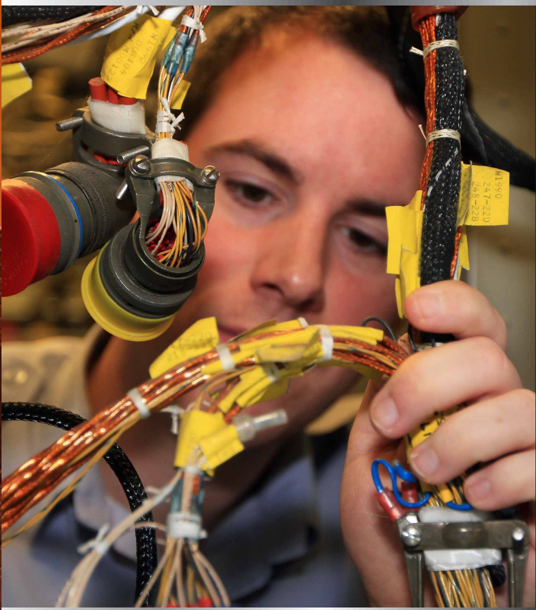
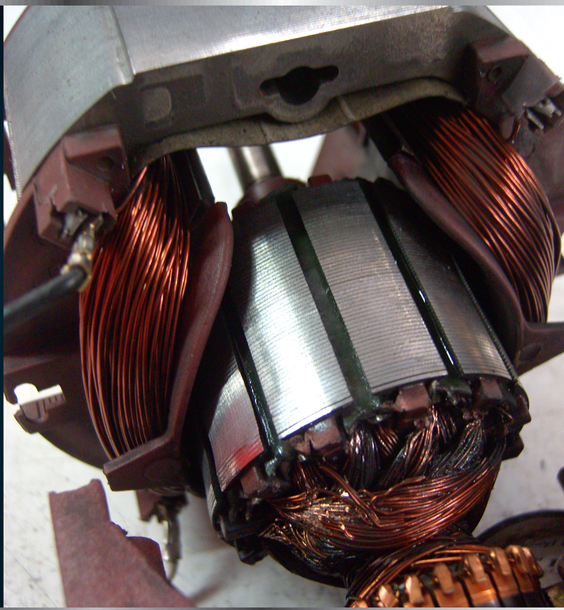
Module 03
FOR B1 & B2 CERTIFICATION

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

COMPLIANT WITH EASA European Aviation Safety Agency EASA PART 66/147

EASA Part-66 Aviation Maintenance Technician Certification Series

NO COST REVISION/UPDATE SUBSCRIPTION PROGRAM

Complete EASA Part-66 Aviation Maintenance Technician Certification Series

NO COST REVISION/UPDATE PROGRAM

Aircraft Technical Book Company offers a revision/update program to all who purchase an EASA Module from the EASA Aviation Maintenance Technician Certification Series. The update is good for two (2) years from time of registration of any EASA Module or EASA bundled kit. If a revision occurs within two (2) years from date of registration, we will send you the revised eBook FREE of cost to your registered email.

HERE IS HOW TO SIGN UP FOR YOUR SUBSCRIPTION

Please send an email to *info@actechbooks.com* with the following information:

1. Name
2. Email
3. Order Number and/or School

Please know that we try to keep our records as current as possible. If your email address changes please let us know so we can update your account.

If you have any questions about this process please contact us at: *info@actechbooks.com*

AIRCRAFT TECHNICAL BOOK COMPANY

MODULE 03

FOR B1 & B2 CERTIFICATION

ELECTRICAL FUNDAMENTALS

Aviation Maintenance Technician Certification Series

COMPLIANT WITH EASA PART 66/147

AIRCRAFT TECHNICAL BOOK COMPANY

72413 U.S. Hwy 40
Tabernash, CO 80478-0270 USA

www.actechbooks.com

+1 970 726-5111

AVAILABLE IN
Printed Edition and Electronic (eBook) Format

AVIATION MAINTENANCE TECHNICIAN CERTIFICATION SERIES

Contributors Roger Petersen
Layout/Design Michael Amrine

Version 04 - Effective Date 07.01.2019

To order books or for Customer Service, please call +1 970 726-5111.

www.actechbooks.com

Printed in the United States of America

ISBN 978-1941144848

For comments or suggestions about this book, please call or write to:
1.970.726.5111 | comments@actechbooks.com

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	Module Creation and Release
002	2016 10	Format Updates
003	2017 03	Content Updates and Subject Clarification
004	2019 07	Fine tuned Sub-Module content sequence based on Appendix-A. Updated layout and styling.

FORWARD

PART-66 and the Acceptable Means of Compliance (AMC) and Guidance Material (GM) of the European Aviation Safety Agency (EASA), Appendix 1 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 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		

GENERAL KNOWLEDGE REQUIREMENTS

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

Level 3
A detailed knowledge of the theoretical and practical aspects of the subject and a capacity to combine and apply the separate elements of knowledge in a logical and comprehensive manner.
Objectives:
a. The applicant should know the theory of the subject and interrelationships with other subjects.
b. The applicant should be able to give a detailed description of the subject using theoretical fundamentals and specific examples.
c. The applicant should understand and be able to use mathematical formula related to the subject.
d. The applicant should be able to read, understand and prepare sketches, simple drawings and schematics describing the subject.
e. The applicant should be able to apply his knowledge in a practical manner using manufacturer's instructions.
f. The applicant should be able to interpret results from various sources and measurements and apply corrective action where appropriate.

PART-66 - APPENDIX I
BASIC KNOWLEDGE REQUIREMENTS

	LEVELS B1	LEVELS 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
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 - 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

PART-66 - APPENDIX I
BASIC KNOWLEDGE REQUIREMENTS

	LEVELS B1	LEVELS B2
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		
(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		
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

PART-66 - APPENDIX I
BASIC KNOWLEDGE REQUIREMENTS

	LEVELS B1	LEVELS B2
Sub-Module 12 - DC Motor/Generator Theory 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 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 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 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 Operation, application and uses of the following filters: low pass, high pass, band pass, band stop.	1	1
Sub-Module 17 - AC Generators 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 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

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

SUB-MODULE 07
RESISTANCE/RESISTOR

SUB-MODULE 08
POWER

SUB-MODULE 09
CAPACITANCE/CAPACITOR

SUB-MODULE 10
MAGNETISM

SUB-MODULE 11
INDUCTANCE/INDUCTOR

CONTENTS

SUB-MODULE 15
TRANSFORMERS

SUB-MODULE 16
FILTERS

SUB-MODULE 17
AC GENERATORS

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; Molecular structure of conductors, semiconductors and insulators.	1	1

3.1 - ELECTRON THEORY

STRUCTURE AND DISTRIBUTION OF ELECTRICAL CHARGES WITHIN ATOMS, MOLECULES, IONS, AND COMPOUNDS

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 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.

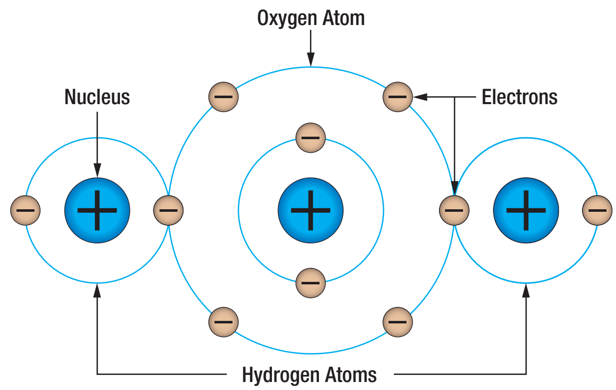


Figure 1-1. A water molecule.

ATOMS

The atom is considered to be the most basic building block of all matter. Atoms are composed of three subatomic particles. These three subatomic 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 (***Figure 1-2***), 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.

IONS

An ion is an atom or molecule that has a non-zero net electrical charge (its total number of electrons is not equal to its total number of protons). A cation is a positively charged ion, while an anion is negatively charged. Because of their opposite electric charges, cations and anions attract each other and readily form ionic compounds such as salts.

Periodic Table of Elements

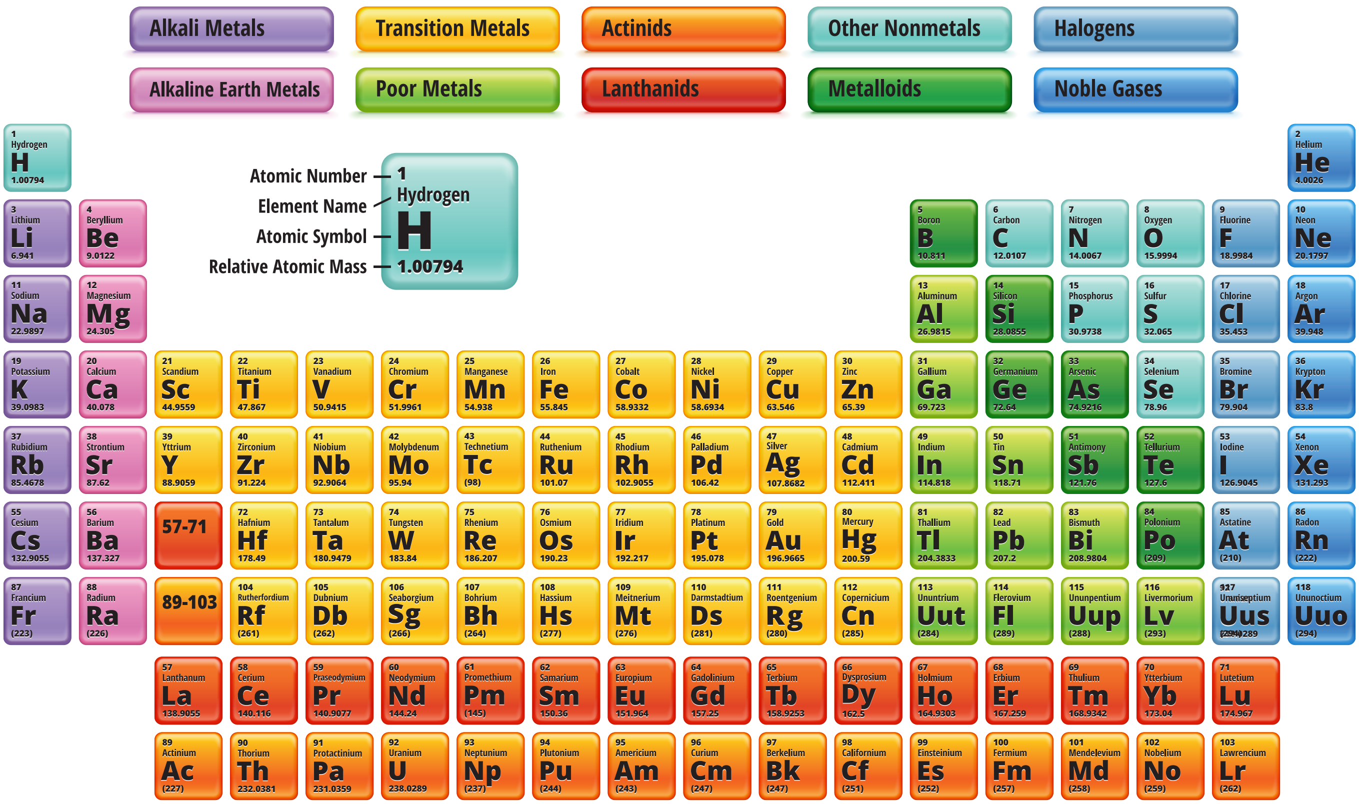


Figure 1-2. Periodic table of elements.

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 neutron 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 1-3***. 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 1-4***, 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.

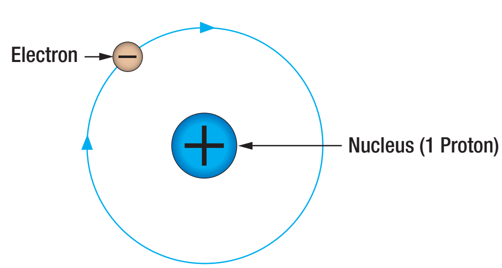


Figure 1-3. Hydrogen atom.

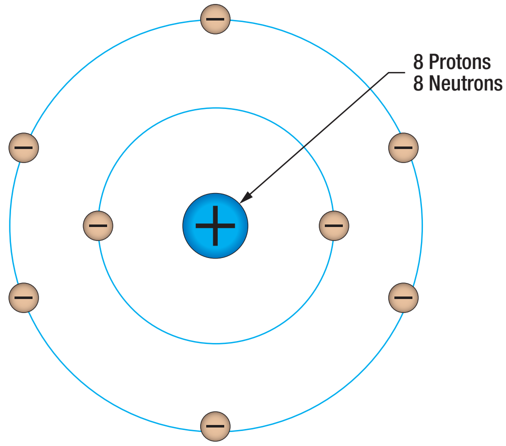


Figure 1-4. Oxygen atom.

MOLECULAR STRUCTURE OF CONDUCTORS, SEMICONDUCTORS AND INSULATORS

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 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 subshell 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. (***Figure 1-2***)

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.

Ionization

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.

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 _________________.

Question: 1-4
What determines whether an element will be good electrical insulator?

Question: 1-5
Which atomic particle is typically not considered when determining the mass of an atom?

Question: 1-6
Where can you determine the physical qualities of an element?

ANSWERS

Answer: 1-1
Electron shells.

Answer: 1-2
a conductor.

Answer: 1-3
semiconductor.

Answer: 1-4
The element's atom contains no free electrons.

Answer: 1-5
The electron weighs less than 1/1 800th the weight of a proton or neutron and so is not considered.

Answer: 1-6
The Periodic Table of Elements.

ELECTRICAL FUNDAMENTALS

STATIC ELECTRICITY AND CONDUCTION

SUB-MODULE 02

PART-66 SYLLABUS LEVELS	B1	B2
CERTIFICATION CATEGORY →		

Sub-Module 02
STATIC ELECTRICITY AND CONDUCTION
Knowledge Requirements

	B1	B2
3.2 - 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

3.2 - STATIC ELECTRICITY AND CONDUCTION

ELECTROSTATIC LAWS OF ATTRACTION AND REPULSION

STATIC ELECTRICITY AND ELECTROSTATIC CHARGES

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.

A static electric charge can be created whenever two surfaces contact and separate, and at least one of the surfaces has a high resistance to electric current (an insulator). The effects of static electricity are familiar to most people because we can feel, hear, and even see the spark as the excess charge is neutralized as it is brought close to an electrical conductor or a path to ground. The familiar phenomenon of a static shock, or more specifically, an electrostatic discharge is caused by the neutralization of that charge.

Lightning is a dramatic natural example of static discharge. (***Figure 2-1***) While the details are not completely understood, the initial charge is thought to be associated with contact between ice particles within storm clouds. The lightning is simply a scaled up version of the sparks seen in more common static discharges. The flash occurs because the air in the discharge is heated to such a high temperature that it emits light. The thunder is the shock wave created as the superheated air expands explosively.

Figure 2-1. Lightning is a natural occurrence of static electricity.

TRIBOELECTRIC EFFECT

Electrons can be exchanged between materials on contact. Materials with weakly bound electrons tend to lose them while materials with sparsely filled outer shells tend to gain them. This is known as the triboelectric effect and results in one material becoming positively charged and the other negatively charged. The triboelectric effect is the main cause of static electricity as observed in everyday life.

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 2-2***, 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 2-2***. 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 2-2***.

Contact Induced Separation

Styrofoam peanuts cling to a cat's fur due to static electricity. The triboelectric effect causes an electrostatic charge to build on the cat's fur due to its motions. The electric field of the charge causes polarization of the molecules of the styrofoam due to electrostatic induction resulting in a slight attraction of the light styrofoam to the charged fur. This effect is also the cause of static cling in clothes.

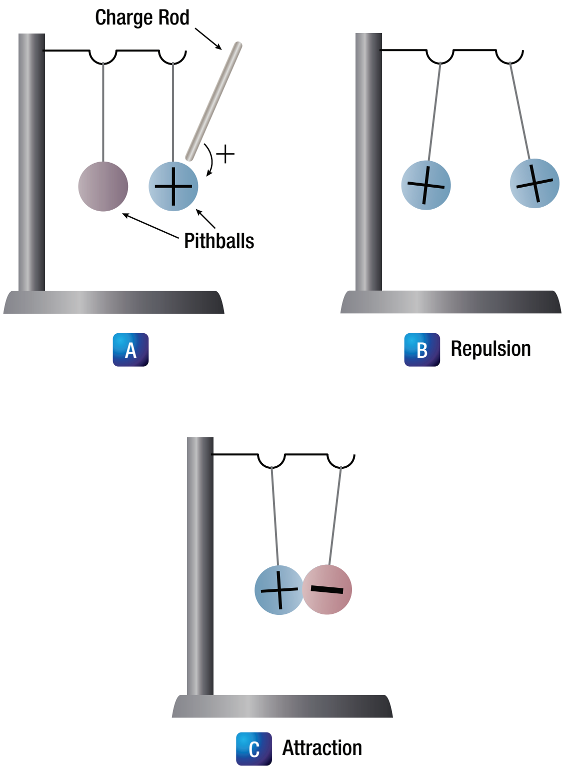


Figure 2-2. Reaction of like and unlike charges.

Charge Induced Separation

A charged object brought close to an electrically neutral object causes a separation of charge within the neutral object. Charges of the same polarity are repelled and charges of the opposite polarity are attracted. The effect is greatest when the neutral object is an electrical conductor as the charges are more free to move around. Careful grounding of part of an object with a charge induced charge separation can permanently add or remove electrons, leaving the object with a permanent charge. This process describes the workings of the Van de Graaff generator, a device commonly used to demonstrate the effects of static electricity.

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 2-3***, 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 2-3***, 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 2-4 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.

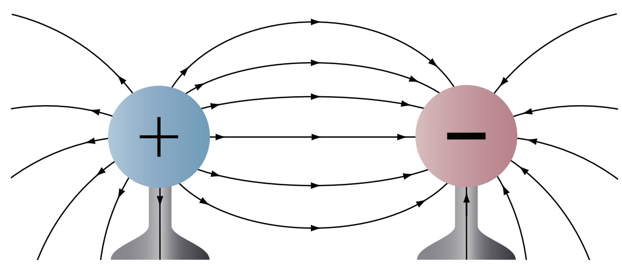


Figure 2-3. Direction of electric field around positive and negative charges.

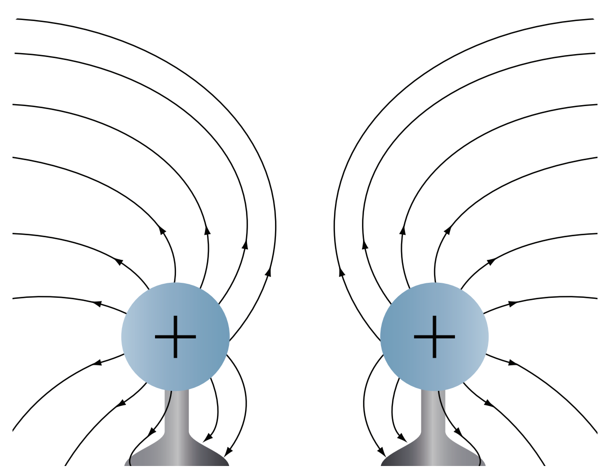


Figure 2-4. Field around two positively charged bodies.

It is important to know how a charge is distributed on an object. ***Figure 2-5*** 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 2-6***, is the charge on a hollow sphere. Although the sphere is made of conducting material, the charge is evenly distributed over the outside surface. The inner surface is completely neutral. This phenomenon is used to safeguard operating personnel of the large Van de 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 2-7*** 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 2-5. Even distribution of charge on metal disk.

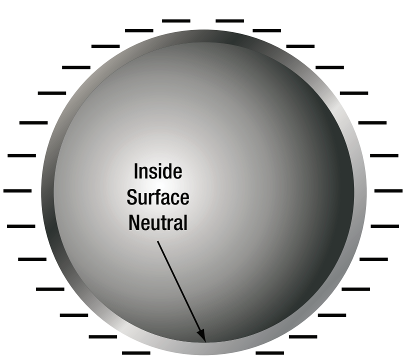


Figure 2-6. Charge on a hollow sphere.

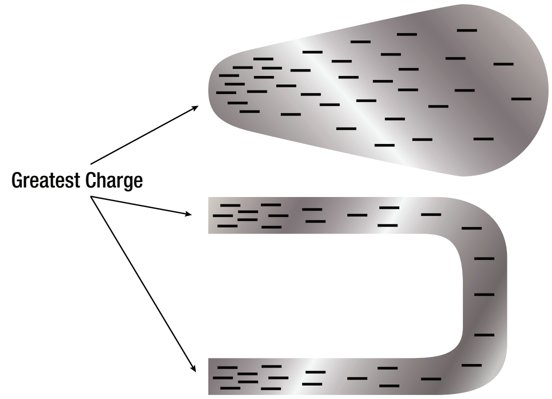


Figure 2-7. Charge on irregularly shaped objects.

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 the 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.

Static Build-up with Flammable Materials

Static electricity is also a hazard when refueling aircraft. Discharge of static electricity can create severe hazards where the flowing movement of low conductive fluids can build up static electricity and a small electrical spark can ignite explosive mixtures.

UNITS OF CHARGE; COULOMB'S LAW

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.

A single elementary charge (e) is the charge that a single proton (or electron) possesses. The coulomb (C) is an International Standard (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 2-8***. 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 2-9***. A positively charged rod is brought near, but does not touch, an uncharged metal bar. Electrons in the metal bar are attracted to the end of the bar nearest the positively charged rod, leaving a deficiency

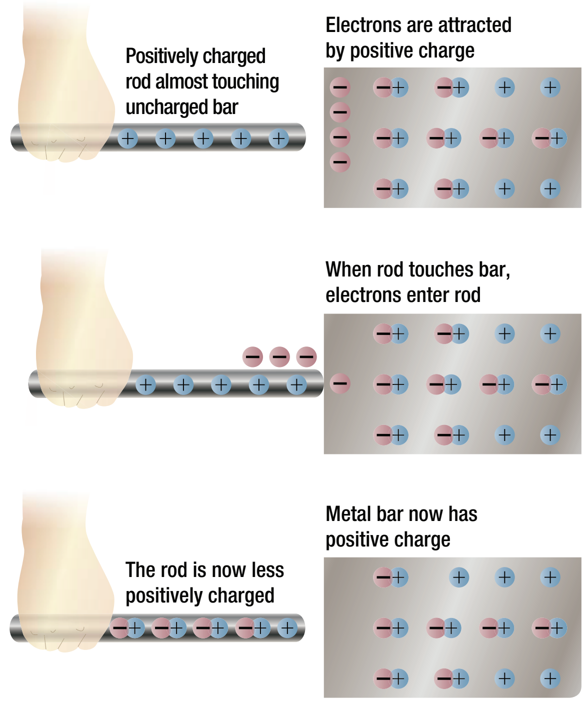


Figure 2-8. Charging by contact.

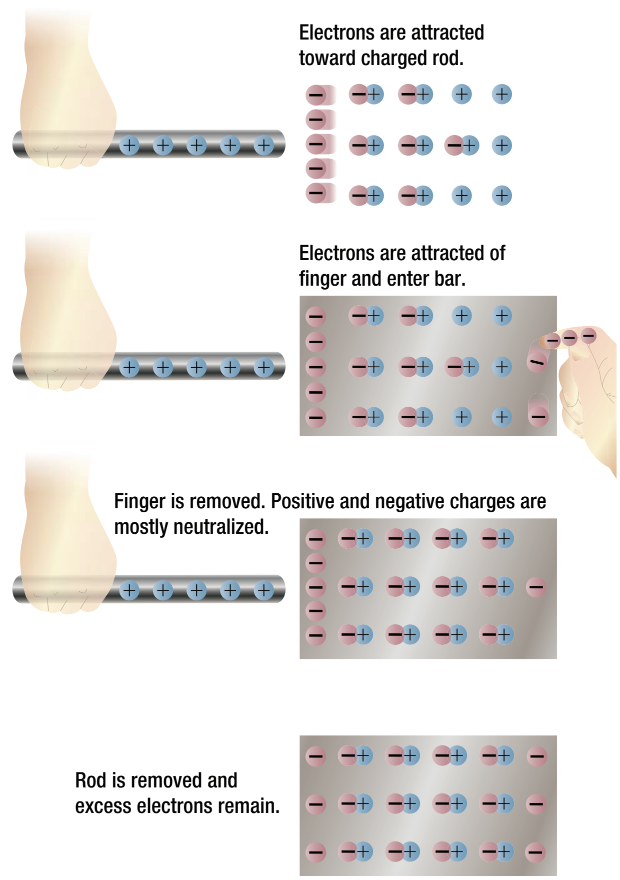


Figure 2-9. Charging a bar by induction.

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.

CONDUCTION IN SOLIDS, LIQUIDS, GASES AND A VACUUM

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.

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
Name 2 instances when the prevention of electrostatic discharge is critical.

Question: 2-4
What does Coulomb's law describe?

Question: 2-5
If a positively charged material is rubbed onto a neutral material, the positively charged material will become ________________ charged.

Question: 2-6
What does the triboelectric effect describe?

ANSWERS

Answer: 2-1
static electricity.

Answer: 2-2
neutral.

Answer: 2-3
When handling electronics; when fueling aircraft.

Answer: 2-4
The repelling and attraction of like and unlike charges.

Answer: 2-5
negatively

Answer: 2-6
The flow of electrons between positively and negatively charged materials.

ELECTRICAL FUNDAMENTALS

ELECTRICAL TERMINOLOGY

SUB-MODULE 03

PART-66 SYLLABUS LEVELS		
CERTIFICATION CATEGORY →	B1	B2
Sub-Module 03 ELECTRICAL TERMINOLOGY Knowledge Requirements		
3.3 - 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

3.3 - ELECTRICAL TERMINOLOGY

ELECTRICAL TERMS, THEIR UNITS, AND THE FACTORS AFFECTING THEM

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 millimeters, but larger distances are more meaningfully expressed in feet, yards, or meters of kilometers. 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 1 kV. 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.

POTENTIAL DIFFERENCE

Potential difference is the work done when moving a unit of positive electric charge from one point to another. For example, if you connect both ends of a wire to opposite ends of a battery, current will flow through it due to the potential difference between the two ends of the battery.

It is sometimes helpful to think of potential difference as a difference of 'electrical pressure' forcing a current through a load. In order for current to flow in a circuit then a potential difference must exist between any two points in that circuit and each point in the circuit must be at a different potential. However because there is very little opposition to current flow in conducting wires, very little potential difference is required to push the current along the wires, and it is normally assumed to be zero. Whenever the opposition to current flow is significant, then a potential different exists across that component to push the electrons through the device.

The practical unit for potential difference is the volt "V".

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.

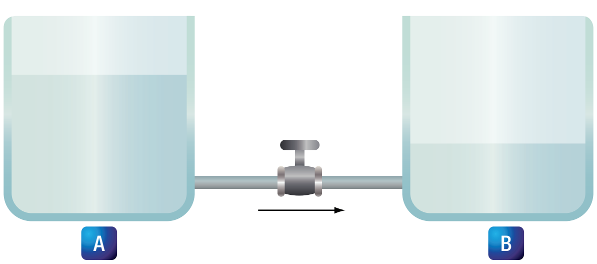


Figure 3-2. Difference of pressure.

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).

The Unit of Volt

We know that anything that has energy has the ability to do work, but in electricity we are more concerned with the rate at which work is done, which is called power "P". The unit of power is Watt "W". Since voltage is related to this power it is defined as: The volt is the difference in electrical potential between two points on a conductor carrying a current of one ampere, when energy is dissipated between these two points at the rate of one Watt. (***Figure 3-3***)

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

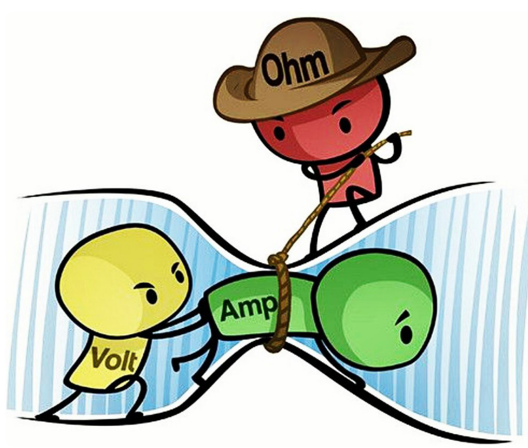


Figure 3-3. The relation between volts, current, and ohms passing through a conductor (wire).

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.

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

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:

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

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 (101^8) 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 AC current, 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 3-4***.

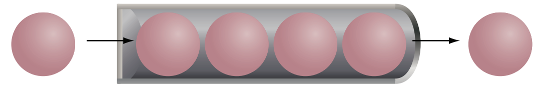


Figure 3-4. Electron movement.

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. Electric current can be viewed as instantaneous, even though it is the result of a relatively slow drift of electrons.

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. The measure of resistance is known as the Ohm. (***Figure 3-3***) Ohm's law will be discussed in detail in *Sub-Module 06*, DC Circuits.

CONDUCTANCE

Conductance describes the ease with which electric current flows through a substance. It is basically the opposite of resistance. In equations, conductance is symbolized by the letter "G" with the standard measuring unit being the Siemens"S".

When a current of one ampere passes through a component across which a voltage of one volt exists, then the conductance of that component is one Siemen which is equivalent to one ampere per volt. If "G" is the conductance of a component, "I" is the current through the component (in amps), and "E" is the voltage across the component (in volts), then: G = I ÷ E.

In general, when the applied voltage is constant, the current in a direct current (DC) circuit is directly proportional to the conductance. If the conductance is doubled, the current is also doubled; if the conductance is cut to a 1/4 of its original value, the current also becomes a 1/4 as great.

CHARGE

In an atom of matter, an electrical charge (symbolized by the letter "Q") occurs whenever the number of protons in the nucleus differs from the number of electrons surrounding that nucleus. If there are more electrons than protons, the atom has a negative charge. If there are fewer electrons than protons, the atom has a positive charge. The amount of charge in an atom is always a combined charge carried by each single electron and proton. An atom with negative charge is said to have negative electric polarity. An atom with positive charge is said to have positive electric polarity. In an object comprised of many atoms, the net charge is equal to the sum of the charges of all the atoms taken together.

The unit of electrical charge in the International System of Units is the Coulomb "C", where 1C is equal to approximately 6.24×10^{18} elementary charges. It is not unusual for real world objects to hold charges of many Coulombs.

An electrical field or an electrostatic field, surrounds any object that has charge. The field strength at any given distance from an object is proportional to the amount of charge on the object.

When two objects having electric charge are brought near each other, an electrostatic force is manifested between them. If the charges are of the same polarity, the electrostatic force is repulsive. If the charges are of opposite polarity, the electrostatic force is attractive.

In space (a vacuum), if the charges on the two nearby objects in coulombs are "q_1" and "q_2" and the centers of the objects are separated by a distance "r" in meters, the net force "F" between the objects, (in newtons) is given by the formula shown in ***Figure 3-5***.

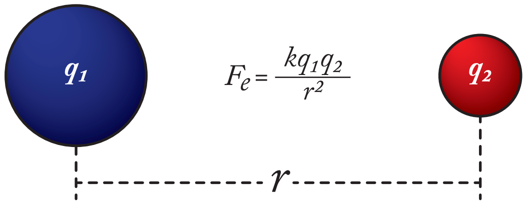


Figure 3-5. Per Coulomb's law; the closer two charges are, the stronger the force between them.

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. (***Figure 3-6***)

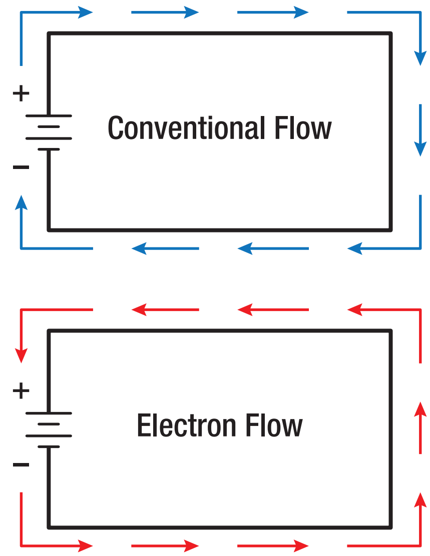


Figure 3-6. Conventional flow theory versus electron flow theory.

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.

Question: 3-1
Arrange the following SI prefixes from largest to smallest: pico. milli, micro, deci, nano, centi.

Question: 3-2
In electron flow theory, electrons flow form ________________ to ________________.

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: 3-4
The rate at which an electrical charge flows through a conductor is called ________________.

Question: 3-5
What are the two factors which contribute to the strength of an electrical field?

Question: 3-6
Which electrical measure represents the force with which electricity flows through a conductor?

ANSWERS

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

Answer: 3-2
negative.
positive.

Answer: 3-3
resistance.

Answer: 3-4
amperage.

Answer: 3-5
The strength of the charge; the distance to the charged material.

Answer: 3-6
The Volt.

ELECTRICAL FUNDAMENTALS

GENERATION OF ELECTRICITY

SUB-MODULE 04

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.	1	1

3.4 - GENERATION OF ELECTRICITY

PRODUCTION OF ELECTRICITY

LIGHT

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.

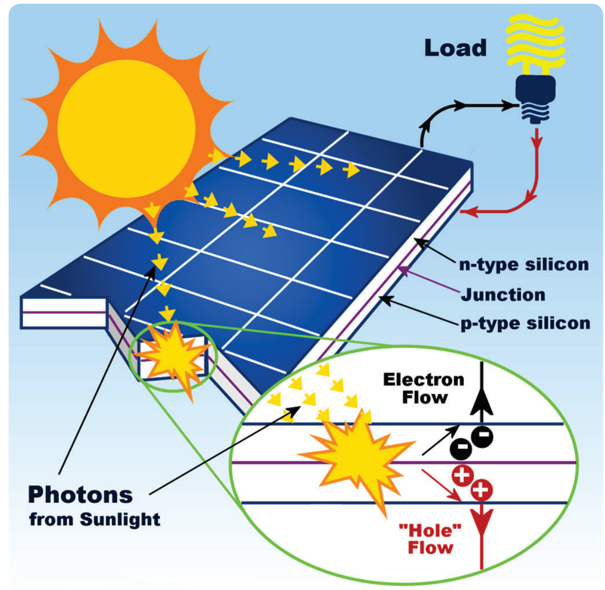


Figure 4-1. The operation of a solar cell.

HEAT

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. (***Figure 4-1***)

In case of uniformly heated wires no potential difference between the wires can exist because under identical temperature conditions there is no thermal gradient to produce a current. (***Figure 4-2***)

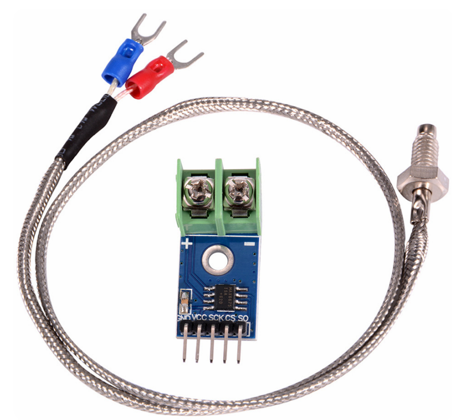


Figure 4-2. A typical thermocouple sensor and receiving device.

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*.

PRESSURE

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. (***Figure 4-3***)

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

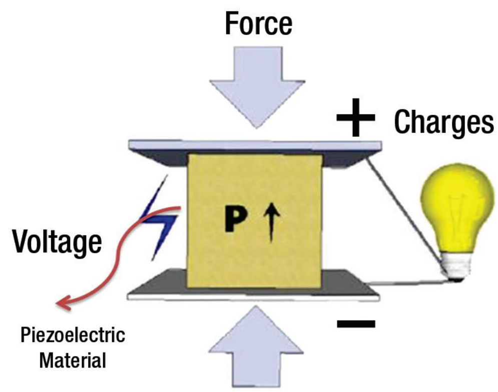


Figure 4-3. Piezoelectric materials when squeezed generate an electrical field.

(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 ACTION

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. (***Figure 4-4***)

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 *Sub-Module 10* in this book. (***Figure 4-5***)

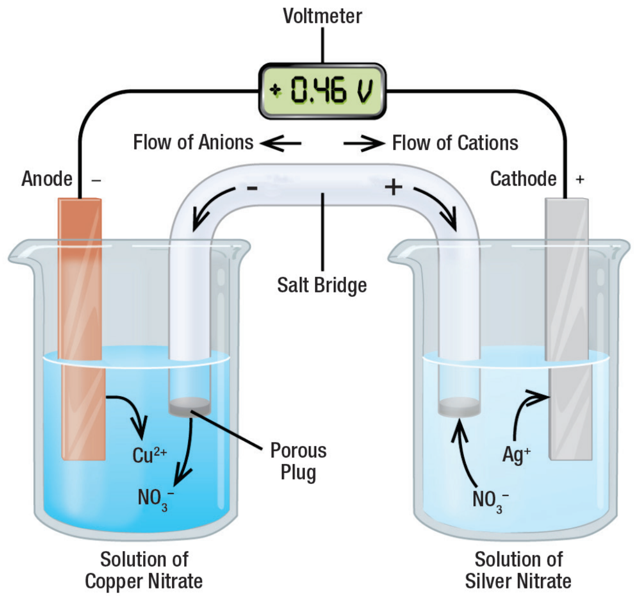


Figure 4-4. In this standard galvanic cell, electrons can flow through a wire and do electrical work.

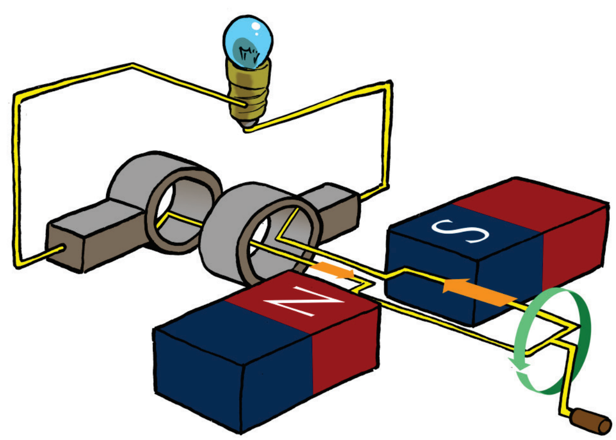


Figure 4-5. A simple generator converts mechanical energy and magnetism into electrical energy.

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?

Question: 4-4
What is required regarding temperature for thermoelectric generation?

Question: 4-5
What causes the generation of electricity from light?

Question: 4-6
What type of electricity is typically produced by friction?

ANSWERS

Answer: 4-1
piezoelectric.

Answer: 4-2
A battery.

Answer: 4-3
An electromotive force is created and current flows in the conductor.

Answer: 4-4
A difference in temperature between two conductors.

Answer: 4-5
Photons break loose electrons from an atom.

Answer: 4-6
Static electricity.

ELECTRICAL FUNDAMENTALS

DC SOURCES OF ELECTRICITY

SUB-MODULE 05

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

CONSTRUCTION AND CHEMICAL ACTION OF PRIMARY CELLS, SECONDARY CELLS, LEAD ACID CELLS, NICKEL CADMIUM CELLS AND OTHER TYPES OF CELLS

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. (***Figure 5-1***)

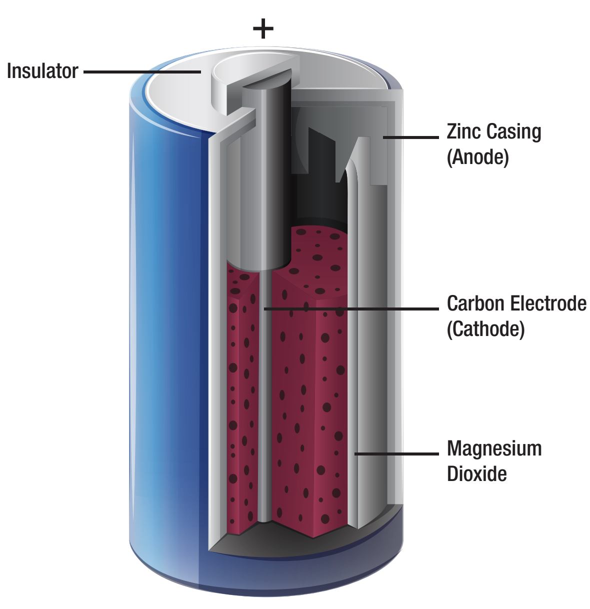


Figure 5-1. Primary cell; a common household battery.

Alkaline Batteries

Alkaline batteries are a type of primary battery dependent upon the reaction between zinc and manganese dioxide (Zn/MnO_2). Another type of alkaline batteries are secondary rechargeable alkaline battery, which allows reuse of specially designed cells. Compared with standard zinc carbon batteries, alkaline batteries have a higher energy density and longer shelf life with the same voltage.

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 Cells

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 5-2*** illustrates each cell contains positive plates of lead dioxide (PbO_2), 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 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 nonspill 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 5-3*** 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 5-4***) The complete assembly is enclosed in an acid resisting metal container (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 5-5***)

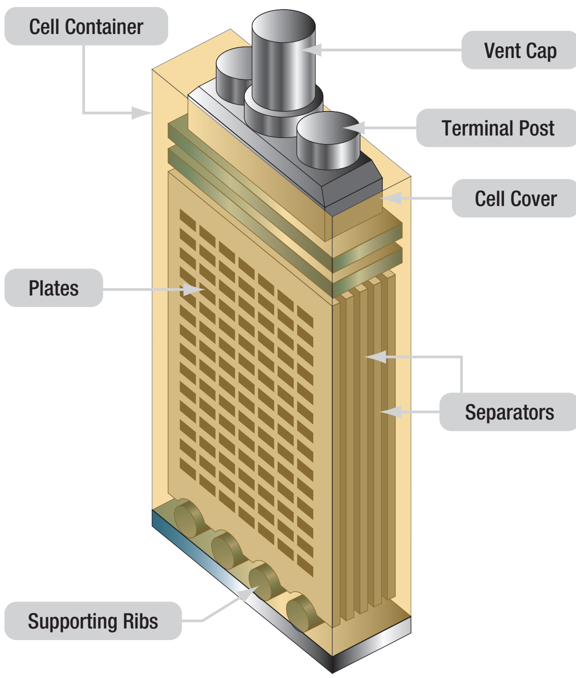


Figure 5-2. Lead-acid cell construction.

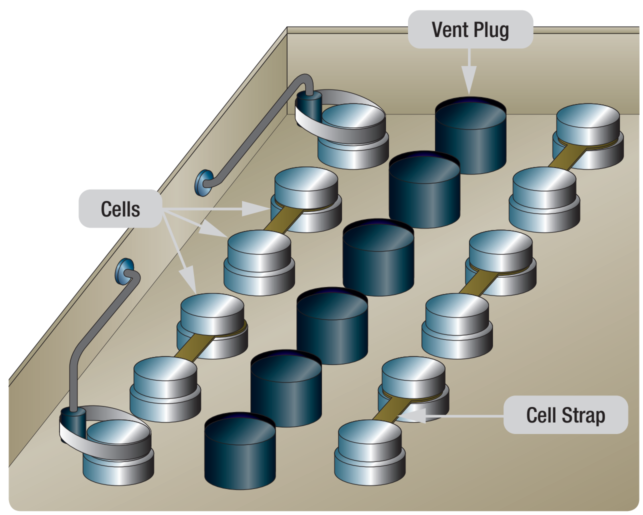


Figure 5-4. Connection of storage battery.

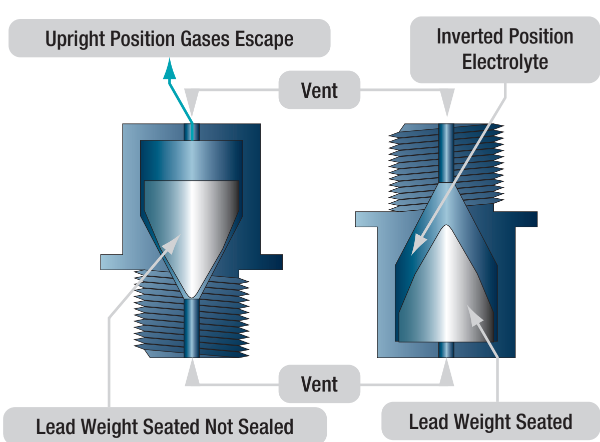


Figure 5-3. Non-spill battery vent plug.

