FM 55-509-1

INTRODUCTION TO MARINE ELECTRICITY

HEADQUARTERS, DEPARTMENT OF THE ARMY

Field Manual
No. 55-509-1

HEADQUARTERS
DEPARTMENT OF THE ARMY
Washington, DC, 1 September 1994

INTRODUCTION TO MARINE ELECTRICITY

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PREFACE

This manual is an electrical reference text for the marine engineering field. It provides information for the 88L10, 88L20, 88L30, 88L40, 881A1, and 881A2 military occupational specialties (MOSs).

This text reinforces good marine electrical practices. A good knowledge of marine electricity helps maintain the health and welfare of the crew by promoting the safe operation of the many electrical systems on board a vessel.

This manual covers marine electrical safety and alternating current (AC) and direct current (DC) fundamentals. It details the vessel distribution system as well as circuit protection and the electrical motor load. This information corresponds with the program of instruction presented to the marine engineering students at Fort Eustis.

The marine engineer must understand the entire production, distribution, and user end of the electrical process. He will be required to maintain and overhaul all the electrical apparatus for safely operating the vessel.

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Unless this publication states otherwise, masculine nouns and pronouns do not refer exclusively to men.

CHAPTER 1

SAFETY

INTRODUCTION

Successfully completing everyday activities depends on safe execution. Preparation and conduct during these activities reflects on performance. In no other field is this more significant than in the marine field.

Safety is an encompassing subject. This text does not repeat existing electrical safety practices outlined in other references. Instead it emphasizes those standards necessary to successfully complete Army watercraft missions.

Current is the measure of shock intensity. The passage of even a very small current through a vital part of the human body can kill. At about 100 milliamperes (0.1 ampere), the shock is fatal if it lasts for one second or more. Fatalities have resulted from voltages as low as 30 volts.

Conditions on board a vessel add to the chance of receiving an electrical shock. The body is likely to be in contact with the metal structure of the vessel. The body's resistance may be low because of perspiration or damp clothing. Personnel must be aware that electrical shock hazards exist.

Accidentally placing or dropping a metal tool, ruler, flashlight case, or other conducting article across an energized terminal can cause short circuits. The resulting arc and fire, even on relatively low-voltage circuits, may extensively damage equipment and seriously injure personnel.

Touching one conductor of an ungrounded electrical system while the body is in contact with the hull of the ship or other metal equipment enclosures could be fatal.

WARNING

Treat all energized electric circuits as potential hazards at all times.

DANGER SIGNALS

Be constantly alert for any signs that might indicate a malfunction of electrical equipment. When any danger signals are noted, report them immediately to the chief engineer or electrical officer. The following are examples of danger signals:

- Fire, smoke, sparks, arcing, or an unusual sound from an electric motor or contactor.
- Frayed and damaged cords or plugs.
- Receptacles, plugs, and cords that feel warm to the touch.
- Slight shocks felt when handling electrical equipment.
- Unusually hot running electric motors and other electrical equipment.
- An odor of burning or overheated insulation.
- Electrical equipment that either fails to operate or operates irregularly.
- Electrical equipment that produces excessive vibrations.

CAUTION

Do not operate faulty equipment. Stand clear of any suspected hazard, and instruct others to do likewise.

ELECTRIC SHOCK

Electric shock is a jarring, shaking sensation. Usually it feels like receiving a sudden blow. If the voltage and current are sufficiently high, unconsciousness occurs. Electric shock may severely burn the skin. Muscular spasms may cause the hands to clasp the apparatus or wire making it impossible to let go.

Rescue and Care of Shock Victims

For complete coverage of cardiopulmonary resuscitation (CPR) and treatment of burn and shock victims, refer to *Ship's Medicine Chest and Medical Aid at Sea* from the US Department of Health and Human Services.

The following procedures are recommended for the rescue and care of shock victims:

- Remove the victim from electrical contact at once, but do not endanger yourself. Touching a shock victim who is still in contact with the energized circuit will make you another shock victim. Help the shock victim by de-energizing the affected circuit. Then use a dry stick, rope, belt, coat, blanket, shirt, or any other nonconductor of electricity to drag or push the victim to safety.

- Determine the cardiopulmonary status of the casualty. (Start CPR if spontaneous respiration or circulation is absent.)

- Once the person is stabilized, attend other physical injuries as they would normally be treated. Lay the victim face up in a prone position. The feet should be about 12 inches higher than the head. Chest or head injuries require the head to be slightly elevated. If there is vomiting or if there are facial injuries that cause bleeding into the throat, place the victim on his stomach with his head turned to one side. The head should be 6 to 12 inches lower than the feet.

- Keep the victim warm. The injured person's body heat must be conserved. Cover the victim with one or more blankets, depending on the weather and the person's exposure to the elements. Avoid artificial means of warming, such as hot water bottles.

- Do not give drugs, food and liquids if medical attention will be available within a short time. If necessary, liquids may be administered. Use small amounts of water, tea, or coffee. Never give alcohol, opiates, and other depressant substances.

- Send for medical personnel (a doctor, if available) at once, but do not under any circumstances leave the victim until medical help arrives.

Safety Precautions for Preventing Electric Shock

Observe the following safety precautions when working on electrical equipment:

- When work must be done in the immediate vicinity of electrical equipment, check with the senior engineer responsible for maintaining the equipment to avoid any potential hazards. Stand clear of operating radar and navigational equipment.

- Never work alone. Another person could save your life if you receive an electric shock.

- Work on energized circuits only when absolutely necessary. The power source should be tagged out at the nearest source of electricity for the component being serviced.

- Keep covers for all fuse boxes, junction boxes, switch boxes, and wiring accessories closed. Report any cover that is not closed or that is missing to the senior engineer responsible for its maintenance. Failure to do so may result in injury to personnel or damage to equipment if an accidental contact is made with exposed live circuits.

- Discharge capacitors before working on de-energized equipment. Take special care to discharge capacitors properly. Injury or damage to equipment could result if improper procedures are used.

- When working on energized equipment, stand on a rubber mat to insulate yourself from the steel deck.

- When working on an energized circuit, wear approved electrical insulating rubber gloves. (The rubber gloves used with NBC suits are not acceptable.) Cover as much of your body as practical with an insulating material, such as shirt sleeves. This is especially important when working in a warm space where you may perspire.

- If possible, de-energize equipment before hooking up or removing test equipment.
- When working on energized electrical equipment, work with only one hand inside the equipment. Keep the other hand clear of all conductive materials that may provide a path for current flow.
- Wear safety goggles. Sparks could damage your eyes. The sulfuric acid contained in batteries and the oils in electrical components can cause blindness.
- Ensure that all tools are adequately insulated when working on energized electrical equipment.
- Never work on electrical equipment while wearing rings, watches, identification tags, or other jewelry.
- Never work on electrical equipment while wearing loose-fitting clothing. Be careful of loose sleeves and the battle dress uniform (BDU) shirttails.
- Ensure all rotating and reciprocating parts of the electric motors are adequately protected by guards.
- Remain calm and consider the possible consequences before performing any action.

DAMAGE AND FIRE

Never enter a flooded compartment that has a generator actively producing power. Transfer the load and secure the generator before entering.

Secure power to the affected circuits if there is an electrical fire in a compartment. If critical systems are involved that prevent power from being secured (determined by the chief engineer), extinguish the fire using a nonconducting agent, such as dry chemical, carbon dioxide (CO_2), or halon.

WARNING

The use of water in any form is not permitted.

Carbon dioxide is the choice for fighting electrical fires. It has a nonconductive extinguishing agent and does not damage equipment. However, the ice that forms on the horn of the extinguisher will conduct electricity.

WARNING

Personnel exposed to a high concentration of CO_2 will suffocate.

Burning electrical insulation is toxic and can kill in a matter of moments. Use the oxygen breathing apparatus (OBA) when fighting electrical fires. For more information, refer to ***Marine Fire Prevention, Firefighting and Fire Safety*** from the Maritime Administration.

PORTABLE AND TEMPORARY ELECTRICAL EQUIPMENT

Ensure all electrical extension cords are approved by either the chief engineer or the electrical officer. Never use an extension cord or power hand tool without it being properly grounded. Regularly inspect all extension cords and portable electrical equipment. Ground all metal multimeters and test equipment to the hull. Some military meters have a grounding jack for this connection.

WARNING

An ungrounded portable power tool can kill.

REPAIR SAFETY

Before starting any electrical work, secure the power to the circuit and affix a temporary warning tag to the affected circuit breaker or power source. Check the de-energized circuit with a multimeter. If you must leave the repair and return at a later time, always ensure that the circuit is de-energized before resuming work.

Figure 1-1 shows a temporary warning tag available through the supply system. Any tag can be used as long as it contains the following minimum amount of information

- Time and date work is started.
- The person performing the work.
- The affected circuits.
- The approval and signature of the chief engineer or electrical officer.
- The required position of the affected switch, breaker, or fuse, such as closed, open, or removed.

When you are engaged in electrical repairs on board a vessel, always work in teams of two or more. Never start working on an electrical system until the chief engineer or electrical officier has been informed. A unit's operational status reflects the vessel's operational status and its ability to get under way. All vessel systems are interrelated. What may appear to be a minor repair may ultimately determine whether or not the vessel is fully operational.

Battery design forces the electrolyte to explode upwards. Never service batteries without proper eye protection. If battery electrolyte gets in your eyes, flush them immediately for 15 minutes and seek medical attention.

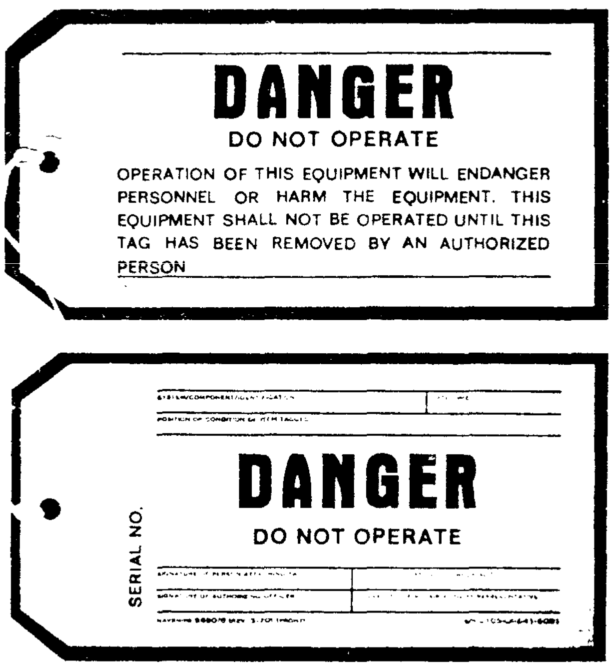


FIGURE 1-1. Temporary Warning Tag (NAVSHIPS 9890/8).

CHAPTER 2

FUNDAMENTALS OF ELECTRICITY

INTRODUCTION

Electricity is a fundamental entity of nature. It consists mainly of negatively and positively charged particles commonly found in the atom. Through man-made influence and natural phenomena, it is possible to observe how the electron (negatively charged) and the proton (positively charged) interact magnetically.

The attraction and repulsion principles of magnetism are used to make electricity perform work. Magnetic principles determine certain reactions; for example, the attraction or repulsion of two magnetically charged objects. These principles can be used in a motor to cause motion and to turn a water pump. Electricity, in other words, uses the magnetic properties of subatomic particles to develop magnetic fields at a given place and time to perform work.

Taking a magnetically neutral atom and artificially separating the electron from the rest of the atom leaves a positive ion. Exciting this atom through mechanical or chemical means prevents the electron and positive. ion from returning to its natural state. Nature seeks equilibrium or a natural balance and order.

