9%
Gold	—	5%
Silver	—	10%
No color	—	20%

Figure 7-7. Resistor color code.
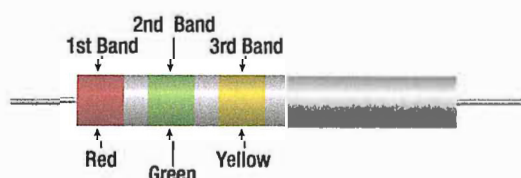
Color	Numerical Value	Significance
1st Band — Red	2	1st Digit
2nd Band — Green	5	2nd Digit
3rd Band — Yellow	4	No. of Zeroes to Add

Figure 7-8. End-to-center band marking.

Since the 20 percent tolerance is plus or minus:

Maximum resistance
= 250 000 Ω + 50 000 Ω
= 300 000 Ω

Minimum resistance
= 250 000 Ω – 50 000 Ω
= 200 000 Ω

The following paragraphs provide a few extra examples of resistor color band decoding. *Figure 7-9* contains a resistor with another set of colors.

This resistor code should be read as follows:
The resistance of this resistor is 86 000 ± 10 percent ohms. The maximum resistance is 94 600 ohms, and the minimum resistance is 77 400 ohms.

As another example, the resistance of the resistor in *Figure 7-10* is 960 ± 5 percent ohms. The maximum resistance is 1 008 ohms, and the minimum resistance is 912 ohms.

Sometimes circuit considerations dictate that the tolerance must be smaller than 20 percent. *Figure 7-11* shows an example of a resistor with a 2 percent tolerance. The resistance value of this resistor is 2 500 ± 2 percent ohms. The maximum resistance is 2 550 ohms, and the minimum resistance is 2 450 ohms.

Figure 7-12 contains an example of a resistor with a black third color band. The color code value of black is zero, and the third band indicates the number of zeros to be added to the first two digits.

In this case, a zero number of zeros must be added to the first two digits; therefore, no zeros are added. Thus, the resistance value is 10 ± 1 percent ohms. The maximum resistance is 10.1 ohms, and the minimum resistance is 9.9 ohms. There are two exceptions to the rule stating the third color band indicates the number of zeros. The first of these exceptions is illustrated in *Figure 7-13*. When the third band is gold in color, it indicates that the first two digits must be multiplied by 10 percent. The value of this resistor in this case is:

$10 \times 0.10 \pm 2\% = 1 = 0.02$ ohms

When the third band is silver, as is the case in *Figure 7-14*, the first two digits must be multiplied by 1 percent. The value of the resistor is 0.45 ± 10 percent ohms.

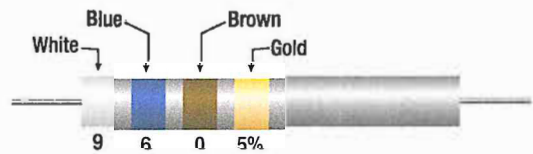Figure 7-9. Resistor color code example.
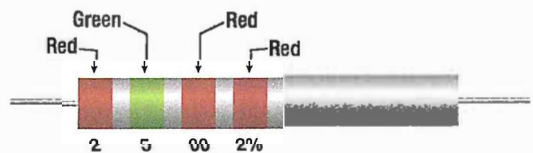

Figure 7-10. Resistor color code example.

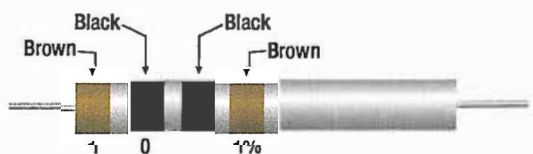Figure 7-11. Resistor with two percent tolerance.

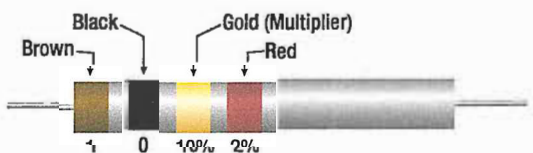Figure 7-12. Resistor with black third color band.
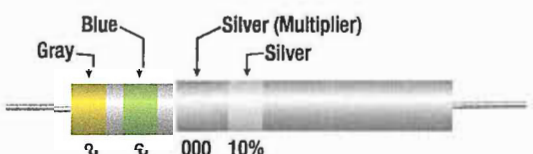

Figure 7-13. Resistor with gold third band.

Figure 7-14. Resistor with a silver third band.

WIRE WOUND

Wire wound resistors typically control large amounts of current and have high power ratings. Resistors of this type are constructed by winding a resistance wire around an insulating rod, usually made of porcelain. The windings are then coated with an insulation material for physical protection and heat conduction. Both ends of the windings are then connected to terminals, which are used to connect the resistor to a circuit. (*Figure 7-15*)

A wire wound resistor with tap is a special type of fixed resistor that can be adjusted. These adjustments can be made by moving a slide bar tap or by moving the tap to a preset incremental position. While the tap may be adjustable, the adjustments are usually set at the time of installation to a specific value and then operated in service as a fixed resistor. Another type of wire-wound resistor is that constructed of Manganin wire, used where high precision is needed.

VARIABLE RESISTORS

Variable resistors are constructed so that the resistive value can be changed easily. This adjustment can be manual or automatic, and the adjustments can be made while the system that it is connected to is in operation. There are two basic types of manual adjustor's. One is the rheostat and the second is the potentiometer.

RHEOSTAT

The schematic symbol for the rheostat is shown in *Figure 7-16*. A rheostat is a variable resistor used to vary the amount of current flowing in a circuit. *Figure 7-17* shows a rheostat connected in series with an ordinary resistance in a series circuit. As the slider arm moves from point A to B, the amount of rheostat resistance (AB) is increased. Since the rheostat resistance and the fixed resistance are in series, the total resistance in the circuit also increases, and the current in the circuit decreases. On the other hand, if the slider arm is moved toward point A, the total resistance decreases and the current in the circuit increases.

POTENTIOMETER

The schematic symbol for the potentiometer is shown in *Figure 7-18*. The potentiometer is considered a three terminal device. As illustrated, terminals 1 and 2 have the entire value of the potentiometer resistance between them. Terminal 3 is the wiper or moving contact. Through this wiper, the resistance between terminals
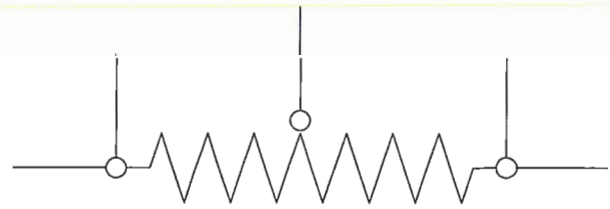

Figure 7-15. Wire-wound resistors.
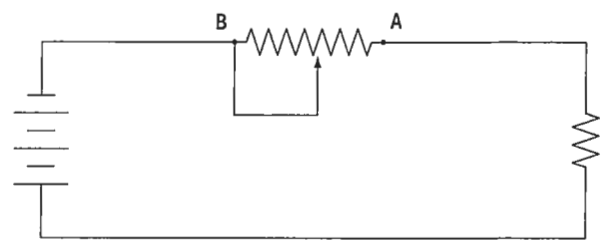

Figure 7-16. Rheostat schematic symbol.

Figure 7-17. Rheostat connected in series.
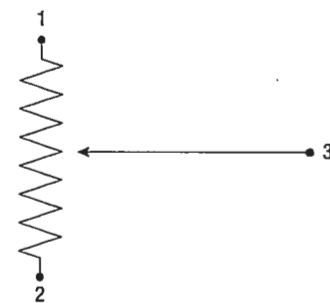
Figure 7-18. Potentiometer schematic symbol.

1 and 3 or terminals 2 and 3 can be varied. While the rheostat is used to vary the current in a circuit, the potentiometer is used to vary the voltage in a circuit. A typical use for this component can be found in the volume controls on an audio panel and input devices for flight data recorders, among many other applications.

In *Figure 7-19A*, a potentiometer is used to obtain a variable voltage from a fixed voltage source to apply to an electrical load. The voltage applied to the load is the voltage between points 2 and 3. When the slider arm is moved to point 1, the entire voltage is applied to the electrical device (load); when the arm is moved

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to point 3, the voltage applied to the load is zero. The potentiometer makes possible the application of any voltage between zero and full voltage to the load.

The current flowing through the circuit of *Figure 7-19* leaves the negative terminal electron flow of the battery and divides, one part flowing through the lower portion of the potentiometer (points 3 to 2) and the other part through the load. Both parts combine at point 2 and flow through the upper portion of the potentiometer (points 2 to 1) back to the positive terminal of the battery. In View B of *Figure 7-19*, a potentiometer and its schematic are shown.

In choosing a potentiometer resistance, the amount of current drawn by the load should be considered as well as the current flow through the potentiometer at all settings of the slider arm. The energy of the current through the potentiometer is dissipated in the form of heat. It is important to keep this wasted current as small as possible by making the resistance of the potentiometer as large as practicable. In most cases, the resistance of the potentiometer can be several times the resistance of the load. *Figure 7-20* shows how a potentiometer can be wired to function as a rheostat.

Linear Potentiometers

In a linear potentiometer, the resistance between both terminal and the wiper varies linearly with the position of the wiper. To illustrate, one quarter of a turn on the potentiometer will result in one quarter of the total resistance. The same relationship exists when one-half or three-quarters of potentiometer movement. *Figure 7-21* schematically depicts this.

Tapered Potentiometers

Resistance varies in a nonlinear manner in the case of the tapered potentiometer. *Figure 7-22* illustrates this. Keep in mind that one-half of full potentiometer travel doesn't necessarily correspond to one-half the total resistance of the potentiometer.

THERMISTORS

Figure 7-23 shows the schematic symbol for the thermistor. The thermistor is a type of a variable resistor, which is temperature sensitive. This component has what is known as a negative temperature coefficient, which means that as the sensed temperature increases, the resistance of the thermistor decreases.
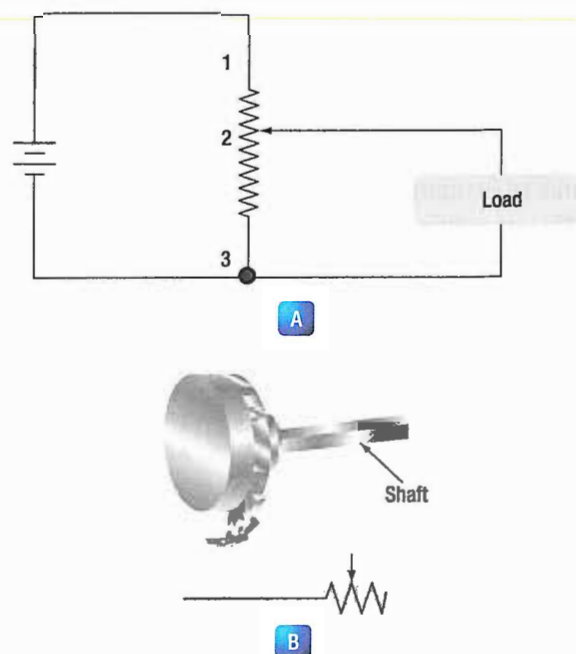

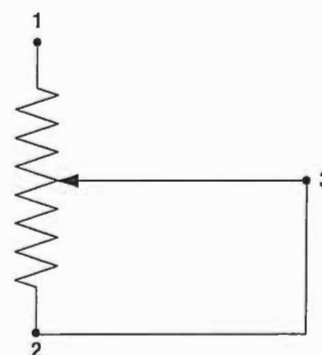Figure 7-19. Potentiometer and schematic.

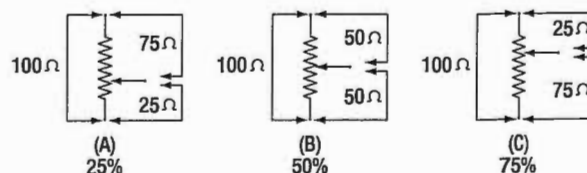Figure 7-20. Potentiometer wired to function as rheostat.
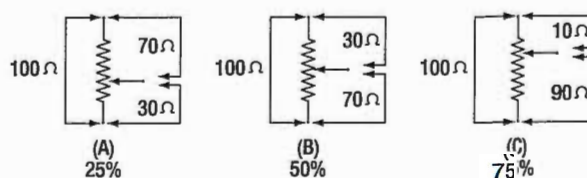

Figure 7-21. Linear potentiometer schematic.

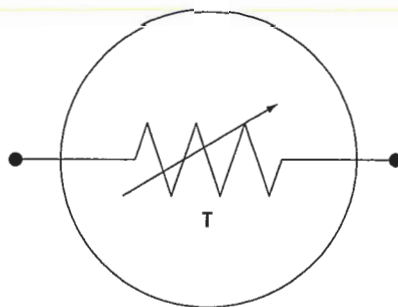

Figure 7-22. Tapered potentiometer.

Figure 7-23. Schematic symbol for thermistor.

PHOTOCONDUCTIVE CELLS

The photoconductive cell is similar to the thermistor. Like the thermistor, it has a negative temperature coefficient. Unlike the thermistor, the resistance is controlled by light intensity. This kind of component can be found in radio control heads where the intensity of the ambient light is sensed through the photoconductive cell resulting in the back lighting of the control heads to adjust to the cockpit lighting conditions. *Figure 7-24* shows the schematic symbol component.
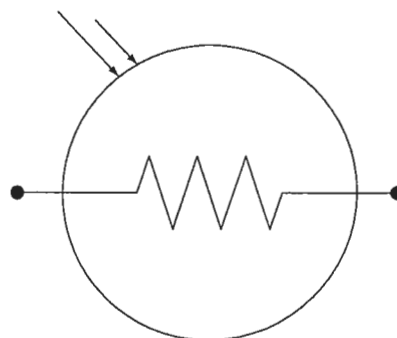
Figure 7-24. Photoconductive cell schematic symbol component.

WHEATSTONE BRIDGE

A Wheatstone Bridge is a useful electric wiring circuit constructed of three resistors with known values (R_1, R_2, R_3) and a voltmeter (V_G). A fourth resistor (R_X) of unknown value is also included as shown in *Figure 7-25*. When wired as shown, the voltage values at D and B vary with the total resistance on each side of the "bridge". Stated another way, the ratio of $R_2 / R_1 = R_X / R_3$. Thus, when the resistance on both sides of the circuit bridge are equal, there is no difference in potential at points D and B and the voltmeter wired between these points indicates "0".

To find the unknown value of R_X, The equation above can be rewritten and solved for R_X as follows: $R_X = R_1 / R_2 * R_3$. Alternatively, the voltage shown on the voltmeter can be used to calculate the unknown value of R_X by using Kirchoff's laws.

Of primary importance is the fact that when constructed as shown, the bridge circuit is balanced between both sides when the voltmeter indicates zero. It must be noted that similar bridge circuits can be used to measure capacitance, inductance and impedance.
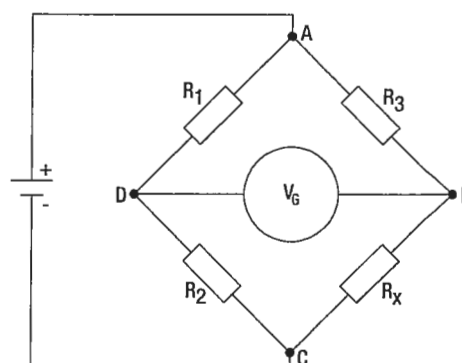
Figure 7-25. A Wheatstone Bridge circuit.

Question: 7-1

If the voltage across a resistor doubles, the current through the resistor _____ (resistance remains the same).

Question: 7-2

The best _____ are materials, chiefly metals, which possess a large number of free electrons; conversely, the best _____ are materials having few free electrons.

Question: 7-3

For most conductors, an increase in temperature causes resistance to _____.

Question: 7-4

The percentage variation between the marked value and the actual value of a resistor is known as the _____ of a resistor.

Question: 7-5

A wire wound resistor typically controls
    A. large amounts of current.
    B. small amounts of current.
    C. uneven current flows.

Question: 7-6

The two types of potentiometer as it relates to degree of movement of the wiper versus the amount of resistance established are _____ and _____.

Question: 7-7

A circuit constructed of three resistors of known value and a voltmeter used to determine the value of a forth resister in the circuit is called a _____.

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ANSWERS

Answer: 7-1
doubles.

Answer: 7-5
A large amounts of current.

Answer: 7-2
conductors, insulators.

Answer: 7-6
linear, tapered.

Answer: 7-3
increase.

Answer: 7-7
Wheatstone Bridge.

Answer: 7-4
tolerance.

PART-66 SYLLABUS LEVELS

	CERTIFICATION CATEGORY →	B1	B2

Sub-Module 08
POWER
Knowledge Requirements

3.8 – Power

	B1	B2
Power, work and energy (kinetic and potential);	2	2
Dissipation of power by a resistor;		
Power formula;		
Calculations involving power, work and energy.		

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

POWER

POWER AND ENERGY

POWER IN AN ELECTRICAL CIRCUIT

This section covers power in the DC circuit and energy consumption. Whether referring to mechanical or electrical systems, power is defined as the rate of energy consumption or conversion within that system — that is, the amount of energy used or converted in a given amount of time.

From the scientific discipline of physics, the fundamental expression for power is:

$$P = \frac{\mathcal{E}}{t}$$

Where:
P = Power measured in Watts (W)
$\mathcal{E}$ = Energy measured in Joules (J)
t = Time measured in Seconds (s)

The unit measurement for power is the watt (W), which refers to a rate of energy conversion of 1 joule/second. Therefore, the number of joules consumed in 1 second is equal to the number of watts. A simple example is given below.

Suppose 300 J of energy is consumed in 10 seconds. What would be the power in watts?

General formula:

$$P = \frac{energy}{time}$$

$$P = \frac{300 \text{ J}}{10 \text{ s}}$$

$$P = 30 \text{ W}$$

The watt is named for James Watt, the inventor of the steam engine. Watt devised an experiment to measure the power of a horse in order to find a means of measuring the mechanical power of his steam engine. One horsepower is required to move 33 000 pounds 1 foot in 1 minute. Since power is the rate of doing work, it is equivalent to the work divided by time. Stated as a formula, this is:

$$Power = \frac{33\,000 \text{ ft-lb}}{60 \text{ sec}}$$

$$P = 550 \text{ ft-lb/sec}$$

Electrical power can be rated in a similar manner. For example, an electric motor rated as a 1 horsepower motor requires 746 watts of electrical energy.

POWER FORMULAS USED IN THE STUDY OF ELECTRICITY

When current flows through a resistive circuit, energy is dissipated in the form of heat. Recall that voltage can be expressed in the terms of energy and charge as given in the expression:

$$E = \frac{W}{Q}$$

Where:
E = potential difference in volts
W = energy expanded or absorbed in joules (J)
Q = Charge measured in coulombs

Current I, can also be expressed in terms of charge and time as given by the expression:

$$Current = \frac{Charge}{Time}$$

Or,

$$I = \frac{Q}{t}$$

Where:
I = Current in Amperes (A)
Q = Charge in Coulombs (C)
t = time

When voltage $^W/_Q$ and current $^Q/_t$ are multiplied, the charge Q is divided out leaving the basic expression from physics:

$$E \times I = \frac{\mathcal{E}}{Q} \times \frac{Q}{t} = \frac{\mathcal{E}}{t} = power$$

For a simple DC electrical system, power dissipation can then be given by the equation:

General Power Formula

$$P = I(E)$$

Where $\quad$ P = Power
$\qquad\quad$ I = Current
$\qquad\quad$ E = Volts

If a circuit has a known voltage of 24 volts and a current of 2 amps, then the power in the circuit will be:

$$P = I(E)$$
$$P = 2A(24V)$$
$$P = 48\ W$$

Now recall Ohm's laws which states that $E = I(R)$. If we now substitute IR for E in the general formula, we get a formula that uses only current I and resistance R to determine the power in a circuit.

$$P = I(IR)$$

Second Form of Power Equation

$$P = I^2R$$

If a circuit has a known current of 2 amps and a resistance of 100 Ω, then the power in the circuit will be:

$$P = I^2R$$
$$P = (2A)^2\ 100\ \Omega$$
$$P = 400\ W$$

Using Ohm's law again, which can be stated as $I = E/R$, we can again make a substitution such that power can be determined by knowing only the voltage (E) and resistance (R) of the circuit.

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

Third Form of Power Equation

$$P = \frac{E^2}{R}$$

If a circuit has a known voltage of 24 volts and a resistance of 20 Ω, then the power in the circuit will be:

$$P = \frac{E^2}{R}$$
$$P = \frac{(24V)^2}{20\ \Omega}$$
$$P = 28.8\ W$$

POWER IN A SERIES AND PARALLEL CIRCUIT

The total power dissipated in both a series and parallel circuit is equal to the sum of the power dissipated in each resistor in the circuit. Power is simply additive and can be stated as:

$$P_T = P_1 + P_2 + P_3 + \dots P_N$$

Figure 8-1 provides a summary of all the possible transpositions of the Ohm's law formula and the power formula.
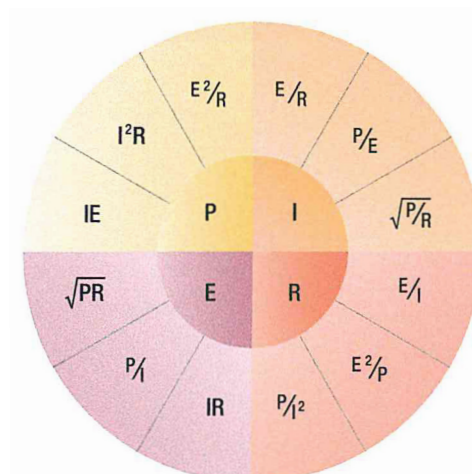
Figure 8-1. Ohm's law formula.

POWER

ENERGY IN AN ELECTRICAL CIRCUIT

Energy is defined as the ability to do work. Because power is the rate of energy usage, power used over a span of time is actually energy consumption. If power and time are multiplied together, we will get energy.

The joule is defined as a unit of energy. There is another unit of measure which is perhaps more familiar. Because power is expressed in watts and time in seconds, a unit of energy can be called a watt second (Ws) or more recognizable from the electric bill, a kilowatt hour (kWh).

Question: 8-1

The amount of energy used or converted in a given amount of time is known as _____.

Question: 8-2

The general formula for power is _____.

Question: 8-3

For DC current, the formula for power is

_____.

Question: 8-4

In a series-parallel circuit, the sum of the power dissipated in each resistor is _____.

ANSWERS

Answer: 8-1

power.

Answer: 8-3

P = EI (power equals voltage × current)

Answer: 8-2

$$Power = \frac{Energy}{time}$$

Answer: 8-4

the total power dissipated.

Sub-Module 09
CAPACITANCE/CAPACITOR
Knowledge Requirements

3.9 – Capacitance/Capacitor

	B1	B2
Operation and function of a capacitor;	2	2

Factors affecting capacitance area of plates, distance between plates, number of plates, dielectric and dielectric constant, working voltage, voltage rating;

Capacitor types, construction and function;

Capacitor colour coding;

Calculations of capacitance and voltage in series and parallel circuits;

Exponential charge and discharge of a capacitor, time constants;

Testing of capacitors.

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

CAPACITANCE/CAPACITOR

CAPACITANCE

Another important property in AC circuits besides resistance and inductance is capacitance. While inductance is represented in a circuit by a coil, capacitance is represented by a capacitor. Its most basic form the capacitor is constructed of two parallel plates separated by a nonconductor, called a dielectric. In an electrical circuit, a capacitor serves as a reservoir or storehouse for electricity.

CAPACITORS IN DIRECT CURRENT

When a capacitor is connected across a source of direct current, such as a storage battery in the circuit shown in *Figure 9-1A*, and the switch is then closed, the plate marked B becomes positively charged, and the A plate negatively charged. Current flows in the external circuit during the time the electrons are moving from B to A. The current flow in the circuit is at a maximum the instant the switch is closed, but continually decreases thereafter until it reaches zero. The current becomes zero as soon as the difference in voltage of A and B becomes the same as the voltage of the battery. If the switch is opened as shown in *Figure 9-1B*, the plates remain charged. Once the capacitor is shorted, it will discharge quickly as shown *Figure 9-1C*.
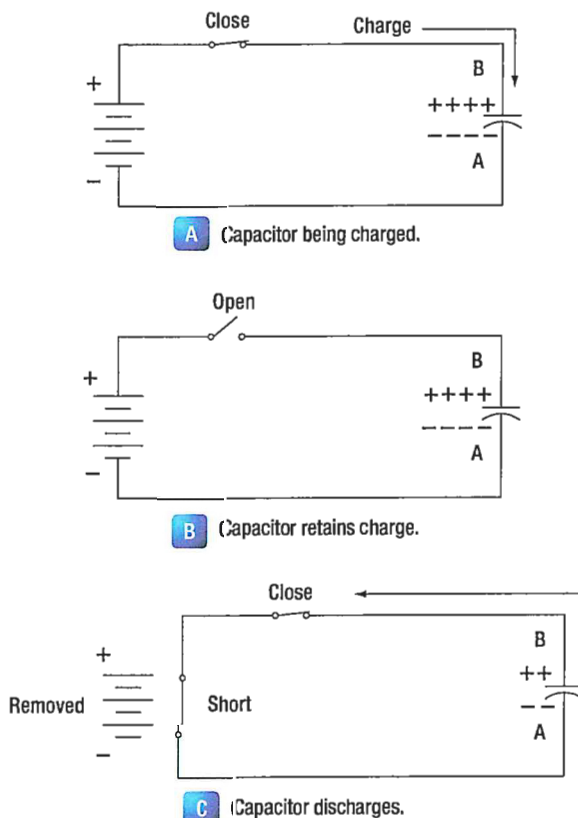
It should be clear that during the time the capacitor is being charged or discharged, there is current in the circuit, even though the circuit is broken by the gap between the capacitor plates. Current is present only during the time of charge and discharge, and this period of time is usually short.

THE RC TIME CONSTANT

The time required for a capacitor to attain a full charge is proportional to the capacitance and the resistance of the circuit. The resistance of the circuit introduces the element of time into the charging and discharging of a capacitor.

When a capacitor charges or discharges through a resistance, a certain amount of time is required for a full charge or discharge. The voltage across the capacitor will not change instantaneously. The rate of charging or discharging is determined by the time constant of the circuit. The time constant of a series RC (resistor/capacitor) circuit is a time interval that equals the product of the resistance in ohms and the capacitance in farad and is symbolized by the greek letter tau (τ).

$$\tau = RC$$

The time in the formula is that required to charge to 63% of the voltage of the source. The time required to bring the charge to about 99% of the source voltage is approximately 5τ. *Figure 9-2* illustrates this relationship of a time constant characteristics of charging.

A Capacitor being charged.

B Capacitor retains charge.

C Capacitor discharges.

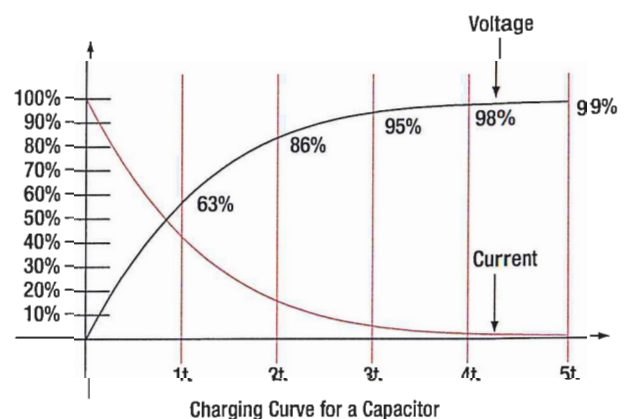Figure 9-1. Capacitors in direct current.

Charging Curve for a Capacitor

Figure 9-2. Capacitance charging curve.

The measure of a capacitor's ability to store charge is its capacitance. The symbol used for capacitance is the letter C.

As can be seen from the time constant illustration there can be no continuous movement of direct current through a capacitor. A good capacitor will block direct current and will pass the effects of pulsing DC or alternating current.

UNITS OF CAPACITANCE

Electrical charge, which is symbolized by the letter Q, is measured in units of coulombs. The coulomb is given by the letter C, as with capacitance. Unfortunately this can be confusing. One coulomb of charge is defined as a charge having 6.24×10^{18} electrons. The basic unit of capacitance is the farad and is given by the letter f. By definition, one farad is one coulomb of charge stored with one volt across the plates of the capacitor.

The general formula for capacitance in terms of charge and voltage is:

$$C = \frac{Q}{E}$$

Where:
C = Capacitance measured in farads.
E = Applied voltage measured in volts.
Q = Charge measured in coulombs.

In practical terms, one farad is a large amount of capacitance. Typically, in electronics, much smaller units are used. The two more common smaller units are the microfarad (μF), which is 10^{-6} farad and the picofarad (pF), which is 10^{-12} farad.

VOLTAGE RATING OF A CAPACITOR

Capacitors have their limits as to how much voltage can be applied across the plates. The aircraft technician must be aware of the voltage rating, which specifies the maximum DC voltage that can be applied without the risk of damage to the device. This voltage rating is typically called the breakdown voltage, the working voltage, or simply the voltage rating. If the voltage applied across the plates is too great, the dielectric will break down and arcing will occur between the plates. The capacitor is then short circuited, and the possible flow of direct current through it can cause damage to other parts of the equipment.

A capacitor that can be safely charged to 500 volts DC cannot be safely subjected to AC or pulsating DC whose effective values are 500 volts. An alternating voltage of 500 volts (RMS) has a peak voltage of 707 volts, and a capacitor to which it is applied should have a working voltage of at least 750 volts. The capacitor should be selected so that its working voltage is at least 50 percent greater than the highest voltage to be applied.

The voltage rating of the capacitor is a factor in determining the actual capacitance because capacitance decreases as the thickness of the dielectric increases. A high voltage capacitor that has a thick dielectric must have a larger plate area in order to have the same capacitance as a similar low voltage capacitor having a thin dielectric.

FACTORS AFFECTING CAPACITANCE

The capacitance of parallel plates is directly proportional to their area. A larger plate area produces a larger capacitance and a smaller area produces less capacitance. If we double the area of the plates, there is room for twice as much charge. The charge that a capacitor can hold at a given potential difference is doubled, and since $C = \frac{Q}{E}$ the capacitance is doubled.

The capacitance of parallel plates is inversely proportional to their spacing.

The dielectric material affects the capacitance of parallel plates. The dielectric constant of a vacuum is defined as 1, and that of air is very close to 1. These values are used as a reference, and all other materials have values specified in relation to air (vacuum).

The strength of some commonly used dielectric materials is listed in *Figure 9-3*. The voltage rating also depends on frequency because the losses, and the resultant heating effect, increase as the frequency increases.

CAPACITANCE/CAPACITOR

Dielectric	K	Dielectric Strength (volts per .001 inch)
Air	1.0	80
Paper		
(1) Paraffined	2.2	1 200
(2) Beeswaxed	3.1	1 800
Glass	4.2	200
Castor Oil	4.7	380
Bakelite	6.0	500
Mica	6.0	2 000
Fiber	6.5	50

Figure 9-3. Strength of some dielectric materials.

TYPES OF CAPACITORS

Capacitors come in all shapes and sizes and are usually marked with their value in farads. They may also be divided into two groups: fixed and variable. The fixed capacitors, which have approximately constant capacitance, may then be further divided according to the type of dielectric used. Some varieties are: paper, oil, mica, electrolytic and ceramic capacitors.

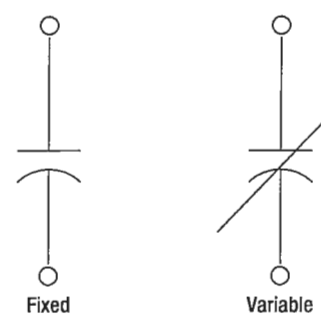*Figure 9-4* shows the schematic symbols for a fixed and variable capacitor.

Figure 9-4. Schematic symbols for a fixed and variable capacitor.

FIXED CAPACITORS

MICA CAPACITORS
The fixed mica capacitor is made of metal foil plates that are separated by sheets of mica, which form the dielectric. The whole assembly is covered in molded plastic, which keeps out moisture. Mica is an excellent dielectric and will withstand higher voltages than paper without allowing arcing between the plates. Common values of mica capacitors range from approximately 50 micromicrofarads, to about 0.02 microfarads.

CERAMIC
The ceramic capacitor is constructed with materials, such as titanium acid barium for a dielectric. Internally these capacitors are not constructed as a coil, so they are well suited for use in high frequency applications. They are shaped like a disk, available in very small capacitance values and very small sizes. This type is fairly small, inexpensive, and reliable. Both the ceramic and the electrolytic are the most widely available and used capacitor.

ELECTROLYTIC
Two kinds of electrolytic capacitors are in use: (1) wet electrolytic and (2) dry electrolytic. The wet electrolytic capacitor is designed of two metal plates separated by an electrolyte with an electrolyte dielectric, which is basically conductive salt in solvent. For capacitances greater than a few microfarads, the plate areas of paper or mica capacitors must become very large; thus, electrolytic capacitors are usually used instead. These units provide large capacitance in small physical sizes. Their values range from 1 to about 1 500 microfarads. Unlike the other types, electrolytic capacitors are generally polarized, with the positive lead marked with a "+" and the negative lead marked with a '–" and should only be subjected to direct voltage or pulsating direct voltage only.

The electrolyte in contact with the negative terminal, either in paste or liquid form, comprises the negative electrode. The dielectric is an exceedingly thin film of oxide deposited on the positive electrode of the capacitor. The positive electrode, which is an aluminum

sheet, is folded to achieve maximum area. The capacitor is subjected to a forming process during manufacture, in which current is passed through it. The flow of current results in the deposit of the thin coating of oxide on the aluminum plate.

The close spacing of the negative and positive electrodes gives rise to the comparatively high capacitance value, but allows greater possibility of voltage breakdown and leakage of electrons from one electrode to the other.

The electrolyte of the dry electrolytic unit is a paste contained in a separator made of an absorbent material, such as gauze or paper. The separator not only holds the electrolyte in place but also prevents it from short circuiting the plates. Dry electrolytic capacitors are made in both cylindrical and rectangular block form and may be contained either within cardboard or metal covers. Since the electrolyte cannot spill, the dry capacitor may be mounted in any convenient position. Electrolytic capacitors are shown in *Figure 9-5*.

TANTALUM
Similar to the electrolytic, these capacitors are constructed with a material called tantalum, which is used for the electrodes. They are superior to electrolytic capacitors, having better temperature and frequency characteristics. When tantalum powder is baked in order to solidify it, a crack forms inside. This crack is used to store an electrical charge. Like electrolytic capacitors, the tantalum capacitors are also polarized and are indicated with the "+" and "−" symbols.

POLYESTER FILM
In this capacitor, a thin polyester film is used as a dielectric. These components are inexpensive, temperature stable, and widely used. Tolerance is approximately 5–10 percent. It can be quite large depending on capacity or rated voltage.

OIL CAPACITORS
In radio and radar transmitters, voltages high enough to cause arcing, or breakdown, of paper dielectrics are often used. Consequently, in these applications capacitors that use oil or oil impregnated paper for the dielectric material are preferred. Capacitors of this type are considerably more expensive than ordinary paper capacitors, and their use is generally restricted to radio and radar transmitting equipment. (*Figure 9-6*)

VARIABLE CAPACITORS
Variable capacitors are mostly used in radio tuning circuits, and they are sometimes called "tuning capacitors." They have very small capacitance values, typically between 100pF and 500pF.

TRIMMERS
The trimmer is actually an adjustable or variable capacitor, which uses ceramic or plastic as a dielectric. Most of them are color coded to easily recognize their tunable size. The ceramic type has the value printed on them. Colors are: yellow (5pF), blue (7pF), white (10pF), green (30pF), and brown (60pf).

Figure 9-5. Electrolytic capacitors.

Figure 9-6. Oil capacitor.

CAPACITANCE/CAPACITOR

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VARACTORS

A voltage variable capacitor or varactor is also known as a variable capacitance diode or a varicap. This device utilizes the variation of the barrier width in a reversed-biased diode. Because the barrier width of a diode acts as a nonconductor, a diode forms a capacitor when reversed biased. Essentially the N-type material becomes one plate and the junctions are the dielectric. If the reversed bias voltage is increased, then the barrier width widens, effectively separating the two capacitor plates and reducing the capacitance.

CAPACITORS IN SERIES

When capacitors are placed in series, the effective plate separation is increased and the total capacitance is less than that of the smallest capacitor. Additionally, the series combination is capable of withstanding a higher total potential difference than any of the individual capacitors. *Figure 9-7* is a simple series circuit. The bottom plate of C1 and the top plate of C2 will be charged by electrostatic induction. The capacitors charge as current is established through the circuit. Since this is a series circuit, the current must be the same at all points. Since the current is the rate of flow of charge, the amount of charge (Q) stored by each capacitor is equal to the total charge.

Figure 9-7. Simple series circuit.

$$Q_T = Q_1 + Q_2 + Q_3$$

According to Kirchhoff's voltage law, the sum of the voltages across the charged capacitors must equal the total voltage, ET. This is expressed as:

$$E_T = E_1 + E_2 + E_3$$

Equation $E = Q/C$ can now be substituted into the voltage equation where we now get:

$$\frac{Q_T}{C_T} = \frac{Q_1}{E_1} + \frac{Q_2}{E_2} + \frac{Q_3}{E_3}$$
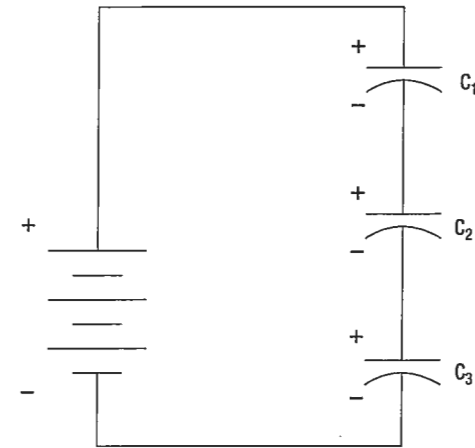
Since the charge on all capacitors is equal, the Q terms can be factored out, leaving us with the equation:

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Consider the following example:

If $C_1 = 10\mu F$, $C_2 = 5\mu F$ and $C_3 = 8\mu F$

Then $$\frac{1}{C_T} = \frac{1}{10\mu F} + \frac{1}{5\mu F} + \frac{1}{8\mu F}$$

$$C_T = \frac{1}{0.425\mu F} = 2.35\mu F$$

CAPACITORS IN PARALLEL

When capacitors are connected in parallel, the effective plate area increases, and the total capacitance is the sum of the individual capacitances. *Figure 9-8* shows a simplified parallel circuit. The total charging current from the source divides at the junction of the parallel branches. There is a separate charging current through each branch so that a different charge can be stored by each capacitor.

Using Kirchhoff's current law, the sum of all of the charging currents is then equal to the total current. The sum of the charges (Q) on the capacitors is equal to the total charge. The voltages (E) across all of the parallel branches are equal.

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With all of this in mind, a general equation for capacitors in parallel can be determined as:

$$Q_T = Q_1 + Q_2 + Q_3$$

Voltages can be factored out because:

$$E_T = E_1 + E_2 + E_3$$

Leaving us with the equation for capacitors in parallel:

$$C_T = C_1 + C_2 + C_3$$

Consider the following example:

If C1 = 330μF, C2 = 220μF
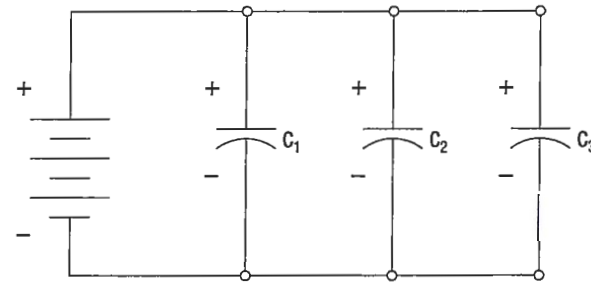
Then CT = 330μF + 220μF = 550μF

Figure 9-8. Simplified parallel circuit.

CAPACITORS IN ALTERNATING CURRENT

If a source of alternating current is substituted for the battery, the capacitor acts quite differently than it does with direct current. When an alternating current is applied in the circuit, the charge on the plates constantly changes. (*Figure 9-9*) This means that electricity must flow first from Y clockwise around to X, then from X counterclockwise around to Y, then from Y clockwise around to X, and so on. Although no current flows through the insulator between the plates of the capacitor, it constantly flows in the remainder of the circuit between X and Y. In a circuit in which there is only capacitance, current leads the applied voltage as contrasted with a circuit in which there is inductance, where the current lags the voltage.
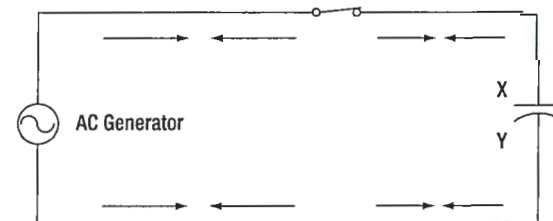
Figure 9-9. Capacitor in an AC circuit.

CAPACITIVE REACTANCE Xc

The effectiveness of a capacitor in allowing an AC flow to pass depends upon the capacitance of the circuit and the applied frequency. To what degree a capacitor allows an AC flow to pass depends largely upon the capacitive value of the capacitor given in farads (f). The greater the capacitance of the capacitor, the greater the number of electrons, measured in Coulombs, necessary to bring the capacitor to a fully charged state. Once the capacitor approaches or actually reaches a fully charged condition, the polarity of the capacitor will oppose the polarity of the applied voltage, essentially acting then as an open circuit. To further illustrate this characteristic and how it manifests itself in an AC circuit, consider the following.

If a capacitor has a large capacitive value, meaning that it requires a relatively large number of electrons to bring it to a fully charged state, then a rather high frequency current can alternate through the capacitor without the capacitor ever reaching a full charge. In this case,

if the frequency is high enough and the capacitance large enough that there is never enough time for the capacitor to ever reach a full charge, it is possible that the capacitor may offer very little or no resistance to the current. However, the smaller the capacitance, the fewer electrons are required to bring it up to a full charge and it is more likely that the capacitor will build up enough of an opposing charge that it can present a great deal of resistance to the current if not to the point of behaving like an open circuit.

In between these two extreme conditions lies a continuum of possibilities of current opposition depending on the combination of applied frequency and the selected capacitance. Current in an AC circuit can be controlled by changing the circuit capacitance in a similar manner that resistance can control the current. The actual AC reactance X_c, which just like resistance, is measured in ohms (Ω). Capacitive reactance X_c is determined by the following:

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

Where X_c = Capacitive Reactance
   f = frequency in cps
   C = capacity in farads
   2π = 6.28

Sample Problem:
A series circuit is assumed in which the impressed voltage is 110 volts at 60 cps, and the capacitance of a condenser is 80 Mf. Find the capacitive reactance and the current flow.

Solution:
To find capacitive reactance, the equation $X_c = 1/(2\ p\ f\ C)$ is used. First, the capacitance, 80 Mf, is changed to farads by dividing 80 by 1 000 000, since 1 million microfarads is equal to 1 farad. This quotient equals 0.000 080 farad. This is substituted in the equation and

$$X_C = \frac{1}{6.25 \times 60 \times 0.000\ 080}$$

$$X_C = 33.2 \text{ ohms reactance}$$

Once the reactance has been determined, ohm's law can then be used in the same manner as it is used in DC circuits to determine the current.

$$\text{Current} = \frac{\text{Voltage}}{\text{Capacitive reactance}}, \text{ or}$$

$$I = \frac{E}{X_C},$$

Find the current flow:

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

$$I = \frac{110}{33.2}$$

$$I = 3.31 \text{ amperes}$$

CAPACITIVE REACTANCES IN SERIES AND IN PARALLEL

When capacitors are connected in series, the total reactance is equal to the sum of the individual reactances. Thus,

$$X_{ct} = (X_c)_1 + (X_c)_2$$

The total reactance of capacitors connected in parallel is found in the same way total resistance is computed in a parallel circuit:

$$(X_c)t = \frac{1}{\frac{1}{(X_c)_1} + \frac{1}{(X_c)_2} + \frac{1}{(X_c)_3}}$$

PHASE OF CURRENT AND VOLTAGE IN REACTIVE CIRCUITS

Unlike a purely resistive circuit, the capacitive and inductive reactance has a significant effect on the phase relationship between the applied AC voltage and the corresponding current in the circuit.

In review, when current and voltage pass through zero and reach maximum value at the same time, the current and voltage are said to be in phase. (*Figure 9-10A*) If the current and voltage pass through zero and reach the maximum values at different times, the current and voltage are said to be out of phase. In a circuit containing only inductance, the current reaches a maximum value later than the voltage, lagging the voltage by 90°, or one-fourth cycle. (*Figure 9-10B*)

In a circuit containing only capacitance, the current reaches its maximum value ahead of the voltage and the current leads the voltage by 90°, or one-fourth cycle. (*Figure 9-10C*) The amount the current lags or leads the voltage in a circuit depends on the relative amounts of resistance, inductance, and capacitance in the circuit.
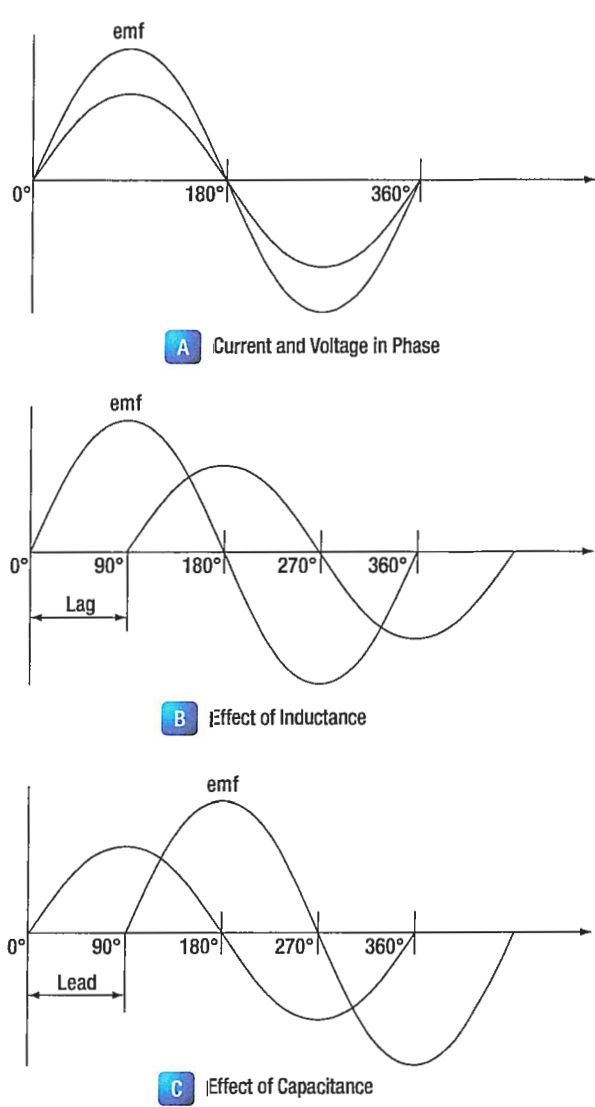

A   Current and Voltage in Phase

B   Effect of Inductance

C   Effect of Capacitance

Figure 9-10. Phase of current and voltage.

TESTING CAPACITORS

Testing a capacitors in best performed after removing it from the circuit. While some testing to determine compete failure is possible with an multimeter, a digital capacitor tester is recommended for testing capacitors.

The farad is the unit of measurement used when measuring a capacitor's ability to store an electric charge. A capacitor capable of holding a farad is capable of holding 1 coulomb of electricity under a force of one volt. A coulomb is 10^{18} electrons.)

A capacitor tester is calibrated to measure microfarads or farads as needed. Simply touch the test unit leads to the individual terminals of the capacitor and read the scale.

Note of caution: High voltage capacitors can store enough electrical energy to cause injury if the charge is released through the human body. Always short the capacitor leads across one another before removing the capacitor from the circuit.

Question: 9-1

When does current flow in a circuit where a capacitor is connected across a DC storage battery?

Question: 9-5

The formula for total capacitance of a parallel circuit is

_____.

Question: 9-2

Capacitance is measured in _____.

Question: 9-6

Opposition to current flow in an AC circuit depends on the capacitance of the capacitor and the _____ of the applied voltage.

Question: 9-3

Name 3 materials used as the dielectric in the construction of fixed capacitors.

Question: 9-7

The total reactance of capacitors connected in parallel is found in the same way _____ is computed in a parallel circuit.

Question: 9-4

Capacitors in series can withstand _____ total potential than any of the individual capacitors.

ANSWERS

Answer: 9-1
only when the capacitor is being charged or discharged.

Answer: 9-5
$C_T = C_1 + C_2 + C_3$

Answer: 9-2
farads (f).

Answer: 9-6
frequency.

Answer: 9-3
mica.
paper.
ceramic (titanium acid barium).
oil.
electrolytic (wet or dry).

Answer: 9-7
total resistance.

Answer: 9-4
higher.

PART-66 SYLLABUS CERTIFICATION CATEGORY →	LEVELS	
	B1	**B2**

Sub-Module 10
MAGNETISM
Knowledge Requirements

3.10 – Magnetism

(a)	Theory of magnetism;	2	2
	Properties of a magnet;		
	Action of a magnet suspended in the Earth's magnetic field;		
	Magnetisation and demagnetisation;		
	Magnetic shielding;		
	Various types of magnetic material;		
	Electromagnets construction and principles of operation;		
	Hand clasp rules to determine: magnetic field around current carrying conductor;		
(b)	Magnetomotive force, field strength, magnetic flux density, permeability, hysteresis loop, retentivity, coercive force reluctance, saturation point, eddy currents;	2	2
	Precautions for care and storage of magnets.		

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

MAGNETISM

MAGNETISM

Magnetism is defined as the property of an object to attract certain metallic substances. In general, these substances are ferrous materials; that is, materials composed of iron or iron alloys, such as soft iron, steel, and alnico. These materials, sometimes called magnetic materials, today include at least three nonferrous materials: nickel, cobalt, and gadolinium, which are magnetic to a limited degree. All other substances are considered nonmagnetic, and a few of these nonmagnetic substances can be classified as diamagnetic since they are repelled by both poles of a magnet. *Figure 10-1*. One end of magnetized strip points to the magnetic north pole.