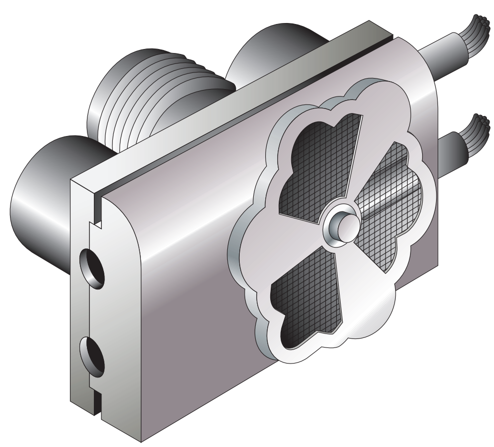


Figure 5-5. A battery quick-disconnect assembly.

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.

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 15.5°C. 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.

Battery Ratings

The voltage of a battery is determined by the number of cells connected in series to form the battery. 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 1/2 hour, or 1/3 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 is the 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 5-6***) 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

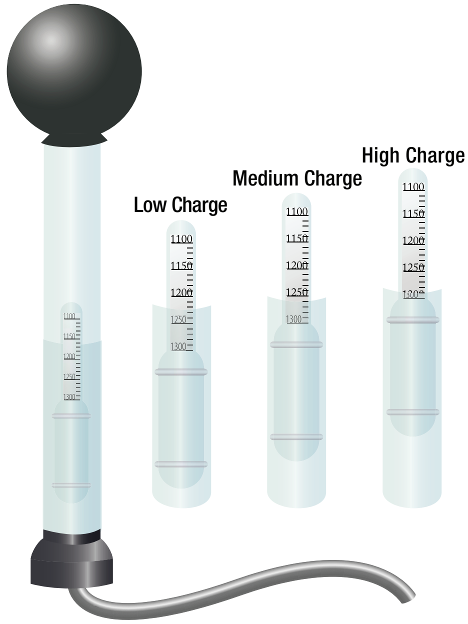


Figure 5-6. Hydrometer (specific gravity readings).

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 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 21°C and 32°C, since the variation is not great enough to consider. When temperatures are greater than 32°C or less than 21°C, 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.

Batteries are charged by either the constant voltage or constant current method. In the constant voltage method (***Figure 5-7A***), 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 5-7B***), 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.

Nickel Cadmium (NiCad) Cells

Chemistry and Construction

Active materials in nickel cadmium cells (NiCad) 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.

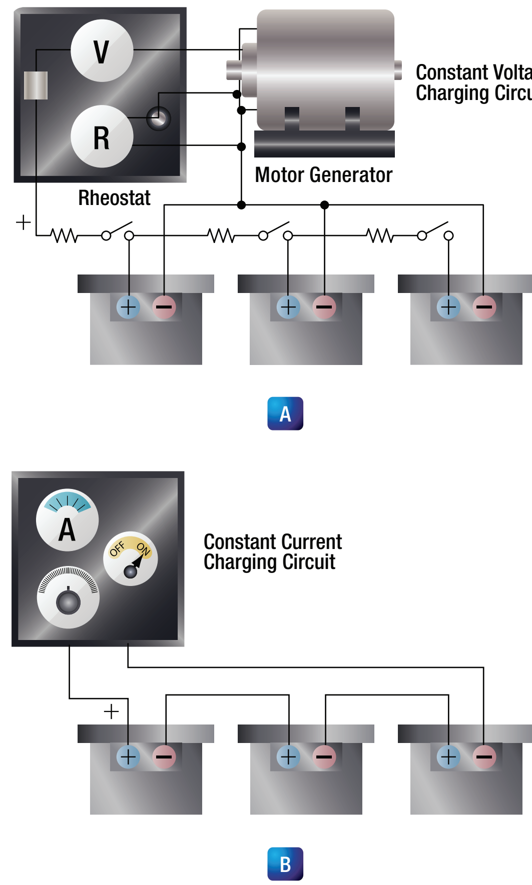


Figure 5-7. Battery charging methods.

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 NiCad 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. (***Figure 5-8***)

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.

NiCad Maintenance and Safety
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.

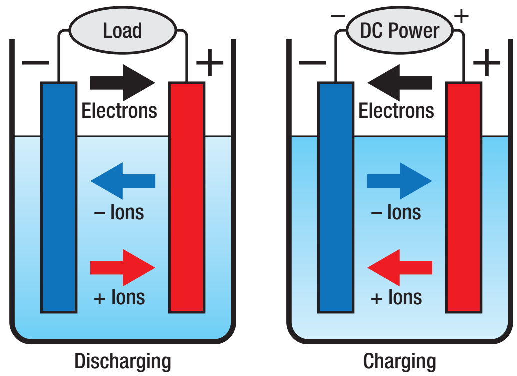


Figure 5-8. The charge and discharge cycle of a NiCad battery.

Electrolyte spillage can form grounding paths. 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 NiCad batteries. One leading characteristic of NiCad 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 NiCad battery to match as many as twenty individual cells in order to prevent unbalance and thus cell reversal during end of discharge. With SLA batteries, cell matching is inherent in each battery. NiCads also have an undesirable characteristic caused by constant overcharge and infrequent discharges, as in standby applications. It is technically known as "voltage depression" and commonly but erroneously called "memory effect." SLA batteries do not have this characteristic voltage depression (memory) phenomenon, and therefore do not require scheduled deep cycle maintenance as do NiCads.

The NiCad emergency battery pack requires relatively complicated test equipment due to the complex characteristics of the NiCad. 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.

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.

Lithium Ion Batteries

A lithium ion battery is a type of rechargeable battery in which lithium ions move from the negative lithium electrode to the positive electrode during discharge and back when charging. The electrolyte, which allows for ionic movement, and the two electrodes are the constituent components of a lithium ion cell. (***Figure 5-9***)

Lithium ion batteries can pose unique safety hazards since they contain a pressurized flammable electrolyte. A battery cell charged too quickly could cause a short circuit, leading to explosions and fires. Because of these risks, testing standards are more stringent than those for acid electrolyte batteries, requiring both a broader range of test conditions and additional specific tests.

Figure 5-9. A 28 volt lithium ion battery designed for turbine aircraft capable of 44 ampere hours of power.

CELLS CONNECTED IN SERIES OR PARALLEL

Components of an electrical circuit or electronic circuit can be connected in many different ways. The two simplest of these are called series and parallel. Components connected in series are connected along a single path, so the same current flows through all of the components. Components connected in parallel are connected along multiple paths, so the same voltage is applied to each component. A circuit composed solely of components connected in series is known as a series circuit; likewise, one connected completely in parallel is known as a parallel circuit.

In a series circuit, the current through each of the components is the same, and the voltage across the circuit is the sum of the voltages across each component. In a parallel circuit, the voltage across each of the components is the same, and the total current is the sum of the currents through each component.

Consider a very simple circuit consisting of four light bulbs and one 6V battery. If a wire joins the battery to one bulb, to the next bulb, to the next bulb, to the next bulb, then back to the battery, in one continuous loop, the bulbs are said to be in series. If each bulb is wired to the battery in a separate loop, the bulbs are said to be in parallel. If the four light bulbs are connected in series, there is same current through all of them, and the voltage drop is 1.5V across each bulb, which may not be sufficient to make them glow. If the light bulbs are connected in parallel, the currents through the light bulbs combine to form the current in the battery, while the voltage drop is across each bulb and they all glow.

In addition, in a series circuit, every device must function for the circuit to be complete. One bulb burning out in a series circuit breaks the circuit. In parallel circuits, each light bulb has its own circuit, so all but one light could be burned out, and the last one will still function. (***Figure 5-10***)

The voltage of a cell of a typical lead acid battery is approximately 2 volts. In order to attain the voltage required, each cell is connected in series with heavy gauge metal straps. As the voltage required for engine starting is 12 or 24 volts. This is achieved by connecting six cells or twelve cells in series and enclosing them in one plastic box.

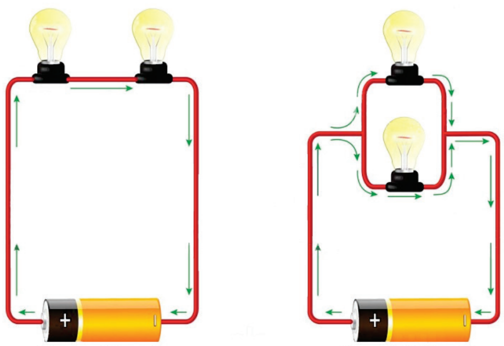


Figure 5-10. The wiring pattern of series versus parallel circuits.

When connecting multiple batteries, the ampere hour capacity depends upon its total effective plate area. Connecting batteries in parallel increases ampere hour capacity. Connecting batteries in series increases the total voltage but not the ampere hour capacity.

INTERNAL RESISTANCE AND ITS EFFECT ON A BATTERY

The internal resistance of a battery increases over time as the active material inside the battery converts to lead sulfate as loads are placed on it. As the lead sulfate builds up, resistance increases. This resistance can be calculated using the difference between the no load voltage and the load voltage for a particular circuit.

A battery with low internal resistance delivers high current on demand. As resistance builds, it causes the battery to heat up and the voltage to drop. Temperature also affects the resistance; heat lowers it and cold raises it. Heating the battery will momentarily lower the internal resistance to provide extra run time.

Lead acid batteries have a very low internal resistance and the battery responds well to high current bursts that last for a few seconds. However, lead acid batteries do not perform well on a sustained high current discharge. The battery soon gets tired and needs a rest to recover. This is because power delivery is not based on internal resistance alone but also on the responsiveness of the chemistry, as well as temperature. In this respect, nickel and lithium based technologies are more responsive than lead acid.

CONSTRUCTION, MATERIAL, AND OPERATION OF THERMOCOUPLES

Mentioned in *Sub-Module 04* as a thermal means for generation of electricity, thermocouples have significant application in aviation. (***Figure 4-2***) 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 engine 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. The main limitation with thermocouples is accuracy; system errors of less than one degree Celsius (°C) can be difficult to achieve.

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.

OPERATION OF 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. (***Figure 5-11***)

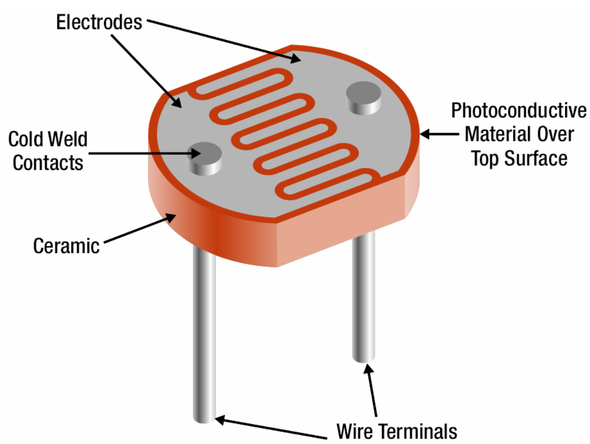


Figure 5-11. A typical photocell and its components; this one with a resistance of 200KΩ when dark to 10KΩ when exposed to light

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: 5-2
series.

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: 5-4
constant voltage.
constant current.

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

Answer: 5-6
electron.

ELECTRICAL FUNDAMENTALS

DC CIRCUITS

SUB-MODULE 06

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

DC CIRCUITS

3.6 - DC CIRCUITS

OHM'S LAW, KIRCHOFF'S VOLTAGE AND CURRENT LAWS AND RELATED CALCULATIONS

SIMPLE DC CIRCUITS AND OHM'S LAW

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 Ω and R_2 = 30 Ω. 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:

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

For ***Figure 6-2***, this will be:

$R_T = 10\ \Omega + 30\ \Omega$

$R_T = 40\ \Omega$

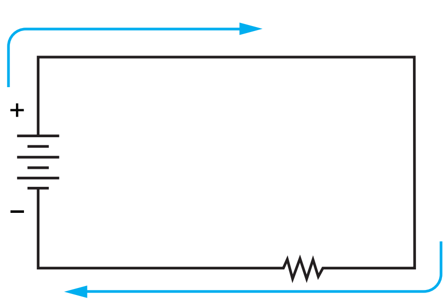


Figure 6-1. Simple DC circuit.

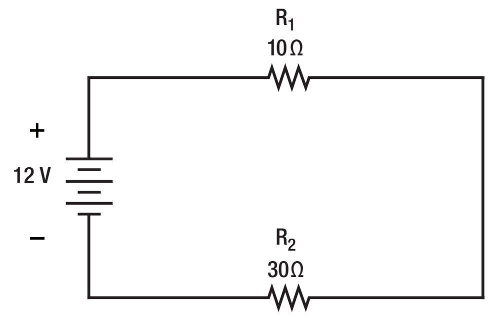


Figure 6-2. Simple DC circuit with additional resistor.

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

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

Current in circuits, $I = 0.3\text{A}$

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

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

Current in circuits, $I = 0.15\text{A}$

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

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

Current in circuits, $I = 0.6$A

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, $I = 1$mA
$R_1 = 1\text{ k}\Omega$
$R_2 = 3\text{ k}\Omega$
$R_3 = 5\text{ k}\Omega$

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: $E_1 = I_T\,(R_1)$
$E_1 = 1\text{ mA}\,(1\text{ k}\Omega) = 1$ volt
Voltage across R_2: $E_2 = I_T\,(R_2)$
$E_2 = 1\text{ mA}\,(3\text{ k}\Omega) = 3$ volt
Voltage across R_3: $E_3 = I_T\,(R_3)$
$E_3 = 1\text{ mA}\,(5\text{ k}\Omega) = 5$ volt

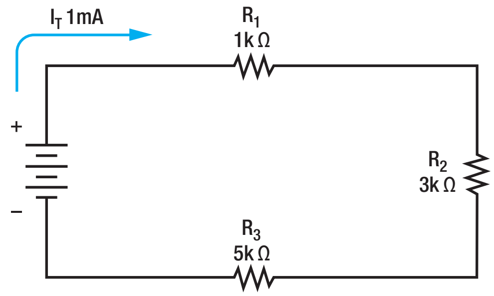


Figure 6-3. Example of three resistors in series.

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
$E_S = I\,(R_T)$

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

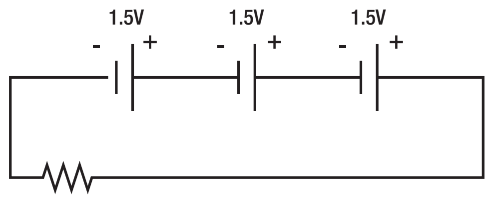


Figure 6-4. Voltage sources in series add algebraically.

The addition is simple enough:
$E_T = 1.5v + 1.5v + 1.5v = + 4.5$ volts

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:
$E_T = + 1.5v - 1.5v + 1.5v = +1.5$ 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:
$E_S - E_1 - E_2 - E_3 \ldots -E_N = 0$ 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.

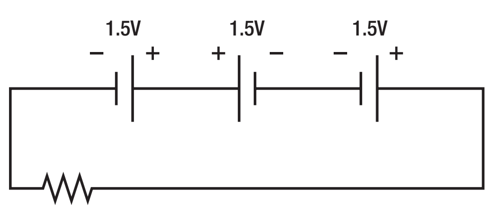


Figure 6-5. Voltage sources add algebraically; one source reversed.

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:
$E_S - E_1 - E_2 - E_3 = 0$ volts

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

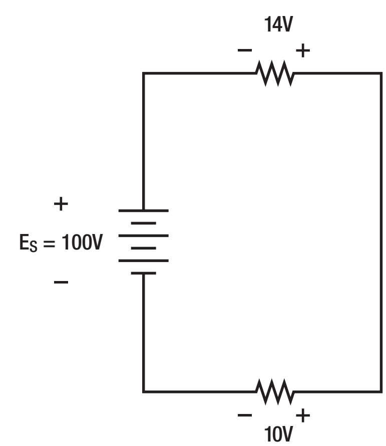


Figure 6-6. Kirchhoff's voltage law.

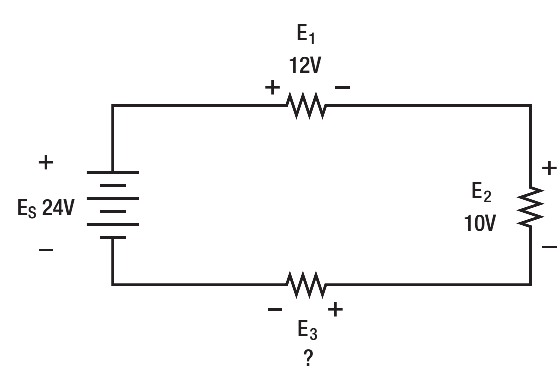


Figure 6-7. Determine the unknown voltage drop.

Determine the value of E_4 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 $\quad E_1 = 2\text{ volts}$

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

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

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: $68v - E_4 = 0$

Solve for unknown: $E_4 = 68v$

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

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.

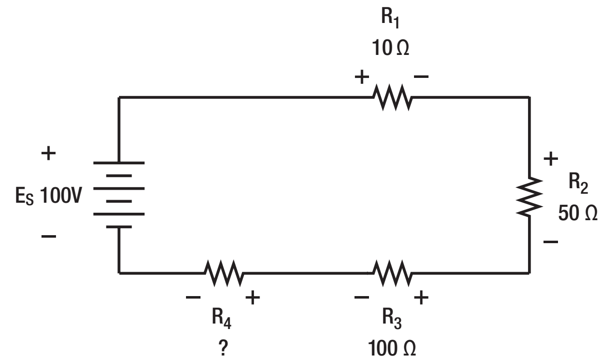


Figure 6-8. Determine the unknown voltage drop.

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.

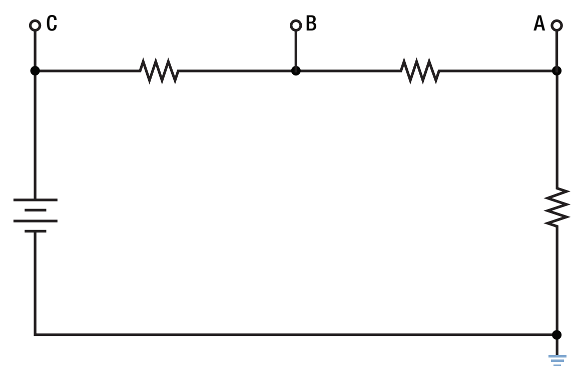


Figure 6-9. A voltage divider circuit.

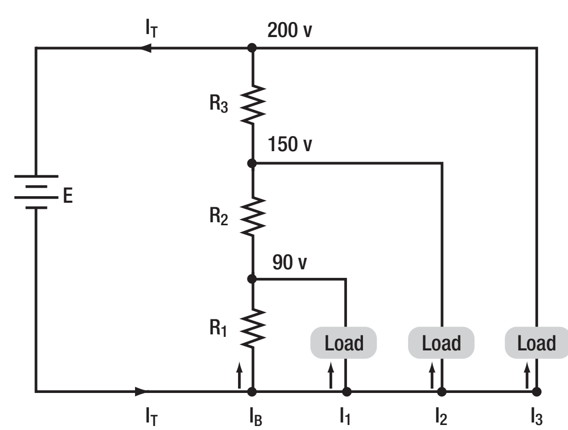


Figure 6-10. A typical voltage divider.

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.

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 R_3. 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; 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.

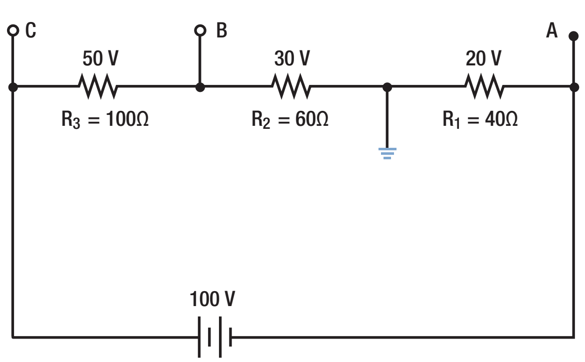


Figure 6-11. Positive and negative voltage on a voltage divider.

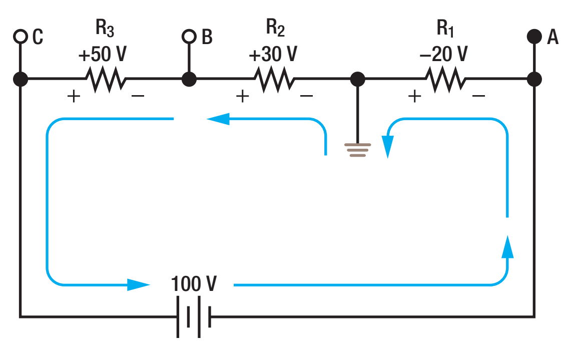


Figure 6-12. Current flow through a voltage divider.

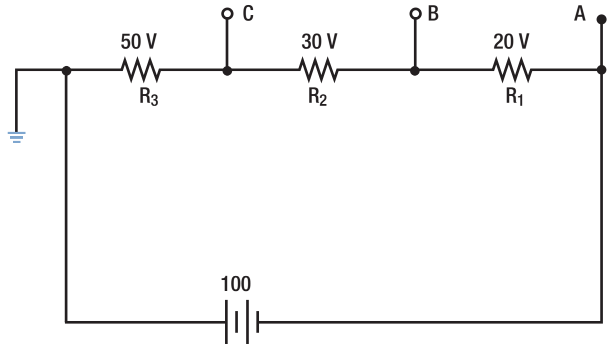


Figure 6-13. Voltage divider with changed ground.

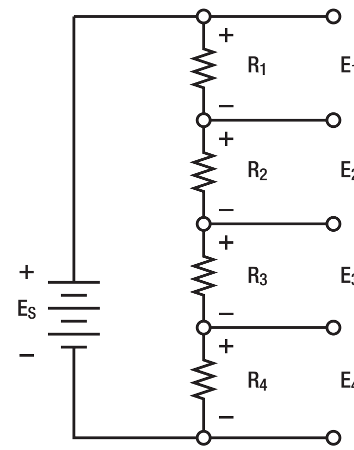


Figure 6-14. Network of three resistors and one voltage source.

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

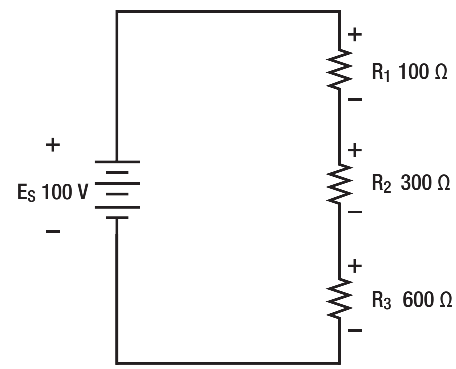


Figure 6-15. Kirchhoff's current law.

Voltage drop over 100 Ω resistor is:

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

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

Voltage drop over 300 Ω resistor is:

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

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

Voltage drop over 600 Ω resistor is:

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

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

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

PARALLEL DC CIRCUITS

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.

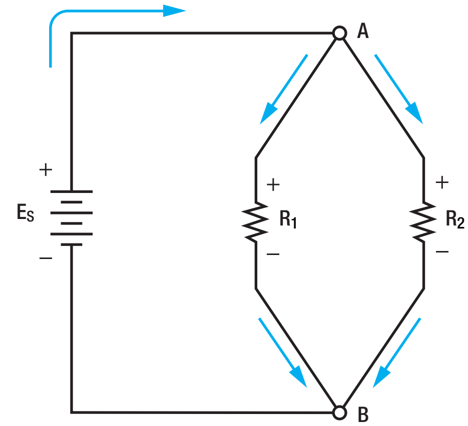


Figure 6-16. Basic parallel circuit.

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 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 varies according to its individual resistance. The total current of the circuit is the sum of the current in all branches. It can be determined by inspection that the total current is greater than that of any given branch. Using Ohm's Law to calculate the total resistance based on the applied voltage and the total current, it can be determined that the total resistance is less than any 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 is less than the 5 Ω.

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:

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

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

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

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.

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

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

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 example. 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 $I_T = 5\text{mA} + 12\text{mA}$
$I_T = 17\text{mA}$

The total current entering node B is also the same.

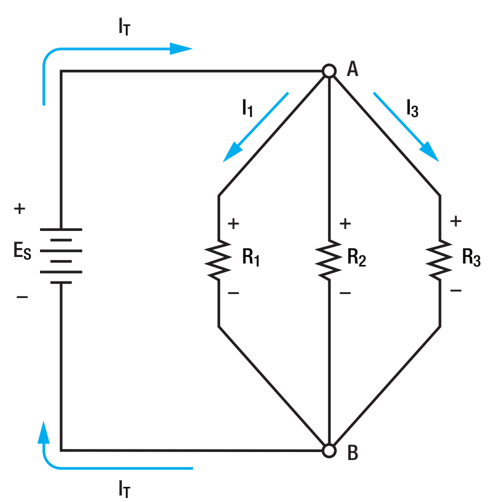


Figure 6-17. Individual branch currents.

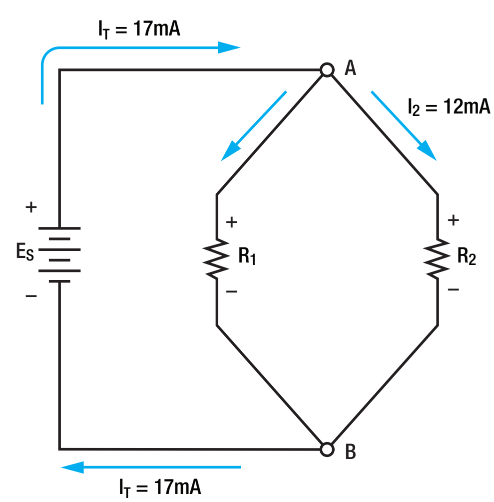


Figure 6-18. Determining an unknown circuit in branch 2.

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	$75 \text{ mA} = 30 \text{ mA} + I_2 + 20 \text{ mA}$
Solve I_2	$I_2 = 75 \text{ mA} - 30 \text{ mA} - 20 \text{ mA}$
	$I_2 = 25 \text{ mA}$

Current Dividers

It can now be easily seen that the parallel circuit is a current divider. As shown 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 is 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.

$$E_S = I_T R_T$$

Substituting $I_T R_T$ for E_S $\quad I_X = \dfrac{I_T R_T}{R_X}$

Rearranging $\quad I_X = \left(\dfrac{R_T}{R_X}\right) I_T$

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

And $\quad I_1 = \left(\dfrac{R_1}{R_T}\right) I_T$

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.

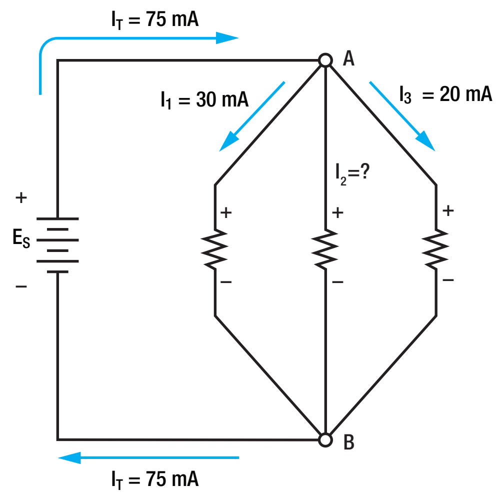


Figure 6-19. Series-parallel circuits.

SERIES PARALLEL DC CIRCUITS

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. 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.

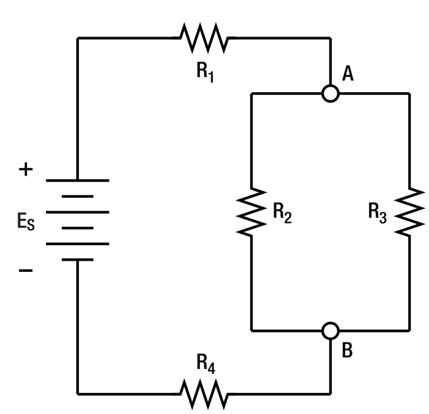


Figure 6-20. Equivalent circuit with three series connected resistors.

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.

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

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

Solve for R_{EQ} $\quad R_{23} = \frac{6k\,\Omega}{5k\,\Omega}$

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

Solve for R_T $\quad R_T = 1k\,\Omega + 1.2k\,\Omega$

$R_T = 2.2k\,\Omega$

With the total resistance R_T now determined, the total I_T can be determined.

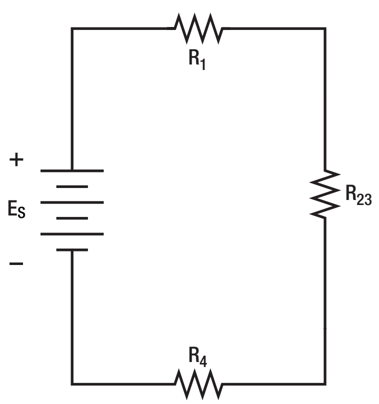


Figure 6-21. Determining total resistance.

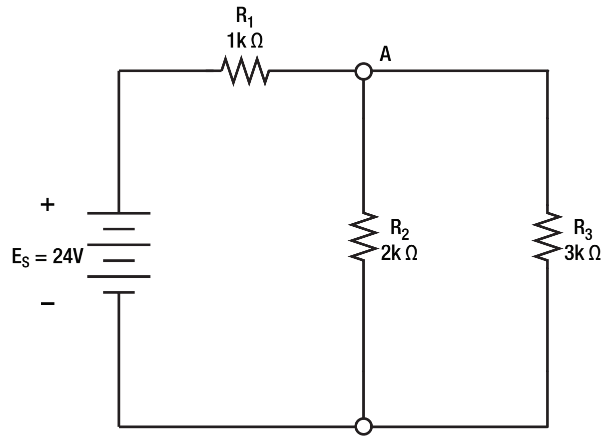


Figure 6-22. Determining total resistance.

Using Ohm's law:

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

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

$I_T = 10.9mA$

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

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

Substitute Values for I_2 $\quad I_2 = \left(\frac{R_3}{R_2 + R_3}\right)\left(I_T\right)$

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

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

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

$I_2 = 6.54\ mA$

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

$I_T = I_2 + I_3$

$I_3 = I_T - I_2$

$I_3 = 10.9\ mA - 6.54\ mA$

$I_3 = 4.36\ mA$

INTERNAL RESISTANCE OF A SUPPLY (BATTERY)

A battery can be ideally represented as an EMF (or voltage) source connected in series with a resistor, which is its internal resistance.

The internal resistance value depends on the nature and conductivity of the electrolyte. As a battery loses it's potential to produce its rated voltage, it's terminal voltage decreases. When a battery is connected to a constant linear resistive load, as its potential decreases, its terminal voltage decreases due to the internal resistance increasing. Effectively more voltage is dropped across the internal resistance than the load resistance. If the load was decreased (so that the battery current decreases) the voltage drop across the internal resistance would decrease (ohms law) - hence the terminal (load) voltage would increase.

When a battery falls below an acceptable potential level, the internal resistance has built up so much that the battery can no longer supply the required power to its load. The internal resistance value will depend on the load value, the state of charge (potential) of the battery, and temperature. For a lead acid battery, heat can lower the internal resistance while colder temperatures will raise it. (***Figure 6-23***)

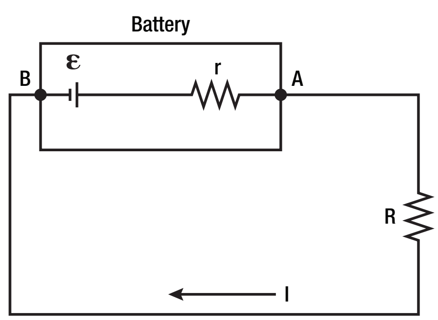


Figure 6-23. Internal resistance of a battery.

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

Answer: 6-3
Kirchhoff's voltage law.

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.

Answer: 6-5
less.

Answer: 6-6
sum.

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

ELECTRICAL FUNDAMENTALS

RESISTANCE/RESISTOR

SUB-MODULE 07

PART-66 SYLLABUS LEVELS

	CERTIFICATION CATEGORY → B1	B2
Sub-Module 07 RESISTANCE/RESISTOR Knowledge Requirements		
3.7 – Resistance/Resistor		
(a) Resistance and affecting factors; Specific resistance; Resistor color 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

RESISTANCE AND AFFECTING FACTORS

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 20 Ω. 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.

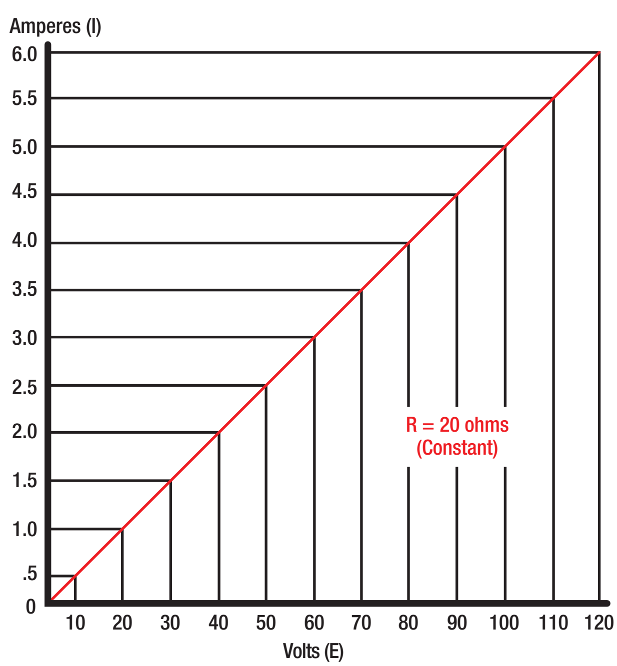


Figure 7-1. Voltage vs current in a constant-resistance circuit.

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.

If $E = 10V$

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

If $E = 60V$

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

If $E = 120V$

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

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.

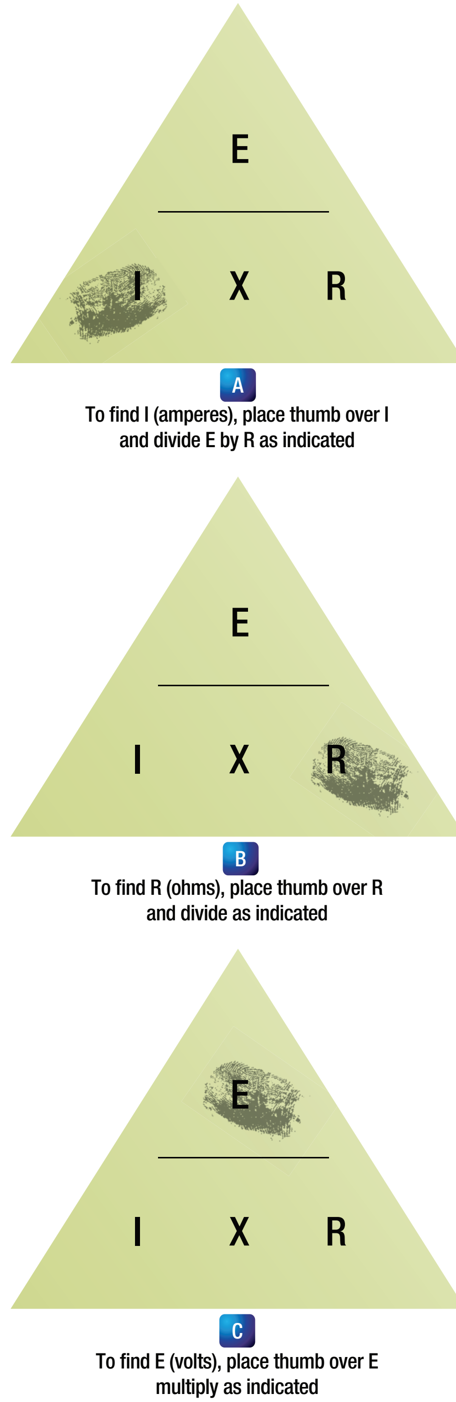


Figure 7-2. Ohm's law chart.

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 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.

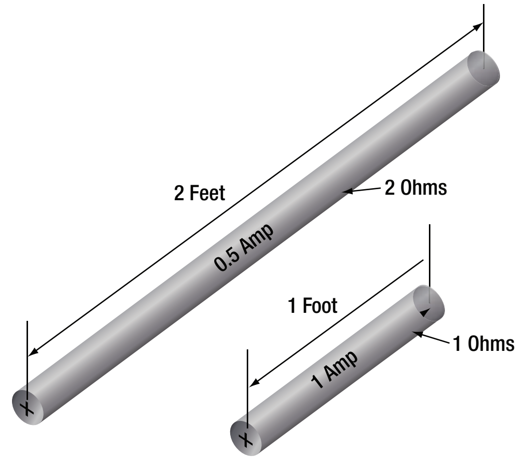


Figure 7-3. Resistance varies with length of conductor.

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. Specific resistance, or resistivity, is the resistance of a unit volume and unit length of a material. The standard dimensions are 1 meter length by 1 square meter; the resistivity is measured at a standard temperature of 20°C (as resistance of materials varies with temperature).

Various tables are available for different materials each with their specific resistance's, or resistivity, to compare their resistance and conductivity characteristics. ***Figure 7-4*** shows a table for "resistivity" of some common electric conductors.

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

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^{-8}
Iron	12.0×10^{-8}
Constantan	49.0×10^{-8}
Nichrome II	110×10

Figure 7-4. Resistivity table.

RESISTANCE AND WIRE SIZING

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 mm^2 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 mm^2?

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

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

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 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

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.

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

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 3/8 inch thick and 4 inches wide. The 3/8 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).

SPECIFIC RESISTANCE

Specific Resistance (resistivity) is the resistance offered by a cube of material at 0°C. It is a method of comparing the resistive properties of different materials. From knowledge of the specific resistance, the resistance of non uniform materials can be calculated.

Specific resistance is determined using the equation $\rho = RA/L$ where;

- R is the measured resistance of some length of the material.
- A is its cross sectional area (which must be uniform)
- L is its length.
- ρ (the Greek letter "rho") is the specific resistance

Some times it is more convenient to think in terms of how well a material conducts current, rather than to think in terms of how well it opposes it. Thus the property of conductance is often used. Conductance is the opposite of resistance. Conductance (G) = 1 ÷ Resistance and is measured in Siemens.

RESISTOR COLOR CODE, VALUES, TOLERANCE, AND WATTAGE RATINGS

FIXED RESISTORS

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.

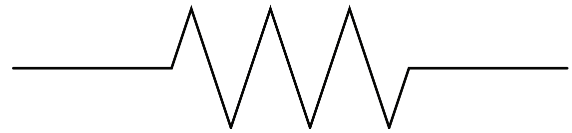


Figure 7-6. Fixed resistor schematic.

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 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.

WIRE WOUND RESISTORS

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 7-7***)

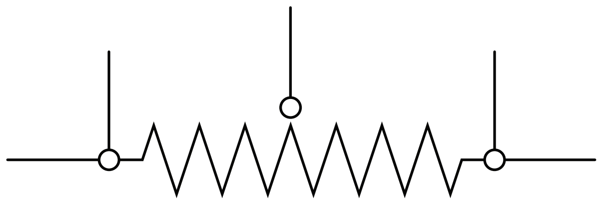


Figure 7-7. Wire wound resistors.

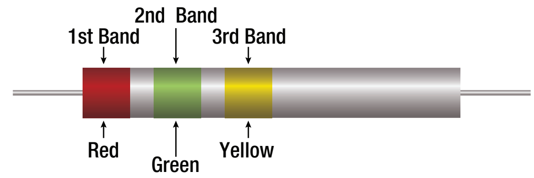
A wire wound resistor with tap is a special type of fixed resistor that can be adjusted. These adjustments can be made by moving a slide bar tap or by moving the tap to a preset incremental position. While the tap may be adjustable, the adjustments are usually set at the time of installation to a specific 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.

RESISTOR COLOR CODE

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 7-9***. If there is no fourth band, the tolerance is understood to be 20 percent.



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.

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%

Figurer 7-9. Resistor color code.

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.

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 7-10*** 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 7-11*** 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 7-12*** 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 7-13 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 7-14***. 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:

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

When the third band is silver, as is the case in ***Figure 7-15***, the first two digits must be multiplied by 1 percent. The value of the resistor is 0.45 ± 10 percent ohms.

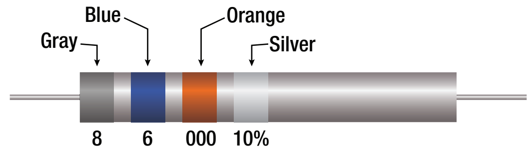


Figure 7-10. Resistor color code example.

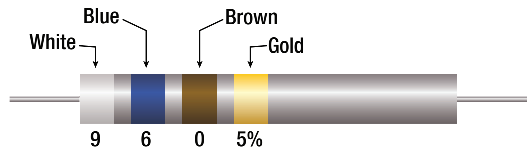


Figure 7-11. Resistor color code example.

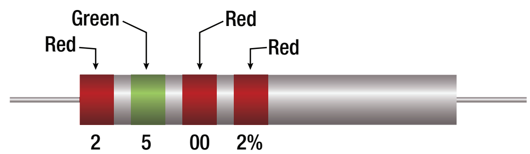


Figure 7-12. Resistor with two percent tolerance.

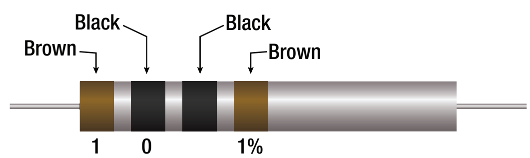


Figure 7-13. Resistor with black third color band.

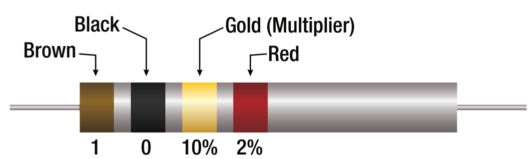


Figure 7-14. Resistor with gold third band.

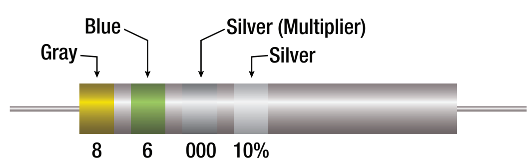


Figure 7-15. Resistor with a silver third band.

RESISTOR VALUES AND TOLERANCE

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 7-9***)

WATTAGE RATINGS

The Resistor Power Rating is sometimes called the Wattage Rating and is defined as the amount of heat that a resistive element can dissipate for an indefinite period of time without degrading its performance.

CALCULATIONS OF RESISTANCE IN SERIES, PARALLEL AND COMBINATIONS

The sections below show the methods of calculations for determining the total resistance for circuits in series, parallel, and in series/parallel combinations. Further explanations of Ohm's Law and computing resistance have been previously discussed in *Sub-Module 06*.

RESISTORS IN SERIES

Refer to ***Figure 7-16***. For resistors connected in series, the total resistance is given by the formula:

$$R\,(\text{total}) = R_1 + R_2 + R_3$$

RESISTORS IN PARALLEL

Refer to ***Figure 7-17***. For resistors connected in parallel, the total resistance is given by the formula:

$$\frac{1}{R\,(\text{total})} + \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Which in this case transposes to:

$$R\,(\text{total}) = \frac{R_1\,R_2\,R_3}{(R_2\,R_3) + (R_1\,R_3) + (R_1\,R_2)}$$

It's more common to find the equivalent resistance of just two resistors, using the formula:

$$R_{1\,2} = \frac{R_1\,R_2}{[R_1 + R_2]}$$

RESISTORS IN SERIES/PARALLEL

Series and parallel resistor combinations are best solved by treating individual series or parallel segments, to simplify the circuit in stages. (***Figure 7-18***)

$$R_6 + R_7 = 2 + 2 = \text{ohms}$$

To find the equivalent of R_5 and $R_{6\,7}$

$$R_{5\,6\,7} = \frac{R_5 \times R_{6\,7}}{R_5 + R_{6\,7}} = \frac{4 \times 4}{4 + 4} = 2\text{ ohms}$$

Following on:

$$R_4 + R_{5\,6\,7} = 10 + 2 = 12\text{ ohms}$$
$$R_{2\,3} = 4 + 8 = 12\text{ ohms}$$

The equivalent resistance of $R_{2\,3}$ and $R_{4\,5\,6\,7}$ in parallel.

$$R_{2\,3\,4\,5\,6\,7} = \frac{R_5 \times R_{6\,7}}{R_5 + R_{6\,7}} = \frac{12 \times 12}{12 + 12} = 6\text{ ohms}$$

Finally:

$$R_1 + R_{2\,3\,4\,5\,6\,7} = 4 + 6 = 10\text{ ohms}$$

Thus the equivalent resistance of the circuit is 10 ohms.