A battery or generator forces all the electrons to one terminal and positive ions to the other terminal. As long as the atoms are stimulated, this imbalance or difference between the terminals remains. If excitation of the atoms is stopped nature will cause the negative electrons to return to their positive ions through the principles of magnetism.

If excitation of the atoms continues and a complete path of conductive material connects the two terminals (where the negative electrons and positive ions have gathered), a complete circuit is created. Because positive and negative polarities attract, the electron follows this path from its terminal to the positive ion terminal seeking equilibrium. In doing so, a magnetic field from the electron is developing in the entire circuit.

An electron is surrounded by a magnetic field. Wherever an electron is present there is also the magnetic field. The more electrons, the greater the magnetic field in the circuit. The greater the magnetic field in the circuit, the greater the ability to attract or repel other magnets or ferrometallic objects.

Current is measured in amperes and is known mathematically as a quantity of electrons passing a specific point in a circuit in a given time period (coulomb per second).

Voltage is the force that allows the electron to be available to be attracted to the positive ion. Initially, when the electrically neutral atom was excited, a difference in potential was created. This produced negative electrons at one terminal and positive ions at the other terminal. The greater the difference in potential, the greater the number of electrons gathered at one terminal and positive ions at the other terminal. The greater this difference, the greater the potential to do work as the electrons move throughout the circuit carrying their magnetic field. As long as an imbalance at the terminals results from the exciting of atoms artificially, there will be a difference in potential, which is another term for voltage. The greater the difference in potential, the greater the voltage. The greater the negative and positive attraction, the greater the force to attract electrons back to the positive ions seeking equilibrium.

All the electrons (current) will move through the circuit at once, unless impeded or slowed down by some outside force. Wire size or an electrical light filament will restrict or resist the flow of the electrons returning to the positive ions. Everything that prevents or resists the maximum flow of electrons in their natural desire to seek out their positive ions is called resistance. If there is no resistance, a short circuit, which is a very dangerous condition, exists.

MATTER

Matter is anything that occupies space. Examples of matter are air, water, automobiles, clothing, and even our own bodies. Matter can be found in any one of three states: solid, liquid, and gaseous.

Subatomic particles are the building blocks of all matter. Even though these particles cannot be measured by the usual mechanical tools, they are nonetheless matter. Over 99 percent of the matter in the universe is subatomic material called plasma. Plasma exists throughout the universe as interstellar gases and stars. Plasma is a kind of "subatomic particle soup." Plasma exists on earth only in small quantities. It is seen in the form of the Aurora Borealis, inside neon lamps, lightning bolts, and electricity. Plasma is a collection of positive and negative charges, about equal in number or density and forming a neutral charge (distribution) of matter. Plasma is considered the fourth state of matter.

Elements and Compounds

An element is a substance that cannot be reduced to a simpler substance by chemical means. It is composed of only one type of atom. Some examples are iron, gold, silver, copper, and oxygen. Now more than 100 elements are known. All substances are composed of one or more of these elements.

When two or more elements are chemically combined, the resulting substance is a compound. A compound is a chemical combination of elements that can be separated by chemical but not by physical means. Examples of common compounds are water (hydrogen and oxygen) and table salt (sodium and chlorine). A mixture is a combination of elements and / or compounds, not chemically combined, that can be separated by physical means. Examples of mixtures are air, which is made up of nitrogen, oxygen, carbon dioxide, and small amounts of several rare gases, and sea water, which consists chiefly of salts and water.

Atoms and Molecules

An atom is the smallest particle of an element that retains the characteristics of that element. The atoms of one element differ from the atoms of all other elements. Since more than 100 elements are known, there must be more than 100 different atoms, or a different atom for each element. Just as thousands of words can be made by combining the proper letters of the alphabet, so thousands of different materials can be made by chemically combining the proper atoms.

Any particle that is a chemical combination of two or more atoms is a molecule. In a compound, the molecule is the smallest particle that has all the characteristics of that compound. Water, for example, is a compound made up of two atoms of hydrogen and one atom of oxygen. It maybe chemically or electrically divided into its separate atoms, but it cannot be divided by physical means.

The electrons, protons, and neutrons of one element are identical to those of any other element. However, the number and arrangement of electrons and protons within the atom are different for each element.

The electron is a small negative charge of electricity. The proton has a positive charge equal and opposite to the electron. Scientists have measured the mass and size of the electron and proton and found the mass of the proton is approximately 1,837 times that of the electron. In the nucleus is a neutral particle called the neutron. A neutron has a mass approximately equal to that of a proton, but with no electrical charge. According to a popular theory, the electrons, protons, and neutrons of the atoms are arranged like a miniature solar system. The protons and neutrons form the heavy nucleus with a positive charge around which the very light electrons revolve.

Figure 2-1 is a theoretical representation of one hydrogen and one helium atom. Each has a relatively simple structure. The hydrogen atom has only one proton in the nucleus with one electron rotating around it. The helium atom has a nucleus made up of two protons and two neutrons, with two electrons rotating outside the nucleus. Elements are classified numerically according to the complexity of their atoms. The number of protons in the atom's nucleus determines its atomic number.

Individually, an atom contains an equal number of protons and electrons. An atom of hydrogen, which contains one proton and one electron, has an atomic number of 1. Helium, with two protons and two electrons, has an atomic number of 2. The complexity of atomic structure increases with the number of protons and electrons.

ENERGY LEVELS

Since an electron in an atom has both mass and motion, it contains two types of energy. By virtue of its motion, the electron contains kinetic energy. Due to its position, it also contains potential energy. The total energy contained by an electron (kinetic plus potential) is the factor that determines the radius of the electron orbit. To keep this orbit, an electron must neither gain nor lose energy.

Light is a form of energy, but the physical form in which this energy exists is not known. One accepted theory proposes the existence of light as tiny packets of energy called photons. Photons can contain various quantities of energy. The amount depends upon the color of the light involved. If a photon of sufficient energy collides with an orbital electron, the electron absorbs the photon's energy (Figure 2-2). The electron, which now has a greater than normal amount of energy, will jump to a new orbit farther from the nucleus. The first new orbit to which the electron can jump has a radius four times the radius of the original orbit. Had the electron received a greater amount of energy, the next possible orbit to which it could jump would have a radius nine times the original. Thus, each orbit represents one of a large number of energy levels that the electron may attain. However, the electron cannot jump to just any orbit. The electron will remain in its lowest orbit until a sufficient amount of energy is available, at which time the electron will accept the energy and jump to one of a series of permissible orbits. An electron cannot exist in the space between energy levels. This indicates that the electron will not accept a photon of energy unless it contains enough energy to elevate itself to one of the higher energy levels. Heat energy and collisions with other particles can also cause the electron to jump orbits.

Once the electron is elevated to an energy level higher than the lowest possible energy level, the atom is in an excited state. The electron remains in this excited condition for only a fraction of a second before it radiates the excess energy and returns to a lower energy orbit.

To illustrate this principle, assume that a normal electron has just received a photon of energy sufficient to raise it from the first to the third energy level. In a short period of time, the electron may jump back to the first level and emit a new photon identical to the one it received. Another alternative would be for the electron to return to the lower level in two jumps: from the third to the second, and then from the second to the first. In this case, the electron would emit two photons, one for each jump. Each of these photons would have less energy than the original photon which excited the electron.

This principle is used in the fluorescent light where ultraviolet light photons, invisible to the human eye, bombard a phosphor coating on the inside of a glass tube. When the phosphor electrons return to their normal orbits, they emit photons of light that are visible. By using the proper chemicals for the phosphor coating, any color of light, including white, may be obtained.

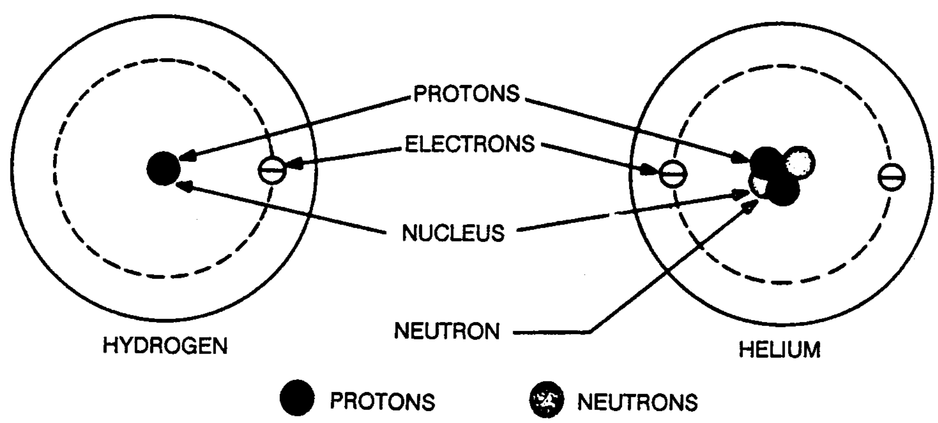


FIGURE 2-1. Structures of Simple Atoms.

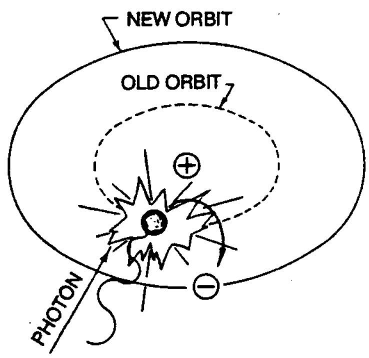


FIGURE 2-2. Excitation by a Photon.

These basic principles apply equally to the atoms of more complex elements. In atoms containing two or more electrons, the electrons interact with each other and the exact path of any one electron is very difficult to predict. However, each electron lies in a specific energy band and the orbits are considered as an average of the electron's position.

SHELLS AND SUBSHELLS

The difference between the chemical activity and stability of atoms depends on the number and position of the electrons within the atom. In general, the electrons reside in groups of orbits called shells. These shells are elliptically shaped and are assumed to be located at fixed intervals. Thus, the shells are arranged in steps that correspond to freed energy levels. The shells and the number of electrons required to fill them maybe predicted by the employment of Pauli's exclusion principle. This principle specifies that each shell will contain a maximum of 2n squared electrons, where n corresponds to the shell number starting with the one closest to the nucleus. By this principle the second shell, for example, would contain $2(2^2)$ or 8 electrons when full.

In addition to being numbered, the shells are given letter designations (Figure 2-3). Starting with the shell closest to the nucleus and progressing outward, the shells are labeled K, L, M, N, O, P, and Q, respectively. The shells are considered full or complete when they contain the following quantities of electrons: 2 in the K shell, 8 in the L shell, 18 in the M shell, and so on, in accordance with the exclusion principle. Each of these shells is a major shell and can be divided into four subshells, labeled s, p, d, and f. Like the major shells, the subshells are limited as to the number of electrons they can contain. Thus, the s subshell is complete when it contains 2 electrons, the p subshell when it contains 6, the d subshell when it contains 10, and the f subshell when it contains 14 electrons.

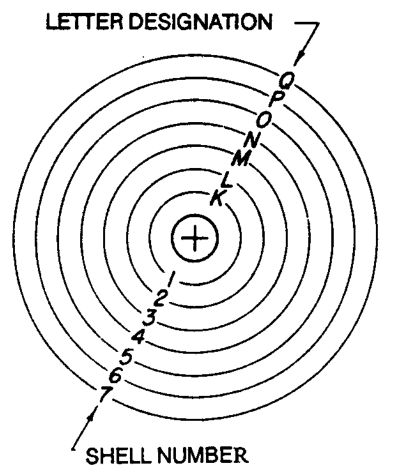


FIGURE 2-3. Shell Designation.