Magnetism is an invisible force, the ultimate nature of which has not been fully determined. It can best be described by the effects it produces. Examination of a simple bar magnet similar to that illustrated in *Figure 10-1* discloses some basic characteristics of all magnets. If the magnet is suspended to swing freely, it will align itself with the earth's magnetic poles. One end is labeled "N," meaning the north seeking end or pole of the magnet. If the "N" end of a compass or magnet is referred to as north seeking rather than north, there will be no conflict in referring to the pole it seeks, which is the north magnetic pole. The opposite end of the magnet, marked "S" is the south seeking end and points to the south magnetic pole. Since the earth is a giant magnet, its poles attract the ends of the magnet. These poles are not located at the geographic poles.

The somewhat mysterious and completely invisible force of a magnet depends on a magnetic field that surrounds the magnet as illustrated in *Figure 10-2*. This field always exists between the poles of a magnet, and will arrange itself to conform to the shape of any magnet.

The theory that explains the action of a magnet holds that each molecule making up the iron bar is itself a tiny magnet, with both north and south poles as illustrated in *Figure 10-3A*. These molecular magnets each possess a magnetic field, but in an unmagnetized state, the molecules are arranged at random throughout the iron bar. If a magnetizing force, such as stroking with a lodestone, is applied to the unmagnetized bar, the molecular magnets rearrange themselves in line with the magnetic field of the lodestone, with all north ends of the magnets pointing in one direction and all south ends
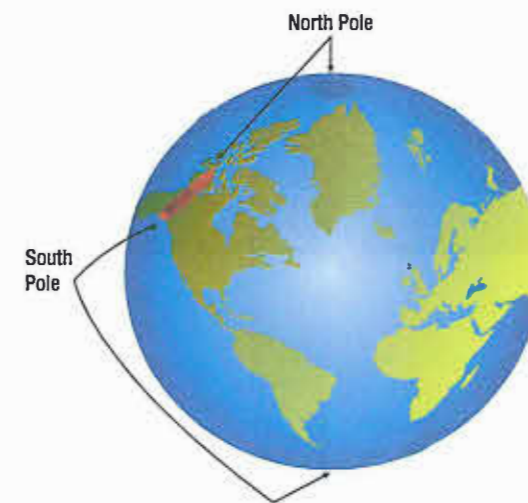

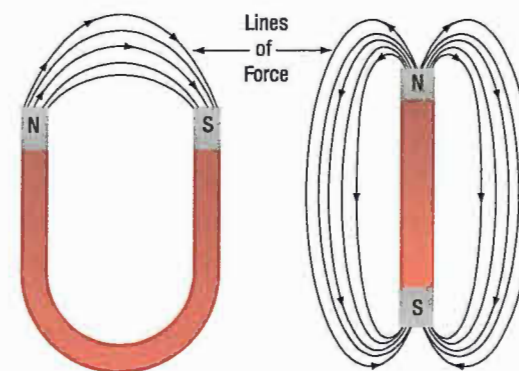Figure 10-1. One end of magnetized strip points to the magnetic north pole.

Figure 10-2. Magnetic field around magnets.
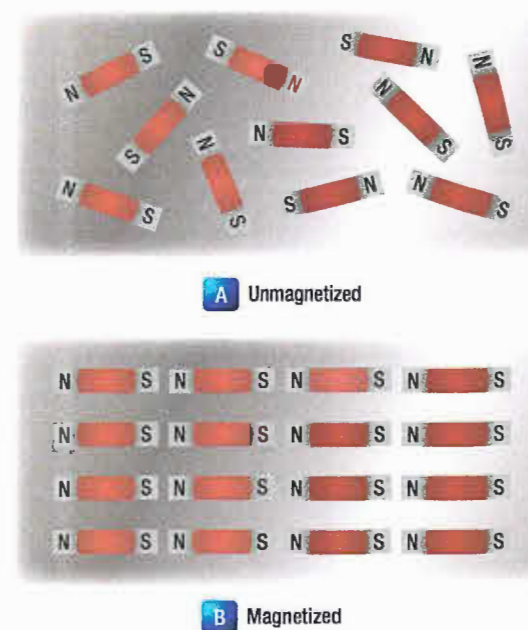

A Unmagnetized

B Magnetized

Figure 10-3. Arrangement of molecules in a piece of magnetic material.

in the opposite direction. This is illustrated in *Figure 10-3B*. In such a configuration, the magnetic fields of the magnets combine to produce the total field of the magnetized bar.

When handling a magnet, avoid applying direct heat, or hammering or dropping it. Heating or sudden shock will cause misalignment of the molecules, causing the strength of a magnet to decrease. When a magnet is to be stored, devices known as "keeper bars" are installed to provide an easy path for flux lines from one pole to the other. This promotes the retention of the molecules in their north south alignment.

The presence of the magnetic force or field around a magnet can best be demonstrated by the experiment illustrated in *Figure 10-4*. A sheet of transparent material, such as glass or Lucite™, is placed over a bar magnet and iron filings are sprinkled slowly on this transparent shield. If the glass or Lucite is tapped lightly, the iron filings will arrange themselves in a definite pattern around the bar, forming a series of lines from the north to south end of the bar to indicate the pattern of the magnetic field.
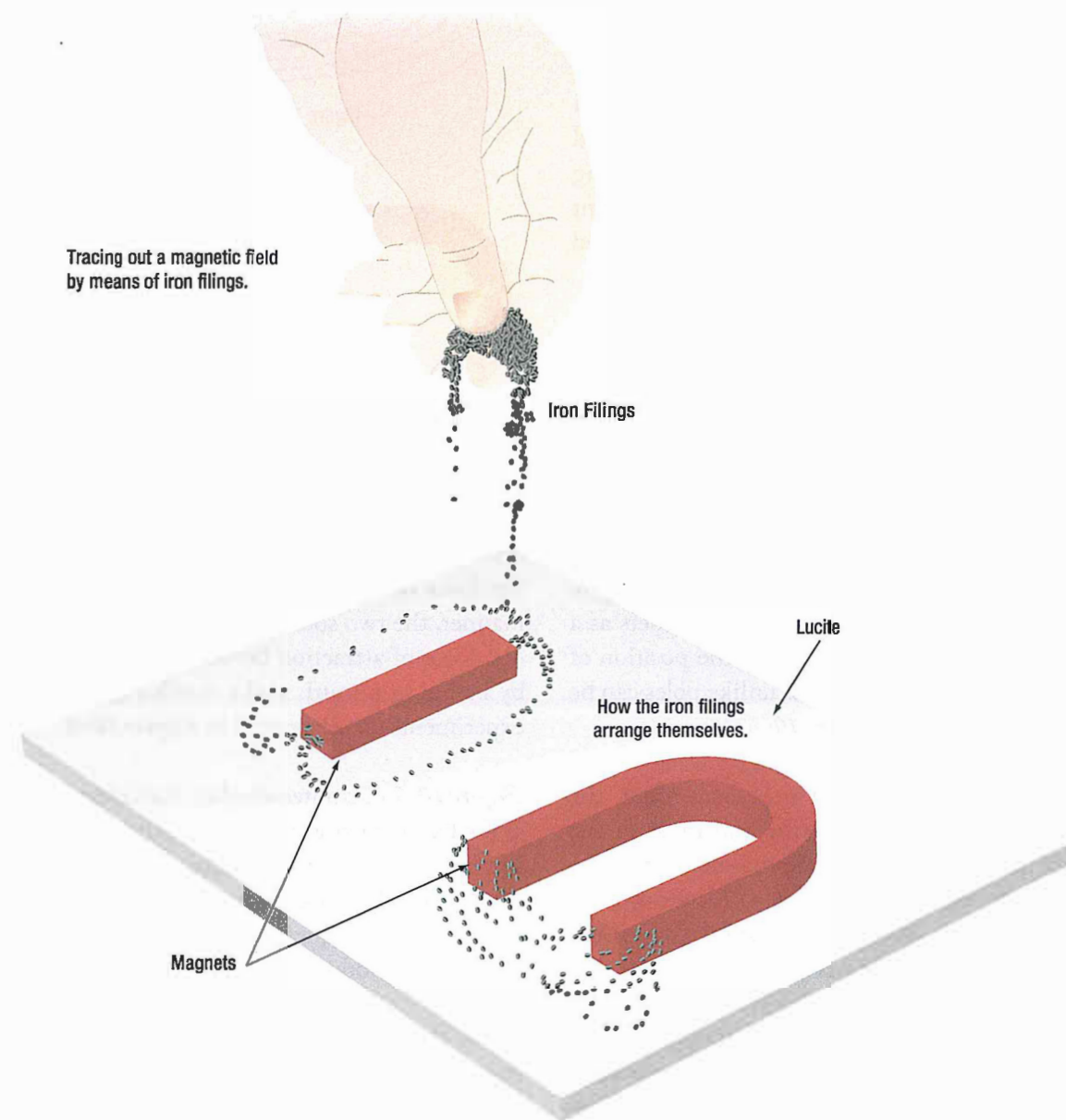

Tracing out a magnetic field by means of iron filings.

Iron Filings

Lucite

How the iron filings arrange themselves.

Magnets

Figure 10-4. Tracing out a magnetic field with iron filings.

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As shown, the field of a magnet is made up of many individual forces that appear as lines in the iron filing demonstration. Although they are not "lines" in the ordinary sense, this word is used to describe the individual nature of the separate forces making up the entire magnetic field. These lines of force are also referred to as magnetic flux.

They are separate and individual forces, since one line will never cross another; indeed, they actually repel one another. They remain parallel to one another and resemble stretched rubber bands, since they are held in place around the bar by the internal magnetizing force of the magnet.

The demonstration with iron filings further shows that the magnetic field of a magnet is concentrated at the ends of the magnet. These areas of concentrated flux are called the north and south poles of the magnet. There is a limit to the number of lines of force that can be crowded into a magnet of a given size. When a magnetizing force is applied to a piece of magnetic material, a point is reached where no more lines of force can be induced or introduced. The material is then said to be saturated.

The characteristics of the magnetic flux can be demonstrated by tracing the flux patterns of two bar magnets with like poles together, as shown in *Figure 10-5*. The two like poles repel one another because the lines of force will not cross each other. As the arrows on the individual lines indicate, the lines turn aside as the two like poles are brought near each other and travel in a path parallel to each other. Lines moving in this manner repel each other, causing the magnets as a whole to repel each other. By reversing the position of one of the magnets, the attraction of unlike poles can be demonstrated, as shown in *Figure 10-6*.

As the unlike poles are brought near each other, the lines of force rearrange their paths and most of the flux leaving the north pole of one magnet enters the south pole of the other. The tendency of lines of force to repel each other is indicated by the bulging of the flux in the air gap between the two magnets. To further demonstrate that lines of force will not cross one another, a bar magnet and a horseshoe magnet can be positioned to display a magnetic field similar to that of *Figure 10-7*. The magnetic fields of the two magnets do not combine, but are rearranged into a distorted flux pattern.
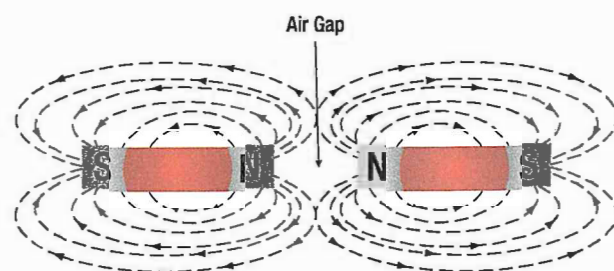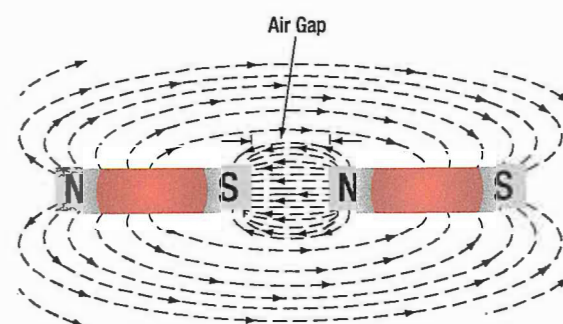

Figure 10-5. Like poles repel.
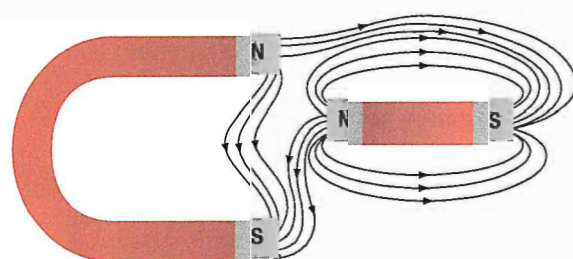

Figure 10-6. Unlike poles attract.

Figure 10-7. Bypassing flux lines.

The two bar magnets may be held in the hands and the north poles brought near each other to demonstrate the force of repulsion between like poles. In a similar manner, the two south poles can demonstrate this force. The force of attraction between unlike poles can be felt by bringing a south and a north end together. These experiments are illustrated in *Figure 10-8*.

Figure 10-9 illustrates another characteristic of magnets. If the bar magnet is cut or broken into pieces, each piece immediately becomes a magnet itself, with a north and south pole. This feature supports the theory that each molecule is a magnet, since each successive division of the magnet produces still more magnets.

Since the magnetic lines of force form a continuous loop, they form a magnetic circuit. It is impossible to say where in the magnet they originate or start. Arbitrarily, it is assumed that all lines of force leave the north pole

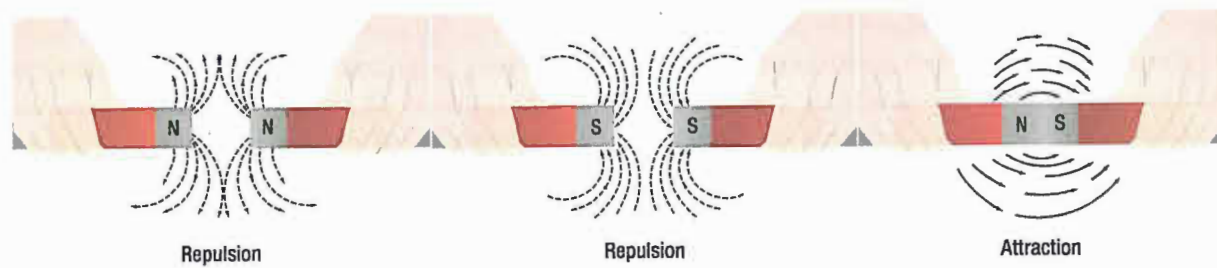Repulsion   Repulsion   Attraction

Figure 10-8. Repulsion and attraction of magnet poles.

of any magnet and enter at the south pole. There is no known insulator for magnetic flux, or lines of force, since they will pass through all materials. However, they will pass through some materials more easily than others.

Thus it is possible to shield items such as instruments from the effects of the flux by surrounding them with a material that offers an easier path for the lines of force. *Figure 10-10* shows an instrument surrounded by a path of soft iron, which offers very little opposition to magnetic flux. The lines of force take the easier path, the path of greater permeability, and are guided away from the instrument.

Materials such as soft iron and other ferrous metals are said to have a high permeability, the measure of the ease with which magnetic flux can penetrate a material. The permeability scale is based on a perfect vacuum with a rating of one. Air and other nonmagnetic materials are so close to this that they are also considered to have a rating of one. The nonferrous metals with a permeability greater than one, such as nickel and cobalt, are called paramagnetic. The term ferromagnetic is applied to iron and its alloys, which have by far the greatest permeability. Any substance, such as bismuth, having a permeability of less than one, is considered diamagnetic.

Reluctance, the measure of opposition to the lines of force through a material, can be compared to the resistance of an electrical circuit. The reluctance of soft iron, for instance, is much lower than that of air. *Figure 10-11* demonstrates that a piece of soft iron placed near the field of a magnet can distort the lines of force, which follow the path of lowest reluctance through the soft iron.

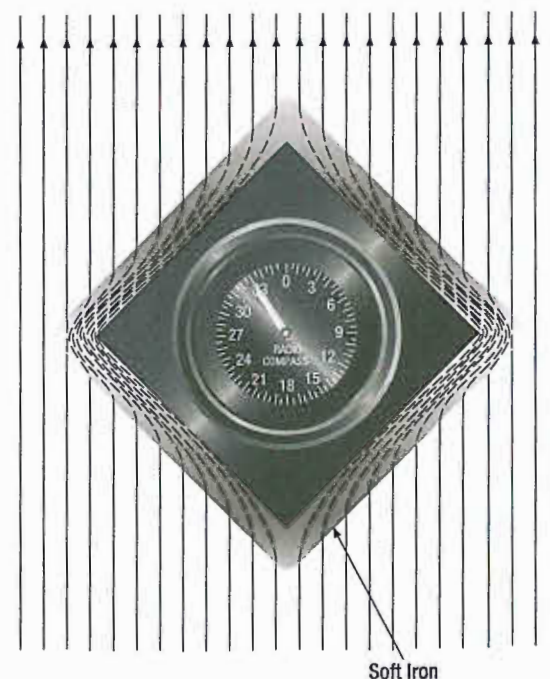Figure 10-9. Magnetic poles in a broken magnet.
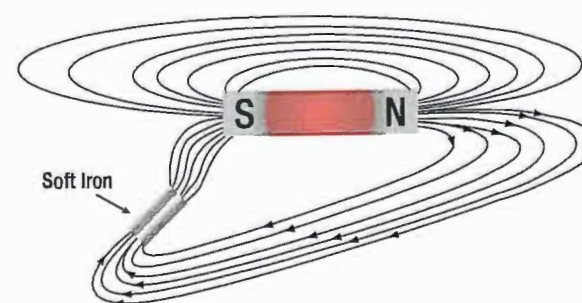

Soft Iron

Figure 10-10. Magnetic shield.

Soft Iron

Figure 10-11. Effect of a magnetic substance in a magnetic field.

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The magnetic circuit can be compared in many respects to an electrical circuit. The magnetomotive force, causing lines of force in the magnetic circuit, can be compared to the electromotive force or electrical pressure of an electrical circuit. The magnetomotive force is measured in gilberts, symbolized by the capital letter "F." The symbol for the intensity of the lines of force, or flux, is the Greek letter phi, and the unit of field intensity is the gauss. An individual line of force, called a maxwell, in an area of one square centimeter produces a field intensity of one gauss. Using reluctance rather than permeability, the law for magnetic circuits can be stated: a magnetomotive force of one gilbert will cause one maxwell, or line of force, to be set up in a material when the reluctance of the material is one.

MAGNETIC PROPERTIES AND THE HYSTERESIS LOOP

When magnetizing a material, there is a direct relationship between the intensity of the magnetizing force and the amount of magnetism developed in a material as demonstrated by the amount of flux (flux density) produced. A phenomenon called hysteresis loop reveals more about this relationship. (*Figure 10-12*)

By measuring the magnetic flux of a ferromagnetic material as the magnetizing force applied to the material is manipulated, the loop is drawn. Beginning at the origin for a material which is non magnetized or has lost nearly all of its magnetism, as the magnetizing force is increased, the flux density (magnetic field) increases. Near point A, increases in magnetizing force produces very little increase in magnetic flux and the material is said to be magnetically *saturated*.

When the magnetizing force is reduce to zero, some magnetic flux remains in the material (point B). This is referred to as a material's retentivity. Application of a reversed magnetizing force removes the flux than remained in the magnetizing material (point C). This is known as coercivity. As the reversed magnetizing force is increased, a similar flux build-up related to the intensity of the magnetizing force occurs with polarity opposite to the original (point D). Again, a point of saturation is reached as further increasing the intensity of the magnifying force produces virtually no change in flux density.

When the magnetizing force is removed, retentivity caused some magnetic flux to remain (point E). Then, as the magnetizing intensity is increased in the original
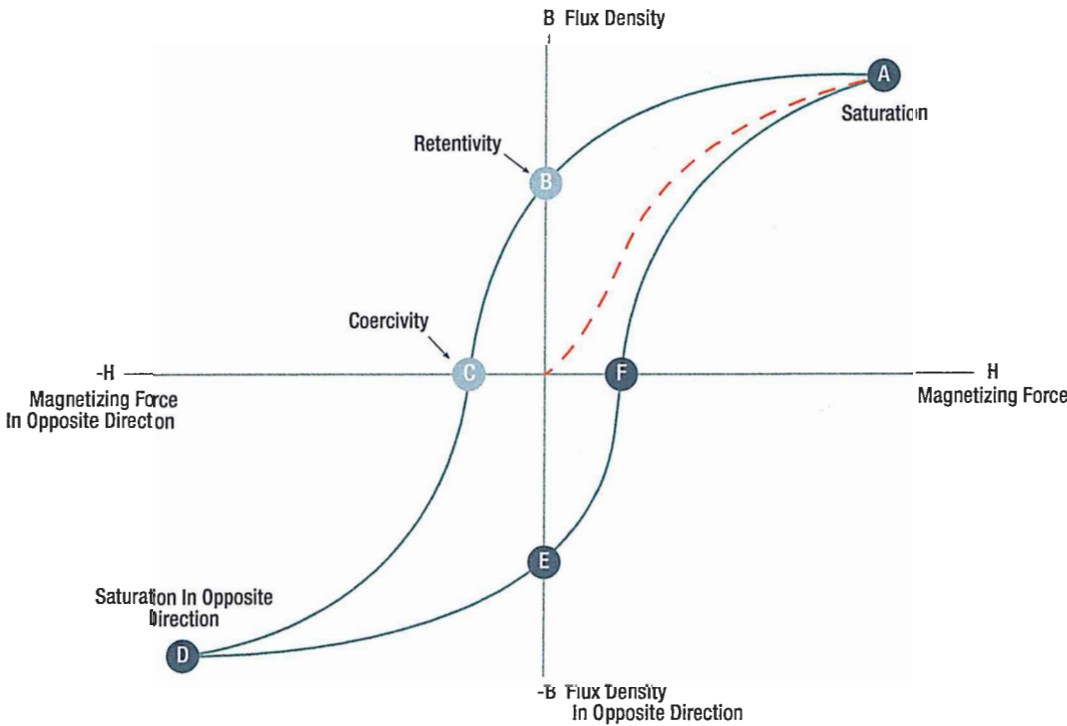

Figure 10-12. The hysteresis loop.

direction, the magnetic flux increases in the original direction once again until saturation is reached. (Some of the magnetizing force is used to remove the retentive flux so the flux curve does not pass through the origin.) Thus, a loop is formed that incorporates the hysteresis of the lingering flux (retentivity) in the magnetized material. The coercive force is the magnetizing force in the opposite direction that needs to be applied to remove the retained flux. The coercive force reluctance of the material is the opposition to giving up the retained magnetic flux that remains after the magnetizing force is removed.

EDDY CURRENTS

When the magnetic field in a conductor is changed, eddy currents develop. The eddy currents induce their own magnetic fields. The forces oppose their own development or dissipation as well as the development and dissipation of the conductor's magnetic field. The faster the change in the conductor magnetic field, the greater the eddy currents and associated magnetic fields.

Eddy currents tend to generate heat and reduce the efficiency of devices that rely on changing magnetic fields. Use of permeable laminations in the magnetic material helps suppress eddy currents. The choice of magnetic core material with low electrical conductivity also helps.

TYPES OF MAGNETS

Magnets are either natural or artificial. Since naturally occurring magnets or lodestones have no practical use, all magnets considered in this study are artificial or manmade. Artificial magnets can be further classified as permanent magnets, which retain their magnetism long after the magnetizing force has been removed, and temporary magnets, which quickly lose most of their magnetism when the external magnetizing force is removed.

Modern permanent magnets are made of special alloys that have been found through research to create increasingly better magnets. The most common categories of magnet materials are made out of Aluminum-Nickel- Cobalt (Alnicos), Strontium-Iron (Ferrites, also known as Ceramics), Neodymium-Iron-Boron (Neo magnets), and Samarium-Cobalt. Alnico, an alloy of iron, aluminum, nickel and cobalt, and is considered one of the very best. Others with excellent magnetic qualities are alloys such as Remalloy™ and Permendur™.

The ability of a magnet to hold its magnetism varies greatly with the type of metal and is known as retentivity. Magnets made of soft iron are very easily magnetized but quickly lose most of their magnetism when the external magnetizing force is removed. The small amount of magnetism remaining, called residual magnetism, is of great importance in such electrical applications as generator operation.

Horseshoe magnets are commonly manufactured in two forms. (*Figure 10-13*) The most common type is made from a long bar curved into a horseshoe shape, while a variation of this type consists of two bars connected by a third bar, or yoke.

Magnets can be made in many different shapes, such as balls, cylinders, or disks. One special type of magnet is the ring magnet, or Gramme ring, often used in instruments. This is a closed loop magnet, similar to the type used in transformer cores, and is the only type that has no poles.

Sometimes special applications require that the field of force lie through the thickness rather than the length of a piece of metal. Such magnets are called flat magnets and are used as pole pieces in generators and motors.
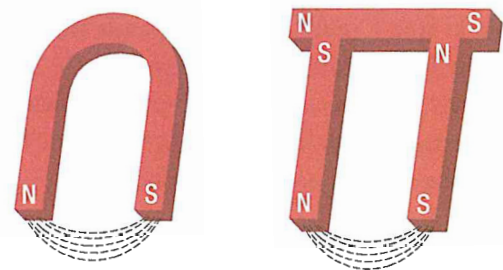

Figure 10-13. Two forms of horseshoe magnets.

CARE AND STORAGE OF MAGNETS

While durable permanent magnets are not indestructible they should be handled with care and kept from being dropped or receiving mechanical shock. Magnets should be stored at room temperature although any temperature below the temperature that they lose their permanent magnetism is acceptable. Most magnets don't lose their permanent magnetism until temperature is elevated above 400 °C.

Magnets should be stored in a dry place. Although most common magnets are not susceptible to moisture degradation, neodymium magnets may suffer. Separate storage of magnets is recommended. If magnets are stored together they should be stored with opposite poles next to each other. The use of a keeper across the pole ends of a magnet is also recommended when possible.
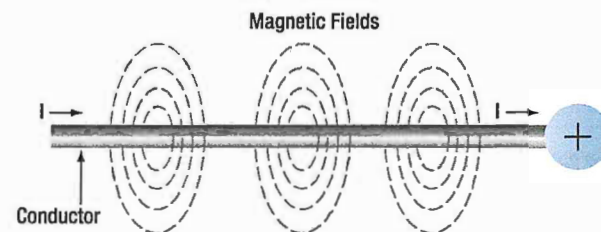
ELECTROMAGNETISM

In 1820, the Danish physicist, Hans Christian Oersted, discovered that the needle of a compass brought near a current carrying conductor would be deflected. When the current flow stopped, the compass needle returned to its original position. This important discovery demonstrated a relationship between electricity and magnetism that led to the electromagnet and to many of the inventions on which modern industry is based.

Oersted discovered that the magnetic field had no connection with the conductor in which the electrons were flowing, because the conductor was made of nonmagnetic copper. The electrons moving through the wire created the magnetic field around the conductor. Since a magnetic field accompanies a charged particle, the greater the current flow, and the greater the magnetic field. *Figure 10-14* illustrates the magnetic field around a current carrying wire. A series of concentric circles around the conductor represent the field, which if all the lines were shown would appear more as a continuous cylinder of such circles around the conductor.

As long as current flows in the conductor, the lines of force remain around it. (*Figure 10-15*) If a small current flows through the conductor, there will be a line of force extending out to circle A. If the current flow is increased, the line of force will increase in size to circle B, and a further increase in current will expand it to circle C. As the original line (circle) of force expands from circle A to B, a new line of force will appear at circle A. As the current flow increases, the number of circles of force increases, expanding the outer circles farther from the surface of the current carrying conductor.

Figure 10-14. Magnetic field formed around a conductor in which current is flowing.
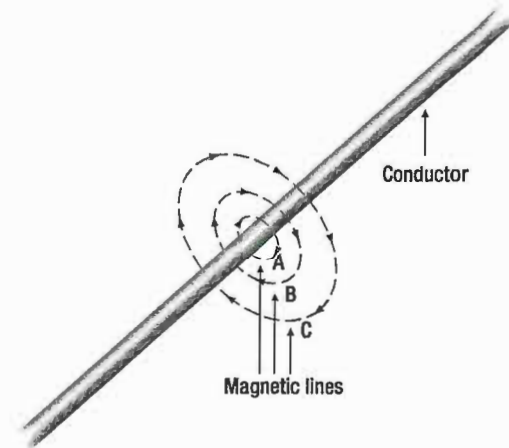
Figure 10-15. Expansion of magnetic field as current increases.

If the current flow is a steady nonvarying direct current, the magnetic field remains stationary. When the current stops, the magnetic field collapses and the magnetism around the conductor disappears.

A compass needle is used to demonstrate the direction of the magnetic field around a current carrying conductor. (*Figure 10-16*) View A shows a compass needle positioned at right angles to, and approximately one inch from, a current carrying conductor. If no current were flowing, the north seeking end of the compass needle
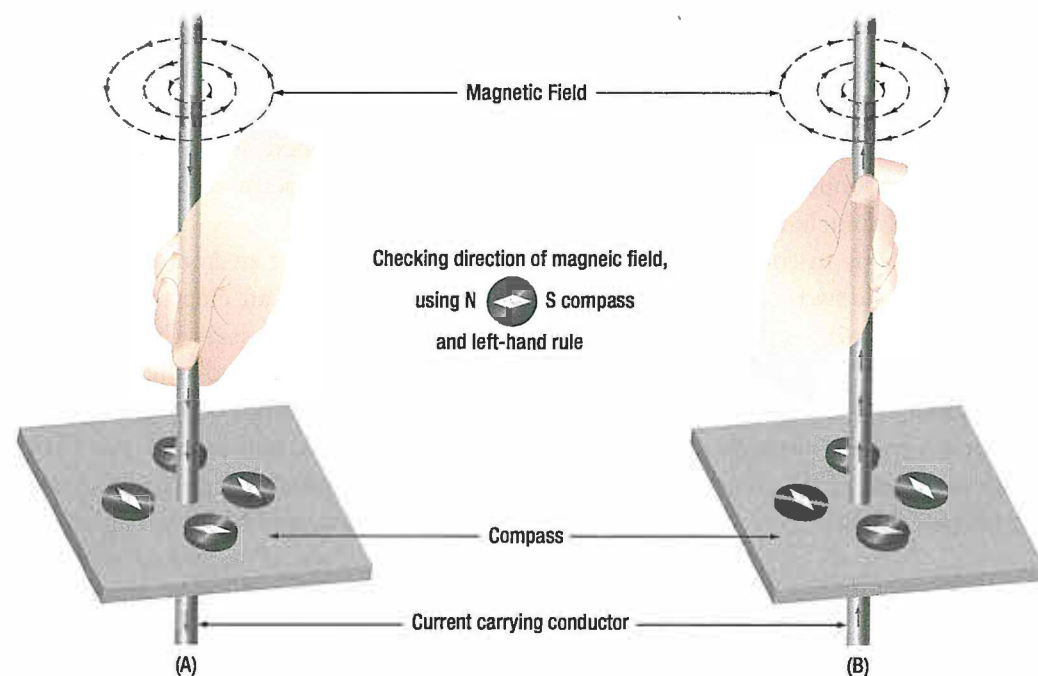
Figure 10-16. Magnetic field around a current-carrying conductor.

would point toward the earth's magnetic pole. When current flows, the needle lines itself up at right angles to a radius drawn from the conductor. Since the compass needle is a small magnet, with lines of force extending from south to north inside the metal, it will turn until the direction of these lines agrees with the direction of the lines of force around the conductor. As the direction of the compass needle is moved around the conductor, it will maintain itself in a position at right angles to the conductor, indicating that the magnetic field around a current carrying conductor is circular. As shown in View B of *Figure 10-16*, when the direction of current flow through the conductor is reversed, the compass needle will point in the opposite direction, indicating the magnetic field has reversed its direction.

A method used to determine the direction of the lines of force when the direction of the current flow is known, is shown in *Figure 10-17*. If the conductor is grasped in the left hand, with the thumb pointing in the direction of current flow, the fingers will be wrapped around the conductor in the same direction as the lines of the magnetic field. This is called the left-hand rule.

Although it has been stated that the lines of force have direction, this should not be construed to mean that the lines have motion in a circular direction around the conductor. Although the lines of force tend to act in a clockwise or counterclockwise direction, they are not

revolving around the conductor. Since current flows from negative to positive, many illustrations indicate current direction with a dot symbol on the end of the conductor when the electrons are flowing toward and a plus sign when the current is flowing away from the observer. (*Figure 10-18*)
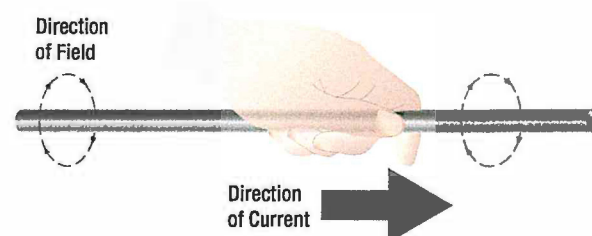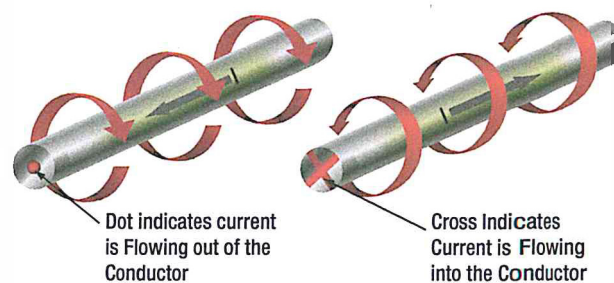

Figure 10-17. Left-hand rule.

Dot indicates current is Flowing out of the Conductor

Cross Indicates Current is Flowing into the Conductor

Figure 10-18. Direction of current flow in a conductor.

MAGNETISM

When a wire is bent into a loop and an electric current flows through it, the left-hand rule remains valid. (*Figure 10-19*)

If the wire is coiled into two loops, many of the lines of force become large enough to include both loops Lines of force go through the loops in the same direction, circle around the outside of the two coils, and come in at the opposite end. (*Figure 10-20*)

When a wire contains many such loops, it is called a coil. The lines of force form a pattern through all the loops, causing a high concentration of flux lines through the center of the coil. (*Figure 10-21*)

In a coil made from loops of a conductor, many of the lines of force are dissipated between the loops of the coil. By placing a soft iron bar inside the coil, the lines of force will be concentrated in the center of the coil, since soft iron has a greater permeability than air. (*Figure 10-22*)

This combination of an iron core in a coil of wire loops, or turns, is called an electromagnet, since the poles (ends) of the coil possess the characteristics of a bar magnet. The addition of the soft iron core does two things for the current carrying coil. First, the magnetic flux is increased, and second, the flux lines are more highly concentrated. When direct current flows through the coil, the core will become magnetized with the same polarity (location of north and south poles) as the coil would have without the core. If the current is reversed, the polarity will also be reversed.

The polarity of the electromagnet is determined by the left-hand rule in the same manner as the polarity of the coil without the core was determined. If the coil is grasped in the left hand in such a manner that the fingers curve around the coil in the direction of electron flow (minus to plus), the thumb will point in the direction of the north pole. (*Figure 10-23*)

The strength of the magnetic field of the electromagnet can be increased by either increasing the flow of current or the number of loops in the wire. Doubling the current flow approximately doubles the strength of the field,

Figure 10-19. Magnetic field around a looped conductor.
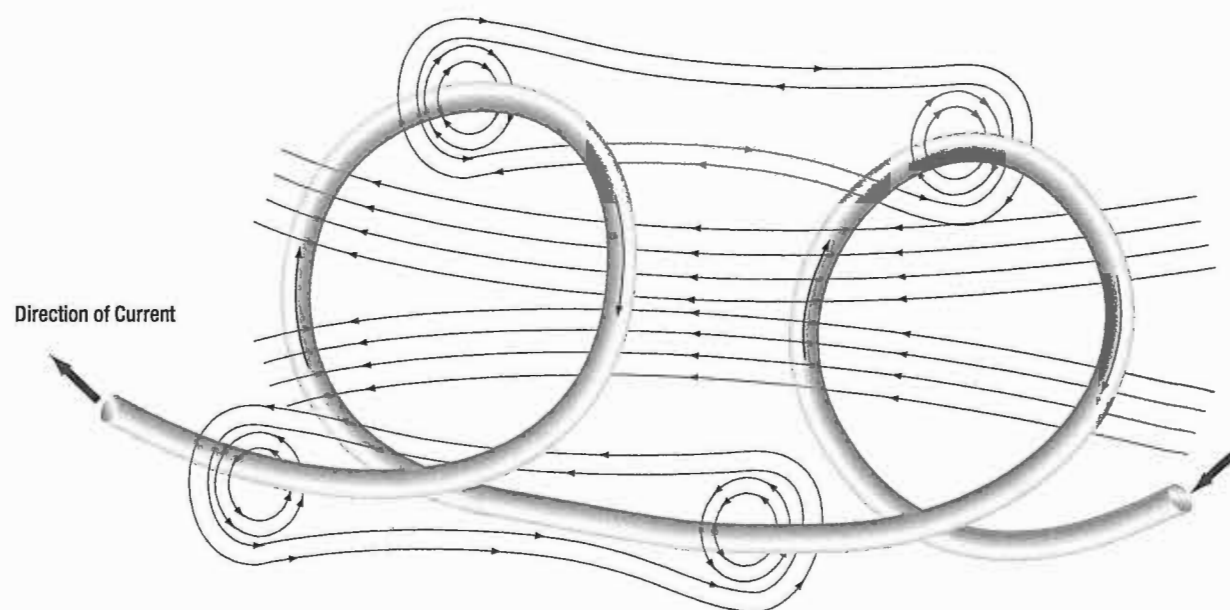

Direction of Current

Figure 10-20. Magnetic field around a conductor with two loops.
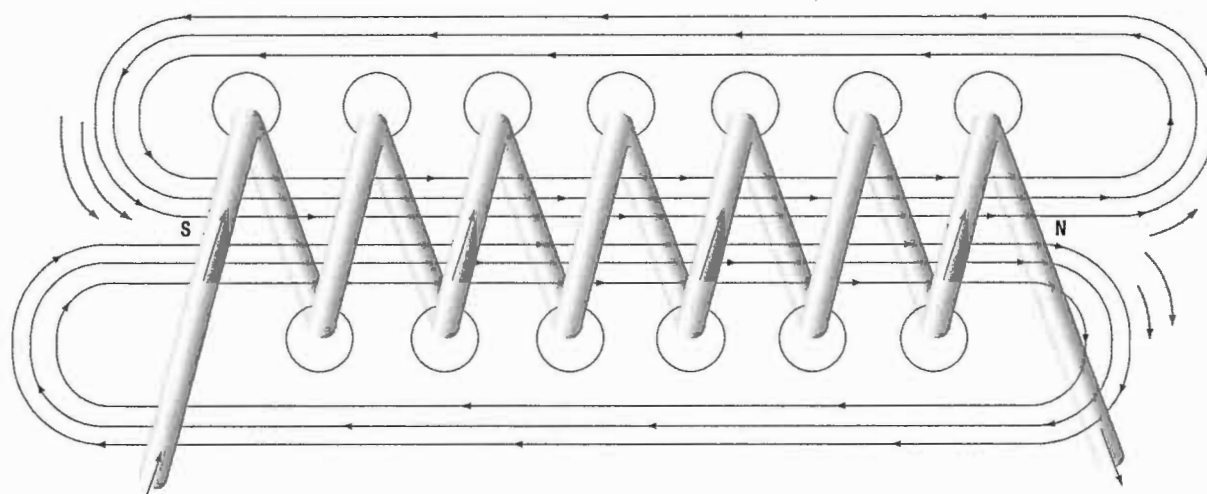
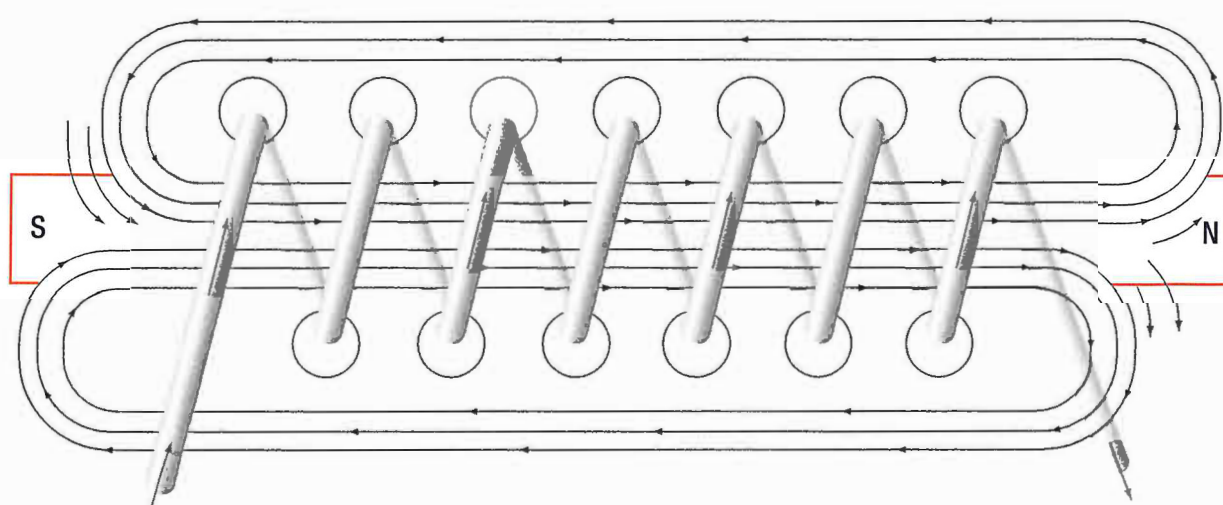Figure 10-21. Magnetic field of a coil.
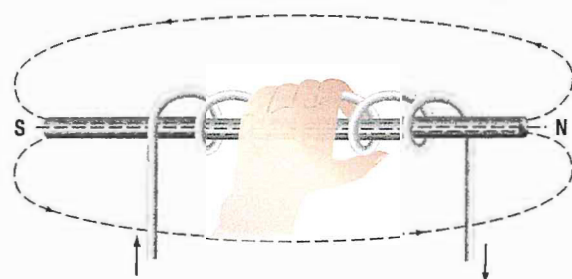

Figure 10-22. Electromagnet.

Figure 10-23. Left-hand rule applied to a coil.

and in a similar manner, doubling the number of loops approximately doubles magnetic field strength. Finally, the type metal in the core is a factor in the field strength of the electromagnet.

A soft iron bar is attracted to either pole of a permanent magnet and, likewise, is attracted by a current carrying coil. The lines of force extend through the soft iron, magnetizing it by induction and pulling the iron bar toward the coil. If the bar is free to move, it will be drawn into the coil to a position near the center where the field is strongest. (*Figure 10-24*)

Electromagnets are used in electrical instruments, motors, generators, relays, and other devices. Some electromagnetic devices operate on the principle that an iron core held away from the center of a coil will be rapidly pulled into a center position when the coil is energized. This principle is used in the solenoid, also called solenoid switch or relay, in which the iron core is spring-loaded off center and moves to complete a circuit when the coil is energized.
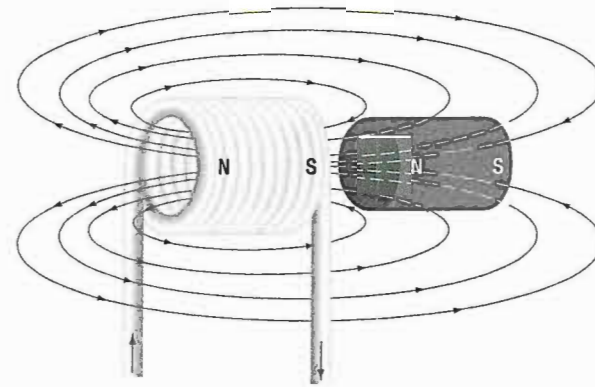

Figure 10-24. Energized coil with an iron core.

Question: 10-1

A _____ always exists between the poles of a magnet.

Question: 10-4

The greater the current flow through a conductor, the _____ the magnetic field that forms around the conductor.

Question: 10-2

When a magnetizing force is applied to a piece of magnetic material, a point is reached where no more lines of force can be induced or introduced. The material is then said to be _____.

Question: 10-5

If the number of loops of conductor in a coil are doubled, the strength of the magnetic field approximately _____.

Question: 10-3

A material that easily passes magnetic flux is said to have high _____.

ANSWERS

Answer: 10-1
magnetic field.

Answer: 10-2
saturated.

Answer: 10-3
permeability.

Answer: 10-4
stronger.

Answer: 10-5
doubles.

ELECTRICAL FUNDAMENTALS

INDUCTANCE/INDUCTOR

SUB-MODULE 11

PART-66 SYLLABUS	LEVELS	
CERTIFICATION CATEGORY →	B1	B2

Sub-Module 11
INDUCTANCE/INDUCTOR
Knowledge Requirements

3.11 – Inductance/Inductor

	B1	B2
Faraday's Law;	2	2

Action of inducing a voltage in a conductor moving in a magnetic field;

Induction principles;

Effects of the following on the magnitude of an induced voltage: magnetic field strength, rate of change of flux, number of conductor turns;

Mutual induction;

The effect the rate of change of primary current and mutual inductance has on induced voltage;

Factors affecting mutual inductance: number of turns in coil, physical size of coil, permeability of coil, position of coils with respect to each other;

Lenz's Law and polarity determining rules;

Back emf, self induction;

Saturation point;

Principle uses of inductors.

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

INDUCTANCE

CHARACTERISTICS OF INDUCTANCE

Michael Faraday discovered that by moving a magnet through a coil of wire, a voltage was induced across the coil. If a complete circuit was provided, then a current was also induced. The amount of induced voltage is directly proportional to the rate of change of the magnetic field with respect to the coil. The simplest of experiments can prove that when a bar magnet is moved through a coil of wire, a voltage is induced and can be measured on a voltmeter. This is commonly known as Faraday's Law or the law of electromagnetic induction, which states:

The induced EMF or electromagnetic force in a closed loop of wire is proportional to the rate of change of the magnetic flux through a coil of wire.

Conversely, current flowing through a coil of wire produces a magnetic field. When this wire is formed into a coil, it then becomes a basic inductor. The magnetic lines of force around each loop or turn in the coil effectively add to the lines of force around the adjoining loops. This forms a strong magnetic field within and around the coil. *Figure 11-1A*, illustrates this idea of a coil of wire strengthening a magnetic field. The magnetic lines of force around adjacent loops are deflected into an outer path when the loops are brought close together. This happens because the magnetic lines of force between adjacent loops are in opposition with each other. The total magnetic field for the two loops is shown in *Figure 11-1B*. As more loops are added close together, the strength of the magnetic field will increase. *Figure 11-1C* illustrates the combined effects of many loops of a coil. The result is a strong electromagnet.

The primary aspect of the operation of a coil is its property to oppose any change in current through it. This property is called inductance. When current flows through any conductor, a magnetic field starts to expand from the center of the wire. As the lines of magnetic force grow outward through the conductor, they induce an EMF in the conductor itself. The induced voltage is always in the direction opposite to the direction of the current flow. The effects of this countering EMF are to oppose the immediate establishment of the maximum current. This effect is only a temporary condition. Once
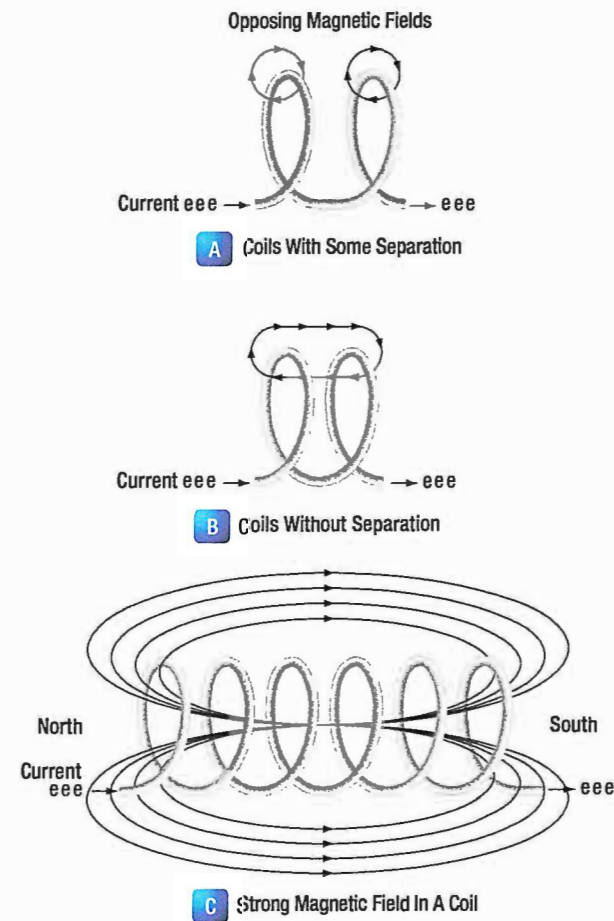

Figure 11-1. Many loops of a coil.

the current reaches a steady value in the conductor, the lines of magnetic force will no longer be expanding and the countering EMF will no longer be present.

At the starting instant, the countering EMF nearly equals the applied voltage, resulting in a small current flow. However, as the lines of force move outward, the number of lines cutting the conductor per second becomes progressively smaller, resulting in a diminished counter EMF. Eventually, the counter EMF drops to zero and the only voltage in the circuit is the applied voltage and the current is at its maximum value.

THE RL TIME CONSTANT

Because the inductor's basic action is to oppose a change in its current, it then follows that the current cannot change instantaneously in the inductor. A certain time is required for the current to make a change from one value to another. The rate at which the current changes is determined by a time constant represented by the greek letter tau (τ). The time constant for the RL circuit is:

$$\tau = \frac{L}{R}$$

Where:

τ = seconds

L = inductance (H)

R = Resistance (Ω)

In a series RL circuit, the current will increase to 63% of its full value in 1 time constant after the circuit is closed. This build up of course is similar to the build up of voltage in a capacitor when charging an RC circuit. Both follow an exponential curve and reach 99% value after the 5th time constant. *Figure 11-2* illustrates this characteristic.

PHYSICAL PARAMETERS

Some of the physical factors that affect inductance are:

1. The number of turns: Doubling the number of turns in a coil will produce a field twice as strong, if the same current is used. General rule, the inductance varies as the square of the number of turns.