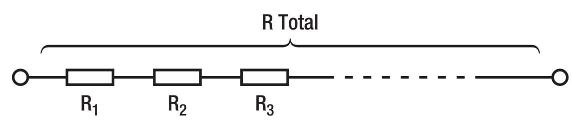


Figure 7-16. Calculations of resistance for resistors in series.

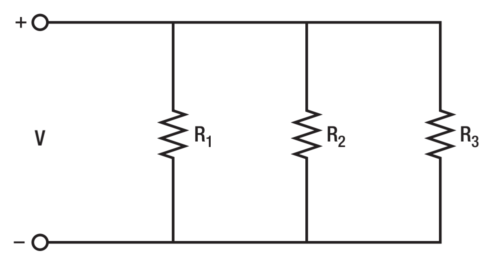


Figure 7-17. Calculations of resistance for resistors in parallel.

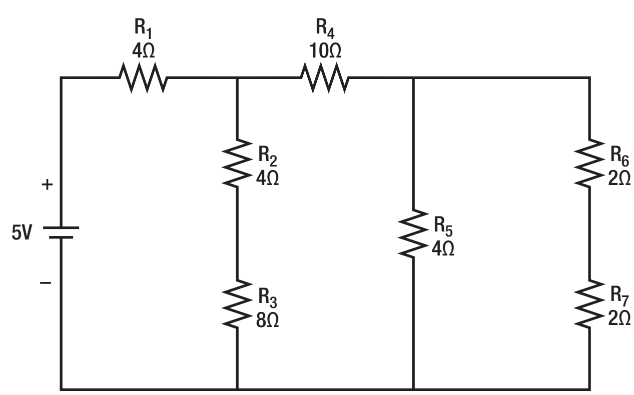


Figure 7-18. Calculations of resistance in circuits containing combinations of series and parallel paths.

VARIABLE RESISTORS - OPERATION

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.

RHEOSTATS

The schematic symbol for the rheostat is shown in ***Figure 7-19***. A rheostat is a variable resistor used to vary the amount of current flowing in a circuit. ***Figure 7-20*** 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 7-21***. 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 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.

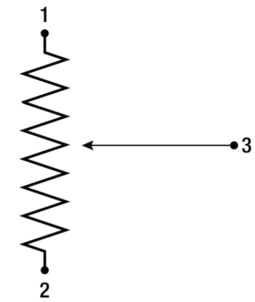


Figure 7-21. Potentiometer schematic symbol.

In ***Figure 7-22A***, 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 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 7-22*** 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

Figure 7-19. Rheostat schematic symbol.

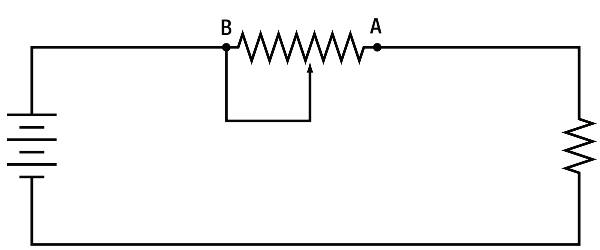


Figure 7-20. Rheostat connected in series.

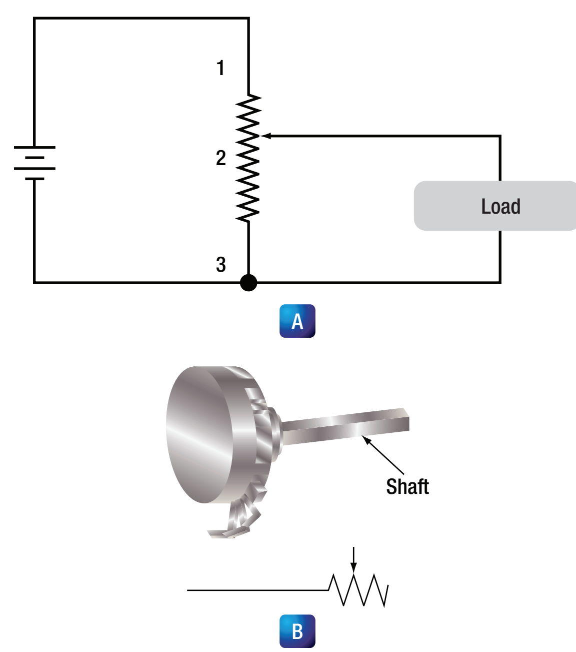


Figure 7-22. Potentiometer and schematic.

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 7-22***, 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 7-23*** shows how a potentiometer can be wired to function as a rheostat.

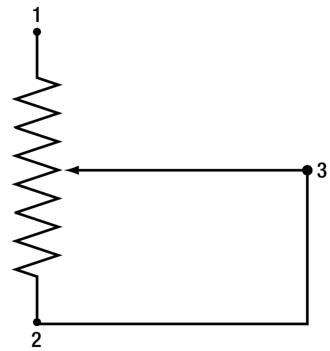


Figure 7-23. Potentiometer wired to function as rheostat.

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 7-24*** schematically depicts this.

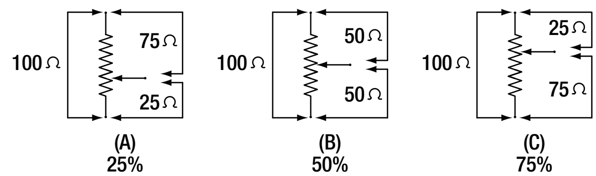


Figure 7-24. Linear potentiometer schematic.

Tapered Potentiometers

Resistance varies in a nonlinear manner in the case of the tapered potentiometer. ***Figure 7-25*** 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.

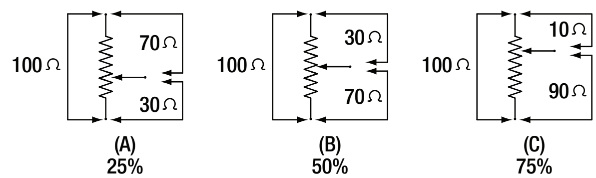


Figure 7-25. Tapered potentiometer.

THERMISTORS

Figure 7-26 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.

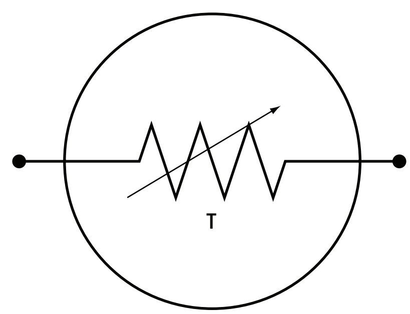


Figure 7-26. Schematic symbol for thermistor.

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 7-27*** shows the schematic symbol component.

OPERATION AND CONSTRUCTION OF A WHEATSTONE BRIDGE

A Wheatstone bridge is commonly used to measure changes in pressure or strain. A Wheatstone bridge is nothing more than two simple series circuits connected in parallel across a power supply.

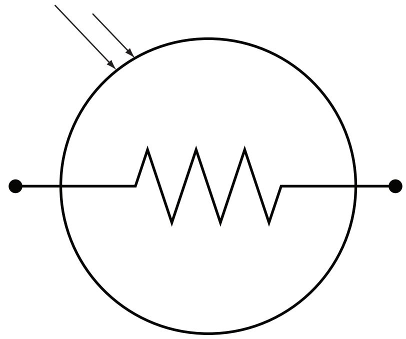


Figure 7-27. Photoconductive cell schematic symbol component.

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 7-28***. 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 $R_2 \div R_1 = R_X \div R_3$. 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: $R_X = R_2 \div R_1 \times R_3$. 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.

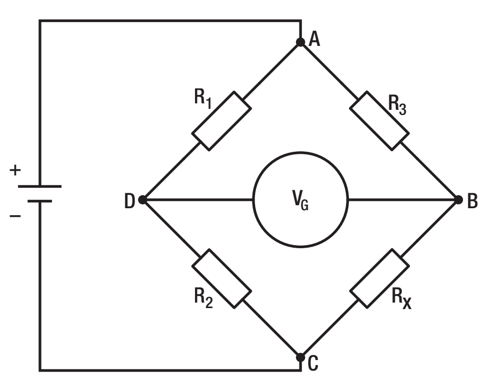


Figure 7-28. A Wheatstone Bridge circuit.

TEMPERATURE COEFFICIENT CONDUCTANCE

Most conductive materials change their specific resistance with changes in temperature. This is why figures of specific resistance are always stated at a standard temperature (usually 20°C). The resistance change factor per degree of temperature change is called the temperature coefficient of resistance. This factor is represented by the Greek lower case letter "alpha" (α).

POSITIVE TEMPERATURE COEFFICIENT

A positive coefficient for a material means that its resistance increases with an increase in temperature. Pure metals typically have positive temperature coefficients of resistance. Coefficients approaching zero can be obtained by alloying certain metals.

NEGATIVE TEMPERATURE COEFFICIENT

A negative coefficient for a material means that its resistance decreases with an increase in temperature. Semiconductor materials (carbon, silicon, germanium) typically have negative temperature coefficients of resistance. You might have noticed on the table for specific resistances (***Figure 7-4***) that all figures were specified at a temperature of 20° Celsius.

FIXED RESISTORS

Fixed resistors enable an opposing current to have a fixed value. 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.

METHODS OF CONSTRUCTION

A carbon 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 resistive value of the resistor. This mixture is compressed 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.

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, or metal as an insulating oxide for the metal oxide resistor.

VOLTAGE DEPENDENT RESISTORS

A voltage dependent resistor is an electronic component with an electrical resistance that varies with the applied voltage. Voltage dependent resistors (VDRs), have a nonlinear, non-ohmic current voltage characteristic that is similar to that of a diode.

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 _________________.

ANSWERS

Answer: 7-1
doubles.

Answer: 7-2
conductors, insulators.

Answer: 7-3
increase.

Answer: 7-4
tolerance.

Answer: 7-5
A large amounts of current.

Answer: 7-6
linear, tapered.

Answer: 7-7
Wheatstone Bridge.

ELECTRICAL FUNDAMENTALS

POWER

SUB-MODULE 08

PART-66 SYLLABUS LEVELS		
CERTIFICATION CATEGORY →	B1	B2
Sub-Module 08 POWER Knowledge Requirements		
3.8 - Power Power, work and energy (kinetic and potential); Dissipation of power by a resistor; Power formula; Calculations involving power, work and energy.	2	2

3.8 - POWER

POWER, WORK 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: $P = \frac{\text{energy}}{\text{time}}$

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

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

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:

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

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

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.

ELECTRICAL WORK

Electrical work is done if a quantity of charge in coulombs (Q) is moved between two points which are at different electrical potentials. The SI unit of work is the 'joule'. One joule of work is done when a charge of one coulomb moves through a potential difference (PD) of one volt.

Electrical Work (joule) = Charge (coulomb) / PD (volt)
Work = Q / V joules

Similarly, if the potential difference between two points is 1 Volt, then one joule of work is done in displacing one coulomb from a point of lower potential to a point of higher potential.

ELECTRICAL ENERGY

Electrical energy is the ability of an electrical system to do work. Energy is expended when work is done and the amount of energy used is equal to the work done. The units of energy and work is joules and the same equation is used for both.

Energy = Work = V / t joules

The energy a body contains may be determined by calculating the electrical work to give it that energy. Conversely, the work that a body could do if it used up all its energy may be determined by calculating how much energy it contains. This assumes that no energy is lost in the conversion. In practice energy is often lost in the form of heat. However no energy is actually destroyed. It is simply converted into some other form. This is stated in the Law of Conservation of Energy which states that energy can neither be created nor destroyed but merely changed into other forms.

DISSIPATION OF POWER BY A RESISTOR

The surface area and size of a component determines the rate at which heat is dissipated from the component to its surroundings. Generally the larger a component, the higher its power rating.

For example, with the resistor being a bulb, each is given a wattage rating and if this is exceeded the component will overheat. The more power consumed by a device the more heat or light it produces in a given time; a 100W lamp gives more light than a 60W lamp. The rating 6V 12W on a lamp means that if is connected to a 6V supply, its resistance is such that it develops 12W of power.

Note that the above bulb consumes 12W only at the correct voltage. If the voltage is increased more power is developed and the component may be damaged. A fluorescent tube of 12W rating produces more light than a 12W filament bulb because the tube produces much less heat and is therefore more efficient.

Electrical equipment can only stand a certain amount of heat production without damage. The safe power which a piece of equipment can consume without damage is its 'power rating' or 'wattage rating'.

POWER FORMULAS AND CALCULATIONS

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:

$$\text{Current} = \frac{\text{Charge}}{\text{time}}$$

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:

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

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

General Power Formula:

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

Where
- P = Power
- I = Current
- 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:

$$P = I\,(E)$$
$$P = 2A\,(24\text{ V})$$
$$P = 48\text{ W}$$

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:

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

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.

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

POWER

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:

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

$$P = \frac{(24\ V)^2}{20\ \Omega}$$

$$P = 28.8\ W$$

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:

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

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

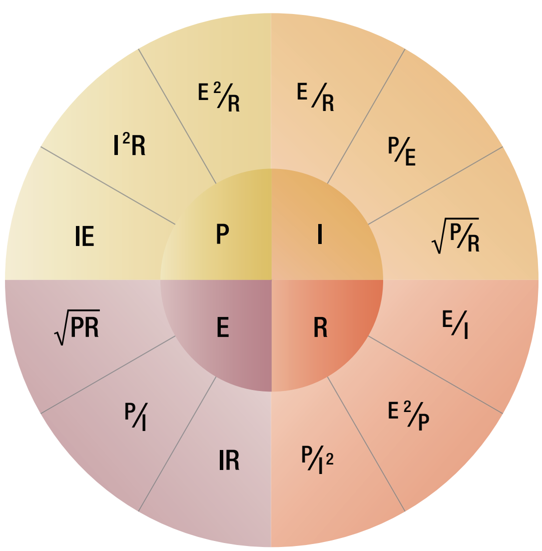


Figure 8-1. Ohm's law formula.

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: 8-2

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

Answer: 8-3
P = EI (power equals voltage × current)

Answer: 8-4
the total power dissipated.

ELECTRICAL FUNDAMENTALS

CAPACITANCE/CAPACITOR

SUB-MODULE 09

PART-66 SYLLABUS LEVELS		
CERTIFICATION CATEGORY →	B1	B2
Sub-Module 09 CAPACITANCE/CAPACITOR Knowledge Requirements		
3.9 - 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 color 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

3.9 - CAPACITANCE/CAPACITOR

OPERATION AND FUNCTION OF A CAPACITOR

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***.

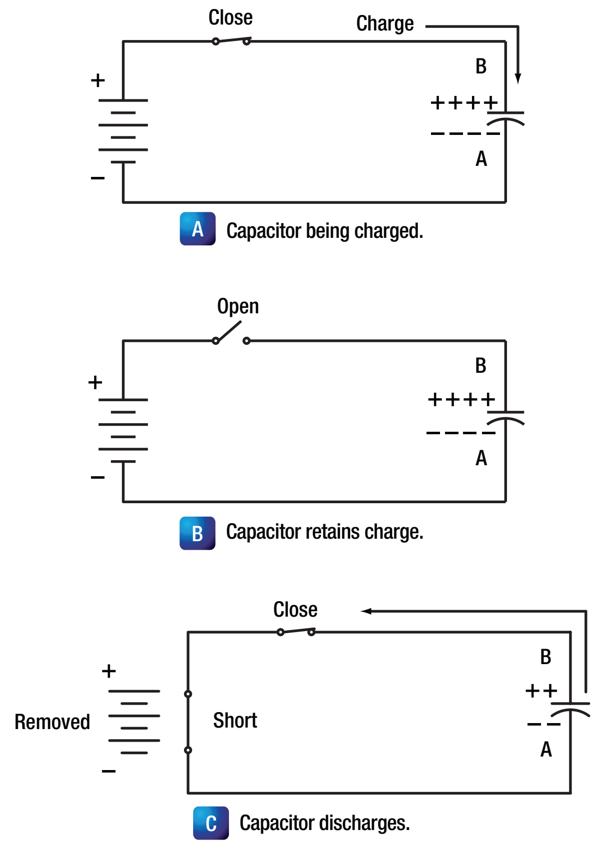


Figure 9-1. Capacitors in direct current.

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.

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.

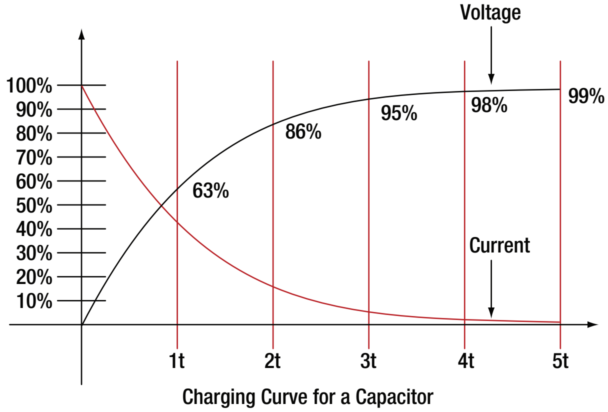


Figure 9-2. Capacitance charging curve.

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.

FACTORS AFFECTING CAPACITANCE

There are several factors which determine the amount of capacitance created. These factors all dictate capacitance by affecting how much electric field flux (relative difference of electrons between plates) will develop for a given amount of electric field force (voltage between the two plates).

AREA OF PLATES

The capacitance of parallel plates is directly proportional to their area. Greater plate area gives greater capacitance. Larger plate area results in more field flux (charge collected on the plates) for a given field force (voltage across the plates). 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 $C = Q/_E$ the capacitance is doubled.

DISTANCE BETWEEN PLATES

The capacitance of parallel plates is inversely proportional to their spacing. Further plate spacing gives less capacitance. Closer spacing results in a greater field force (voltage across the capacitor divided by the distance between the plates) which results in a greater field flux (charge collected on the plates) for any given voltage applied across the plates.

DIELECTRIC CONSTANT

The choice of dielectric material affects the capacitance of parallel plates. Greater permittivity of the dielectric gives greater capacitance.

To explain, some materials offer less opposition to field flux for a given amount of field force. Materials with a greater permittivity allow for more flux (offer less opposition), and thus a greater collected charge for any given amount of field (applied voltage).

Relative permittivity means the permittivity of a material compared to that of a vacuum. The greater the number, the greater the permittivity. Glass, for instance, with a permittivity of 7, has seven times the permittivity of a vacuum, and so will allow for the establishment of an electric field flux seven times stronger than that in a vacuum. ***Table 9-1*** lists the relative permittivity (dielectric constant) of some common substances.

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.

VOLTAGE RATING AND WORKING VOLTAGE

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

Material Relative Permittivity	Dielectric Constant
Vacuum	1.0000
Air	1.0006
PTFE, FEP (Teflon™)	2.0
Polypropylene	2.20 – 2.28
ABS Resin	2.4 – 3.2
Polystyrene	2.45 – 4.0
Waxed Paper	2.5
Transformer Oil	2.5 – 4.0
Hard Rubber	2.5 – 4.80
Wood (Oak)	3.3
Silicones	3.4 – 4.3
Bakelite	3.5 – 6.0
Quartz, Fused	3.8
Wood (Maple)	4.4
Glass	4.9 – 7.5
Castor Oil	5.0
Wood (Birch)	5.2
Mica, Muscovite	5.0 – 8.7
Glass Bonded Mica	6.3 – 9.3
Porcelain, Steatite	6.5
Alumina	8.0 – 10.0
Distilled Water	80.0
Barium Strontium Titanium	7500

Table 9-1. The relative permittivity (dielectric constant) of some common substances.

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.

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.

CAPACITOR TYPES

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 include: paper, oil, mica, electrolytic and ceramic capacitors. ***Figure 9-4*** shows the 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

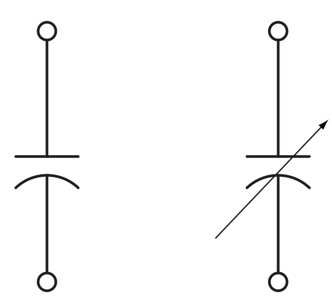


Figure 9-4. Schematic symbols for a fixed and variable capacitor.

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 Capacitors

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 Capacitors

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 Capacitors

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 Capacitors

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

Figure 9-5. Electrolytic capacitors.

Figure 9-6. Oil capacitor.

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).

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.

CAPACITOR COLOR CODING

The values of Capacitance, Voltage or Tolerance are generally marked onto the body of the capacitors in the form of alphanumeric characters. However, when the value of the capacitance is a decimal, problems arise as decimal point could easily not be noticed resulting in a misreading of the actual value. Instead letters such as 'p' (pico) or 'n' (nano) are used in place of the decimal point to identify its position and the weight of the number.

For example, a capacitor can be labeled as, n47 = 0.47nF, 4n7 = 4.7nF, or 47n = 47nF, and so on. Sometimes capacitors are marked with the capital letter 'K' to signify a value of one thousand picofarads. A capacitor with the markings of 100K would be 100 × 1000pF or 100nF.

To reduce this confusion, an international color coding scheme was developed as a simple way of identifying values and tolerances. It consists of colored bands (in spectral order) known as the Capacitor Color Code system and whose meanings are illustrated in ***Figure 9-7***.

CALCULATIONS OF 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 C_1 and the top plate of C_2 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.

$$Q_T = Q_1 + Q_2 + Q_3$$

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:

$$\frac{Q_T}{C_T} = \frac{Q_1}{E_1} + \frac{Q_2}{E_2} + \frac{Q_3}{E_3}$$

Color	Digit 1	Digit 2	Multiplier	Tolerance		Voltage
Black	0	0	1	+/– 20%	+/– 2.0 pF	100
Brown	1	1	10	+/– 1%	+/– .1 pF	200
Red	2	2	100	+/– 2%	+/– .25 pF	300
Orange	3	3	1 000	+/– 3%	-	400
Yellow	4	4	10 000	+/– 4%	-	500
Green	5	5	100 000	+/– 5%	+/– .5 pF	600
Blue	6	6	Not Used	-	-	700
Violet	7	7	Not Used	-	-	800
Grey	8	8	.01	+80%; -20%	-	900
White	9	9	.1	-	+/– 1.0 pF	1 000

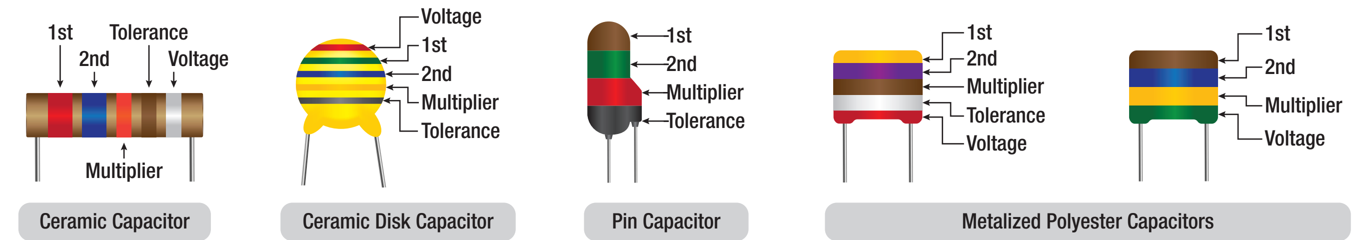


Figure 9-7. Identification key for capacitor color coding.

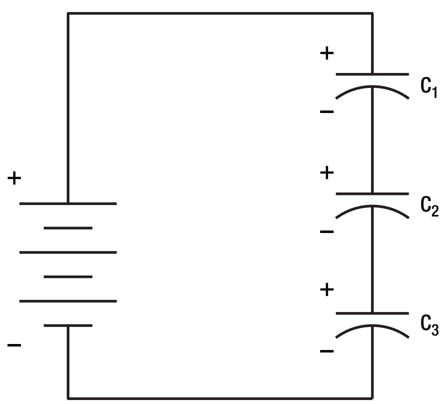


Figure 9-8. Simple series circuit.

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:

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

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

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

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 9-9*** 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.

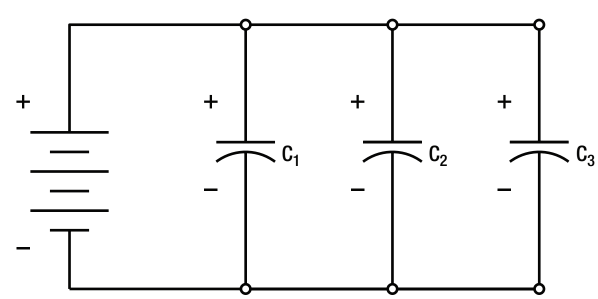


Figure 9-9. Simplified parallel circuit.

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

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 9-10***) 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.

CAPACITIVE REACTANCE X_C

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.

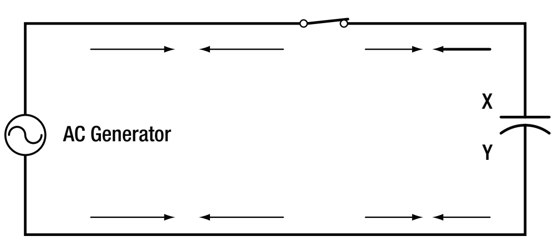


Figure 9-10. Capacitor in an AC circuit.

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.

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 Xc = 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 9-11A***) 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 9-11B***)

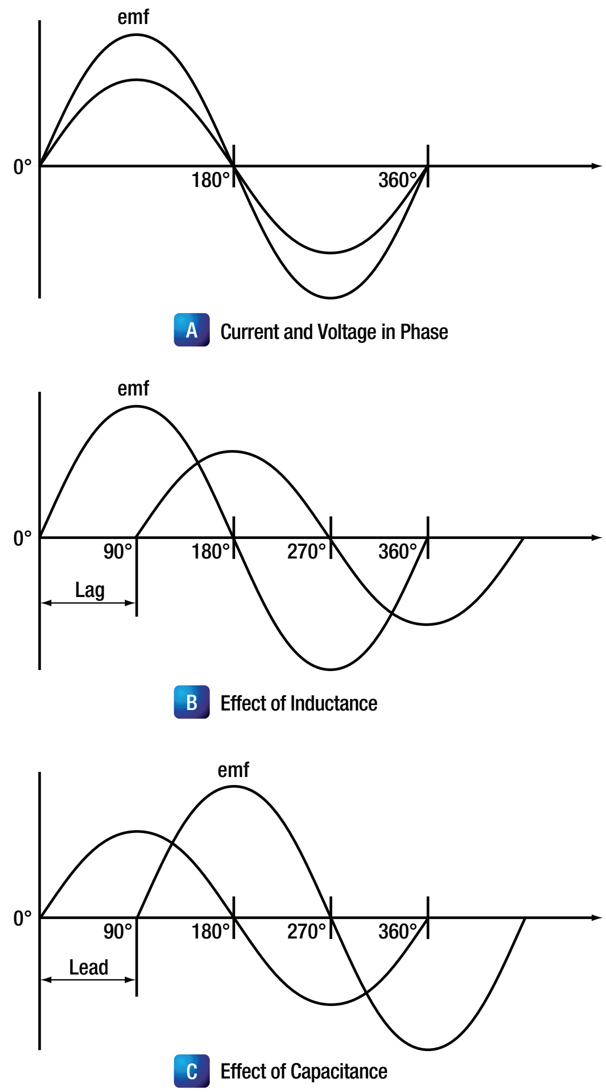


Figure 9-11. Phase of current and voltage.

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 9-11C***) 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.

EXPONENTIAL CHARGE/DISCHARGE
When a capacitor is charged by connecting it directly to a power supply, there is very little resistance in the circuit

and the capacitor seems to charge instantaneously. *Figure 9-12* shows how the current changes with time when a capacitor is charging or discharging.

Figure 9-12 shows that:
- The charging current falls as the charge on the capacitor and the voltage across the capacitor rise.
- The charging current decreases by the same proportion in equal time intervals.

To calculate the charge flow:
- Estimate the number of whole squares between the graph line and the time axis.
- Multiply this by the 'charge value' of each square, obtained by calculating ΔQ × Δt for a single square.

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. When a capacitor charges or discharges through a resistance an additional 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 the time that equals the product of the resistance in ohms and the capacitance in farads and symbolized by the Greek letter tau (τ).

$$\tau = RC$$

The time in the formula is what is required to charge to 63 percent of the voltage of the source. The time required to bring the charge to about 99 percent of the source voltage is approximately 5τ. *Figure 9-13* illustrates this relationship.

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.

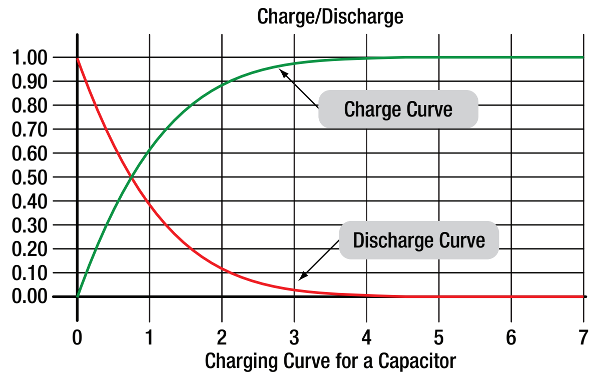


Figure 9-12. Exponential charge and discharge of a capacitor.

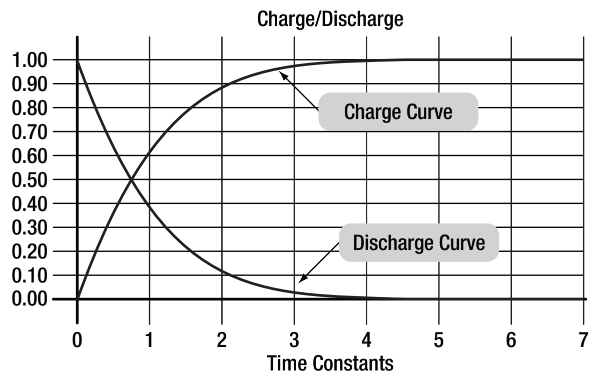


Figure 9-13. The RC time contstant relationship.

Figure 9-14. Testing a capacitor with a digital capacitor tester.

Question: 9-1
When does current flow in a circuit where a capacitor is connected across a DC storage battery?

Question: 9-2
Capacitance is measured in _________________.

Question: 9-3
Name 3 materials used as the dielectric in the construction of fixed capacitors.

Question: 9-4
Capacitors in series can withstand _________________ total potential than any of the individual capacitors.

Question: 9-5
The formula for total capacitance of a parallel circuit is _________________.

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: 9-7
The total reactance of capacitors connected in parallel is found in the same way _________________ is computed in a parallel circuit.

ANSWERS

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

Answer: 9-2
farads (f).

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

Answer: 9-4
higher.

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

Answer: 9-6
frequency.

Answer: 9-7
total resistance.

ELECTRICAL FUNDAMENTALS

MAGNETISM

SUB-MODULE 10

PART-66 SYLLABUS LEVELS		
CERTIFICATION CATEGORY →	B1	B2
Sub-Module 10 MAGNETISM Knowledge Requirements		
3.10 - Magnetism		
(a) Theory of magnetism; Properties of a magnet; Action of a magnet suspended in the Earth's magnetic field; Magnetization and demagnetization; 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

MAGNETISM

THEORY AND PROPERTIES OF 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.

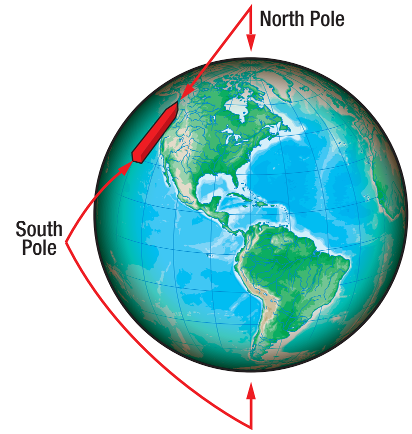


Figure 10-1. One end of the magnetized strip points to the magnetic north pole.

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.

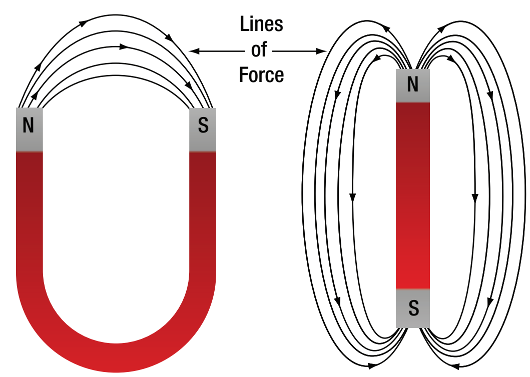


Figure 10-2. Magnetic field around magnets.

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 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.

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.

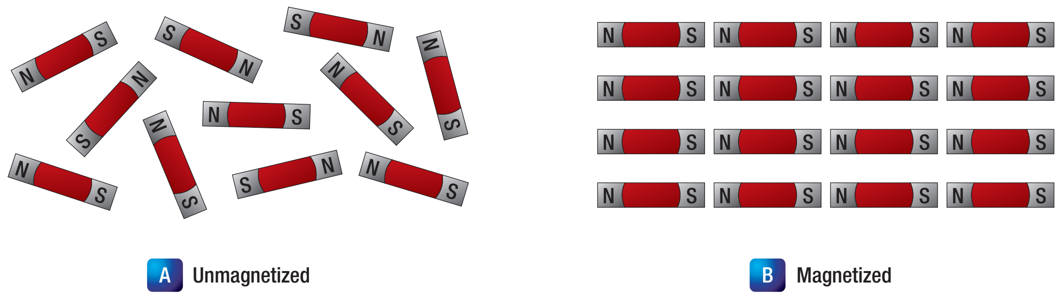


Figure 10-3. Arrangement of molecules in a piece of magnetic material.

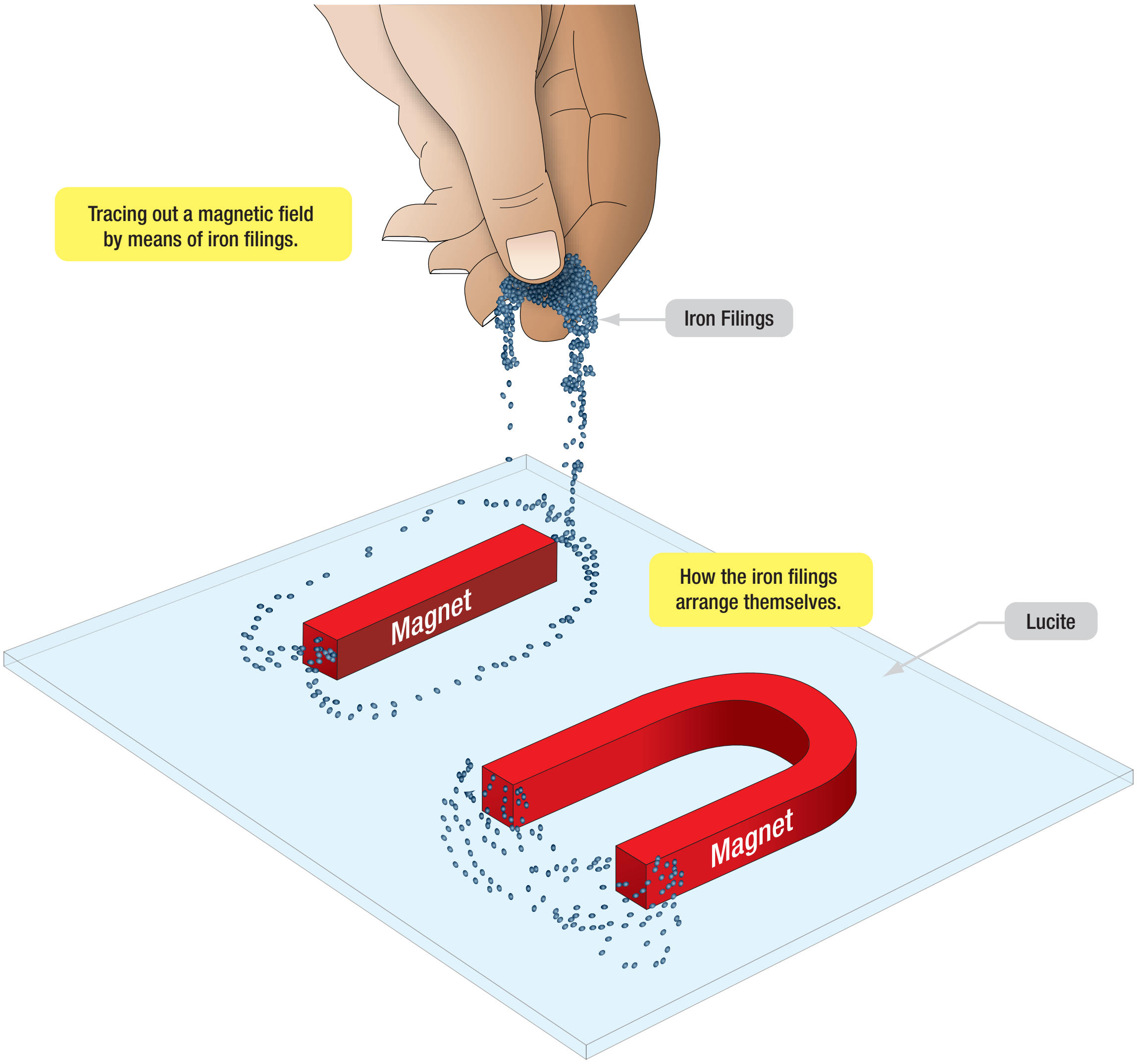


Figure 10-4. Tracing out a magnetic field with iron filings.

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

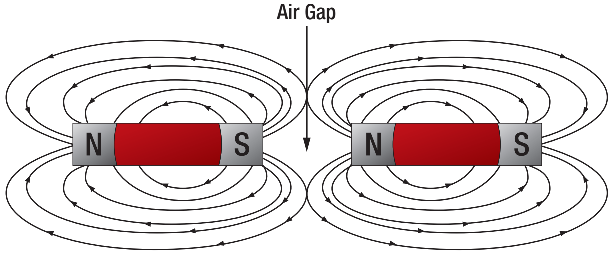


Figure 10-5. Like poles repel.

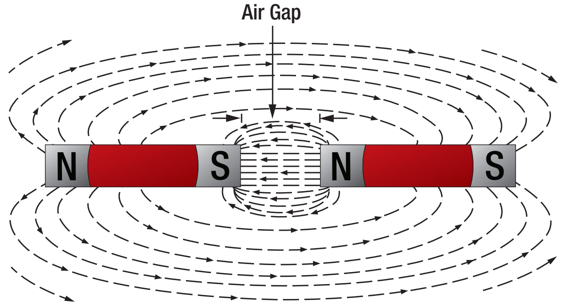


Figure 10-6. Unlike poles attract.

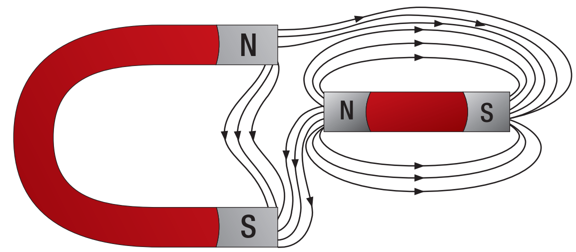


Figure 10-7. Bypassing flux lines.

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.

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 of any magnet and enter at the south pole.

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 10-10*** 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.

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

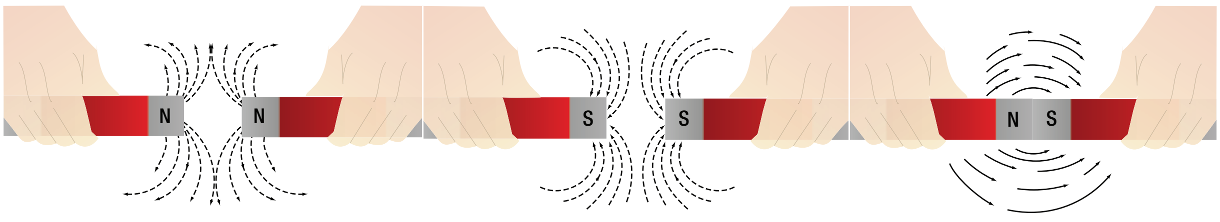


Figure 10-8. Repulsion and attraction of magnet poles.

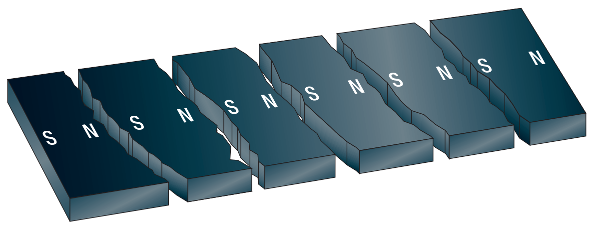


Figure 10-9. Magnetic poles in a broken magnet.

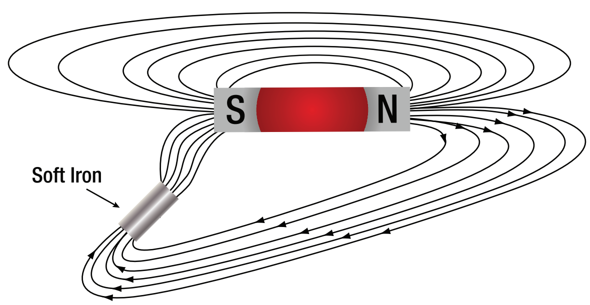


Figure 10-10. Effect of a magnetic substance in a magnetic field.

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.

ACTION OF A MAGNET SUSPENDED IN THE EARTH'S MAGNETIC FIELD

A freely suspended magnet always points in the North-South direction even in the absence of any other magnet. This suggests that the Earth itself behaves as a magnet which causes a freely suspended magnet (compass needle) to point always in a particular direction: North and South. The shape of the Earth's magnetic field resembles that of a bar magnet of a length of 20% of the Earth's diameter buried at its center. (*Figure 10-11*)

METHODS OF MAGNETIZATION AND DEMAGNETIZATION

Remagnetizing a magnet is often necessary if the magnet has been mistreated. There are also often needs to make a tool magnetic to perform a desired function. Sometimes tools may inadvertently become magnetic with unwanted consequences and there is a need for demagnetization.

There are a few methods of magnetizing of an object which is made of the right type of ferrous material. To test suitability of a material you wish to magnetize, bring it in close proximity to a strong magnet. Then use the magnetized item to pick up iron filings or paper clips or other suitable object. If, after removing the magnet for a few minutes, there is little adhering, it will not be useful as a permanent magnet.

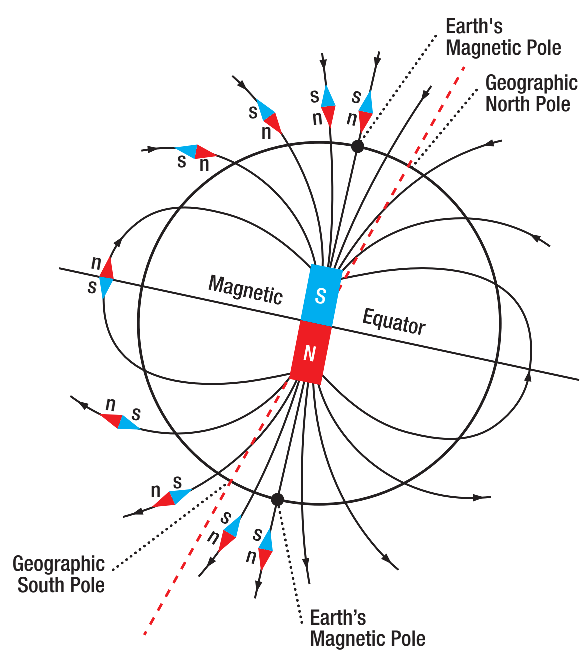


Figure 10-11. Earth's magnet.