Since the K shell can contain no more than two electrons, it must have only one subshell, the s subshell. The M shell has three subshells: s, p, and d. Adding together the electrons in the s, p, and d subshells equals 18, the exact number required to fill the M shell. Figure 2-4 shows the electron configuration for copper. The copper atom contains 29 electrons, which completely fill the first three shells and subshells, leaving one electron in thes subshell of the N shell.

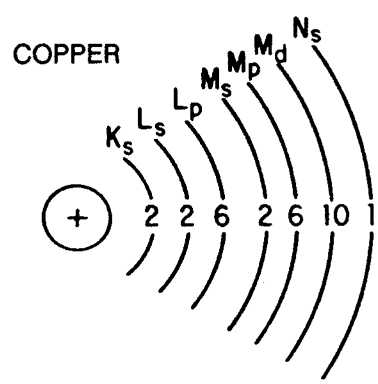


FIGURE 2-4. Copper Atom.

VALENCE

The number of electrons in the outermost shell determines the valence of an atom. The outer shell of an atom is called the valence shell and its electrons are called valence electrons. The valence of an atom determines its ability to gain or lose an electron, which in turn determines the chemical and electrical properties of the atom. An atom lacking only one or two electrons from its outer shell will easily gain electrons to complete its shell. However, a large amount of energy is required to free any of its electrons. An atom with a relatively small number of electrons in its shell compared to the number of electrons required to fill the shell will easily lose these valence electrons.

IONIZATION

For an atom to lose or gain an electron, it must be ionized. For ionization to take place, the internal energy of the atom must be changed by a transfer of energy. An atom with more than its normal amount of electrons acquires a negative charge and is called a negative ion. The atom that gives up some of its normal electrons is left with less negative charges than positive charges and is called a positive ion. Thus, ionization is the process by which an atom loses or gains electrons.

CONDUCTORS, SEMICONDUCTORS, AND INSULATORS

Since every electrical device is constructed of parts made from ordinary matter, the effects of electricity on matter must be well understood. Depending on their ability to conduct an electric current, all elements of matter fit into one of three categories: conductors, semiconductors, and insulators. Conductors are elements that transfer electrons very readily. Insulators have an extremely high resistance to the flow of electrons. All material between these two extremes is referred to as a semiconductor.

The electron theory states that all matter is composed of atoms and the atoms are composed of smaller particles called protons, electrons, and neutrons. The electrons orbit the nucleus, which contains the protons and neutrons. Electricity is most concerned with the valence electrons. These electrons break loose from their parent atom the easiest. Normally, conductors have no more than three valence electrons; insulators have five or more, and semiconductors have four.

The electrical conductivity of matter depends on the atomic structure of the material from which the conductor is made. In any solid material, such as copper, the atoms that make up the molecular structure are bound firmly together. At room temperature, copper contains a large amount of heat energy. Since heat energy is one method of removing electrons from their orbits, copper contains many free electrons that can move from atom to atom. When not under the influence of an external force, these electrons move in a haphazard manner within the conductor. This movement is equal in all directions so that electrons are not lost or gained by any part of the conductor. When controlled by an external force, the electrons move generally in the same direction. The effect of this movement is felt almost instantly from one end of the conductor to the other. This electron movement is called an electric current.

Some metals are better conductors of electricity than others. Silver, copper, gold, and aluminum exchange valence electrons readily and make good conductors. Silver is the best conductor, followed by copper, gold, and aluminum. Copper is used more often than silver because of cost. Aluminum is used where weight is a major consideration, such as in high-tension power lines with long spans between supports. Gold is used where oxidation or corrosion is a consideration and good conductivity is required. The ability of a conductor to handle current also depends on its physical dimensions. Conductors are usually found in the form of wire, but may be bars, tubes, or sheets.

Nonconductors fail to exchange valence electrons because their outer shells are completed with tightly bound valence electrons of their own. These materials are called insulators. Some examples of these materials are rubber, plastic, enamel, glass, dry wood, and mica. Just as there is no perfect conductor, neither is there a perfect insulator.

Some materials are neither good conductors nor good insulators, since their electrical characteristics fall between those of conductors and insulators. These in-between materials are semiconductors. Germanium and silicon are two common semiconductors used in solid-state devices.

ELECTROSTATICS

Electrostatics is electricity at rest. An example of an effect of electrostatics is the way a person's hair stands on end after a vigorous rubbing. Studying electrostatics provides important background knowledge for developing concepts essential to understanding electricity and electronics.

When an amber rod is rubbed with fur, the rod attracts some very light objects such as bits of paper and shavings of wood. Other substances possess qualities of attraction similar to amber. Among these are glass, when rubbed with silk, and ebonite, when rubbed with fur. All the substances with properties similar to those of amber are called electrics, a word of Greek origin meaning amber. A substance such as amber or glass when given a vigorous rubbing is electrified or charged with electricity.

When a glass rod is rubbed with fur, both the glass rod and the fur become electrified. Certain substances attracted to the glass rod are repelled by the fur and vice versa. There are two opposite kinds of electricity positive and negative. The charge produced on a glass rod when it is rubbed with silk is positive. The charge produced on the silk is negative. Those bodies that are not electrified or charged are neutral.

STATIC ELECTRICITY

In a natural or neutral state, each atom in a body of matter has the proper number of electrons in orbit around it. Thus, the whole body of matter composed of the neutral atoms is also electrically neutral. In this state, it has zero net charge. Electrons will neither leave nor enter the neutrally charged body if it comes in contact with other neutral bodies. If, however, any electrons are removed from the atoms of a body of matter, more protons than electrons will remain and the whole body of matter will become electrically positive. If the positively charged body comes in contact with a body having a normal charge or a negative (too many electrons) charge, an electric current will flow between them. Electrons will leave the more negative body and enter the positive body. This electron flow will continue until both bodies have equal charges. When two bodies of matter with unequal charges are near one another, an electric force is exerted between them. However, since they are not in contact, their charges cannot equalize. Such an electric force, where current cannot flow, is called static electricity. (Static in this instance means not moving.) It is also referred to as an electrostatic force.

One of the easiest ways to create a static charge is by friction. When two pieces of matter are rubbed together, electrons can be wiped off one material onto the other. If both materials are good conductors, it is hard to obtain a detectable charge on either since equalizing currents can flow easily between the conducting materials. These currents equalize the charges almost as fast as they are created. A static charge is more easily created between nonconducting materials. When a hard rubber rod is rubbed with fur, the rod will accumulate electrons given up by the fur (Figure 2-5). Since both materials are poor conductors, very little equalizing current can flow and an electrostatic charge builds up. When the charge becomes great enough, current will flow regardless of the poor conductivity of the materials. These currents cause visible sparks and produce a crackling sound.

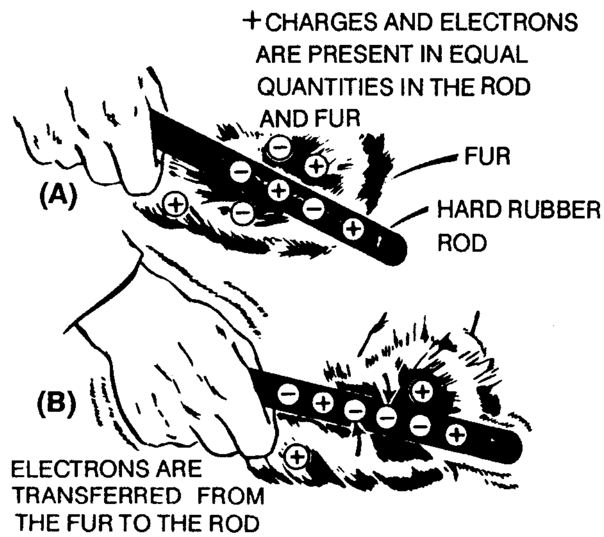


FIGURE 2-5. Producing Static Electricity by Friction.

NATURE OF CHARGES

When in a natural or neutral state, an atom has an equal number of electrons and protons. Because of this balance, the net negative charge of the electrons in orbit is exactly balanced by the net positive charge of the protons in the nucleus, making the atom electrically neutral.

An atom becomes a positive ion whenever it loses an electron and has an overall positive charge. Conversely, whenever an atom acquires an extra electron, it becomes a negative ion and has a negative charge.

Due to normal molecular activity, ions are always present in any material. If the number of positive ions and negative ions is equal, the material is electrically neutral. When the number of positive ions exceeds the number of negative ions, the material is positively charged. The material is negatively charged whenever the negative ions outnumber the positive ions.

Since ions are actually atoms without their normal number of electrons, the excess or lack of electrons in a substance determines its charge. In most solids, the transfer of charges is by movement of electrons rather than ions. The transfer of charges by ions is more significant when considering the electrical activity in liquids and gases.

CHARGED BODIES

A fundamental law of electricity is that like charges repel each other and unlike charges attract each other. A positive charge and negative charge, being unlike, tend to move toward each other. In the atom, the negative electrons are drawn toward the positive protons in the nucleus. This attractive force is balanced by the electron's centrifugal force caused by its rotation about the nucleus. As a result, the electrons remain in orbit and are not drawn into the nucleus. Electrons repel each other because of their like negative charges. Protons repel each other because of their like positive charges.

A simple experiment demonstrates the law of charged bodies. Suspend two pith (paper pulp) balls near one another by threads (Figure 2-6). Rub a hard rubber rod with fur to give it a negative charge. Then hold it against the right-handball (view A). The rod will give off a negative charge to the ball. The right-hand ball has a negative charge with respect to the left-hand ball. Release the two balls. They will be drawn together (view A). They Will touch and remain in contact until the left-hand ball gains a portion of the negative charge of the right-handball. Then they will swing apart. If a positive or a negative charge is placed on both balls (views B and C), the balls will repel each other.

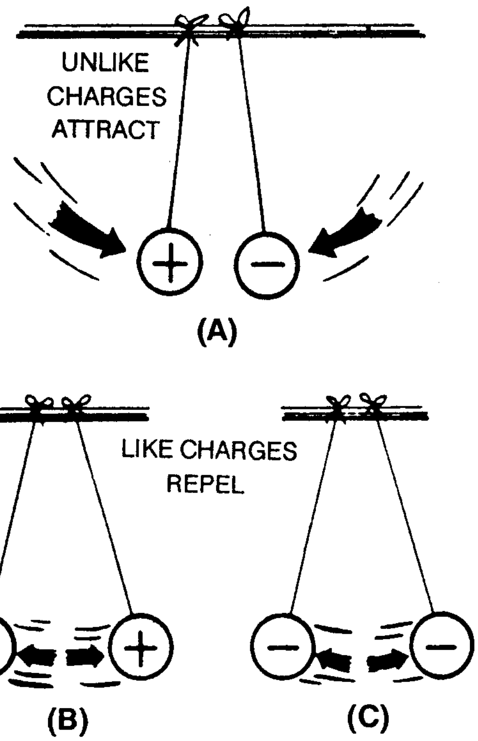


FIGURE 2-6. Reaction Between Charged Bodies.

COULOMB'S LAW OF CHARGES

A French scientist named Charles Coulomb first discovered the relationship between attracting or repelling charged bodies. Coulomb's Law states that charged bodies attract or repel each other with a force that is directly proportional to the product of their individual charges and is inversely proportional to the square of the distance between them. The strength of the attracting or repelling force between two electrically charged bodies in free space depends on two things: their charges and the distance between them.

ELECTRIC FIELDS

The space between and around charged bodies in which their influence is felt is an electric field of force. It can exist in air, glass, paper, or a vacuum. Electrostatic fields and dielectric fields are other names for this region of force.

Fields of force spread out in the space surrounding their point of origin. They generally diminish in proportion to the square of the distance from their source.