2. The cross-sectional area of the coil: The inductance of a coil increases directly as the cross-sectional area of the core increases. Doubling the radius of a coil increases the inductance by a factor of four.

3. The length of a coil: Doubling the length of a coil, while keeping the same number of turns, halves the value of inductance.

4. The core material around which the coil is formed: Coils are wound on either magnetic or nonmagnetic materials. Some nonmagnetic materials include air, copper, plastic, and glass. Magnetic materials include nickel, iron, steel, or cobalt, which have a permeability that provides a better path for the magnetic lines of force and permit a stronger magnetic field.
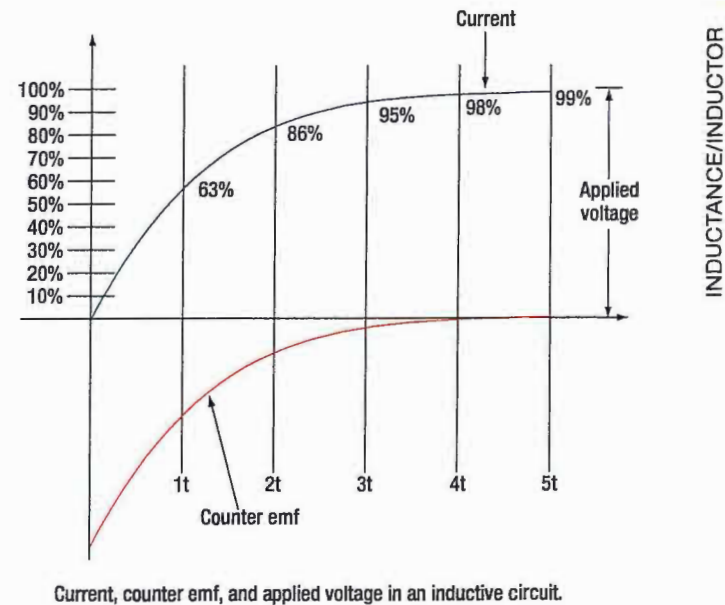

Current, counter emf, and applied voltage in an inductive circuit.

Figure 11-2. Inductor curve.

SELF-INDUCTANCE

The characteristic of self-inductance was summarized by German physicist Heinrich Lenz in 1833 and gives the direction of the induced electromotive force (EMF) resulting from electromagnetic induction. This is commonly known as Lenz's Law, which states: The EMF induced in an electric circuit always acts in such a direction that the current it drives around a closed circuit produces a magnetic field which opposes the change in magnetic flux.

Self inductance is the generation of a voltage in an electric circuit by a changing current in the same circuit. Even a straight piece of wire will have some degree of inductance because current in a conductor produces a magnetic field. When the current in a conductor changes direction, there will be a corresponding change in the polarity of the magnetic field around the conductor. Therefore, a changing current produces a changing magnetic field around the wire. To further intensify the magnetic field, the wire can be rolled into a coil, which is called an inductor. The changing magnetic field around the inductor induces a voltage across the coil. This induced electromotive force is called self-inductance and tends to oppose any change in current within the circuit. This property is usually called inductance and symbolized with the letter L.

MUTUAL INDUCTION

Mutual induction occurs when the varying of a magnetic field in one circuit causes a EMF to be produced in a neighboring circuit due to their proximity to each other. The rate of change of the field as well as the proximity of the circuits to each other determine the influence of the mutual induction.

TYPES OF INDUCTORS

Inductors used in radio can range from a straight wire at UHF to large chokes and transformers used for filtering the ripple from the output of power supplies and in audio amplifiers. *Figure 11-3* shows the schematic symbol for common inductors. Values of inductors range from nano-Henries to tens of Henries.

Inductors are classified by the type of core and the method of winding them. The number of turns in the inductor winding and the core material determine the capacity of the inductor. Cores made of dielectric material like ceramics, wood, paper provide small amounts of stored energy while cores made of ferrite substances have a much higher degree of stored energy.

The core material is usually the most important aspect of the inductors construction. The conductors typically used in the construction of an inductor offer little resistance to the flow of current. However, with the introduction of a core, resistance is introduced in the circuit and the current now builds up in the windings until the resistance of the core is overcome. This buildup is stored as magnetic energy in the core. Depending on the core resistance, the buildup soon reaches a point of magnetic saturation and it can be released when necessary. The most common core materials are: Air, solid ferrite, powdered ferrite, steel, toroid and ferrite toroid.

UNITS OF INDUCTANCE

The Henry is the basic unit of inductance and is symbolized with the letter H. An electric circuit has an inductance of one Henry when current changing at the rate of one ampere per second induces a voltage of one volt into the circuit. In many practical applications, millihenries (mH) and microhenries (μH) are more common units. The typical symbol for an inductor is shown in *Figure 11-3*.
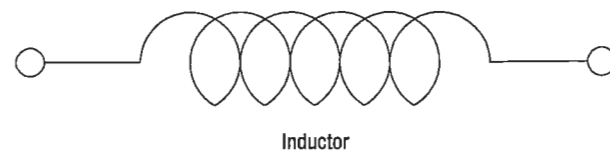

Inductor

Figure 11-3. Typical symbol for an inductor.

INDUCTORS IN SERIES

If we connect two inductors in series as shown in *Figure 11-4*, the same current flows through both inductors and, therefore, both will be subject to the same rate of change of current. When inductors are connected in series, the total inductance LT, is the sum of the individual inductors. The general equation for n number of inductors in series is:
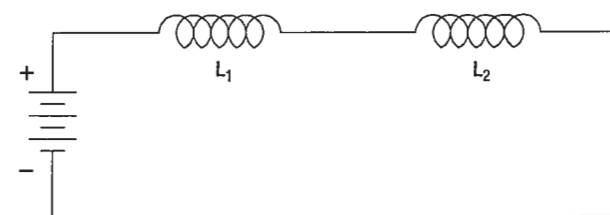
$$L_T = L_1 + L_2 + L_3 + \dots L_N$$

Figure 11-4. Two inductors in series.

INDUCTORS IN PARALLEL

When two inductors are connected in parallel as shown in *Figure 11-5*, each must have the same potential difference between the terminals. When inductors are connected in parallel, the total inductance is less than the smallest inductance. The general equation for n number of inductors in parallel is:

$$L_T = \cfrac{1}{\cfrac{1}{L_1} + \cfrac{1}{L_2} + \cfrac{1}{L_3} + ... \cfrac{1}{L_N}}$$

A simple example would be:

$$L_1 = 10mH, \; L_2 = 5mH, \; L_3 = 2mH$$

$$L_T = \cfrac{1}{\cfrac{1}{10mH} + \cfrac{1}{5mH} + \cfrac{1}{2mH}}$$

$$L_T = \cfrac{1}{0.8mH}$$

$$L_T = 1.25mH$$
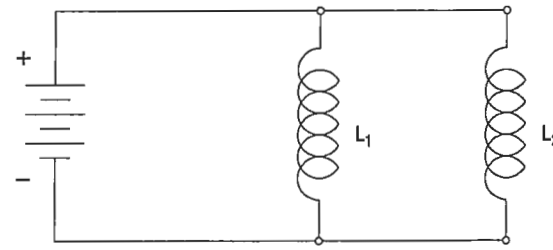
Figure 11-5. Two inductors in parallel.

INDUCTIVE REACTANCE

Alternating current is in a constant state of change; the effects of the magnetic fields are a continuously induced voltage opposition to the current in the circuit. This opposition is called inductive reactance, symbolized by X_L, and is measured in ohms just as resistance is measured. Inductance is the property of a circuit to oppose any change in current and is measured in henries. Inductive reactance is a measure of how much the countering EMF in the circuit will oppose current variations.

The inductive reactance of a component is directly proportional to the inductance of the component and the applied frequency to the circuit. By increasing either the inductance or applied frequency, the inductive reactance will likewise increase and present more opposition to current in the circuit. This relationship is given as:

$$X_L = 2\pi fL$$

Where:
X_L = inductive reactance in ohms
f = frequency in cycles per second
π = 3.141 6

In *Figure 11-6*, an AC series circuit is shown in which the inductance is 0.146 Henry and the voltage is 110 volts at a frequency of 60 cycles per second. Inductive reactance is determined by the following method.

$$X_L = 2\,\pi \times f \times L$$
$$X_L = 6.28 \times 60 \times 0.146$$
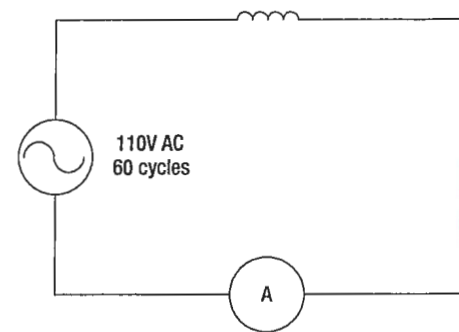

110V AC
60 cycles

A

Figure 11-6. AC circuit containing inductance.

To find current:

In any circuit where there is only resistance, the expression for the relationship of voltage and current is given by Ohm's law: $I = \frac{E}{R}$. Similarly, when there is inductance in an AC circuit, the relationship between voltage and current can be expressed as:

$$\text{Current} = \frac{\text{Voltage}}{\text{Reactance}} \text{ or } I = \frac{E}{X_L}$$

Where:
X_L = inductive reactance of the circuit in ohms.

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

$$I = \frac{110}{55}$$

$$I = 2 \text{ amperes}$$

In AC series circuits, inductive reactances are added like resistances in series in a DC circuit. (*Figure 11-7*) Thus, the total reactance in the illustrated circuit equals the sum of the individual reactances. The total reactance of inductors connected in parallel is found the same way as the total resistance in a parallel circuit. (*Figure 11-8*) Thus, the total reactance of inductances connected in parallel, as shown, is expressed as:

$$(X_L)T = \frac{1}{\dfrac{1}{(X_L)_1} + \dfrac{1}{(X_L)_2} + \dfrac{1}{(X_L)_3}}$$
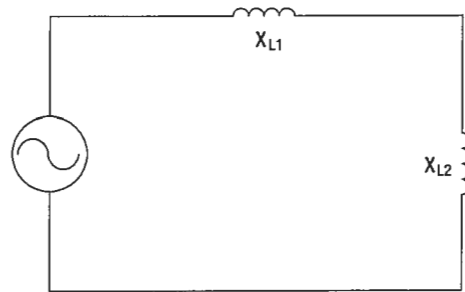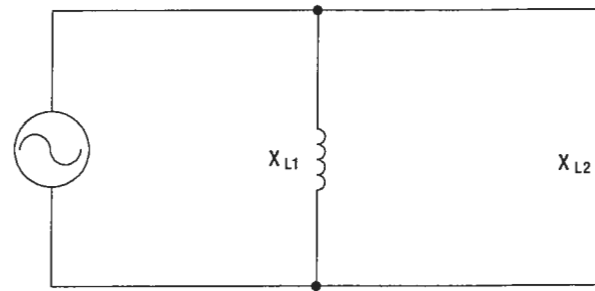

Figure 11-7. Inductances in series.

Figure 11-8. Inductances in parallel.

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Question: 11-1

The induced emf or electromotive force in a closed loop of wire is proportional to the _____ of the magnetic flux through the wire.

Question: 11-4

What is the general equation for inductors in a parallel circuit?

Question: 11-2

The primary effect of a coil is its property to oppose any change in current through it. This property is called
   A. resistance.
   B. inductance.
   C. capacitive reactance.

Question: 11-5

The opposition offered by a coil to the flow of alternating current is called _____.
(disregard resistance)
   A. impedance.
   B. reluctance.
   C. inductive reactance.

Question: 11-3

Name three physical factors that affect inductance.

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ANSWERS

Answer: 11-1
rate of change.

Answer: 11-4
$$L_T = \cfrac{1}{\cfrac{1}{L_1} + \cfrac{1}{L_2} + \cfrac{1}{L_3} + ... \cfrac{1}{L_N}}$$

Answer: 11-2
B.

Answer: 11-5
C.

Answer: 11-3
The number of turns.
The cross sectional area of the coil.
The length the coil.
The core material around which the coil is formed.

ELECTRICAL FUNDAMENTALS

DC MOTOR/GENERATOR THEORY

SUB-MODULE 12

PART-66 SYLLABUS LEVELS		
CERTIFICATION CATEGORY →	**B1**	**B2**

Sub-Module 12
DC MOTOR/GENERATOR THEORY
Knowledge Requirements

3.12 - DC Motor/Generator Theory

	B1	B2
Basic motor and generator theory;	2	2

Construction and purpose of components in DC generator;

Operation of, and factors affecting output and direction of current flow in DC generators;

Operation of, and factors affecting output power, torque, speed and direction of rotation of DC motors;

Series wound, shunt wound and compound motors;

Starter Generator construction.

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

DC GENERATORS AND CONTROLS

DC generators transform mechanical energy into electrical energy. As the name implies, DC generators produce direct current and are typically found on light aircraft. In many cases, DC generators have been replaced with DC alternators.

Both devices produce electrical energy to power the aircraft's electrical loads and charge the aircraft's battery. Even though they share the same purpose, the DC alternator and DC generator are very different. DC generators require a control circuit in order to ensure the generator maintains the correct voltage and current for the current electrical conditions of the aircraft. Typically, aircraft generators maintain a nominal output voltage of approximately 14 volts or 28 volts.

GENERATORS

The principles of electromagnetic induction are key to understanding generator operation. When lines of magnetic force are cut by a conductor passing through them, voltage is induced in the conductor. The strength of the induced voltage is dependent upon the speed of the conductor and the strength of the magnetic field. If the ends of the conductor are connected to form a complete circuit, a current is induced in the conductor. The conductor and the magnetic field make up an elementary generator.

This simple generator is illustrated in *Figure 12-1*, together with the components of an external generator circuit which collect and use the energy produced by the simple generator. The loop of wire (*A and B of Figure 12-1*) is arranged to rotate in a magnetic field. When the plane of the loop of wire is parallel to the magnetic lines of force, the voltage induced in the loop causes a current to flow in the direction indicated by the arrows in *Figure 12-1*. The voltage induced at this position is maximum, since the wires are cutting the lines of force at right angles and are thus cutting more lines of force per second than in any other position relative to the magnetic field.

As the loop approaches the vertical position shown in *Figure 12-2*, the induced voltage decreases because both sides of the loop (*A and B*) are approximately parallel to the lines of force and the rate of cutting is reduced. When the loop is vertical, no lines of force are cut since

the wires are momentarily traveling parallel to the magnetic lines of force, and there is no induced voltage.

As the rotation of the loop continues, the number of lines of force cut increases until the loop has rotated an additional 90° to a horizontal plane. As shown in *Figure 12-3*, the number of lines of force cut and the induced voltage once again are maximum. The direction of cutting, however, is in the opposite direction to that occurring in *Figures 12-1* and *12-2*, so the direction (polarity) of the induced voltage is reversed.
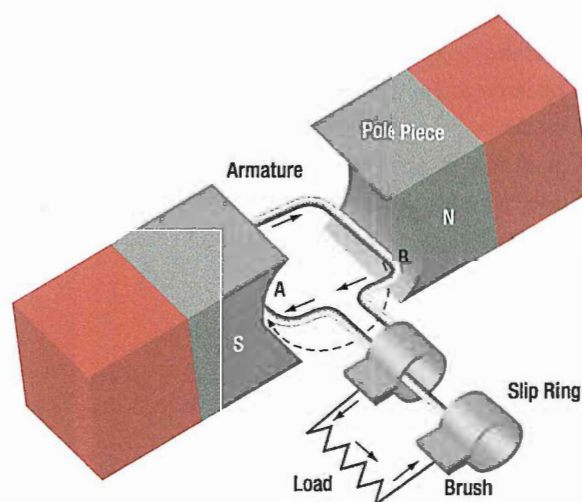

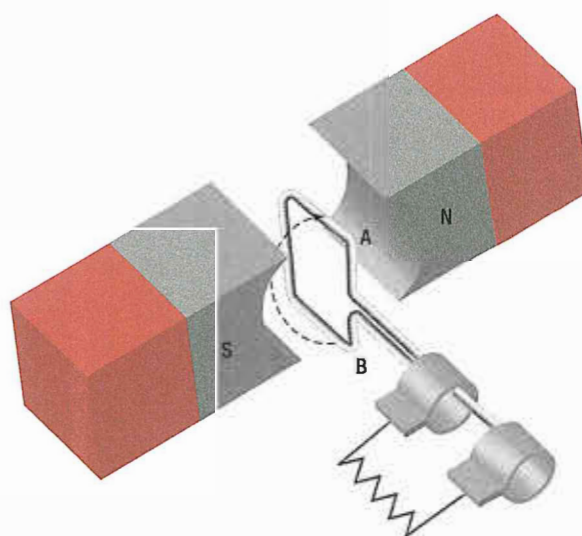Figure 12-1. Inducing maximum voltage in an elementary generator.

Figure 12-2. Inducing minimum voltage in an elementary generator.

As rotation of the loop continues, the number of lines of force having been cut again decreases, and the induced voltage becomes zero at the position shown in *Figure 12-4*, since the wires A and B are again parallel to the magnetic lines of force.

These principles show that voltage is induced in the armature of a generator throughout the entire 360° rotation of the conductor. The armature is the rotating portion of a DC generator. As shown, the voltage being induced is AC. (*Figure 12-5*)

Since the conductor loop is constantly rotating, some means must be provided to connect this loop of wire to the electrical loads. As shown in *Figure 12-6*, slip rings

Figure 12-5. Output of an elementary generator.
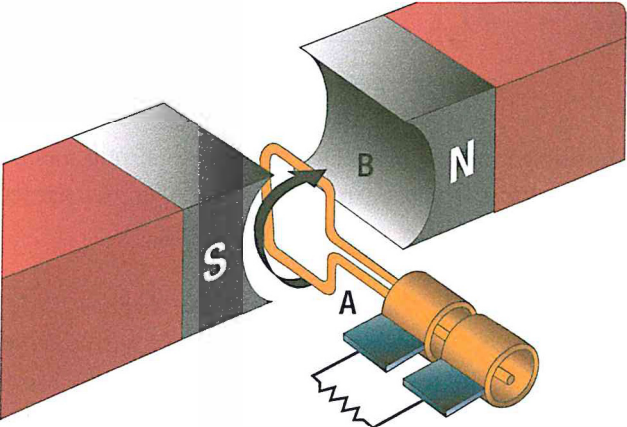
Figure 12-6. Generator slip rings and loop rotate; brushes are stationary.

and brushes can be used to transfer the electrical energy from the rotating loop to the stationary aircraft loads. The slip rings are connected to the loop and rotate; the brushes are stationary and allow a current path to the electrical loads. The slip rings are typically a copper material and the brushes are a soft carbon substance.

It is important to remember that the voltage being produced by this basic generator is AC, and AC voltage is supplied to the slip rings. Since the goal is to supply DC loads, some means must be provided to change the AC voltage to a DC voltage. Generators use a modified slip ring arrangement, known as a commutator, to change the AC produced in the generator loop into a DC voltage. The action of the commutator allows the generator to produce a DC output.

By replacing the slip rings of the basic AC generator with two half cylinders (the commutator), a basic DC generator is obtained. In *Figure 12-7*, the red side of the coil is connected to the red segment and the amber side of the coil to the amber segment. The segments are insulated from each other. The two stationary brushes are placed on opposite sides of the commutator and are so mounted that each brush contacts each segment of the

Figure 12-3. Inducing maximum voltage in the opposite direction.

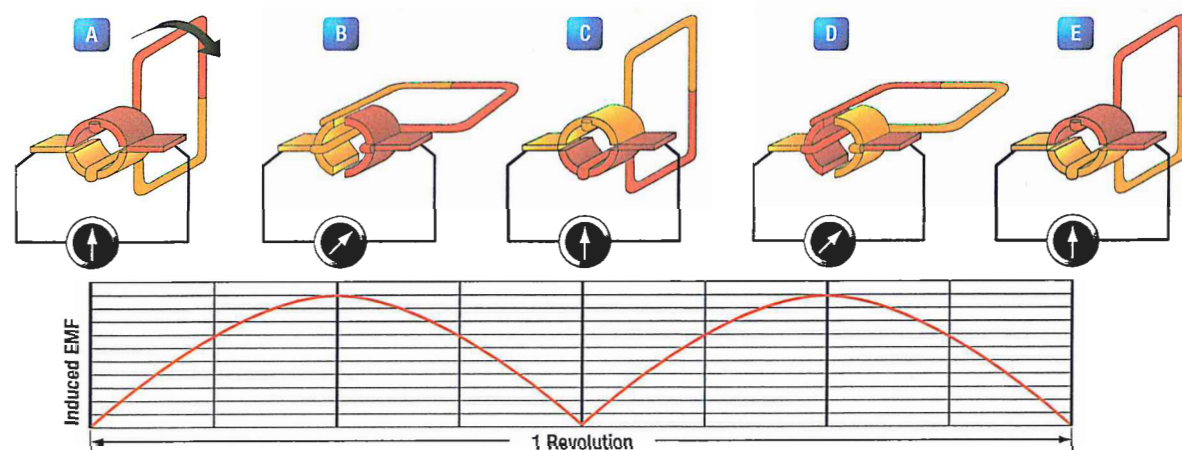Figure 12-4. Inducing a minimum voltage in the opposite direction.

Figure 12-7. A two-piece slip ring, or commutator, allows brushes to transfer current that flows in a single direction (DC).

commutator as the commutator revolves simultaneously with the loop. The rotating parts of a DC generator (coil and commutator) are called an armature.

As seen in the very simple generator of *Figure 12-7*, as the loop rotates the brushes make contact with different segments of the commutator. In positions A, C, and E, the brushes touch the insulation between the brushes; when the loop is in these positions, no voltage is being produced. In position B, the positive brush touches the red side of the conductor loop. In position D, the positive brush touches the amber side of the armature conductor. This type of connection reversal changes the AC produced in the conductor coil into DC to power the aircraft. An actual DC generator is more complex, having several loops of wire and commutator segments.
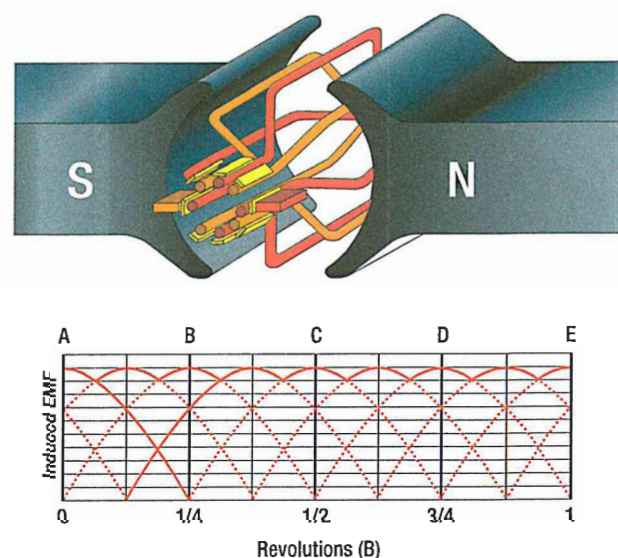
Because of this switching of commutator elements, the red brush is always in contact with the coil side moving downward, and the amber brush is always in contact with the coil side moving upward. Though the current actually reverses its direction in the loop in exactly the same way as in the AC generator, commutator action causes the current to flow always in the same direction through the external circuit or meter. The voltage generated by the basic DC generator in *Figure 12-7* varies from zero to its maximum value twice for each revolution of the loop. This variation of DC voltage is called ripple and may be reduced by using more loops, or coils, as shown in *Figure 12-8*.

As the number of loops is increased, the variation between maximum and minimum values of voltage is reduced (*Figure 12-8*), and the output voltage of the generator approaches a steady DC value. For each
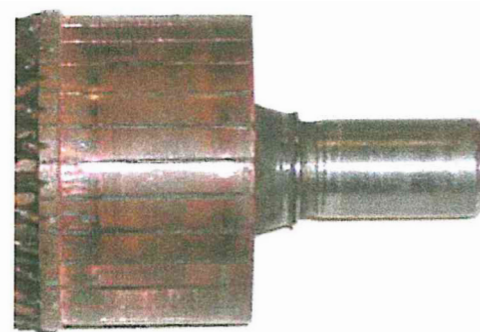
additional loop in the rotor, another two commutator segments is required. A photo of a typical DC generator commutator is shown in *Figure 12-9*.

Figure 12-8. Increasing the number of coils reduces the ripple in the voltage.

Figure 12-9. Typical DC generator commutator.

12.4

Module 03 - Electrical Fundamentals

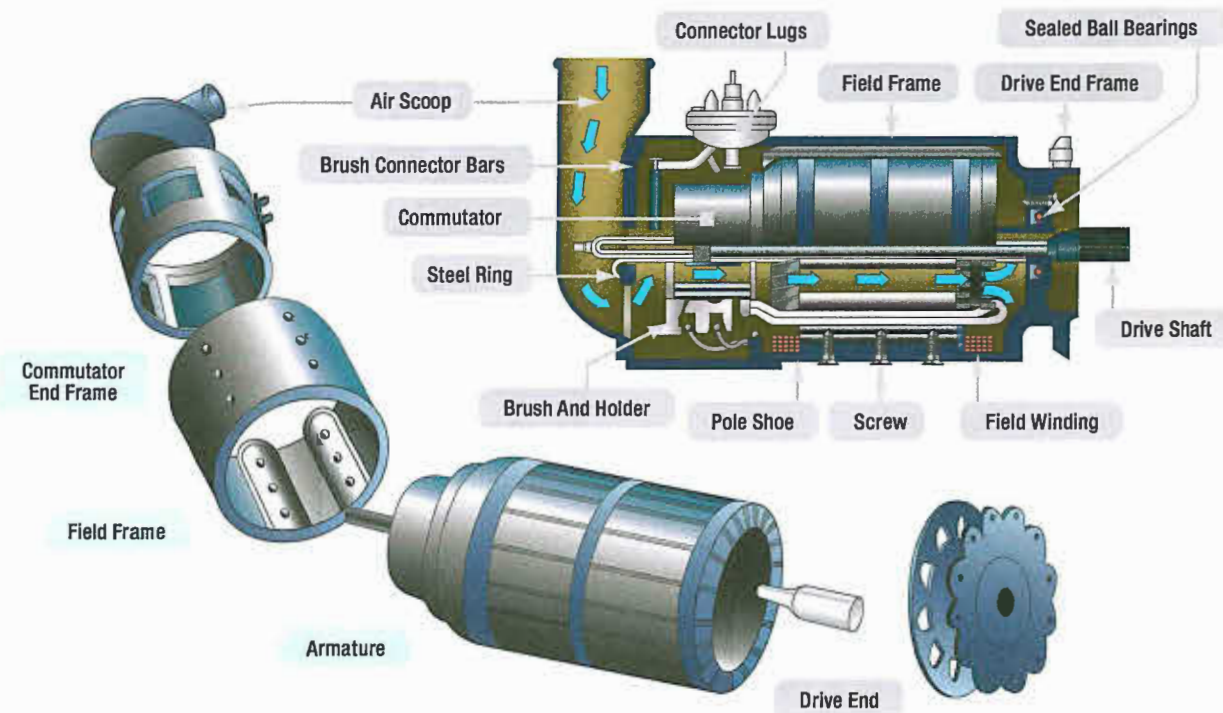# CONSTRUCTION FEATURES OF DC GENERATORS

Figure 12-10. Typical 24-volt aircraft generator.

The major parts, or assemblies, of a DC generator are a field frame, a rotating armature, and a brush assembly. The parts of a typical aircraft generator are shown in *Figure 12-10*.

FIELD FRAME

The frame has two functions: to hold the windings needed to produce a magnetic field, and to act as a mechanical support for the other parts of the generator. The actual electromagnet conductor is wrapped around pieces of laminated metal called field poles. The poles are typically bolted to the inside of the frame and laminated to reduce eddy current losses and serve the same purpose as the iron core of an electromagnet; they concentrate the lines of force produced by the field coils. The field coils are made up of many turns of insulated wire and are usually wound on a form that fits over the iron core of the pole to which it is securely fastened. (*Figure 12-11*)

A DC current is fed to the field coils to produce an electromagnetic field. This current is typically obtained from an external source that provides voltage and current regulation for the generator system. Generator control systems are discussed later in this chapter.
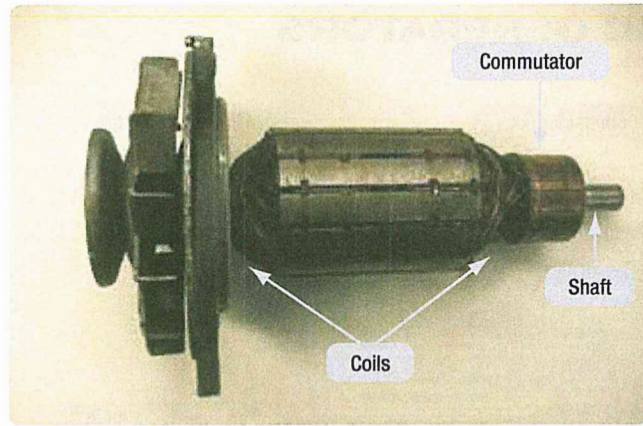

Figure 12-11. Generator field frame.

ARMATURE

The armature assembly of a generator consists of two primary elements: the wire coils (called windings) wound around an iron core and the commutator assembly. The armature windings are evenly spaced around the armature and mounted on a steel shaft. The armature rotates inside the magnetic field produced by the field coils. The core of the armature acts as an iron conductor in the magnetic field and, for this reason, is laminated to prevent the circulation of eddy currents. A typical armature assembly is shown in *Figure 12-12*.

Figure 12-12. A drum-type armature.

Figure 12-13. An eight-section, ring-type armature.

GRAMME-RING ARMATURE

There are two general kinds of armatures: the ring and the drum. *Figure 12-13* shows a ring-type armature made up of an iron core, an eight-section winding, and an eight-segment commutator. The disadvantage of this arrangement is that the windings, located on the inner side of the iron ring, cut few lines of flux. As a result, they have very little voltage induced in them. For this reason, the Gramme-ring armature is not widely used.

DRUM-TYPE ARMATURE

A drum-type armature is shown in *Figure 12-13*. The armature core is in the shape of a drum and has slots cut into it where the armature windings are placed. T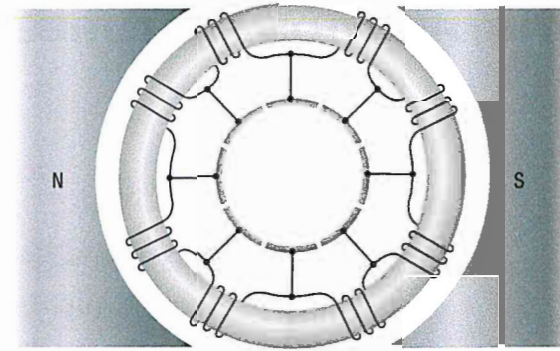he advantage is that each winding completely surrounds the core so that the entire length of the conductor cuts through the magnetic flux. The total induced voltage in this arrangement is far greater than that of the Gramme ring type armature.

Drum-type armatures are usually constructed in one of two methods, each method having its own advantage. The two types of winding methods are the lap winding and the wave winding. Lap windings are used in generators that are designed for high current. The windings are connected in parallel paths and for this reason require several brushes. The wave winding is used in generators that are designed for high voltage outputs. The two ends of each coil are connected to commutator segments separated by the distance between poles. This results in a series arrangement of the coils and is additive of all the induced voltages.

COMMUTATORS

Figure 12-14 shows a cross-sectional view of a typical commutator. The commutator is located at the end of an armature and consists of copper segments divided by a thin insulator. The insulator is often made from the mineral mica. The brushes ride on the surface of the commutator forming the electrical contact between the armature coils and the external circuit. A flexible, braided copper conductor, commonly called a pigtail, connects each brush to the external circuit. The brushes are free to slide up and down in their holders in order to follow any irregularities in the surface of the commutator.

The constant making and breaking of electrical connections between the brushes and the commutator segments, along with the friction between the commutator and the brush, causes brushes to wear out and need regular attention or replacement. For these reasons, the material commonly used for brushes is high-grade carbon. The carbon must be soft enough to prevent undue wear of the commutator and yet hard enough to provide reasonable brush life. Since the contact resistance of carbon is fairly high, the brush must be quite large to provide a current path for the armature windings. The commutator surface is highly polished to reduce friction as much as possible. Oil or grease must never be used on a commutator, and extreme care must be used when cleaning it to avoid marring or scratching the surface.
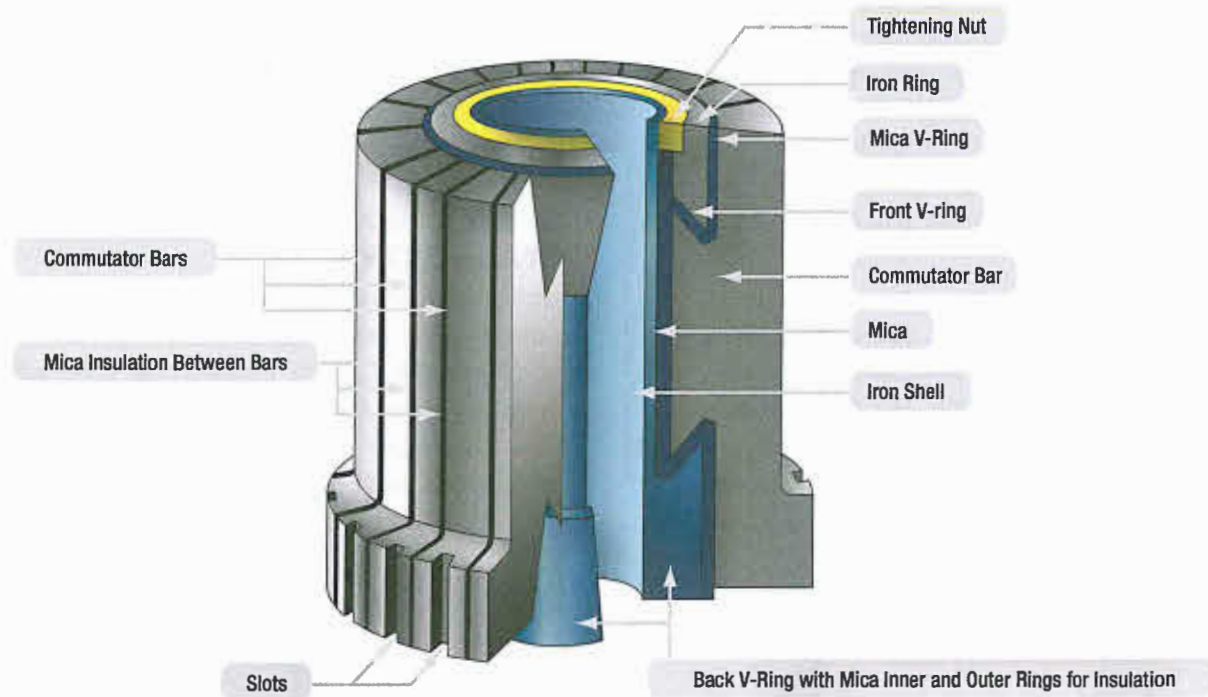
Figure 12-14. Commutator with portion removed to show construction.

Labels in figure:
- Tightening Nut
- Iron Ring
- Mica V-Ring
- Front V-ring
- Commutator Bar
- Mica
- Iron Shell
- Commutator Bars
- Mica Insulation Between Bars
- Slots
- Back V-Ring with Mica Inner and Outer Rings for Insulation

TYPES OF DC GENERATORS

There are three types of DC generator: series wound, parallel (shunt) wound, and series-parallel (or compound wound). The appropriate generator is determined by the connections to the armature and field circuits with respect to the external circuit. The external circuit is the electrical load powered by the generator. In general, the external circuit is used for charging the aircraft battery and supplying power to all electrical equipment being used by the aircraft. As their names imply, windings in series have characteristics different from windings in parallel.

SERIES WOUND DC GENERATORS

The series generator contains a field winding connected in series with the external circuit. (*Figure 12-15*) Series generators have very poor voltage regulation under changing load, since the greater the current is through the field coils to the external circuit, the greater the induced EMF's and the greater the output voltage is. When the aircraft electrical load is increased, the voltage increases; when the load is decreased, the voltage decreases. Since the series wound generator has such poor voltage and current regulation, it is never employed as an airplane generator. Generators in airplanes have field windings, that are connected either in shunt or in compound formats.
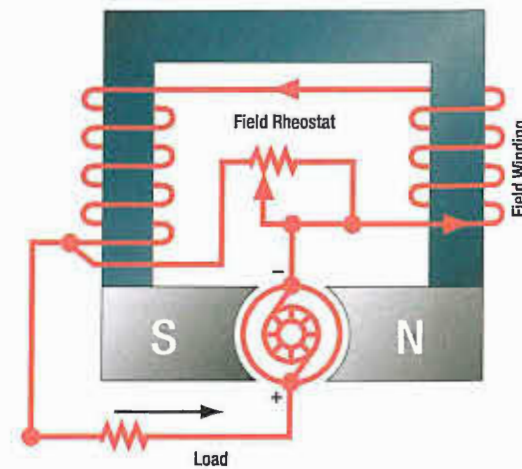

Figure 12-15. Diagram of a series wound generator.

PARALLEL (SHUNT) WOUND DC GENERATORS

A generator having a field winding connected in parallel with the external circuit is called a shunt generator. (*Figure 12-16*) It should be noted that, in electrical terms, shunt means parallel. Therefore, this type of generator could be called either a shunt generator or a parallel generator.

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In a shunt generator, any increase in load causes a decrease in the output voltage, and any decrease in load causes an increase output voltage. This occurs since the field winding is connected in parallel to the load and armature, and all the current flowing in the external circuit passes only through the armature winding (not the field).

As shown in *Figure 12-16A*, the output voltage of a shunt generator can be controlled by means of a rheostat inserted in series with the field windings. As the resistance of the field circuit is increased, the field current is reduced; consequently, the generated voltage is also reduced. As the field resistance is decreased, the field current increases and the generator output increases. In the actual aircraft, the field rheostat would be replaced with an automatic control device, such as a voltage regulator.

COMPOUND WOUND DC GENERATORS

A compound wound generator employs two field windings one in series and another in parallel with the load. (*Figure 12-17*) This arrangement takes advantage of both the series and parallel characteristics described earlier. The output of a compound wound generator is relatively constant, even with changes in the load.
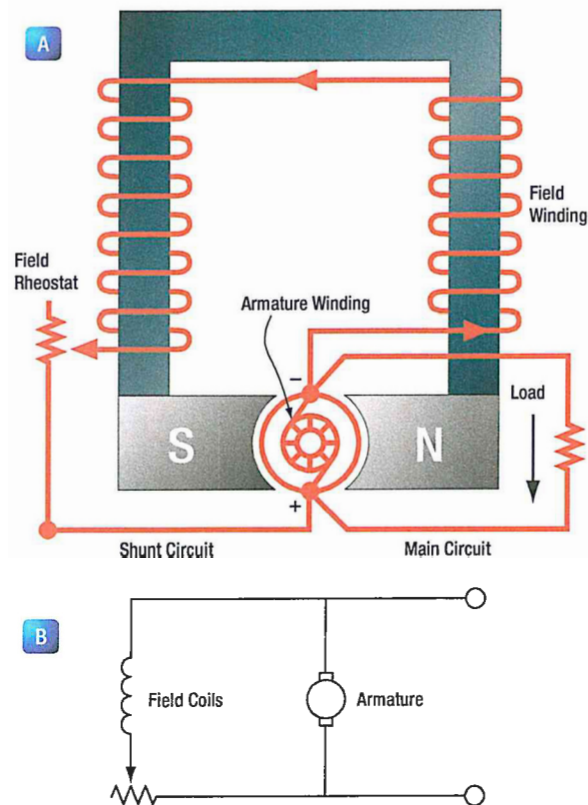

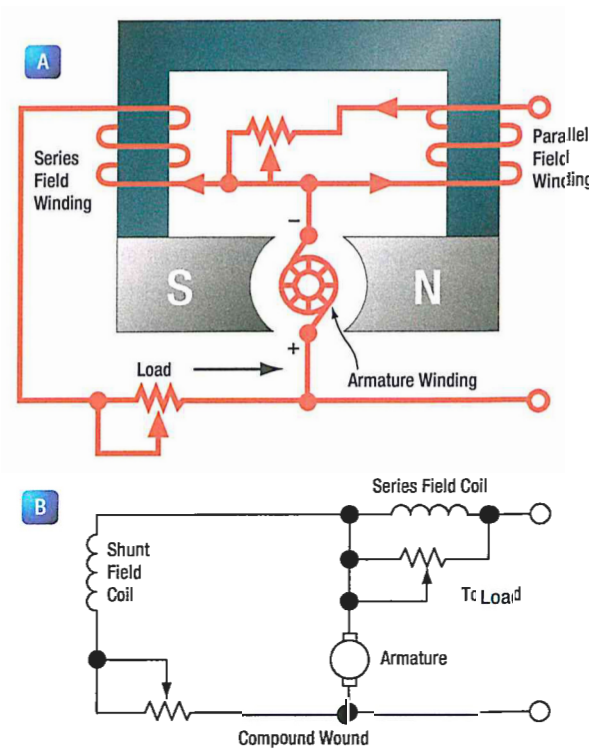Figure 12-16. Shunt wound generator.

Figure 12-17. Compound wound generator.

GENERATOR RATINGS

A DC generator is typically rated for its voltage and power output. Each generator is designed to operate at a specified voltage, approximately 14 or 28 volts. It should be noted that aircraft electrical systems are designed to operate at one of these two voltage values. The aircraft's voltage depends on which battery is selected for that aircraft. Batteries are either 12 or 24 volts when fully charged.

The generator selected must have a voltage output slightly higher than the battery voltage. Hence, the 14 or 28 volt rating is required for aircraft DC generators.

The power output of any generator is given as the maximum number of amperes the generator can safely supply. Generator rating and performance data are

stamped on the nameplate attached to the generator. When replacing a generator, it is important to choose one of the proper ratings.

The rotation of generators is termed either clockwise or counterclockwise, as viewed from the driven end. The direction of rotation may also be stamped on the data plate. It is important that a generator with the correct rotation be used; otherwise, the polarity of the output voltage is reversed. The speed of an aircraft engine varies from idle rpm to takeoff rpm; however, during the major portion of a flight, it is at a constant cruising speed. The generator drive is usually geared to turn the generator between 1⅛ and 1½ times the engine crankshaft speed. Most aircraft generators have a speed at which they begin to produce their normal voltage. Called the "coming in" speed, it is usually about 1 500 rpm.

DC GENERATOR MAINTENANCE

The following information about the inspection and maintenance of DC 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 seals, blow out dirt with compressed air.
4. Condition of generator brushes.
5. Generator operation.
6. Voltage regulator operation.

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 and possible replacement of various components. (*Figure 12-18*)

Manufacturers usually recommend the following procedures to seat brushes that do not make good contact with slip rings or commutators. Lift the brush sufficiently to permit the insertion of a strip of extra-fine 000 (triple aught) grit, or finer, sandpaper under the brush, rough side towards the carbon brush. (*Figure 12-19*)
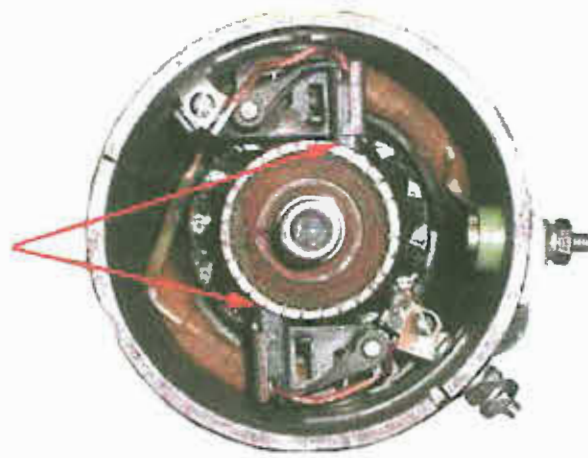

Figure 12-18. Wear areas of commutator and brushes.

Unseated Brush

1/32" to 1/16"

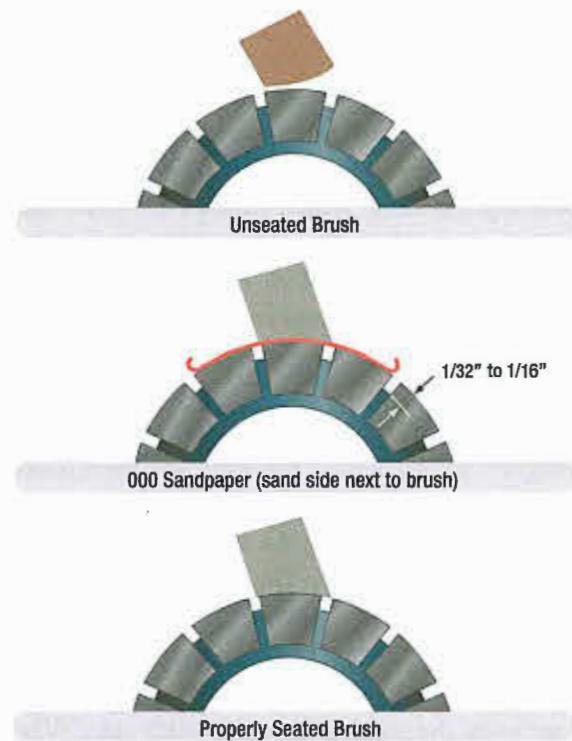000 Sandpaper (sand side next to brush)

Properly Seated Brush

Figure 12-19. Seating brushes with sandpaper.

Pull the 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, raise the brush so it does not ride on the sandpaper. Sand the brush only in the direction of rotation. Carbon dust resulting from brush sanding should be thoroughly cleaned from all parts of the generators after a sanding operation.

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. Under no

circumstances should emery cloth or similar abrasives be used for seating brushes (or smoothing commutators), since they contain conductive materials that cause arcing between brushes and commutator bars. It is important that the brush spring pressure be correct. Excessive pressure causes rapid wear of brushes. Too little pressure, however, allows bouncing of the brushes, resulting in burned and pitted surfaces. The pressure recommended by the manufacturer should be checked by the use of a spring scale graduated in ounces. Brush spring tension on some generators can be adjusted. A spring scale is used to measure the pressure that a brush exerts on the commutator.

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 from the armature, through the brushes, to the external circuit of the generator.

DC MOTORS

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 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 *Figure 12-20*. A wire is located between two permanent magnets. The lines of force in the magnetic field are from the north pole to the south pole. When no current flows, as in *Figure 12-20A*, 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 *Figure 12-*

20B. 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 counterclockwise 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 counterclockwise 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 *Figure 12-20*C. The wire is always pushed away from the side where the field is strongest.

(A)
Wire without current located
in a magnetic field.

(B)
Wire with current and
accompanying field.

(C)
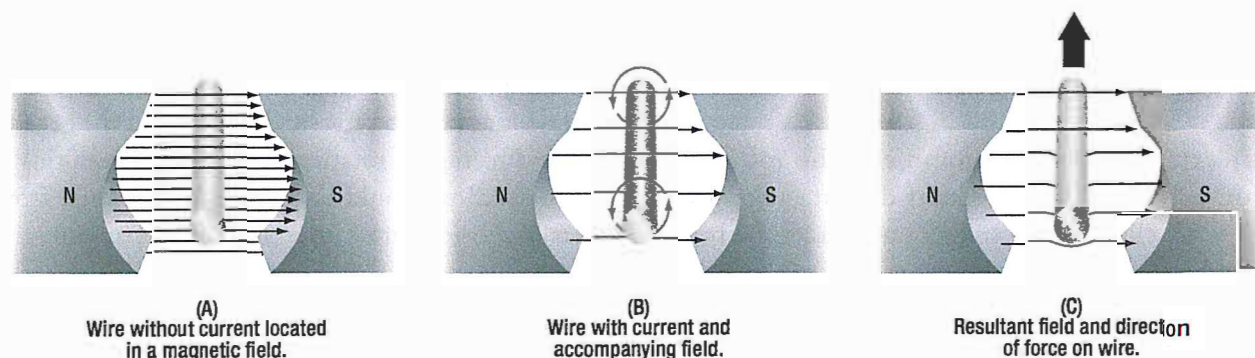Resultant field and direction
of force on wire.

Figure 12-20. 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.

FORCE BETWEEN PARALLEL CONDUCTORS

Two wires carrying current in the vicinity of one another exert a force on each other because of their magnetic fields. An end view of two conductors is shown in *Figure 12-21*. In A, electron flow in both conductors is toward the reader, and the magnetic fields are clockwise around the conductors. Between the wires, the fields cancel because the directions of the two fields oppose each other. The wires are forced in the direction of the weaker field, toward each other. This force is one of attraction. In B, the electron flow in the two wires is in opposite directions.

The magnetic fields are, therefore, clockwise in one and counterclockwise in the other, as shown. The fields reinforce each other between the wires, and the wires are forced in the direction of the weaker field, away from each other. This force is one of repulsion. To summarize: conductors carrying current in the same direction tend to be drawn together; conductors carrying current in opposite directions tend to be repelled from each other.
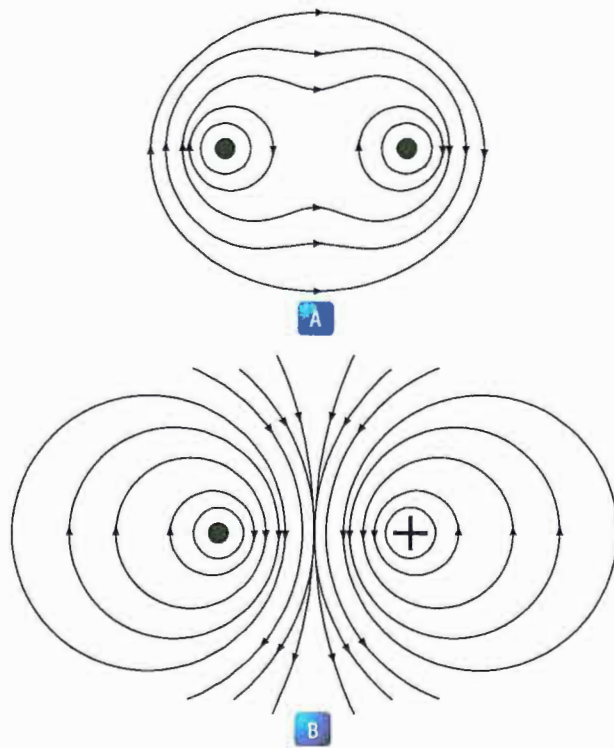

Figure 12-21. Fields surrounding parallel conductors.