MAGNETIZATION BY HAMMERING

Hammering a rod will cause it to become slightly magnetic if laid along a magnetic field (North-South) or demagnetize it if laid across the field lines (East-West). Do not try to improve an existing magnet by hammering. Hammering could easily reduce the field strength below that already present.

MAGNETIZATION BY STROKING

There are two methods of magnetization by stroking; single touch and divided touch. With single touch, a magnet is drawn over the rod completely over its length. Magnetic lines are then pulled into alignment as the magnet passes. The best results are obtained after about twenty passes with the magnet taken in a big loop far away from the bar in between passes.

The divided touch method uses two magnets at the same time in what may be thought of as a mirroring action. This method produces a stronger magnet than with single touch. Beware of polarity: If this method is done using two similar poles facing the bar it is possible to create a magnet with two like poles at either end. These are termed consequent poles. (***Figure 10-12***)

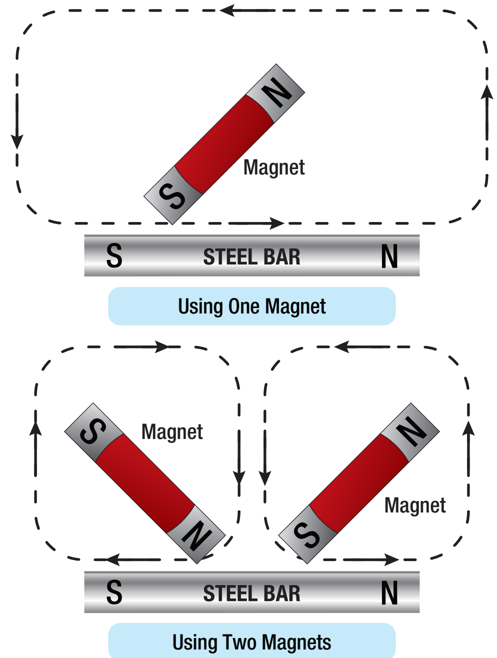


Figure 10-12. Magnetization with the stroking method.

MAGNETIZATION BY COOLING

This method can create a magnetized bar without any apparent magnet being present (just the earth's field). The bar is heated to above its curie point which varies from metals but is typically hotter than red hot. At this point the bar has changed from being ferromagnetic to paramagnetic. As the bar cools it becomes ferromagnetic again and the field align with the external field. Demagnetization can be achieved by allowing the bar to cool in an East-West orientation shielded from magnetic influences.

MAGNETIZATION WITH ELECTRICITY

Modern methods tend to use electricity as it is easily controlled. A current passing through a coil will produce a magnetic field. The strength of the field is proportional to the current.

The polarity of the field is set by the path of conventional current in the coil. If at the end of the coil the current is flowing clockwise it will produce the south seeking pole. The other end will then be counterclockwise producing a north seeking pole. A higher current for a short duration is most efficient. (***Figure 10-13***)

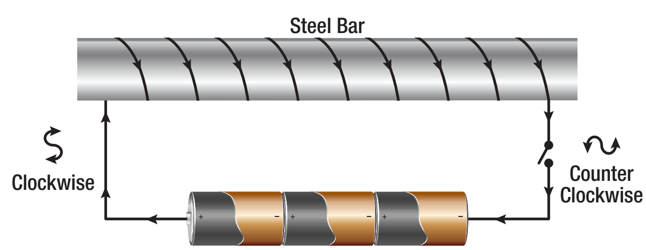


Figure 10-13. Magnetization by electricity.

Demagnetizing involves taking the bar through decreasing hysteresis cycles. An alternating current is used to create a field that overcomes the existing field in a magnet. Alternatively the rod can be drawn out and away from a constant amplitude alternating field.

MAGNETIC SHIELDING

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 10-14*** 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.

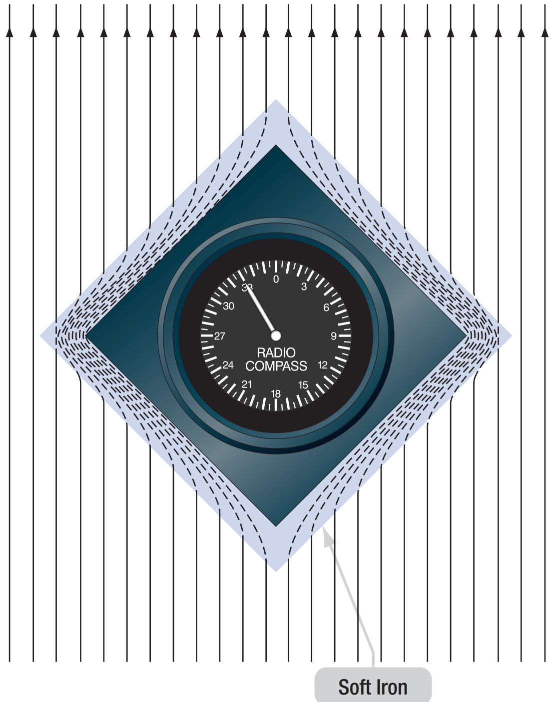


Figure 10-14. Magnetic shield.

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.

TYPES OF MAGNETIC MATERIAL

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 man made. 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 (Neomagnets), 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 10-15***) 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.

ELECTROMAGNETIC CONSTRUCTION AND PRINCIPLES

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

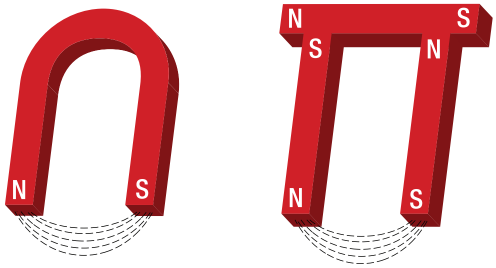


Figure 10-15. Two forms of horseshoe magnets.

MAGNETISM

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 10-16*** 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 10-17***) 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.

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.

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, 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 10-18***)

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

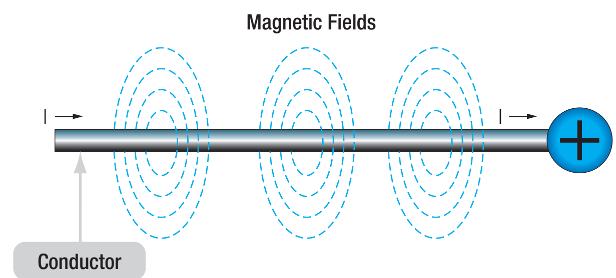


Figure 10-16. Magnetic field formed around a conductor in which current is flowing.

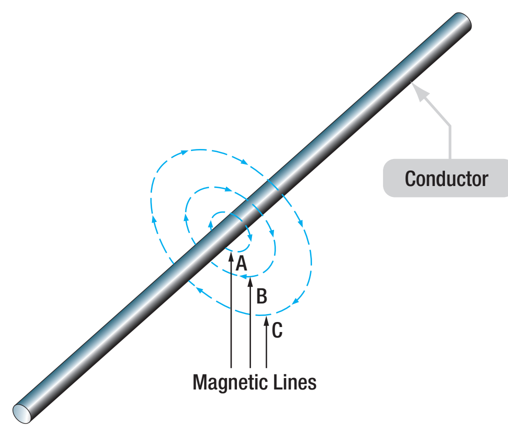


Figure 10-17. Expansion of magnetic field as current increases.

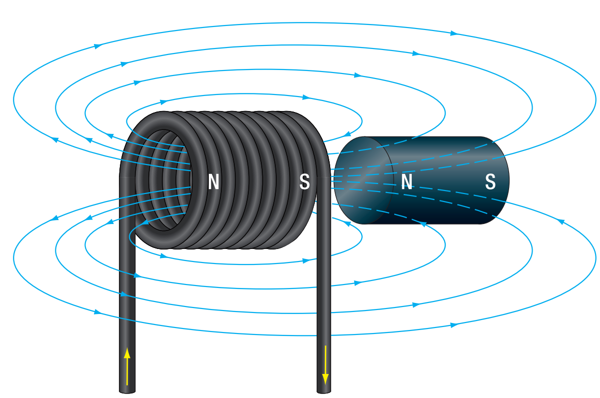


Figure 10-18. Energized coil with an iron core.

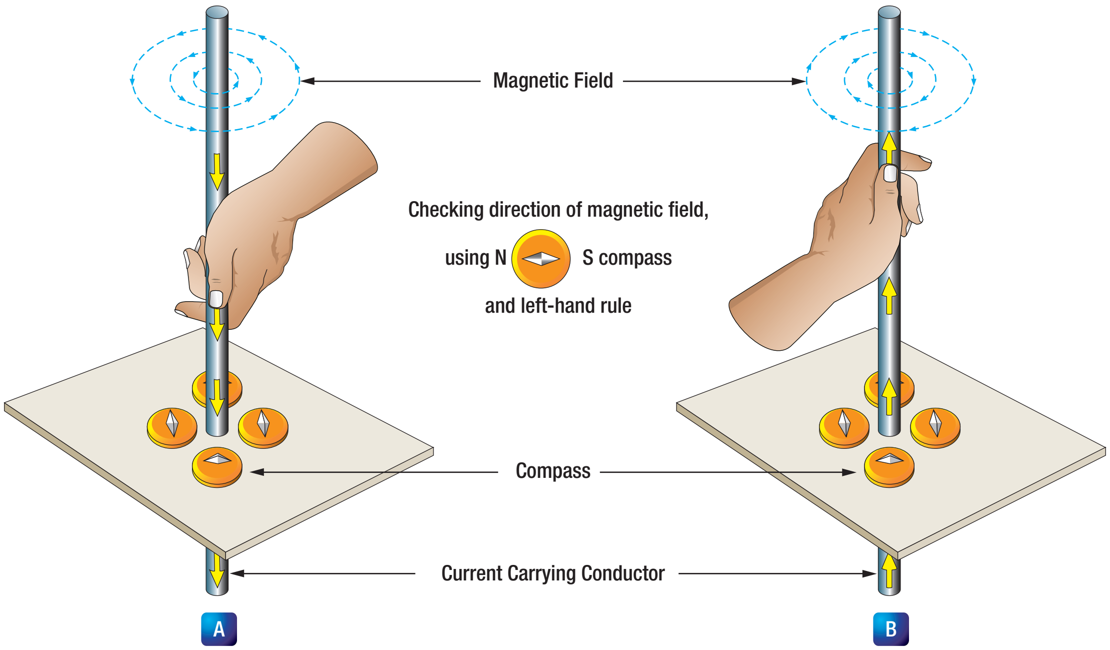


Figure 10-19. Magnetic field around a current carrying conductor.

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.

DETERMINE MAGNETIC FIELD AROUND CURRENT CARRYING CONDUCTORS

A compass needle is used to demonstrate the direction of the magnetic field around a current carrying conductor. (***Figure 10-19***) 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 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 10-19***, 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 10-20***. 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 10-21***)

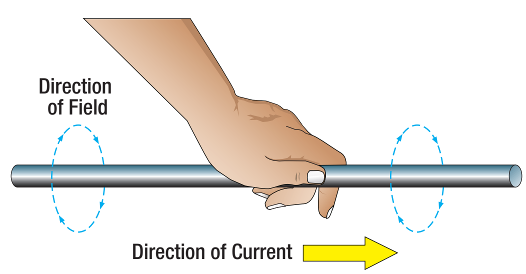


Figure 10-20. Left-hand rule.

MAGNETISM

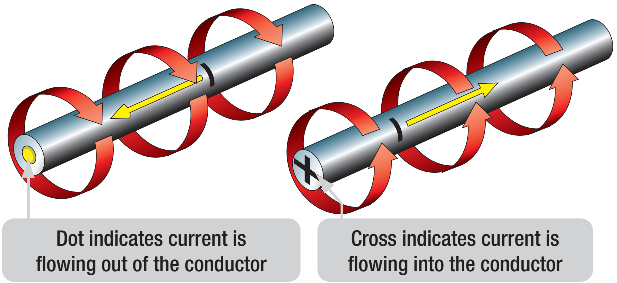


Figure 10-21. Direction of current flow in a conductor.

When a wire is bent into a loop and an electric current flows through it, the left-hand rule remains valid. (*Figure 10-22*)

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 10-23*)

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 10-24*)

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 10-25*)

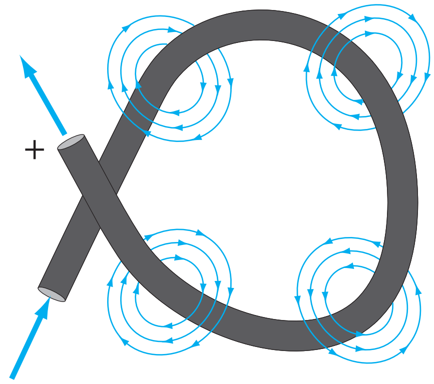


Figure 10-22. Magnetic field around a looped conductor.

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 10-26*)

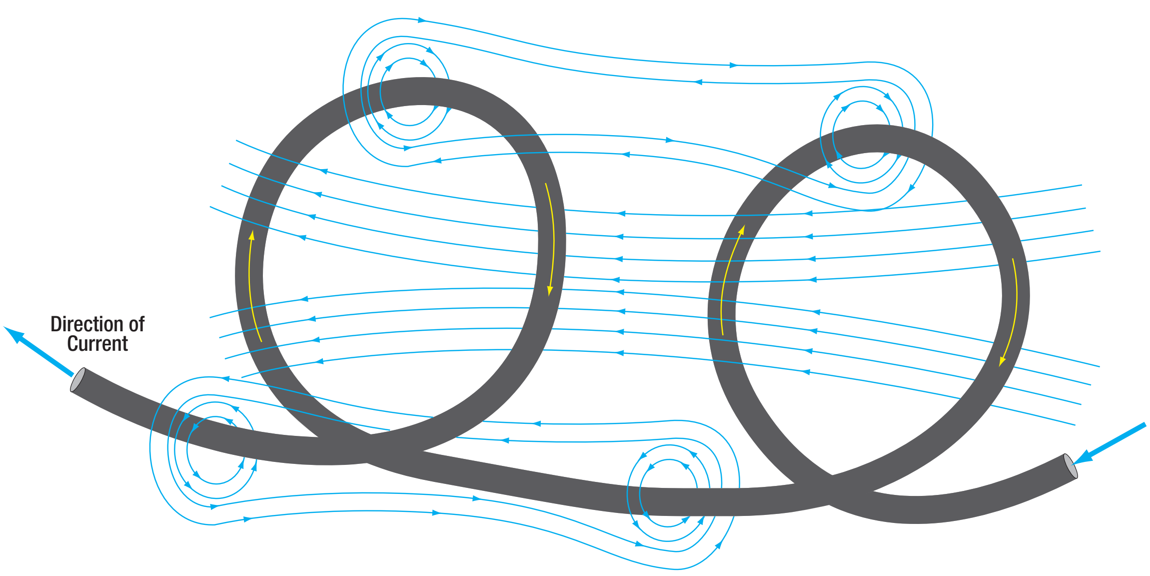


Figure 10-23. Magnetic field around a conductor with two loops.

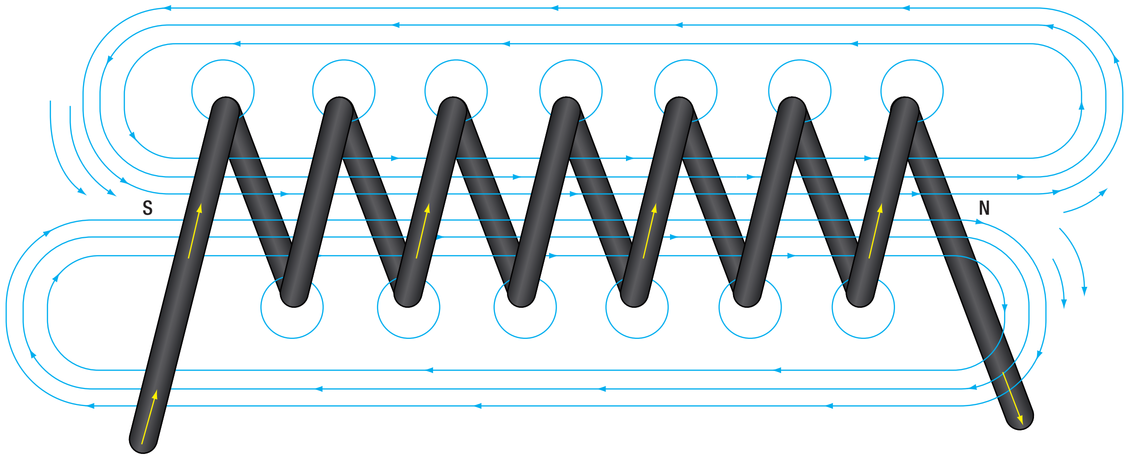


Figure 10-24. Magnetic field of a coil.

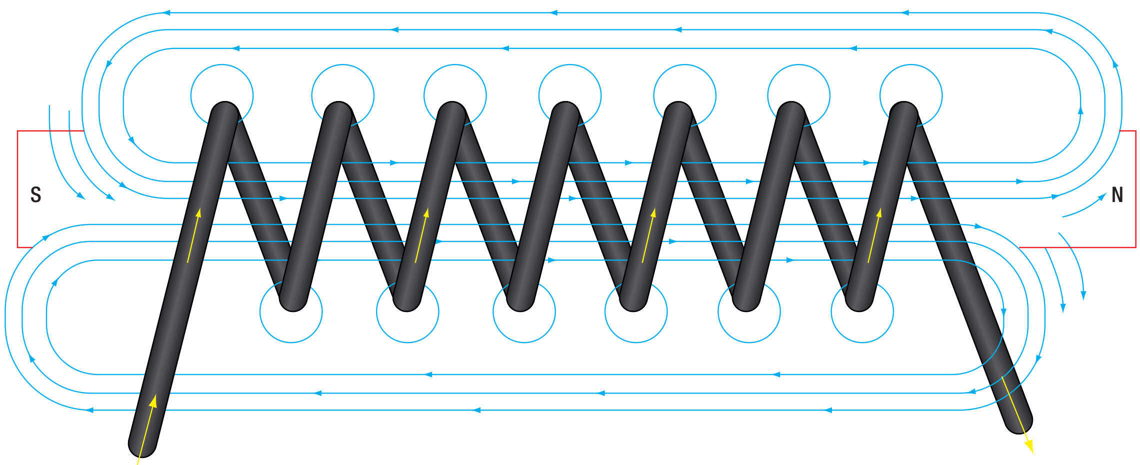


Figure 10-25. Electromagnet.

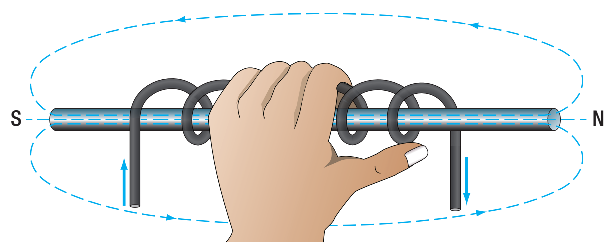


Figure 10-26. Left-hand rule applied to a coil.

OTHER MAGNETO-ELECTRICAL PHENOMENA

MAGNETOMOTIVE FORCE

Magnetomotive force, also known as magnetic potential, is the property of certain substances which gives rise to magnetic field. Magnetomotive force is comparable to electromotive force or voltage. The standard unit of magnetomotive force is the ampere-turn (AT), represented by a steady, current of one ampere flowing in a conducting material in a vacuum . Sometimes a unit called the gilbert (G) is used to quantify magnetomotive force. The gilbert is a slightly smaller unit than the AT. To convert from ampere-turns to gilberts, multiply by 1.26. Conversely, multiply by 0.796.

Although the standard definition of magnetomotive force involves current passing through a conductor, permanent magnets also exhibit magnetomotive force. The same is true for planets with magnetic fields, including Earth. (***Figure 10-27***)

FIELD STRENGTH

Magnetic field strength is one of two ways to describe the intensity of a magnetic field. Technically, a distinction is made between magnetic field strength measured in amperes per meter, and magnetic flux density measured in Newton-meters per ampere or also called teslas.

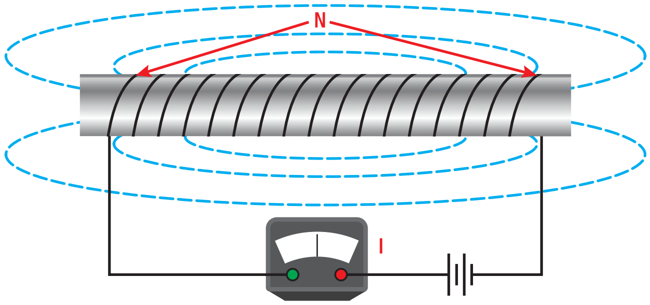


Figure 10-27. Magnetomotive force.

The magnetic field can be visualized as magnetic field lines. The field strength corresponds to the density of the field lines. The total number of magnetic field lines penetrating an area is called the magnetic flux. The unit of the magnetic flux is the tesla meter squared.

Magnetic flux density diminishes with distance from a current carrying wire. At a given location of that wire, the flux density is directly proportional to the current in amperes. If a magnetic object such as a piece of iron is brought into a magnetic field, the magnetic force exerted on that object is proportional to the gradient of the magnetic field strength where the object is located. (***Figure 10-28***)

MAGNETIC FLUX DENSITY

Magnetic Flux Density is a measure of the strength of a magnetic field at a given point, expressed by the force on a conductor carrying current at that point.

The tesla (T) is the standard unit of magnetic flux density. 1 T represents one kilogram per second squared per ampere. In practice, the tesla is a large unit, and is used primarily in industrial electromagnetics. When dealing with practical magnets of the sort encountered in aviation, a smaller unit of flux density called the Gauss (G) is often used. There are ten thousand G in one tesla.

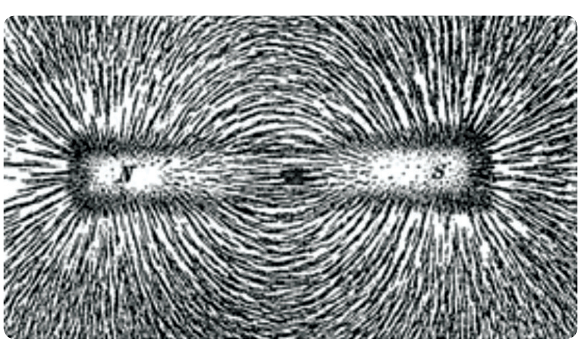


Figure 10-28. Magnetic field pictured through the pattern of iron filings.

PERMEABILITY

Magnetic permeability is a proportionality between magnetic induction and magnetic field intensity. This constant is equal to approximately 1.257×10^{-6} henry per meter in a vacuum. In other materials it can be substantially different.

Materials that cause the lines of flux to move farther apart, resulting in decreased magnetic flux density are called diamagnetic. Materials that concentrate magnetic flux are called paramagnetic. Materials that concentrate flux by a factor of more than 10 are called ferromagnetic. The permeability of some substances change with temperature or with the intensity of the applied magnetic field.

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 10-29***)

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 buildup 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.

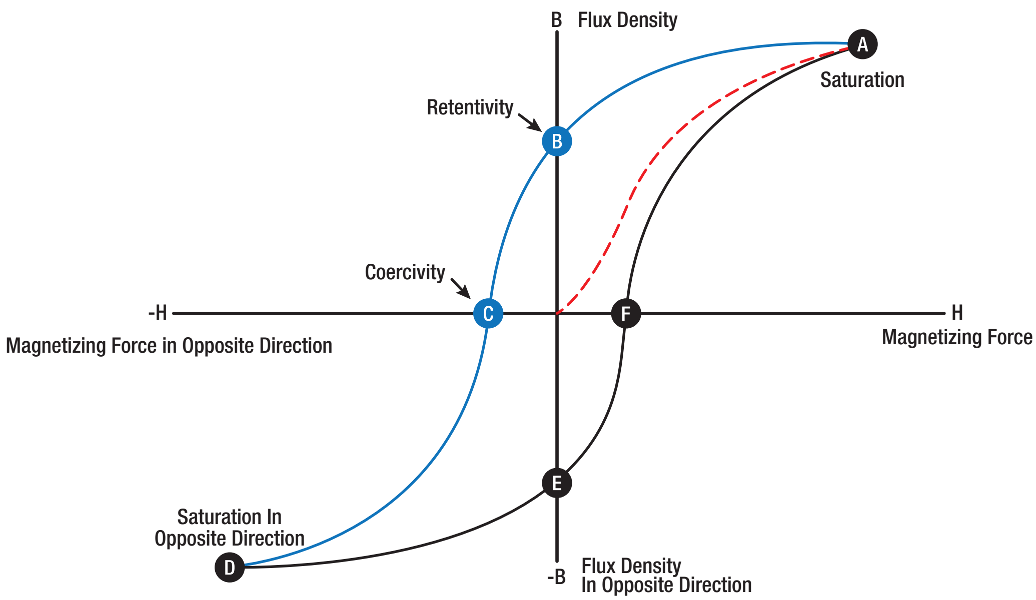


Figure 10-29. The hysteresis loop.

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 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.

RETENTIVITY

Retentivity is the ability to retain magnetism after the action of the magnetizing force has ceased.

COERCIVE FORCE

Magnetic coercivity, coercive field, or coercive force, is a measure of the ability of a ferromagnetic material to withstand an external magnetic field without becoming demagnetized.

RELUCTANCE

Reluctance is the property of a magnetic circuit of opposing the passage of magnetic flux lines, equal to the ratio of the magnetomotive force to the magnetic flux.

SATURATION POINT

Saturation is the state when an increase in applied magnetic fields can not increase the magnetization further so the total magnetic flux density levels off.

Saturation is best seen in the magnetization curve (also called hysteresis curve) as a bending to the right of the curve. (***Figure 10-30***) As the H field increases, the B field approaches a maximum value representing its saturation limit.

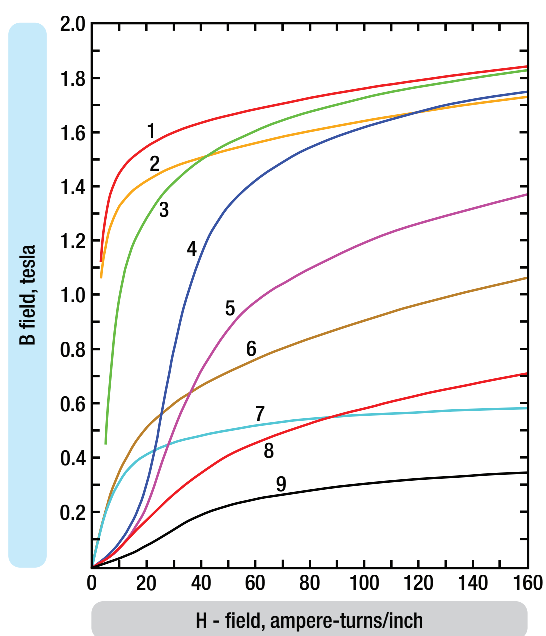


Figure 10-30. Magnetization saturation curves of 9 materials: 1-Sheet steel, 2-Silicon steel, 3-Cast steel, 4-Tungsten steel, 5-Magnet steel, 6-Cast iron, 7-Nickel, 8-Cobalt, and 9-Magnetite.

MAGNETISM

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. (***Figure 10-31***)

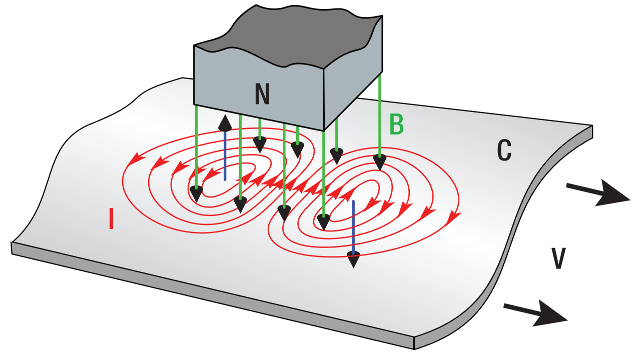


Figure 10-31. Eddy currents (red) induced in a conductive metal plate (C) as it moves to right under a magnet.

PRECAUTIONS FOR 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 that in which they lose their permanent magnetism is acceptable. Most magnets don't lose their permanent magnetism at temperatures below about 400°C.

Magnets should be stored in a dry place. Although most common magnets are not susceptible to moisture degradation, neodymium magnets may suffer in humid environments. 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. (***Figure 10-32***)

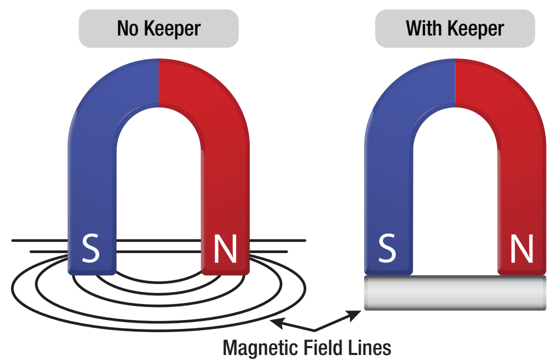


Figure 10-32. The use of a keeper bar during storage.

Question: 10-1
A ________________ always exists between the poles of a magnet.

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: 10-3
A material that easily passes magnetic flux is said to have high ________________.

Question: 10-4
The greater the current flow through a conductor, the ________________ the magnetic field that forms around the conductor.

Question: 10-5
If the number of loops of conductor in a coil are doubled, the strength of the magnetic field approximately ________________.

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 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

3.11 - INDUCTANCE/INDUCTOR

FARADAY'S LAW

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 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.

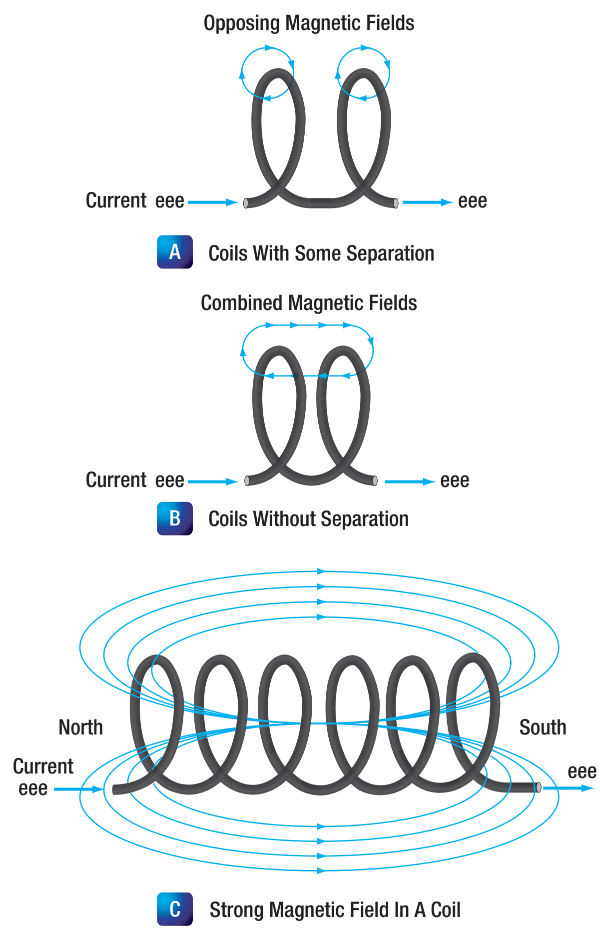


Figure 11-1. Many loops of a coil.

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.

INDUCING VOLTAGE IN A CONDUCTOR

If a magnet is moved into or out of a coil of wire a meter will record a flow of current as long as the magnet is moving. This same result is obtained if the magnet is kept stationary and the loop is moved. The meter therefore shows that there is a current as long as there is relative movement between the loop (coil) and the magnet (magnetic field). Note that energy is not being produced but simply converted from mechanical energy to electrical energy.

INDUCTION PRINCIPLES

PHYSICAL PARAMETERS

Some of the physical factors that affect inductance are:

1. 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.

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. This characteristic is illustrated in ***Figure 11-2***.

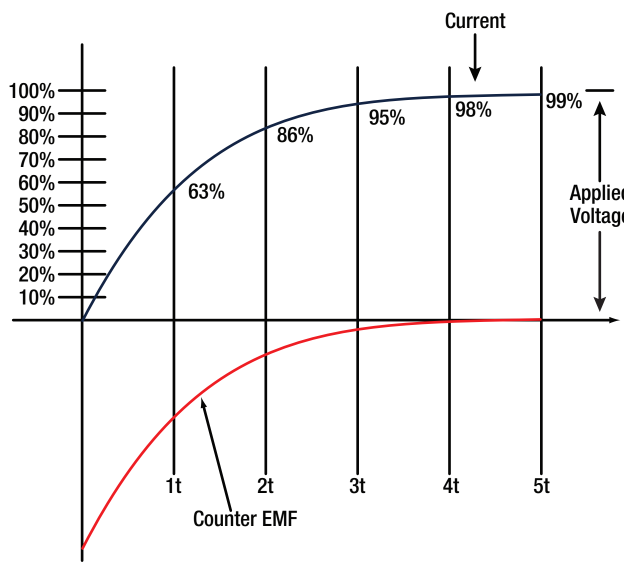
UNITS OF INDUCTANCE

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***.

EFFECTS ON THE MAGNITUDE OF INDUCED VOLTAGE

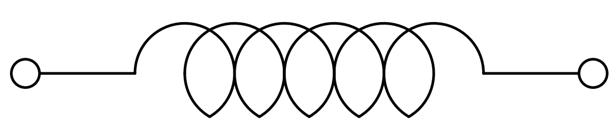
MAGNETIC FIELD

A magnetic field is a force field created by moving electric charges and magnetic dipoles, and exerts a force on other nearby moving charges and dipoles. At any given point, it has a direction and a magnitude, and so represented by a vector field.



Current, Counter EMF, and applied voltage in an inductive circuit.

Figure 11-2. Inductor curve.



Inductor

Figure 11-3. Typical symbol for an inductor.

RATE OF CHANGE OF FLUX

Magnetic flux (F) is defined by F = BA where B is the magnetic field (or average magnetic field) and A is the area perpendicular to the magnetic field. Note that for a given rate of change of the flux through the coil, the voltage generated is proportional to the number of turns (N) which the flux penetrates.

NUMBER OF CONDUCTOR TURNS

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

INDUCTIVE REACTANCE

Alternating current is in a constant state of change; the effects of the magnetic fields are a continuously inducted 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 11-4***, 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.

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

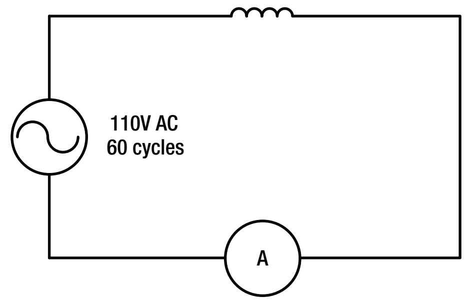


Figure 11-4. AC circuit containing inductance.

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 = $^E/_R$. 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 amperes

In AC series circuits, inductive reactances are added like resistances in series in a DC circuit. (***Figure 11-5***) 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 11-6***) Thus, the total reactance of inductances connected in parallel, as shown, is expressed as:

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

MUTUAL INDUCTANCE

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. (***Figure 11-7***)

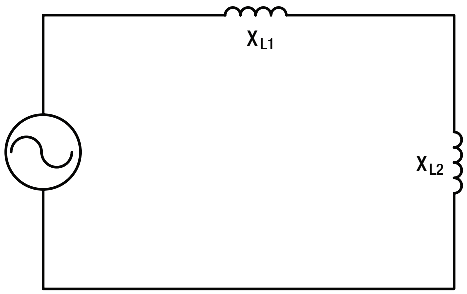


Figure 11-5. Inductances in series.

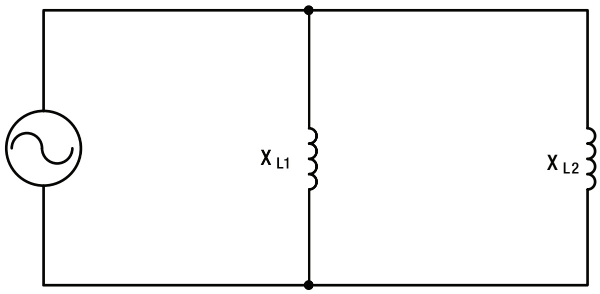


Figure 11-6. Inductances in parallel.

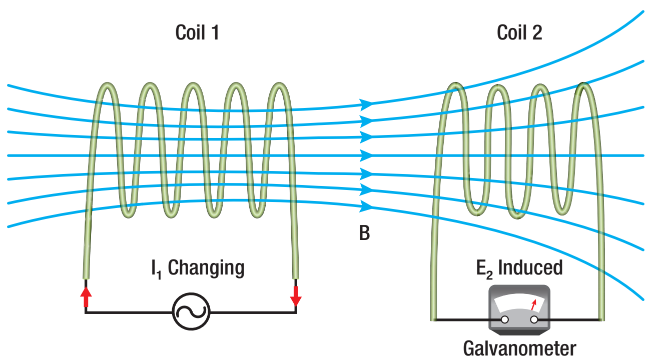


Figure 11-7. Due to proximity, voltage generated through Coil 1 is induced via magnetic fields into Coil 2.

EFFECT THAT CURRENT AND MUTUAL INDUCTANCE HAS ON VOLTAGE

The effect that current and mutual inductance has on voltage Mutual induction concerns a pair of coils. A current which builds in one coil (the primary coil) produces an expanding magnetic field around it. This in turn induces a current to flow in the other coil. The induced current flows in such a direction as to produce a magnetic field opposite in direction to the primary magnetic field. As the magnetic fields are directed towards each other, their total effect is reduced. (***Figure 11-8***)

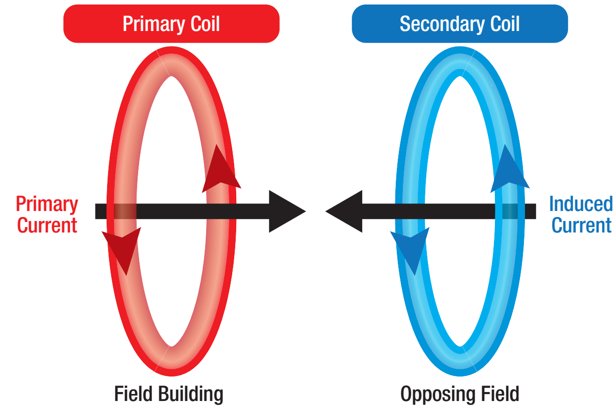


Figure 11-8. Opposing fields flow in opposite directions.

When the primary current direction is reversed its magnetic field direction is also reversed. This has the effect of producing current in the secondary coil in a reverse direction with its magnetic field direction. In this case the magnetic fields are now in opposing directions. As with self inductance, the back EMF is proportional to the rate of the current change.

$$\text{Back EMF} \propto -(\text{rate of current change})$$

$$E = -M\frac{di}{dt}$$

Where M (mutual inductance) is the constant of proportion. There is another important link between self and mutual inductance. It can be shown, (assuming 100% flux linkage) that:

$$M = \sqrt{L_P L_S}$$

Where L_P and L_S are the self inductances of primary and secondary coils. Thus the back EMF (E_S in the secondary coil) relates to the rate of current change dIp/dt in the primary coil.

$$E_S = -M\frac{dI_P}{dt}$$

FACTORS AFFECTING MUTUAL INDUCTANCE

Number of Turns in the Primary

When the same current is used, doubling the number of turns in the primary coil will produce a field twice as strong. A field twice as strong, cutting twice the number of turns, will induce 4 times the voltage. Therefore, it can be said that the inductance varies as the square of the number of turns.

Physical Size of Coil Area

Physically, it requires more wire to construct a large diameter coil than a small diameter coil with an equal number of turns. Therefore, more lines of force exist to induce a back EMF in the coil with the larger diameter. The inductance of a coil increases directly as the cross sectional area of the core increases. Recall the formula for the area of a circle: $A = \pi r^2$. Doubling the radius of a coil increases the inductance by a factor of four.

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

Permeability of the Coil Material

Coils are wound on either magnetic or nonmagnetic materials. Magnetic materials include nickel, iron, steel, or cobalt have a higher permeability that provides a better path for the magnetic lines and so permit a stronger magnetic field. All other factors being equal, the greater the magnetic permeability of the core in which the coil is wrapped, the greater the inductance.

LENZ'S LAW AND POLARITY RULES

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.

BACK EMF (EDDY CURRENTS)

When the magnetic field in a conductor is charged, eddy currents develop. The eddy currents induce their own magnetic fields which then opposes their own development as well as the development of the conductor's own magnetic field. The faster the change in the conductor's field, the greater the eddy currents and associated fields.

Eddy currents tend to generate heat and reduce the efficiency of devices that rely on changing magnetic fields. Use of permeable lamination in the magnetic material and the choice of magnetic core material helps suppress eddy currents.

Eddy currents flow in closed loops within conductors perpendicular to the magnetic field. They can be induced within nearby stationary conductors by a varying electromagnet field created by AC or by relative motion between a magnet and a nearby conductor.
(***Figure 11-9***)

The magnitude of the current in a given loop is proportional to the strength of the field, the area of the loop, and the rate of change of flux; and is inversely proportional to the resistivity of the material.

By Lenz's law, an eddy current creates a magnetic field that opposes the change in the field that created it. For example, a nearby conductive surface will exert a drag force on a moving magnet due to eddy currents induced

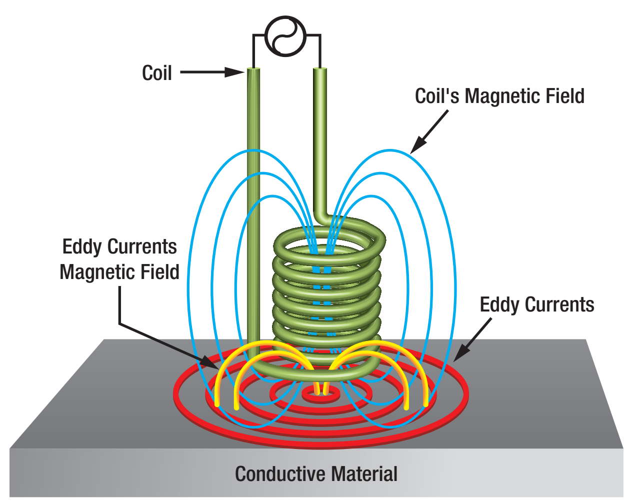


Figure 11-9. Eddy currents form perpendicular to the electromagnetic field.

in the surface by the moving field. This effect can be used to power eddy current brakes which for example can be used to stop rotating power tools quickly when they are turned off.

The resistance of the conductor also dissipates energy as heat in the material. Thus eddy currents are a cause of energy loss in alternating current (AC) inductors, transformers, electric motors and generators, and other AC machinery.

Eddy currents can also be used to heat objects in induction furnaces and to detect cracks and flaws in metal parts using eddy current testing instruments.

TYPES AND USES OF INDUCTORS

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.

Like resistors and capacitors, inductors are passive elements which are used to store electric energy in the form of a magnetic field.

Inductors are sometimes used to block AC while allowing DC to pass and when designed for this purpose, are called chokes. They are also used in electronic filters to separate signals of different frequencies. When used in combination with capacitors, inductors can make tuned circuits as used to tune radio and TV receivers. (***Figure 11-10***)

They will produce the magnetic flux (field) around them by the flow of an alternating current through it. An ideal inductor has no inductive reactance and so it acts as short circuit.