The field about a charged body is normally represented by lines called electrostatic lines of force. These imaginary lines represent the direction and strength of the field. To avoid confusion, the lines of force exerted by a positive charge are always shown leaving the charge. For a negative charge they are shown entering. Figure 2-7 shows these lines to represent the field about charged bodies. View A shows the repulsion of like-charged bodies and their associated fields. View B shows the attraction of unlike-charged bodies and their associated fields.

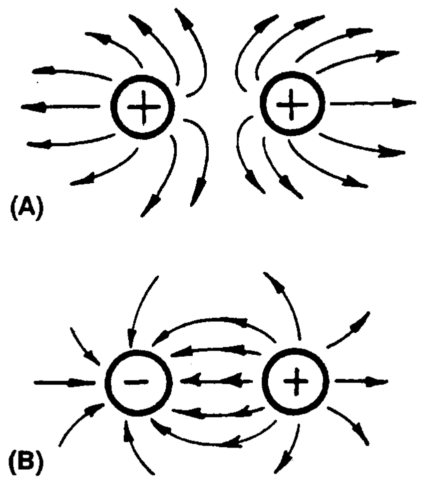


FIGURE 2-7. Electrostatic Lines of Force.

MAGNETISM

To understand the principles of electricity, it is necessary to study magnetism and the effects of magnetism on electrical equipment. Magnetism and electricity are so closely related that the study of either subject would be incomplete without at least a basic knowledge of the other.

Much of today's modern electrical and electronic equipment could not function without magnetism. Modern computers, tape recorders, and video reproduction equipment use magnetized tape. High-fidelity speakers use magnets to convert amplifier outputs into audible sound. Electrical motors use magnets to convert electrical energy into mechanical motion. Generators use magnets to convert mechanical motion into electrical energy.

Magnetic Materials

Magnetism is generally defined as that property of material which enables it to attract pieces of iron. A material possessing this property is a magnet. The word originated with the ancient Greeks who found stones with this characteristic. Materials that are attracted by a magnet, such as iron, steel, nickel, and cobalt, can become magnetized. These are called magnetic materials. Materials, such as paper, wood, glass, or tin, which are not attracted by magnets, are nonmagnetic. Nonmagnetic materials cannot become magnetized.

The most important materials connected with electricity and electronics are the ferromagnetic materials. Ferromagnetic materials are relatively easy to magnetize. They include iron, steel, cobalt, and the alloys Alnico and Permalloy. (An alloy is made by combining two or more elements, one of which must be a metal.) These new alloys can be very strongly magnetized. They can obtain a magnetic strength great enough to lift 500 times their own weight.

Natural Magnets

Magnetic stones such as those found by the ancient Greeks are natural magnets. These stones can attract small pieces of iron in a manner similar to the magnets common today. However, the magnetic properties attributed to the stones are products of nature and not the result of the efforts of man. The Greeks called these substances magnetite.

The Chinese are said to have been aware of some of the effects of magnetism as early as 2600 B.C. They observed that stones similar to magnetite, when freely suspended, had a tendency to assume a nearly north and south direction. Because of the directional quality of these stones, they are referred to as lodestones or leading stones.

Natural magnets, found in the United States, Norway, and Sweden, no longer have any practical use. It is now possible to easily produce more powerful magnets.

Artificial Magnets

Magnets produced from magnetic materials are called artificial magnets. They can be made in a variety of shapes and sizes and are used extensively in electrical apparatus. Artificial magnets are generally made from special iron or steel alloys which are usually magnetized electrically. The material to be magnetized is inserted into a coil of insulated wire.

A heavy flow of electrons is produced by stroking a magnetic material with magnetite or with another artificial magnet. The forces causing magnetization are represented by magnetic lines of force, very similar in nature to electrostatic lines of force.

Artificial magnets are usually classified as permanent or temporary, depending on their ability to retain their magnetic properties after the magnetizing force has been removed. Magnets made from substances, such as hardened steel and certain alloys which retain a great deal of their magnetism, are called permanent magnets. These materials are relatively difficult to magnetize because of the opposition offered to the magnetic lines of force as the lines of force try to distribute themselves throughout the material. The opposition is called reluctance. All permanent magnets are produced from materials having a high reluctance.

A material with a low reluctance, such as soft iron or annealed silicon steel, is relatively easy to magnetize. However, it retains only a small part of its magnetism once the magnetizing force is removed. Materials that easily lose most of their magnetic strength are called temporary magnets. The amount of magnetism that remains in a temporary magnet is referred to as its residual magnetism. The ability of a material to retain an amount of residual magnetism is called the retentivity of the material.

The difference between a permanent and temporary magnet is indicated in terms of reluctance. A permanent magnet has a high reluctance, and a temporary magnet has a low reluctance. Magnets are also described in terms of the permeability of their materials or the ease with which magnetic lines of force distribute themselves throughout the material. A permanent magnet, produced from a material with a high reluctance, has a low permeability. A temporary magnet, produced from a material with a low reluctance, has a high permeability.

Magnetic Poles

The magnetic force surrounding a magnet is not uniform. There is a great concentration of force at each end of the magnet and a very weak force at the center. To prove this fact, dip a magnet into iron tilings (Figure 2-8). Many filings will cling to the ends of the magnet, while very few adhere to the center. The two ends, which are the regions of concentrated lines of force, are called the poles of the magnet. Magnets have two magnetic poles, and both poles have equal magnetic strength.

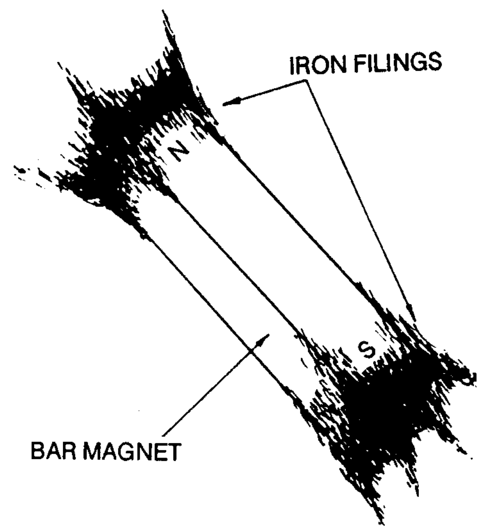


FIGURE 2-8. Iron Filings Cling to the Poles of a Magnet.

Law of Magnetic Poles. To demonstrate the law of magnetic poles, suspend a bar magnet freely on a string (Figure 2-9). It will align itself in a north and south direction. Repeat this experiment. The same pole of the magnet will always swing toward the north geographical pole of the earth. Therefore, it is called the north-seeking pole or simply the north pole. The other pole of the magnet is the south-seeking pole or the south pole.

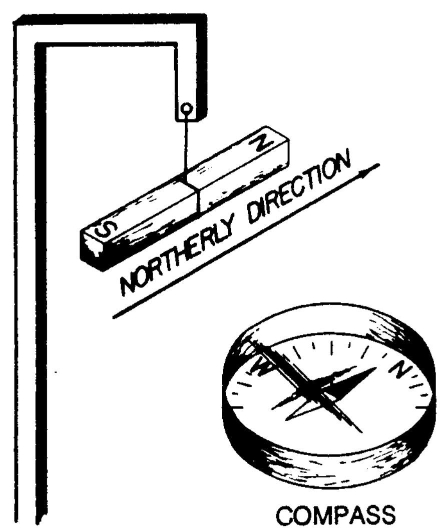


FIGURE 2-9. A Bar Magnet Acts as a Compass.

A practical use of the directional characteristic of the magnet is the compass. The compass has a freely rotating magnetized needle indicator that points toward the North Pole. The poles of a suspended magnet always move to a definite position. This indicates opposite magnetic polarity exists.

The law of electricity regarding the attraction and repulsion of charged bodies may also be applied to magnetism if the pole is considered as a charge. The north pole of a magnet will always be attracted to the south pole of another magnet and will show a repulsion to another north pole. The law of magnetic poles is that like poles repel and unlike poles attract.

The Earth's Magnetic Poles. The fact that a compass needle always aligns itself in a particular direction, regardless of its location on earth, indicates that the earth is a huge natural magnet. The distribution of the magnetic force about the earth is the same as that which might be produced by a giant bar magnet running through the center of the earth (Figure 2-10). The magnetic axis of the earth is about 15 degrees from its geographical axis, thereby locating the magnetic poles some distance from the geographical poles. The ability of the north pole of the compass needle to point toward the north geographical pole is due to the presence of the magnetic pole nearby. This magnetic pole of the earth is popularly considered the magnetic north pole. However, it actually must have the polarity of magnet's south pole since it attracts the north pole of a compass needle. The reason for this conflict in terminology can be traced to the early users of the compass. Because they did not know that opposite magnetic poles attract, they called the end of the compass needle that pointed toward the north geographical pole the north pole of a compass needle. However, the north pole of a compass needle (a small bar magnet) can be attracted only by an unlike magnetic pole, a pole with the same magnetic polarity as the south pole of a magnet.

Theories of Magnetism

Weber's Theory. A popular theory of magnetism considers the molecular alignment of the material. This is known as Weber's Theory. This theory assumes that all magnetic substances are composed of tiny molecular magnets. Any magnetized material has the magnetic forces of its molecular magnets, thereby eliminating any magnetic effect. A magnetized material will have most of its molecular magnets lined up so that the north pole of each molecule points in one direction and the south pole faces the opposite direction. A material with its molecules thus aligned will then have one effective north pole and one effective south pole. Figure 2-11 illustrates Weber's Theory. When a steel bar is stroked several times in the same direction by a magnet, the magnetic force from the north pole of the magnet causes the molecules to align themselves.

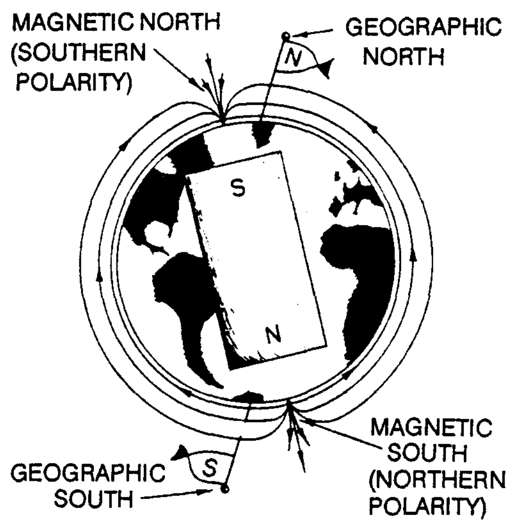


FIGURE 2-10. The Earth Is a Magnet.

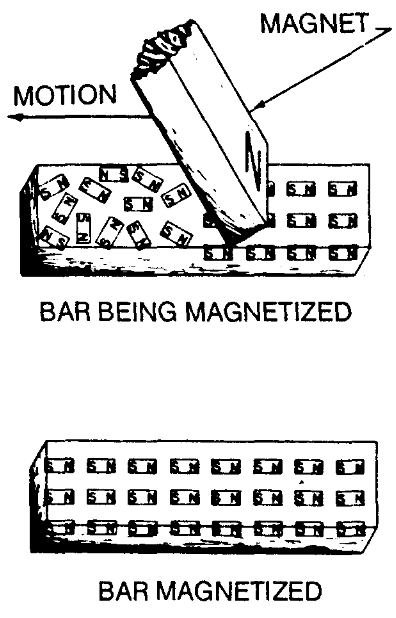


FIGURE 2-11. Molecular Magnets.