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 *Figure 12-22*, current flows inward on side A and outward on side B. The magnetic field about B is clockwise and that about A, counterclockwise. 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 coil will thus rotate until its plane is perpendicular to the magnetic lines between the north and south poles of the magnet, as indicated in *Figure 12-22* 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 *Figure 12-23*, 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.

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 that produces a strong field. Since there is torque acting on each turn, the greater the number of turns on the coil,
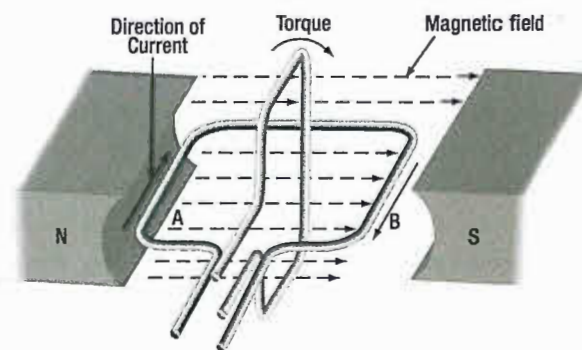

Figure 12-22. Developing a torque.

AIRCRAFT
TECHNICAL
BOOK COMPANY

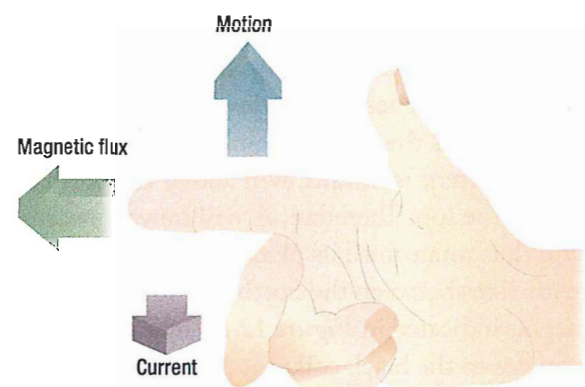the greater the torque. In a coil carrying a steady current located in a uniform magnetic field, the torque will vary at successive positions of rotation, as shown in *Figure 12-24*. When the plane of the coil is parallel to the lines of force, the torque is zero. When its plane cuts the lines of force at right angles, the torque is 100 percent. At intermediate positions, the torque ranges between zero and 100 percent.
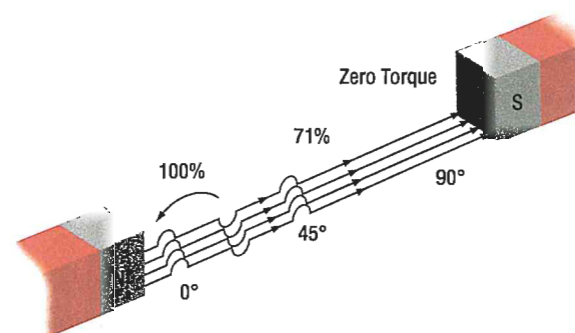

Figure 12-23. Right-hand motor rule.

Figure 12-24. Torque on a coil at various angles of rotation.

BASIC DC 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 DC motor. *Figure 12-25* 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 therefore necessary 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 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 *Figure 12-25*, the coil terminal segments are labeled 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.

POSITION A
When the coil is positioned as shown in *Figure 12-25A*, 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 counterclockwise. The torque at this position of the coil is maximum, since the greatest number of lines of force is being cut by the coil.

POSITION B
When the coil has rotated 90° to the position shown in *Figure 12-25B*, 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 counterclockwise rotation.

POSITION C

On passing through the position shown in *Figure 12-25C*, the torque again reaches maximum.

POSITION D

Continued rotation carries the coil again to a position of minimum torque, as in *Figure 12-25D*. 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 DC 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.
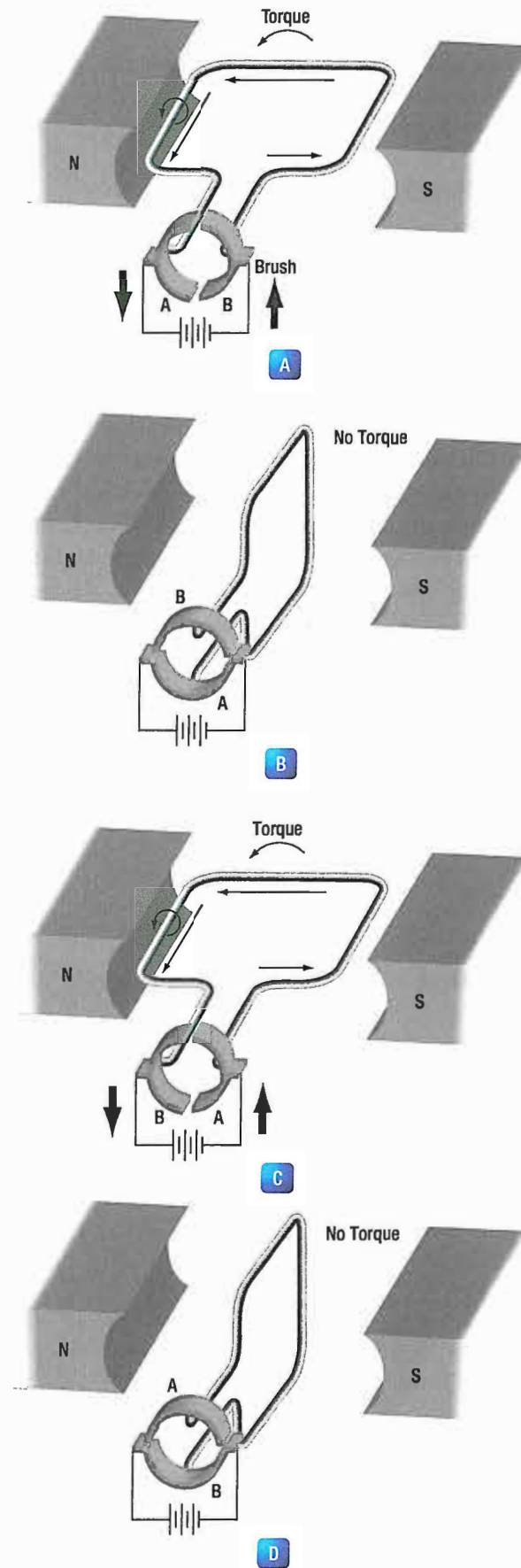
Figure 12-25. Basic DC motor operation.

DC MOTOR CONSTRUCTION

The major parts in a practical motor are the armature assembly, the field assembly, the brush assembly, and the end frame. (*Figure 12-26*)

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 segments in place.

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 brushes are usually small blocks of graphitic 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. Springs hold the brushes firmly against the commutator. A commutator and two types of brushes are shown in *Figure 12-27*.
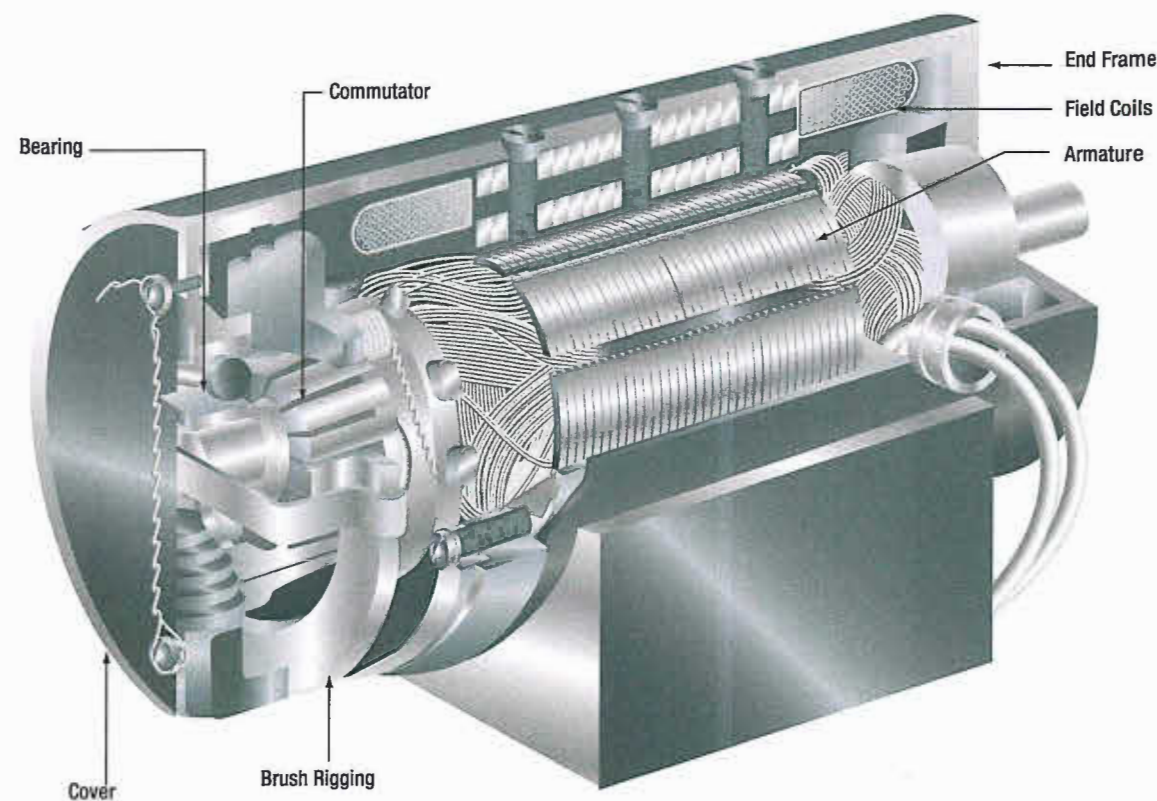

Figure 12-26. Cutaway view of practical DC motor.

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.
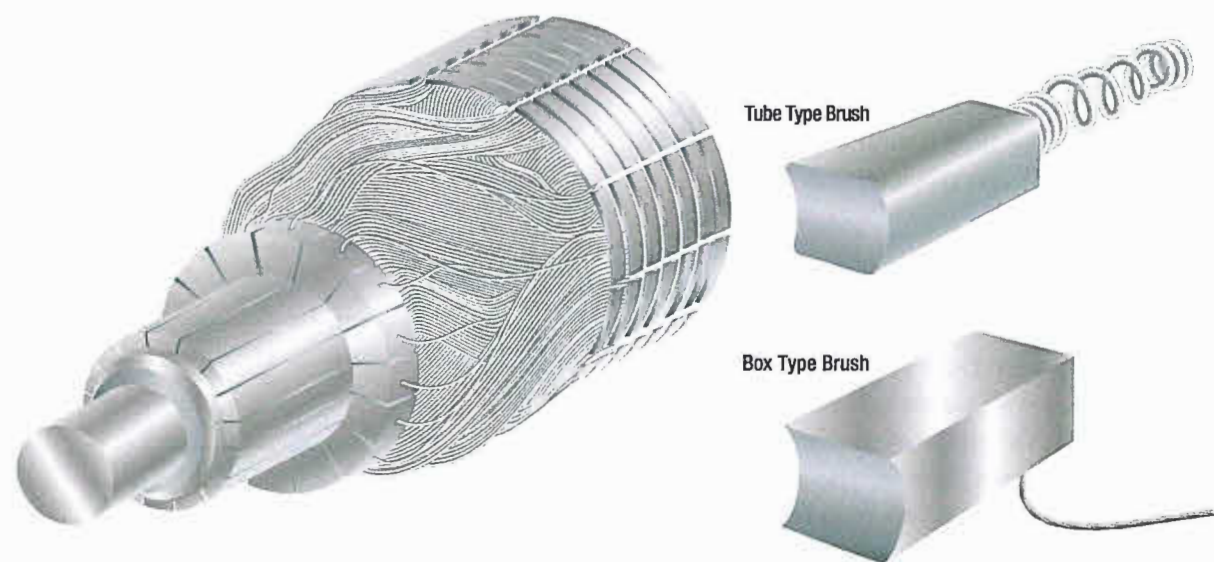
Tube Type Brush

Box Type Brush

Figure 12-27. Commutator and brushes.

TYPES OF DC MOTORS

They differ largely in the method in which their field and armature coils are connected. There are three basic types of DC motors:

1. Series motors,
2. Shunt motors, and
3. Compound motors.

SERIES DC 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 are shown in *Figure 12-28*. 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.

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.

Wire

Commutator
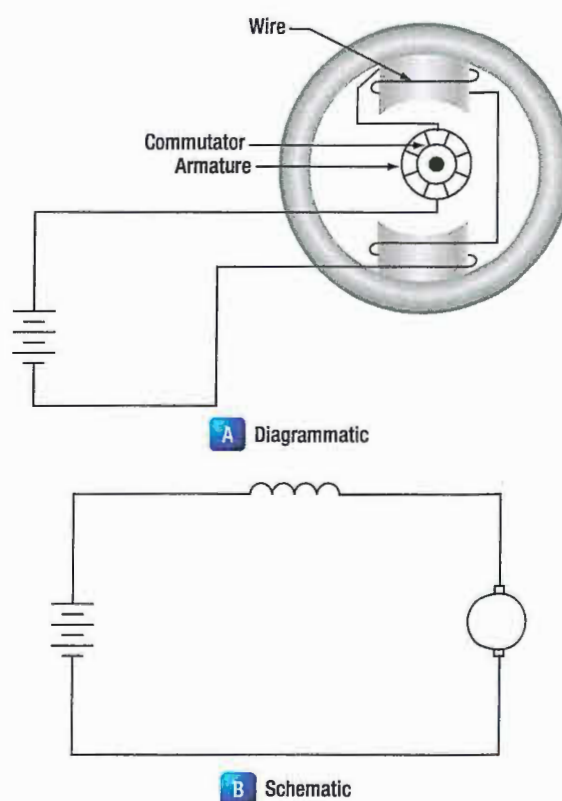Armature

A Diagrammatic

B Schematic

Figure 12-28. Series motor.

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 gear, cowl flaps and wing flaps.

SHUNT DC MOTOR

In the shunt motor, the field winding is connected in parallel or in shunt with the armature winding. (*Figure 12-29*)

The resistance in the field winding is high. Since 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.
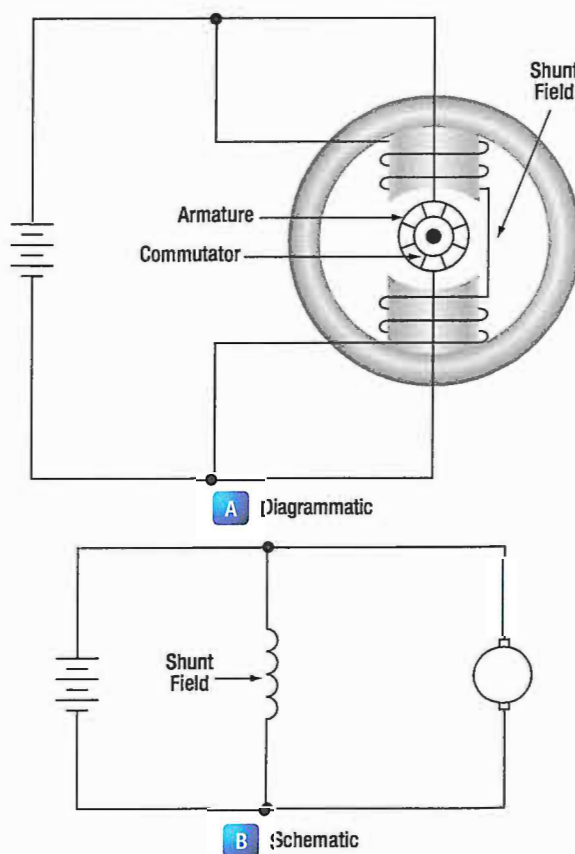

Figure 12-29. Shunt motor.

COMPOUND DC 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 *Figure 12-30*. 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 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 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). 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.
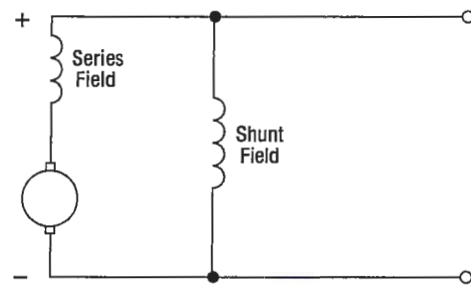
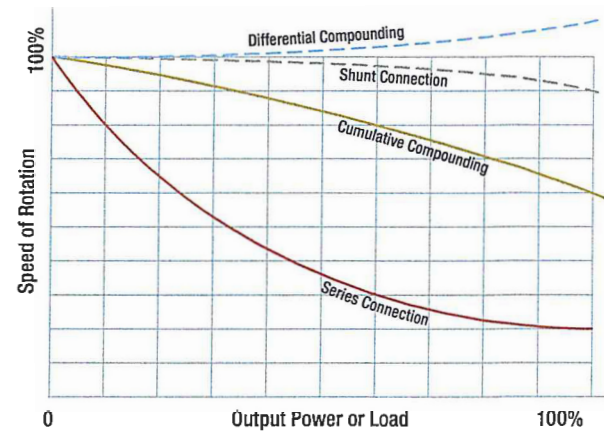Rarely is this type of motor used in aircraft systems. A graph of the variation in speed with changes of load of the various types of DC. (*Figure 12-31*)

Figure 12-30. Compound motor.

Figure 12-31. Load characteristics of DC motors.

COUNTER ELECTROMOTIVE FORCE (EMF)

The armature resistance of a small, 28-volt DC motor is extremely low, about 0.1 ohm. When the armature is connected across the 28-volt source, current through the armature will apparently be

$$I = \frac{E}{R} = \frac{28}{0.1} = 280 \text{ amperes}$$

This high value of current flow is not only impracticable but also unreasonable, especially when the current drain, during normal operation of a motor, is found to be about 4 amperes. This is because the current through a motor armature during operation is determined by more factors than ohmic resistance.

When the armature in a motor rotates in a magnetic field, a voltage is induced in its windings. This voltage is called the back or counter EMF (electromotive force) and is opposite in direction to the voltage applied to the motor from the external source.

Counter EMF opposes the current, which causes the armature to rotate. The current flowing through the armature, therefore, decreases as the counter EMF increases. The faster the armature rotates, the greater the counter EMF. For this reason, a motor connected to a battery may draw a fairly high current on starting, but as the armature speed increases, the current flowing

through the armature decreases. At rated speed, the counter EMF may be only a few volts less than the battery voltage. Then, if the load on the motor is increased, the motor will slow down, less counter EMF will be generated, and the current drawn from the external source will increase.

In a shunt motor, the counter EMF affects only the current in the armature, since the field is connected in parallel across the power source. As the motor slows down and the counter EMF decreases, more current flows through the armature, but the magnetism in the field is unchanged. When the series motor slows down, the counter EMF decreases and more current flows through the field and the armature, thereby strengthening their magnetic fields. Because of these characteristics, it is more difficult to stall a series motor than a shunt motor.

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 as before.

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. *Figure 12-32* 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 upper pole piece. When the switch is placed in the upper position, current flows through 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 *Figure 12-33*, current direction may be reversed through the field but not through the armature.
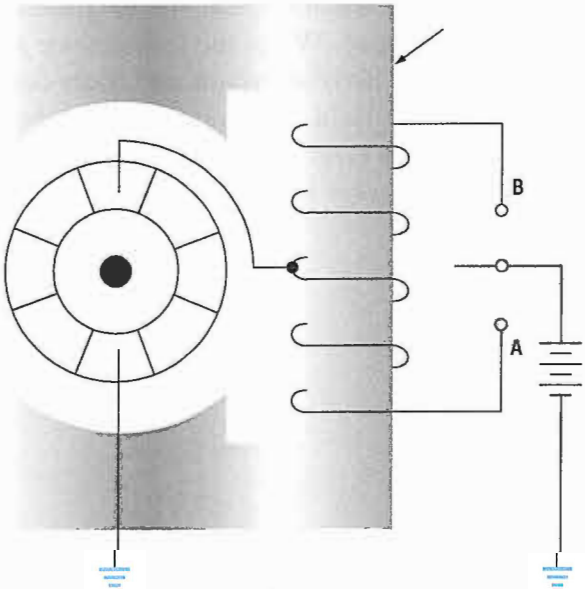

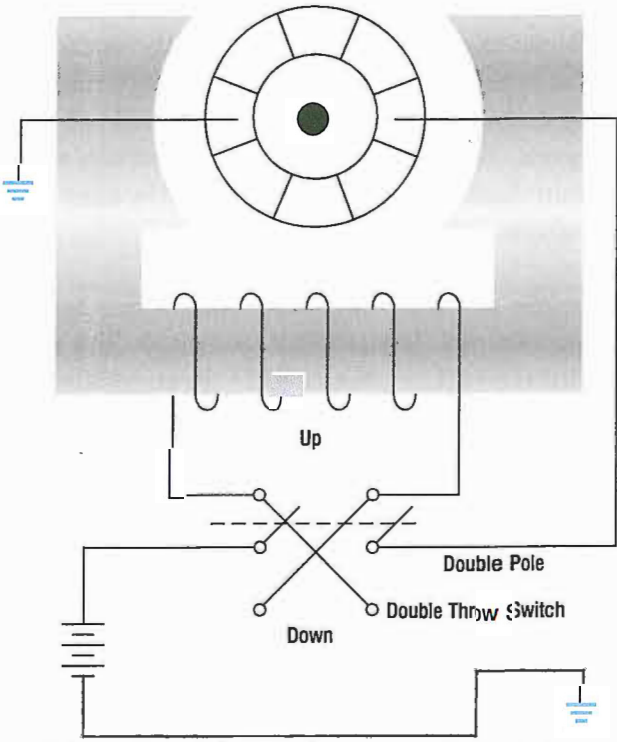Figure 12-32. Split field series motor.

Figure 12-33. Switch method of reversing motor direction.

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.

MOTOR SPEED

Motor speed can be controlled by varying the current in the field windings. When the amount of current flowing through the field windings is increased, the field strength increases, but the motor slows down since a greater amount of counter EMF is generated in the armature windings. When the field current is decreased, the field strength decreases, and the motor speeds up because the counter EMF is reduced. A motor in which speed can be controlled is called a variable speed motor. It may be either a shunt or series motor.

In the shunt motor, speed is controlled by a rheostat in series with the field windings. (*Figure 12-34*) The speed depends on the amount of current that flows through the rheostat to the field windings. To increase the motor speed, the resistance in the rheostat is increased, which decreases the field current. As a result, there is a decrease in the strength of the magnetic field and in the counter EMF. This momentarily increases the armature current and the torque. The motor will then automatically speed up until the counter EMF increases and causes the armature current to decrease to its former value.
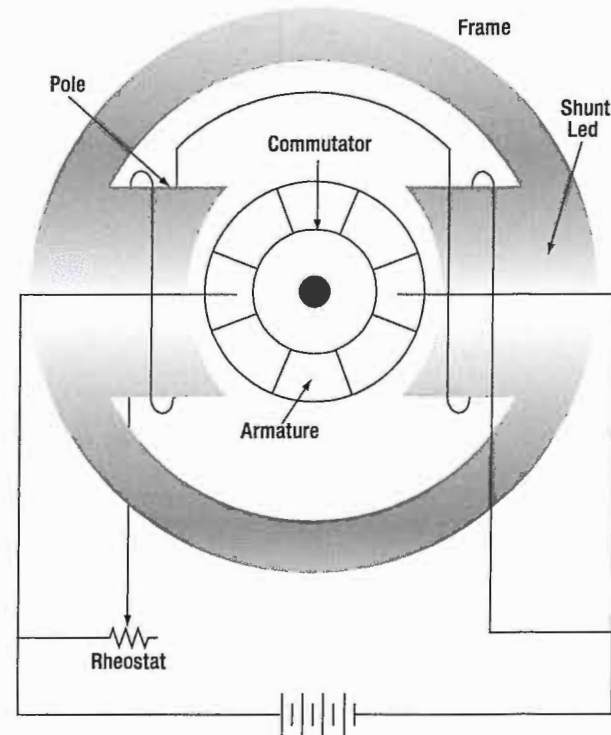
When this occurs, the motor will operate at a higher fixed speed than before. To decrease the motor speed, the resistance of the rheostat is decreased. More current flows through the field windings and increases the strength of the field; then, the counter EMF increases momentarily and decreases the armature current. As a result, the torque decreases and the motor slows down until the counter EMF decreases to its former value; then the motor operates at a lower fixed speed than before.

Figure 12-34. Shunt motor with variable speed control.

In the series motor, the rheostat speed control is connected either in parallel or in series with the motor field, or in parallel with the armature. When the rheostat is set for maximum resistance, the motor speed is increased in the parallel armature connection by a decrease in current. When the rheostat resistance is maximum in the series connection, motor speed is reduced by a reduction in voltage across the motor. For above normal speed operation, the rheostat is in parallel with the series field. Part of the series field current is bypassed and the motor speeds up. (*Figure 12-35*)
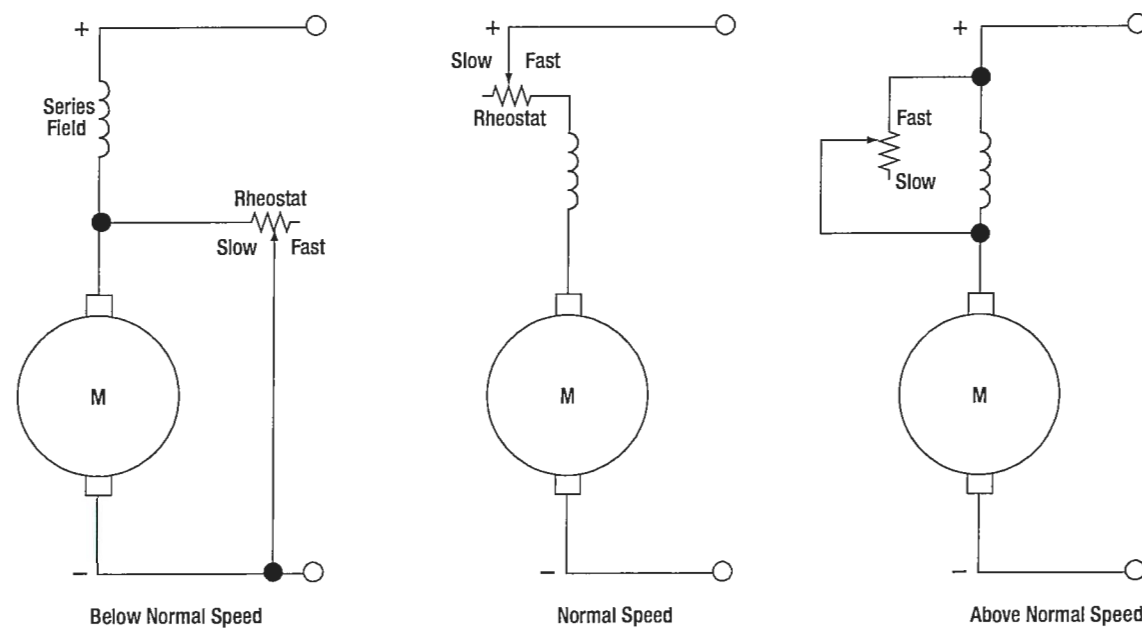
Figure 12-35. Controlling the speed of a series DC motor.

ENERGY LOSSES IN DC 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 square 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 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 (DC 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 EMF 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.

INSPECTION AND MAINTENANCE OF DC 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 specifications 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 brushes from the commutator). Clean dirty commutators with a cloth moistened with the recommended 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.
6. Inspect exposed wiring for evidence of overheating. Replace motor if the insulation on leads or windings are burned, cracked, or brittle.
7. Lubricate only if called for by manufacturer's instructions. 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 manufacturer's instructions covering the unit.

When trouble develops in a DC motor system, check 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 due to an open circuit. A blown fuse usually indicates an accidental ground or short circuit. A low battery usually causes the chattering of the relay switch, which controls the motor. 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.

ELECTRIC STARTING SYSTEMS AND STARTER GENERATOR STARTING SYSTEM

Electric starting systems for gas turbine aircraft are of two general types: direct cranking electrical systems and starter generator systems. Direct cranking electric starting systems are used mostly on small turbine engines, such as Auxiliary Power Units (APUs), and some small turboshaft engines. Many gas turbine aircraft are equipped with starter generator systems. Starter generator starting systems are also similar to direct cranking electrical systems except that after functioning as a starter, they contain a second series of windings that allow it to switch to a generator after the engine has reached a self-sustaining speed. This saves weight and space on the engine.

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. The starter generator unit is basically a shunt generator with an additional heavy series winding. (*Figure 12-36*) This series winding is electrically connected to produce a strong field and a resulting high torque for starting. 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 has four field windings: a series field (C field), a shunt field, a compensating field, and an interpole or commutating winding. (*Figure 12-37*) During starting, the 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 peak amperes is usually required for starting.

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 or interpole windings provide almost sparkless commutation from no load to full load. *Figure 12-38* 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 keep it operating until the engine is rotating fast enough to sustain combustion.

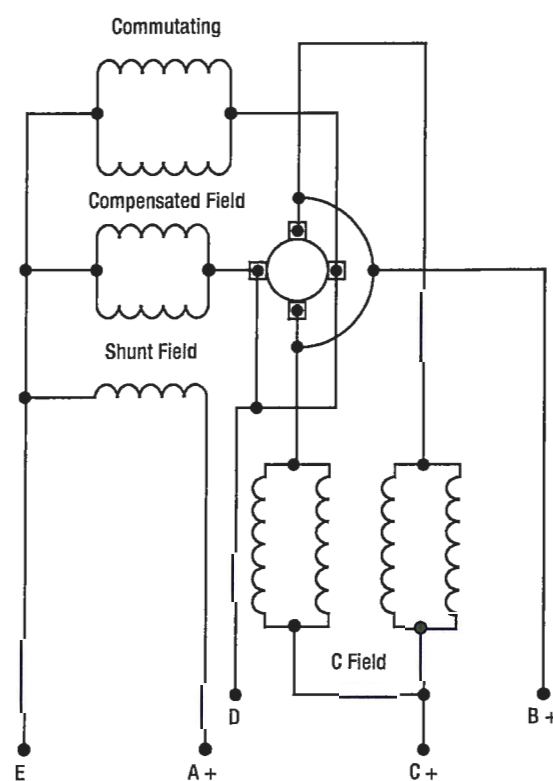Figure 12-36. Typical starter generator.

Figure 12-37. Starter generator internal circuit.

The control block of the undercurrent controller contains two relays. One is the motor relay that controls the input to the starter; the other, the undercurrent relay, controls the operation of the motor relay.

The sequence of operation for the starting system is discussed in the following paragraphs. (*Figure 12-38*) 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: the motor relay, ignition relay, and 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; the battery cutout relay disconnects the battery. 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 completes 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. 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 deenergizing of these relay coils halts the start operation.

After these procedures 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.
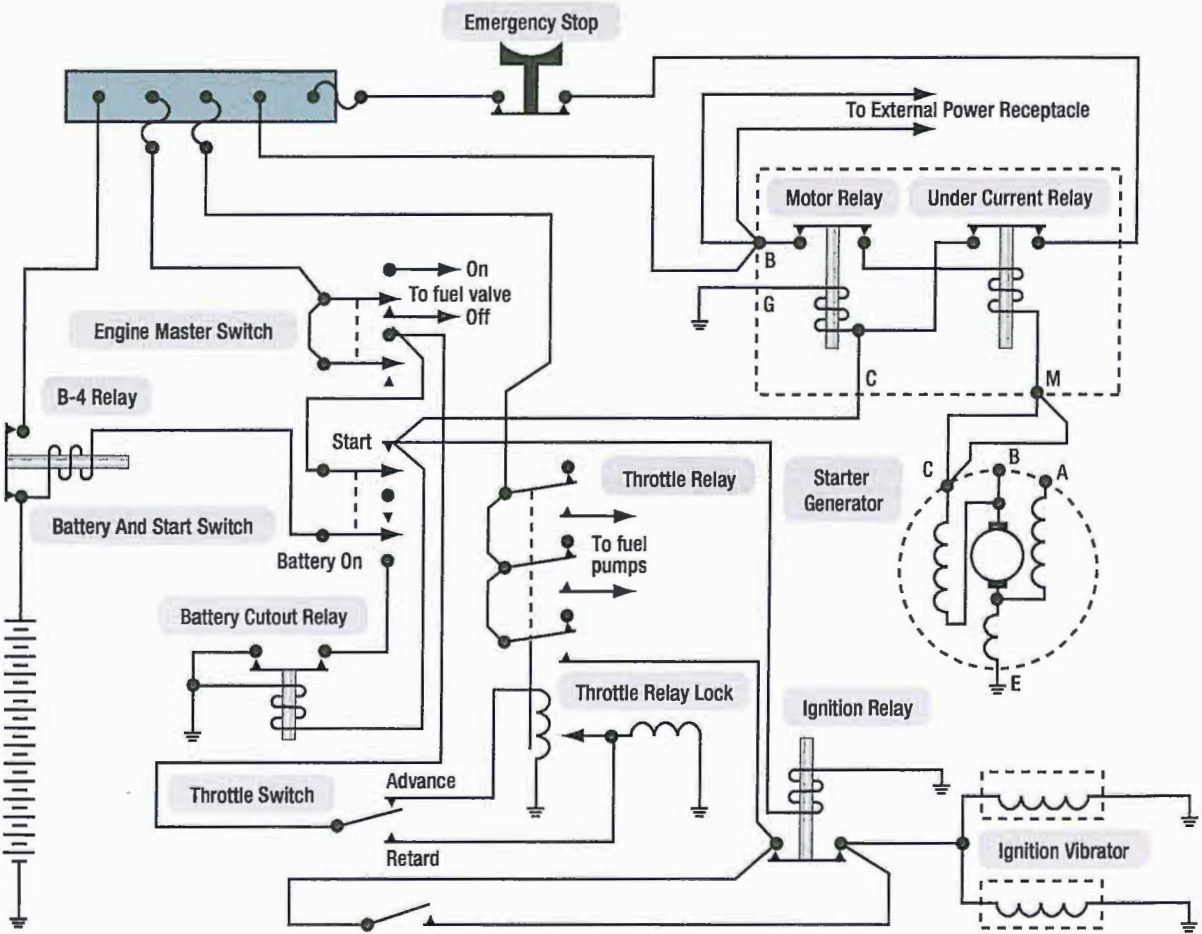
Figure 12-38. Starter generator circuit.

TROUBLESHOOTING A STARTER GENERATOR STARTING SYSTEM

The procedures listed in *Figure 12-39* 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.

Starter Generator Starting System Troubleshooting Procedures		
Probable Cause	**Isolation Procedure**	**Remedy**
Engine does not rotate during start attempt		
• Low supply voltage to the starter • Power switch is defective • Ignition switch in throttle quadrant • Start-lockout relay is defective • Battery series relay is defective • Starter relay is defective • Defective starter • Start lock-in relay defective • Starter drive shaft in component drive gearbox is sheared	• Check voltage of the battery or external power source. • Check switch for continuity. • Check switch for continuity. • Check position of generator control switch. • With start circuit energized, check for 48 volts DC across series relay coil. • With start circuit energized, check for 48 volts DC across starter relay coil. • With start circuit energized, check for proper voltage at the starter. • With start circuit energized, check for 28 volts DC across the relay coil. • Listen for sounds of starter rotation during an attempted start. If the starter rotates but the engine does not, the drive shaft is sheared.	• Adjust voltage of the external power source or charge batteries. • Replace switch. • Replace switch. • Place switch in OFF position. • Replace relay if no voltage is present. • Replace relay if no voltage is present. • Replace the starter if voltage is present. • Replace relay if voltage is not present. • 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.

Figure 12-39. Starter generator starting system troubleshooting procedures.

AIRCRAFT
TECHNICAL
BOOK COMPANY

Question: 12-1

The commutator of a generator

A. Changes direct current produced in the armature into alternating current as it is taken from the armature.

B. Changes alternating current produced in the armature into direct current as it is taken from the armature.

C. Reverses the current in the field coils at the proper time in order to produce direct current.

Question: 12-2

What enables the output voltage of a generator to approach a steady DC value?

Question: 12-3

DC generators are rated for voltage and

_____ .

Question: 12-4

Conductors carrying current in the same direction are _____ to each other.

Question: 12-5

Name the major parts of a DC motor.

Question: 12-6

Which type of motor has a shunt winding and a series winding in its field?

Question: 12-7

What is done to reduce the losses caused by Eddy currents in the core of an armature?

Question: 12-8

One of the main advantages of a starter-generator is _____ .

ANSWERS

Answer: 12-1
B.

Answer: 12-5
Armature assembly.
Field assembly.
Brush assembly
End frame.

Answer: 12-2
Increasing the number of loops that rotate in the
magnetic field.

Answer: 12-6
Compound motor.

Answer: 12-3
power output.

Answer: 12-7
A laminated core is used.

Answer: 12-4
attracted.

Answer: 12-8
weight savings.
space savings.
fewer spare parts.

PART-66 SYLLABUS LEVELS

CERTIFICATION CATEGORY →

	B1	B2

Sub-Module 13
AC THEORY
Knowledge Requirements

3.13 – AC Theory

	B1	B2
Sinusoidal waveform: phase, period, frequency, cycle;	2	2
Instantaneous, average, root mean square, peak, peak to peak current values and calculations of these values, in relation to voltage, current and power;		
Triangular/Square waves;		
Single/3 phase principles.		

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

ALTERNATING CURRENT AND VOLTAGE

Alternating current has largely replaced direct current in commercial power systems for a number of reasons. It can be transmitted over long distances more readily and more economically than direct current, since AC voltages can be increased or decreased by means of transformers.

Because more and more units are being operated electrically in airplanes, the power requirements are such that a number of advantages can be realized by using AC. Space and weight can be saved, since AC devices, especially motors, are smaller and simpler than DC devices. In most AC motors no brushes are required, and commutation trouble at high altitude is eliminated. Circuit breakers will operate satisfactorily under load at high altitudes in an AC system, whereas arcing is so excessive on DC systems that circuit breakers must be replaced frequently. Finally, most airplanes using a 24-volt DC system have special equipment that requires a certain amount of 400 cycle AC current.

AC AND DC COMPARED

"AC" stands for Alternating Current. Many of the principles, characteristics, and effects of AC are similar to those of direct current. Similarly, there are a number of differences, which will be explained. Direct current flows constantly in only one direction with a constant polarity. It changes magnitude only when the circuit is opened or closed, as shown in the DC waveform in *Figure 13-1*. Alternating current changes direction at regular intervals, increases in value at a definite rate from zero to a maximum positive strength, and decreases back to zero; then it flows in the opposite direction, similarly increasing to a maximum negative value, and again decreasing to zero. DC and AC waveforms are compared in *Figure 13-1*.

Since alternating current constantly changes direction and intensity, the following two effects (to be discussed later) take place in AC circuits that do not occur in DC circuits:

1. Inductive reactance.
2. Capacitive reactance.
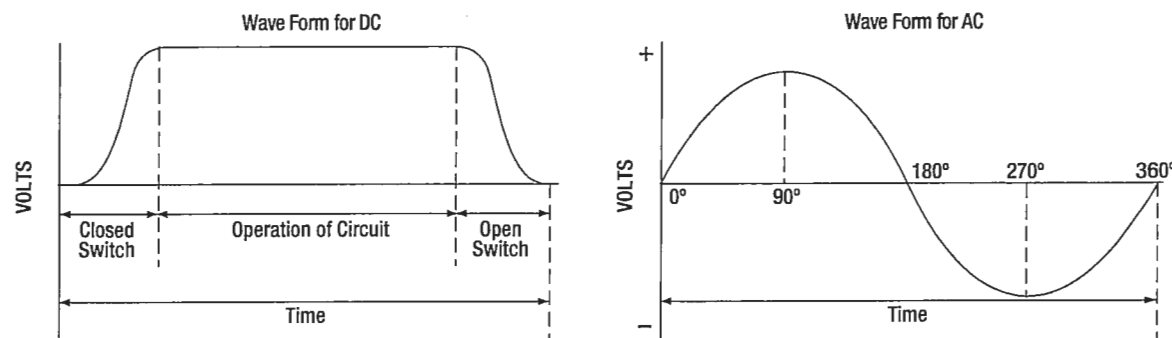
Figure 13-1. DC and AC voltage curves.

GENERATOR PRINCIPLES

After the discovery that an electric current flowing through a conductor creates a magnetic field around the conductor, there was considerable scientific speculation about whether a magnetic field could create a current flow in a conductor. In 1831, it was demonstrated this could be accomplished.

To show how an electric current can be created by a magnetic field, a demonstration similar to that illustrated in *Figure 13-2* can be used. Several turns of a conductor are wrapped around a cylindrical form, and the ends of the conductor are connected together to form a complete circuit, which includes a galvanometer. If a simple bar magnet is plunged into the cylinder, the galvanometer can be observed to deflect in one direction from its zero (center) position (*Figure 13-2A*).

When the magnet is at rest inside the cylinder, the galvanometer shows a reading of zero, indicating that no current is flowing (*Figure 13-2B*).

In *Figure 13-2C*, the galvanometer indicates a current flow in the opposite direction when the magnet is pulled from the cylinder.

The same results may be obtained by holding the magnet stationary and moving the cylinder over the magnet, indicating that a current flows when there is relative motion between the wire coil and the magnetic field.

These results obey a law first stated by the German scientist, Heinrich Lenz. Lenz's law states: *The induced current caused by the relative motion of a conductor and a magnetic field always flows in such a direction that its magnetic field opposes the motion.*

When a conductor is moved through a magnetic field, an electromotive force (EMF) is induced in the conductor. (*Figure 13-3*)

The direction (polarity) of the induced EMF is determined by the magnetic lines of force and the direction the conductor is moved through the magnetic field. The generator left-hand rule (not to be confused with the left-hand rules used with a coil) can be used to determine the direction of the induced EMF. (*Figure 13-4*)

The left-hand rule is summed up as follows:
The first finger of the left hand is pointed in the direction of the magnetic lines of force (north to south), the thumb is pointed in the direction of movement of the conductor through the magnetic field, and the second finger points in the direction of the induced EMF.

When a loop conductor is rotated in a magnetic field, a voltage is induced in each side of the loop. (*Figure 13-5*) The two sides cut the magnetic field in opposite directions, and although the current flow is continuous, it moves in opposite directions with respect to the two sides of the loop. If sides A and B and the loop are rotated half a turn and the sides of the conductor have exchanged positions, the induced EMF in each wire reverses its direction, since the wire formerly cutting the lines of force in an upward direction is now moving downward.
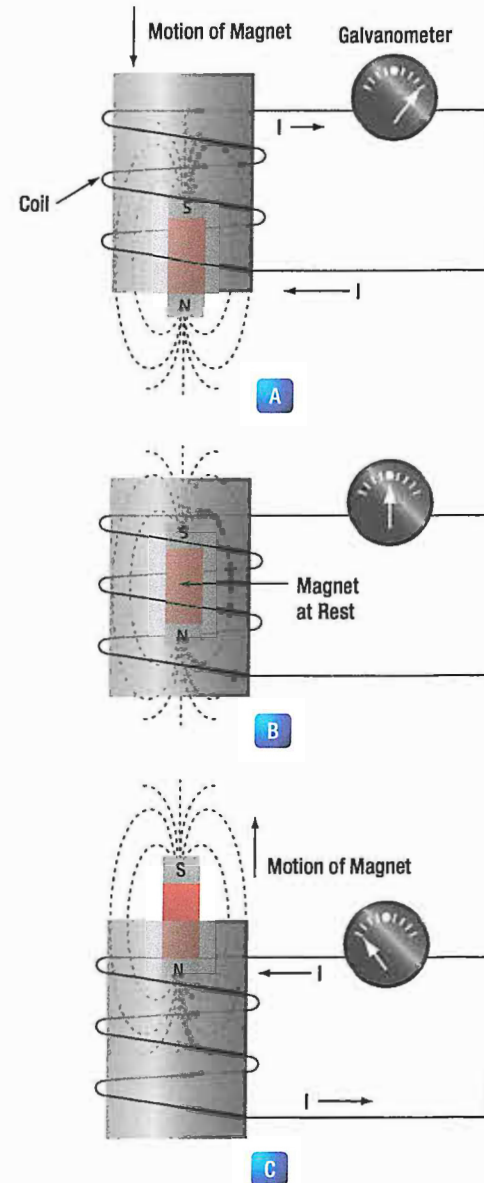
Figure 13-2. Inducing a current flow.
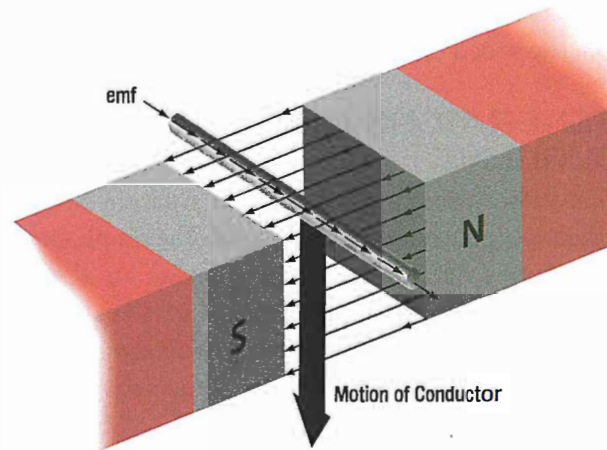
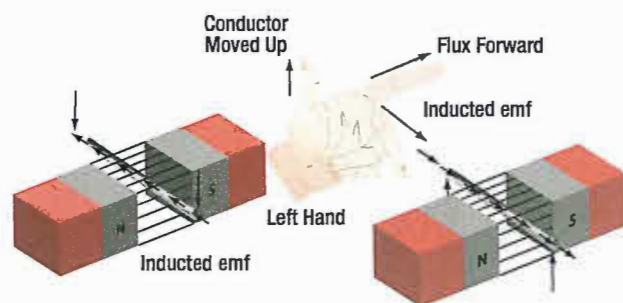Figure 13-3. Inducing an emf in a conductor.

Figure 13-4. Application of the generator left-hand rule.
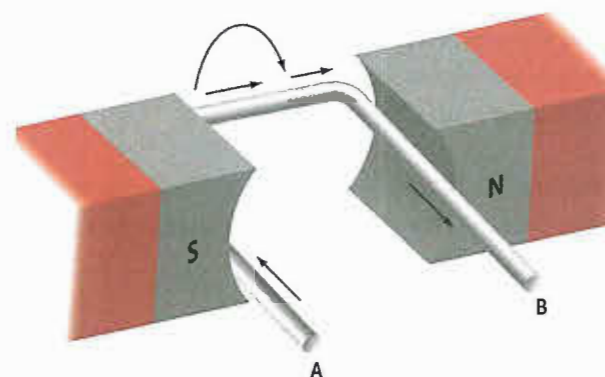

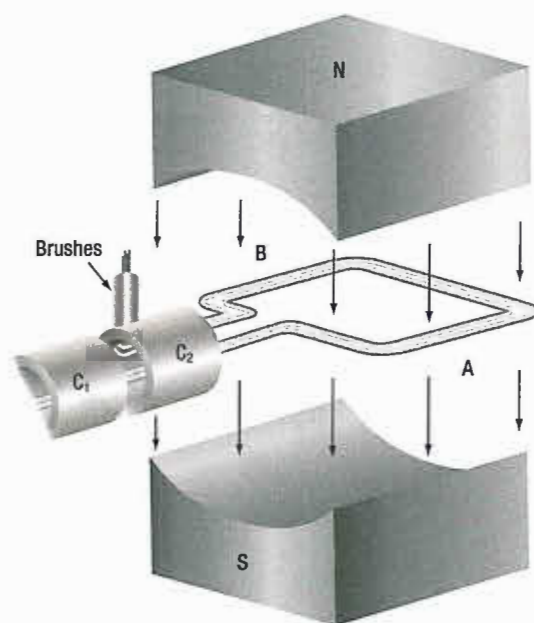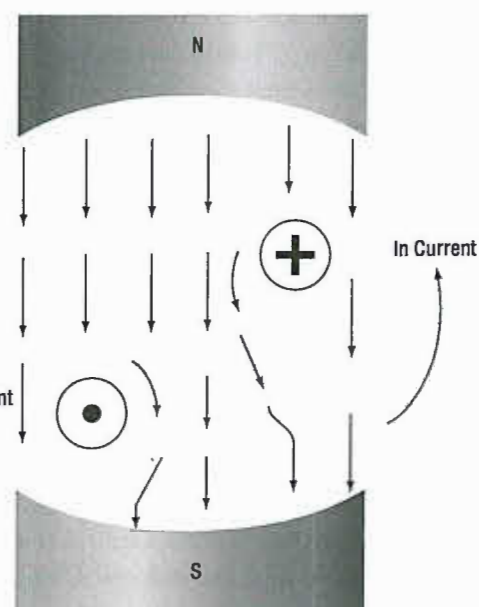
Figure 13-5. Voltage induced in a loop.

Figure 13-6. Simple generator.

The value of an induced EMF depends on three factors:
1. The number of wires moving through the magnetic field.
2. The strength of the magnetic field.
3. The speed of rotation.

GENERATORS OF ALTERNATING CURRENT

Generators used to produce an alternating current are called AC generators or alternators. The simple generator constitutes one method of generating an alternating voltage. (*Figure 13-6*) It consists of a rotating loop, marked A and B, placed between two magnetic poles, N and S. The ends of the loop are connected to two metal slip rings (collector rings), C1 and C2.

Current is taken from the collector rings by brushes. If the loop is considered as separate wires A and B, and the left-hand rule for generators is applied, then it can be observed that as wire A moves up across the field, a voltage is induced which causes the current to flow inward. As wire B moves down across the field, a voltage is induced which causes the current to flow outward. When the wires are formed into a loop, the voltages induced in the two sides of the loop are combined. Therefore, for explanatory purposes, the action of either conductor, A or B, while rotating in the magnetic field is similar to the action of the loop.

Figure 13-7 illustrates the generation of alternating current with a simple loop conductor rotating in a magnetic field. As it is rotated in a counterclockwise direction, varying values of voltages are induced in it.

Position 1
Rotating conductors moving parallel to magnetic field, cutting minimum lines of force.