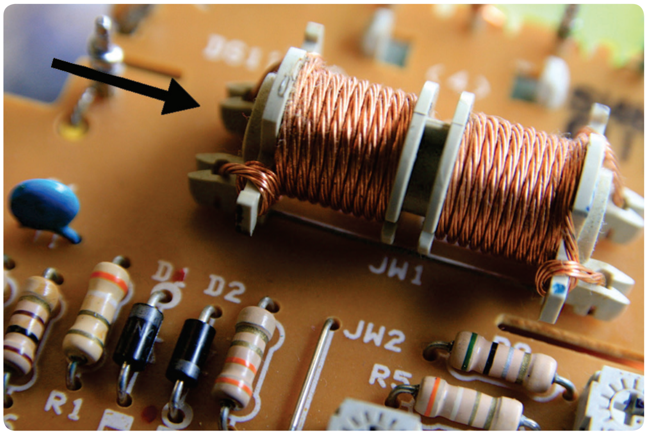


Figure 11-10. A typical inductor placed on a circuit board.

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: 11-2
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: 11-3
Name three physical factors that affect inductance.

Question: 11-4
The opposition offered by a coil to the flow of alternating current is called ________________.
(disregard resistance)
A. impedance.
B. reluctance.
C. inductive reactance.

Question: 11-5
Given a charged conductor and a magnet, what is required for induction to occur?

Question: 11-6
Name two negative consequences of eddy currents.

ANSWERS

Answer: 11-1
rate of change.

Answer: 11-2
B.

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.

Answer: 11-4
C.

Answer: 11-5
Movement between the conductor and magnet.

Answer: 11-6
1. They produce heat.
2. They limit efficiency by weakening the magnetic field.

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 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

3.12 - DC MOTOR/GENERATOR THEORY

BASIC DC GENERATOR THEORY

Theory of Operation In the study of alternating current, basic generator principles were introduced to explain the generation of an AC voltage by a coil rotating in a magnetic field. Since this is the basis for all generator operation, it is necessary to review the principles of generation of electrical energy. 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 (***Figure 12-1A and B***) 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, 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. 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.

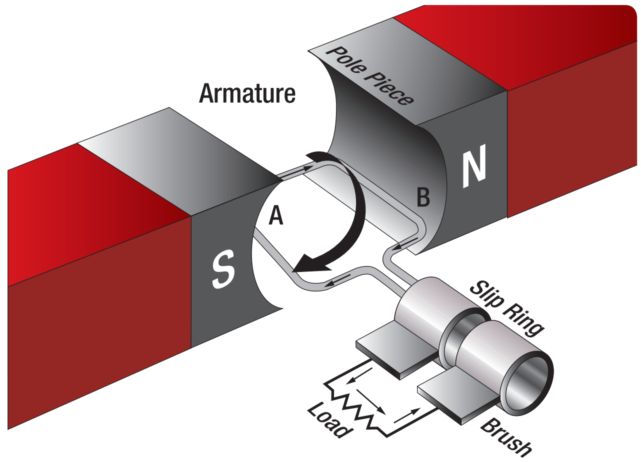


Figure 12-1. Inducing maximum voltage in an elementary generator.

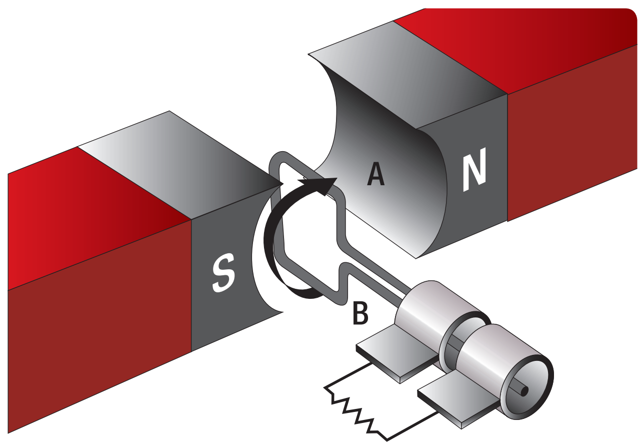


Figure 12-2. Inducing minimum voltage in an elementary generator.

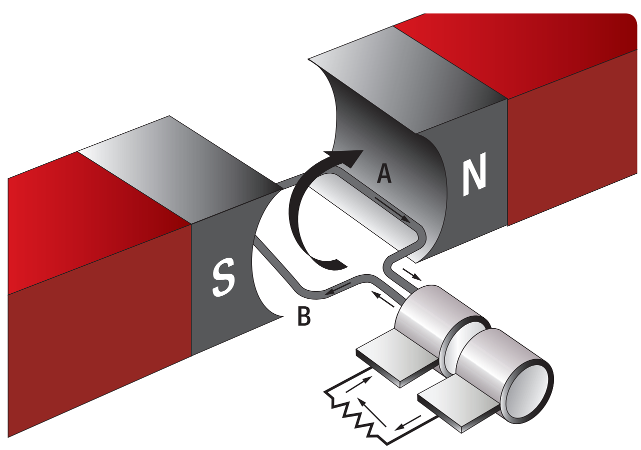


Figure 12-3. Inducing maximum voltage in the opposite direction.

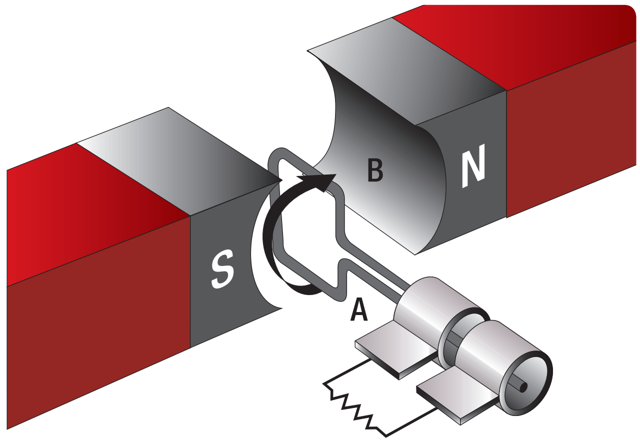


Figure 12-4. Inducing a minimum voltage in the opposite direction.

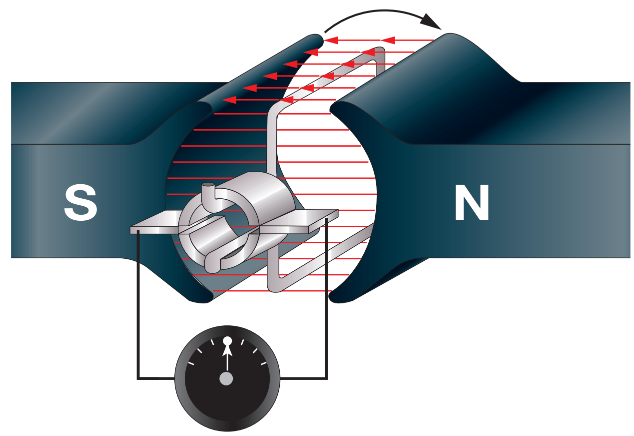


Figure 12-6. Basic DC generator.

If the voltage induced throughout the entire 360° of rotation is plotted, the curve shown in ***Figure 12-5*** results. This voltage is called an alternating voltage because of its reversal from positive to negative value; first in one direction and then in the other.

To use the voltage generated in the loop for producing a current flow in an external circuit, some means must be provided to connect the loop of wire in series with the external circuit. Such an electrical connection can be effected by opening the loop of wire and connecting its two ends to two metal rings, called slip rings, against which two metal or carbon brushes ride. The brushes are connected to the external circuit. By replacing the slip rings of the basic AC generator with two half cylinders, called a commutator, a basic DC generator is obtained. (***Figure 12-6***) In this illustration, the black side of the coil is connected to the black segment, and the white side of the coil to the white 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 commutator as the latter revolves simultaneously with the loop. The rotating parts of a DC generator (coil and commutator) are called an armature.

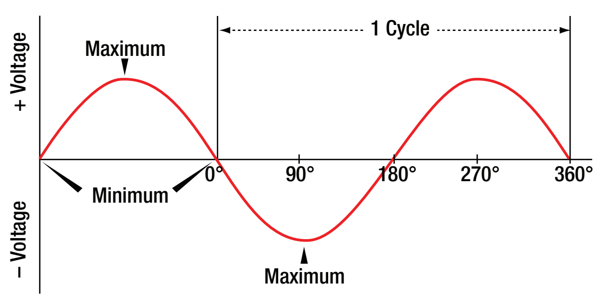


Figure 12-5. Output of an elementary generator.

The generation of an emf by the loop rotating in the magnetic field is the same for both AC and DC generators, but the action of the commutator produces a DC voltage.

GENERATION OF DC VOLTAGE

Figure 12-7 illustrates in an elementary, step by step manner, how a DC voltage is generated. This is accomplished by showing a single wire loop rotating through a series of positions within a magnetic field.

Position A

The loop starts in position A and is rotating clockwise. However, no lines of force are cut by the coil sides, which means that no emf is generated. The black brush is shown coming into contact with the black segment of the commutator, and the white brush is just coming into contact with the white segment.

Position B

In position B, the flux is now being cut at a maximum rate, which means that the induced emf is maximum. At this time, the black brush is contacting the black segment, and the white brush is contacting the white segment. The deflection of the meter is toward the right, indicating the polarity of the output voltage.

Position C

At position C, the loop has completed 180° of rotation. Like position A, no flux lines are being cut and the output voltage is zero. The important condition to observe at position C is the action of the segments and brushes. The black brush at the 180° angle is contacting both black and white segments on one side of the commutator, and the white brush is contacting both

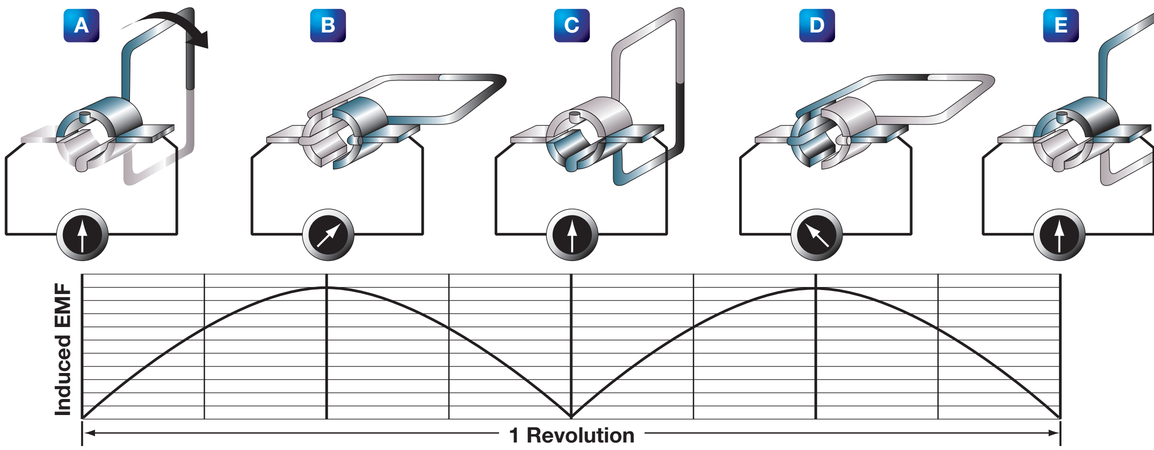


Figure 12-7. Operation of a basic DC generator.

segments on the other side of the commutator. After the loop rotates slightly past the 180° point, the black brush is contacting only the white segment, and the white brush is contacting only the black segment.

Because of this switching of commutator elements, the black brush is always in contact with the coil side moving downward, and the white 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.

Position D

At position D, commutator action reverses the current in the external circuit, and the second half cycle has the same waveform as the first half cycle. The process of commutation is sometimes called rectification, since rectification is the converting of AC voltage to DC voltage.

The Neutral Plane

At the instant that each brush is contacting two segments on the commutator (***Figure 12-7A, C, and E***), a direct short circuit is produced. If an emf were generated in the loop at this time, a high current would flow in the circuit, causing an arc and thus damaging the commutator. For this reason, the brushes must be placed in the exact position where the short occurs when the generated emf is zero. This position is called the neutral plane. If the brushes are installed properly, no sparking occurs between the brushes and the commutator. Sparking is an indication of improper brush placement, which is the main cause of improper commutation.

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 12-8A***. As the number of loops is increased, the variation between maximum and minimum values of voltage is reduced (***Figure 12-8B***), and the output voltage of the generator approaches a steady DC value. In ***Figure 12-8A***, the number of commutator segments is increased in direct proportion to the number of loops; that is, there are two segments for one loop, four segments for two loops, and eight segments for four loops.

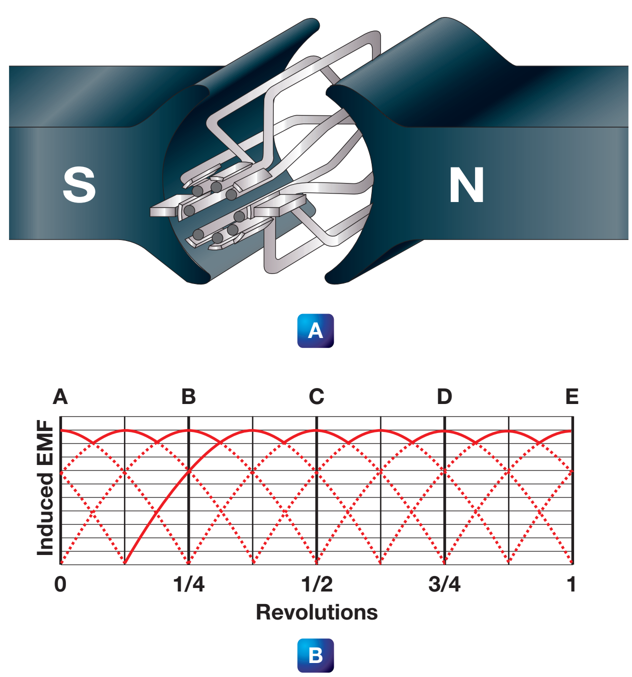


Figure 12-8. Increasing the number of coils reduces the ripple in the voltage.

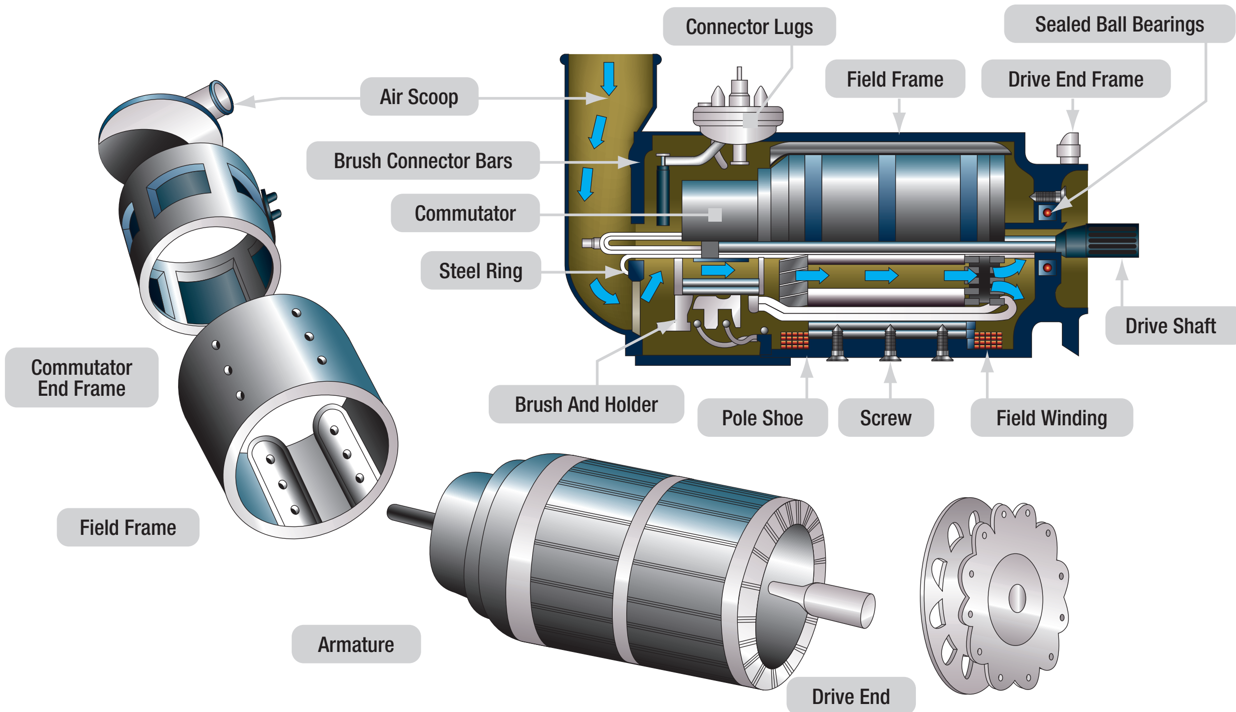


Figure 12-9. Typical 24-volt aircraft generator.

The voltage induced in a single turn loop is small. Increasing the number of loops does not increase the maximum value of generated voltage, but increasing the number of turns in each loop increases this value. Within narrow limits, the output voltage of a DC generator is determined by the product of the number of turns per loop, the total flux per pair of poles in the machine, and the speed of rotation of the armature.

An AC generator, or alternator, and a DC generator are identical as far as the method of generating voltage in the rotating loop is concerned. However, if the current is taken from the loop by slip rings, it is an alternating current, and the generator is called an AC generator, or alternator. If the current is collected by a commutator, it's direct current, and the generator is called a DC generator.

CONSTRUCTION FEATURES OF DC GENERATORS

Generators used on aircraft may differ somewhat in design, since various manufacturers make them. All, however, are of the same general construction and operate similarly. The major parts, or assemblies, of a DC generator are a field frame (or yoke), a rotating armature, and a brush assembly. The parts of a typical aircraft generator are shown in ***Figure 12-9***.

FIELD FRAME

The field frame is also called the yoke, which is the foundation or frame for the generator. The frame has two functions: It completes the magnetic circuit between the poles and acts as a mechanical support for the other parts of the generator. In ***Figure 12-10A***, the frame for a two-pole generator is shown in a cross sectional view. A four pole generator frame is shown in ***Figure 12-10B***.

In small generators, the frame is made of one piece of iron, but in larger generators, it is usually made up of two parts bolted together. The frame has high magnetic properties and, together with the pole pieces, forms the major part of the magnetic circuit. The field poles are bolted to the inside of the frame and form a core on which the field coil windings are mounted. ***(Figure 12-10)***

The poles are usually laminated to reduce eddy current losses and serve the same purpose as the iron core of an electromagnet; that is, they concentrate the lines of force produced by the field coils. The entire frame, including field poles, is made from high-quality magnetic iron or sheet steel.

A practical DC generator uses electromagnets instead of permanent magnets. To produce a magnetic field of the necessary strength with permanent magnets would greatly increase the physical size of the generator.

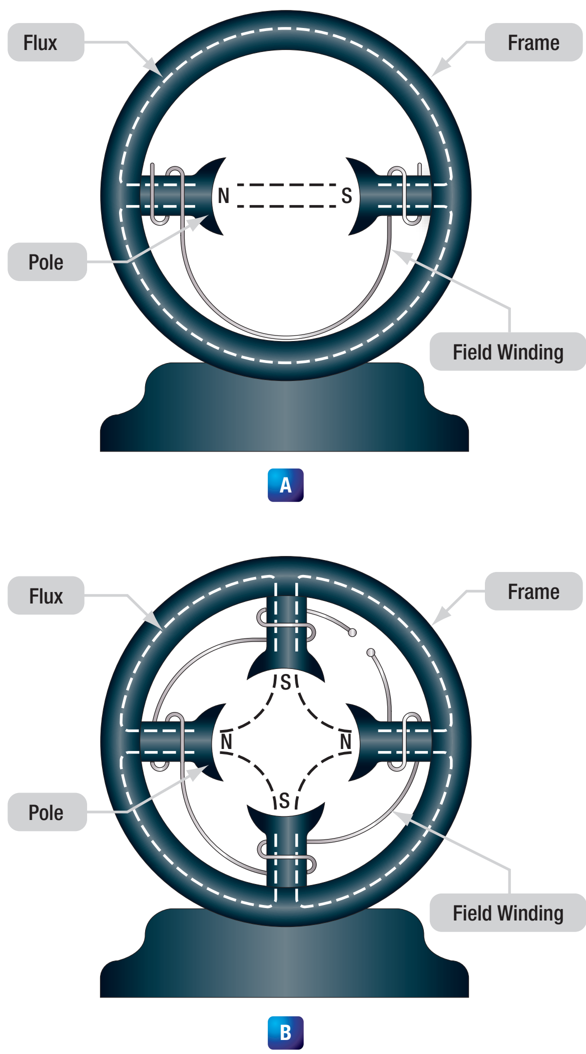


Figure 12-10. A two-pole and a four-pole frame assembly.

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***) The exciting current, which is used to produce the magnetic field and which flows through the field coils, is obtained from an external source or from the generated DC of the machine. No electrical connection exists between the windings of the field coils and the pole pieces.

Most field coils are connected so that the poles show alternate polarity. Since there is always one north pole for each south pole, there must always be an even number of poles in any generator.

Note that the pole pieces in ***Figure 12-10*** project from the frame. Because air offers a great amount of reluctance to the magnetic field, this design reduces the length of the air gap between the poles and the rotating armature and increases the efficiency of the generator. When the pole pieces are made to project they are called salient poles. (***Figure 12-10***)

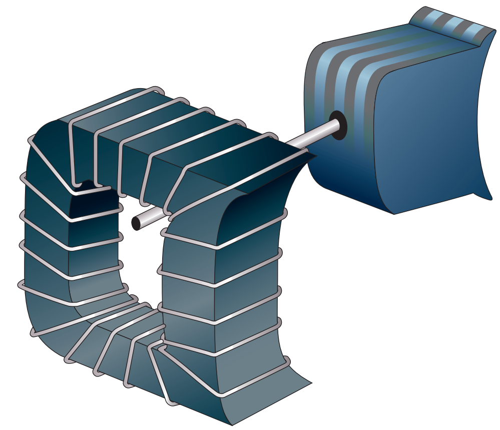


Figure 12-11. A field coil removed from a field pole.

ARMATURE

The armature assembly of a generator consists of many armature coils wound on an iron core, a commutator, and associated mechanical parts. These additional loops of wire are actually called windings and are evenly spaced around the armature so that the distance between each winding is the same. Mounted on a shaft, it rotates through 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.

Gramme-Ring Armature

There are two general kinds of armatures: the ring and the drum. ***Figure 12-12*** 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

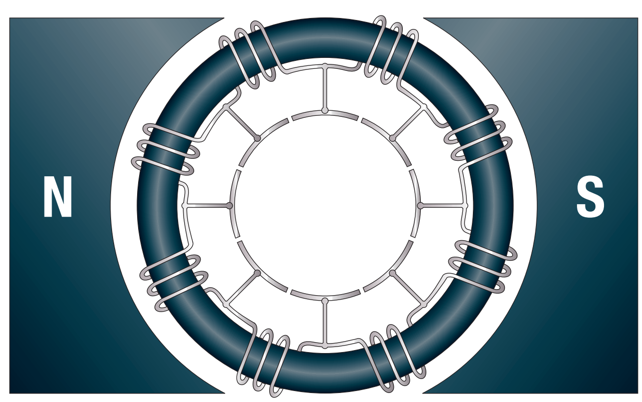


Figure 12-12. An eight-section, ring-type armature.

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. The 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: lap winding and the wave winding. Each method having its own advantage. 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.

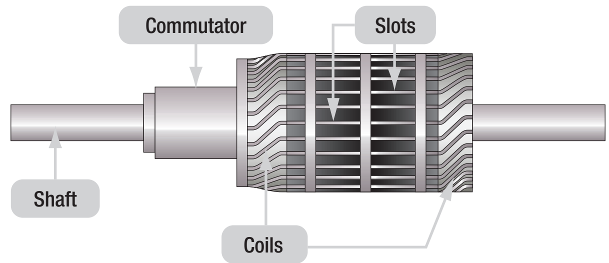


Figure 12-13. A drum-type armature.

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 wedge shaped segments of hard drawn copper, insulated from each other by thin sheets of mica. The segments are held in place by steel V-rings or clamping flanges fitted with bolts. Rings of mica insulate the segments from the flanges. The raised portion of each segment is called a riser, and the leads from the armature coils are soldered to the risers. When the segments have no risers, the leads are soldered to short slits in the ends of the segments.

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, usually made of high grade carbon and held in place by brush holders

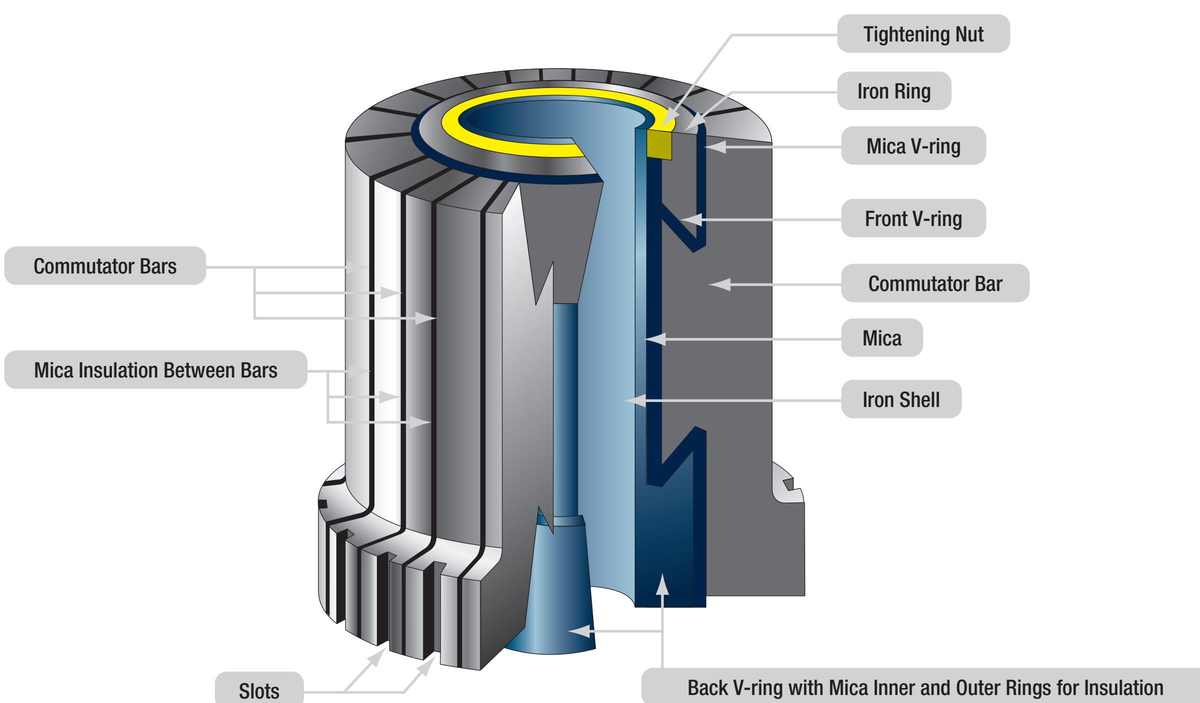


Figure 12-14. Commutator with portion removed to show construction.

insulated from the frame, are free to slide up and down in their holders in order to follow any irregularities in the surface of the commutator. The brushes are usually adjustable so that the pressure of the brushes on the commutator can be varied and the position of the brushes with respect to the segments can be adjusted.

The constant making and breaking of connections to the coils in which a voltage is being induced necessitates the use of material for brushes, which has a definite contact resistance. Also, this material must be such that the friction between the commutator and the brush is low, to prevent excessive wear. 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 large area of contact. 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.

TYPES OF DC GENERATORS

There are three types of DC generators: series wound, shunt wound, and shunt series or compound wound. The difference in type depends on the relationship of the field winding to the external circuit.

Series Wound DC Generators

The field winding of a series generator is connected in series with the external circuit called the load. (***Figure 12-15***) The field coils are composed of a few turns of large wire; the magnetic field strength depends more on the current flow rather than the number of turns in the coil. Series generators have very poor voltage regulation under changing load, since the greater the current through the field coils to the external circuit, the greater the induced emf and the greater the terminal or output voltage. Therefore, when the load is increased, the voltage increases; likewise, when the load is decreased, the voltage decreases. The output voltage of a series wound generator may be controlled by a rheostat in parallel with the field windings. (***Figure 12-285A***) Since the series wound generator has such poor regulation, it is never employed as an airplane generator. Generators in airplanes have field windings, which are connected either in shunt or in compound.

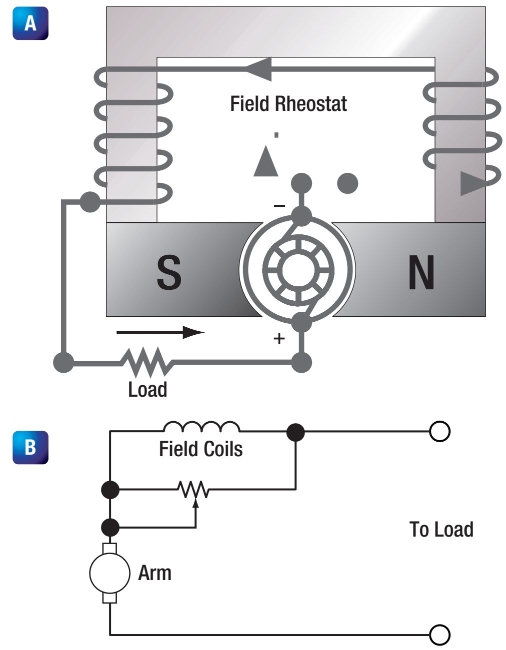


Figure 12-15. Diagram and schematic of a series wound generator.

Shunt Wound DC Generators

A generator having a field winding connected in parallel with the external circuit is called a shunt generator. (***Figure 12-16A and B***) The field coils of a shunt generator contain many turns of small wire; the magnetic strength is derived from the large number of turns rather than the current strength through the coils. If a constant voltage is desired, the shunt wound generator is not suitable for rapidly fluctuating loads. Any increase in load causes a decrease in the terminal or output voltage, and any decrease in load causes an increase in terminal voltage; since the armature and the load are connected in series, all current flowing in the external circuit passes through the armature winding. Because of the resistance in the armature winding, there is a voltage drop (IR drop = current . resistance). As the load increases, the armature current increases and the IR drop in the armature increases. The voltage delivered to the terminals is the difference between the induced voltage and the voltage drop; therefore, there is a decrease in terminal voltage. This decrease in voltage causes a decrease in field strength, because the current in the field coils decreases in proportion to the decrease in terminal voltage; with a weaker field, the voltage is further decreased. When the load decreases, the output voltage increases accordingly, and a larger current flows in the windings. This action is cumulative, so the output voltage continues to rise to a point called field saturation, after which there is no further increase in output voltage.

The terminal voltage of a shunt generator can be controlled by means of a rheostat inserted in series with the field windings. (***Figure 12-16A***) As the resistance is increased, the field current is reduced; consequently, the generated voltage is reduced also. For a given setting of the field rheostat, the terminal voltage at the armature brushes is approximately equal to the generated voltage minus the IR drop produced by the load current in the armature; thus, the voltage at the terminals of the generator drops as the load is applied. Certain voltage sensitive devices are available that automatically adjust the field rheostat to compensate for variations in load. When these devices are used, the terminal voltage remains essentially constant.

Compound Wound DC Generators

A compound wound generator combines a series winding and a shunt winding in such a way that the characteristics of each are used to advantage. The series field coils are made of a relatively small number of turns of large copper conductor, either circular or rectangular in cross section, and are connected in series with the armature circuit. These coils are mounted on the same poles on which the shunt field coils are mounted and, therefore, contribute a magnetomotive force which influences the main field flux of the generator. A diagrammatic and a schematic illustration of a compound wound generator is shown in Figure ***12-17A and B***.

If the ampere turns of the series field act in the same direction as those of the shunt field, the combined magnetomotive force is equal to the sum of the series and shunt field components. Load is added to a compound generator in the same manner in which load is added to a shunt generator, by increasing the number of parallel paths across the generator terminals. Thus, the decrease in total load resistance with added load is accompanied by an increase in armature circuit and series field circuit current. The effect of the additive series field is that of increased field flux with increased load. The extent of the increased field flux depends on the degree of saturation of the field as determined by the shunt field current. Thus, the terminal voltage of the generator may increase or decrease with load, depending on the influence of the series field coils. This influence is referred to as the degree of compounding. A flat compound generator is one in which the no load and full load voltages have the same value; whereas an under compound generator has a full load voltage less than the no load value, and an over compound generator has a full load voltage which

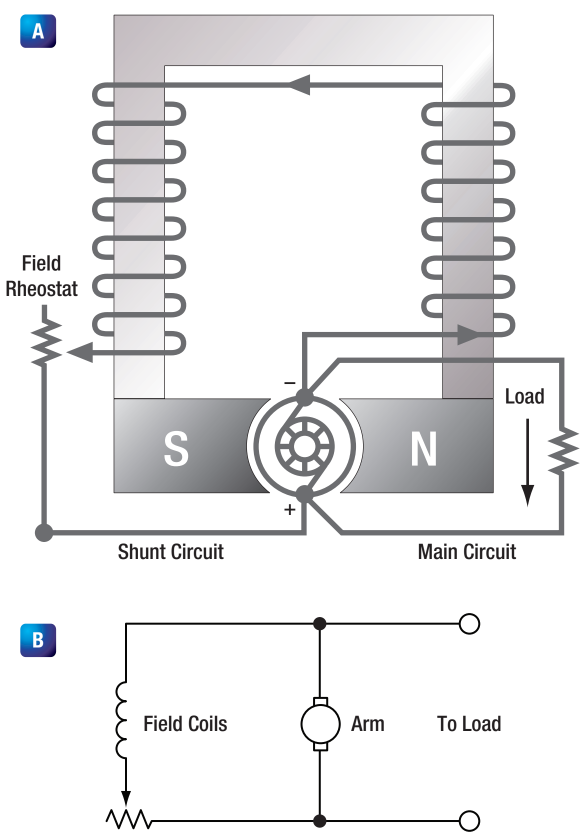


Figure 12-16. Shunt wound generator.

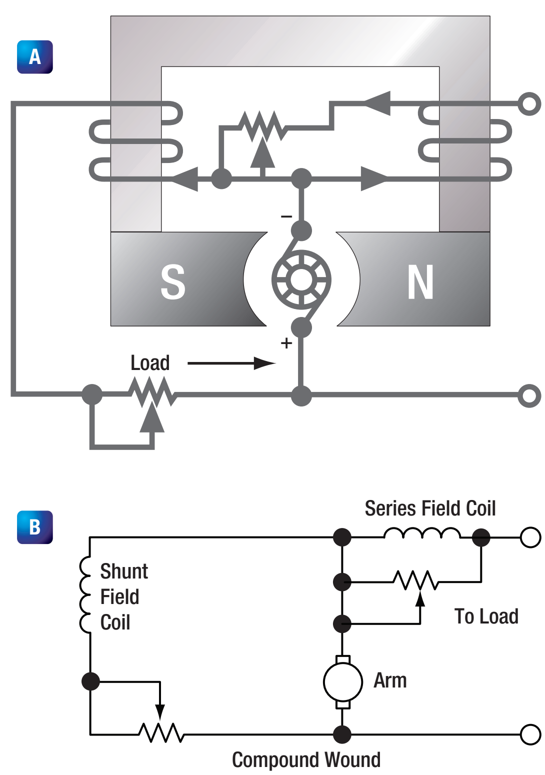


Figure 12-17. Compound wound generator.

is higher than the no load value. Changes in terminal voltage with increasing load depend upon the degree of compounding.

If the series field aids the shunt field, the generator is said to be cumulative compounded. If the series field opposes the shunt field, the machine is said to be differentially compounded or is called a differential generator. Compound generators are usually designed to be over compounded. This feature permits varied degrees of compounding by connecting a variable shunt across the series field. Such a shunt is sometimes called a diverter. Compound generators are used where voltage regulation is of prime importance.

Differential generators have somewhat the same characteristics as series generators in that they are essentially constant current generators. However, they generate rated voltage at no load, the voltage dropping materially as the load current increases. Constant current generators are ideally suited as power sources for electric arc welders and are used almost universally in electric arc welding.

If the shunt field of a compound generator is connected across both the armature and the series field, it is known as a long shunt connection, but if the shunt field is connected across the armature alone, it is called a short shunt connection. These connections produce essentially the same generator characteristics. A summary of the characteristics of the various types of generators discussed is shown in ***Figure 12-18***.

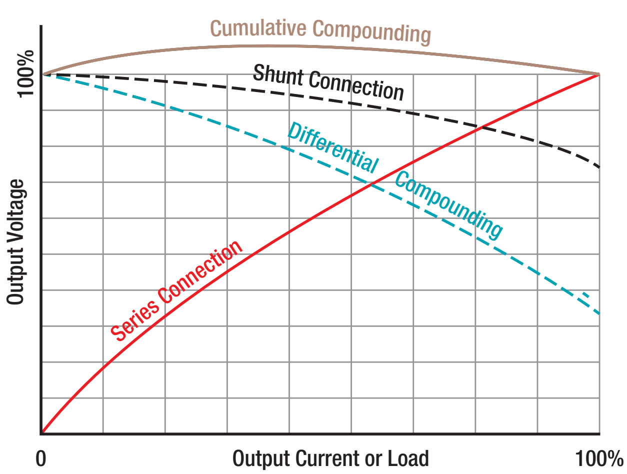


Figure 12-18. Generator characteristics.

OPERATION AND FACTORS AFFECTING THE OUTPUT OF DC GENERATORS

ARMATURE REACTION

Current flowing through the armature sets up the electromagnetic fields in the windings. These new fields tend to distort or bend the magnetic flux between the poles of the generator from a straight-line path. Since armature current increases with load, the distortion becomes greater with an increase in load. This distortion of the magnetic field is called armature reaction. (***Figure 12-19***)

Armature windings of a generator are spaced so that, during rotation of the armature, there are certain positions when the brushes contact two adjacent segments, thereby shorting the armature windings to these segments. When the magnetic field is not

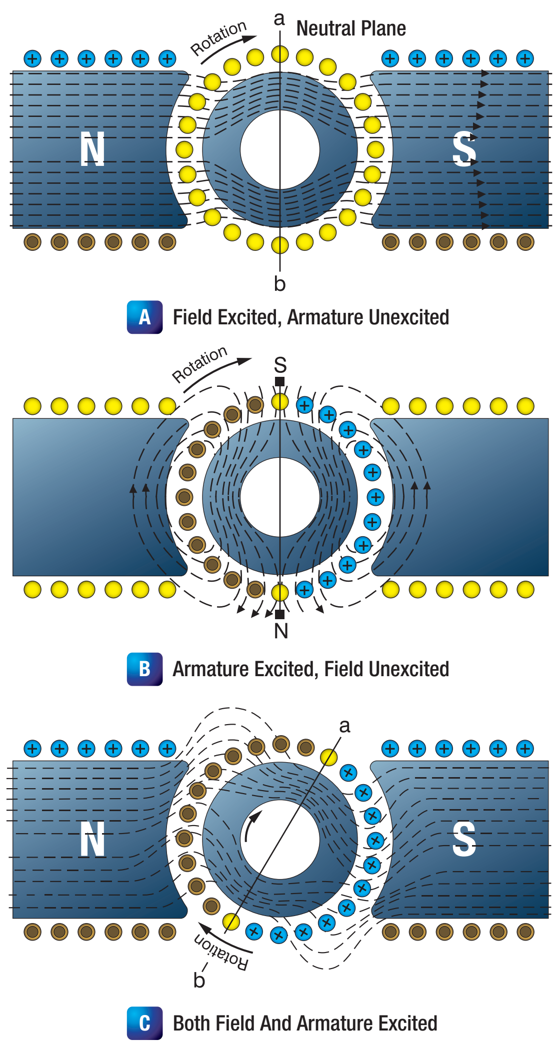


Figure 12-19. Armature reaction.

distorted, there is usually no voltage being induced in the shorted windings, and therefore no harmful results occur from the shorting of the windings. However, when the field is distorted, a voltage is induced in these shorted windings, and sparking takes place between the brushes and the commutator segments. Consequently, the commutator becomes pitted, the wear on the brushes becomes excessive, and the output of the generator is reduced. To correct this condition, the brushes are set so that the plane of the coils, which are shorted by the brushes, is perpendicular to the distorted magnetic field, which is accomplished by moving the brushes forward in the direction of rotation. This operation is called shifting the brushes to the neutral plane or plane of commutation. The neutral plane is the position where the plane of the two opposite coils is perpendicular to the magnetic field in the generator. On a few generators, the brushes can be shifted manually ahead of the normal neutral plane to the neutral plane caused by field distortion. On nonadjustable brush generators, the manufacturer sets the brushes for minimum sparking.

Compensating windings or interpoles may be used to counteract some of the effects of field distortion, since shifting the brushes is inconvenient and unsatisfactory, especially when the speed and load of the generator are changing constantly.

COMPENSATING WINDINGS

The compensating windings consist of a series of coils embedded in slots in the pole faces. These coils are also connected in series with the armature. Consequently, this series connection with the armature produces a magnetic field in the compensating windings that varies directly with the armature current. The compensating windings are wound in such a manner that the magnetic field produced by them counteracts the magnetic field produced by the armature. As a result, the neutral plane remains stationary any magnitude of armature current. With this design, once the brushes are set correctly, they do not need to be moved again. ***Figure 12-20A*** illustrates how the windings are set into the pole faces.

INTERPOLES

An interpole is a pole placed between the main poles of a generator. An example of interpole placement is shown in ***Figure 12-20B***. This is a simple two-pole generator with two interpoles.

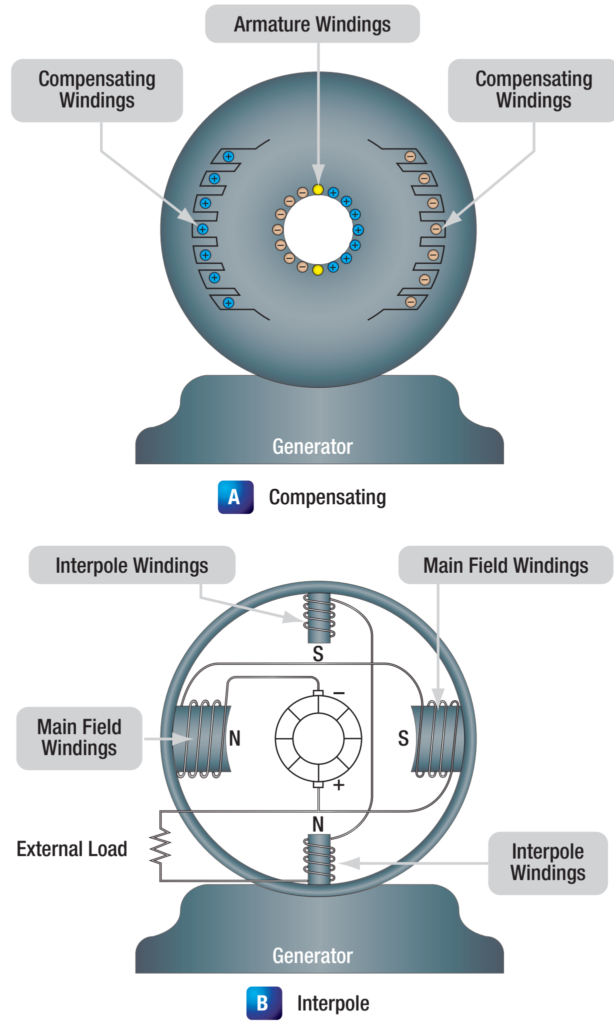


Figure 12-20. Simple two-pole generator with two interpoles.

An interpole has the same polarity as the next main pole in the direction of rotation. The magnetic flux produced by an interpole causes the current in the armature to change direction as an armature winding passes under it. This cancels the electromagnetic fields about the armature windings. The magnetic strength of the interpoles varies with the load on the generator; and since field distortion varies with the load, the magnetic field of the interpoles counteracts the effects of the field set up around the armature windings and minimizes field distortion. Thus, the interpole tends to keep the neutral plane in the same position for all loads on the generator; therefore, field distortion is reduced by the interpoles, and the efficiency, output, and service life of the brushes are improved.

GENERATOR RATINGS

A generator is rated in power output. Since a generator is designed to operate at a specified voltage, the rating usually is given as the number of amperes the generator can safely supply at its rated voltage. 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 rating.