Domain Theory. A more modern theory of magnetism is based on the electron spin principle. All matter is composed of vast quantities of atoms, each atom containing one or more orbital electron. The electrons are considered to orbit in various shells and subshells depending on their distance from the nucleus. The structure of the atom has previously been compared to the solar system. The electrons orbiting the nucleus correspond to the planets orbiting the sun. Along with its orbital motion about the sun, each planet also revolves on its axis. It is believed that the electron also revolves on its axis as it orbits the nucleus of an atom.

An electron has a magnetic field about it along with an electric field. The number of electrons spinning in each direction determines the effectiveness of the magnetic field of an atom. If an atom has equal numbers of electrons spinning in opposite directions, the magnetic fields surrounding the electrons cancel one another and the atom is unmagnetized. However, if more electrons spin in one direction than another, the atom is magnetized. An atom with an atomic number of 26, such as iron, has 26 protons in the nucleus and 26 revolving electrons orbiting its nucleus. If 13 electrons are spinning in a clockwise direction and 13 electrons are spinning in a counterclockwise direction, the opposing magnetic fields will be neutralized. When more than 13 electrons spin in either direction, the atom is magnetized. Figure 2-12 shows an example of a magnetized atom of iron.

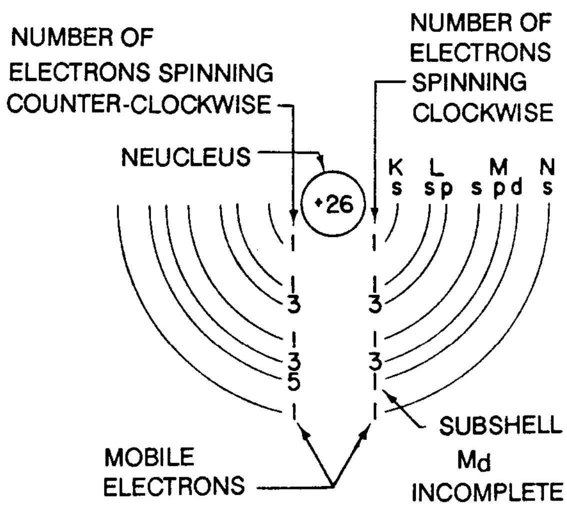


FIGURE 2-12. Iron Atom.

Magnetic Fields

The space surrounding a magnet where magnetic forces act is the magnetic field. Magnetic forces have a pattern of directional force observed by performing an experiment with iron filings. Place a piece of glass over a bar magnet. Then sprinkle iron filings on the surface of the glass. The magnetizing force of the magnet will be felt through the glass, and each iron filing becomes a temporary magnet. Tap the glass gently. The iron particles will align themselves with the magnetic field surrounding the magnet just as the compass needle did previously. The filings form a definite pattern, which is a visible representation of the forces comprising the magnetic field. The arrangements of iron filings in Figure 2-13 indicate that the magnetic field is very strong at the poles and weakens as the distance from the poles increases. They also show that the magnetic field extends from one pole to the other in a loop around the magnet.

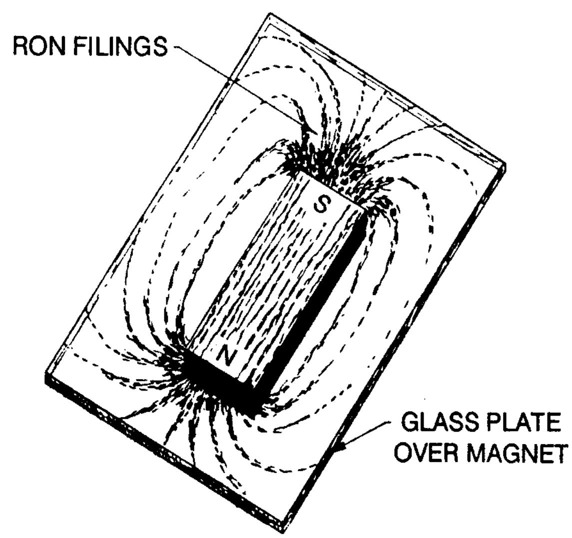


FIGURE 2-13. Pattern Formed by Iron Filings.

Lines of Force

To further describe and work with magnetic phenomena, lines are used to represent the force existing in the area surrounding a magnet (Figure 2-14). These magnetic lines of force are imaginary lines used to illustrate and describe the pattern of the magnetic field. The magnetic lines of force are assumed to emanate from the north pole of a magnet, pass through the surrounding space, and enter the south pole. They then travel inside the magnet from the south pole to the north pole, thus completing a closed loop.

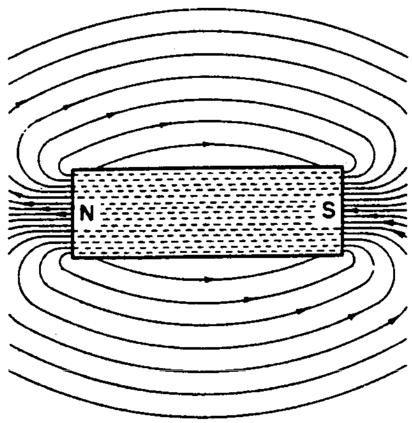


FIGURE 2-14. Bar Magnet Showing Lines of Force.

When two magnetic poles are brought close together, the mutual attraction or repulsion of the poles produces a more complicated pattern than that of a single magnet. These magnetic lines of force can be plotted by placing a compass at various points throughout the magnetic field, or they can be roughly illustrated using iron filings as before. Figure 2-15 shows a diagram of magnetic poles placed close together.

Although magnetic lines of force are imaginary a simplified version of many magnetic phenomena can be explained by assuming they have certain real properties. The lines of force are similar to rubber bands which stretch outward when a force is exerted on them and contract when the force is removed. Characteristics of magnetic lines of force are as follows:

- Magnetic lines of force are continuous and will always form closed loops.
- Magnetic lines of force will never cross one another.
- Parallel magnetic lines of force traveling in the same direction repel one another. Parallel magnetic lines of force traveling in opposite directions extend to unite with each other and form single lines traveling in a direction determined by the magnetic poles creating the limes of force.
- Magnetic lines of force tend to shorten themselves. Therefore, the magnetic lines of force existing between two unlike poles cause the poles to be pulled together.
- Magnetic lines of force pass through all materials, both magnetic and nonmagnetic.
- Magnetic lines of force always enter or leave a magnetic material at right angles to the surface.

Magnetic Effects

Magnetic Flux. The total number of magnetic lines of force leaving or entering the pole of a magnet is called magnetic flux. The number of flux lines per unit area is called flux density.

Field Intensity. The intensity of a magnetic field is directly related to the magnetic force exerted by the field.

Attraction / Repulsion. The intensity of attraction or repulsion between magnetic poles may be described by a law almost identical to Coulomb's Law of Charged Bodies. The force between two poles is directly proportional to the product of the pole strengths and inversely proportional to the square of the distance between the poles.

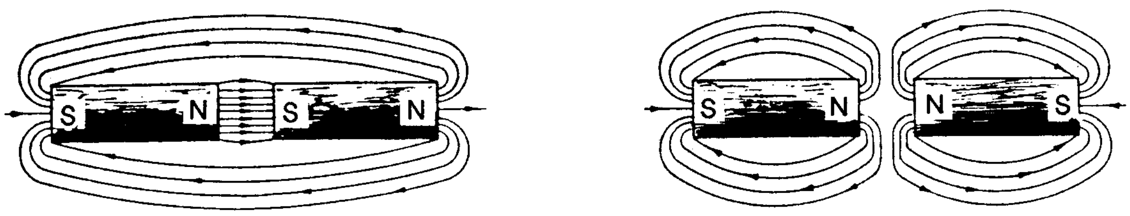


FIGURE 2-15. Magnetic Poles in Close Proximity.

Magnetic Induction

All substances that are attracted by a magnet can become magnetized. The fact that a material is attracted by a magnet indicates the material must itself be a magnet at the time of attraction. Knowing about magnetic fields and magnetic lines of force simplifies the understanding of how a material becomes magnetized when brought near a magnet. As an iron nail is brought close to a bar magnet (Figure 2-16), some flux lines emanating from the north pole of the magnet pass through the iron nail in completing their magnetic path. Since magnetic lines of force travel inside a magnet from the south pole to the north pole, the nail will be magnetized so its south pole will be adjacent to the north pole of the bar magnet.

If another nail is brought in contact with the end of the first nail, it is magnetized by induction. This process can be repeated until the strength of the magnetic flux weakens as distance from the bar magnet increases. However, as soon as the first iron nail is pulled away from the bar magnet, all the nails will fall. Each nail had become a temporary magnet, but once the magnetizing force was removed, the nails' domains once again assumed a random distribution.

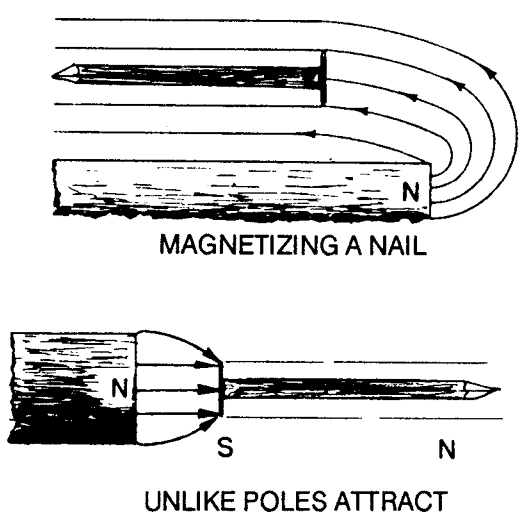


FIGURE 2-16. Magnetized Nail.

Magnetic induction always produces a pole polarity on the material being magnetized opposite that of the adjacent pole of the magnetizing force. It is sometimes possible to bring a weak north pole of a magnet near a strong magnet north pole and note attraction between the poles. The weak magnet, when placed within the magnetic field of the strong magnet, has its magnetic polarity reversed by the field of the stronger magnet. Therefore, it is attracted to the opposite pole. For this reason, keep a very weak magnet, such as a compass needle, away from a very strong magnet.

Magnetism can be induced in a magnetic material by several means. The magnetic material may be placed in the magnetic field, brought into contact with a magnet, or stroked by a magnet. Stroking and contact both indicate actual contact with the material but are considered in magnetic studies as magnetizing by induction.

Magnetic Shielding

Magnetic flux has no known insulator. If a nonmagnetic material is placed in a magnetic field, there is no appreciable change in flux. That is, the flux penetrates the nonmagnetic material. For example, a glass plate placed between the poles of a horseshoe magnet will have no appreciable effect on the field, although glass itself is a good insulator in an electric circuit. If a magnetic material such as soft iron is placed in a magnetic field, the flux may be redirected to take advantage of the greater permeability of the magnetic material (Figure 2-17). Permeability is the quality of a substance that determines the ease with which it can be magnetized.

Stray magnetic fields can influence the sensitive mechanisms of electric instruments and meters causing errors in their readings. Instrument mechanisms cannot be insulated against magnetic flux. Therefore, the flux must be directed around the instrument by placing a soft-iron case, called a magnetic screen or magnetic shield, about the instrument. Because the flux is established more readily through the iron (even though the path is larger) than through the air inside the case, the instrument is effectively shielded. Figure 2-18 shows a soft iron magnetic shield around a watch.

Magnetic Shapes

Because of their many uses, magnets are found in various shapes and sizes. However, they usually come under one of three general classifications: bar, ring, or horseshoe magnets.

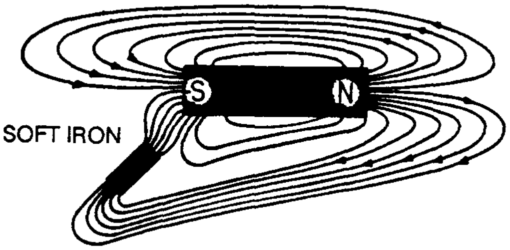


FIGURE 2-17. Effects of a Magnetic Substance in a Magnetic Field.