Position 2
Quarter Turn Completed
Conductors cutting directly across the magnetic field as conductor A passes across the north magnetic pole and B passes across the S pole.

Position 3
One Half Turn Completed
Conductor again moving parallel to magnetic field, cutting minimum lines of force.

Position 4
Quarter Turn Completed
Conductors again moving directly across magnetic field A passes across south magnetic pole and B across N magnetic pole.

Position 5
One Half Turn Completed
Conductor A has made one complete cycle and is in same position as in position A. The generator has generated one complete cycle of alternating voltage or current.

Figure 13-7. Generation of a sine wave.

POSITION 1

The conductor A moves parallel to the lines of force. Since it cuts no lines of force, the induced voltage is zero. As the conductor advances from position 1 to position 2, the voltage induced gradually increases.

POSITION 2

The conductor is now moving perpendicular to the flux and cuts a maximum number of lines of force; therefore, a maximum voltage is induced. As the conductor moves beyond position 2, it cuts a decreasing amount of flux at each instant, and the induced voltage decreases.

POSITION 3

At this point, the conductor has made one-half of a revolution and again moves parallel to the lines of force, and no voltage is induced in the conductor. As the A conductor passes position 3, the direction of induced voltage now reverses since the A conductor is moving downward, cutting flux in the opposite direction. As the

A conductor moves across the south pole, the induced voltage gradually increases in a negative direction, until it reaches position 4.

POSITION 4

Like position 2, the conductor is again moving perpendicular to the flux and generates a maximum negative voltage. From position 4 to 5, the induced voltage gradually decreases until the voltage is zero, and the conductor and wave are ready to start another cycle.

POSITION 5

The curve shown at position 5 is called a sine wave. It represents the polarity and the magnitude of the instantaneous values of the voltages generated. The horizontal base line is divided into degrees, or time, and the vertical distance above or below the base line represents the value of voltage at each particular point in the rotation of the loop.

CYCLE AND FREQUENCY

CYCLE DEFINED

A cycle is a repetition of a pattern. Whenever a voltage or current passes through a series of changes, returns to the starting point, and then again starts the same series of changes, the series is called a cycle. The cycle is represented by the symbol of a wavy line in a circle ~ . In the cycle of voltage shown in *Figure 13-8*, the voltage increases from zero to a maximum positive value, decreases to zero; then increases to a maximum negative value, and again decreases to zero. At this point, it is ready to go through the same series of changes. There are two alternations in a complete cycle: the positive alternation and the negative. Each is half a cycle.

FREQUENCY DEFINED

The frequency is the number of cycles of alternating current per second (1 second). The standard unit of frequency measurement is the hertz (Hz). (*Figure 13-9*)

In a generator, the voltage and current pass through a complete cycle of values each time a coil or conductor passes under a north and south pole of the magnet. The number of cycles for each revolution of the coil or conductor is equal to the number of pairs of poles. The frequency, then, is equal to the number of cycles in one revolution multiplied by the number of revolutions per second. Expressed in equation form.

$$F = \frac{\text{Number of Poles}}{2} \times \frac{\text{rpm}}{60}$$

Where $^{P}/_{2}$ is the number of pairs of poles, and $^{RPM}/_{2}$ the number of revolutions per second. If in a 2 pole generator, the conductor is turning at 3 600 rpm, the revolutions per second are:

$$\text{rps} = \frac{3\ 600}{60} = 60 \text{ revolutions per second}$$

Since there are 2 poles, $^{P}/_{2}$ is 1, and the frequency is 60 cycles per second (cps). In a 4 pole generator with an armature speed of 1 800 rpm, substitute in the equation,

$$F = \frac{P}{2} \times \frac{\text{rpm}}{60}$$

$$F = \frac{4}{2} \times \frac{1\ 800}{60}$$
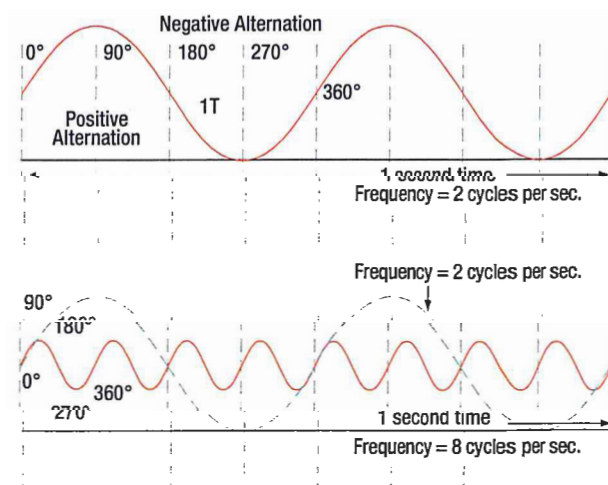
$$F = 2 \times 30$$

$$F = 60 \text{ cps}$$

Positive Alternation

Vertical Scale (Voltage)

Horizontal Scale (Time)

1T 2T 3T 4T

Negative alternation

One Cycle
One Period
(Time)

Second Cycle
(Repeated)

One Wavelength
(Distance)

Cycle is Defined as a Repetitive Pattern

Figure 13-8. Cycle of voltage.

Negative Alternation

0° 90° 180° 270°

360°

1T

Positive Alternation

1 second time
Frequency = 2 cycles per sec.

Frequency = 2 cycles per sec.

90°
180°

0°
360°
270°

1 second time
Frequency = 8 cycles per sec.

Figure 13-9. Frequency in cycles per second.

PERIOD DEFINED

The time required for a sine wave to complete one full cycle is called a period. (*Figure 13-8*) The period of a sine wave is inversely proportional to the frequency. That is to say that the higher the frequency, the shorter the period will be. The mathematical relationship between frequency and period is given as:

Period is: $\quad t = \dfrac{1}{f}$

Frequency is: $\quad f = \dfrac{1}{t}$

WAVELENGTH DEFINED

The distance that a waveform travels during a period is commonly referred to as a wavelength and is indicated by the Greek letter lambda (λ). The measurement of wavelength is taken from one point on the waveform to a corresponding point on the next waveform.
(*Figure 13-8*)

PHASE RELATIONSHIPS

In addition to frequency and cycle characteristics, alternating voltage and current also have a relationship called "phase." In a circuit that is fed (supplied) by one alternator, there must be a certain phase relationship between voltage and current if the circuit is to function efficiently. In a system fed by two or more alternators, not only must there be a certain phase relationship between voltage and current of one alternator, but there must be a phase relationship between the individual voltages and the individual currents. Also, two separate circuits can be compared by comparing the phase characteristics of one to the phase characteristics of the other.

IN PHASE CONDITION

Figure 13-10A, shows a voltage signal and a current signal superimposed on the same time axis. Notice that when the voltage increases in the positive alternation that the current also increases. When the voltage reaches it peak value, so does the current. Both waveforms then reverse and decrease back to a zero magnitude, then proceed in the same manner in the negative direction as they did in the positive direction. When two waves, such as these in *Figure 13-10A*, are exactly in step with each other, they are said to be in phase. To be in phase, the two waveforms must go through their maximum and minimum points at the same time and in the same direction.

OUT OF PHASE CONDITION

When two waveforms go through their maximum and minimum points at different times, a phase difference will exist between the two. In this case, the two waveforms are said to be out of phase with each other. The terms lead and lag are often used to describe the phase difference between waveforms. The waveform that reaches its maximum or minimum value first is said to lead the other waveform.

Figure 13-10B shows this relationship. Voltage source one starts to rise at the 0° position and voltage source two starts to rise at the 90° position. Because voltage source one begins its rise earlier in time (90°) in relation to the second voltage source, it is said to be leading the second source. On the other hand, the second source is
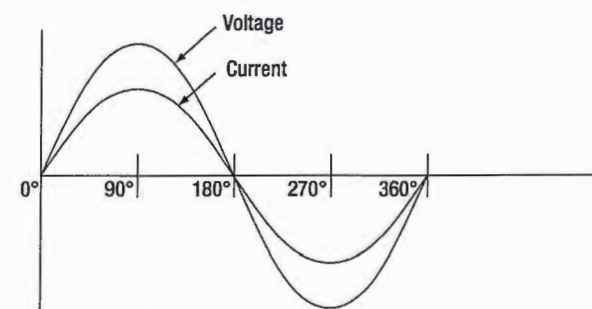
A Voltage and current are in phase.
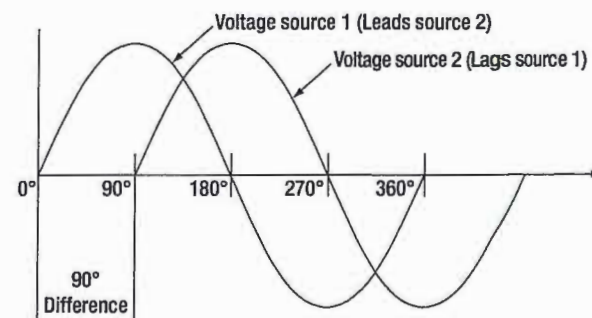
B Two voltage waves. 90° out of phase.
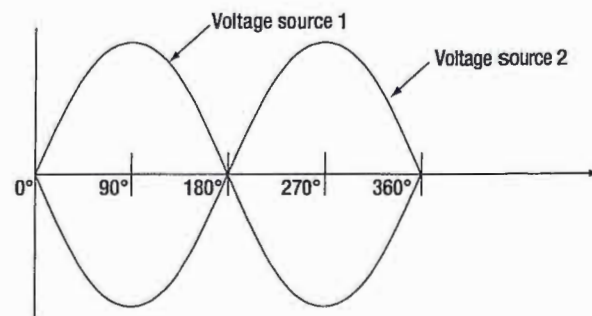
C Two voltage waves. 180° out of phase.

Figure 13-10. In phase and out of phase conditions.

said to be lagging the first source. When a waveform is said to be leading or lagging, the difference in degrees is usually stated. If the two waveforms differ by 360°, they are said to be in phase with each other. If there is a 180° difference between the two signals, then they are still out of phase even though they are both reaching their minimum and maximum values at the same time. (*Figure 13-10C*)

A practical note of caution: When encountering an aircraft that has two or more AC buses in use, it is possible that they may be split and not synchronized to be in phase with each other. When two signals that are not locked in phase are mixed, much damage can occur to aircraft systems or avionics.

VALUES OF ALTERNATING CURRENT

There are three values of alternating current, which are instantaneous, peak, and effective (root mean square, RMS).

INSTANTANEOUS VALUE

An instantaneous value of voltage or current is the induced voltage or current flowing at any instant during a cycle. The sine wave represents a series of these values. The instantaneous value of the voltage varies from zero at 0° to maximum at 90°, back to zero at 180°, to maximum in the opposite direction at 270°, and to zero again at 360°. Any point on the sine wave is considered the instantaneous value of voltage.

PEAK VALUE

The peak value is the largest instantaneous value. The largest single positive value occurs when the sine wave of voltage is at 90°, and the largest single negative value occurs when it is at 270°. Maximum value is 1.41 times the effective value. These are called peak values.

EFFECTIVE VALUE

The effective value is also known as the RMS value or root mean square, which refers to the mathematical process by which the value is derived. Most AC voltmeters will display the effective or RMS value when used. The effective value is less than the maximum value, being equal to .707 times the maximum value.

The effective value of a sine wave is actually a measure of the heating effect of the sine wave. *Figure 13-11* illustrates what happens when a resistor is connected across an AC voltage source. In illustration A, a certain amount of heat is generated by the power in the resistor. Illustration B shows the same resistor now inserted into a DC voltage source. The value of the DC voltage source can now be adjusted so that the resistor dissipates the same amount of heat as it did when it was in the AC

circuit. The RMS or effective value of a sine wave is equal to the DC voltage that produces the same amount of heat as the sinusoidal voltage.

The peak value of a sine wave can be converted to the corresponding RMS value using the following relationship:

$$Vrms = (\sqrt{0.5}) \times Vp$$
$$Vrms = 0.707 \times Vp$$

This can be applied to either voltage or current.

Algebraically rearranging the formula and solving for Vp can also determine the peak voltage. The resulting formula is:

$$Vp = 1.414 \times Vrms$$

Thus, the 110 volt value given for alternating current supplied to homes is only 0.707 of the maximum voltage of this supply. The maximum voltage is approximately 155 volts (110 x 1.41 = 155 volts maximum).
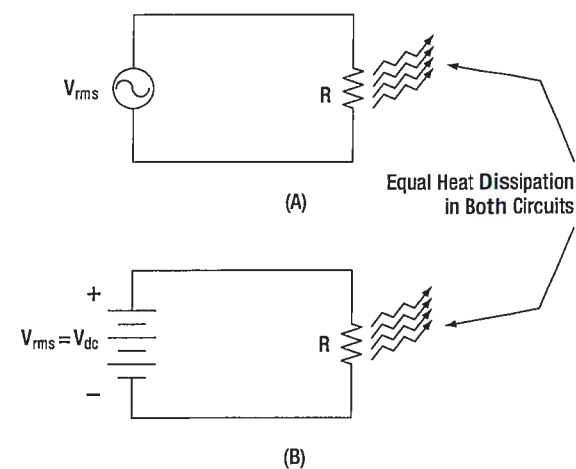

Figure 13-11. Sine wave effective value.

In the study of alternating current, any values given for current or voltage are assumed to be effective values unless otherwise specified, and in practice, only the effective values of voltage and current are used. Similarly, alternating current voltmeters and ammeters measure the effective value.

TRIANGULAR/SQUARE WAVES

It should be noted that other types of waveforms exist for voltage and current in addition to the sinusoidal waves mentioned. Waveforms are characteristic of different types of circuits. For example, a square wave is produced when there is a flow of electrons for a set period of time that stops abruptly for a set period of time and then repeats. Triangular waves can also be created. These and other special waves can be created by oscillators. Unique waveforms are common in electronics and will be discussed further in *Modules 04 and 05* of this series.

Question: 13-1

The value of an induced emf depends on what three factors?

Question: 13-3

Name three values of alternating current.

Question: 13-2

_____ is the number of cycles of alternating current per second (1 second).

Question: 13-4

_____ value is equal to .707 times the maximum value.

ANSWERS

Answer: 13-1
The number of wires moving through the magnetic field.
The strength of the magnetic field.
The speed of rotation.

Answer: 13-3
instantaneous
peak
effective (root mean square, RMS).

Answer: 13-2
frequency.

Answer: 13-4
Effective.

ELECTRICAL FUNDAMENTALS

RESISTIVE (R), CAPACITIVE (C) AND INDUCTIVE (L) CIRCUITS

SUB-MODULE 14

PART-66 SYLLABUS LEVELS

CERTIFICATION CATEGORY → **B1 B2**

Sub-Module 14

RESISTIVE (R), CAPACITIVE (C) AND INDUCTIVE (L) CIRCUITS

Knowledge Requirements

3.14 – Resistive (R), Capacitive (C) and Inductive (L) Circuits

	B1	B2	
Phase relationship of voltage and current in L, C and R circuits, parallel, series and series parallel;	2	2	RESISTIVE, CAPACITIVE, INDUCTIVE CIRCUITS
Power dissipation in L, C and R circuits;			
Impedance, phase angle, power factor and current calculations;			
True power, apparent power and reactive power calculations.			

Level 2
A general knowledge of the theoretical and practical aspects of the subject
and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical
fundamentals of the subject.
(b) The applicant should be able to give a general description of the
subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in
conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches,
drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical
manner using detailed procedures.

AC CIRCUITS

OHM'S LAW FOR AC CIRCUITS

The rules and equations for DC circuits apply to AC circuits only when the circuits contain resistance alone, as in the case of lamps and heating elements. In order to use effective values of voltage and current in AC circuits, the effect of inductance and capacitance with resistance must be considered.

The combined effects of resistance, inductive reactance, and capacitive reactance make up the total opposition to current flow in an AC circuit. This total opposition is called impedance and is represented by the letter Z. The unit for the measurement of impedance is the ohm.

SERIES AC CIRCUITS

If an AC circuit consists of resistance only, the value of the impedance is the same as the resistance, and Ohm's law for an AC circuit, I = E/Z, is exactly the same as for a DC circuit. In *Figure 4-1* a series circuit containing a lamp with 11 ohms resistance connected across a source is illustrated. To find how much current will flow if 110 volts DC is applied and how much current will flow if 110 volts AC are applied, the following examples are solved:

$$I = \frac{E}{R} \qquad\qquad I = \frac{E}{Z} \text{ (where Z = R)}$$

$$I = \frac{110 \text{ V}}{11 W} \qquad\qquad I = \frac{110 \text{ V}}{11 W}$$

$$I = 10 \text{ amperes DC} \qquad I = 10 \text{ amperes AC}$$

When AC circuits contain resistance and either inductance or capacitance, the impedance, Z, is not the same as the resistance, R. The impedance of a circuit is the circuit's total opposition to the flow of current. In an AC circuit, this opposition consists of resistance and reactance, either inductive or capacitive or elements of both.

Resistance and reactance cannot be added directly, but they can be considered as two forces acting at right angles to each other. Thus, the relation between resistance, reactance, and impedance may be illustrated by a right triangle. (*Figure 14-1*)

Since these quantities may be related to the sides of a right triangle, the formula for finding the impedance, or total opposition to current flow in an AC circuit, can be found by using the law of right triangles. This theorem, called the Pythagorean theorem, applies to any right triangle. It states that the square of the hypotenuse is equal to the sum of the squares of the other two sides. Thus, the value of any side of a right triangle can be found if the other two sides are known. If an AC circuit contains resistance and inductance, as shown in *Figure 14-2*, the relation between the sides can be stated as:

$$Z^2 = R^2 + X_L^2$$

The square root of both sides of the equation gives:

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

This formula can be used to determine the impedance when the values of inductive reactance and resistance are known. It can be modified to solve for impedance in circuits containing capacitive reactance and resistance by substituting X_C in the formula in place of X_L. In circuits containing resistance with both inductive and capacitive reactance, the reactances can be combined, but because
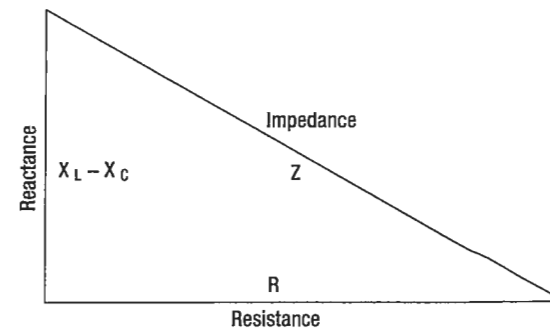
Figure 14-1. Impedance triangle.
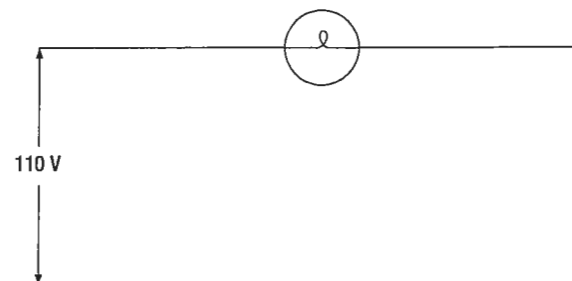
Figure 14-2. Applying DC and AC to a circuit.

their effects in the circuit are exactly opposite, they are combined by subtraction:

$X = X_L - X_C$ or $X = X_C - X_L$ (the smaller number is always subtracted from the larger.)

In *Figure 14-3*, a series circuit consisting of resistance and inductance connected in series is connected to a source of 110 volts at 60 cycles per second. The resistive element is a lamp with 6 ohms resistance, and the inductive element is a coil with an inductance of 0.021 henry. What is the value of the impedance and the current through the lamp and the coil?

Solution:
First, the inductive reactance of the coil is computed:

$X_L = 2\,\pi \times f \times L$
$X_L = 6.28 \times 60 \times 0.021$
$X_L = 8$ ohms inductive reactance

$Z = \sqrt{R^2 + X_L^2}$
$Z = \sqrt{6^2 + 8^2}$
$Z = \sqrt{36 + 64}$
$Z = \sqrt{100}$
$Z = 10$ ohms impedance

Then the current flow,

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

$I = \dfrac{110}{10}$

$I = 11$ amperes current

The voltage drop across the resistance (ER) is:
$E^R = I \times R$
$E^R = 11 \times 6 = 66$ volts

The voltage drop across the inductance (E_{XL}) is:
$E_{XL} = I \times X_L$
$E_{XL} = 11 \times 8 = 88$ volts

The sum of the two voltages is greater than the impressed voltage. This results from the fact that the two voltages are out of phase and, as such, represent the maximum voltage. If the voltage in the circuit is measured by a voltmeter, it will be approximately 110 volts, the impressed voltage.
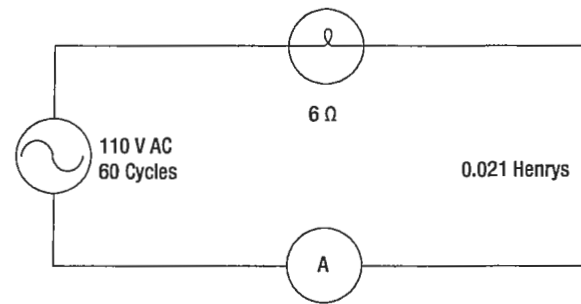
Figure 14-3. A circuit containing resistance and inductance.

This can be proved by the following equation:

$E = \sqrt{(E_R)^2 + (E_{XL})^2}$
$E = \sqrt{66^2 + 88^2}$
$E = \sqrt{4\,356 + 7\,744}$
$E = \sqrt{12\,100}$
$E = 110$ volts

In *Figure 14-4*, a series circuit is illustrated in which a capacitor of 200 µf is connected in series with a 10 ohm lamp. What is the value of the impedance, the current flow, and the voltage drop across the lamp?

Solution:
First the capacitance is changed from microfarads to farads. Since 1 million microfarads equal 1 farad, then:

$200\ \mu f = \dfrac{200}{1\,000\,000} = 0.000\,200$ farads

$X_C = \dfrac{1}{2\,\pi\,f\,C}$

$X_C = \dfrac{1}{6.28 \times 60 \times 0.002\,00\ \text{farads}}$

$X_C = \dfrac{1}{0.075\,36}$

$X_C = 13$ ohms capacitive reactance
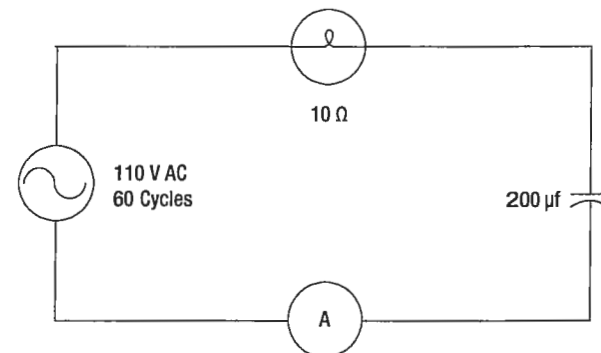
Figure 14-4. A circuit containing resistance and capacitance.

To find the impedance:

$$Z = \sqrt{R^2 + X_C{}^2}$$
$$Z = \sqrt{10^2 + 13^2}$$
$$Z = \sqrt{100 + 169}$$
$$Z = \sqrt{269}$$
$$Z = 16.4 \text{ ohms capacitive reactance}$$

To find the current:

$$I = \frac{E}{Z}$$
$$I = \frac{110}{16.4}$$
$$I = 6.7 \text{ amperes}$$

The voltage drop across the lamp (E^R) is
$$E^R = 6.7 \times 10$$
$$E^R = 67 \text{ volts}$$

The voltage drop across the capacitor (E_{XC}) is:
$$E_{XC} = I \times X_C$$
$$E_{XC} = 6.7 \times 13$$
$$E_{XC} = 86.1 \text{ volts}$$

The sum of these two voltages does not equal the applied voltage, since the current leads the voltage. To find the applied voltage:

The formula $E_T = \sqrt{(E_R)^2 + (E_{XC})^2}$ is used.

$$E_T = \sqrt{(E_R)^2 + (E_{XC})^2}$$
$$E_T = \sqrt{4\,489 + 7\,413}$$
$$E_T = \sqrt{11\,902}$$
$$E_T = 110 \text{ volts}$$

When the circuit contains resistance, inductance, and capacitance, the equation:

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

is used to find the impedance.

Example: What is the impedance of a series circuit, consisting of a capacitor with a reactance of 7 ohms, an inductor with a reactance of 10 ohms, and a resistor with a resistance of 4 ohms? (*Figure 14-5*)
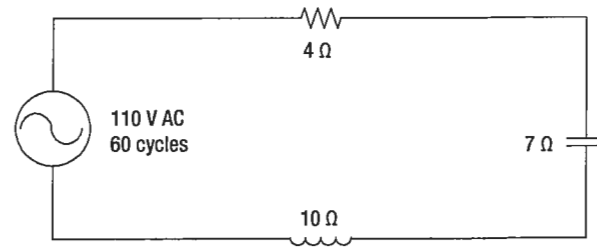
Figure 14-5. A circuit containing resistance, inductance, and capacitance.

Solution:
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$
$$Z = \sqrt{4^2 + (10 - 7)^2}$$
$$Z = \sqrt{4^2 + 3^2}$$
$$Z = \sqrt{25}$$
$$Z = 5 \text{ ohms}$$

Assuming that the reactance of the capacitor is 10 ohms and the reactance of the inductor is 7 ohms, then X_C is greater than X_L.

Thus,
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$
$$Z = \sqrt{4^2 + (7 - 10)^2}$$
$$Z = \sqrt{4^2 + (-3)^2}$$
$$Z = \sqrt{16 + 9}$$
$$Z = \sqrt{25}$$
$$Z = 5 \text{ ohms}$$

PARALLEL AC CIRCUITS

The methods used in solving parallel AC circuit problems are basically the same as those used for series AC circuits. Out of phase voltages and currents can be added by using the law of right triangles. However, in solving circuit problems, the currents through the branches are added since the voltage drops across the various branches are the same and are equal to the applied voltage. In *Figure 14-6*, a parallel AC circuit containing an inductance and a resistance is shown schematically.
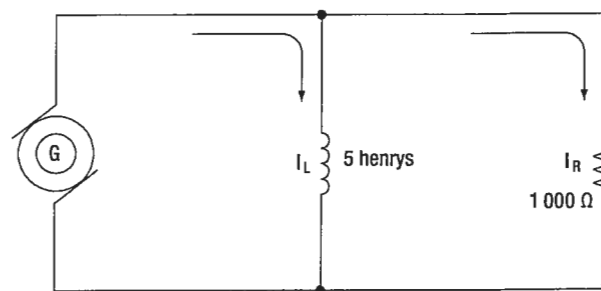
Figure 14-6. AC parallel circuit containing inductance and resistance.

The current flowing through the inductance, IL, is 0.058 4 ampere, and the current flowing through the resistance is 0.11 ampere. What is the total current in the circuit?

Solution:

$$E_T = \sqrt{(I_L)^2 + (E_{X_C})^2}$$

Since inductive reactance causes voltage to lead the current, the total current, which contains a component of inductive current, lags the applied voltage. If the current and voltages are plotted, the angle between the two, called the phase angle, illustrates the amount the current lags the voltage. In *Figure 14-7*, a 110-volt generator is connected to a load consisting of a 2 µf capacitance and a 10 000- ohm resistance in parallel. What is the value of the impedance and total current flow?

Solution:
First, find the capacitive reactance of the circuit:

$$X_C = \frac{1}{2\pi f C}$$

Changing 2 µf to farads and entering the values into the formula given:

$$= \frac{1}{2 \times 3.14 \times 60 \times 0.000\ 002}$$

$$= \frac{1}{0.000\ 753\ 60} \text{ or } \frac{10\ 000}{0.000\ 753\ 60}$$

$$= 1\ 327\ X_C \text{ capacitive reactance.}$$

To find the impedance, the impedance formula used in a series AC circuit must be modified to fit the parallel circuit:

$$Z = \sqrt{\frac{R X_C}{R^2 + X_C^2}}$$

$$= \sqrt{\frac{10\ 000 \times 1\ 327}{(10\ 000)^2 + (1\ 327)^2}}$$

$$= 0.131\ 5\ W \text{ (approx.)}$$

To find the current through the capacitance:

$$I_C = \frac{E}{X_C}$$

$$I_C = \frac{110}{1\ 327}$$

$$= 0.082\ 9 \text{ ampere}$$

To find the current flowing through the resistance:

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

$$= \frac{110}{10\ 000}$$

$$= 0.082\ 9 \text{ ampere}$$

To find the total current in the circuit:

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

$$= \frac{110}{10\ 000}$$

$$= 0.011 \text{ ampere}$$

To find the total current in the circuit:

$$I_T^2 = \sqrt{I_R^2 + I_C^2}$$

$$I_T = \sqrt{I_L^2 + I_R^2}$$

$$= 0.131\ 5\ W \text{ (approx.)}$$
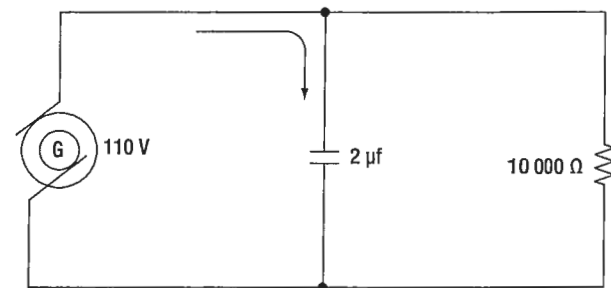
Figure 14-7. A parallel AC circuit containing capacitance and resistance.

RESONANCE

It has been shown that both inductive reactance (X_L = 2 × f L) and capacitive reactance, are functions of an alternating current frequency. Decreasing the frequency decreases the ohmic value of the inductive reactance, but a decrease in frequency increases the capacitive reactance. At some particular frequency, known as the resonant frequency, the reactive effects of a capacitor and an inductor will be equal. Since these effects are the opposite of one another, they will cancel, leaving only the ohmic value of the resistance to oppose current flow in a circuit. If the value of resistance is small or consists only of the resistance in the conductors, the value of current flow can become very high.

$$X_C = \frac{1}{2 \pi f C}$$

In a circuit where the inductor and capacitor are in series, and the frequency is the resonant frequency, or frequency of resonance, the circuit is said to be "in resonance" and is referred to as a series resonant circuit. The symbol for resonant frequency is Fn.

If, at the frequency of resonance, the inductive reactance is equal to the capacitive reactance, then:

$$X_L = X_C, \text{ or}$$

$$2 \pi f C = \frac{1}{2 \pi f C}$$

Dividing both sides by 2 fL,

$$Fn2 = \frac{1}{(2 \pi) 2 LC}$$

Extracting the square root of both sides gives:

$$Fn2 = \frac{1}{2 \pi \ LC}$$

Where Fn is the resonant frequency in cycles per second, C is the capacitance in farads, and L is the inductance in henries. With this formula, the frequency at which a capacitor and inductor will be resonant can be determined.

To find the inductive reactance of a circuit use:

$$X_L = 2 (\pi) f L$$

The impedance formula used in a series AC circuit must be modified to fit a parallel circuit.

$$Z = \sqrt{\frac{X_L}{R^2 = X_L^2}}$$

To find the parallel networks of inductance and capacitive reactors, use:

$$X = \sqrt{\frac{X_L + X_C}{X_L + X_C}}$$

To find the parallel networks with resistance capacitive and inductance, use:

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

Since at the resonant frequency X_L cancels X_C, the current can become very large, depending on the amount of resistance. In such cases, the voltage drop across the inductor or capacitor will often be higher than the applied voltage.

In a parallel resonant circuit, the reactances are equal and equal currents will flow through the coil and the capacitor. (**Figure 14-8**)

Since the inductive reactance causes the current through the coil to lag the voltage by 90°, and the capacitive reactance causes the current through the capacitor to lead the voltage by 90°, the two currents are 180° out of phase. The canceling effect of such currents would mean that no current would flow from the generator and the parallel combination of the inductor, and the capacitor would appear as infinite impedance. In practice, no such circuit is possible, since some value of resistance is always present, and the parallel circuit, sometimes called a tank circuit, acts as very high impedance. It is also
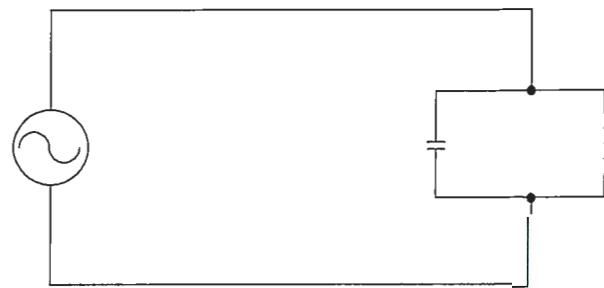

Figure 14-8. A parallel resonant circuit.

called an antiresonant circuit, since its effect in a circuit is opposite to that of a series resonant circuit, in which the impedance is very low.

POWER IN AC CIRCUITS

In a DC circuit, power is obtained by the equation, P = EI, (watts equal volts times amperes). Thus, if 1 ampere of current flows in a circuit at a pressure of 200 volts, the power is 200 watts. The product of the volts and the amperes is the true power in the circuit.

TRUE POWER DEFINED

The power dissipated in the resistance of a circuit, or the power actually used in the circuit. In an AC circuit, a voltmeter indicates the effective voltage and an ammeter indicates the effective current. The product of these two readings is called the apparent power.

APPARENT POWER DEFINED

That power apparently available for use in an AC circuit containing a reactive component. It is the product of effective voltage times the effective current, expressed in volt-amperes. It must be multiplied by the power factor to obtain true power available.

Only when the AC circuit is made up of pure resistance is the apparent power equal to the true power. (*Figure 14-9*) When there is capacitance or inductance in the circuit, the current and voltage are not exactly in phase, and the true power is less than the apparent power. The true power is obtained by a wattmeter reading. The ratio of the true power to the apparent power is called the power factor and is usually expressed in percent.

In equation form, the relationship is:

$$\text{Power Factor (PF)} = \frac{100 \times \text{Watts (True Power)}}{\text{Volts} \times \text{Amperes (Apparent Power)}}$$

Example:
A 220-volt AC motor takes 50 amperes from the line, but a wattmeter in the line shows that only 9 350 watts are taken by the motor. What are the apparent power and the power factor?

Solution:
Apparent power = Volts × Amperes
Apparent power = 220 × 50 = 11 000 watts or
volt-amperes.

$$(\text{PF}) = \frac{\text{Watts (True Power)} \times 100}{\text{VA (Apparent Power)}}$$

$$(\text{PF}) = \frac{9\,350 \times 100}{11\,000}$$

$$(\text{PF}) = 85 \text{ or } 85\%$$
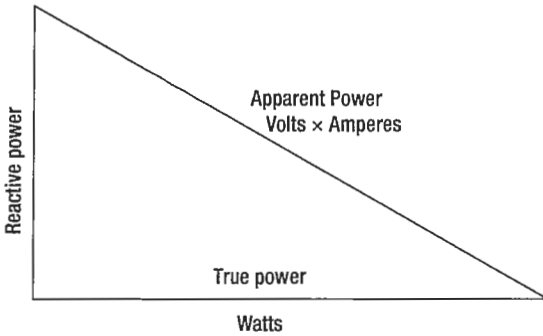
Figure 14-9. Power relations in AC circuit.

Question: 14-1
The total opposition to current flow in an AC circuit is called _____.

Question: 14-2
At what frequency are the reactive effects of a capacitor and an inductor equal?

Question: 14-3
The power dissipated in the resistance of a circuit or the power actually used in a circuit is called

_____.

ANSWERS

Answer: 14-1
impedance.

Answer: 14-3
true power.

Answer: 14-2
Resonant frequency.

PART-66 SYLLABUS **LEVELS**
CERTIFICATION CATEGORY → **B1 B2**

Sub-Module 15
TRANSFORMERS
Knowledge Requirements

3.15 - Transformers

	B1	B2
Transformer construction principles and operation;	2	2
Transformer losses and methods for overcoming them;		
Transformer action under load and no-load conditions;		
Power transfer, efficiency, polarity markings;		
Calculation of line and phase voltages and currents;		
Calculation of power in a three phase system;		
Primary and Secondary current, voltage, turns ratio, power, efficiency;		
Auto transformers.		

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

TRANSFORMERS

A transformer changes electrical energy of a given voltage into electrical energy at a different voltage level. It consists of two coils that are not electrically connected, but are arranged so that the magnetic field surrounding one coil cuts through the other coil. When an alternating voltage is applied to (across) one coil, the varying magnetic field set up around that coil creates an alternating voltage in the other coil by mutual induction. A transformer can also be used with pulsating DC, but a pure DC voltage cannot be used, since only a varying voltage creates the varying magnetic field that is the basis of the mutual induction process.

A transformer consists of three basic parts. (*Figure 15-1*) These are an iron core which provides a circuit of low reluctance for magnetic lines of force, a primary winding which receives the electrical energy from the source of applied voltage, and a secondary winding which receives electrical energy by induction from the primary coil.

The primary and secondary of this closed core transformer are wound on a closed core to obtain maximum inductive effect between the two coils. There are two classes of transformers: (1) voltage transformers used for stepping up or stepping down voltages, and (2) current transformers used in instrument circuits.

In voltage transformers, the primary coils are connected in parallel across the supply voltage as shown in *Figure 15-2A*. The primary windings of current transformers are connected in series in the primary circuit (*Figure 15-2B*). Of the two types, the voltage transformer is the more common.

There are many types of voltage transformers. Most of these are either step-up or step-down transformers. The factor that 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 to the number of turns in the secondary winding. For example, the turns ratio of the step-down transformer shown in *Figure 15-3A* 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 *Figure 15-3B* has a 1 to 4 turns ratio.
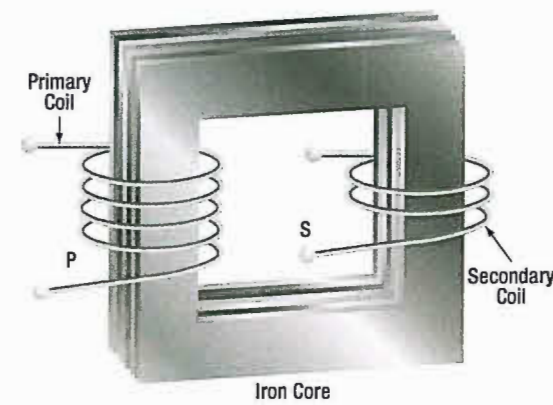
Figure 15-1. An iron-core transformer.
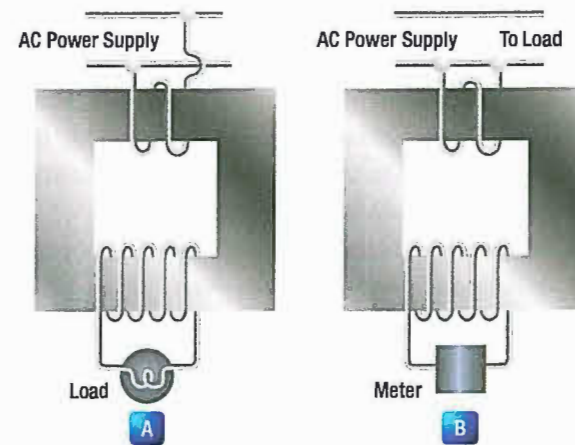
Figure 15-2. Voltage and current transformers.
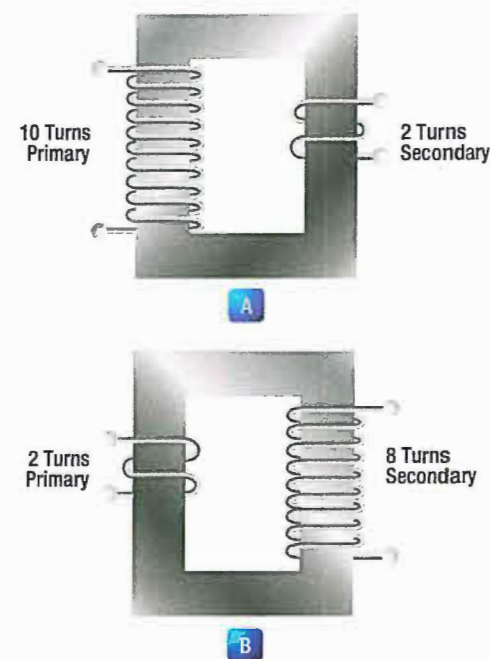
Figure 15-3. A step-down and a step-up transformer.

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 *Figure 15-3A*, two volts are induced in the secondary. If 10 volts are applied to the primary of the transformer in *Figure 15-3B*, 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 all 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, leaks out of the magnetic circuit. The measure of 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 be 0.9 or, stated another way, the transformer would be 90 percent efficient.

When an AC voltage is connected across the primary terminals of a transformer, an alternating current will flow and self induce a voltage in the primary coil that 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 a 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 coil and allow more primary current to flow. 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 exciting 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:

$$\frac{E_2}{R_1} = \frac{N_2}{N_1}$$

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:

$$E_2 = \frac{E_1 N_2}{N_1}$$

The most commonly used types of voltage transformers are as follows:

1. Power transformers are used to step up or step down voltages and current in many types of power supplies. They range in size from the small power transformer shown in *Figure 15-4* used in a radio receiver to the large transformers used to step down high power line voltage to the 110 – 120 volt level used in homes. *Figure 15-5* shows the schematic symbol for an iron core transformer. In this case, the secondary is made up of three separate windings. Each winding supplies a different circuit with a specific voltage, which saves the weight, space, and expense of three separate transformers. Each secondary has a midpoint connection, called a "center tap," which provides a selection of half the voltage across the whole winding. The leads from the various windings are color coded by the manufacturer, as labeled in *Figure 15-5*. This is a standard color code, but other codes or numbers may be used.

2. Audio transformers resemble power transformers. They have only one secondary and are designed to operate over the range of audio frequencies (20 to 20 000 cps).
3. RF transformers are designed to operate in equipment that functions in the radio range of frequencies. The symbol for the RF transformer is the same as for an RF choke coil. It has an air core as shown in *Figure 15-6*.
4. Autotransformers are normally used in power circuits; however, they may be designed for other uses. Two different symbols for autotransformers used in power or audio circuits are shown in *Figure 15-7*. If used in an RF communication or navigation circuit (*Figure 15-7B*), it is the same, except there is no symbol for an iron core.

The autotransformer uses part of a winding as a primary; and, depending on whether it is step up or step down, it uses all or part of the same winding as the secondary. For example, the autotransformer shown in *Figure 15-7A* could use the following possible choices for primary and secondary terminals.
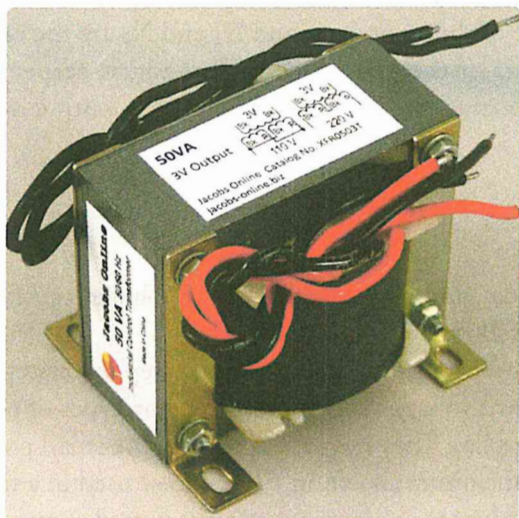
Figure 15-4. Power supply transformer.
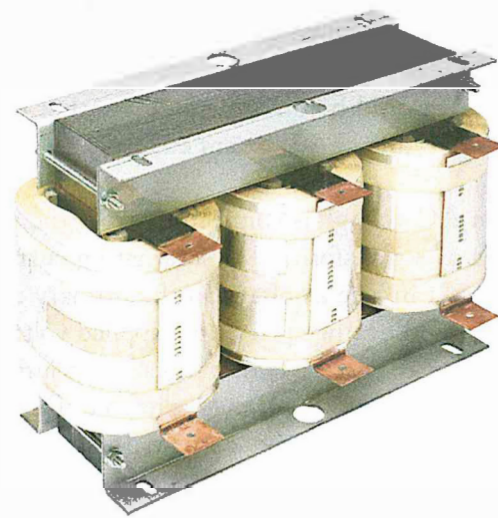
Figure 15-6. An air-core transformer.
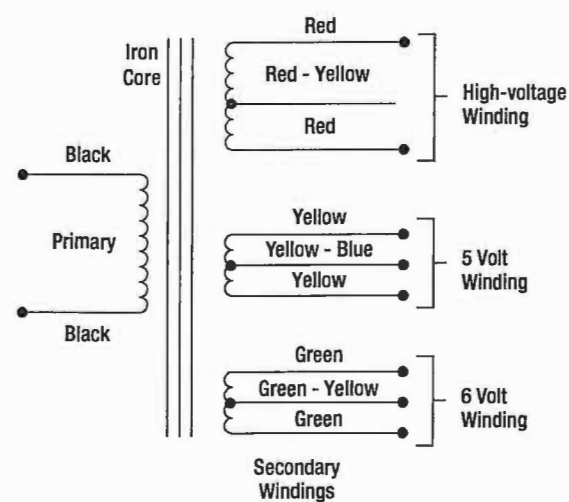
Figure 15-5. Schematic symbol for an iron-core power transformer.

Primary			Secondary
1–2	used with		1–3
1–2	"	"	2–3
1–3	"	"	1–2
1–3	"	"	2–3
2–3	"	"	1–3
2–3	"	"	1–2
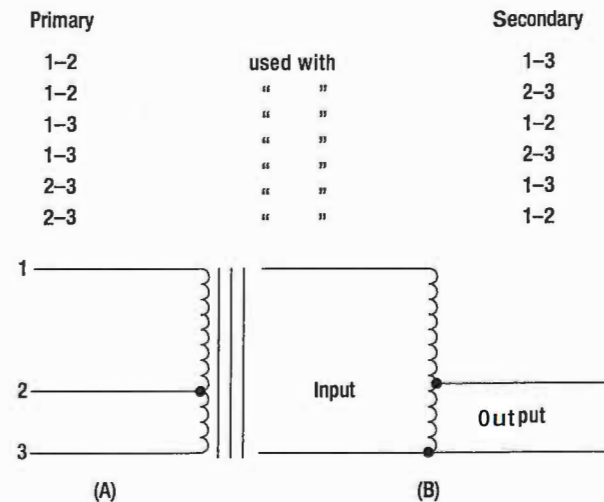
Figure 15-7. Autotransformers.

CURRENT TRANSFORMERS

Current transformers are used in AC power supply systems to sense generator line current and to provide a current, proportional to the line current, for circuit protection and control devices.

The current transformer is a ring-type transformer using a current carrying power lead as a primary (either the power lead or the ground lead of the AC generator). The current in the primary induces a current in the secondary by magnetic induction.

The sides of all current transformers are marked "H1" and "H2" on the unit base. The transformers must be installed with the "H1" side toward the generator in the circuit in order to have proper polarity. The secondary of the transformer should never be left open while the system is being operated; to do so could cause dangerously high voltages, and could overheat the transformer. Therefore, the transformer output connections should always be connected with a jumper when the transformer is not being used but is left in the system.

TRANSFORMER LOSSES

In addition to the power loss caused by imperfect coupling, transformers are subject to "copper" and "iron" losses. The resistance of the conductor comprising the turns of the coil causes copper loss. The iron losses are of two types called hysteresis loss and eddy current loss. Hysteresis loss is the electrical energy required to magnetize the transformer core, first in one direction and then in the other, in step with the applied alternating voltage. Eddy current loss is caused by electric currents (eddy currents) induced in the transformer core by the varying magnetic fields. To reduce eddy current losses, cores are made of laminations coated with an insulation, which reduces the circulation of induced currents.

POWER IN TRANSFORMERS

Since a transformer does not add any electricity to the circuit but merely changes or transforms the electricity that already exists in the circuit from one voltage to another, the total amount of energy in a circuit must remain the same. If it were possible to construct a perfect transformer, there would be no loss of power in it; power would be transferred undiminished from one voltage to another.

Since power is the product of volts times amperes, an increase in voltage by the transformer must result in a decrease in current and vice versa. There cannot be more power in the secondary side of a transformer than there is in the primary. The product of amperes times volts remains the same.

The transmission of power over long distances is accomplished by using transformers. At the power source, the voltage is stepped up in order to reduce the line loss during transmission. At the point of utilization, the voltage is stepped down, since it is not feasible to use high voltage to operate motors, lights, or other electrical appliances.

Question: 15-1
Name the three parts of a basic transformer.

Question: 15-3
True or false: There cannot be more power in the secondary side of a transformer than there is in the primary.

Question: 15-2
Name 3 types of transformers.

ANSWERS

Answer: 15-1
Primary coil.
Secondary coil.
Core.

Answer: 15-3
True.

Answer: 15-2
Power.
Audio.
RF.
Autotransformers.

ELECTRICAL FUNDAMENTALS

FILTERS

SUB-MODULE 16

PART-66 SYLLABUS LEVELS

CERTIFICATION CATEGORY → | **B1** | **B2**

Sub-Module 16
FILTERS
Knowledge Requirements

3.16 – Filters

Operation, application and uses of the following filters: low pass, high pass, band pass, band stop.   **1**   **1**

Level 1
A familiarization with the principal elements of the subject.

Objectives:
(a) The applicant should be familiar with the basic elements of the subject.
(b) The applicant should be able to give a simple description of the whole subject, using common words and examples.
(c) The applicant should be able to use typical terms.

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FILTERS

FILTERING

One of the more common uses of the capacitor and inductor that the technician may find in the field is that of the filter.

FILTERING CHARACTERISTICS OF CAPACITORS

The nature of capacitance opposes a voltage change across its terminal by storing energy in its electrostatic field. Whenever the voltage tends to rise, the capacitor converts this voltage change to stored energy. When the voltage tends to fall, the capacitor converts this stored energy back to voltage. The use of a capacitor for filtering the output of a rectifier is illustrated in *Figure 16-1*.

The rectifier is shown as a block, and the capacitor C1 is connected in parallel with the load R1. The capacitor C1 is chosen to offer very low impedance to the AC ripple frequency and very high impedance to the DC component. The ripple voltage is therefore bypassed to ground through the low impedance path of the capacitor, while the DC voltage is applied unchanged to the load. The effect of the capacitor on the output of the rectifier can be seen in the wave shapes shown in *Figure 16-2*.