The rotation of generators is termed either clockwise or counterclockwise, as viewed from the driven end. Usually, the direction of rotation is stamped on the data plate. If no direction is stamped on the plate, the rotation may be marked by an arrow on the cover plate of the brush housing. It is important that a generator with the correct direction of rotation be used; otherwise, the 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 revolve the generator between 1-1⁄8 and 1-1⁄2 times the engine crankshaft speed. Most aircraft generators have a speed at which they begin to produce their normal voltage. Termed the "coming in" speed, it is usually about 1 500 rpm.

GENERATOR TERMINALS

On most large 24-volt generators, electrical connections are made to terminals marked B, A, and E. The positive armature lead in the generator connects to the B terminal. The negative armature lead connects to the E terminal. The positive end of the shunt field winding connects to terminal A, and the opposite end connects to the negative terminal brush. Terminal A receives current from the negative generator brush through the shunt field winding. This current passes through the voltage regulator and back to the armature through the positive brush. Load current, which leaves the armature through the negative brushes, comes out of the E lead and passes through the load before returning to the armature through the positive brushes.

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 12-21***. 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 12-21A***, 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 12-21B***. 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 12-21C***. The wire is always pushed away from the side where the field is strongest. 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 12-22***. 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.

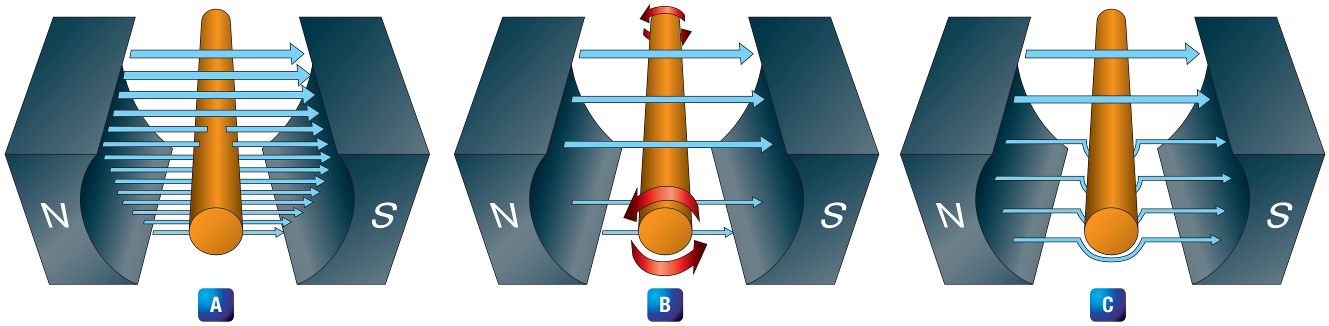


Figure 12-21. Force on a current carrying wire.

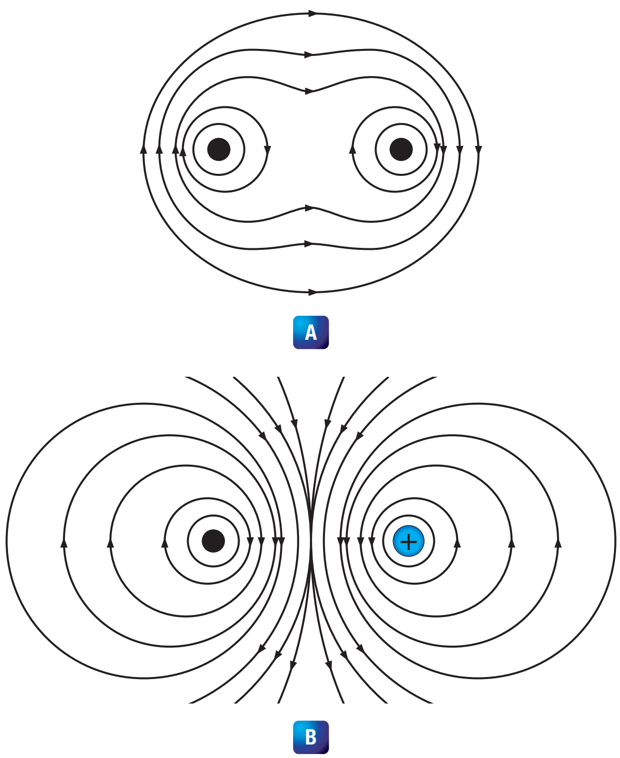


Figure 12-22. Fields surrounding parallel conductors.

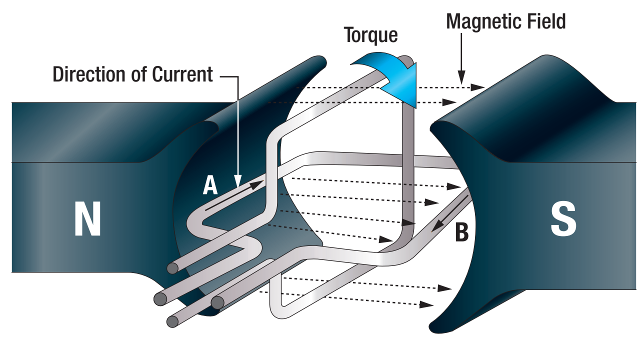


Figure 12-23. Developing a torque.

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.

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 12-23***, 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 12-23*** 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 12-24***, 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.

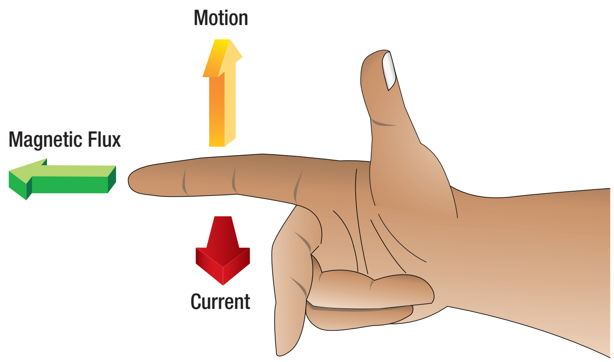


Figure 12-24. Right-hand motor rule.

The amount of torque developed in a coil depends upon several factors: the strength of the magnetic field, the number of turns in the coil, and the position of the coil in the field. Magnets are made of special steel that produces a strong field. Since there is torque acting on each turn, the greater the number of turns on the coil, the greater the torque. In a coil carrying a steady current located in a uniform magnetic field, the torque will vary at successive positions of rotation, as shown in ***Figure 12-25***. 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.

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 12-26*** 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.

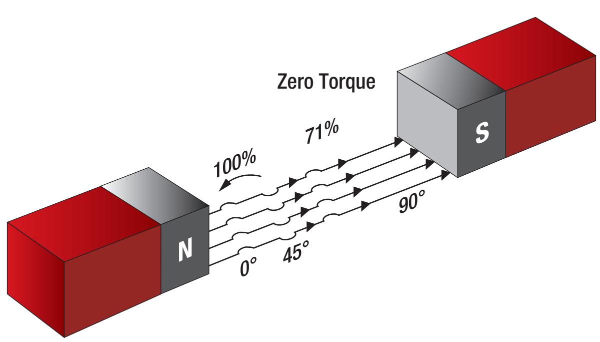


Figure 12-25. Torque on a coil at various angles of rotation.

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 12-26***, 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 12-26A***, 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 12-26B***, 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

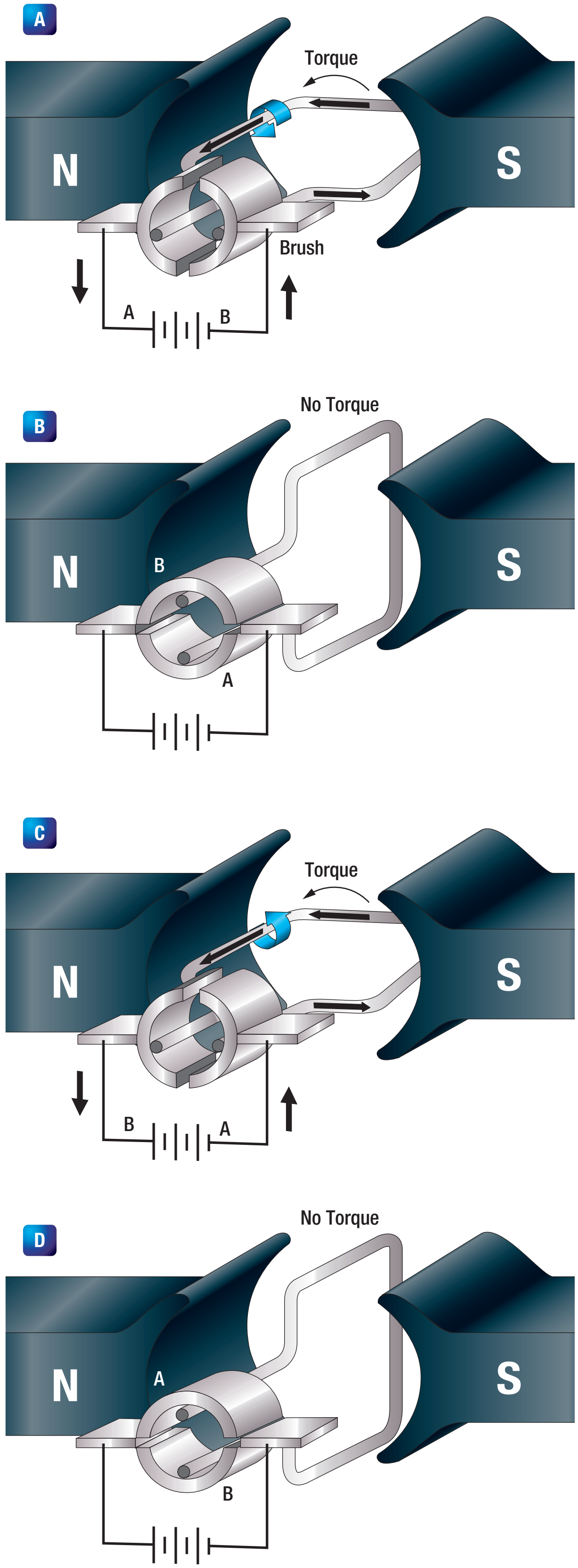


Figure 12-26. Basic DC motor operation.

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 12-26C***, the torque again reaches maximum.

Position D

Continued rotation carries the coil again to a position of minimum torque, as in ***Figure 12-26D***. 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.

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 12-27***)

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

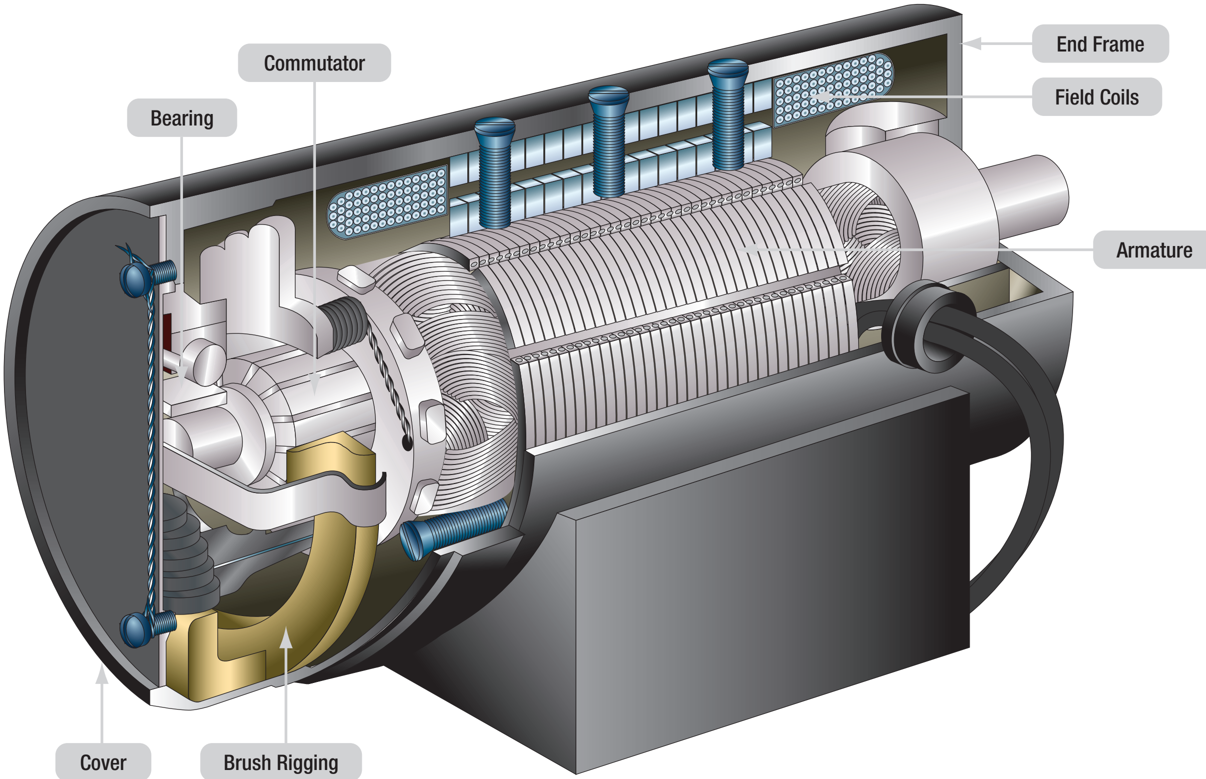


Figure 12-27. Cutaway view of practical DC motor.

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 12-28***.

End Frame
The end frame is the part of the motor opposite the commutator. Usually, the end frame is designed so that it can be connected to the unit to be driven. The bearing for the drive end is also located in the end frame. Sometimes the end frame is made a part of the unit driven by the motor. When this is done, the bearing on the drive end may be located in any one of a number of places.

TYPES OF 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.

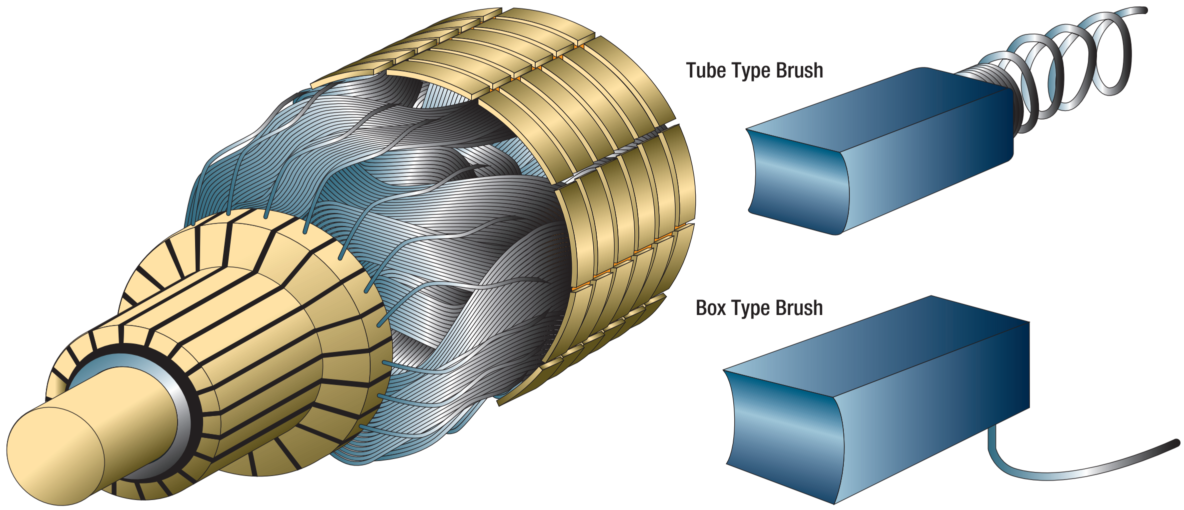


Figure 12-28. Commutator and brushes.

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 12-29***. 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.

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 12-30***)

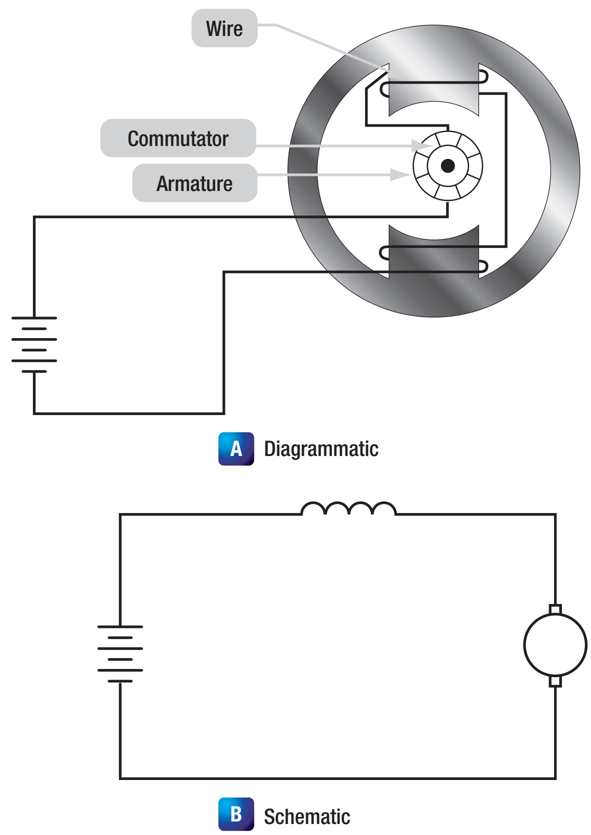


Figure 12-29. Series motor.

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.

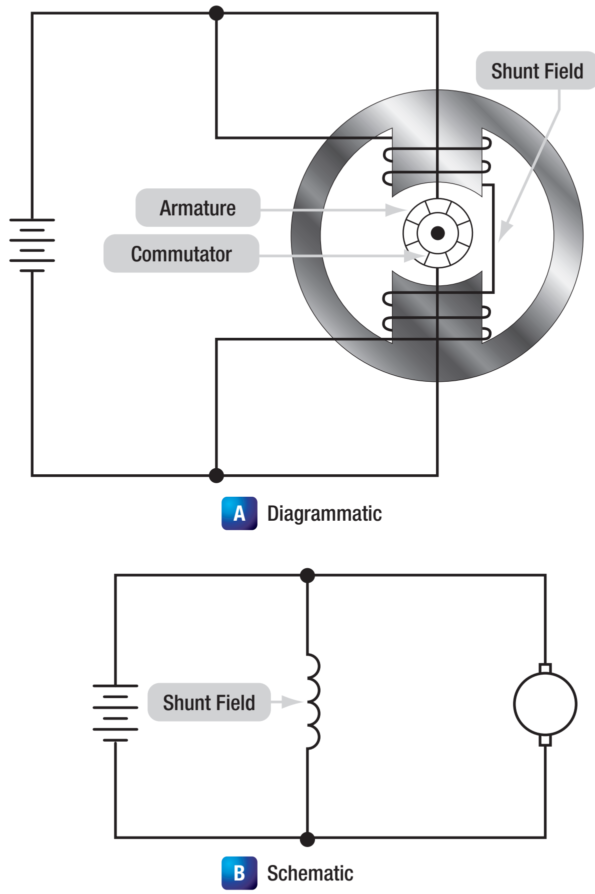


Figure 12-30. Shunt motor.

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.

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 12-31***. 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.

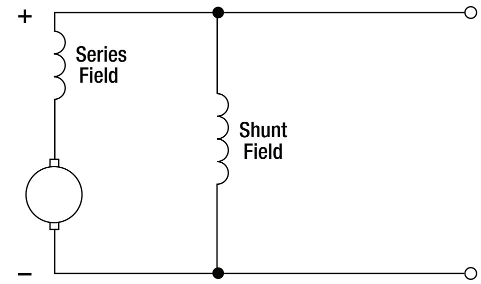


Figure 12-31. Compound motor.

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 12-32***)

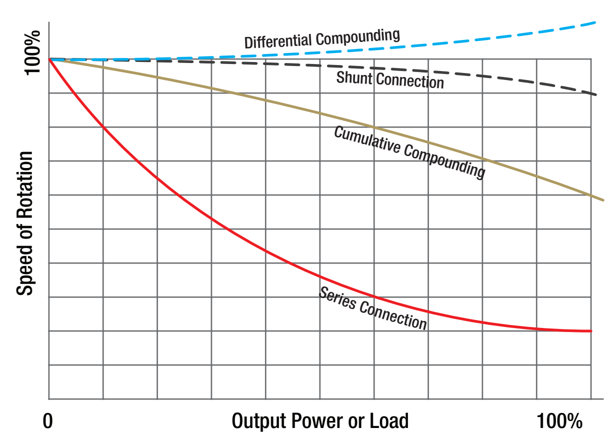


Figure 12-32. Load characteristics of DC motors.

OPERATIONAL FACTORS OF DC MOTORS

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.

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.

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 12-33*** 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

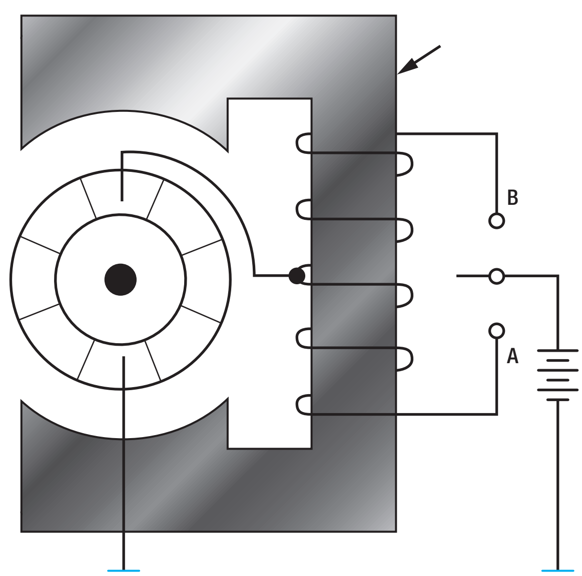


Figure 12-33. Split field series motor.

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 12-34***, current direction may be reversed through the field but not through the armature.

When the switch is thrown to the "up" position, current flows through the field winding to establish a north pole at the right side of the motor and a south pole at the left side of the motor. When the switch is thrown to the "down" position, this polarity is reversed and the armature rotates in the opposite direction.

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 12-35***) 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

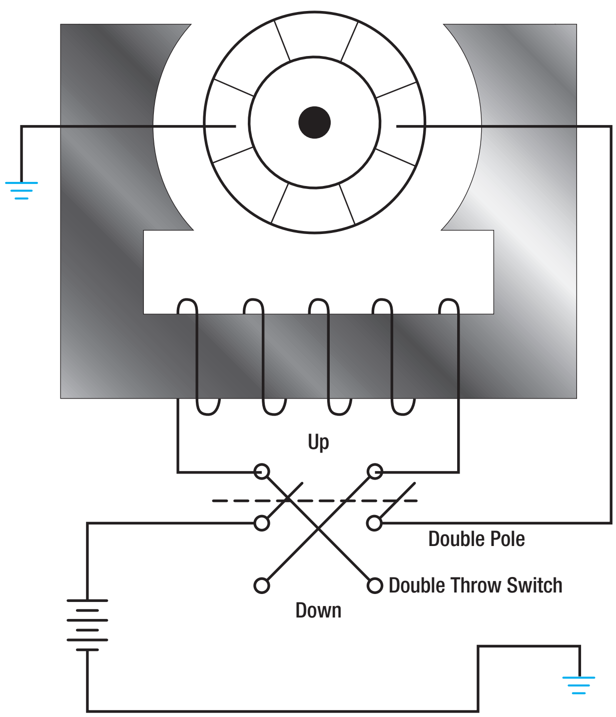


Figure 12-34. Switch method of reversing motor direction.

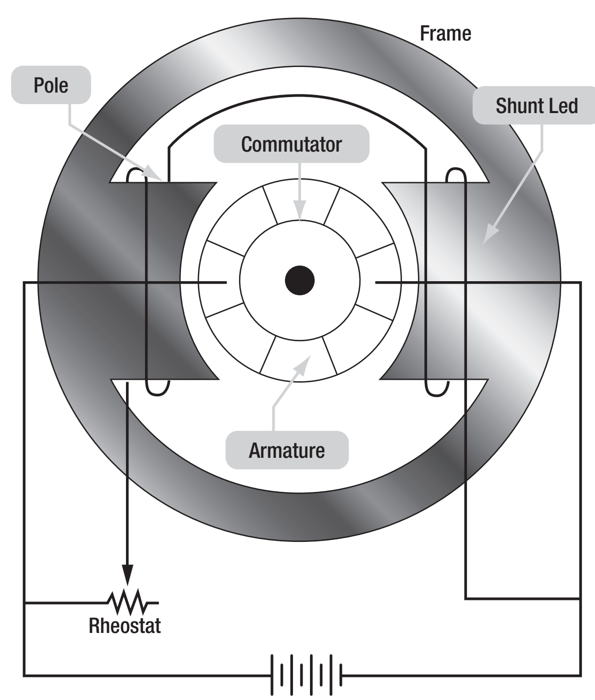


Figure 12-35. Shunt motor with variable speed control.

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.

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 12-36***)

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.

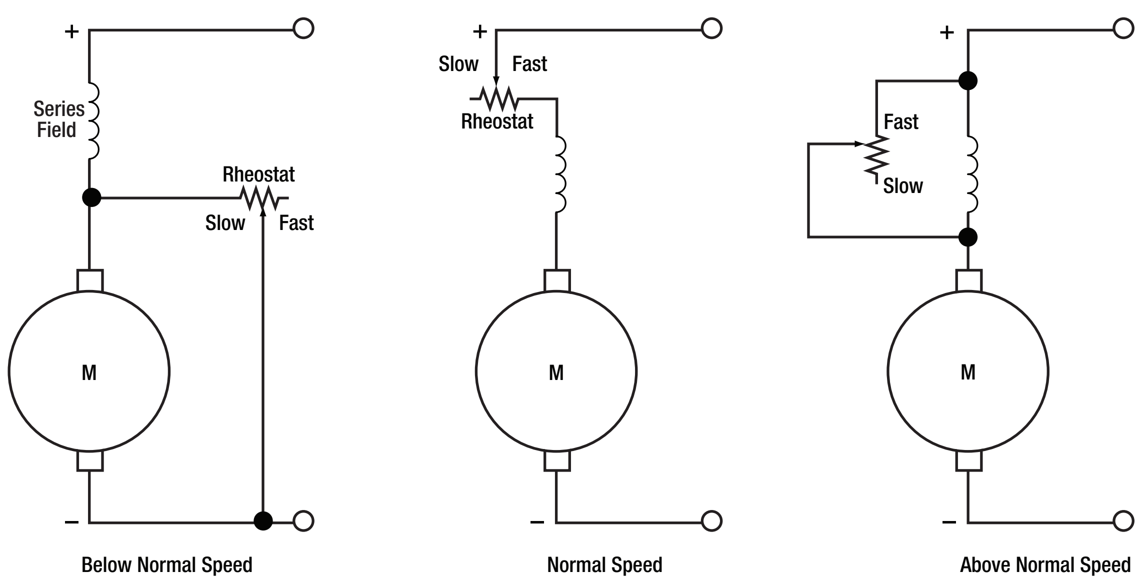


Figure 12-36. Controlling the speed of a series DC motor.

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.

STARTER GENERATOR CONSTRUCTION

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 12-37***) 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 12-38***) 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 12-39*** 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. 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 12-39***) 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

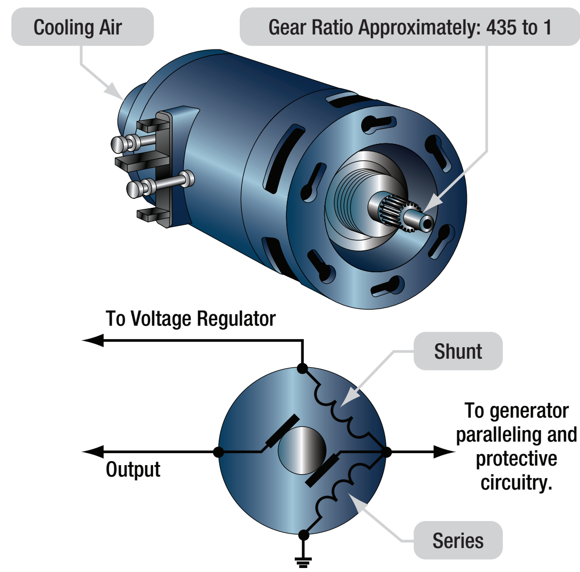


Figure 12-37. Typical starter generator.

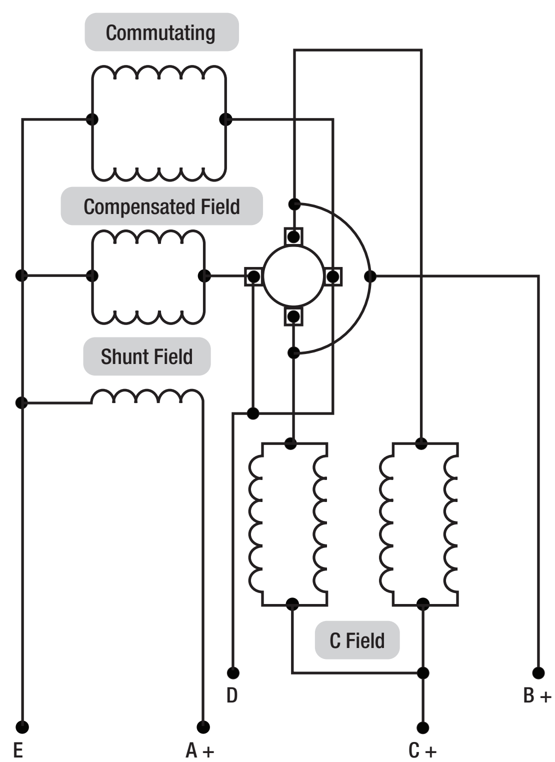


Figure 12-38. Starter generator internal circuit.

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

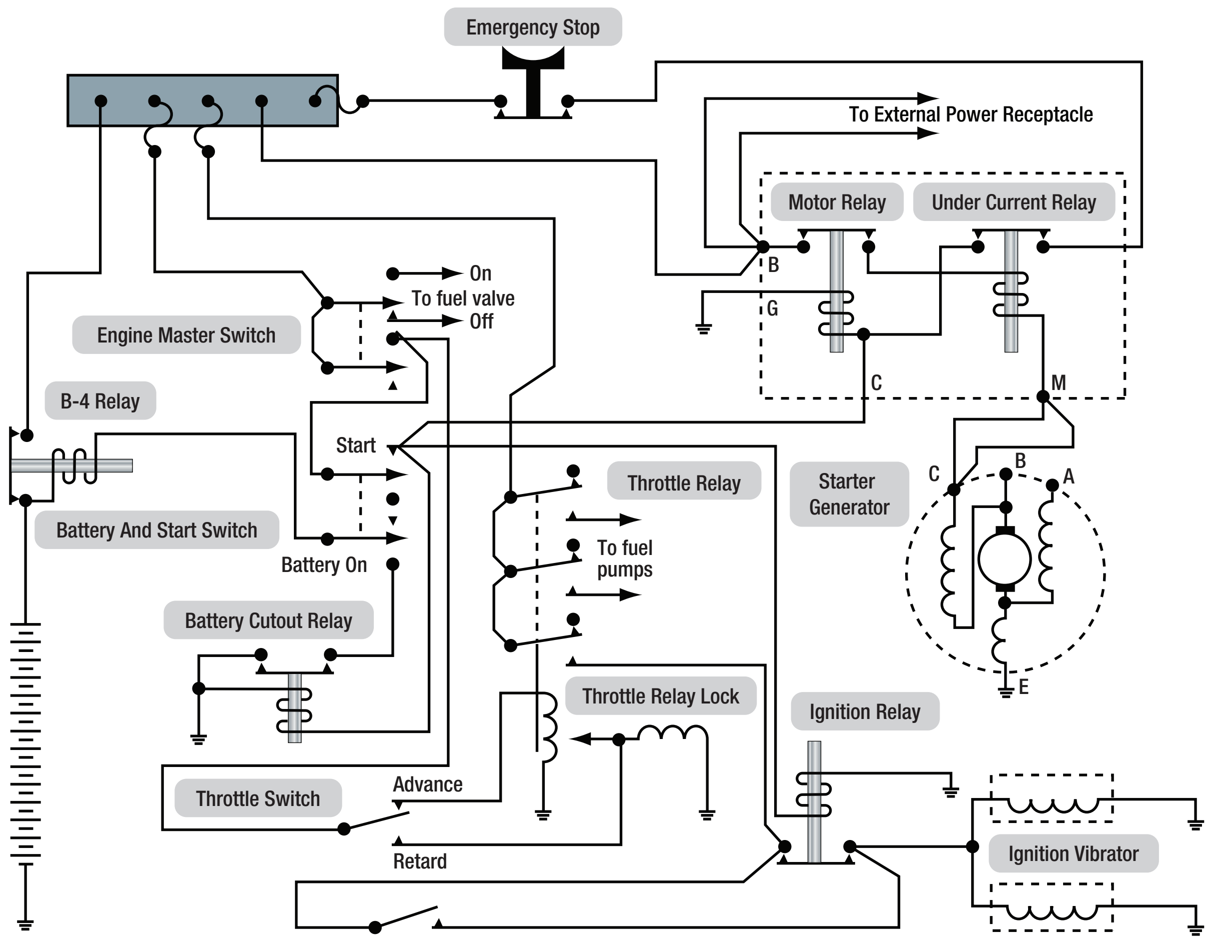


Figure 12-39. Starter generator circuit.

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.

TROUBLESHOOTING A STARTER GENERATOR

The procedures listed in ***Figure 12-40*** 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 12-40. Starter generator starting system troubleshooting procedures.

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: 12-2
Increasing the number of loops that rotate in the magnetic field.

Answer: 12-3
power output.

Answer: 12-4
attracted.

Answer: 12-5
Armature assembly.
Field assembly.
Brush assembly
End frame.

Answer: 12-6
Compound motor.

Answer: 12-7
A laminated core is used.

Answer: 12-8
weight savings.
space savings.
fewer spare parts.

ELECTRICAL FUNDAMENTALS

AC THEORY

SUB-MODULE 13

PART-66 SYLLABUS LEVELS		
CERTIFICATION CATEGORY →	B1	B2

Sub-Module 13

AC THEORY

Knowledge Requirements

	B1	B2
3.13 - AC Theory 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

3.13 - AC THEORY

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. (***Figure 13-1***)

Alternating current changes direction at regular intervals. AC increases in value at a definite rate from zero to a maximum positive strength; then decreases back to zero; then flows in the opposite direction, increasing to a maximum negative value, and again returning 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.

SINUSOIDAL WAVEFORM

CYCLE

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 13-2***, 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

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 13-3***)

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

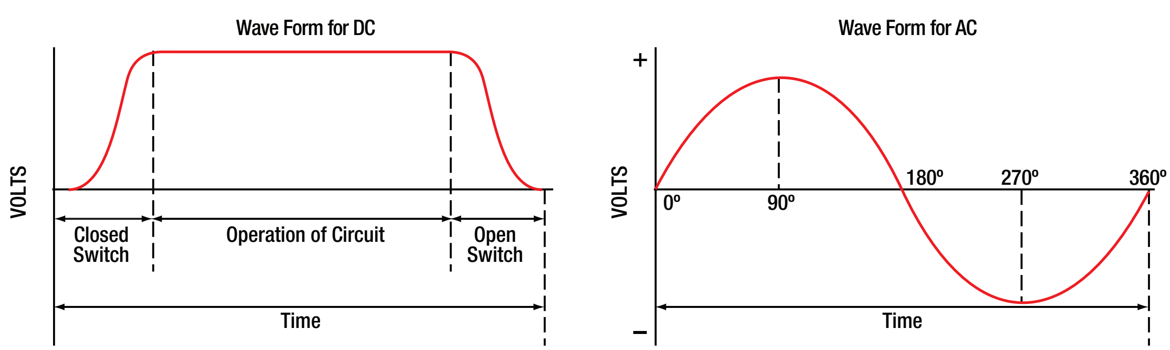


Figure 13-1. DC and AC voltage curves.

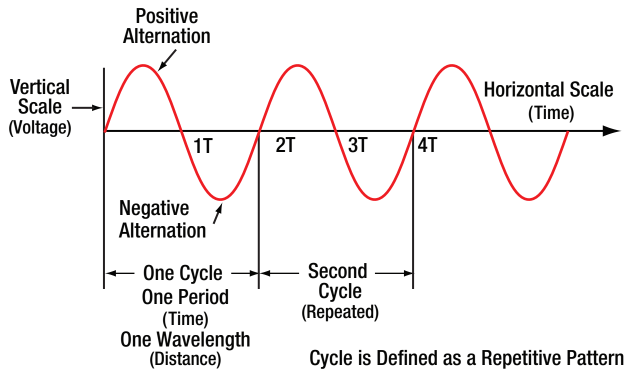


Figure 13-2. Cycle of voltage.

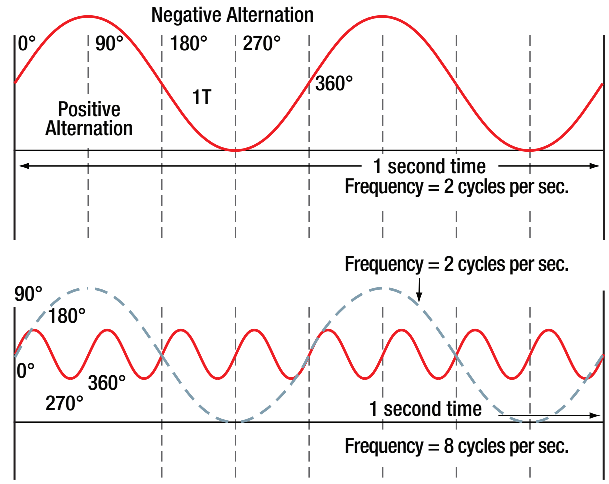


Figure 13-3. Frequency in cycles per second.

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.

PERIOD

The time required for a sine wave to complete one full cycle is called a period. (***Figure 13-2***) 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.

WAVELENGTH

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 13-2***)

PHASE

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 13-4A, 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 13-4A***, 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 13-4B 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 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 13-4C***)

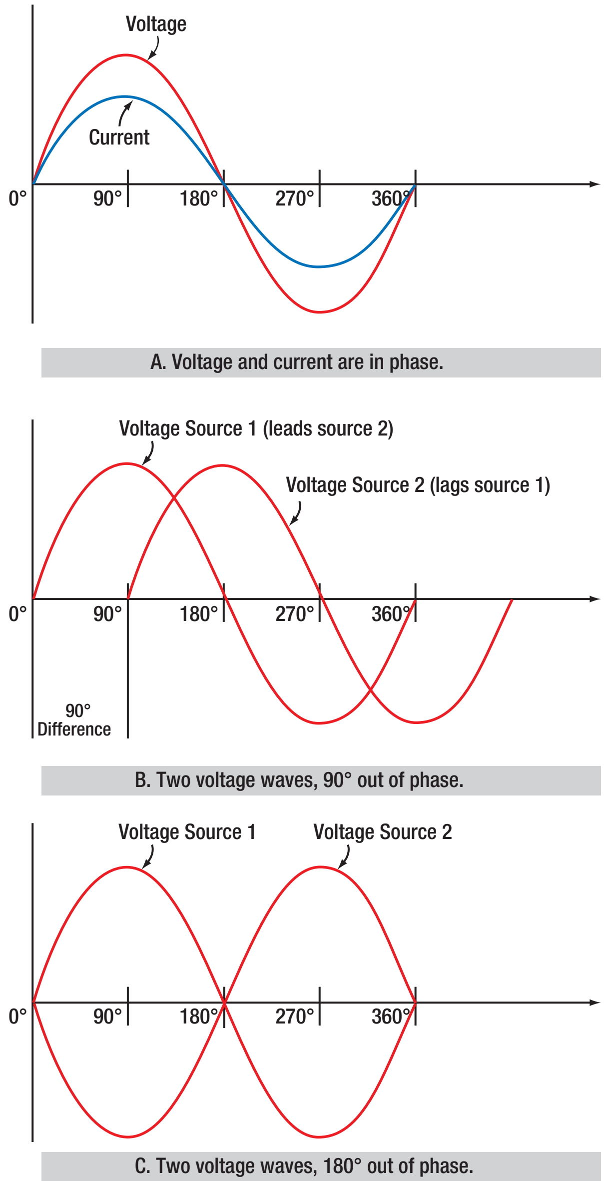


Figure 13-4. In phase and out of phase conditions.

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

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.

AVERAGE VALUE

Average value is the average of all the instantaneous values during one half cycle. Since voltage increases from zero to peak and back to zero during one half cycle, the average value must be between those limits. You can determine the average value by adding a series of instantaneous values of the half cycle (between 0°-180°), then divide the sum by the number of instantaneous values used.

EFFECTIVE VALUE (ROOT MEAN SQUARE)

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.

PEAK-TO-PEAK VALUE

Peak-to-peak (pk-pk) is the difference between the maximum positive and the maximum negative amplitudes of a waveform. (***Figure 13-5***) If there is no direct current (DC) component in an alternating current (AC) wave, then the pk-pk amplitude is twice the peak amplitude.

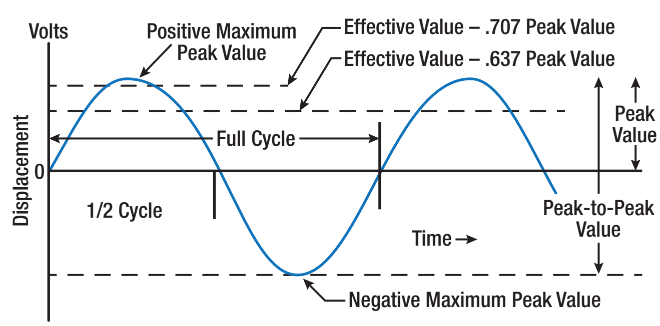


Figure 13-5. Peak-to-peak (pk-pk) is the difference between the maximum positive and the maximum negative amplitudes of a waveform.

CURRENT AND POWER

The power dissipated in an AC circuit is the average of all the instantaneous values of a full cycle. To find instantaneous power at any moment, the instantaneous values of voltage and current at a specific moment are multiplied together. Thus at the moment shown in ***Figure 13-6***, the voltage is A volts and the current is B amperes. The power at this moment is therefore A × B watts and is represented by point C. If this process is carried out over a full cycle, the value shown in ***Figure 13-6*** B will be obtained.

We are mostly interested in average power, since the frequency of an AC supply is usually so high that during the normal operations, a large number of cycles will occur. Thus the peak value is the maximum voltage multiplied by the maximum current, and the average power is half the peak power value in a resistive circuit.

TRIANGULAR/SQUARE WAVES

It should be noted that other types of wave forms exist for voltage and current in addition to the sinusoidal waves mentioned. Wave forms 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 then 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. (***Figure 13-7***)

Typically, peak amplitude of standard sin waves are measured from the zero axis to the maximum positive or negative value. However, for non-sinusoidal square and triangular waves, peak-to-peak amplitude is the better measurement because they can have unsymmetrical peaks.

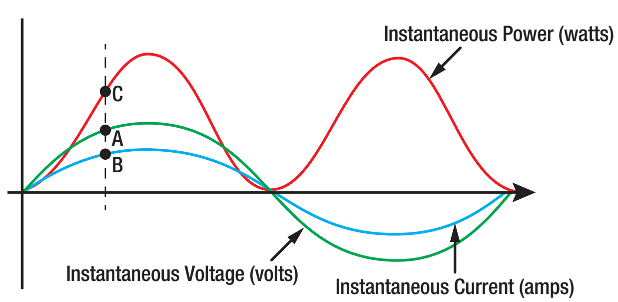


Figure 13-6. Computing average power by determining instantaneous values.