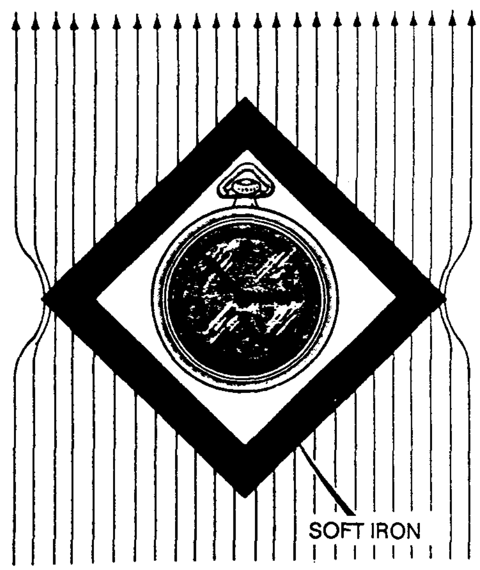


FIGURE 2-18. Magnetic Shield.

The bar magnet is most often used in schools and laboratories for studying the properties and effects of magnetism. The bar magnet helped demonstrate magnetic effects in Figure 2-14.

The ring magnet is used for computer memory cores. A common application for a temporary ring magnet is the shielding of electrical instruments.

The horseshoe magnet is most frequently used in electrical and electronic equipment. A horseshoe magnet is similar to a bar magnet but is bent in the shape of a horseshoe. The horseshoe magnet is magnetically stronger than a bar magnet of the same size and material because the magnetic poles are closer together. The magnetic strength from one pole to the other is greatly increased because the magnetic field is concentrated in a smaller area. Electrical measuring devices often use horseshoe magnets.

Care of Magnets

A piece of steel that has been magnetized can lose much of its magnetism by improper handling. If it is jarred or heated, its domains will be misaligned, and it loses some of its effective magnetism. If this piece of steel formed the horseshoe magnet of a meter, the meter would no longer operate or would give inaccurate readings. Therefore, be careful when handling instruments containing magnets. Severe jarring or subjecting the instrument to high temperatures will damage the device.

A magnet may also become weakened from loss of flux. When storing magnets, always try to avoid excess leakage of magnetic flux. Always store a horseshoe magnet with a keeper, a soft iron bar used to join the magnetic poles. By storing the magnet with a keeper, the magnetic flux continuously circulates through the magnet and does not leak off into space.

When storing bar magnets, follow the same principle. Always store bar magnets in pairs with a north pole and a south pole placed together. This provides a complete path for the magnetic flux without any flux leakage.

ENERGY AND WORK

In the field of physical science, work is defined as the product of force and displacement. That is, the force applied to move an object and the distance the object is moved are the factors of work performed. No work is accomplished unless the force applied causes a change in position of a stationary object or a change in the velocity of a moving object. For example, a worker may tire by pushing against a heavy wooden crate, but unless the crate moves, no work will be accomplished.

In the study of energy and work, energy is defined as the ability to do work. To perform any kind of work, energy must be expended (converted from one form to another). Energy supplies the required force or power whenever any work is accomplished.

One form of energy is that contained by an object in motion. When a hammer is set in motion in the direction of a nail, it possesses energy of motion. As the hammer strikes the nail, the energy of motion is converted into work as the nail is driven into the wood. The distance the nail is driven into the wood depends on the velocity of the hammer at the time it strikes the nail. Energy contained in an object due to its motion is called kinetic energy.

If a hammer is suspended one meter above a nail by a string, gravity will pull the hammer downward. If the string is suddenly cut, the force of gravity will pull the hammer down against the nail, driving it into the wood. While the hammer is suspended above the nail, it has the ability to do work because of its elevated position in the earth's gravitational field. Since energy is the ability to do work, the hammer contains energy.

Energy contained in an object because of its position is called potential energy. The amount of potential energy available equals the product of the force required to elevate the hammer and the height to which it is elevated.

Another example of potential energy is that contained in a tightly coiled spring. The amount of energy released when the spring unwinds depends on the amount of force required to wind the spring initially.

ELECTRICAL CHARGES

The study of electrostatics shows that a field of force exists in the space surrounding any electrical charge. The strength of the field depends directly on the force of the charge.

The charge of one electron might be used as a unit of electrical charge since displacing electrons creates charges. However, the charge of one electron is so small that it is impractical to use. The practical unit adopted for measuring charges is the coulomb, named after the scientist Charles Coulomb. A coulomb equals the charge 6,242,000,000,000,000,000 (six quintillion, two hundred forty-two quadrillion or 6.242 times 10 to the 18th power) electrons.

When a charge of 1 coulomb exists between two bodies, one unit of electrical potential energy exists. This difference in potential between the two bodies is called electromotive force (EMF) or voltage. The unit of measure is the volt.

Electrical charges are created by the displacement of electrons, so that there is an excess of electrons at one point and a deficiency at another point. Therefore, a charge must always have either a negative or positive polarity. A body with an excess of electrons is negative; a body with a deficiency of electrons is positive.

A difference in potential can exist between two points or bodies only if they have different charges. In other words, there is no difference in potential between two bodies if both have a deficiency of electrons to the same degree. If, however, one body is deficient by 6 coulombs (6 volts) and the other is deficient by 12 coulombs (12 volts), the difference in potential is 6 volts. The body with the greater deficiency is positive with respect to the other.

In most electrical circuits only the difference in potential between two points is important. The absolute potentials of the points are of little concern. Often it is convenient to use one standard reference for all of the various potentials throughout a piece of equipment. For this reason, the potentials at various points in a circuit are generally measured with respect to the metal chassis on which all parts of the circuit are mounted. The chassis is considered to be at zero potential and all other potentials are either positive or negative with respect to the chassis. When used as the reference point, the chassis is said to be at ground potential.

Sometimes rather large values of voltage may be encountered and the volt becomes too small a unit for convenience. In this situation, the kilovolt (kV), meaning 1,000 volts, is used. For example, 20,000 volts would be written as 20 kV. Sometimes the volt may be too large a unit when dealing with very small voltages. For this purpose, the millivolt (mV), meaning one-thousandth of a volt, and the microvolt (uV), meaning one-millionth of a volt, are used. For example, 0.001 volt would be written as 1 mV, and 0.000025 volt would be written as 25 uV.

When a difference in potential exists between two charged bodies connected by a conductor, electrons will flow along the conductor. This flow is from the negatively charged body to the positively charged body until the two charges are equalized and the potential difference no longer exists.

Figure 2-19 shows an analogy of this action in the two water tanks connected by a pipe and valve. At first, the valve is closed and all the water is in tank A. Thus, the water pressure across the valve is at

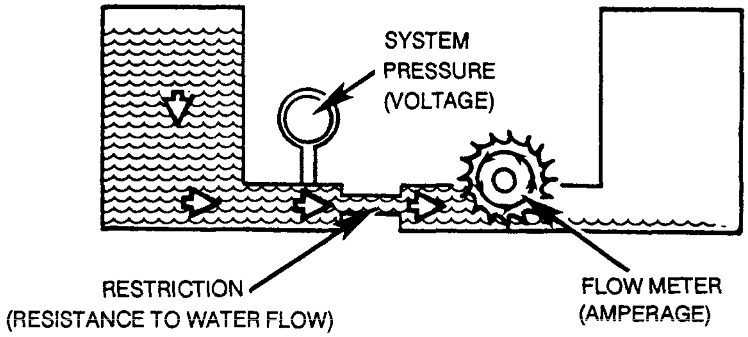


FIGURE 2-19. Water Analogy of Electric Difference in Potential.

maximum. When the valve is opened, the water flows through the pipe from A to B until the water level becomes the same in both tanks. The water then stops flowing in the pipe because there is no longer a difference in water pressure between the two tanks.

Electron movement through an electric circuit is directly proportional to the difference in potential or EMF across the circuit, just as the flow of water through the pipe in Figure 2-19 is directly proportional to the difference in water level in the two tanks.

A fundamental law of electricity is that the electron flow is directly proportional to the applied voltage. If the voltage is increased, the flow is increased. If the voltage is decreased, the flow is decreased.

VOLTAGE PRODUCTION

It has been demonstrated that a charge can be produced by rubbing a rubber rod with fur. Because of the friction involved, the rod acquires electrons from the fur, making it negative. The fur becomes positive due to the loss of electrons. These quantities of charge constitute a difference in potential between the rod and the fur. The electrons that make up this difference in potential are capable of doing work if a discharge is allowed to occur.

To be a practical source of voltage, the potential difference must not be allowed to dissipate. It must be maintained continuously. As one electron leaves the concentration of negative charge, another must be immediately provided to take its place or the charge will eventually diminish to the point where no further work can be accomplished. A voltage source, therefore, is a device that can supply and maintain voltage while an electrical apparatus is connected to its terminals. The internal action of the source is such that electrons are continuously removed from one terminal to keep it positive and simultaneously supplied to the second terminal to keep it negative.

Presently, six methods for producing a voltage or electromotive force are known. Some are more widely used than others, and some are used mostly for specific applications. The six known methods of producing a voltage are–

- Friction. Voltage is produced by rubbing certain materials together.
- Pressure (piezoelectricity). Voltage is produced by squeezing crystals of certain substances.
- Heat (thermoelectricity). Voltage is produced by heating the joint (junction) where two unlike metals are joined.
- Light (photoelectricity). Voltage is produced by light striking photosensitive (light sensitive) substances.
- Chemical action. Voltage is produced by chemical reaction in a battery cell.
- Magnetism. Voltage is produced in a conductor when the conductor moves through a magnetic field, or a magnetic field moves through the conductor so that the magnetic lines of force of the field are cut.

Voltage Produced by Friction

The first method discovered for creating a voltage was generation by friction. The development of charges by rubbing a rod with fur is a prime example of the way friction generates voltage. Because of the nature of the materials producing this voltage, it cannot be conveniently used or maintained. Therefore, this method has very little practical use.

While searching for ways to produce larger amounts of voltage with more practical nature, machines were developed that transferred charges from one terminal to another by rotating glass discs or moving belts. The most notable of these machines is the Van de Graaff generator. It is used today to produce potentials in the order of millions of volts for nuclear research. As these machines have little value outside the field of research, their theory of operation will not be described here.

Voltage Produced by Pressure

One specialized method of generating an EMF uses the characteristics of certain ionic crystals such as quartz, Rochelle salts, and tourmaline. These crystals can generate a voltage whenever stresses are applied to their surfaces. Thus, if a crystal of quartz is squeezed, charges of opposite polarity appear on two opposite surfaces of the crystal. If the force is reversed and the crystal is stretched, charges again appear but are of the opposite polarity from those produced by squeezing. If a crystal of this type is vibrated, it produces a voltage of reversing polarity between two of its sides. Quartz or similar crystals can thus be used to convert mechanical energy into electrical energy. Figure 2-20 shows this phenomenon, called the piezoelectric effect. Some of the common devices that use piezoelectric crystals are microphones, phonograph cartridges, and oscillators used in radio transmitters, radio receivers, and sonar equipment. This method of generating an EMF is not suitable for applications having large voltage or power requirements. But it is widely used in sound and communications systems where small signal voltages can be effectively used.

Crystals of this type also possess another interesting property, the converse piezoelectric effect. They can convert electrical energy into mechanical energy. A voltage impressed across the proper surfaces of the crystal will cause it to expand or contract its surfaces in response to the voltage applied.

(A) Noncrystallized Structure.
(B) Crystallized Structure.
(C) Compression of a Crystal.
(D) Decompression of a Crystal.