Dotted lines show the rectifier output, while the solid lines show the effect of the capacitor. In this example, full-wave rectifier outputs are shown. The capacitor C1 charges when the rectifier voltage output tends to increase and discharges when the voltage output tends to decrease. In this manner, the voltage across the load R1 is kept fairly constant.

FILTERING CHARACTERISTICS OF INDUCTORS

The inductance provided by an inductor may be used as a filter, because it opposes a change in current through it by storing energy in its electromagnetic field. Whenever the current increases, the stored energy in the electromagnetic field increases. When the current through the inductor decreases, the inductor supplies the energy back into the circuit in order to maintain the existing flow of current. The use of an inductor for filtering the output of a rectifier is shown in *Figure 16-3*. Note that in this network the inductor L_1 is in series with the load R_1.

The inductance L_1 is selected to offer high impedance to the AC ripple voltage and low impedance to the DC component. The result is a very large voltage drop across the inductor and a very small voltage drop across the load R_1. For the DC component, however, a very small voltage drop occurs across the inductor and a very large voltage drop across the load. The effect of an inductor on the output of a full-wave rectifier in the output waveshape is shown in *Figure 16-4*.
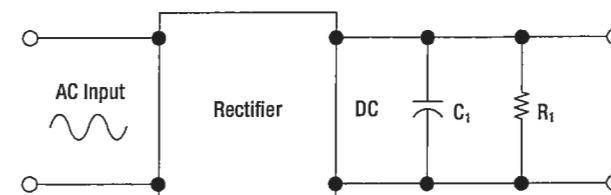
Figure 16-1. A capacitor used as a filter.

Voltage Across C_1 with Large Load Circuit   Voltage Across C_1 With Small Load Circuit
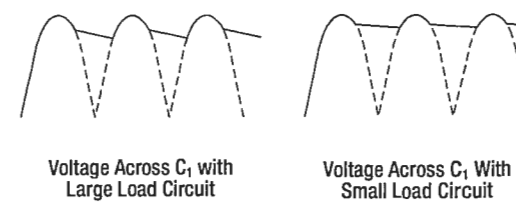
Figure 16-2. Half-wave and full-wave rectifier outputs using capacitor filter.
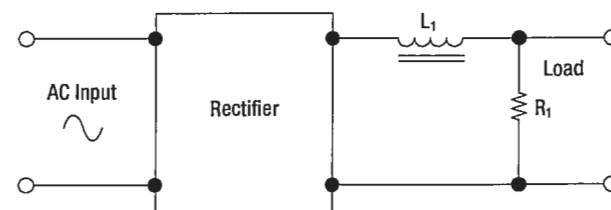
Figure 16-3. An inductor used as a filter.
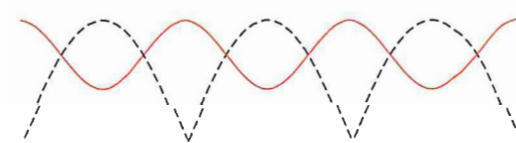
Figure 16-4. Output of an inductor filter rectifier.

COMMON FILTER CONFIGURATIONS

Capacitors and inductors are combined in various ways to provide more satisfactory filtering than can be obtained with a single capacitor or inductor. These are referred to collectively as "LC filters." Several combinations are shown schematically in *Figure 16-5*. Note that the L, or inverted L-type, and the T-type filter sections resemble schematically the corresponding letters of the alphabet. The pi-type filter section resembles the Greek letter pi (π) schematically.

All the filter sections shown are similar in that the inductances are in series and the capacitances are in parallel with the load. The inductances must, therefore, offer very high impedance and the capacitors very low impedance to the ripple frequency. Since the ripple frequency is comparatively low, the inductances are iron core coils having large values of inductance (several henries). Because they offer such high impedance to the ripple frequency, these coils are called chokes. The capacitors must also be large (several microfarads) to offer very little opposition to the ripple frequency. Because the voltage across the capacitor is DC, electrolytic capacitors are frequently used as filter capacitors. Always observe the correct polarity in connecting electrolytic capacitors.

LC filters are also classified according to the position of the capacitor and inductor. A capacitor input filter is one in which the capacitor is connected directly across the output terminals of the rectifier. A choke input filter is one in which a choke precedes the filter capacitor.

If it is necessary to increase the applied voltage to more than a single rectifier can tolerate, the usual solution is to stack them. These rectifiers are similar to resistors added in series. Each resistor will drop a portion of the applied voltage rather than the total voltage. The same theory applies to rectifiers added in series, or stacked. Series stacking increases the voltage rating. If, for example, a rectifier will be destroyed with an applied voltage exceeding 50 volts, and it is to be used in a circuit with an applied voltage of 150 volts, stacking of diodes can be employed. The result is shown in *Figure 16-6*.
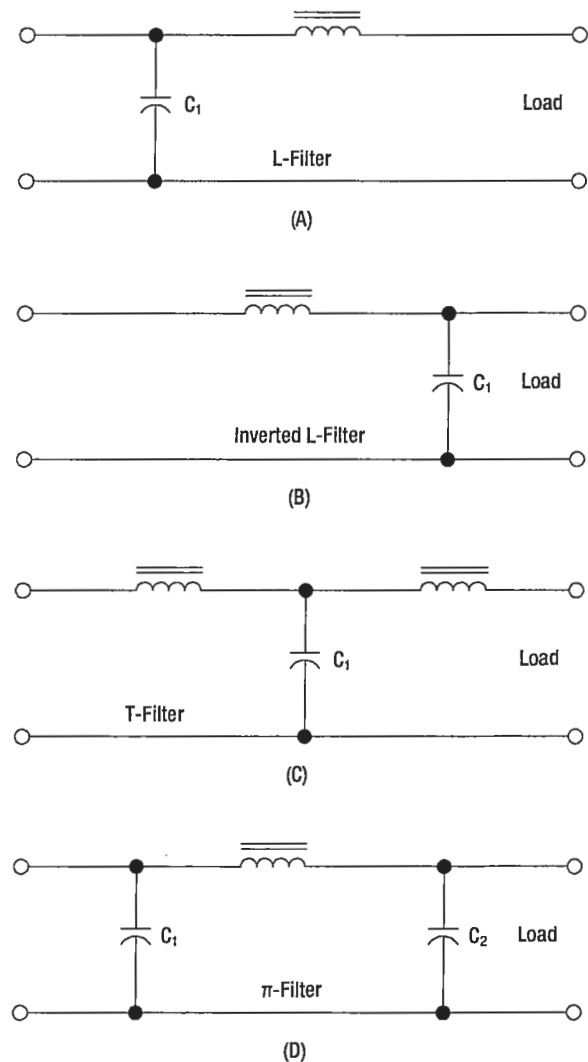
Figure 16-5. LC filters.
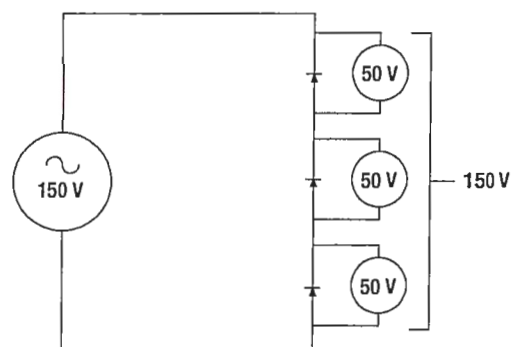
Figure 16-6. Stacking diodes in a circuit.

BASIC LC FILTERS

Analog filters are circuits that perform signal processing functions, specifically intended to remove unwanted signal components such as ripple and enhance desired signals. The simplest analog filters are based on combinations of inductors and capacitors. The four basic categories of filters discussed are: low-pass, high-pass, band-pass and band-stop. All these types are collectively known as passive filters, because they do not depend on any external power source.

The operation of a filter relies on the characteristic of variable inductive and capacitive reactance based on the applied frequency. In review, the inductor will block high-frequency signals (high reactance) and conduct low-frequency signals (low reactance), while capacitors do the reverse. A filter in which the signal passes through an inductor, or in which a capacitor provides a path to earth, presents less attenuation (reduction) to a low-frequency signal than to a high-frequency signal and is considered a low-pass filter. If the signal passes through a capacitor, or has a path to ground through an inductor, then the filter presents less attenuation to high-frequency signals than low-frequency signals and is then considered a high-pass filter. Typically after an AC signal is rectified the pulses of voltage are changed to usable form of DC by way of filtering.

LOW-PASS FILTER

A low-pass filter is a filter that passes low frequencies well, but attenuates (reduces) higher frequencies. The so called cutoff frequency divides the range of frequencies that are passed and the range of frequencies that are stopped. In other words, the frequency components higher than the cutoff frequency will be stopped by a low-pass filter.

The actual amount of attenuation for each frequency varies by filter design.

An Inductive low-pass filter inserts an inductor in series with the load, where a capacitive low-pass filter inserts a resistor in series and a capacitor in parallel with the load. The former filter design tries to "block" the unwanted frequency signal while the latter tries to short it out. *Figure 16-7* illustrates this type of circuit and the frequency/current flow response.
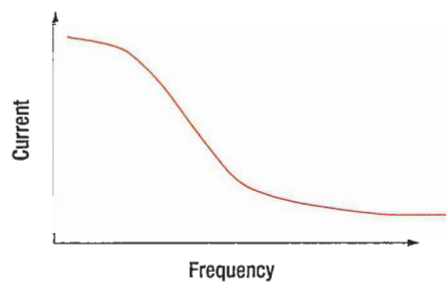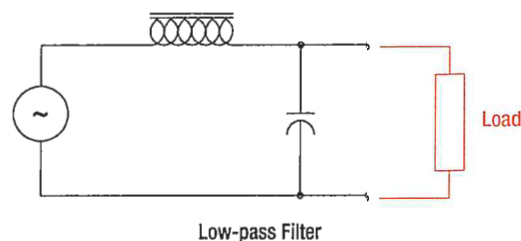
Low-pass Filter

Frequency Response

Figure 16-7. Low-pass filter.

HIGH-PASS FILTER

A high-pass filter (HPF) is a filter that passes high frequencies well, but attenuates (reduces) frequencies lower than the cutoff frequency. The actual amount of attenuation for each frequency varies once again depending on filter design. In some cases it is called a low-cut filter.

A high-pass filter is essentially the opposite of a low-pass filter. It is useful as a filter to block any unwanted low frequency components of a signal while passing the desired higher frequencies. *Figure 16-8* illustrates this type of circuit and the frequency/current flow response.

High-pass Filter

Frequency Response
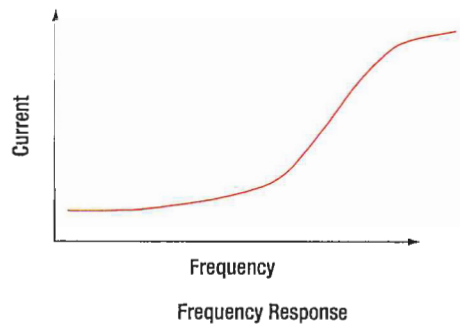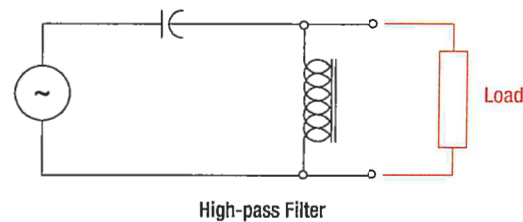
Figure 16-8. High-pass filter.

BAND-PASS FILTER

A band-pass filter is basically a combination of a high-pass and a low-pass. There are some applications where a particular range of frequencies need to be singled out or filtered from a wider range of frequencies. Band-pass filter circuits are designed to accomplish this task by combining the properties of low-pass and high-pass into a single filter. *Figure 16-9* illustrates this type of circuit and the frequency/current flow response.

Band-pass Filter

Band-pass Filter

Frequency Response
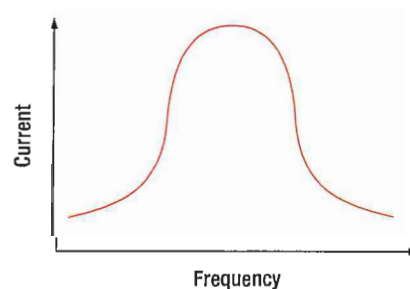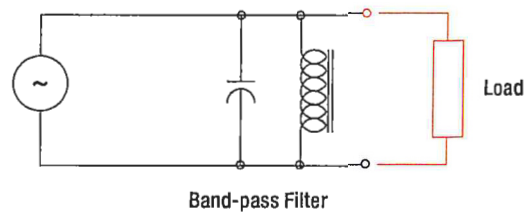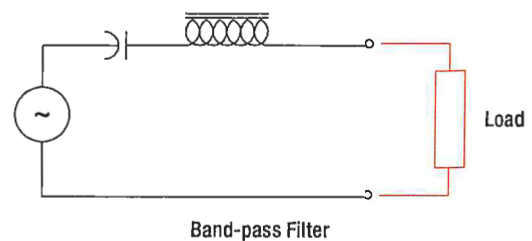
Figure 16-9. Band-pass filter.

FILTERS

BAND-STOP FILTER

In signal processing, a band-stop filter or band-rejection filter is a filter that passes most frequencies unaltered, but attenuates those in a range to very low levels. It is the opposite of a band-pass filter. A notch filter is a band-stop filter with a narrow stopband (high Q factor). Notch filters are used in live sound reproduction (Public Address systems, also known as PA systems) and in instrument amplifier (especially amplifiers or preamplifiers for acoustic instruments such as acoustic guitar, mandolin, bass instrument amplifier, etc.) to reduce or prevent feedback, while having little noticeable effect on the rest of the frequency spectrum. Other names include "band limit filter," "T-notch filter," "band-elimination filter," and "band-rejection filter."

Typically, the width of the stop-band is less than 1 to 2 decades (that is, the highest frequency attenuated is less than 10 to 100 times the lowest frequency attenuated). In the audio band, a notch filter uses high and low frequencies that may be only semitones apart.

A band-stop filter is the general case. A notch filter is a specific type of band-stop filter with a very narrow range. Also called band-elimination, band-reject, or notch filters, this kind of filter passes all frequencies above and below a particular range set by the component values. Not surprisingly, it can be made out of a low-pass and a high-pass filter, just like the band-pass design, except that this time we connect the two filter sections in parallel with each other instead of in series. *Figure 16-10* illustrates this type of circuit and the frequency/current flow response.

Band-stop Filter

Band-stop Filter

Frequency Response
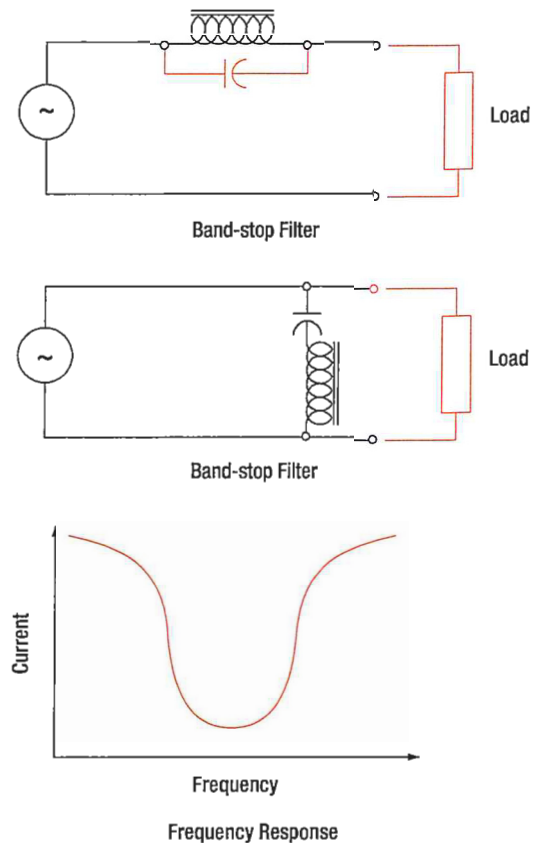
Figure 16-10. Band-stop filter.

Question: 16-1

Capacitance _____ a voltage change across its terminal by storing energy in its electrostatic field.

Question: 16-3

A high-pass filter passes high frequencies well but _____ frequencies lower than the cutoff frequency.

Question: 16-2

_____ and _____ are combined in various ways to provide more satisfactory filtering than can be obtained with a single capacitor or inductor.

ANSWERS

Answer: 16-1
opposes.

Answer: 16-2
Capacitors, inductors.

Answer: 16-3
attenuates (reduces).

Sub-Module 17
AC GENERATORS
Knowledge Requirements

3.17 – AC Generators

	B1	B2
Rotation of loop in a magnetic field and waveform produced;	2	2

Operation and construction of revolving armature and revolving field type AC generators;

Single phase, two phase and three phase alternators;

Three phase star and delta connections advantages and uses;

Permanent Magnet Generators.

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

Module 03 - Electrical Fundamentals

AC GENERATORS

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17.1

ALTERNATORS

ALTERNATORS & CLASSIFICATIONS

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 AC 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 AC generators. This text treats the two terms synonymously and uses the term "alternator" to distinguish between AC and DC generators. The major difference between an alternator and a DC 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 DC generator is connected by a commutator.

METHOD OF EXCITATION

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 DC generator fixed on the same shaft with the AC generator. A variation of this system is a type of alternator which uses DC from the battery for excitation, after which the alternator is self-excited.
2. By transformation and rectification from the AC system. This method depends on residual magnetism for initial AC voltage buildup, after which the field is supplied with rectified voltage from the AC generator.
3. Integrated brushless type. This arrangement has a direct current generator on the same shaft with 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.

Permanent magnet alternators and generators also exist. These utilize permanent magnets to establish the excitation field rather than coils.

NUMBER OF PHASES

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.

ARMATURE OR FIELD ROTATION

Still another means of classification is by the type of stator and rotor used. From this standpoint, 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 DC 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 DC generator, the emf generated in the armature windings is converted into a unidirectional voltage (DC) by means of the commutator. In the revolving armature type of alternator, the generated AC voltage is applied unchanged to the load by means of slip rings and brushes.

The revolving field type of alternator has a stationary armature winding (stator) and a rotating field winding (rotor). (*Figure 17-1*) 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 arc over is a continual
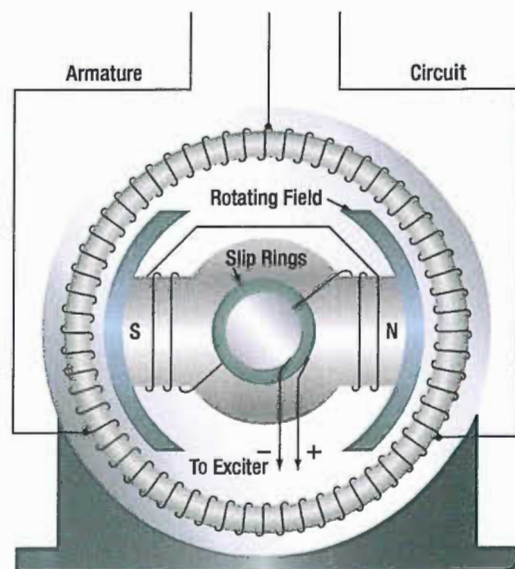

Figure 17-1. Alternator with stationary armature and rotating field.

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. Since the rotating field alternator is used almost universally in aircraft systems, this type will be explained in detail, as a single phase, two phase, and three phase alternator.

SINGLE PHASE ALTERNATOR

Since the emf induced in the armature of a generator is alternating, the same sort of winding can be used on an alternator as on a DC 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.

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. *Figure 17-2* 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, AC voltages are induced in the stator windings.

Since one rotor pole is in the same position relative to a stator winding as any other rotor pole, all stator polar groups are cut by equal numbers 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 windings are connected to each other so that the AC 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 winding 1. 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 coil 3 (clockwise rotation of the field) is the same direction (counterclockwise) 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 AC 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 voltages 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.

A simplified schematic diagram, showing each of three phases, is illustrated in *Figure 17-3*. The rotor is omitted for simplicity. The waveforms of voltage are shown to the
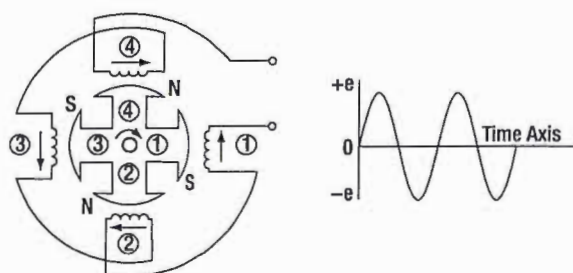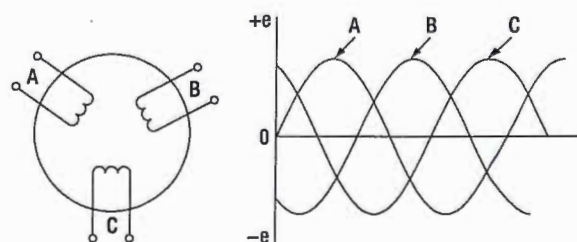

Figure 17-2. Single phase alternator.

Figure 17-3. Simplified schematic of three phase alternator with output waveforms.

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right of the schematic. The three voltages are 120° apart and are similar to the voltages 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.

WYE CONNECTION (THREE PHASE)

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 (*Figure 17-4A*) shows a wye connected stator with the common lead not brought out. Each load is connected across two phases in series. Thus, RAB is connected across phases A and B in series; RAC is connected across phases A and C in series; and RBC is connected across phases B and C in series. Therefore, the voltage across each load is larger than the voltage across a single phase. The total voltage, or line voltage, across any two phases is the vector sum of the individual phase voltages. 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.

DELTA CONNECTION (THREE PHASE)

A three phase stator can also be connected so that the phases are connected end to end as shown in *Figure 17-4B*. This arrangement is called a delta connection. In a delta connection, the voltages are equal to the phase voltages; the line currents are equal to the vector sum of

(A) Wye Connection   (B) Delta Connection
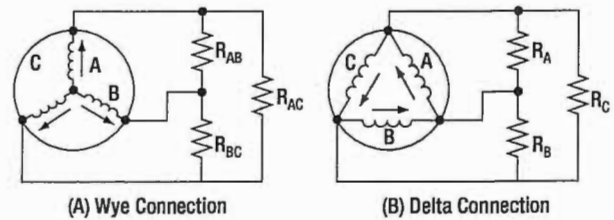
Figure 17-4. Wye and delta connected alternators.

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 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.

ALTERNATOR RECTIFIER UNIT

A type of alternator used in the electrical system of many aircraft weighing less than 12 500 pounds is shown in *Figure 17-5*. This type of power source is sometimes called a DC generator, since it is used in DC systems. Although its output is a DC voltage, it is an alternator rectifier unit. This type of alternator rectifier is a self-excited unit but does not contain a permanent magnet. The excitation for starting is obtained from the battery; immediately after starting, the unit is self-exciting. Cooling air for the alternator is conducted into the unit by a blast air tube on the air inlet cover.

The alternator is directly coupled to the aircraft engine by means of a flexible drive coupling. The output of the alternator portion of the unit is three phase alternating current, derived from a three phase, delta connected
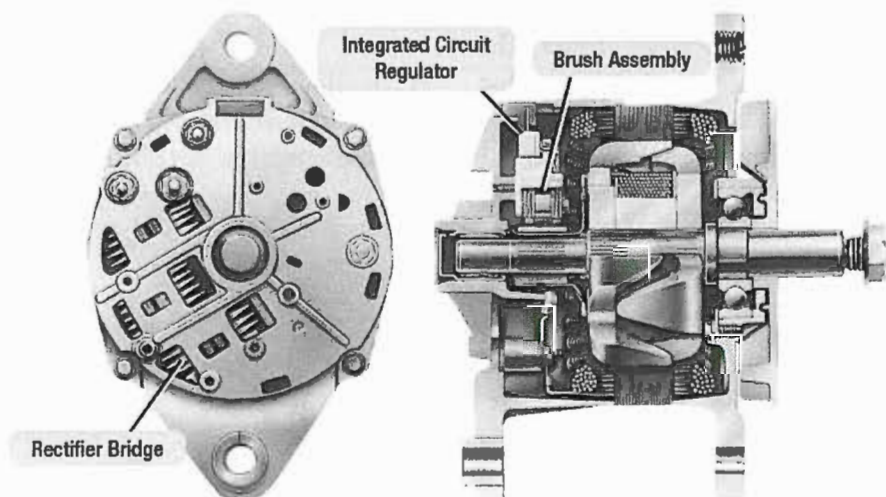
Figure 17-5. Exploded view of alternator rectifier.

system incorporating a three phases, full-wave bridge rectifier. (*Figure 17-6*) This unit operates in a speed range from 2 100 to 9 000 rpm, with a DC output voltage of 26 – 29 volts and 125 amperes.
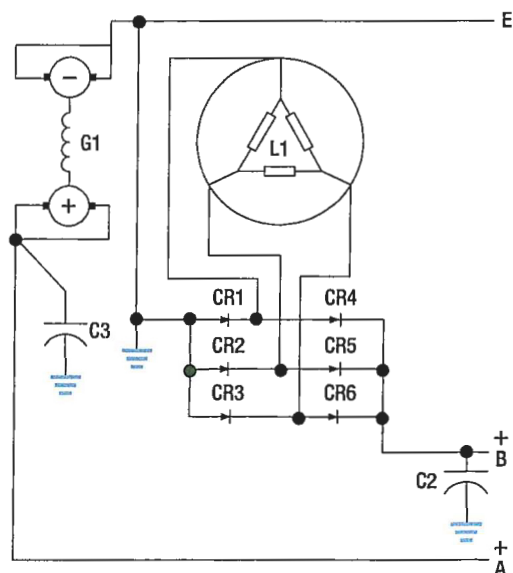

Figure 17-6. Wiring diagram of alternator-rectifier unit.

BRUSHLESS ALTERNATOR

This design is more efficient because there are no brushes to wear down or to arc at high altitudes. This generator consists of a pilot exciter, an exciter, and the main generator system. The need for brushes is eliminated by using an integral exciter with a rotating armature that has its AC output rectified for the main AC field, which is also of the rotating type. A brushless alternator is illustrated in *Figure 17-7*.

The pilot exciter is an 8 pole, 8 000 rpm, 533 cps, AC generator. The pilot exciter field is mounted on the main generator rotor shaft and is connected in series with the main generator field. The pilot exciter armature is mounted on the main generator stator. The AC output of the pilot exciter is supplied to the voltage regulator, where it is rectified and controlled, and is then impressed on the exciter field winding to furnish excitation for the generator.

The exciter is a small AC generator with its field mounted on the main generator stator and its three phase armature mounted on the generator rotor shaft. Included in the exciter field are permanent magnets mounted on the main generator stator between the exciter poles.

The exciter field resistance is temperature compensated by a thermistor. This aids regulation by keeping a nearly constant resistance at the regulator output terminals.

The exciter output is rectified and impressed on the main generator field and the pilot exciter field. The exciter stator has a stabilizing field, which is used to improve stability and to prevent voltage regulator over-corrections for changes in generator output voltage.

The AC generator shown in *Figure 17-7* is a 6 pole, 8 000 rpm unit having a rating of 31.5 kilovoltamperes (kVA), 115/200 volts, 400 cps. This generator is three phase, 4 wire, wye connected with grounded neutrals. By using an integral AC exciter, the necessity for brushes within the generator has been eliminated. The AC output of the rotating exciter armature is fed directly into the three phase, full-wave, rectifier bridge located inside the rotor shaft, which uses high temperature silicon rectifiers. The DC output from the rectifier bridge is fed to the main AC generator rotating field.

Voltage regulation is accomplished by varying the strength of the AC exciter stationary fields. Polarity reversals of the AC generator are eliminated and radio noise is minimized by the absence of the brushes. A noise filter mounted on the alternator further reduces any existing radio noise. The rotating pole structure of the generator is laminated from steel punchings, containing all six poles and a connecting hub section. This provides optimum magnetic and mechanical properties.
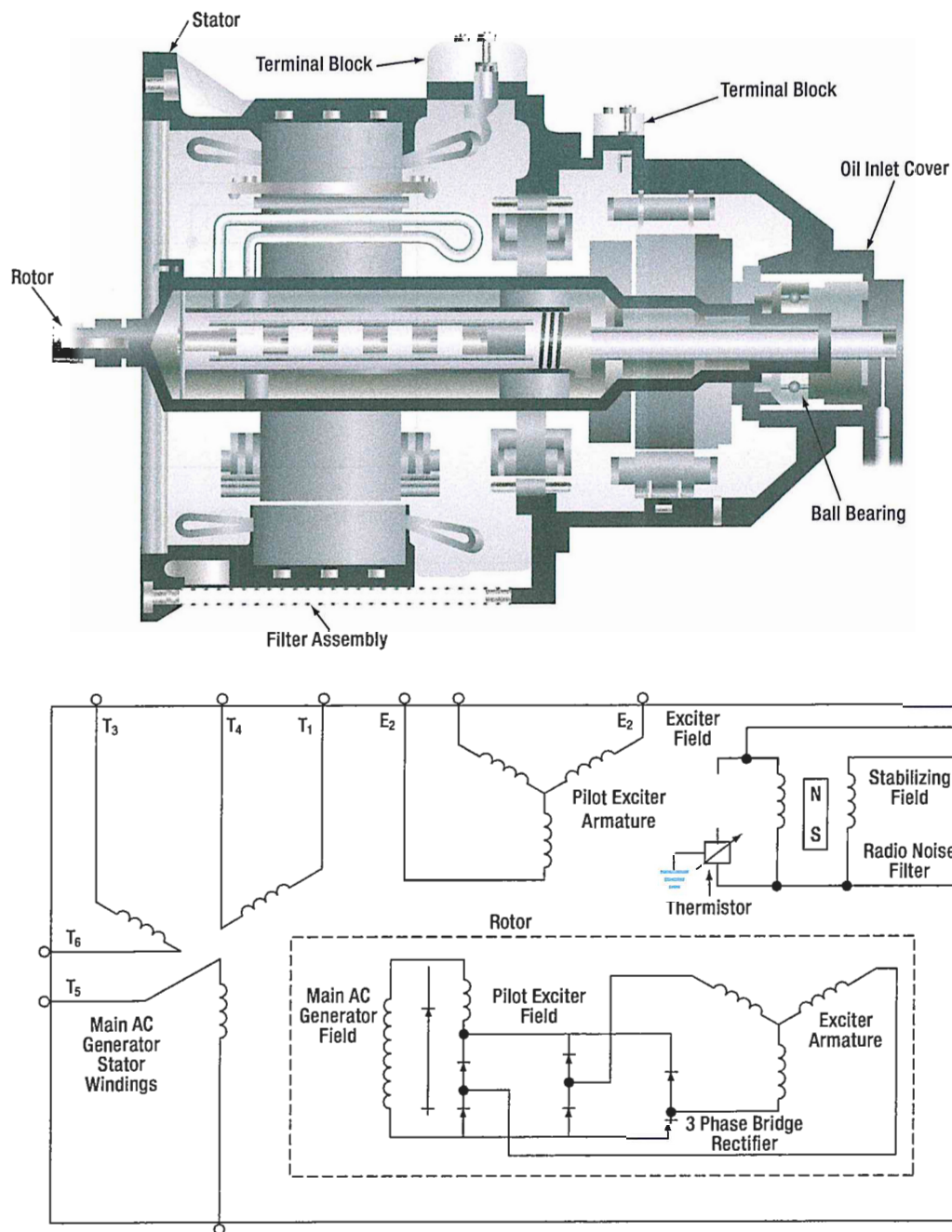
Figure 17-7. A typical brushless alternator.

Some alternators are cooled by circulating oil through steel tubes. The oil used for cooling is supplied from the constant speed drive assembly. Ports located in the flange connecting the generator and drive assemblies make oil flow between the constant speed drive and the generator possible.

Voltage is built up by using permanent magnet interpoles in the exciter stator. The permanent magnets assure a voltage buildup, precluding the necessity of field flashing. The rotor of the alternator may be removed without causing loss of the alternator's residual magnetism.

ALTERNATOR RATING

The maximum current that can be supplied by an alternator depends upon the maximum heating loss (I^2R power loss) that can be sustained in the armature and the maximum heating loss that can be sustained in the field. The armature current of an alternator varies with the load. This action is similar to that of DC generators. In AC generators, however, lagging power factor loads tend to demagnetize the field of an alternator, and terminal voltage is maintained only by increasing DC field current. For this reason, alternating current generators are usually rated according to kVA, power factor, phases, voltage, and frequency. One generator, for example, may be rated at 40 kVA, 208 volts, 400 cycles, three phase, at 75 percent power factor. The kVA indicates the apparent power. This is the kVA output, or the relationship between the current and voltage at which the generator is intended to operate. The power factor is the expression of the ratio between the apparent power (volt-amperes) and the true or effective power (watts). The number of phases is the number of independent voltages generated. Three phase generators generate three voltages 120 electrical degrees apart.

ALTERNATOR FREQUENCY

The frequency of the alternator voltage depends upon the speed of rotation of the rotor and the number of poles. The faster the speed, the higher the frequency will be; the lower the speed, the lower the frequency becomes. The more poles on the rotor, the higher the frequency will be for a given speed. When a rotor has rotated through an angle so that two adjacent rotor poles (a north and a south pole) have passed one winding, the voltage induced in that winding will have varied through one complete cycle. For a given frequency, the greater the number of pairs of poles, the lower the speed of rotation will be. A two-pole alternator rotates at twice the speed of a four-pole alternator for the same frequency of generated voltage.

The frequency of the alternator in cycles per minute is related to the number of poles and the speed, as expressed by the equation;

$$F = \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120}$$

Where P is the number of poles and N the speed in rpm. For example, a two pole, 3 600 rpm alternator has a frequency of;

$$\frac{2 \times 3\,600}{120} = 60 \text{ cps}$$

A four pole, 1 800 rpm alternator has the same frequency; a six pole, 500 rpm alternator has a frequency of;

$$\frac{6 \times 500}{120} = 25 \text{ cps}$$

A 12 pole, 4 000 rpm alternator has a frequency of;

$$\frac{2 \times 4\,000}{120} = 400 \text{ cps}$$

ALTERNATOR MAINTENANCE

Maintenance and inspection of alternator systems are similar to DC systems. Check the exciter brushes for wear and surfacing. On most large aircraft with two or four alternators, 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 can be checked by operating equipment from that particular bus. Consult the manufacturer's instructions for the method of testing each bus.

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 rpm to 9 000 rpm.

A typical test stand motor uses 220/440 volt, 60 cycle, three phase power. Blowers for ventilation, oil coolers, and necessary meters and switches are integral parts of the test stand. A load bank supplies test circuits.

AC GENERATORS

An AC motor generator set for ground testing is shown in *Figure 17-8*. A typical, portable, AC electrical system test set is an analyzer, consisting of a multi-range ohmmeter, a multi-range combination AC/DC voltmeter, an ammeter with a clip-on current transformer, a vibrating reed type frequency meter, and an unmounted continuity light.

A portable load bank unit furnishes a load similar to that on the aircraft 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's instructions on the specific alternator to obtain information on the correct brushes.
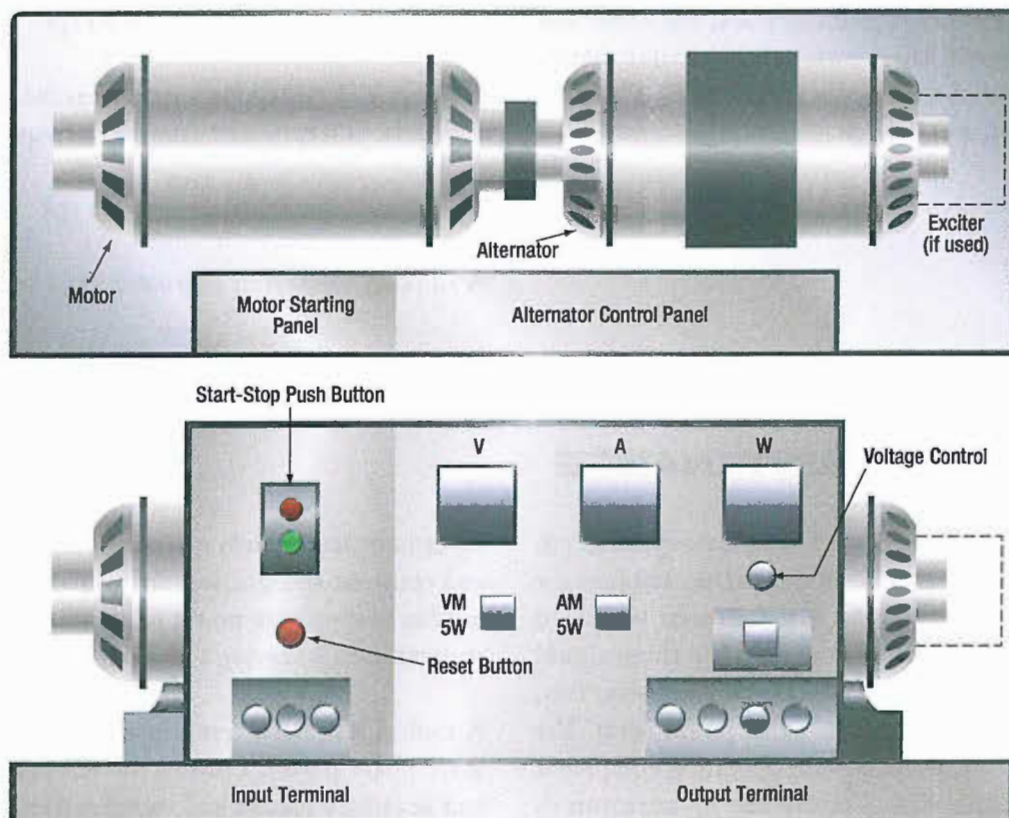
Figure 17-8. AC motor generator set for ground testing.

REGULATION OF GENERATOR VOLTAGE

Efficient operation of electrical equipment in an airplane depends on a constant voltage supply from the generator. Among the factors which determine the voltage output of a generator, only the strength of the field current can be conveniently controlled. To illustrate this control, refer to the diagram in *Figure 17-9* showing a simple generator with a rheostat in the field circuit. If the rheostat is set to increase the resistance in the field circuit, less current flows through the field winding and the strength of the magnetic field in which the armature rotates decreases. Consequently, the voltage output of the generator decreases. If the resistance in the field circuit is decreased with the rheostat, more current flows through the field windings, the magnetic field becomes stronger, and the generator produces a greater voltage.

VOLTAGE REGULATION WITH A VIBRATING-TYPE REGULATOR

Refer to *Figure 17-10*. With the generator running at normal speed and switch K open, the field rheostat is adjusted so that the terminal voltage is about 60 percent of normal. Solenoid S is weak and contact B is held closed by the spring. When K is closed, a short circuit is placed across the field rheostat. This action causes the field current to increase and the terminal voltage to rise.

When the terminal voltage rises above a certain critical value, the solenoid downward pull exceeds the spring tension and contact B opens, thus reinserting the field rheostat in the field circuit and reducing the field current and terminal voltage.

When the terminal voltage falls below a certain critical voltage, the solenoid armature contact B is closed again by the spring, the field rheostat is now shorted, and the terminal voltage starts to rise. The cycle repeats with a rapid, continuous action. Thus, an average voltage is maintained with or without load change.

The dashpot P provides smoother operation by acting as a damper to prevent hunting. The capacitor C across contact B eliminates sparking. Added load causes the field rheostat to be shorted for a longer period of time and; thus, the solenoid armature vibrates more slowly. If the load is reduced and the terminal voltage rises, the armature vibrates more rapidly and the regulator holds the terminal voltage to a steady value for any change in load, from no load to full load, on the generator.

Vibrating-type regulators cannot be used with generators, which require a high field current, since the contacts will pit, or burn.

Heavy-duty generator systems require a different type of regulator, such as the carbon pile voltage regulator.
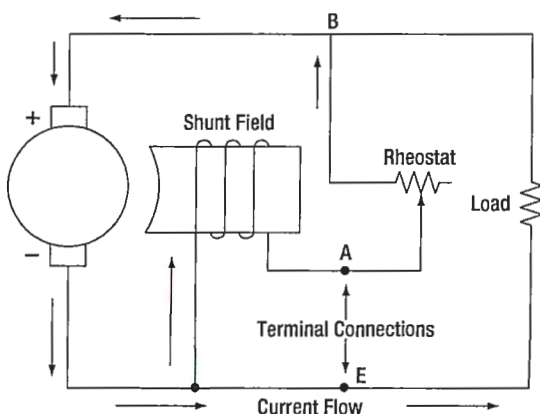
Figure 17-9. Regulation of generator voltage by field rheostat.
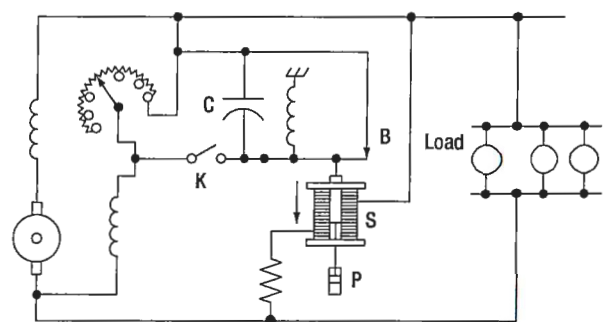
Figure 17-10. Vibrating-type voltage regulator.

THREE UNIT REGULATORS

Many light aircraft employ a three unit regulator for their generator systems. This type of regulator includes a current limiter and a reverse current cutout in addition to a voltage regulator.

The action of the voltage regulator unit is similar to the vibrating-type regulator described earlier. The second of the three units is a current regulator to limit the output current of the generator. The third unit is a reverse current cutout that disconnects the battery from the generator. If the battery is not disconnected, it will discharge through the generator armature when the generator voltage falls below that of the battery, thus driving the generator as a motor. This action is called "motoring" the generator and, unless it is prevented, it will discharge the battery in a short time. The operation of a three unit regulator is described in the following paragraphs. (*Figure 17-11*)

The action of vibrating contact C1 in the voltage regulator unit causes an intermittent short circuit between points R1 and L2. When the generator is not operating, spring S1 holds C1 closed; C2 is also closed by S2. The shunt field is connected directly across the armature. When the generator is started, its terminal voltage will rise as the generator comes up to speed, and the armature will supply the field with current through closed contacts C2 and C1.

As the terminal voltage rises, the current flow through L1 increases and the iron core becomes more strongly magnetized. At a certain speed and voltage, when the

magnetic attraction on the movable arm becomes strong enough to overcome the tension of spring S1, contact points C1 are separated. The field current now flows through R1 and L2. Because resistance is added to the field circuit, the field is momentarily weakened and the rise in terminal voltage is checked. Also, since the L2 winding is opposed to the L1 winding, the magnetic pull of L1 against S1 is partially neutralized, and spring S1 closes contact C1. Therefore, R1 and L2 are again shorted out of the circuit, and the field current again increases; the output voltage increases, and C1 is opened because of the action of L1. The cycle is rapid and occurs many times per second. The terminal voltage of the generator varies slightly, but rapidly, above and below an average value determined by the tension of spring S1, which may be adjusted.

The purpose of the vibrator-type current limiter is to limit the output current of the generator automatically to its maximum rated value in order to protect the generator. As shown in *Figure 17-11*, L3 is in series with the main line and load. Thus, the amount of current flowing in the line determines when C2 will be opened and R2 placed in series with the generator field. By contrast, the voltage regulator is actuated by line voltage, whereas the current limiter is actuated by line current. Spring S2 holds contact C2 closed until the current through the main line and L3 exceeds a certain value, as determined by the tension of spring S2, and causes C2 to be opened. The increase in current is due to an increase in load. This action inserts R2 into the field circuit of the generator and decreases the field current and the generated voltage. When the generated voltage is decreased, the generator current is reduced. The core of L3 is partly demagnetized and the spring closes the contact points. This causes the generator voltage and current to rise until the current reaches a value sufficient to start the cycle again. A certain minimum value of load current is necessary to cause the current limiter to vibrate.

The purpose of the reverse current cutout relay is to automatically disconnect the battery from the generator when the generator voltage is less than the battery voltage. If this device were not used in the generator circuit, the battery would discharge through the generator. This would tend to make the generator operate as a motor, but because the generator is coupled
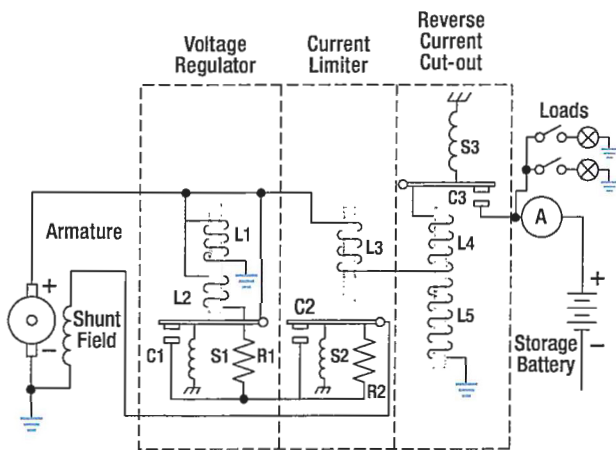

Figure 17-11. Three unit regulator for variable speed generators.

to the engine, it could not rotate such a heavy load. Under this condition, the generator windings may be severely damaged by excessive current.

There are two windings, L4 and L5, on the soft iron core. The current winding, L4, consisting of a few turns of heavy wire, is in series with the line and carries the entire line current. The voltage winding, L5, consisting of a large number of turns of fine wire, is shunted across the generator terminals.

When the generator is not operating, the contacts, C3 are held open by the spring S3. As the generator voltage builds up, L5 magnetizes the iron core. When the current (as a result of the generated voltage) produces sufficient magnetism in the iron core, contact C3 is closed, as shown. The battery then receives a charging current. The coil spring, S3, is so adjusted that the voltage winding will not close the contact points until the voltage of the generator is in excess of the normal voltage of the battery. The charging current passing through L4 aids the current in L5 to hold the contacts tightly closed. Unlike C1 and C2, contact C3 does not vibrate. When the generator slows down or, for any other cause, the generator voltage decreases to a certain value below that of the battery, the current reverses through L4 and the ampere turns of L4 oppose those of L5. Thus, a momentary discharge current from the battery reduces the magnetism of the core and C3 is opened, preventing the battery from discharging into the generator and motoring it. C3 will not close again until the generator terminal voltage exceeds that of the battery by a predetermined value.

DIFFERENTIAL RELAY SWITCH

Aircraft electrical systems normally use some type of reverse current relay switch, which acts not only as a reverse current relay cutout but also serves as a remote control switch by which the generator can be disconnected from the electrical system at any time. One type of reverse current relay switch operates on the voltage level of the generator, but the type most commonly used on large aircraft is the differential relay switch, which is controlled by the difference in voltage between the battery bus and the generator.

The differential type relay switch connects the generator to the main bus bar in the electrical system when the generator voltage output exceeds the bus voltage by 0.35 to 0.65 volt. It disconnects the generator when a nominal reverse current flows from the bus to the generator. The differential relays on all the generators of a multi-engine aircraft do not close when the electrical load is light. For example, in an aircraft having a load of 50 amperes, only two or three relays may close. If a heavy load is applied, the equalizing circuit will lower the voltage of the generators already on the bus and, at the same time, raise the voltage of the remaining generators, allowing their
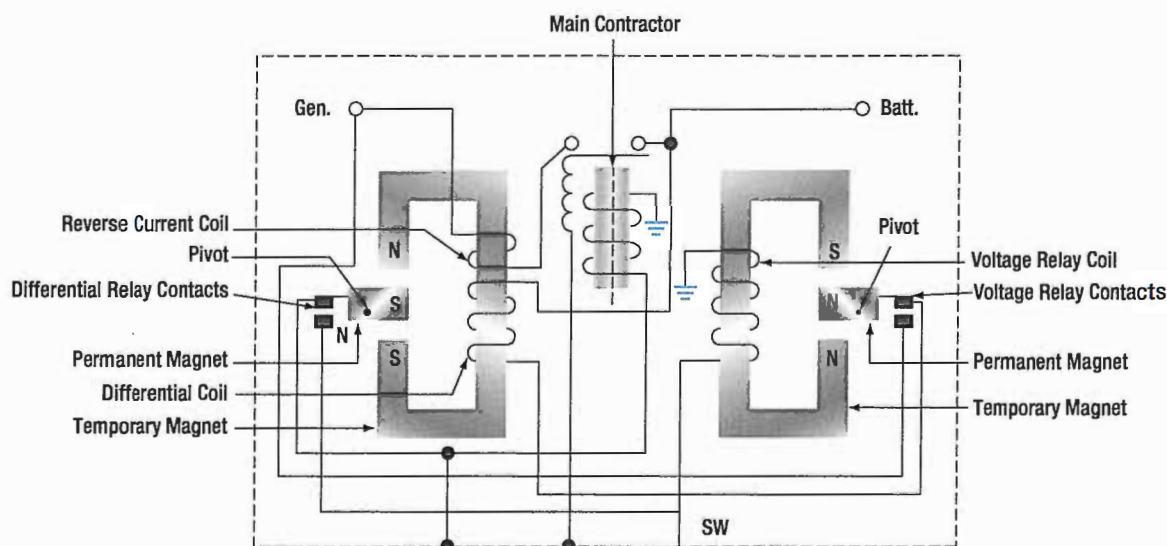
Figure 17-12. Differential generator control relay.

relays to close. If the generators have been paralleled properly, all the relays stay closed until the generator control switch is turned off or until the engine speed falls below the minimum needed to maintain generator output voltage.

The differential generator control relay shown in *Figure 17-12* is made up of two relays and a coil-operated contactor. One relay is the voltage relay and the other is the differential relay. Both relays include permanent magnets, which pivot between the pole pieces of temporary magnets wound with relay coils. Voltages of one polarity set up fields about the temporary magnets with polarities that cause the permanent magnet to move in the direction necessary to close the relay contacts; voltages of the opposite polarity establish fields that cause the relay contacts to open. The differential relay has two coils wound on the same core. The coil-operated contactor, called the main contactor, consists of movable contacts that are operated by a coil with a movable iron core.

Closing the generator switch on the control panel connects the generator output to the voltage relay coil. When generator voltage reaches 22 volts, current flows through the coil and closes the contacts of the voltage relay. This action completes a circuit from the generator to the battery through the differential coil.