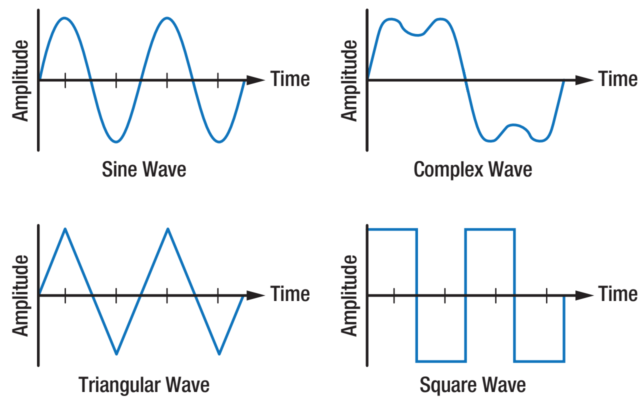


Figure 13-7. Various wave shapes may be formed by repeated changes in voltage or current.

TRIANGULAR WAVES

The triangular wave represents a voltage that slowly increases or decreases with a uniform or linear rate of change to its peak value. This waveform is also called a ramp voltage. If the increasing and decreasing voltage occurs over differing amounts of time, the triangular wave changes to more of a sawtooth type appearance. The sawtooth waveform of voltage or current is often used for horizontal deflection of the electron beam in the cathode-ray tube (CRT) for oscilloscopes and TV receivers.

SQUARE WAVE

A square wave is a non-sinusoidal periodic waveform in which the amplitude alternates at a steady frequency between fixed minimum and maximum values, with the same duration at minimum and maximum. It has been found that square waves are mathematically equivalent to the sum of a sine wave at that same frequency.

SINGLE/THREE PHASE PRINCIPLES

SINGLE PHASE PRINCIPLE

Single phase is the distribution of AC power using a system in which all the voltages of the supply vary in unison. Single phase is used when the loads consist mostly of lighting, heating, and smaller motors.

THREE PHASE PRINCIPLES

Three phase is the most common method used by electrical grids to transfer power and also used to power large motors and heavy loads. The terms symmetry and balance often describing 3 phase systems.

The waveforms of three phase systems are considered symmetrical when the voltage waveforms are of equal magnitude, of the same frequency, and with equal phase displacement. A three phase system is considered balanced when the currents are equal in magnitude, their phase sum is zero and all three phases are equally loaded. A balanced waveform is shown in (***Figure 13-8***). The individual phases are distinguished by the colors red, green, blue. Convention requires that the following conditions apply for a system to be considered symmetrical:

- The red voltage phase is taken as the reference phase.
- The green voltage phase lags the red by 120°.
- The blue voltage phase lags the yellow by 120°.
- All voltage phases are of the same magnitude.

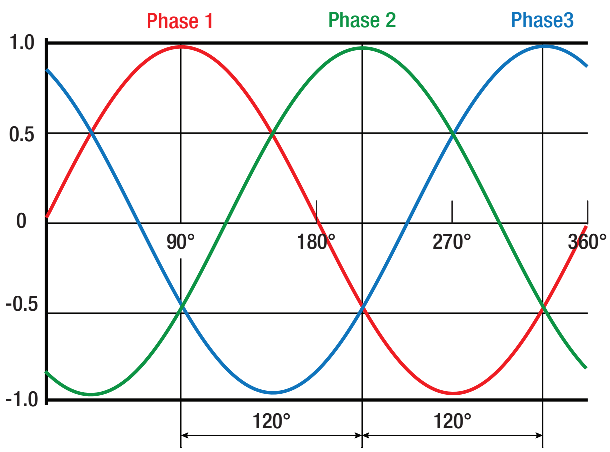


Figure 13-8. Voltage Waveform produced in three-phase AC power source.

Question: 13-1
The value of an induced emf depends on what three factors?

Question: 13-2
________________ is the number of cycles of alternating current per second (1 second).

Question: 13-3
Name three values of alternating current.

Question: 13-4
________________ value is equal to .707 times the maximum value.

Question: 13-5
Name 4 advantages of AC current over DC current in modern aircraft.

Question: 13-6
What is meant by saying that a current is of 400 Hz?

Question: 13-7
How is power defined in an AC cycle?

Question: 13-8
How many times does a conductor rotate through a magnetic field to create one cycle of AC electricity?

ANSWERS

Answer: 13-1
The number of wires moving through the magnetic field.
The strength of the magnetic field.
The speed of rotation.

Answer: 13-2
frequency.

Answer: 13-3
instantaneous
peak
effective (root mean square, RMS).

Answer: 13-4
Effective.

Answer: 13-5
- AC can be transmitted over longer distances.
- AC motors are smaller and lighter weight.
- No problem with commutation at high altitude.
- Circuit breakers are more reliable at high altitude.

Answer: 13-6
A current fluctuates 400 complete cycles each second.

Answer: 13-7
Power is the average of all instantaneous values of a cycle.

Answer: 13-8
One full rotation–360°.

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 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

3.14 - RESISTIVE (R), CAPACITIVE (C) AND INDUCTIVE (L) CIRCUITS

PHASE RELATIONSHIPS OF VOLTAGE AND CURRENT IN PARALLEL SERIES, AND SERIES PARALLEL 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 14-1*** 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:

$$I = \frac{E}{R} \qquad I = \frac{E}{Z} \text{ (where Z = R)}$$

$$I = \frac{110\text{ V}}{11\text{ W}} \qquad I = \frac{110\text{ V}}{11\text{ W}}$$

$$I = 10 \text{ amperes DC} \qquad I = 10 \text{ amperes AC}$$

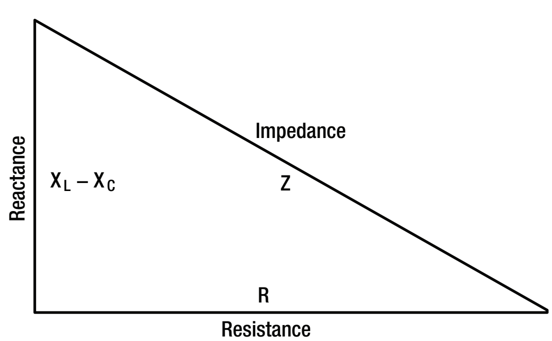


Figure 14-1. Impedance triangle.

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

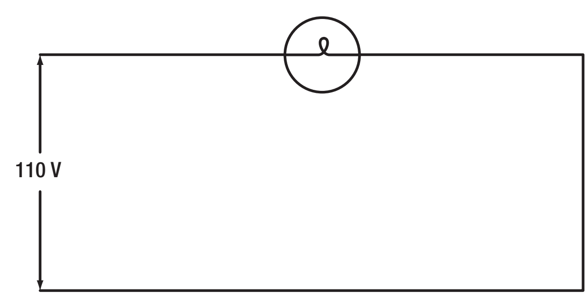


Figure 14-2. Applying DC and AC to a circuit.

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 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:

$$X_L = 2\,\pi \times f \times L$$
$$X_L = 6.28 \times 60 \times 0.021$$
$$X_L = 8 \text{ ohms inductive reactance}$$

$$Z = \sqrt{R^2 + {X_L}^2}$$
$$Z = \sqrt{6^2 + 8^2}$$
$$Z = \sqrt{36 + 64}$$
$$Z = \sqrt{100}$$
$$Z = 10 \text{ ohms impedance}$$

Then the current flow,

$$I = \frac{E}{Z}$$
$$I = \frac{110}{10}$$
$$I = 11 \text{ amperes current}$$

The voltage drop across the resistance (ER) is:

$$E^R = I \times R$$
$$E^R = 11 \times 6 = 66 \text{ volts}$$

The voltage drop across the inductance (E_{XL}) is:

$$E_{XL} = I \times X_L$$
$$E_{XL} = 11 \times 8 = 88 \text{ volts}$$

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.

This can be proved by the following equation:

$$E = \sqrt{(E_R)^2 + (E_{XL})^2}$$
$$E = \sqrt{66^2 + 88^2}$$
$$E = \sqrt{4\,356 + 7\,744}$$
$$E = \sqrt{12\,100}$$
$$E = 110 \text{ volts}$$

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:

$$200\ \mu f = \frac{200}{1\,000\,000} = 0.000\,200 \text{ farads}$$

$$X_C = \frac{1}{2\,\pi\, f\, C}$$

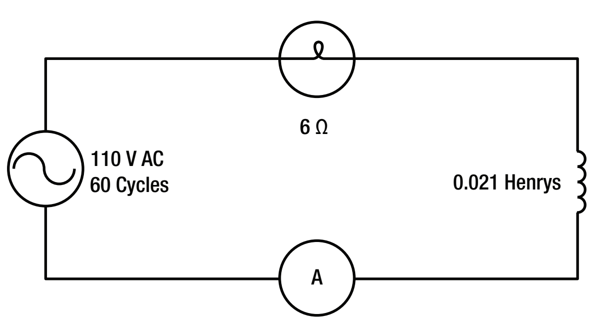


Figure 14-3. A circuit containing resistance and inductance.

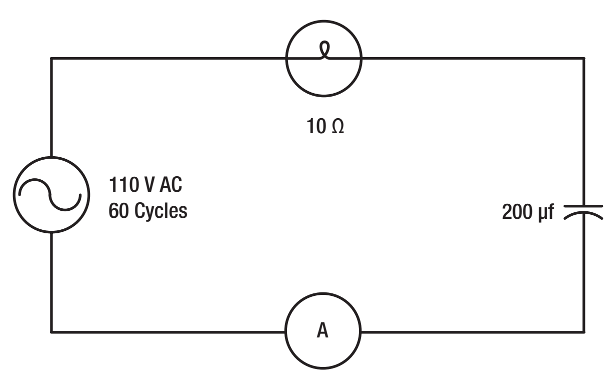


Figure 14-4. A circuit containing resistance and capacitance.

$$X_C = \frac{1}{6.28 \times 60 \times 0.002\,00 \text{ farads}}$$

$$X_C = \frac{1}{0.075\,36}$$

X_C = 13 ohms capacitive reactance

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 ohms capacitive reactance

To find the current:

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

$$I = \frac{110}{16.4}$$

I = 6.7 amperes

The voltage drop across the lamp (E^R) is
$E^R = 6.7 \times 10$
E^R = 67 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 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 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***)

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 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 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.

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?

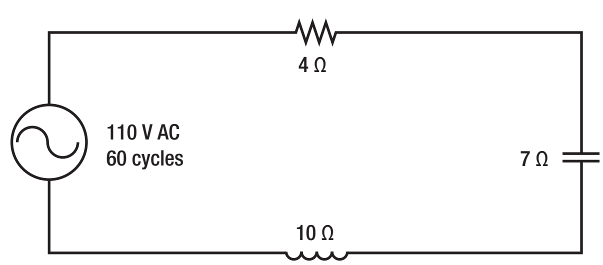


Figure 14-5. A circuit containing resistance, inductance, and capacitance.

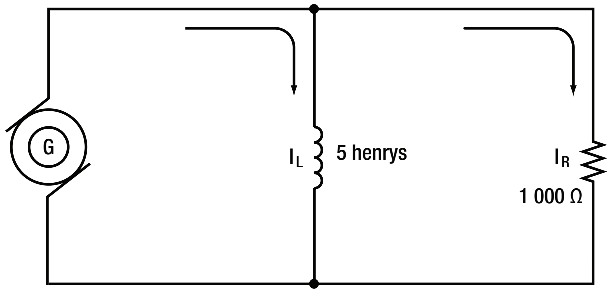


Figure 14-6. AC parallel circuit containing inductance and resistance.

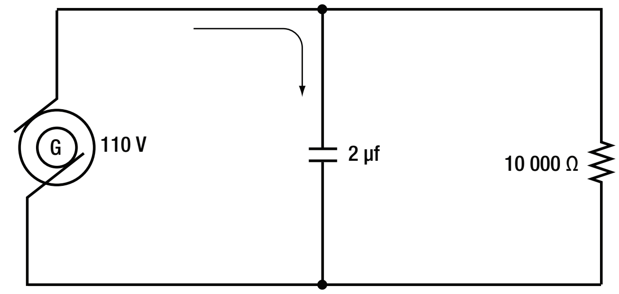


Figure 14-7. A parallel AC circuit containing capacitance and resistance.

Solution:

$$Et = \sqrt{(I_L)^2 + (E_{XC})^2}$$

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:

$$Xc = \frac{1}{2\,\pi\,f\,C}$$

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:

$$Z = \frac{RX_C}{\sqrt{R^2 + X_C{}^2}}$$

$$Z = \frac{10\,000 \times 1\,327}{\sqrt{(10\,000)^2 + (1\,327)^2}}$$

$$= 1\,315\ \Omega \text{ (approx.)}$$

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:

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

$$= \frac{110}{1\,315}$$

$$= 0.083\,6 \text{ ampere}$$

Or,

To find the total current in the circuit:

$$I_T{}^2 = \sqrt{I_R{}^2 + I_C{}^2}$$

$$I_T = \sqrt{I_L{}^2 + I_R{}^2}$$

$$= 0.083\,6 \text{ ampere}$$

POWER DISSIPATION IN (L), (C), AND (R) CIRCUITS

POWER IN AN INDUCTIVE CIRCUIT

The power dissipated in an inductive AC circuit is the average of all the instantaneous values of power over a complete cycle. To find the instantaneous power at any moment, the instantaneous values of voltage and current are multiplied together.

POWER IN AN CAPACITIVE CIRCUIT

In a capacitive circuit, the power curve is positive when current is flowing from 0 to 180° in which the capacitor is being charged. Thus, during the 180-360° interval no useful work has been done even though current has been flowing through the conductors.

POWER IN AN RESISITIVE CIRCUIT

In a purely resistive circuit, all circuit power is dissipated by the resistor. Voltage and current are in phase with each other. In a reactive circuit, no power is dissipated by the load. Rather, power is alternately absorbed from and returned to the AC source. Note that the waveform for power is always positive, never negative in a resistive circuit. This means that power is always being dissipated by the resistive load, and never returned to the source as with reactive loads.

IMPEDANCE, PHASE ANGLE, POWER FACTOR, AND CURRENT CALCULATIONS

OHM'S LAW FOR AC CIRCUITS

The rules and equations for DC circuits apply to AC 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, 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 opposition is called impedance and is represented by the letter "Z". The unit of measurement of impedance is the ohm.

As mentioned, resistance creates an opposition to current in an AC circuit similar to a DC circuit. The current through a resistive portion of an AC circuit is inversely proportional to the resistance and directly proportional to the voltage applied to that circuit. The equations $I = E/R$ and $E = I \times R$ show this relationship. It should be noted that resistance in an AC circuit does not create a phase shift between voltage and current.

INDUCTIVE REACTANCE

When moving a magnet through a coil of wire, a voltage is induced across the coil. If a complete circuit is provided, current will also be induced. The amount of induced voltage is proportional to the rate of change of the magnetic field with respect to the coil. Conversely, current flowing through a coil produces a magnetic field. When this wire is formed into a coil, it then becomes a basic inductor.

The primary effect of a coil is to oppose any change in current through it. This property is called inductance. When current flows through a conductor, a magnetic field expands 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 opposite to the direction of the applied current flow. The effects of this countering EMF is to temporarily oppose the applied current. Once the current reaches a steady value in the conductor, the lines of magnetic force are no longer expanding and the countering EMF is no longer present. Since AC is constantly changing in value, the inductance repeats in a cycle opposite the applied voltage. The unit of measure for inductance is the henry (H).

IMPEDANCE

In order to accurately calculate voltage and current in AC circuits, the effect of impedance must be considered. If a circuit has inductance or capacitance, one must take into consideration resistance (R), inductive reactance (X_L), and/or capacitive reactance (X_C) to determine impedance (Z).

Resistance and reactance (inductive or capacitive) cannot be added directly, but 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 as described earlier in this chapter.

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.

$$Xc = \frac{1}{2\,\pi\, f\, C}$$

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:

$X_L = X_C$, 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 F_N 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 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.

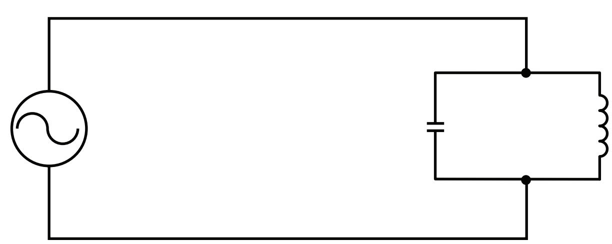


Figure 14-8. A parallel resonant circuit.

PHASE ANGLE

Most (AC) generation, transmission, and use take place through three phase circuits. If you want to understand electric power, you must know something about three phase. Electrical phase is measured in degrees, with 360° corresponding to a complete cycle.

Phase difference, also called phase angle in degrees, is conventionally defined as a number greater than -180, and less than or equal to +180. Leading phase refers to a wave that occurs "ahead" of another wave of the same frequency. Lagging phase refers to a wave that occurs "behind" another wave of the same frequency. ***Figure 14-9*** shows two waves with their phase angles.

POWER FACTOR

As seen earlier in ***Figure 14-10*** the resistive power and the reactive power effect the circuit at right angles to each other. The power factor in an AC circuit is created by this right angle effect. Power factor can be defined as the mathematical difference between true power and apparent power.

Power factor (PF) is always a measurement between 0-100. It is directly related to the phase shift of a circuit. The greater the phase shifts of a circuit the lower the power factor. For example, an AC circuit that is purely inductive (contains reactance only and no resistance) has a phase shift of 90° and a power factor of 0.0. An AC circuit that is purely resistive (has no reactance) has a phase shift of 0 and a power factor of 100.

TRUE POWER, APPARENT POWER, AND REACTIVE POWER CALCULATIONS

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 is 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 14-10***)

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.

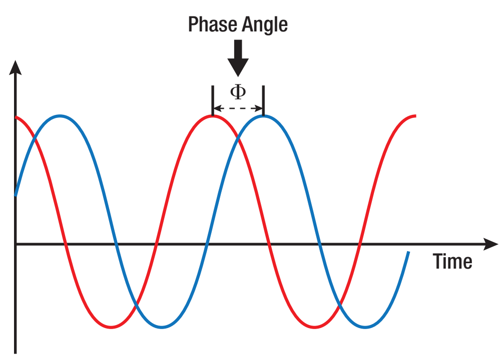


Figure 14-9. Phase angle is shown as the difference between leading and lagging waves.

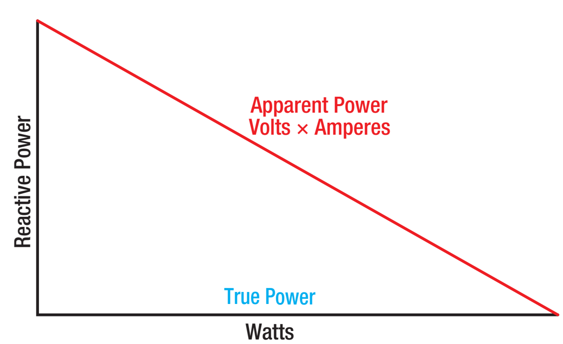


Figure 14-10. Power relations in AC circuit.

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

$$\text{(PF)} = \frac{\text{Watts (True Power)} \times 100}{\text{VA (Apparent Power)}}$$

$$\text{(PF)} = \frac{9\,350 \times 100}{11\,000}$$

(PF) = 85 or 85%

REACTIVE POWER

Reactive power exists in an AC circuit when the current and voltage are not in phase. Instruments called varmeters measure the reactive power in a circuit. A sinusoidally alternating voltage applied to a purely resistive load results in an alternating current that is fully in phase with the voltage. However, in many applications it is common for there to be a reactive component as well. That is, the system possesses capacitance, and/or inductance. These properties cause the current to change phase with respect to the voltage with capacitance tending to lead the voltage in phase, and inductance to lag it. The reactive power Q (measured in units of volt-amperes reactive or VAR) is given by:

$$Q = V\,I\,\sin\theta$$

Only when the AC circuit is made up of pure resistance is the apparent power equal to the true power. 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 ratio of the true power to the apparent power is called the power factor and is usually expressed in percent.

Example:
A 220-volt AC motor takes 50 amperes from the line, but a watt meter 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
(PF) = Watts (True Power) × 100 VA (Apparent Power)
(PF) = 9 350 × 100
11 000
(PF) = 85 or 85%

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 ____________________.

Question: 14-4
What 3 factors make up impedance?

Question: 14-5
In a series AC circuit, as resistance increases what is the effect on impedance?

Question: 14-6
What is the difference between true power and apparent power?

ANSWERS

Answer: 14-1
impedance.

Answer: 14-2
Resonant frequency.

Answer: 14-3
true power.

Answer: 14-4
Resistance, inductive reactance, capacitance.

Answer: 14-5
Impedance increases proportionally.

Answer: 14-6
Apparent power is the power available in an AC circuit. True power is the power actually used in the circuit.

ELECTRICAL FUNDAMENTALS

TRANSFORMERS

SUB-MODULE 15

PART-66 SYLLABUS LEVELS

	CERTIFICATION CATEGORY → B1	B2
Sub-Module 15 TRANSFORMERS Knowledge Requirements		
3.15 - Transformers 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

3.15 - TRANSFORMERS

TRANSFORMER CONSTRUCTION AND OPERATION

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.

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.

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

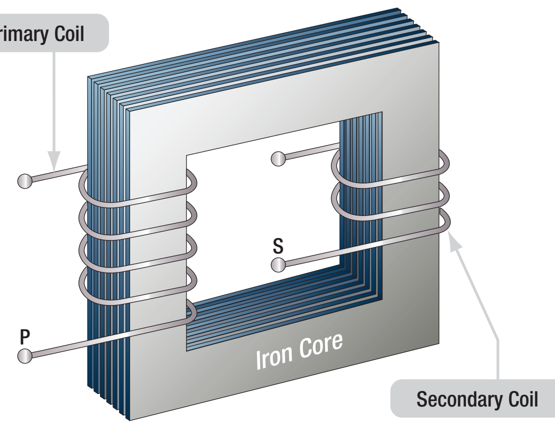


Figure 15-1. An iron-core transformer.

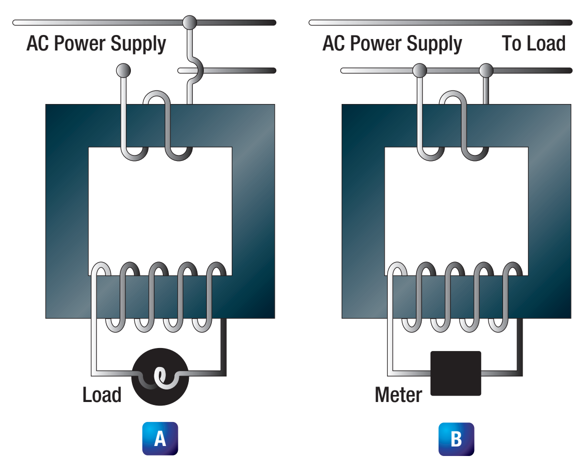


Figure 15-2. Voltage and current transformers.

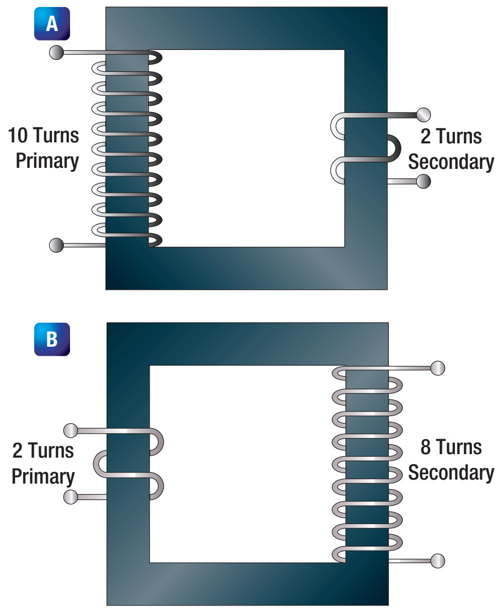


Figure 15-3. A step-down and a step-up transformer.

Figure 15-4. Power supply transformer.

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. Auto-transformers are normally used in power circuits; however, they may be designed for other uses. Two different symbols for auto-transformers 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.

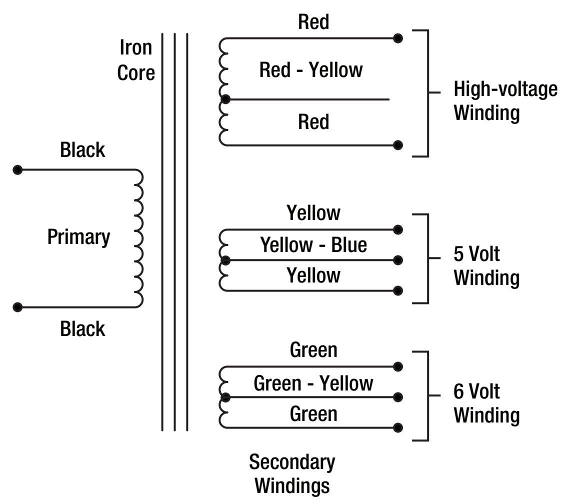


Figure 15-5. Schematic symbol for an iron-core power transformer.

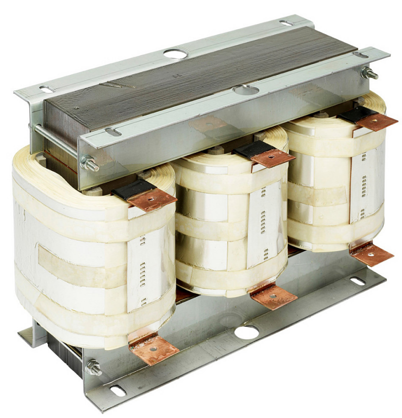


Figure 15-6. An air-core transformer.

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

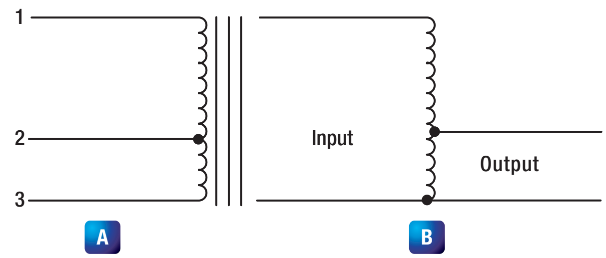


Figure 15-7. Autotransformers.

No transformer can be constructed that is 100 percent efficient, although iron-core transformers can approach this threshold. 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.

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 "H_1" and "H_2" on the unit base. The transformers must be installed with the "H_1" 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 AND METHODS TO OVERCOME THEM

Transformer losses are solely electrical losses (as there are no moving parts in a transformer). They consist of copper and core (iron) losses.

CORE LOSSES

Core losses are divided into Hysteresis losses and Eddy current losses.

- Eddy Currents result from magnetic flux inducing EMF in other parts such as steel or iron core components of the transformer body. Small circulating eddy currents result in energy dissipating as heat. In large power transformers this loss factor can be critical in terms of heat build up resulting sometimes in fire hazards. The core is made up of thin sheet laminations with each sheet separated by lacquer or oxide materials which assists in reducing these currents.
- Hysteresis losses result from the electrical energy required to reverse magnetization (magnetic domains being reversed) of the core during each cycle. Ideal core material having low reluctance, such as iron, or grain oriented steel, and high density cores help to reduce these losses. Stray magnetic flux (that does not link the primary and secondary windings) also contributes to hysteresis losses.

In the construction of high frequency transformers, eddy current losses are reduced by using a core made of a ceramic material containing a large proportion of tiny metal particles; iron dust or manganese zinc. The ceramic insulates the metal particles from each other, giving a similar effect to laminations; performance is better at high frequencies. Frequency harmonic voltages can cause high core losses; reducing these harmonics assists in alleviating these losses.

COPPER LOSSES

Copper losses (so termed as most transformer windings are manufactured from copper) are caused by the ohmic resistance of the primary and secondary windings (I^2R losses). These losses are directly dependent on the transformer load. Increasing transformer load increases current flow and thus results in increase of losses.

Copper losses become very important at high power levels; they're reduced by methods such as: increasing operating voltages; shunt compensation; and balancing loads. Any frequency harmonics currents result in small copper loss increases. Typical losses in power transformers are 3 percent; meaning that transformer efficiency is approximately 97 percent.

TRANSFORMER ACTION

Transformer action varies under load and no-load conditions. In ideal conditions of zero losses, the power in both primary and secondary windings will be the same. With no load, secondary current will be zero, and so secondary power will be zero. With a voltage applied to the primary, no current will flow as the primary power will also be zero. In practice though, with the inherent small losses, there will be a very small primary current to produce the magnetic flux and by the inherent losses. Core losses vary little under load and no-load conditions.

TRANSFORMER ACTION UNDER LOAD AND NO-LOAD CONDITIONS

TRANSFORMER NO-LOAD CONDITION

When describing transformer loading, first let's look at what happens when it is in a no-load condition; that is with no-load connected to its secondary winding and so no secondary current flowing. In other words, nothing is attached and the transformer loading is zero. When an AC supply is connected to the primary winding of a transformer, a small current (I_O) will flow through the primary coil due to the presence of the primary voltage. With the secondary circuit open, (nothing is connected), a back EMF along with the primary winding resistance acts to limit the flow of this primary current. This no-load primary current must only be sufficient to maintain enough magnetic field to produce the required back EMF. Consider the circuit in ***Figure 15-8***.

The ammeter indicates a small current flowing through the primary winding even though the secondary circuit is open. This no-load primary current is made up of two components:

- An in-phase current which supplies the core losses (eddy current and hysteresis).
- A small current which sets up the magnetic flux.

Note that this no-load current is very small compared to the transformer's normal full-load current. Also due to the iron losses in the core as well as a small amount of copper losses in the primary winding, there will be some small phase angle difference.

TRANSFORMER ON-LOAD CONDITION

When an electrical load is connected to the secondary winding and the transformer loading is greater than zero, a current flows out to the load. This secondary current is due to the induced secondary voltage, set up by the magnetic flux in the core from the primary current. The secondary current, (Is) which is determined by the characteristics of the load, creates a self induced secondary magnetic field, (ΦS) in the transformer core which flows in the opposite direction to the main primary field, (Φp). These two magnetic fields oppose each other resulting in a combined field of less strength than the single field produced by the primary winding alone when the secondary circuit was opened. This combined magnetic field reduces the back EMF of the primary winding causing the primary current, (Ip) to increase slightly. The primary current continues to increase until the core's magnetic field is back at its original strength. For a transformer to operate correctly, a balanced condition must exist between the primary and secondary magnetic fields. This results in the power to be balanced and the same on both the primary and secondary sides. Consider the circuit shown in ***Figure 15-9***.

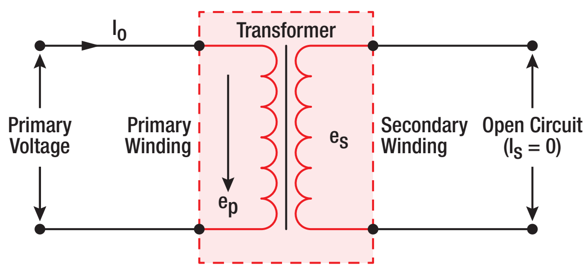


Figure 15-8. Transformer at no-load condition.

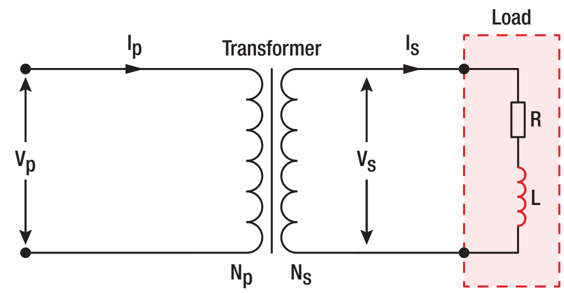


Figure 15-9. Transformer on-load condition.

TRANSFORMER POLARITY

Transformer Polarity refers to the relative direction of the induced voltages between the high and low voltage terminals. During the AC half-cycle, when the applied voltage (or current in the case of a current transformer) is from H_1 to H_2 the secondary induced voltage direction will be from X_1 to X_2.

POLARITY MARKINGS

The position of the high voltage bushings is standardized on all power and instrument transformers. The rule is: when facing the low voltage bushings, the primary bushing H_1 is always on the left hand side and the primary bushing H_2 is on the right hand side (if the transformer is a three-phase unit, H_3 will be to the right of H_2). When only one lead of the high voltage winding is brought out it is designated as H_1. For polarity marking, the H_1 terminal shall always be located on the left when facing the front side of the transformer. (***Figure 15-10***)

CALCULATION OF LINE AND PHASE VOLTAGE, AND CURRENT

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:

$$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$

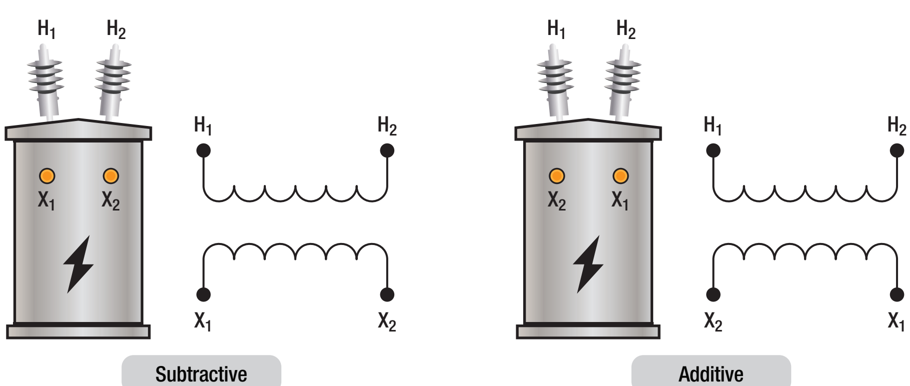


Figure 15-10. Transformer polarity markings.

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:

$$E_2 = \frac{E_1 N_2}{N_1}$$

Transformer current can be calculated using the formula:

$$\frac{N_S}{N_P} = \frac{I_P}{I_S}$$

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.

Three phase voltage supplies are utilized where large power applications are required. More efficient machines can be designed that require three phase AC power. These machines take up less space and are lighter in weight than equivalent machines that would have just a single phase supply to perform the same function. Large airliner AC Generators are nearly always three phase brushless machines.

Three phase transformers are needed to raise and lower voltages over transmission lines; to change the winding configurations; and to split and combine single and three phases. There are two configurations: Delta and Wye (Wye is sometimes referred to as Star configuration). (***Figure 15-11***) The voltage references for Star and Delta configurations, with respect to ***Figure 15-12***.

The relationship between Phase and Line voltage is:

$$V_{phase} = \sqrt[3]{V_{line}}$$

POWER CALCULATIONS IN A THREE PHASE SYSTEM

Most three phase power ratings are expressed in: kilo-volt-amps, or KVA for short. The KVA rating does not take in account the Power Factor (PF) of the output; it is a direct multiplication of voltage and current. It can be termed as "active power".

The output is usually calculated if kilo-watts (KW); this takes into account the PF of the output load.

$$KW = V \times I \times PF$$

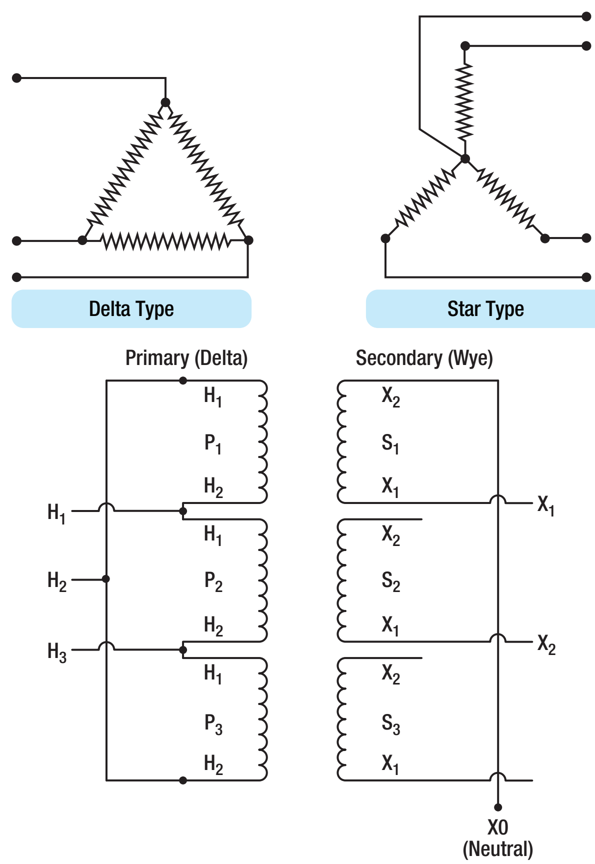


Figure 15-11. The voltages: A-neutral, B-neutral; C-neutral are Phase Voltages.

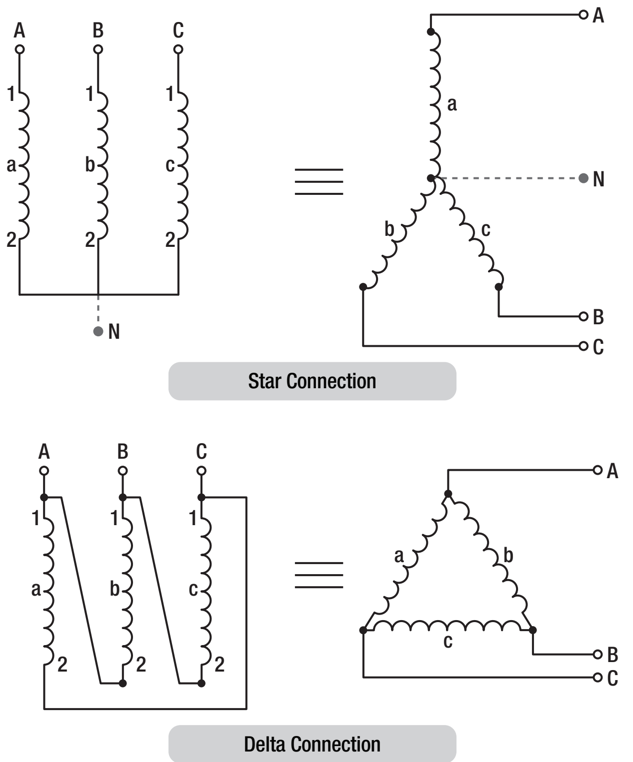


Figure 15-12. The voltages: A-B; A-C; B-C are Line Voltages.

The PF (a value less than unity, or ideally 1) results from any reactive loads that cause phase differences between the voltage and current. It is generally indeterminate in most practical applications. The KW rating can be termed "reactive power".

Power ratings are given to determine the maximum current (hence maximum load) that the system can use.

For single phase: KVA = (V × I) ÷ 1000

For three phase: KVA = (1.732 × V × I) ÷ 1000

Where: **V** is the PHASE VOLTAGE.

Power transformers have maximum power ratings–any excessive loads can cause the transformer to overheat and it can be in a dangerous state.

Generators are generally rated in KVA.

AUTO TRANSFORMERS

An auto transformer (sometimes called a step down transformer) is a transformer with only one winding. ***Figure 15-13***. Portions of the same winding act as both the primary and secondary sides.

Since part of the winding does double-duty, autotransformers have the advantages of being smaller, lighter, and cheaper than typical dual winding transformers, but have the disadvantage of not providing electrical isolation between the primary and secondary circuits. Other advantages include lower leakage, lower losses, lower excitation current, and increased V/A rating for a given size and mass.

Auto transformers are often used to step up or step down voltages in the 110-120 volt range and voltages in the 220-240 volt range. This allows equipment designed for 110V to be used with a 230V supply or vice-versa.

An auto transformer has a single winding with two end terminals, plus one or more terminals at intermediate tap points. The primary voltage is applied across two of the terminals, and the secondary voltage taken from two terminals, with one terminal in common with the primary voltage.

OPERATION OF AUTO TRANSFORMERS

One end of the winding is usually connected in common to both the voltage source and electric lead. The other end of the source and load are connected to taps along the winding. Different taps correspond to different voltages. In a step down transformer the source is usually connected across the entire winding while the load is connected by a tap across only a portion of the winding.

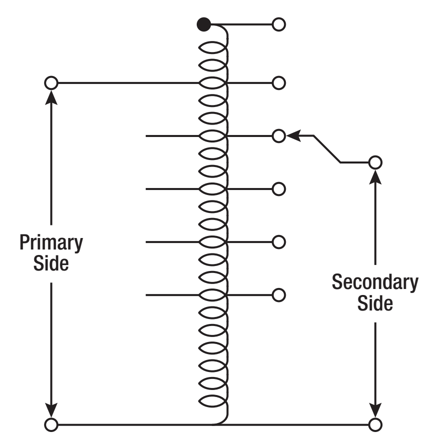


Figure 15-13. Autotransformer.

In a step-up transformer, conversely, the load is attached across the full winding while the source is connected to a tap across a portion of the winding.

As in a two winding transformer, the ratio of secondary to primary voltages is equal to the ratio of the number of turns of the winding they connect to. For example, connecting the load between the middle and bottom of the auto transformer will reduce the voltage by 50%. Depending on the application, that portion of the winding which is used solely in the higher voltage (lower current) portion may be wound with wire of a smaller gauge, though the entire winding is directly connected.

Question: 15-1
Name the three parts of a basic transformer.

Question: 15-2
Name 3 types of transformers.

Question: 15-3
True or false: There cannot be more power in the secondary side of a transformer than there is in the primary.

ANSWERS

Answer: 15-1
Primary coil.
Secondary coil.
Core.

Answer: 15-2
Power.
Audio.
RF.
Auto-transformers.

Answer: 15-3
True.

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

3.16 - FILTERING

OPERATION, APPLICATION, AND USES OF FILTERS

One of the more common uses of the capacitor and inductor that the technician may find in the field is that of the filter. Ideally, filters do not add or change frequencies to the input signal, but they will change the relative amplitudes of the various frequency components and/or their phase relationships. Filters are often used in electronic systems to emphasize signals in certain frequency ranges and reject signals in other frequency ranges.

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 C_1 is connected in parallel with the load R_1. The capacitor C_1 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 C_1 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 R_1 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 wave shape is shown in ***Figure 16-4***.

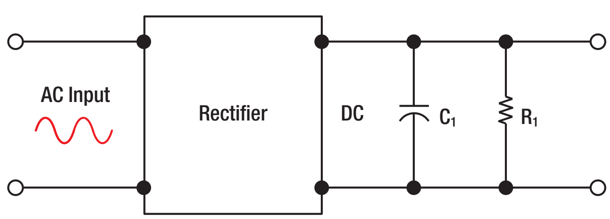


Figure 16-1. A capacitor used as a filter.

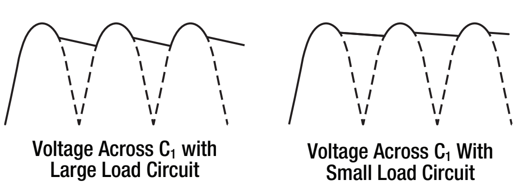


Figure 16-2. Half-wave and full-wave rectifier outputs using capacitor filter.

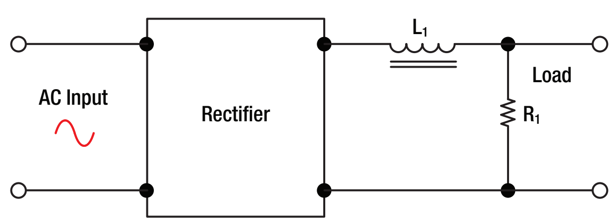


Figure 16-3. An inductor used as a filter.

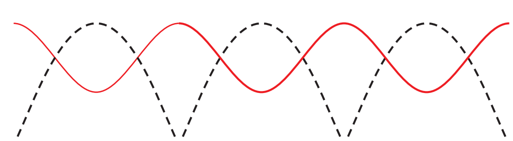


Figure 16-4. Output of an inductor filter rectifier.

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***.

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.