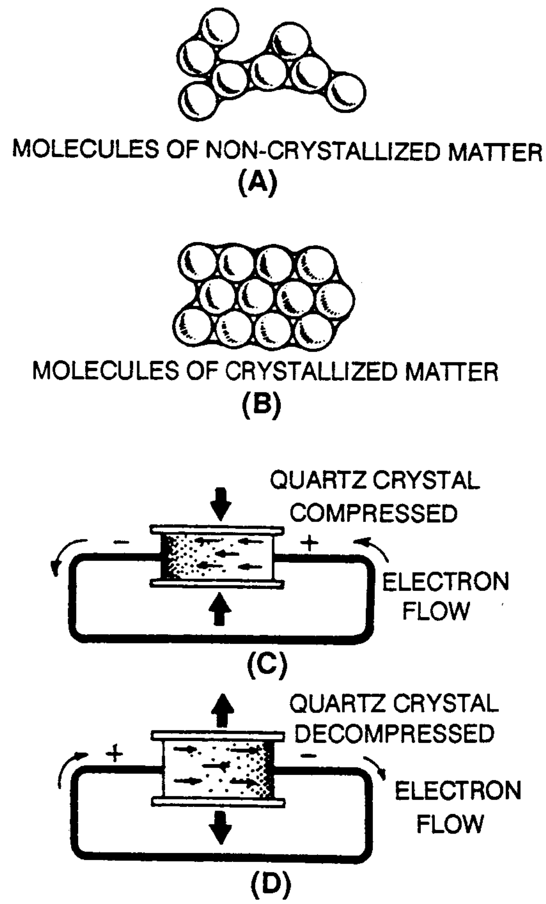


FIGURE 2-20. Piezoelectric Effect.

Voltage Produced by Heat

When a length of metal, such as copper, is heated at one end, valence electrons tend to move away from the hot end toward the cooler end. This is true of most metals. However, in some metals such as iron, the opposite takes place and electrons tend to move toward the hot end. Figure 2-21 illustrates these characteristics. The negative charges (electrons) are moving through the copper away from the heat and through the iron toward the heat. They cross from the iron to the copper through the current meter to the iron at the cold junction. This device is called a thermocouple.

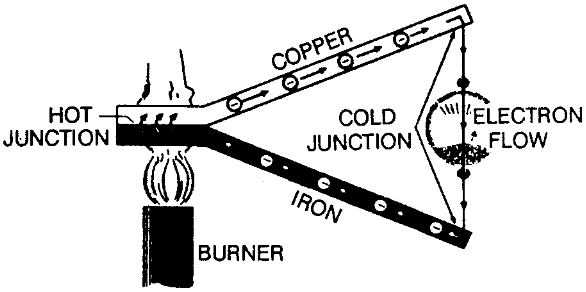


FIGURE 2-21. Voltage Produced by Heat.

Thermocouples have a greater power capacity than crystals, but it is still very small compared to some other sources. The thermoelectric voltage in a thermocouple depends mainly on the difference in temperature between the hot and cold junctions. They are therefore widely used to measure temperature and are used in heat-sensing devices in automatic temperature control equipment. Thermocouples generally can be subjected to much greater temperatures then ordinary thermometers, such as mercury or alcohol types.

Voltage Produced by Light

When light strikes the surface of a substance, it may dislodge electrons from their orbits around the surface atoms of the substance. This occurs because light has energy, the same as any moving force. Some substances, mostly metallic ones, are far more sensitive to light than others. That is, more electrons are dislodged and emitted from the surface of a highly sensitive metal, with a given amount of light, than are emitted from a less sensitive substance. Upon losing electrons, the photosensitive (light-sensitive) metal becomes positively charged, and an electric force is created. Voltage produced in this manner is called photoelectric voltage.

The photosensitive materials most commonly used to produce a photoelectric voltage are various compounds of silver oxide or copper oxide. A complete device which operates with photoelectric voltage is a photoelectric cell. Many different sizes and types of photoelectric cells are in use, and each serves the special purpose for which it is designed. Nearly all, however, have some of the basic features of the photoelectric cells in Figure 2-22.

The cell in view A has a curved, light-sensitive surface focused on the central anode. When light from the direction shown strikes the sensitive surface, it emits electrons toward the anode. The more intense the light, the greater the number of electrons emitted. When a wire is connected between the filament and the back, or dark side of the cell, the accumulated electrons will flow to the dark side. These electrons will eventually pass through the metal of the reflector and replace the electrons leaving the light-sensitive surface. Thus, light energy is converted to a flow of electrons, and a usable current is developed.

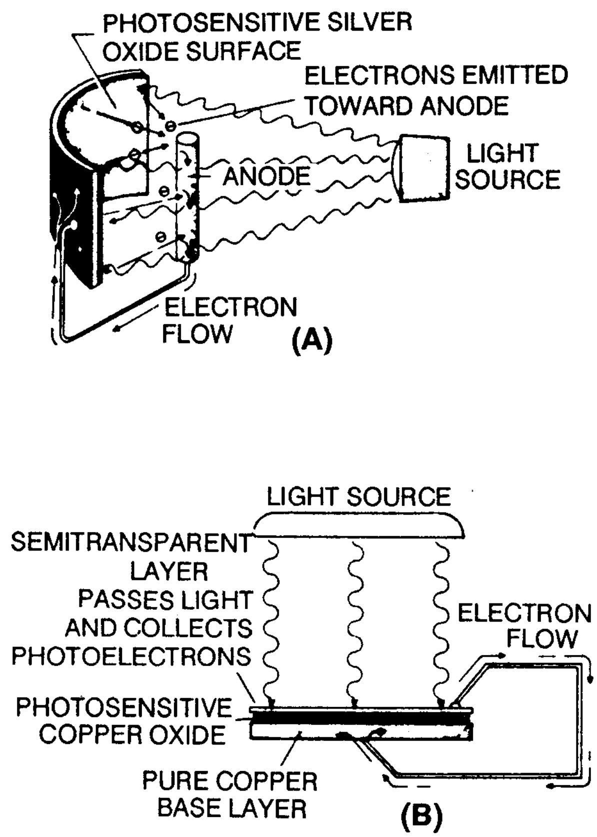


FIGURE 2-22. Voltage Produced by Light.

The cell in view B is constructed in layers. A base plate of pure copper is coated with light-sensitive copper oxide. An extremely the semi-transparent layer of metal is placed over the copper oxide. This additional layer serves two purposes:

- It permits the penetration of light to the copper oxide.
- It collects the electrons emitted by the copper oxide.

An externally connected wire completes the electron path, the same as in the reflector-type cell. The photocell's voltage is used as needed by connecting the external wires to some other device, which amplifies (enlarges) it to a usable level.

The power capacity of a photocell is very small. However, it reacts to light-intensity variations in an extremely short time. This characteristic makes the photocell very useful in detecting or accurately controlling many operations. For instance, the photoelectric cell, or some form of the photoelectric principle, is used in television cameras, automatic manufacturing process controls, door openers, and burglar alarms.

Voltage Produced by Chemical Action

Voltage maybe produced chemically when certain substances are exposed to chemical action. If two dissimilar substances, usually metals or metallic materials, are immersed in a solution that produces a greater chemical action on one substance than on the other, a difference in potential exists between the two. If a conductor is then connected between them, electrons flow through the conductor to equalize the charge. This arrangement is called a primary cell. The two metallic pieces are electrodes, and the solution is the electrolyte. The voltaic cell in Figure 2-23 is a simple example of a primary cell. The difference in potential results from the fact that material from one or both of the electrodes goes into the electrolyte. In the process, ions form near the electrodes. Due to the electric field associated with the charged ions, the electrodes acquire charges. The amount of difference in potential between the electrodes depends mainly on the metals used.

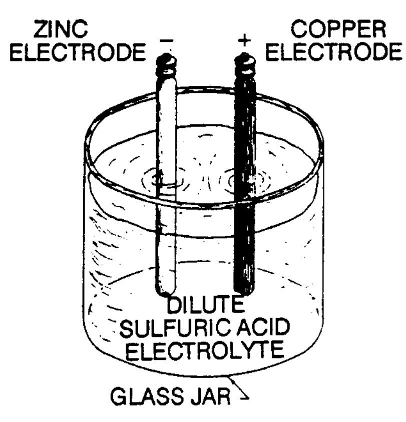


FIGURE 2-23. Voltaic Cell.

The two types of primary cells are the wet cell and the dry cell. In a wet cell, the electrolyte is a liquid. A cell with a liquid electrolyte must remain in an upright position and is not readily transportable. An automotive battery is an example of this type of cell. The dry cell is more commonly used than the wet cell. The dry cell is not actually dry, but it contains an electrolyte mixed with other materials to form a paste. Flashlights and portable radios are commonly powered by dry cells.

Batteries are formed when several cells are connected together to increase electrical output.

Voltage Produced by Magnetism

Magnets or magnetic devices are used for thousands of different jobs. One of the most useful and widely employed applications of magnets is to produce vast quantities of electric power from mechanical sources. A number of different sources may provide the mechanical power, such as gasoline or diesel engines and water or steam turbines. However, the final conversion of these source energies to electricity is done by generators using the principle of electromagnetic induction. There are many types and sizes of these generators. The fundamental operating principle of all electromagnetic induction generators is discussed below.

Three fundamental conditions must exist before a voltage can be produced by magnetism:

- There must be a conductor in which the voltage will be produced.
- There must be a magnetic field in the conductor's vicinity.
- There must be relative motion between the field and conductor. The conductor must be moved so it cuts across the magnetic lines of force, or the field must be moved so the conductor cuts the lines of force.

When a conductor or conductors move across a magnetic field and cut the lines of force, electrons within the conductor are propelled in one direction or another. This creates an electric force or voltage.

Figure 2-24 shows the three conditions needed to create an induced voltage. There is a magnetic field between the poles of the C-shaped magnet. The copper wire is the conductor. The wire is moved back and forth across the magnetic field for relative motion.

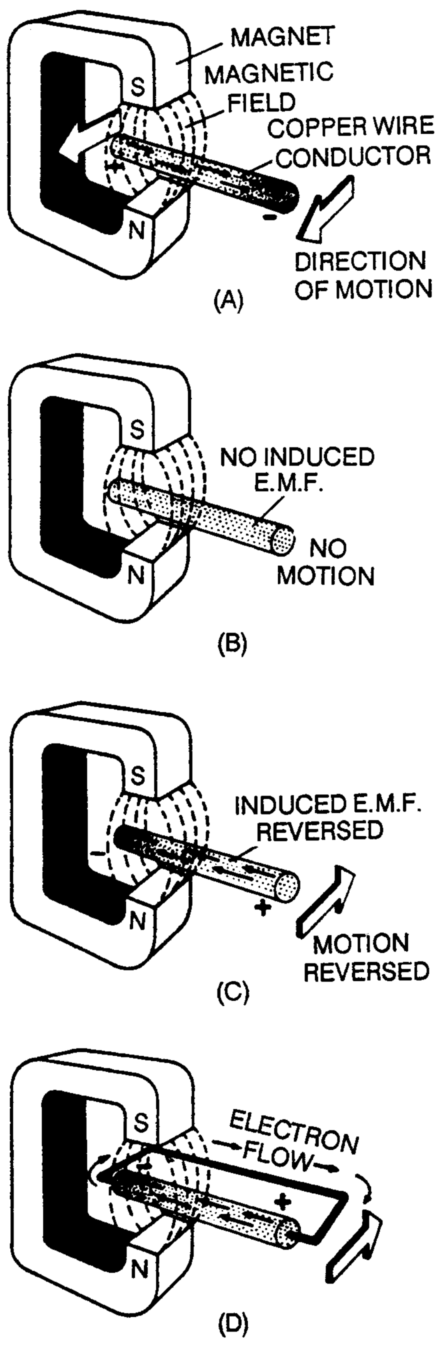


FIGURE 2-24. Voltage Produced by Magnetism.