When the generator voltage exceeds the bus voltage by 0.35 volt, current will flow through the differential coil, the differential relay contact will close and, thus, complete the main contractor coil circuit. The contacts of the main contactor close and connect the generator to the bus. When the generator voltage drops below the bus (or battery) voltage, a reverse current weakens the magnetic field about the temporary magnet of the differential relay. The weakened field permits a spring to open the differential relay contacts, breaking the circuit to the coil of the main contactor relay, opening its contacts, and disconnecting the generator from the bus. The generator battery circuit may also be broken by opening the cockpit control switch, which opens the contacts of the voltage relay, causing the differential relay coil to be de-energized.

OVERVOLTAGE AND FIELD CONTROL RELAYS

Two other items used with generator control circuits are the overvoltage control and the field control relay. As its name implies, the overvoltage control protects the system when excessive voltage exists. The overvoltage relay is closed when the generator output reaches 32 volts and completes a circuit to the trip coil of the field control relay. The closing of the field control relay trip circuit opens the shunt field circuit and completes it

through a resistor, causing generator voltage to drop; also, the generator switch circuit and the equalizer circuit (multiengine aircraft) are opened. An indicator light circuit is completed, warning that an overvoltage condition exists. A "reset" position of the cockpit switch is used to complete a reset coil circuit in the field control relay, returning the relay to its normal position.

GENERATOR CONTROL UNITS (GCU)

The generator control unit (GCU) is more commonly found on turbine power aircraft. The most basic generator control units perform a number of functions related to the regulation, sensing, and protection of the DC generation system.

VOLTAGE REGULATION
The most basic of the GCU functions is that of voltage regulation. Regulation of any kind requires the regulation unit to take a sample of an output and to compare that sample with a controlled reference. If the sample taken falls outside of the limits set by the

reference, then the regulation unit must provide an adjustment to the unit generating the output so as to diminish or increase the output levels. In the case of the GCU, the output voltage from a generator is sensed by the GCU and compared to a reference voltage. If there is any difference between the two, the error is usually amplified and then sent back to the field excitation control portion of the circuit. The field excitation control then makes voltage/excitation adjustments in the field winding of the generator in order to bring the output voltage back into required bus tolerances.

OVERVOLTAGE PROTECTION

Like the voltage regulation feature of the GCU, the overvoltage protection system compares the sampled voltage to reference voltage. The output of the overvoltage protection circuit is used to open the relay that controls the output for the field excitation. These types of faults can occur for a number of reasons. The most common, however, is the failure of the voltage regulation circuit in the GCU.

PARALLEL GENERATOR OPERATIONS

The paralleling feature of the GCU allows for two or more GCU/generator systems to work in a shared effort to provide current to the aircraft electrical system. Comparing voltages between the equalizer bus and the interpole/compensator voltage, and amplifying the differences accomplishes the control of this system. The difference is then sent to the voltage regulation circuit, where adjustments are then made in the regulation output. These adjustments will continue until all of the busses are equalized in their load sharing.

OVER-EXCITATION PROTECTION

When a GCU in a paralleled system fails, a situation can occur where one of the generators becomes overexcited and tries to carry more than its share of the load, if not all of the loads. When this condition is sensed on the equalizing bus, the faulted generation control system will shut down by receiving a de-excitation signal. This signal is then transmitted to the overvoltage circuit, and then opens the field excitation output circuit.

DIFFERENTIAL VOLTAGE

When the GCU allows the logic output to close the generator line contactor, the generator voltage must be within a close tolerance of the load bus. If the output is not within the specified tolerance, then the contactor is not allowed to connect the generator to the bus.

REVERSE CURRENT SENSING

If the generator is unable to maintain the required voltage level, it will eventually begin to draw current instead of providing it. In this case, the faulty generator will be seen as a load to the other generators and will need to be removed from the bus. Once the generator is off-line, it will not be permitted to be reconnected to the bus until such time that the generator faults are cleared and the generator is capable of providing a current to the bus. In most cases, the differential voltage circuit and the reverse current sensing circuit are one in the same.

ALTERNATOR CONSTANT SPEED DRIVE SYSTEM

Alternators are not always connected directly to the airplane engine like DC generators. Since the various electrical devices operating on AC supplied by alternators are designed to operate at a certain voltage and at a specified frequency, the speed of the alternators must be constant; however, the speed of an airplane engine varies. Therefore, the engine, through a constant speed drive installed between the engine and the alternator, drives some alternators.

A typical hydraulic-type drive is shown in *Figure 17-13*. The following discussion of a constant speed drive system will be based on such a drive, found on large multi-engine aircraft. The constant speed drive is a hydraulic transmission, which may be controlled either electrically or mechanically.
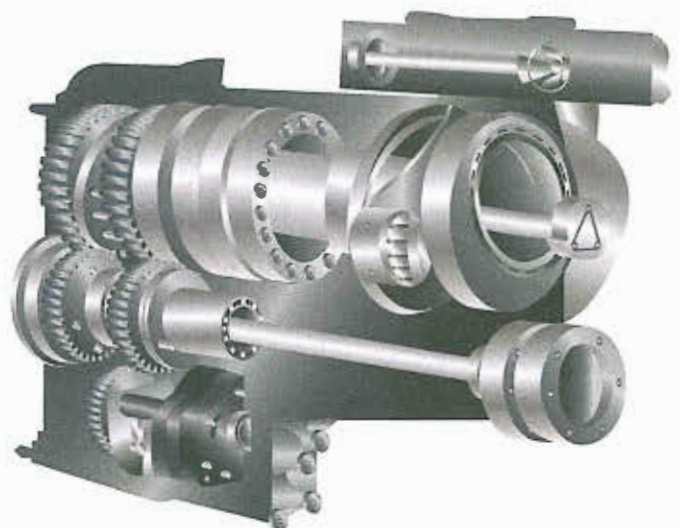
Figure 17-13. Constant speed drive.

AC GENERATORS

The constant speed drive assembly is designed to deliver an output of 6 000 rpm, provided the input remains between 2 800 and 9 000 rpm. If the input, which is determined by engine speed, is below 6 000 rpm, the drive increases the speed in order to furnish the desired output. This stepping up of speed is known as overdrive.

In overdrive, an automobile engine will operate at about the same rpm at 60 mph as it does in conventional drive at 49 mph. In aircraft, this principle is applied in the same manner. The constant speed drive enables the alternator to produce the same frequency at slightly above engine idle rpm as it would at takeoff or cruising rpm.

With the input speed to the drive set at 6 000 rpm, the output speed will be the same. This is known as straight drive and might be compared to an automobile in high gear. However, when the input speed is greater than 6 000 rpm, it must be reduced to provide an output of 6 000 rpm. This is called under drive, which is comparable to an automobile in low gear. Thus, the large input caused by high engine rpm, is reduced to give the desired alternator speed.

As a result of this control by the constant speed drive, the frequency output of the generator varies from 420 cps at no load to 400 cps under full load.

This, in brief, is the function of the constant speed drive assembly. Before discussing the various units and circuits, the overall operation of the transmission should be discussed as follows.

HYDRAULIC TRANSMISSION

The transmission is mounted between the generator and the aircraft engine. Its name denotes that hydraulic oil is used, although some transmissions may use engine oil. Refer to the cutaway view of such a transmission in *Figure 17-14*. The input shaft D is driven from the drive shaft on the accessory section of the engine. The output drive F, on the opposite end of the transmission, engages the drive shaft of the generator.

The input shaft is geared to the rotating cylinder block gear which it drives, as well as to the makeup and scavenger gear pumps E. The makeup (charge) pump delivers oil (300 psi) to the pump and motor cylinder block, to the governor system, and to the pressurized case, whereas the scavenger pump returns the oil to the external reservoir.

The rotating cylinder assembly B consists of the pump and motor cylinder blocks which are bolted to opposite sides of a port plate. The two other major parts are the motor wobbler A and the pump wobbler C. The governor system is the unit at the top of the left side in the illustration.

The cylinder assembly has two primary units. The block assembly of one of the units, the pump, contains 14 cylinders, each of which has a piston and pushrod. Charge pressure from the makeup pump is applied to each piston in order to force it outward against the pushrod. It, in turn, is pushed against the pump wobble plate.

If the plate remained as shown in *Figure 17-15A*, each of the 14 cylinders would have equal pressure, and all pistons would be in the same relative position in their respective cylinders. But with the plate tilted, the top portion moves outward and the lower portion inward, as shown in *Figure 17-15B*. As a result, more oil enters the interior of the upper cylinder, but oil will be forced from the cylinder of the bottom piston.

If the pump block were rotated while the plate remained stationary, the top piston would be forced inward because of the angle of the plate. This action would cause the oil confined within the cylinder to be subjected to increased pressure great enough to force it into the motor cylinder block assembly.

Before explaining what the high-pressure oil in the motor unit will do, it is necessary to know something about this part of the rotating cylinder block assembly. The motor block assembly has 16 cylinders, each with its piston and pushrod. These are constantly receiving charge pressure of 300 psi. The position of the piston depends upon the point at which each pushrod touches the motor wobble plate. These rods cause the wobble plate to rotate by the pressure they exert against its sloping surface.

The piston and pushrod of the motor are pushed outward as oil is forced through the motor valve plate from the pump cylinder. The pushrods are forced against the
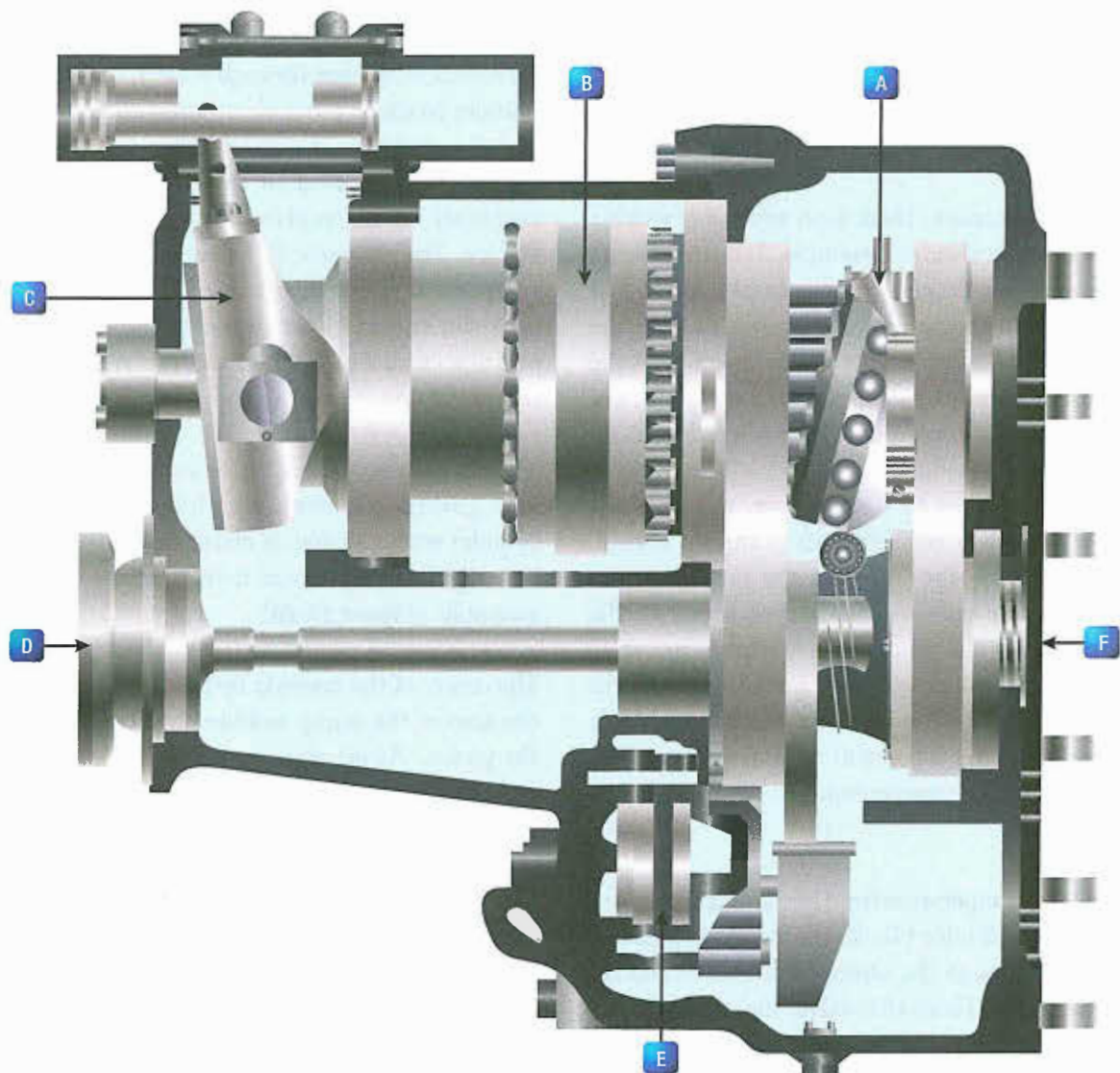
Figure 17-14. Cutaway of a hydraulic transmission.

(A)   (B)
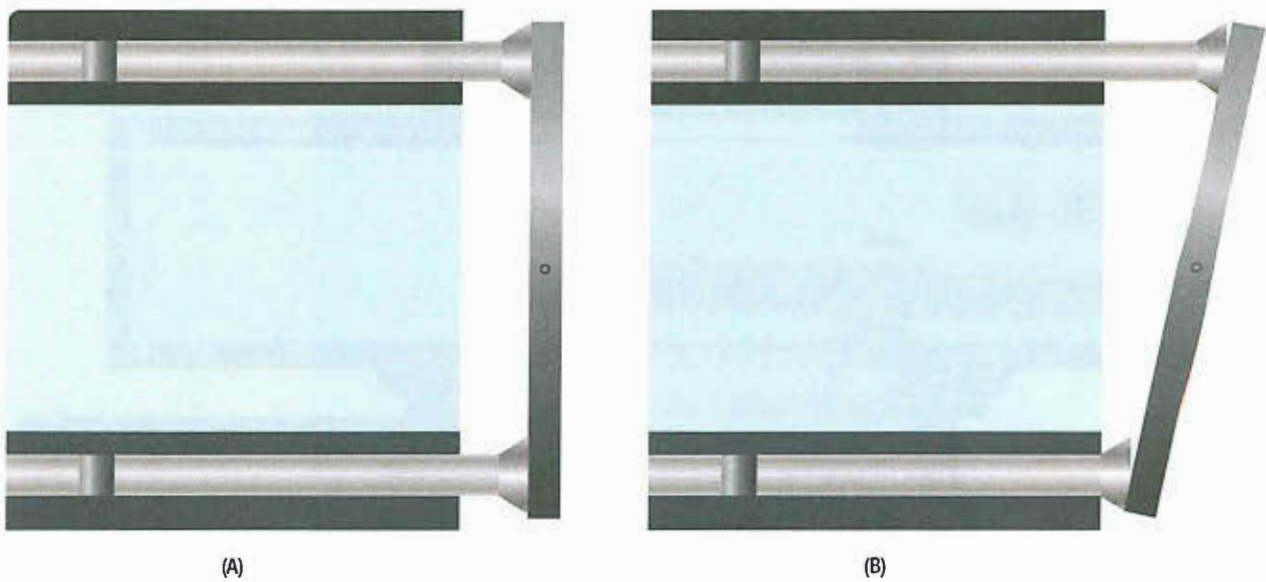
Figure 17-15. Wobble plate position.

motor wobble plate, which is free to rotate but cannot change the angle at which it is set. Since the pushrods cannot move sideways, the pressure exerted against the motor wobble plate's sloping face causes it to rotate.

In the actual transmission, there is an adjustable wobble plate. The control cylinder assembly determines the tilt of the pump wobble plate. For example, it is set at an angle which causes the motor cylinders to turn the motor wobble plate faster than the motor assembly, if the transmission is in overdrive. The greater pressure in the pump and motor cylinders produces the result described.

With the transmission in underdrive, the angle is arranged so there is a reduction in pumping action. The subsequent slippage between the pushrods and motor wobble plate reduces the output speed of the transmission. When the pump wobble plate is not at an angle, the pumping action will be at a minimum and the transmission will have what is known as hydraulic lock. For this condition, the input and output speed will be about the same, and the transmission is considered to be in straight drive.

To prevent the oil temperature from becoming excessively high within the cylinder block, the makeup pressure pump forces oil through the center of this block and the pressure relief valve. From this valve, the oil flows into the bottom of the transmission case. A scavenger pump removes the oil from the transmission case and circulates it through the oil cooler and filters before returning it to the reservoir. At the start of the cycle, oil is drawn from the reservoir, passed through a filter, and forced into the cylinder block by the makeup pressure pump.

The clutch, located in the output gear and clutch assembly, is an overrunning one way, sprag-type device. Its purpose is to ratchet if the alternator becomes motorized; otherwise, the alternator might turn the engine. Furthermore, the clutch provides a positive connection when the transmission is driving the alternator.

There is another unit of the drive that must be discussed. The governor system, which consists of a hydraulic cylinder with a piston, is electrically controlled. Its duty is to regulate oil pressure flowing to the control cylinder assembly. (*Figure 17-16*)

The center of the system's hydraulic cylinder is slotted so the arm of the pump wobble plate can be connected to the piston. As oil pressure moves the piston, the pump wobble plate is placed in either overspeed, under speed, or straight drive. *Figure 17-17* shows the electrical circuit used to govern the speed of the transmission. First, the main points of the complete electrical control circuit will be discussed. (*Figures 17-17 and 17-18*)

Then, for simplification, two portions, the overspeed circuit and the load division circuit, will be considered as individual circuits.
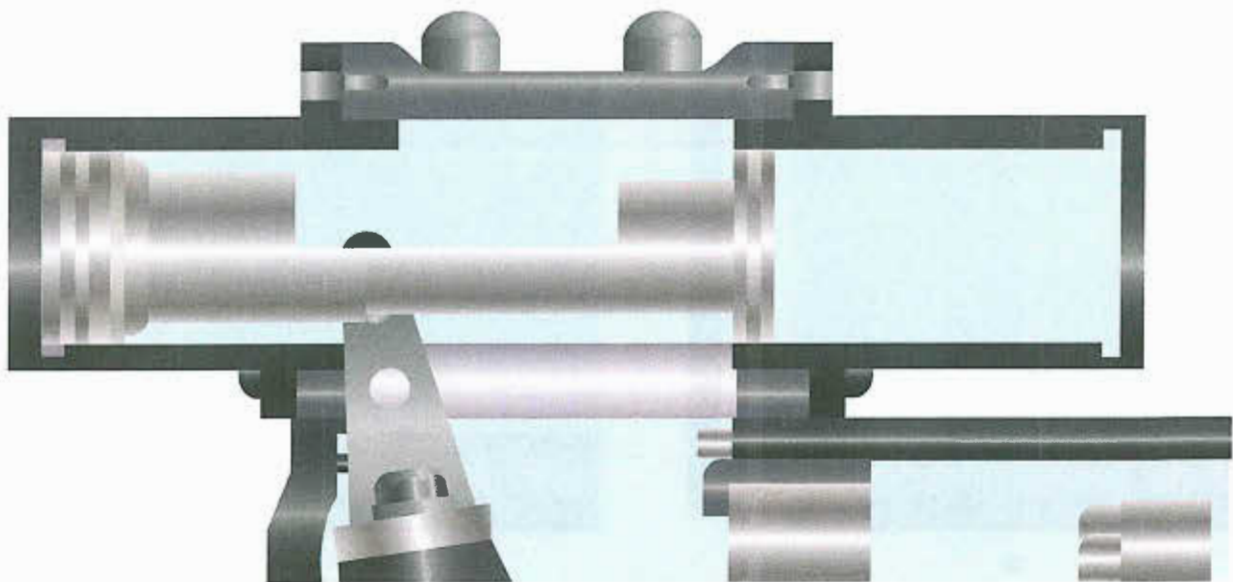
Figure 17-16. Control cylinder.
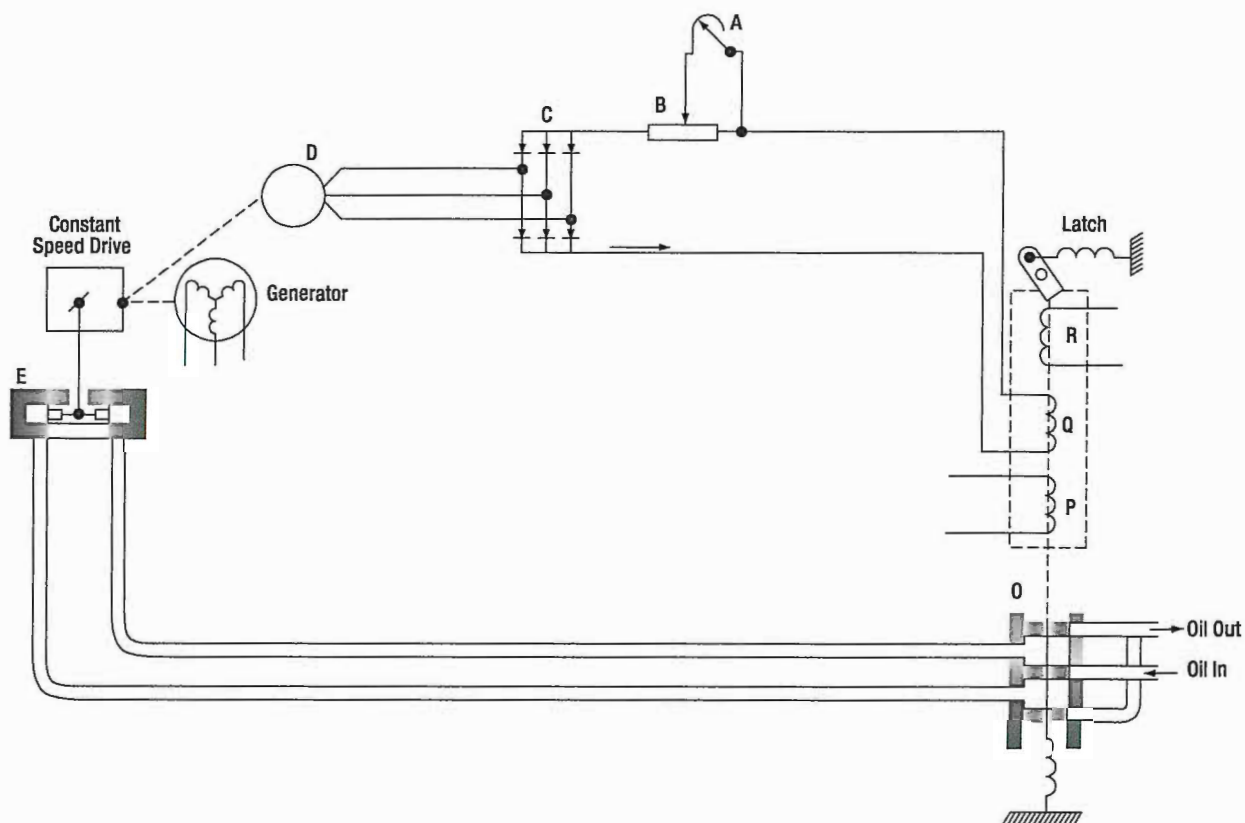
Figure 17-17. Electrical hydraulic control circuit.
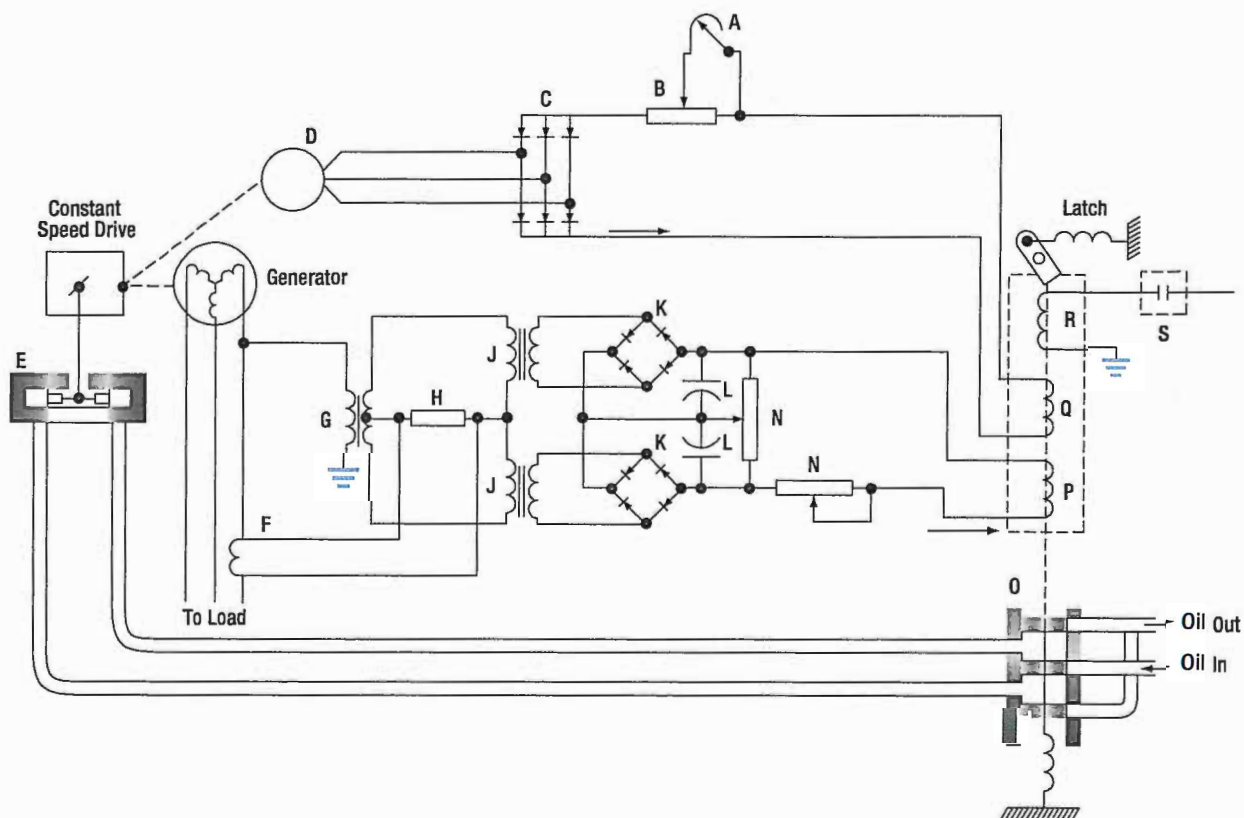
Figure 17-18. Speed control circuit.

Note, then, in *Figure 17-17*, that the circuit has a valve and solenoid assembly O and a control cylinder E, and that it contains such units as the tachometer generator D, the rectifier C, and adjustable resistor B, rheostat A, and the control coil Q.

Since it is driven by a drive gear in the transmission, the tachometer (often called tach) generator, a three phase unit, has a voltage proportional to the speed of the output drive. The rectifier changes its voltage from AC to DC. After rectification, the current flows through the resistor, rheostat, and valve and solenoid. Each of these units is connected in series. (*Figure 17-18*)

Under normal operating conditions, the output of the tach generator causes just enough current to enter the valve and solenoid coil to set up a magnetic field of sufficient strength to balance the spring force in the valve. When the alternator speed increases as the result of a decrease in load, the tach generator output also increases. Because of the greater output, the coil in the solenoid is sufficiently strengthened to overcome the spring force. Thus, the valve moves and, as a result, oil pressure enters the reduced speed side of the control cylinder.

In turn, the pressure moves the piston, causing the angle of the pump wobble plate to be reduced. The oil on the other side of the piston is forced back through the valve into the system return. Since the angle of the pump wobble plate is smaller, there is less pumping action in the transmission. The result is decreased output speed. To complete the cycle, the procedure is reversed.

With the output speed reduction, tach generator output decreases; consequently, the flow of current to the solenoid diminishes. Therefore, the magnetic field of the solenoid becomes so weak that the spring is able to overcome it and reposition the valve.

If a heavy load is put on the AC generator, its speed decreases. The generator is not driven directly by the engine; the hydraulic drive will allow slippage. This decrease will cause the output of the tach generator to taper off and, as a result, weaken the magnetic field of the solenoid coil. The spring in the solenoid will move the valve and allow oil pressure to enter the increase side of the control cylinder and the output speed of the transmission will be raised.

There are still two important circuits, which must be discussed: the overspeed circuit and the load division circuit. The generator is prevented from overspeeding by a centrifugal switch (S in *Figure 17-19*) and the overspeed solenoid coil R, which is located in the solenoid and valve assembly. The centrifugal switch is on the transmission and is driven through the same gear arrangement as the tach generator.

The aircraft DC system furnishes the power to operate the overspeed coil in the solenoid and coil assembly. If the output speed of the transmission reaches a speed of 7 000 to 7 500 rpm, the centrifugal switch closes the
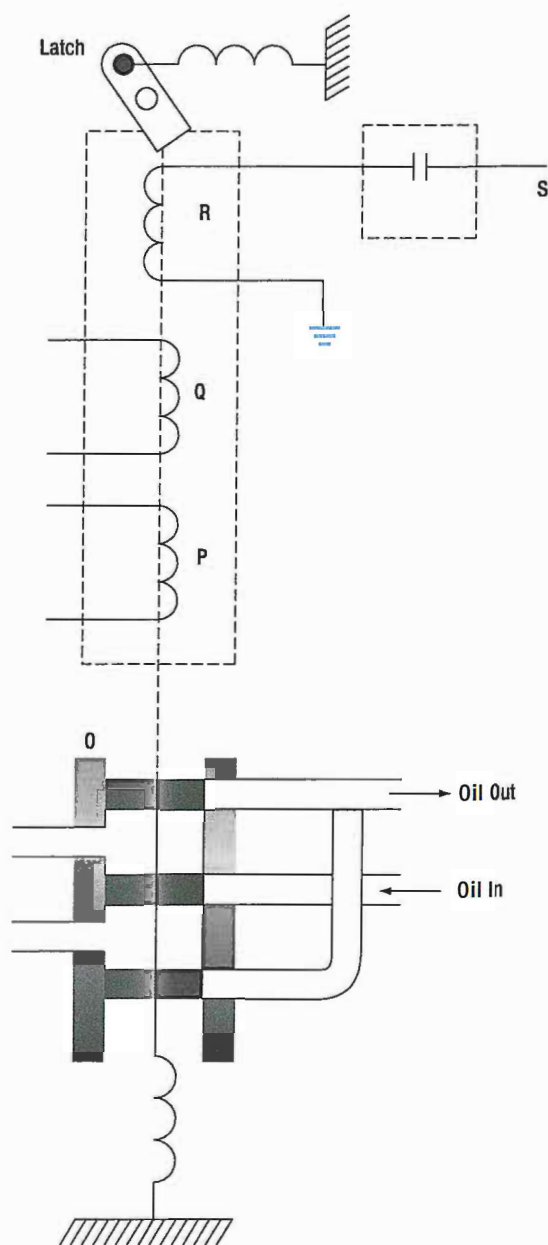
Figure 17-19. Overspeed circuit.

DC circuit and energizes the overspeed solenoid. This component then moves the valve and engages the latch that holds the valve in the underdrive position. To release the latch, energize the underdrive release solenoid.

The load division circuit's function is to equalize the loads placed on each of the alternators, which is necessary to assure that each alternator assumes its share; otherwise, one alternator might be overloaded while another would be carrying only a small load.

In *Figure 17-20*, one phase of the alternator provides power for the primary in transformer G, whose secondary supplies power to the primaries of two other transformers, J1 and J2. Rectifiers K then change the output of the transformer secondaries from AC to DC. The function of the two capacitors, L, is to smooth out the DC pulsations.

The output of the current transformer F depends upon the amount of current flowing in the line of one phase. In this way, it measures the real load of the generator. The output voltage of the current transformer is applied across resistor H. This voltage will be added vectorially to the voltage applied to the upper winding of transformer J by the output of transformer F. At the same time as it adds vectorially to the upper winding of transformer J, it subtracts vectorially from the voltage applied to the lower winding of J.

This voltage addition and subtraction depends on the real load of the generator. The amount of real load determines the phase angle and the amount of voltage impressed across resistor H. The greater the real load, the greater the voltage across H, and hence, the greater the difference between the voltages applied to the two primaries of transformer J. The unequal voltages applied to resistor M by the secondaries of transformer J cause a current flow through the control coil P.

The control coil is wound so that its voltage supplements the voltage for the control coil in the valve and solenoid assembly. The resulting increased voltage moves the valve and slows down the generator's speed. Why should the speed be decreased if the load has been increased? Actually, systems using only one generator would not have decreased speed, but for those having two or more generators, a decrease is necessary to equalize the loads.

The load division circuit is employed only when two or more generators supply power. In such systems, the control coils are connected in parallel. If the source voltage for one of these becomes higher than the others, it determines the direction of current flow throughout the entire load division circuit. As explained before, the real load on the generator determines the amount of voltage on the control coil; therefore, the generator with the highest real load has the highest voltage.
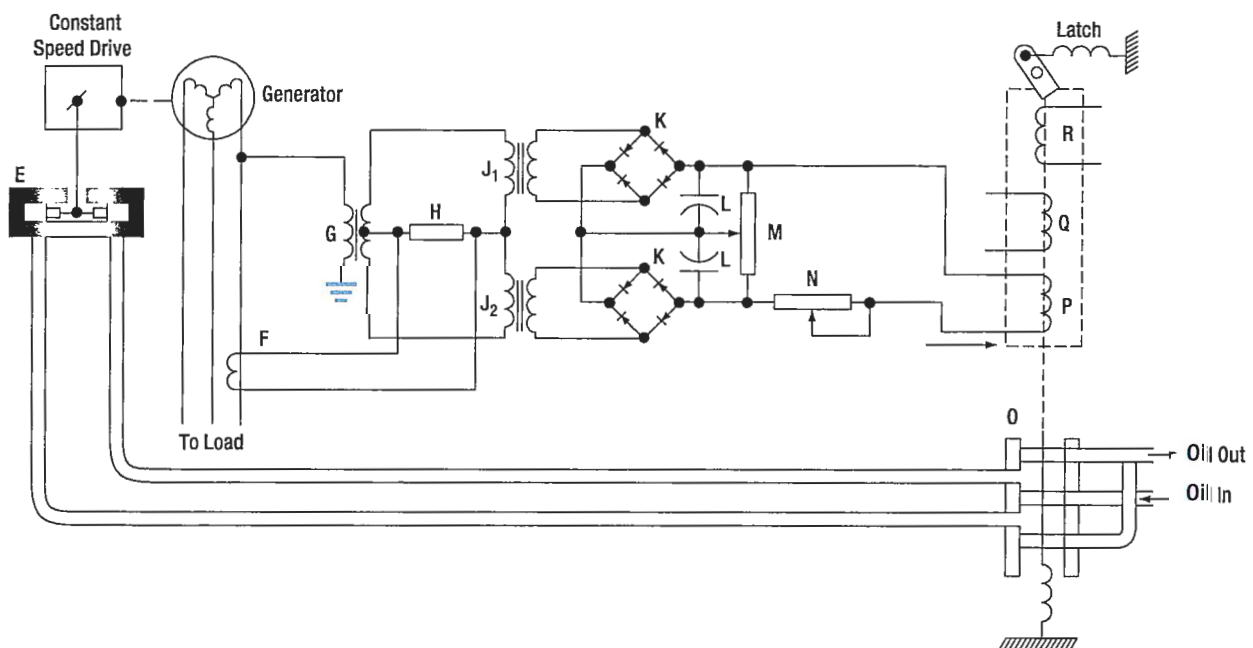
Figure 17-20. Droop circuit.

As shown in *Figure 17-21*, current through No. 1 control coil, where the largest load exists, aids the control coil of the valve and solenoid, thereby slowing down the generator. (The source voltage of the control coils is represented by battery symbols in the illustration.) The current in the remaining control coils opposes the control coil of the valve and solenoid, in order to increase the speed of the other generators so the load will be more evenly distributed.

On some drives, instead of an electrically controlled governor, a flyweight-type governor is employed, which consists of a recess-type revolving valve driven by the output shaft of the drive, flyweights, two coil springs, and a non-rotating valve stem. Centrifugal force, acting on the governor flyweights, causes them to move outward, lifting the valve stem against the opposition of a coil spring.

The valve stem position controls the directing of oil to the two oil outlines. If the output speed tends to exceed 6 000 rpm, the flyweights will lift the valve stem to direct more oil to the side of the control piston, causing the piston to move in a direction to reduce the pump wobble plate angle. If the speed drops below 6 000 rpm, oil is directed to the control piston so that it moves to increase the wobble plate angle.

Overspeed protection is installed in the governor. The drive starts in the underdrive position. The governor coil springs are fully extended and the valve stem is held at the limit of its downward travel. In this condition, pressure is directed to the side of the control piston giving minimum wobble plate angle. The maximum angle side of the control piston is open to the hollow
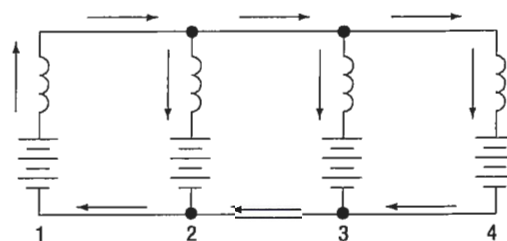
Figure 17-21. Relative direction of current in droop coil circuit with unequal loads.

stem. As the input speed increases, the flyweights start to move outward to overcome the spring bias. This action lifts the valve stem and starts directing oil to the maximum side of the control piston, while the minimum side is opened to the hollow stem.

At about 6 000 rpm, the stem is positioned to stop drainage of either side, and the two pressures seek a balance point as the flyweight force is balanced against the spring bias. Thus, a mechanical failure in the governor will cause an underdrive condition. The flyweight's force is always tending to move the valve stem to the decrease speed position so that, if the coil spring breaks and the stem moves to the extreme position in that direction, output speed is reduced. If the input to the governor fails, the spring will force the stem all the way to the start position to obtain minimum output speed.

An adjustment screw on the end of the governor regulates the output speed of the constant speed drive. This adjustment increases or decreases the compression of a coil spring, opposing the action of the flyweights. The adjustment screws turn in an indented collar, which provides a means of making speed adjustments in known increments. Each "click" provides a small change in generator frequency.

VOLTAGE REGULATION OF ALTERNATORS

The problem of voltage regulation in an AC system does not differ basically from that in a DC system. In each case, the function of the regulator system is to control voltage, maintain a balance of circulating current throughout the system, and eliminate sudden changes in voltage (anti-hunting) when a load is applied to the system. However, there is one important difference between the regulator system of DC generators and alternators operated in a parallel configuration. The load carried by any particular DC generator in either a two or four generator system depends on its voltage

as compared with the bus voltage, while the division of load between alternators depends upon the adjustments of their speed governors, which are controlled by the frequency and droop circuits discussed in the previous section on alternator constant-speed drive systems.

When AC generators are operated in parallel, frequency and voltage must both be equal. Where a synchronizing force is required to equalize only the voltage between DC generators, synchronizing forces are required to equalize both voltage and speed (frequency) between AC

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generators. On a comparative basis, the synchronizing forces for AC generators are much greater than for DC generators. When AC generators are of sufficient size and are operating at unequal frequencies and terminal voltages, serious damage may result if they are suddenly connected to each other through a common bus. To avoid this, the generators must be synchronized as closely as possible before connecting them together.

Regulating the voltage output of a DC exciter, which supplies current to the alternator rotor field, best controls the output voltage of an alternator. This is accomplished by the regulation of a 28-volt system connected in the field circuit of the exciter. A regulator controls the exciter field current and thus regulates the exciter output voltage applied to the alternator field.

ALTERNATOR TRANSISTORIZED REGULATORS

Many aircraft alternator systems use a transistorized voltage regulator to control the alternator output. Before studying this section, a review of transistor principles may be helpful.

A transistorized voltage regulator consists mainly of transistors, diodes, resistors, capacitors, and, usually, a thermistor. In operation, current flows through a diode and transistor path to the generator field. When the proper voltage level is reached, the regulating components cause the transistor to cut off conduction to control the alternator field strength. The regulator operating range is usually adjustable through a narrow range. The thermistor provides temperature compensation for the circuitry. The transistorized voltage regulator shown in *Figure 17-22* will be referred to in explaining the operation of this type of regulator.

The AC output of the generator is fed to the voltage regulator, where it is compared to a reference voltage, and the difference is applied to the control amplifier section of the regulator. If the output is too low, field strength of the AC exciter generator is increased by the circuitry in the regulator. If the output is too high, the field strength is reduced.
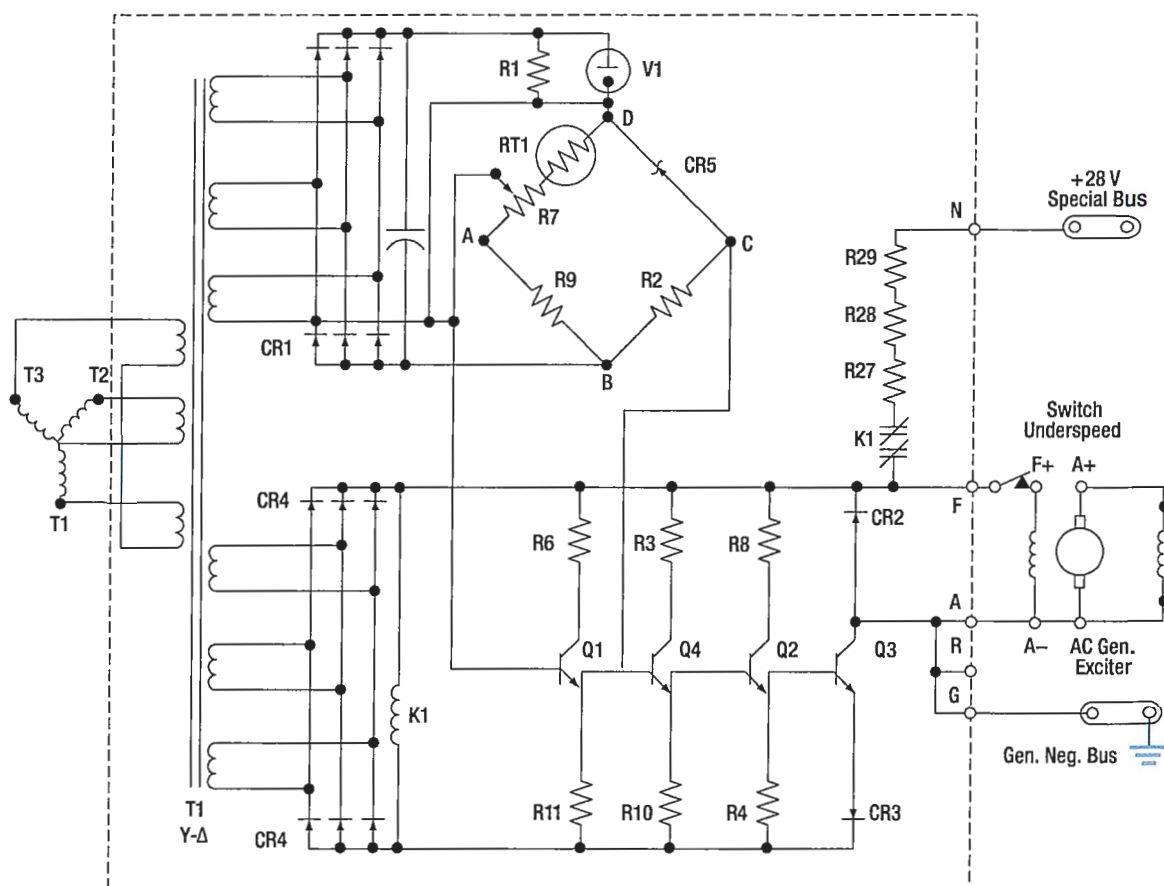
Figure 17-22. Transistorized voltage regulator.

The power supply for the bridge circuit is CR1, which provides full-wave rectification of the three phase output from transformer T1. The DC output voltages of CR1 are proportional to the average phase voltages. Power is supplied from the negative end of the power supply through point B, R2, point C, zener diode (CR5), point D, and to the parallel hookup of V1 and R1. Takeoff point C of the bridge is located between resistor R2 and the zener diode. In the other leg of the reference bridge, resistors R9, R7, and the temperature compensating resistor RT1 are connected in series with V1 and R1 through points B, A, and D. The output of this leg of the bridge is at the wiper arm of R7.

As generator voltage changes occur, for example, if the voltage lowers, the voltage across R1 and V1 (once V2 starts conducting) will remain constant. The total voltage change will occur across the bridge circuit. Since the voltage across the zener diode remains constant (once it starts conducting), the total voltage change occurring in that leg of the bridge will be across resistor R2. In the other leg of the bridge, the voltage change across the resistors will be proportional to their resistance values. Therefore, the voltage change across R2 will be greater than the voltage change across R9 to wiper arm of R7. If the generator output voltage drops, point C will be negative with respect to the wiper arm of R7. Conversely, if the generator voltage output increases, the polarity of the voltage between the two points will be reversed.

The bridge output, taken between points C and A, is connected between the emitter and the base of transistor Q1. With the generator output voltage low, the voltage from the bridge will be negative to the emitter and positive to the base. This is a forward bias signal to the transistor, and the emitter to collector current will therefore increase. With the increase of current, the voltage across emitter resistor R11 will increase. This, in turn, will apply a positive signal to the base of transistor Q4, increasing its emitter to collector current and increasing the voltage drop across the emitter resistor R10.

This will give a positive bias to the base of Q2, which will increase its emitter to collector current and increase the voltage drop across its emitter resistor R4. This positive signal will control output transistor Q3. The positive signal on the base of Q3 will increase the emitter to collector current.

- The control field of the exciter generator is in the collector circuit. Increasing the output of the exciter generator will increase the field strength of the AC generator, which will increase the generator output.
- To prevent exciting the generator when the frequency is at a low value, there is an underspeed switch located near the F+ terminal. When the generator reaches a suitable operating frequency, the switch will close and allow the generator to be excited.

Another item of interest is the line containing resistors R27, R28, and R29 in series with the normally closed contacts of the K1 relay. The operating coil of this relay is found in the lower left-hand part of the schematic. Relay K1 is connected across the power supply (CR4) for the transistor amplifier. When the generator is started, electrical energy is supplied from the 28-volt DC bus to the exciter generator field, to "flash the field" for initial excitation. When the field of the exciter generator has been energized, the AC generator starts to produce, and as it builds up, relay K1 is energized, opening the "field flash" circuit.

INVERTERS

An inverter is used in some aircraft systems to convert a portion of the aircraft's DC power to AC. This AC is used mainly for instruments, radio, radar, lighting, and other accessories. These inverters are usually built to supply current at a frequency of 400 cps, but some are designed to provide more than one voltage; for example, 26 volt AC 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 AC generators and DC motors in one housing. The generator field, or

armature, and the motor field, or armature, are mounted on a common shaft that 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 DC motor and a permanent magnet AC generator assembly. Each has a separate stator mounted within a common housing. The motor armature is mounted on a rotor and connected to the DC supply through a commutator and brush assembly. The motor field windings are mounted on the housing and connected directly to the DC 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 AC to be taken from the inverter without the use of

brushes. *Figure 17-23* shows an 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 AC stator coils, and the magnetic flux developed by the permanent magnets will be cut by the conductors in the AC stator coils. An AC voltage will be produced in the windings whose polarity will change as each pole passes the windings.

This type inverter may be made multiphase by placing more AC stator coils in the housing in order to shift the phase the proper amount in each coil.
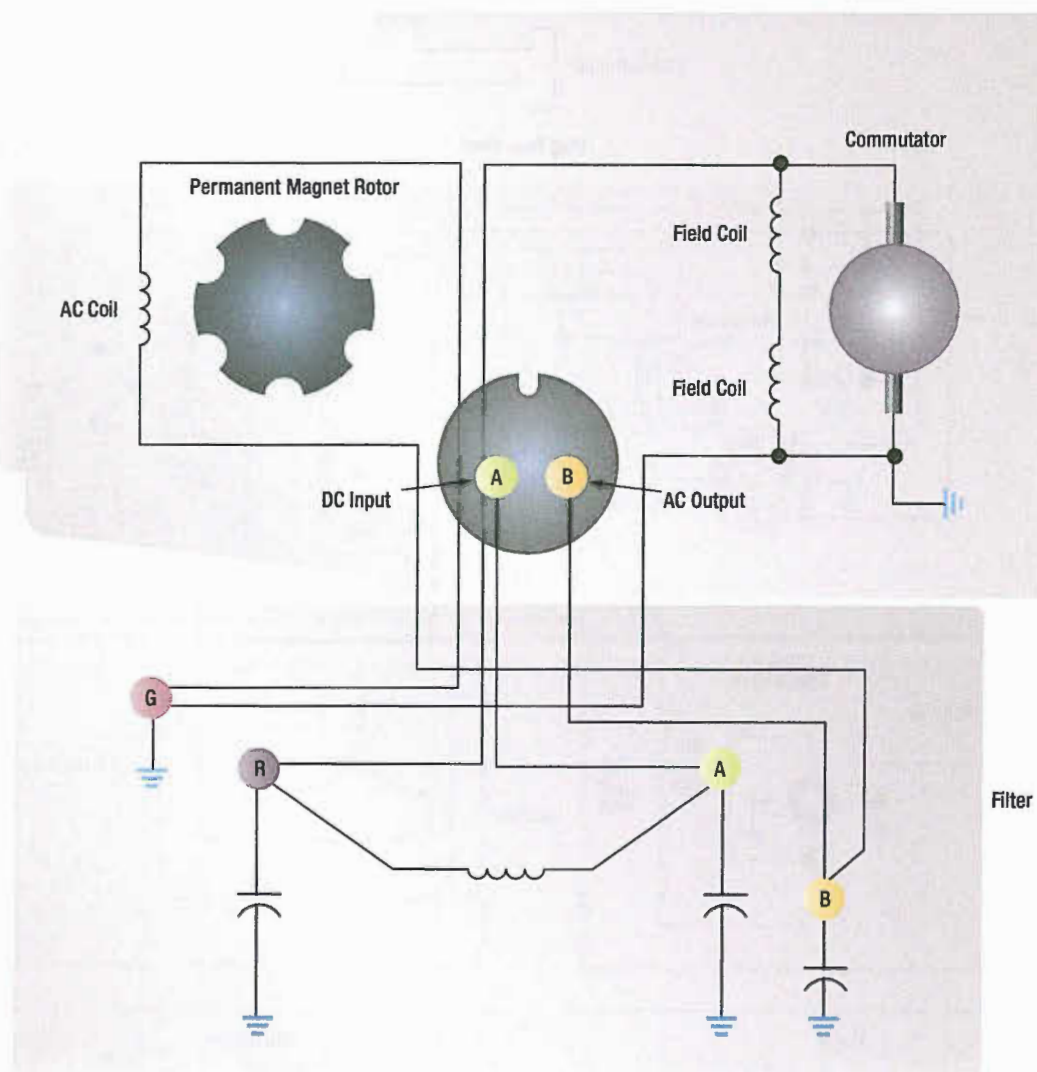
Figure 17-23. Internal wiring diagram of single-phase permanent magnet rotary inverter.