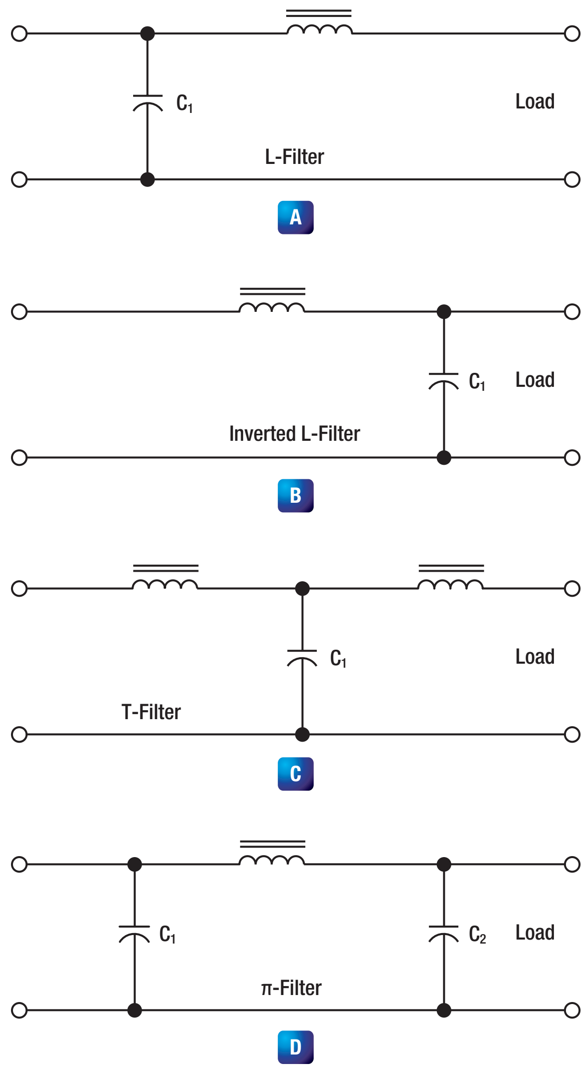


Figure 16-5. LC filters.

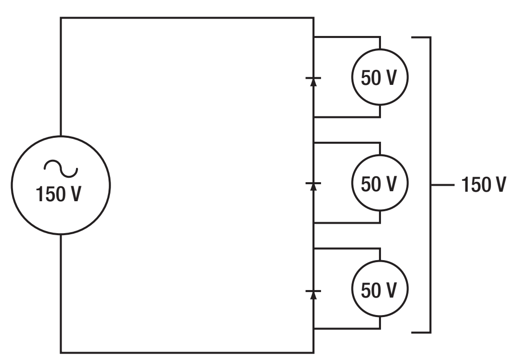


Figure 16-6. Stacking diodes in a circuit.

FILTERS

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.

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.

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-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

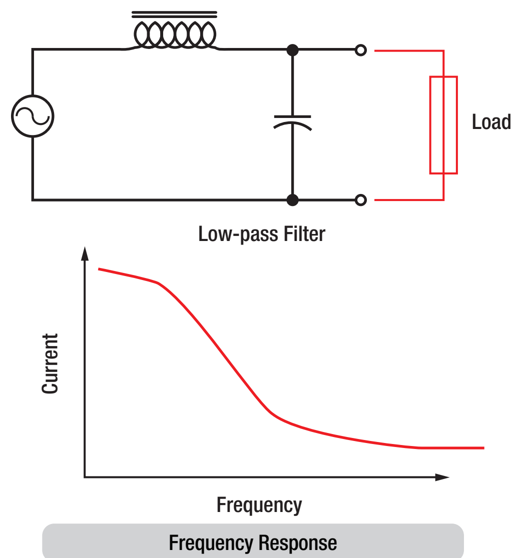


Figure 16-7. Low-pass filter.

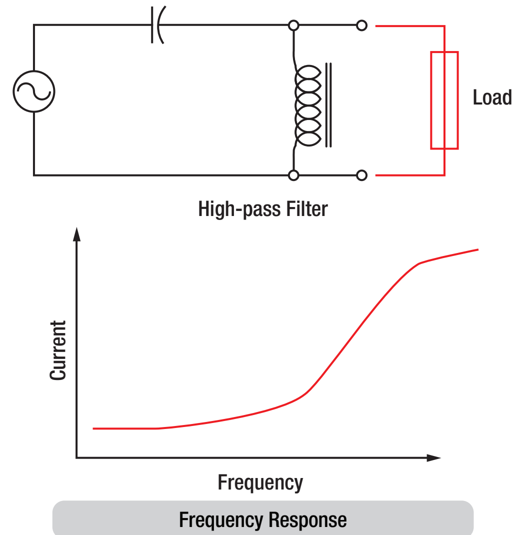


Figure 16-8. High-pass filter.

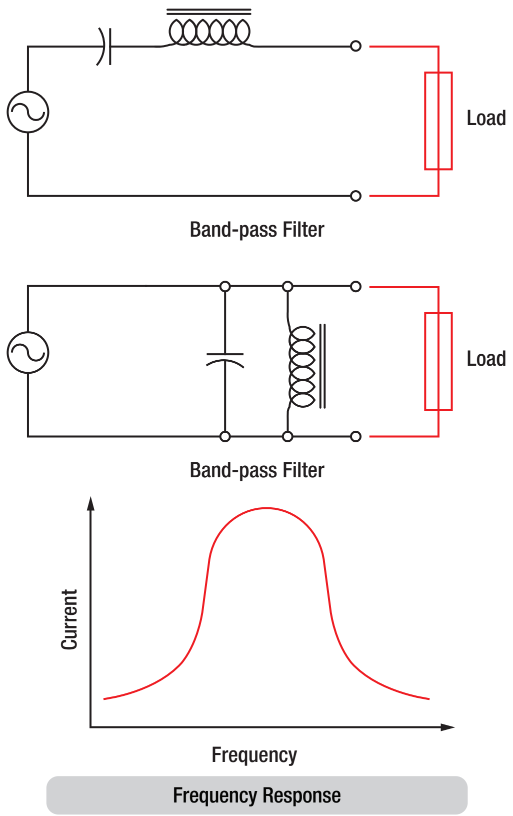


Figure 16-9. Band-pass filter.

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.

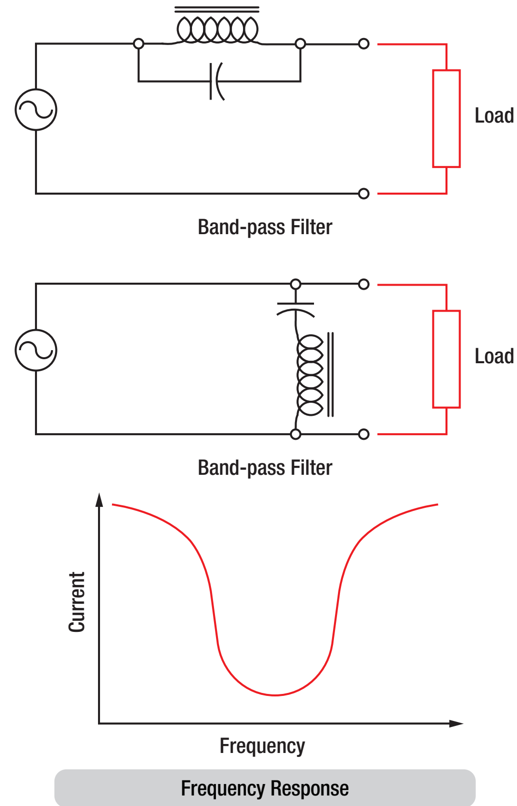


Figure 16-10. Band-stop filter.

Question: 16-1
Capacitance _________________ a voltage change across its terminal by storing energy in its electrostatic field.

Question: 16-2
_________________ and _________________ are combined in various ways to provide more satisfactory filtering than can be obtained with a single capacitor or inductor.

Question: 16-3
A high-pass filter passes high frequencies well but _________________ frequencies lower than the cutoff frequency.

Question: 16-4
A filter in which the signal passes through an inductor is considered a _________________?

ANSWERS

Answer: 16-1
opposes.

Answer: 16-2
Capacitors, inductors.

Answer: 16-3
attenuates (reduces).

Answer: 16-4
Low-pass filter.

ELECTRICAL FUNDAMENTALS

AC GENERATORS

SUB-MODULE 17

PART-66 SYLLABUS LEVELS CERTIFICATION CATEGORY →	B1	B2
Sub-Module 17 AC GENERATORS Knowledge Requirements		
3.17 - AC Generators 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

AC GENERATORS

3.17 - AC GENERATORS

ROTATION OF LOOP IN A MAGNETIC FIELD AND WAVEFORM PRODUCED

Electromagnetic induction occurs when electricity is created by moving a conductor through a magnetic field. It can also occur when a magnet field passes through a conductor. To create electricity in a DC generator, the conductor is rotated and the field is held. In an alternator, the conductor is held stationary and the field is rotated. These principles are described in detail in *Sub-module 13* of this book.

OPERATION AND CONSTRUCTION OF REVOLVING ARMATURES AND FIELD AC GENERATORS

ALTERNATORS & CLASSIFICATION

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 Classification

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 and 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 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

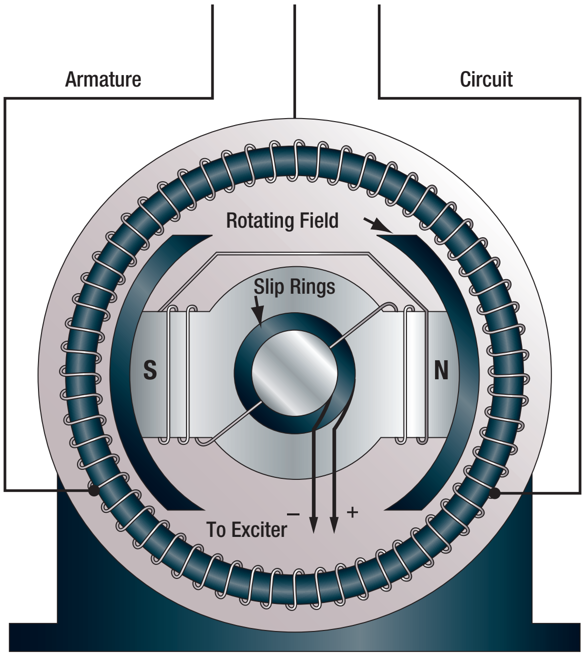


Figure 17-1. Alternator with stationary armature and rotating field.

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.

ALTERNATOR RATINGS

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:

$$\frac{12 \times 4\,000}{120} = 400 \text{ cps}$$

AC GENERATORS

PHASES CATEGORIES AND OTHER ALTERNATOR TYPES

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 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.

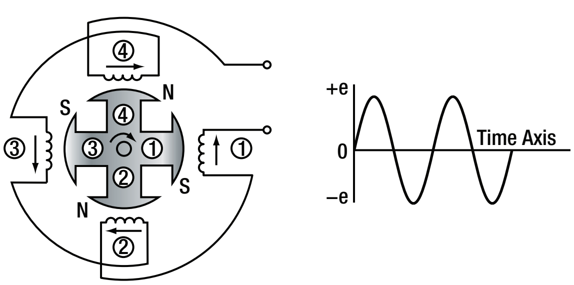


Figure 17-2. Single phase alternator.

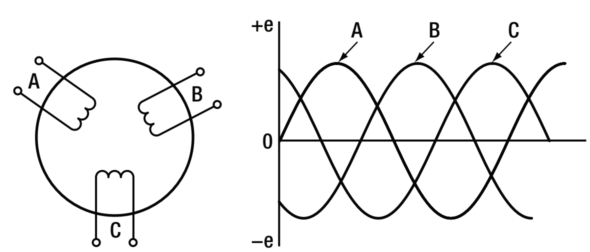


Figure 17-3. Simplified schematic of three phase alternator with output waveforms.

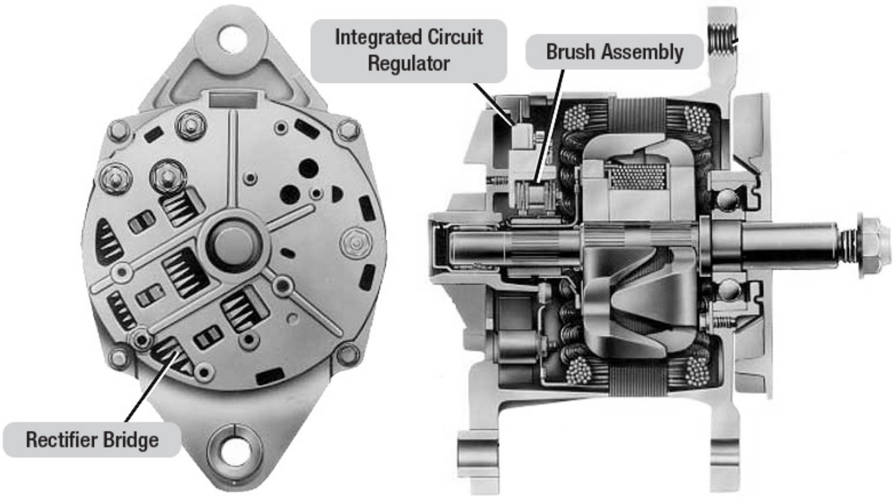


Figure 17-4. Exploded view of alternator rectifier.

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 17-4***. 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 system incorporating a three phases, full-wave bridge rectifier. (***Figure 17-5***) 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.

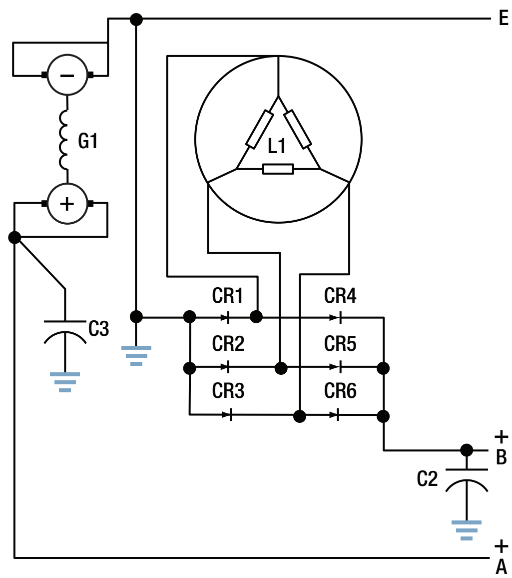


Figure 17-5. Wiring diagram of alternator-rectifier unit.

THREE PHASE START AND DELTA CONNECTION ADVANTAGES AND USES

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 17-6A***) 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.

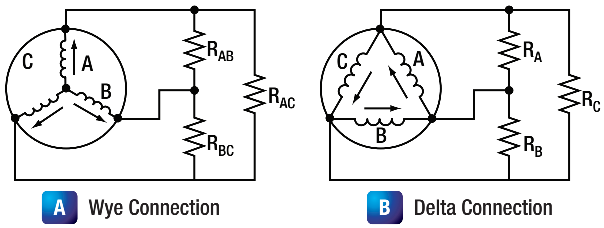


Figure 17-6. Wye and delta connected alternators.

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 17-6B***. 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 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.

PERMANENT MAGNET GENERATORS AND BRUSHLESS ALTERNATORS

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 kilo-volt-amperes (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.

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 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

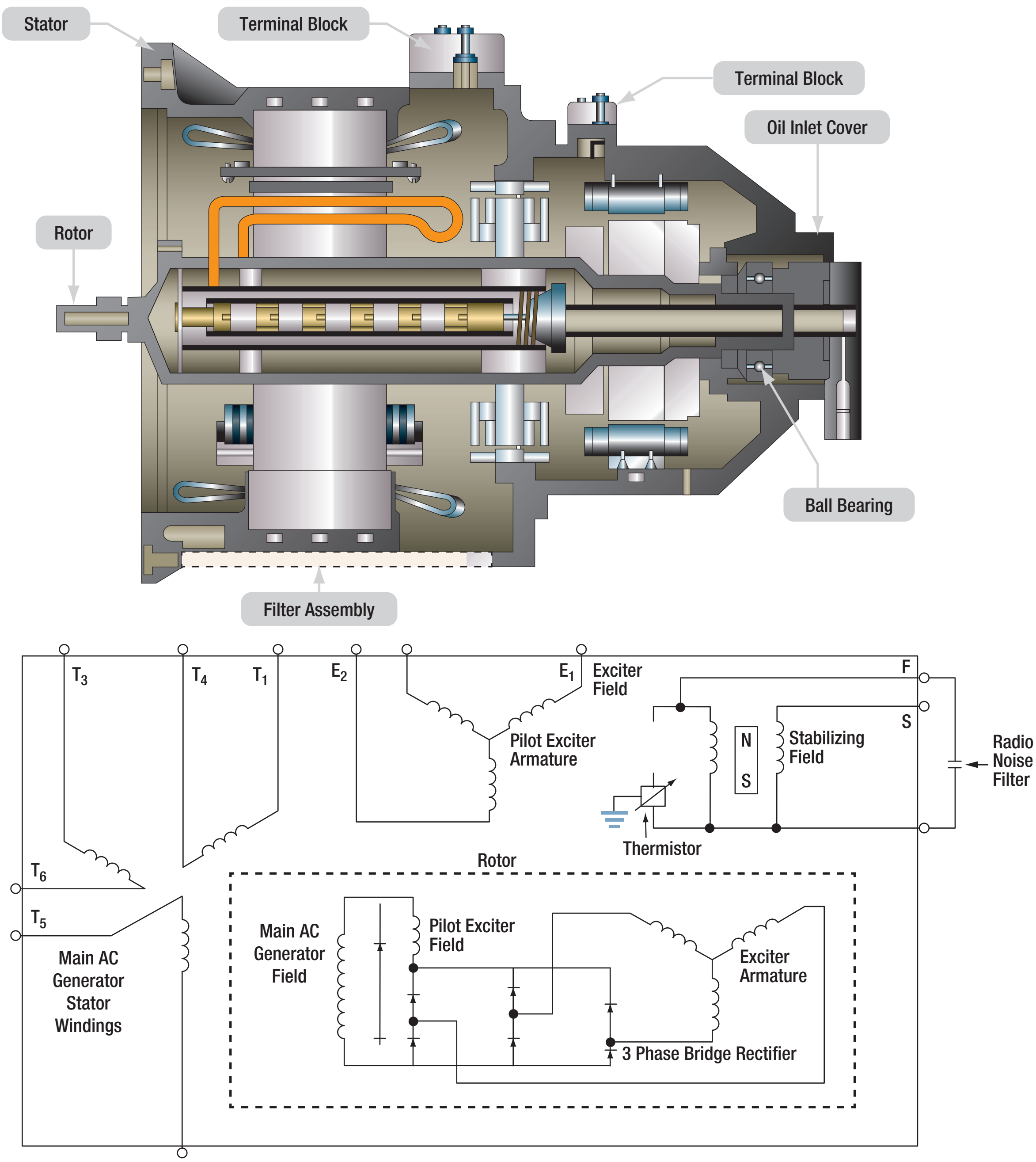


Figure 17-7. A typical brushless alternator.

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.

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 multirange ohmmeter, a multirange combination AC/DC voltmeter, an ammeter with a clip on current transformer, a vibrating reed type frequency meter, and an unmounted continuity light.

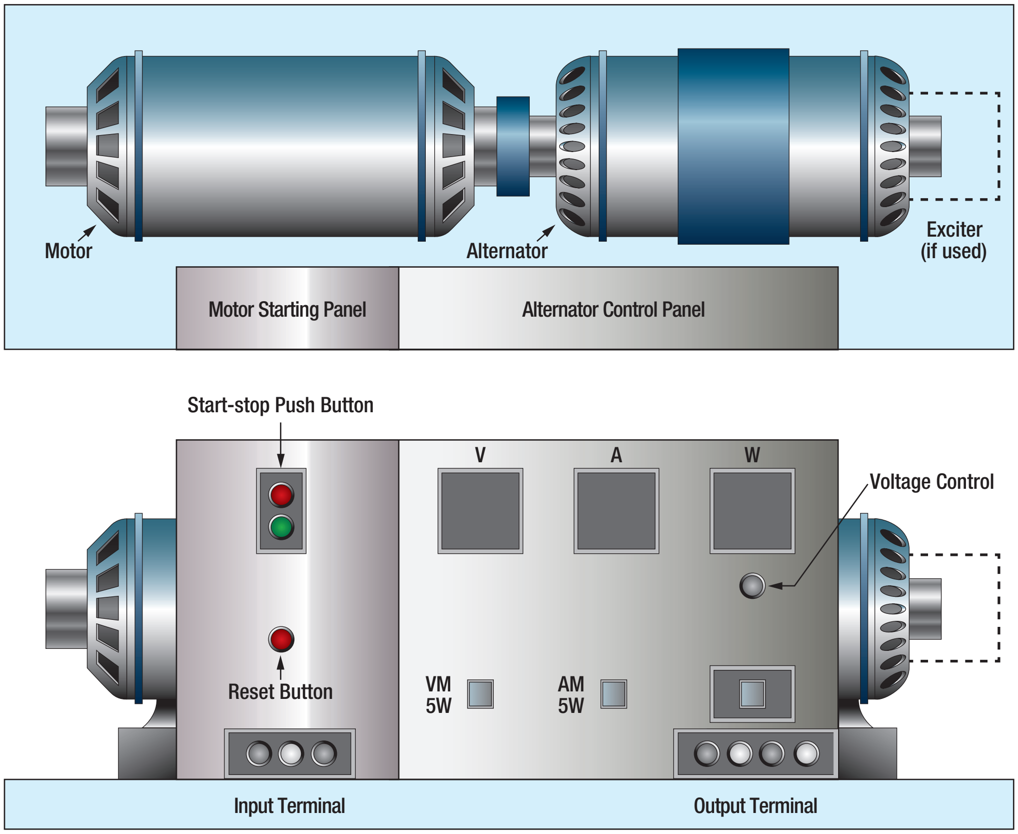


Figure 17-8. AC motor generator set for ground testing.

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.

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
What are two advantages of a permanent magnet alternator in aviation?

Question: 17-5
Name the three principle ways to classify alternators.

Question: 17-6
What two factors determine the frequency of the output of an alternator?

ANSWERS

Answer: 17-1
the method of connection to the external circuit;
slip rings - AC, commutator -DC

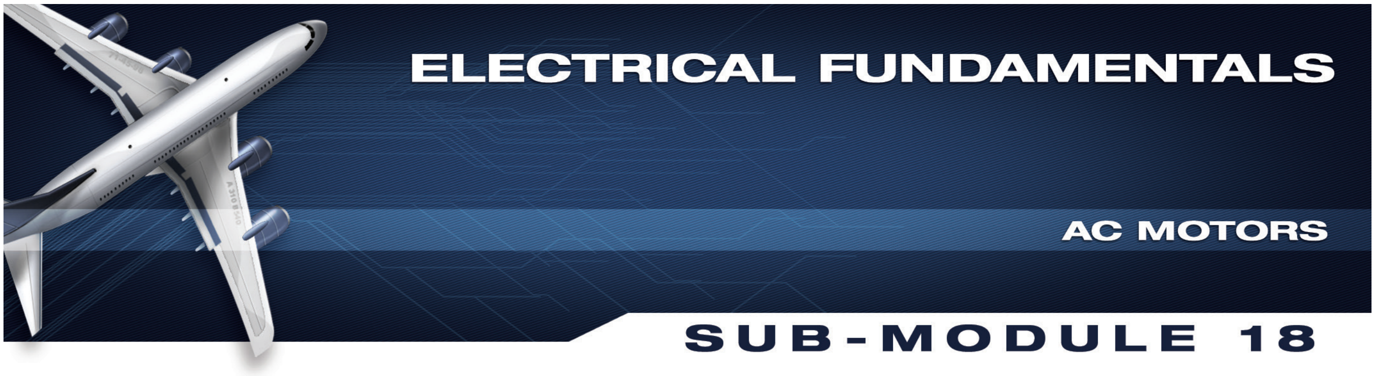
Answer: 17-2
120°

Answer: 17-3
Speed of rotation.
Number of poles.

Answer: 17-4
Reduced maintenance (no brushes to wear);
no electrical arcing at high altitudes.

Answer: 17-5
Method of excitation, number of phases, revolving armature versus revolving field type.

Answer: 17-6
The number of poles, and the rpm of the rotor.



SUB-MODULE 18

PART-66 SYLLABUS LEVELS		
CERTIFICATION CATEGORY →	B1	B2
Sub-Module 18 AC MOTORS Knowledge Requirements		
3.18 - AC Motors 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

3.18 - AC MOTORS

CONSTRUCTION AND PRINCIPLES OF INDUCTION AND SYNCHRONOUS 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:

$$\text{rpm} = \frac{120 \times \text{Frequency}}{\text{Number of Poles}}$$

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.

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.

INDUCTION MOTORS

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

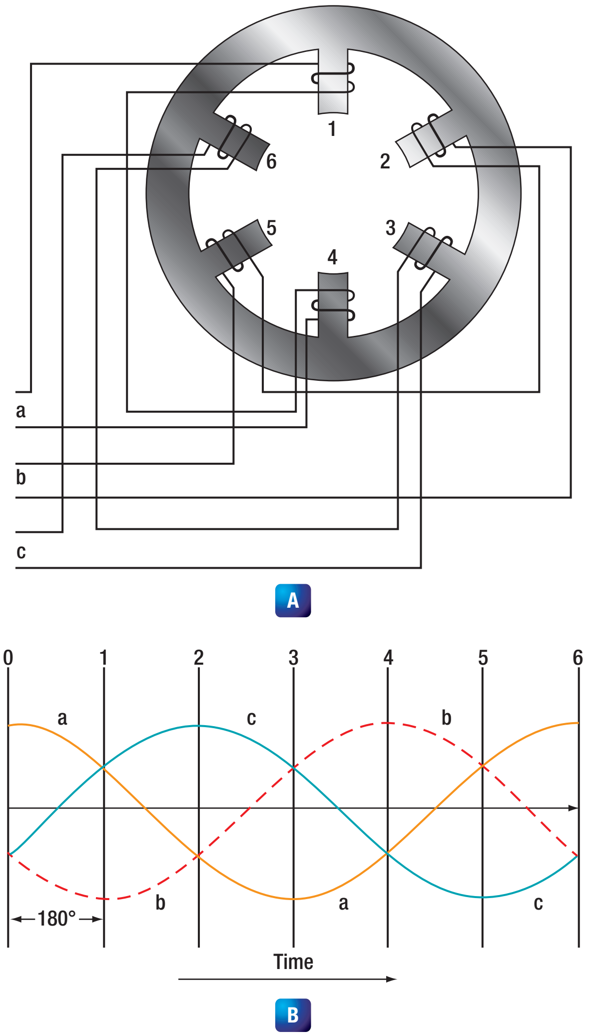


Figure 18-1. Rotating magnetic field developed by application of three phase voltages.

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***)

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.

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

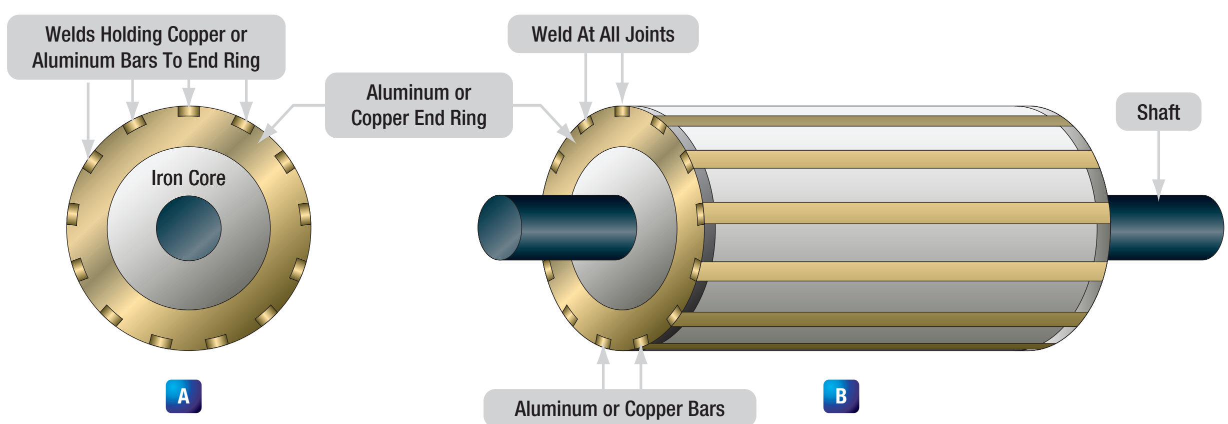


Figure 18-2. Squirrel cage rotor for an AC induction motor.

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.

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 18-3***. 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 18-3*** 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

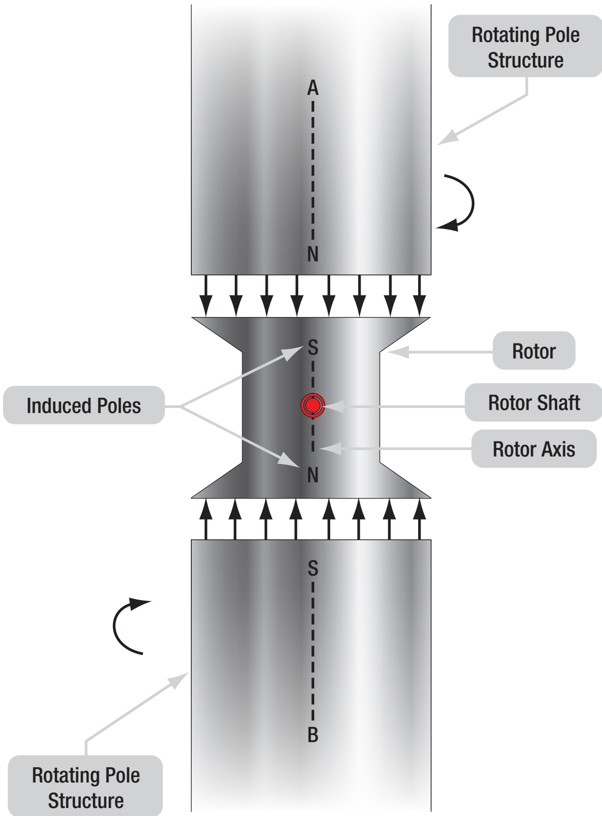


Figure 18-3. Illustrating the operation of a synchronous motor.

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 18-4*** 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.

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.

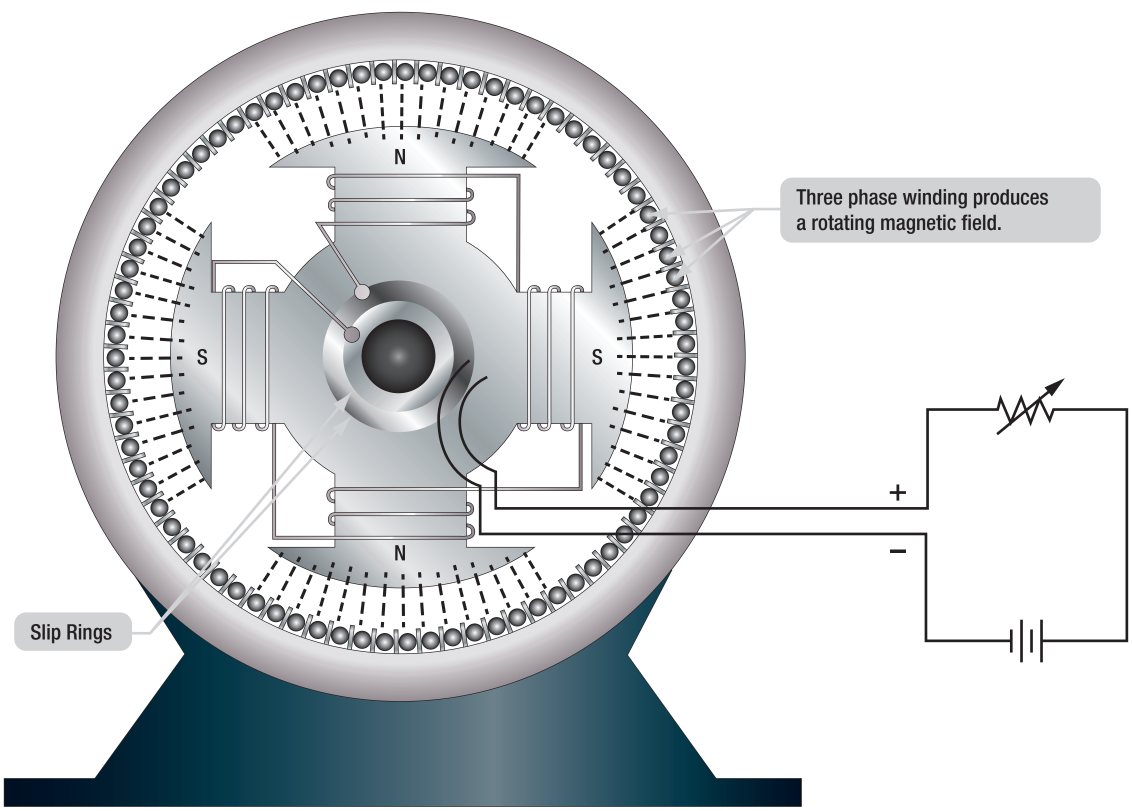


Figure 18-4. Synchronous motor.

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.

SPEED CONTROL AND DIRECTION OF ROTATION

MOTOR SPEED CONTROL

Single phase motors are not normally speed or direction controlled.

Two phase motor control uses reference and a control phase winding. The control winding input can be varied in amplitude and could either lag or lead the reference input so that speed and direction of rotation can be changed.

Three phase motors rely on changing over any two windings, clockwise or counter-clockwise, to reverse the direction of rotation.

Speed can be adjusted by the physical or electrical removal or addition, (usually through relay control), of any pair windings. Reducing the pairs of poles to increase the speed and increasing the pairs of poles to reduce the speed.

Motor speed can also be controlled by varying the current in the field windings. When the amount of current flowing through the 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. Both shunt and series motors may be speed controlled. In the shunt motor, speed is controlled by a rheostat in series with the field windings. (***Figure 18-5***) The speed depends on the amount of current flowing through the rheostat to the field windings.

To increase 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 the counter EMF. This momentarily increases the armature current and the torque. The motor will then 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.

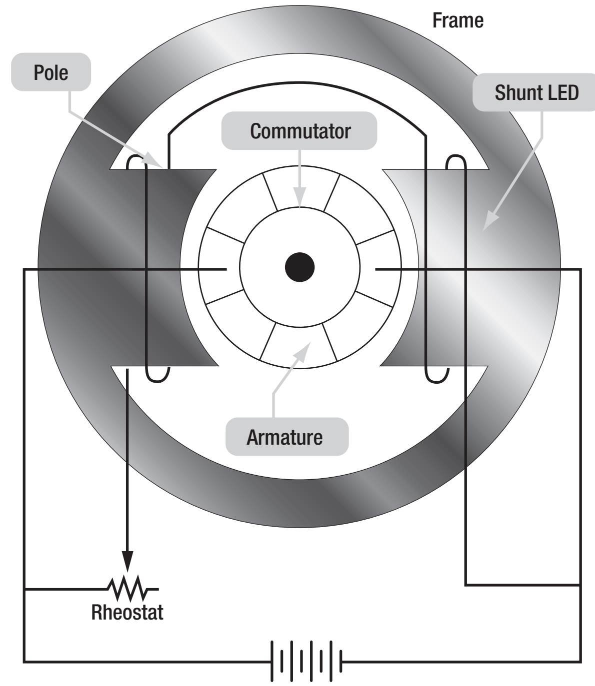


Figure 18-5. Shunt motor with variable speed control.

To decrease speed, the resistance of the rheostat is decreased. More current flows through the field windings and increases the strength of the field. The counter EMF then increases momentarily and decreases the current. As a result, torque decreases and the motor slows down.

DIRECTION OF ROTATION

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.

PRODUCING A ROTATING FIELD; CAPACITOR, INDUCTOR, SHADED OR SPLIT POLE DESIGNS

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 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 3 600 rpm. This speed is known as the synchronous speed of the rotating field.

SHADED POLE INDUCTION MOTORS

The first effort in the development of a self-starting, single-phase motor was the shaded pole induction motor. (***Figure 18-6***)

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

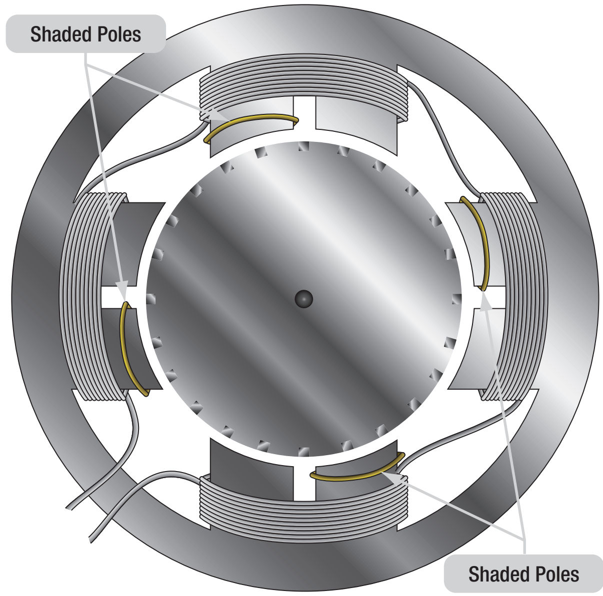


Figure 18-6. Shaded pole induction motor.

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 18-7***, 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 18-7***.

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

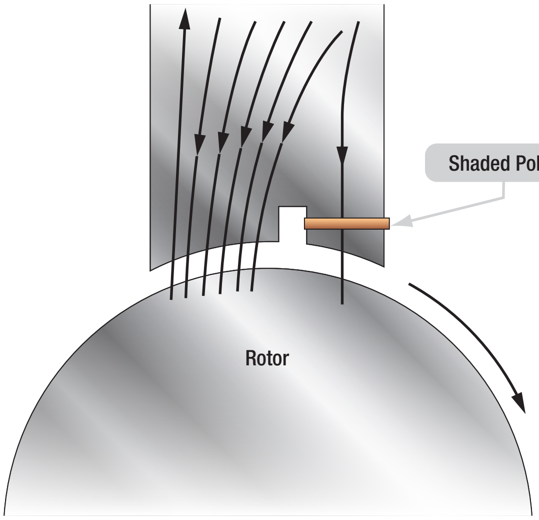


Figure 18-7. Diagram of a shaded pole motor.

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 MOTORS

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 MOTORS

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 18-8***)

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

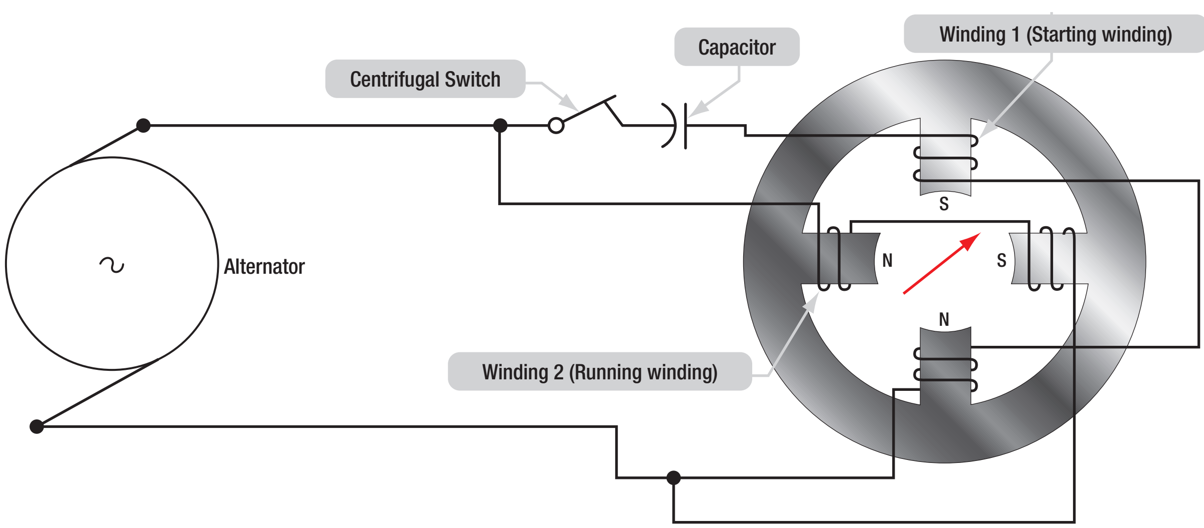


Figure 18-8. Single phase motor with capacitor starting winding.

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.

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 18-9***, the armature is conductively compensated.

If the compensating winding is designed as shown in ***Figure 18-10***, 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 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.

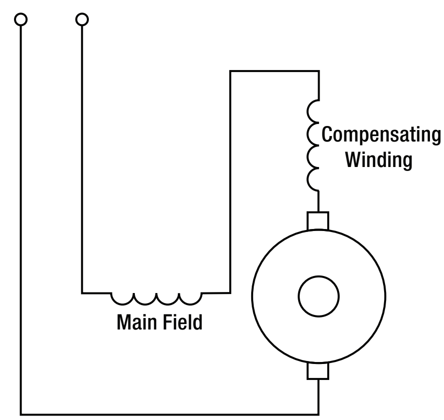


Figure 18-9. Conductivity compensated armature of AC series motor.

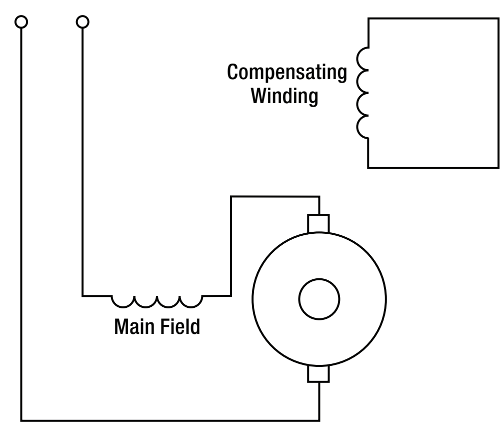


Figure 18-10. Inductively compensated armature of AC series motor.

Sparking at the commutator is reduced by the use of preventive leads P1, P2, P3, and so forth, as shown in ***Figure 18-11***, 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.

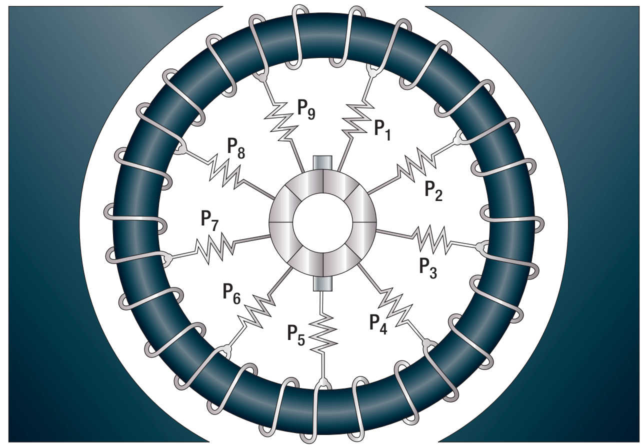


Figure 18-11. Preventive coils in AC series motor.

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.

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.

A	/	Ampere
AC	/	Alternating Current
AMC	/	Acceptable Means of Compliance
BITE	/	Built in Test Equipment
C	/	Coulombs
CD	/	Cadmium
CPS	/	Constant Speed Drive
DC	/	Direct Current
E	/	Voltage
EASA	/	European Aviation Safety Agency
EC	/	European Commission
EMF	/	Electro Magnetic Field
ESD	/	Electro Static Discharge
ESP	/	Electrostatic Precipitator
FAA	/	Federal Aviation Administration
G	/	Conductance
GCU	/	Generator Control Unit
GM	/	Guidance Material
H	/	Henrys
HPF	/	High-pass Filter
HZ	/	Hertz
I	/	Current
IR	/	Insulation Resistance
KOH	/	Potassium Hydroxide
KVA	/	Kilovoltamperes
KWH	/	Kilowatt-hour
L	/	Inductance
LC	/	Load Capacity
LRU	/	Line Replaceable Unit
MH	/	Mutual Induction
PA	/	Pascal Unit
PSI	/	Pounds Per Square Inch
Q	/	Charge in Coulombs
R	/	Resistance
RF	/	Radio Frequency
RL	/	Load Resistance
RMS	/	Effective Value
RPM	/	Revolutions Per Minute
SI	/	International System of Units
SLA	/	Sealed Lead Acid
T	/	Teslas
UH	/	Microhenries
UHF	/	Ultra High Frequency
WS	/	Watt-second
XC	/	Capacitive Reactance

# #

A

B

C

K

L

M

N

O

P

R

S