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AC GENERATORS

As the name of the rotary inverter indicates, it has a revolving armature in the AC generator section. The illustration in *Figure 17-24* shows the diagram of a revolving armature, three phase inverter.

The DC 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 DC 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 that is in series with the shunt field when the motor reaches a certain speed.

The alternator is a three-phase, four-pole, star-connected AC generator. The DC input is supplied to the generator field coils and connected to ground through a voltage regulator. The output is taken off the armature through three slip rings to provide three-phase power.

The inverter 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.
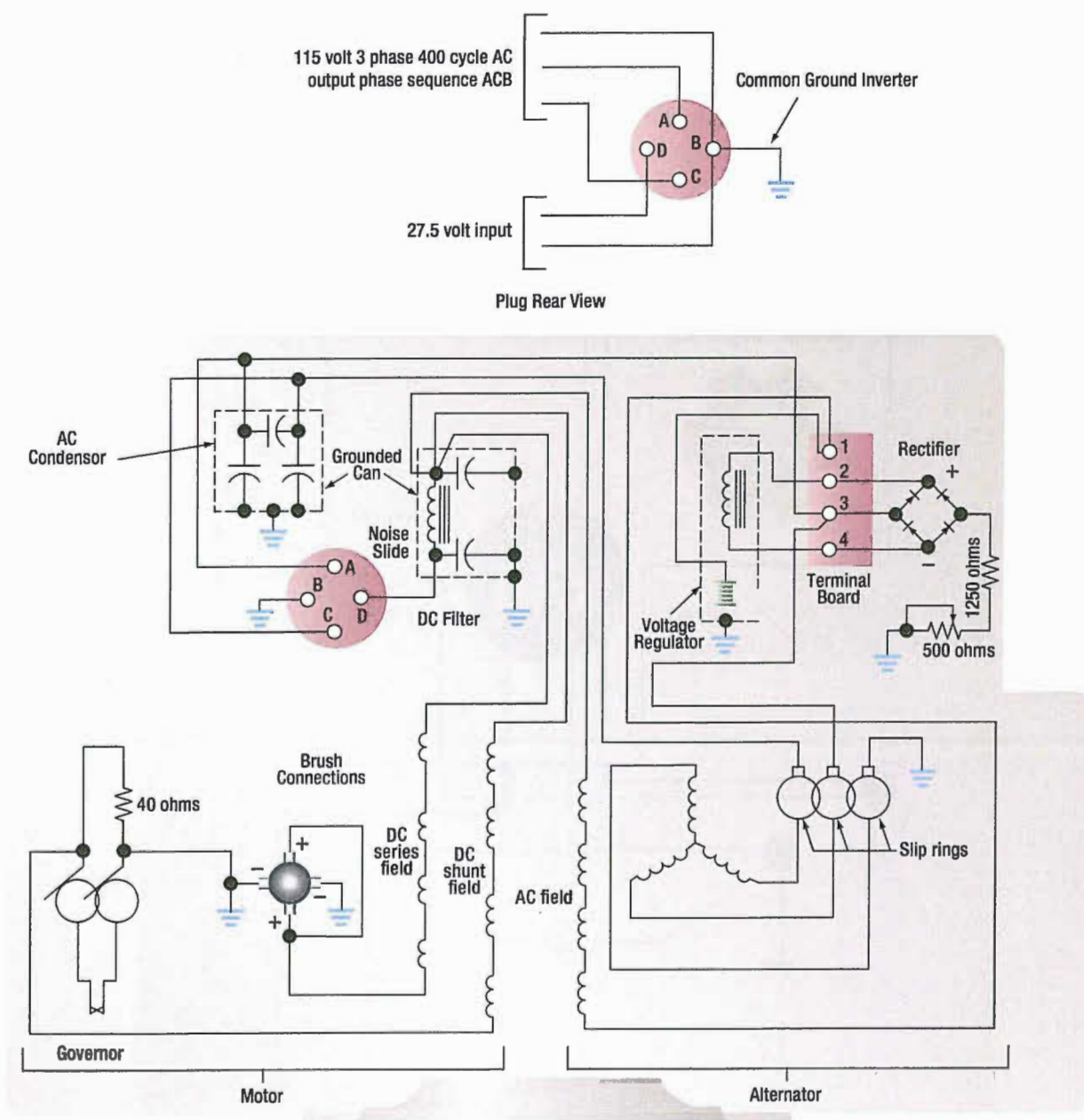
Figure 17-24. Internal wiring diagram of three-phase, revolving armature.

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 *Figure 17-25*. The field coils are wound on one set of stationary poles and the AC armature coils on the other set of stationary poles. When DC 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 AC 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 AC coils.

When the rotor poles are between the stationary poles, there is a high reluctance path for flux, consisting mainly of air; then, there will be a small amount of magnetic flux linking the AC coils. This increase and decrease in flux density in the stator induces an alternating current in the AC coils.

The number of poles and the speed of the motor determine the frequency of this type of inverter. The DC stator field current controls the voltage. A cutaway view of an inductor-type rotary inverter is shown in *Figure 17-26*.

Figure 17-27 is a simplified diagram of a typical aircraft AC power distribution system, utilizing a main and a standby rotary inverter system.

STATIC INVERTERS

In many applications where continuous DC voltage must be converted to alternating voltage, static inverters are used in place of rotary inverters or motor generator sets. The rapid progress made by the semiconductor industry is extending the range of applications of such equipment into voltage and power ranges that would have been impractical a few years ago. Some such applications are power supplies for frequency sensitive military and commercial AC equipment, aircraft emergency AC 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
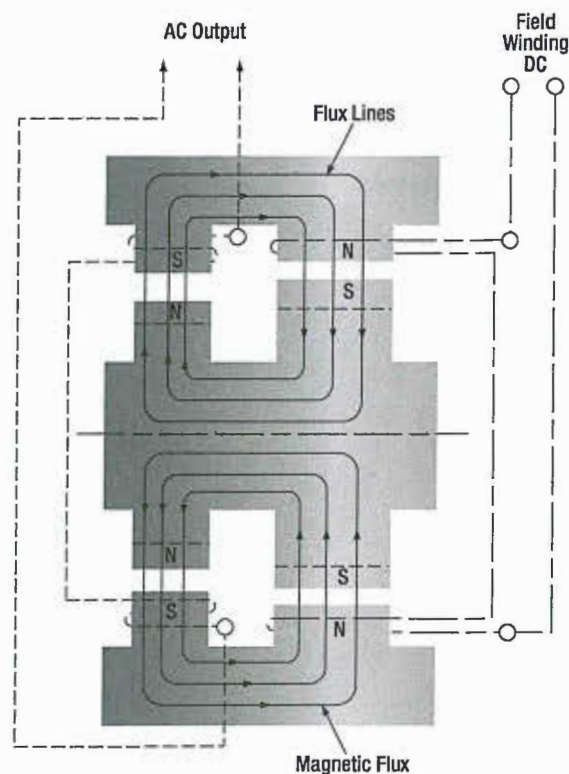
Figure 17-25. Diagram of basic inductor-type inverter.

available for any requirement filled by rotary inverters. For example, 250 VA emergency AC supplies operated from aircraft batteries are in production, as are 2 500 VA main AC 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 AC 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 *Figure 17-28*. This inverter converts a low DC voltage into higher AC voltage. The AC 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 AC outputs. Frequency regulation is typically within a range of one cycle for a 0–100 percent load change. Variations of this type of static inverter are available, many of which provide a square wave output.
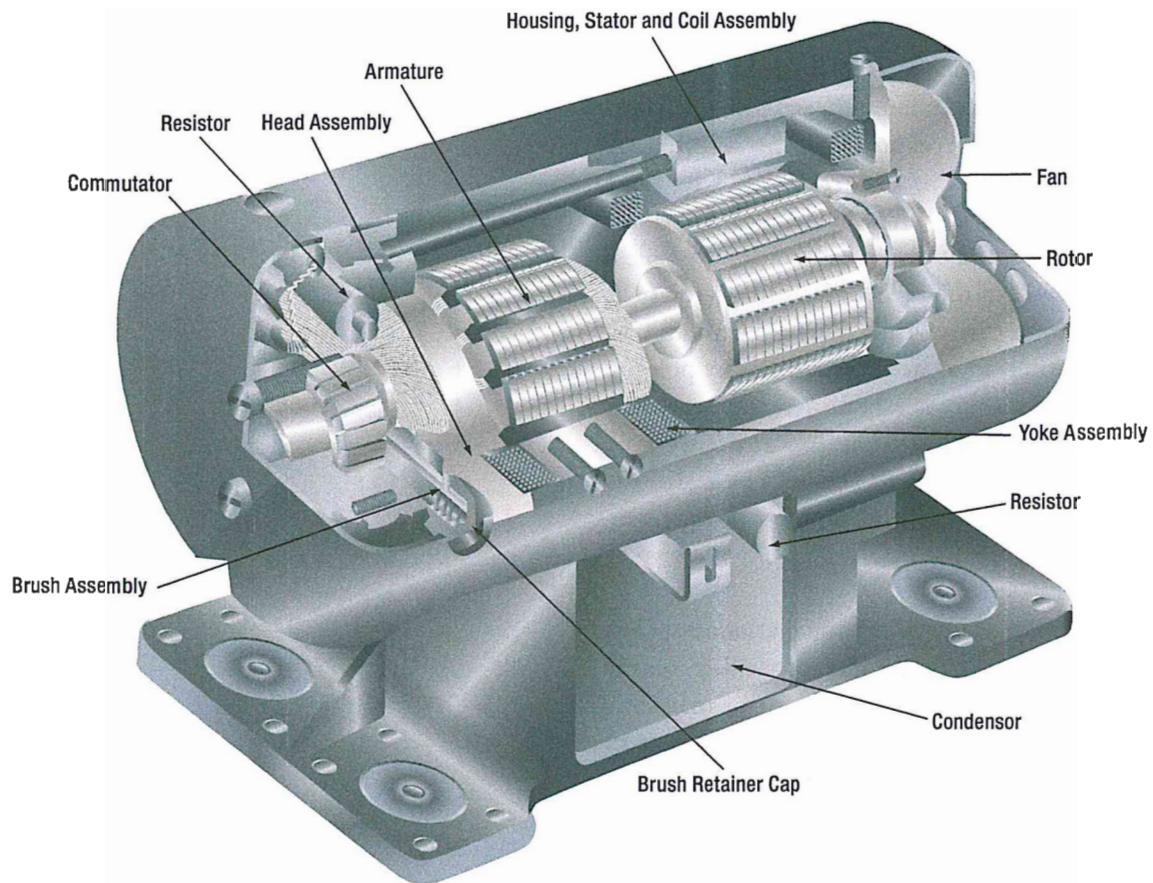
Figure 17-26. Cutaway view of inductor-type rotary inverter.

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 larger 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 warmup period required.
4. Capable of starting under load.
5. Extremely quiet operation.
6. 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. *Figure 17-29* 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.
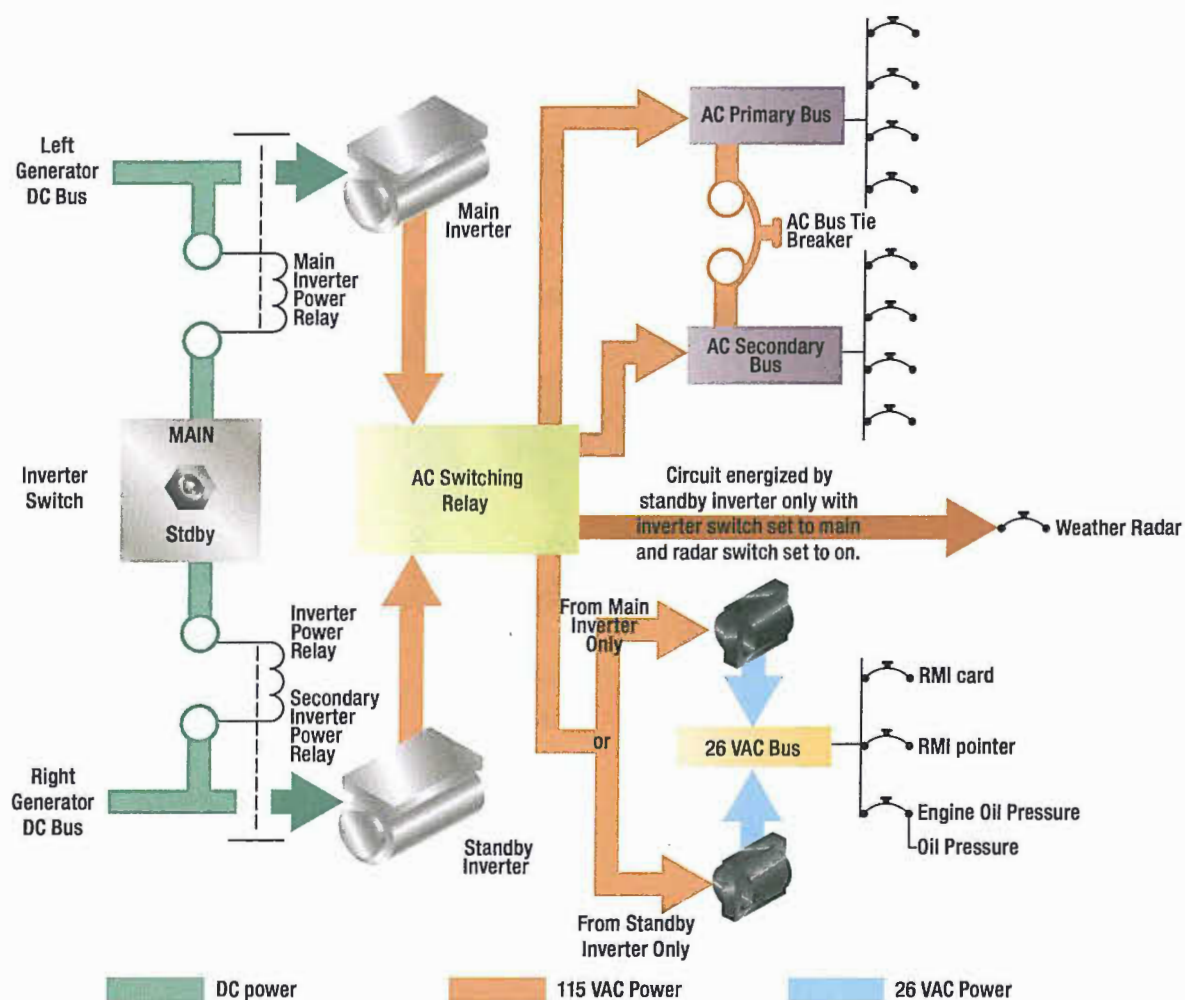
Figure 17-27. A typical aircraft AC power distribution system using main and standby rotary inverters.
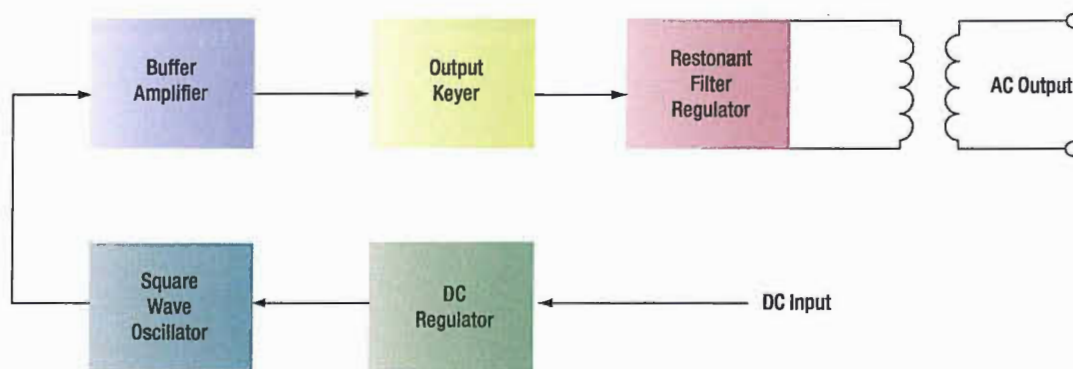
Figure 17-28. Regulated sine wave static inverter.
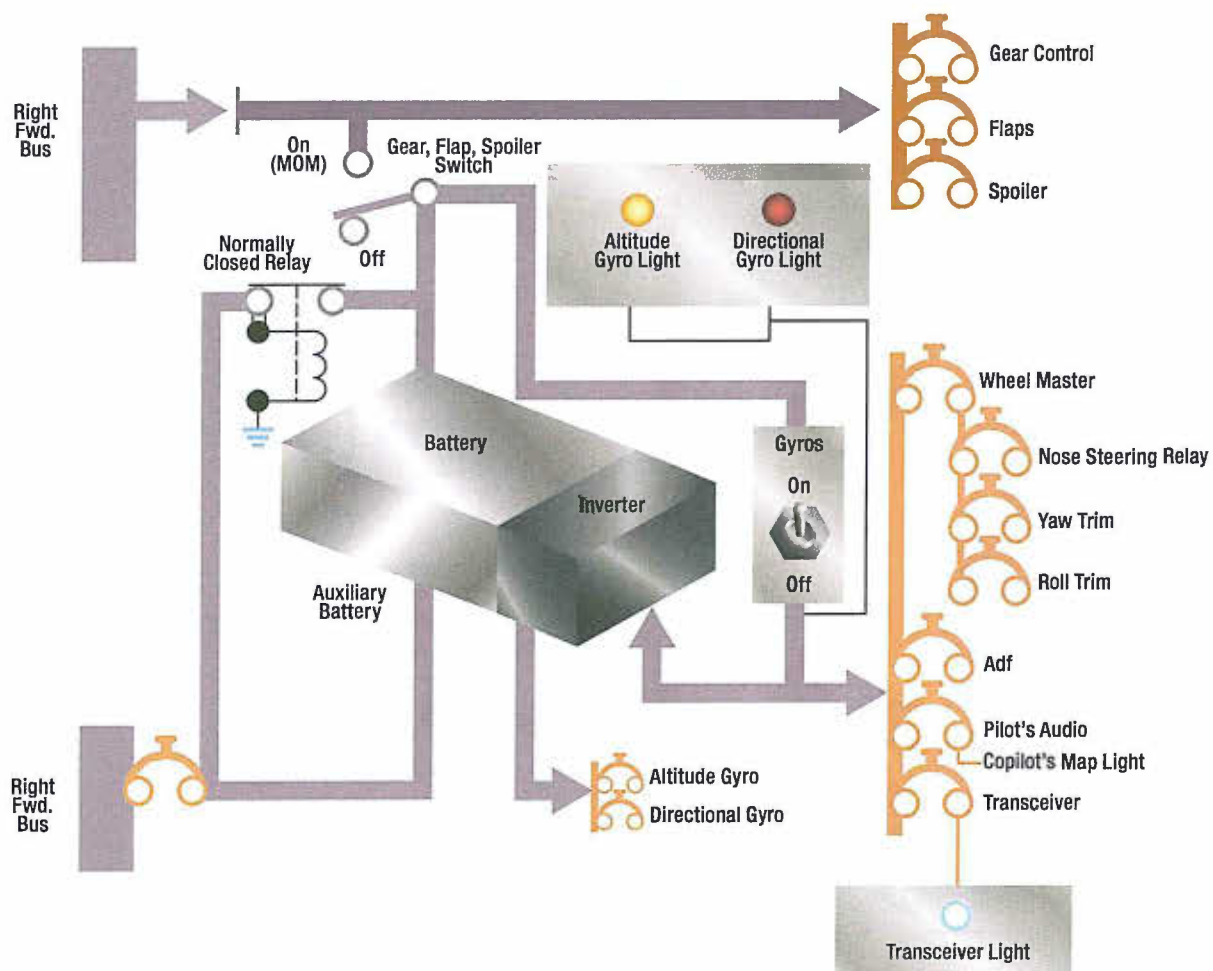
AC GENERATORS

Figure 17-29. Auxiliary battery system using static inverter.

Question: 17-1

The major difference between an alternator and a DC generator is _____ .

Question: 17-2

The three phase alternator has three single phase windings spaced so that the voltage induced in each winding is _____ out of phase with the voltages in the other two windings.

Question: 17-3

Upon what two factors does the frequency of an alternator depend?

Question: 17-4

The strength of the field current can be conveniently controlled to determine voltage _____ of a generator.

Question: 17-5

What device is used to control a number of functions related to regulation, sensing, and protection of the DC generating system?

Question: 17-6

A hydraulic transmission to control generator speed is mounted between the generator and

_____ .

Question: 17-7

AC generators must be _____ as much as possible before connecting them together.

Question: 17-8

Name two types of inverters.

Question: 17-9

Another name for a static inverter is a _____ inverter.

Question: 17-10

Name 4 advantages/features of a static inverter.

ANSWERS

Answer: 17-1
the method of connection to the external circuit; slip rings - AC, commutator -DC.

Answer: 17-2
120°.

Answer: 17-3
speed of rotation.
number of poles.

Answer: 17-4
output.

Answer: 17-5
Generator Control Unit (GCU).

Answer: 17-6
the aircraft engine.

Answer: 17-7
synchronized.

Answer: 17-8
Rotary.
Static.

Answer: 17-9
solid state.

Answer: 17-10
High efficiency.
Low maintenance, long life.
No warmup period required.
Capable of starting under load.
Extremely quiet operation.
Fast response to load changes.

PART-66 SYLLABUS LEVELS

	CERTIFICATION CATEGORY →	**B1**	**B2**

Sub-Module 18
AC MOTORS

Knowledge Requirements

3.18 – AC Motors

	B1	B2
Construction, principles of operation and characteristics of: AC synchronous and induction motors both single and polyphase; Methods of speed control and direction of rotation; Methods of producing a rotating field: capacitor, inductor, shaded or split pole.	2	2

Level 2
A general knowledge of the theoretical and practical aspects of the subject and an ability to apply that knowledge.

Objectives:
(a) The applicant should be able to understand the theoretical fundamentals of the subject.
(b) The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
(c) The applicant should be able to use mathematical formula in conjunction with physical laws describing the subject.
(d) The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
(e) The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

AC MOTORS

AC MOTORS

Because of their advantages, many types of aircraft motors are designed to operate on alternating current. In general, AC motors are less expensive than comparable DC motors. In many instances, AC motors do not use brushes and commutators so sparking at the brushes is avoided. AC motors are reliable and require little maintenance. They are also well suited for constant speed applications and certain types are manufactured that have, within limits, variable speed characteristics. Alternating current motors are designed to operate on polyphase or single phase lines and at several voltage ratings.

The speed of rotation of an AC motor depends upon the number of poles and the frequency of the electrical source of power:

$$rpm = \frac{120 \times Frequency}{Number\ of\ Poles}$$

Since airplane electrical systems typically operate at 400 cycles, an electric motor at this frequency operates at about seven times the speed of a 60 cycle commercial motor with the same number of poles. Because of this high speed of rotation, 400-cycle AC motors are suitable for operating small high-speed rotors, through reduction gears, in lifting and moving heavy loads, such as the wing flaps, the retractable landing gear, and the starting of engines. The 400-cycle induction type motor operates at speeds ranging from 6 000 rpm to 24 000 rpm. Alternating current motors are rated in horsepower output, operating voltage, full load current, speed, number of phases, and frequency. Whether the motors operate continuously or intermittently (for short intervals) is also considered in the rating.

TYPES OF AC MOTORS

There are two general types of AC motors used in aircraft systems: induction motors and synchronous motors. Either type may be single phase, two phase, or three phase. Three phase induction motors are used where large amounts of power are required. They operate such devices as starters, flaps, landing gears, and hydraulic pumps. Single phase induction motors are used to operate devices such as surface locks, intercooler shutters, and oil shutoff valves in which the power requirement is low. Three phase synchronous motors operate at constant synchronous speeds and are commonly used to operate flux gate compasses and propeller synchronizer systems. Single phase synchronous motors are common sources of power to operate electric clocks and other small precision equipment. They require some auxiliary method to bring them up to synchronous speeds; that is, to start them. Usually the starting winding consists of an auxiliary stator winding.

THREE PHASE INDUCTION MOTOR

The three phase AC induction motor is also called a squirrel cage motor. Both single phase and three phase motors operate on the principle of a rotating magnetic field. A horseshoe magnet held over a compass needle is a simple illustration of the principle of the rotating field. The needle will take a position parallel to the magnetic flux passing between the two poles of the magnet. If the magnet is rotated, the compass needle will follow. A rotating magnetic field can be produced by a two or three phase current flowing through two or more groups of coils wound on inwardly projecting poles of an iron frame. The coils on each group of poles are wound alternately in opposite directions to produce opposite polarity, and each group is connected to a separate phase of voltage. The operating principle depends on a revolving, or rotating, magnetic field to produce torque. The key to understanding the induction motor is a thorough understanding of the rotating magnetic field.

ROTATING MAGNETIC FIELD

The field structure shown in *Figure 18-1A* has poles whose windings are energized by three AC voltages, a, b, and c. These voltages have equal magnitude but differ in phase, as shown in *Figure 18-1B*: at the instant of

time shown as 0, 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

Figure 18-1. Rotating magnetic field developed
by application of three phase voltages.

600 rpm. This speed is known as the synchronous speed of the rotating field.

CONSTRUCTION OF INDUCTION MOTOR

The stationary portion of an induction motor is called a stator, and the rotating member is called a rotor. Instead of salient poles in the stator, as shown in A of *Figure 18-1*, distributed windings are used; these windings are placed in slots around the periphery of the stator. It is usually impossible to determine the number of poles in an induction motor by visual inspection, but the information can be obtained from the nameplate of the motor. The nameplate usually gives the number of poles and the speed at which the motor is designed to run. This rated, or non-synchronous, speed is slightly less than the synchronous speed. To determine the number of poles per phase on the motor, divide 120 times the frequency by the rated speed. Written as an equation, it is:

$$P = \frac{120 \times f}{N}$$

Where:
  P is the number of poles per phase,
  f is the frequency in cps,
  N is the rated speed in rpm,
  and 120 is a constant.

The result will be very nearly equal to the number of poles per phase. For example, consider a 60 cycle, three phase motor with a rated speed of 1 750 rpm.

In this case:

$$P = \frac{120 \times 60}{1\ 750} = \frac{7\ 200}{1\ 750} = 4.1$$

Therefore, the motor has four poles per phase. If the number of poles per phase is given on the nameplate, the synchronous speed can be determined by dividing 120 times the frequency by the number of poles per phase. In the example used above, the synchronous speed is equal to 7 200 divided by 4, or 1 800 rpm.

The rotor of an induction motor consists of an iron core having longitudinal slots around its circumference in which heavy copper or aluminum bars are embedded. These bars are welded to a heavy ring of high conductivity on either end. The composite structure is sometimes called a squirrel cage, and motors containing such a rotor are called squirrel cage induction motors. (*Figure 18-2*

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 instant 1, 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. At instant 3, poles 4 and 1 can be considered as north and south poles, respectively, and the field has rotated still farther. At later instants of time, the resultant magnetic field rotates to other positions while traveling in a clockwise direction, a single revolution of the field occurring in one cycle. If the exciting voltages have a frequency of 60 cps, the magnetic field makes 60 revolutions per second, or 3

AC MOTORS

Figure 18-2. Squirrel cage rotor for an AC induction motor.

INDUCTION MOTOR SLIP

When the rotor of an induction motor is subjected to the revolving magnetic field produced by the stator windings, a voltage is induced in the longitudinal bars. The induced voltage causes a current to flow through the bars. This current, in turn, produces its own magnetic field, which combines with the revolving field so that the rotor assumes a position in which the induced voltage is minimized. As a result, the rotor revolves at very nearly the synchronous speed of the stator field, the difference in speed being just sufficient enough to induce the proper amount of current in the rotor to overcome the mechanical and electrical losses in the rotor. If the rotor were to turn at the same speed as the rotating field, the rotor conductors would not be cut by any magnetic lines of force, no emf would be induced in them, no current could flow, and there would be no torque. The rotor would then slow down. For this reason, there must always be a difference in speed between the rotor and the rotating field. This difference in speed is called slip and is expressed as a percentage of the synchronous speed.

For example, if the rotor turns at 1 750 rpm and the synchronous speed is 1 800 rpm, the difference in speed is 50 rpm. The slip is then equal to $^{50}/_{1\,800}$ or 2.78 percent.

SINGLE PHASE INDUCTION MOTOR

The previous discussion has applied only to polyphase motors. A single-phase motor has only one stator winding. This winding generates a field, which merely pulsates, instead of rotating. When the rotor is stationary, the expanding and collapsing stator field induces currents in the rotor. These currents generate a rotor field opposite in polarity to that of the stator. The opposition of the field exerts a turning force on the upper and lower parts of the rotor trying to turn it 180° from its position. Since these forces are exerted through the center of the rotor, the turning force is equal in each direction. As a result, the rotor does not turn. If the rotor has started turning, it will continue to rotate in the direction in which it is started, since the turning force in that direction is aided by the momentum of the rotor.

SHADED POLE INDUCTION MOTOR

The first effort in the development of a self-starting, single-phase motor was the shaded pole induction motor. (*Figure 18-3*)

This motor has salient poles, a portion of each pole being encircled by a heavy copper ring. The presence of the ring causes the magnetic field through the ringed portion of the pole face to lag appreciably behind that through the other part of the pole face. The net effect is the production of a slight component of rotation of the
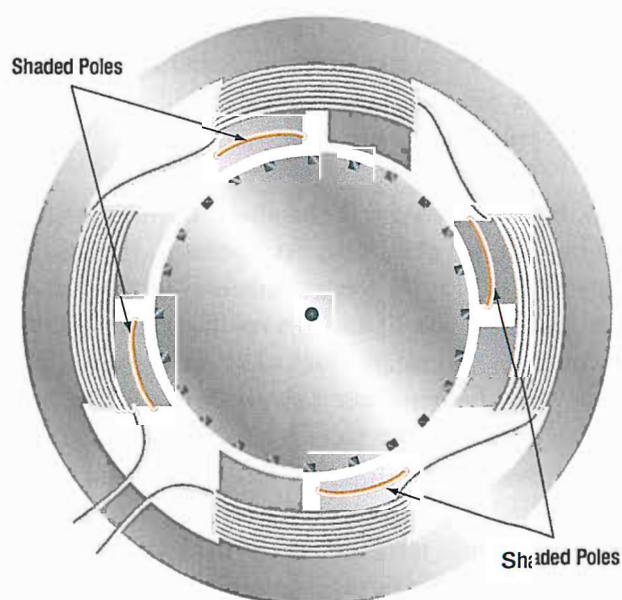
Figure 18-3. Shaded pole induction motor.

field, sufficient to cause the rotor to revolve. As the rotor accelerates, the torque increases until the rated speed is obtained. Such motors have low starting torque and find their greatest application in small fan motors where the initial torque required is low.

In *Figure 18-4*, a diagram of a pole and the rotor is shown. The poles of the shaded pole motor resemble those of a DC motor. A low resistance, short-circuited coil or copper band is placed across one tip of each small pole, from which, the motor gets the name of shaded pole. The rotor of this motor is the squirrel cage type. As the current increases in the stator winding, the flux increases. A portion of this flux cuts the low resistance shading coil. This induces a current in the shading coil, and by Lenz's law, the current sets up a flux that opposes the flux inducing the current. Hence, most of the flux passes through the unshaded portion of the poles, as shown in *Figure 18-4*.

When the current in the winding and the main flux reaches a maximum, the rate of change is zero; thus, no emf is induced in the shading coil. A little later, the shading coil current, which causes the induced emf to lag, reaches zero, and there is no opposing flux. Therefore, the main field flux passes through the shaded portion of the field pole. The main field flux, which is now decreasing, induces a current in the shading coil. This current sets up a flux that opposes the decrease of the main field flux in the shaded portion of the pole. The effect is to concentrate the lines of force in the shaded portion of the pole face. In effect, the shading coil retards, in time phase, the portion of the flux passing through the shaded part of the pole. This
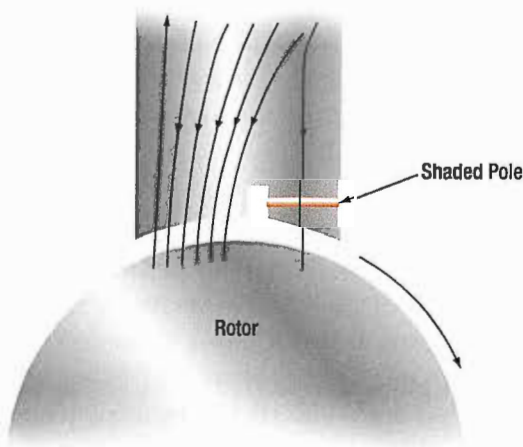
lag in time phase of the flux in the shaded tip causes the flux to produce the effect of sweeping across the face of the pole, from left to right in the direction of the shaded tip. This behaves like a very weak rotating magnetic field, and sufficient torque is produced to start a small motor. The starting torque of the shaded pole motor is exceedingly weak, and the power factor is low. Consequently, it is built in sizes suitable for driving such devices as small fans.

SPLIT PHASE MOTOR

There are various types of self-starting motors, known as split phase motors. Such motors have a starting winding displaced 90 electrical degrees from the main or running winding. In some types, the starting winding has a fairly high resistance, which causes the current in this winding to be out of phase with the current in the running winding. This condition produces, in effect, a rotating field and the rotor revolves. A centrifugal switch disconnects the starting winding automatically, after the rotor has attained approximately 25 percent of its rated speed.

CAPACITOR START MOTOR

With the development of high capacity electrolytic capacitors, a variation of the split phase motor, known as the capacitor start motor, has been made. Nearly all fractional horsepower motors in use today on refrigerators and other similar appliances are of this type. (*Figure 18-5*)

In this adaptation, the starting winding and running winding have the same size and resistance value. The phase shift between currents of the two windings is obtained by using capacitors connected in series with the starting winding. Capacitor start motors have a starting torque comparable to their torque at rated speed and can be used in applications where the initial load is heavy. Again, a centrifugal switch is required for disconnecting the starting winding when the rotor speed is approximately 25 percent of the rated speed. Although some single phase induction motors are rated as high as 2 horsepower (hp), the major field of application is 1 hp, or less, at a voltage rating of 115 volts for the smaller sizes and 110 to 220 volts for one-fourth hp and up. For even larger power ratings, polyphase motors generally are used, since they have excellent starting torque characteristics.

Figure 18-4. Diagram of a shaded pole motor.

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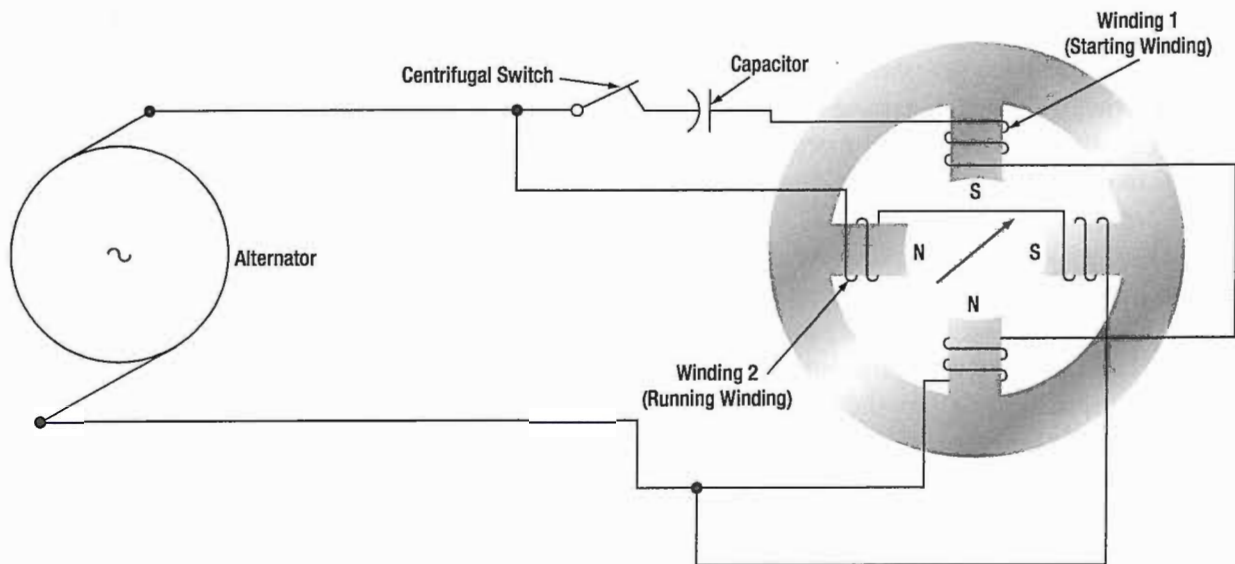
Figure 18-5. Single phase motor with capacitor starting winding.

DIRECTION OF ROTATION OF INDUCTION MOTORS

The direction of rotation of a three phase induction motor can be changed by simply reversing two of the leads to the motor. The same effect can be obtained in a two phase motor by reversing connections to one phase. In a single phase motor, reversing connections to the starting winding will reverse the direction of rotation. Most single phase motors designed for general application have provision for readily reversing connections to the starting winding. Nothing can be done to a shaded pole motor to reverse the direction of rotation because the direction is determined by the physical location of the copper shading ring. If, after starting, one connection to a three phase motor is broken, the motor will continue to run but will deliver only one-third the rated power. Also, a two phase motor will run at one-half its rated power if one phase is disconnected. Neither motor will start under these abnormal conditions.

SYNCHRONOUS MOTOR

The synchronous motor is one of the principal types of AC motors. Like the induction motor, the synchronous motor makes use of a rotating magnetic field. Unlike the induction motor, however, the torque developed does not depend on the induction of currents in the rotor. Briefly, the principle of operation of the synchronous motor is as follows: A multiphase source of AC is applied to the stator windings, and a rotating magnetic field is produced. A direct current is applied to the rotor winding, and another magnetic field is produced. The synchronous motor is so designed and constructed that these two fields react

to each other in such a manner that the rotor is dragged along and rotates at the same speed as the rotating magnetic field produced by the stator windings.

An understanding of the operation of the synchronous motor can be obtained by considering the simple motor of *Figure 18-6*. Assume that poles A and B are being rotated clockwise by some mechanical means in order to produce a rotating magnetic field, they induce poles of opposite polarity in the soft iron rotor, and forces of attraction exist between corresponding north and south poles.

Consequently, as poles A and B rotate, the rotor is dragged along at the same speed. However, if a load is applied to the rotor shaft, the rotor axis will momentarily fall behind that of the rotating field but, thereafter, will continue to rotate with the field at the same speed, as long as the load remains constant. If the load is too large, the rotor will pull out of synchronism with the rotating field and, as a result, will no longer rotate with the field at the same speed. Thus the motor is said to be overloaded.

Such a simple motor as that shown in *Figure 18-6* is never used. The idea of using some mechanical means of rotating the poles is impractical because another motor would be required to perform this work. Also, such an arrangement is unnecessary because a rotating magnetic field can be produced electrically by using phased AC voltages. In this respect, the synchronous motor is similar to the induction motor.

The synchronous motor consists of a stator field winding similar to that of an induction motor. The stator winding produces a rotating magnetic field. The rotor may be a permanent magnet, as in small single phase synchronous motors used for clocks and other small precision equipment, or it may be an electromagnet, energized from a DC source of power and fed through slip rings into the rotor field coils, as in an alternator. In fact, an alternator may be operated either as an alternator or a synchronous motor.

Since a synchronous motor has little starting torque, some means must be provided to bring it up to synchronous speed. The most common method is to start the motor at no load, allow it to reach full speed, and then energize the magnetic field. The magnetic field of the rotor locks with the magnetic field of the stator and the motor operates at synchronous speed.

The magnitude of the induced poles in the rotor shown in *Figure 18-7* is so small that sufficient torque cannot be developed for most practical loads. To avoid such a limitation on motor operation, a winding is placed on the rotor and energized with DC. A rheostat placed in series with the DC source provides the operator of the machine with a means of varying the strength of the rotor poles, thus placing the motor under control for varying loads.
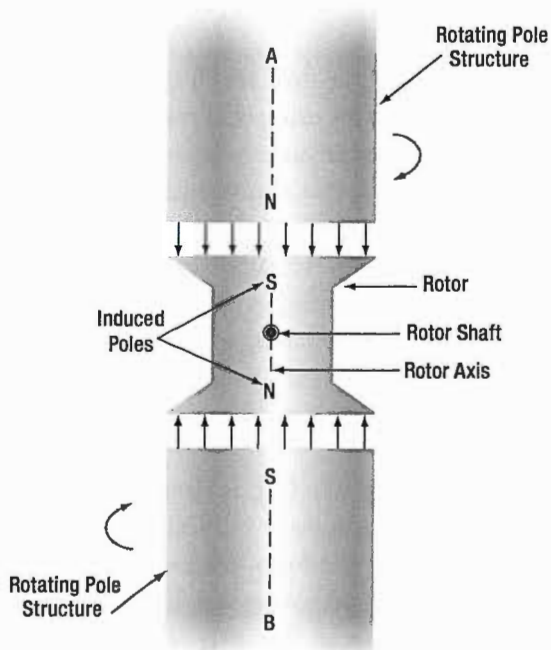
Figure 18-6. Illustrating the operation of a synchronous motor.
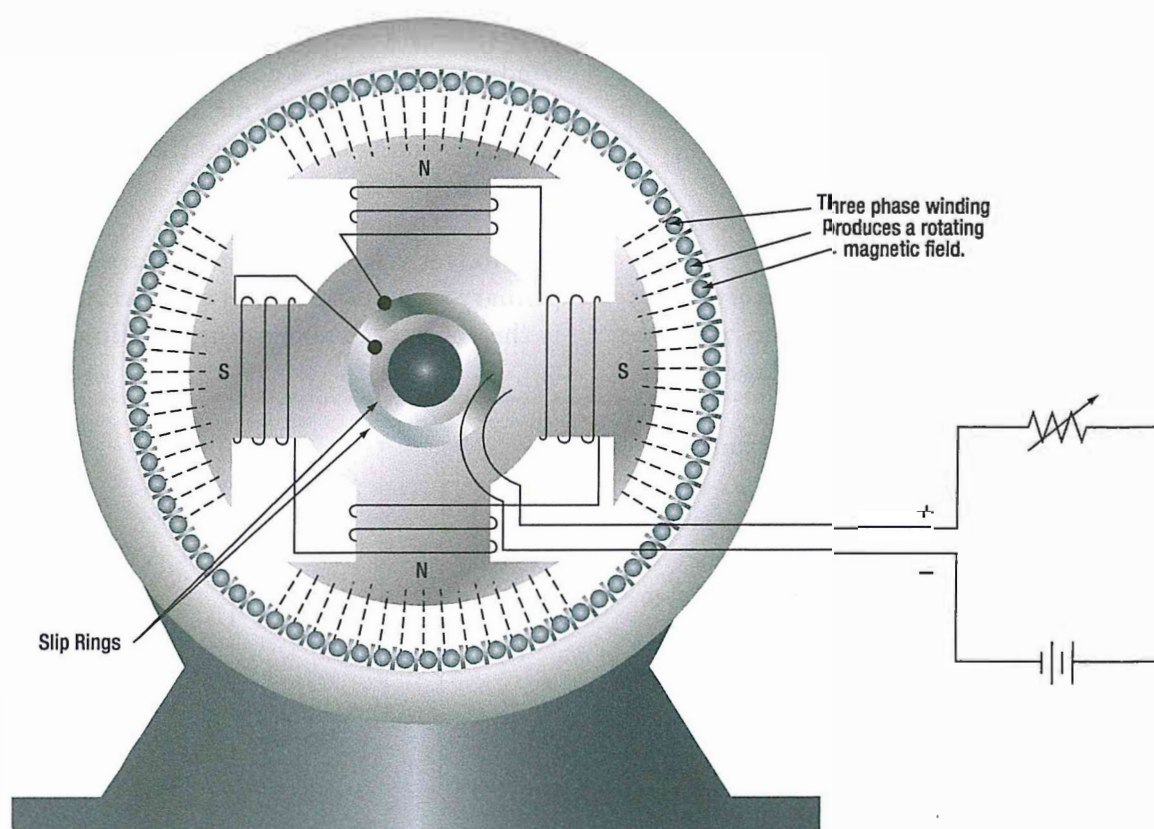
Figure 18-7. Synchronous motor.

AC MOTORS

The synchronous motor is not a self-starting motor. The rotor is heavy and, from a dead stop, it is impossible to bring the rotor into magnetic lock with the rotating magnetic field. For this reason, all synchronous motors have some kind of starting device. One type of simple starter is another motor, either AC or DC, which brings the rotor up to approximately 90 percent of its synchronous speed. The starting motor is then disconnected, and the rotor locks in step with the rotating field.

Another starting method is a second winding of the squirrel cage type on the rotor. This induction winding brings the rotor almost to synchronous speed, and when the DC is connected to the rotor windings, the rotor pulls into step with the field. The latter method is the more commonly used.

AC SERIES MOTOR

An alternating current series motor is a single phase motor, but is not an induction or synchronous motor. It resembles a DC motor in that it has brushes and a commutator. The AC series motor will operate on either AC or DC circuits. It will be recalled that the direction of rotation of a DC series motor is independent of the polarity of the applied voltage, provided the field and armature connections remain unchanged. Hence, if a DC series motor is connected to an AC source, a torque will be developed which tends to rotate the armature in one direction.

A DC series motor does not operate satisfactorily from an AC supply for the following reasons:
- 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.
- The self induction of the field and armature windings causes a low power factor.
- 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 AC, the following changes are made:
- The eddy current losses are reduced by laminating the field poles, frame and armature.
- Hysteresis losses are minimized by using high permeability, transformer-type, silicon steel laminations.
- 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 air gap).
- 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 *Figure 18-8*, the armature is conductively compensated.

If the compensating winding is designed as shown in *Figure 18-9*, the armature is inductively compensated. If the motor is designed for operation on both DC and AC 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 DC 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 acts like the primary of a transformer, the secondary of which is the shorted compensating winding. The shorted
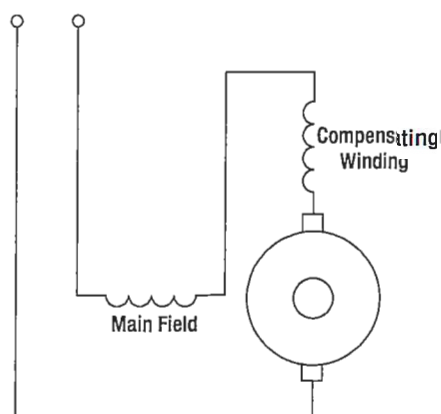
Figure 18-8. Conductivity compensated armature of AC series motor.
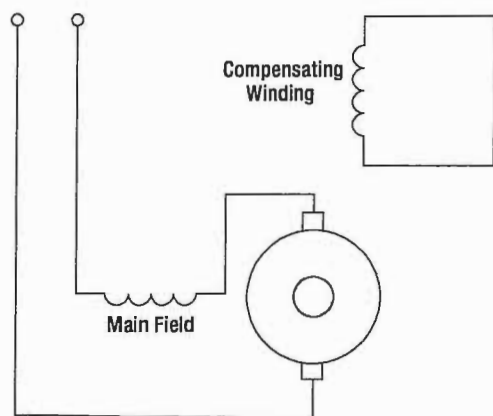
Figure 18-9. Inductively compensated armature of AC series motor.

Figure 18-10. Preventive coils in AC series motor.

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.

Sparking at the commutator is reduced by the use of preventive leads P1, P2, P3, and so forth, as shown in *Figure 18-10*, 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 AC 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.

MAINTENANCE OF AC MOTORS

The inspection and maintenance of AC 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 refuse 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.

In all cases, the inspection and maintenance of all AC motors should be performed in accordance with the applicable manufacturer's instructions.

AC MOTORS

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Question: 18-1
The speed of an AC motor depends on the number of
_____ and the _____ of
the electrical power source.

Question: 18-2
Two types of motors use in aircraft AC systems are
_____ and _____.

Question: 18-3
A motor with starting windings 90 degrees from the
main or running winding that allows self-starting is
called a _____ motor.

Question: 18-4
What is synchronized in a Synchronous motor?

Question: 18-5
Next to temperature, the _____ of a
motor is the best indicator of trouble.

ANSWERS

Answer: 18-1
poles.
frequency.

Answer: 18-2
synchronous.

Answer: 18-3
split phase.

Answer: 18-4
The rotor and the rotating field.

Answer: 18-5
sound.

AC	/	Alternating Current
AMC	/	Acceptable Means of Compliance
BITE	/	Built in Test
CD	/	Cadmium
CPS	/	Constant Speed Drive
DC	/	Direct Current
EASA	/	European Aviation Safety Agency
EC	/	European Commission
EMF	/	Electro Magnetic Field
ESP	/	Electrostatic Precipitator
FAA	/	Federal Aviation Administration
GCU	/	Generator Control Unit
GM	/	Guidance Material
HPF	/	High-pass Filter
HZ	/	Hertz
IR	/	Insulation Resistance
KOH	/	Potassium Hydroxide
KVA	/	Kilovoltamperes
KWH	/	Kilowatt-hour
L	/	Inductance
LC	/	Load Capacity
MH	/	Mutual Induction
PA	/	Pascal Unit
PSI	/	Pounds Per Square Inch
R	/	Resistance
RF	/	Radio Frequency
RL	/	Load Resistance
RMS	/	Effective Value
RPM	/	Revolutions Per Minute
SI	/	International System of Units
SLA	/	Sealed Lead Acid
UH	/	Microhenries
UHF	/	Ultra High Frequency
WS	/	Watt-second
XC	/	Capacitive Reactance

A

B

C

D

E

O

P

R

S

T

U

V

W