In view A, the conductor moves toward the front of the page and the electrons move from left to right. The movement of the electrons occurs because of the magnetically induced EMF acting on the electrons in the copper. The right-hand end becomes negative and the left-hand end positive. The conductor is stopped in view B, and motion is eliminated (one of the three required conditions). Since there is no longer an induced EMF, there is no longer any difference in potential between the two ends of the wire. In view C, the conductor is moving away from the front of the page. An induced EMF is again created. However, the reversal of motion has caused a reversal of direction in the induced EMF.

If a path for electron flow is provided between the ends of the conductor, electrons will leave the negative end and flow to the positive end. View D shows this condition. Electron flow will continue as long as the EMF exists. Note that the induced EMF in Figure 2-24 could also have been created by holding the conductor stationary and moving the magnetic field back and forth.

ELECTRIC CURRENT

Electrons move through a conductor in response to a magnetic field. Electron current is the directed flow of electrons. The direction of electron movement is from a region of negative potential to a region of positive potential. Therefore, electron current flow in a material is determined by the polarity of the applied voltage.

Random Drift

All materials are composed of atoms, each capable of being ionized. If some form of energy, such as heat, is applied to a material, some electrons acquire enough energy to move to a higher energy level. As a result, some electrons are freed from their parent atoms, which then become ions. Other forms of energy, particularly light or an electric field, will also cause ionization.

The number of free electrons resulting from ionization depends on the quantity of energy applied to a material and the atomic structure of the material. At room temperature, some materials, classified as conductors, have an abundance of free electrons. Under a similar condition, materials classified as insulators exchange relatively few free electrons.

In a study of electric current, conductors are of major concern. Conductors consist of atoms with loosely bound electrons in their outer orbits. Due to the effects of increased energy, these outermost electrons frequently break away from their atoms and freely drift throughout the material. The free electrons take an unpredictable path and drift haphazardly about the material. This movement is called random drift. Random drift of electrons occurs in all materials. The degree of random drift is greater in **a** conductor than in an insulator.

Directed Drift

Associated with every charged body is an electrostatic field. Bodies with like charges repel one another, and bodies with unlike charges attract each other. An electron is affectedly an electrostatic field in the same manner as any negatively charged body. It is repelled by a negative charge and attracted by a positive charge. If a conductor has a difference in potential impressed across it, a direction is imparted to the random drift (Figure 2-25). This causes the free electrons to be repelled away from the negative terminal and attracted toward the positive terminal. This constitutes a general migration of electrons from one end of the conductor to the other. The directed migration of free electrons due to the potential difference is called directed drift.

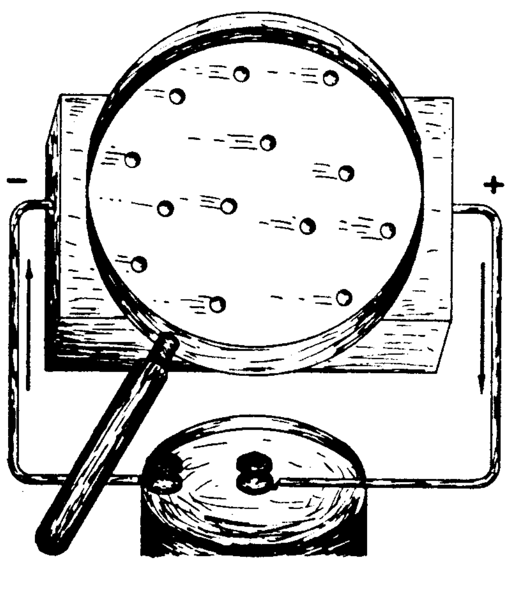


FIGURE 2-25. Directed Drift.

The directed movement of the electrons occurs **at a** relatively low velocity (rate of motion in a particular direction). The effect of this directed movement, however, is almost instantaneous (Figure 2-26). As a difference in potential is impressed across the conductor, the positive terminal of the battery attracts electrons from point A. Point A now has a deficiency of electrons. As a result, electrons are attracted from point B to point A. Point B now has an electron deficiency therefore, it will attract electrons. This same effect occurs throughout the conductor and repeats itself from points D to C. At the same instant the positive battery terminal attracts electrons from point A, the negative terminal repels electrons toward point D. These electrons are attracted to point D as it gives up electrons to point C. This process continues for as long as a difference in potential exists across the conductor. Though an individual electron moves quite slowly through the conductor, the effect of a directed drift occurs almost instantly. As an electron moves into the conductor at point D, an electron is leaving at point A. This action takes place at approximately the speed of light.

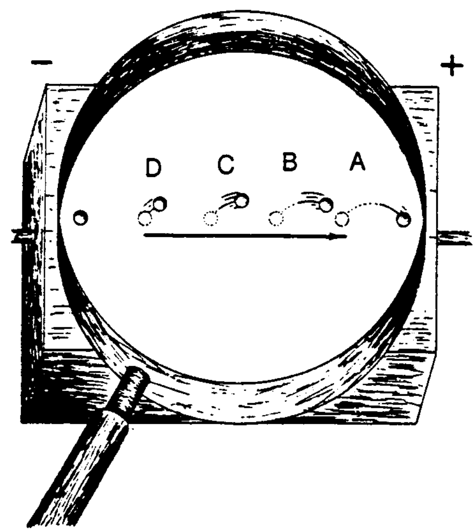


FIGURE 2-26. Effect of Directed Drift.

Magnitude of Current F1ow

Electric current is the directed movement of electrons. Directed drift, therefore, is current, and the terms can be used interchangeably. The term "directed drift" helps distinguish the random and directed motion of electrons. However, "current flow" is the term most commonly used to indicate a directed movement of electrons.

The magnitude of current flow is directly related to the amount of energy that passes through a conductor as a result of the drift action. An increase in the number of energy carriers (moving free electrons) or an increase in the energy of the existing valence electrons increases the current flow. When an electric potential is impressed across a conductor, the velocity of the free electrons increases, causing an increase in the energy of the carriers. An increased number of electrons is also generated, providing added carriers of energy. The additional number of free electrons is relatively small. Thus, the magnitude of current flow depends mainly on the velocity of the existing moving electrons.

The difference in potential affects the magnitude of current flow. Initially, free electrons are given additional energy because of the repelling and attracting electrostatic field. If the difference in potential (voltage) is increased, the electric field will be stronger, the amount of energy imparted to a valence electron will be greater, and the current will be increased. If the potential difference is decreased, the strength of the field is reduced, the energy supplied to the electron is diminished, and the current is decreased.

Measurement of Current

The magnitude of current is measured in amperes. A current of 1 ampere is said to flow when 1 coulomb of charge passes a point in one second (1 coulomb equals the charge of 6.242 times 10 to the 18th power electrons). Often the ampere is much too large a unit for measuring current. Therefore, the milliampere (mA), one-thousandth of an ampere, or the microampere (uA), one-millionth of an ampere, is used. The device that measures current is called an ammeter.

ELECTRICAL RESISTANCE

The directed movement of electrons constitutes a current flow. Electrons do not move freely through a conductor's crystalline structure. Some materials offer little opposition to current flow, while other materials greatly oppose current flow. This opposition to current flow is resistance (R), and the unit of measure is the ohm. The greater the resistance in the circuit, the smaller the current will be from the power supply. Resistance is essential in a circuit. If all the resistance in a circuit was eliminated, a short circuit would result. If not prevented, this maximum current flow will damage the electrical system. The standard of measure for 1 ohm is the resistance provided at 0 degrees Celsius by a column of mercury having a cross-sectional area of 1 square millimeter and a length of 106.3 centimeters. A conductor has 1 ohm of resistance when an applied potential of 1 volt produces a current of 1 ampere. The symbol used to represent the ohm is the Greek letter omega (Ω).

Resistance, although an electrical property, is determined by the physical structure of a material. Many of the same factors that control current flow govern the resistance of a material. Therefore, the factors that affect current flow will help explain the factors affecting resistance.

The magnitude of resistance is determined in part by the number of free electrons available within the material. Since a decrease in the number of free electrons will decrease the current flow, the opposition to current flow (resistance) is greater in a material with fewer free electrons. Thus, the resistance of a material is determined by the number of free electrons available in a material. The conditions that limit current flow also affect resistance. The type of material, physical dimensions, and temperature affect the resistance of a conductor.

Effect of Type of Material

Depending on their atomic structure, different materials have different quantities of free electrons. Therefore, the various conductors used in electrical applications have different values of resistance.

Consider a simple metallic substance. Most metals are crystalline in structure and consist of atoms that are tightly bound in the lattice network. The atoms of such elements are so close together that the electrons in the outer shell of the atom are associated with one atom as much as with its neighbor (Figure2-27 view A). As a result, the force of attachment of an outer electron with an individual atom is practically zero. Depending on the metal, at least one electron, sometimes two, and, in a few cases, three electrons per atom exist in this state. In such a case, a relatively small amount of additional electron energy would free the outer electrons from the attraction of the nucleus. At normal room temperature, materials of thpe type have many free electrons and are good conductors. Good conductors have a low resistance.

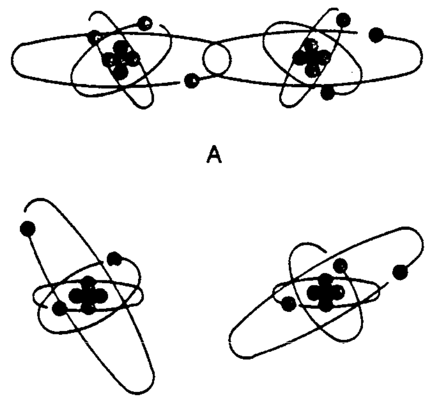


FIGURE 2-27. Atomic Spacing in Conductors.

If the atoms of a material are farther apart, the electrons in the outer shells will not be equally attached to several atoms as they orbit the nucleus (view B). They are attracted to the nucleus of the parent atom only. Therefore, a greater amount of energy is required to free any of these electrons. Materials of this type are poor conductors and have a high resistance.

Silver, gold, and aluminum are good conductors. Therefore, materials composed of their atoms would have a low resistance. The element copper is the conductor most widely used throughout electrical applications. Silver has a lower resistance than copper, but its cost limits usage to circuits where a high conductivity is demanded. Aluminum, which is much lighter than copper, is used as a conductor when weight is a major factor.

Effect of Physical Dimensions

Cross-sectional Area. Cross-sectional area greatly affects the magnitude of resistance. If the cross-sectional area of a conductor is increased, a greater quantity of electrons are available to move through the conductor. Therefore, a larger current will flow for a given amount of applied voltage. An increase in current indicates that when the cross-sectional area of a conductor is increased, the resistance must have decreased. If the cross-sectional area of a conductor is decreased, the number of available electrons decreases and, for a given applied voltage, the current through the conductor decreases. A decrease in current flow indicates that when the cross-sectional area of a conductor is decreased, the resistance must have increased. Thus, the resistance of a conductor is inversely proportional to its cross-sectional area.

Conductor Diameter. The diameter of conductors used in electronics is often only a fraction of an inch. Therefore, the diameter is expressed in mils (thousandths of an inch). It is also standard practice to assign the unit circular mil to the cross-sectional area of the conductor. The circular mil is found by squaring the diameter, when the diameter is expressed in mils. Thus, if the diameter is 35 mils (0.035 inch, the circular mil area equals 35^2 or 1,225 circular mils. Figure 2-28 shows a comparison between a square mil and circular mil.

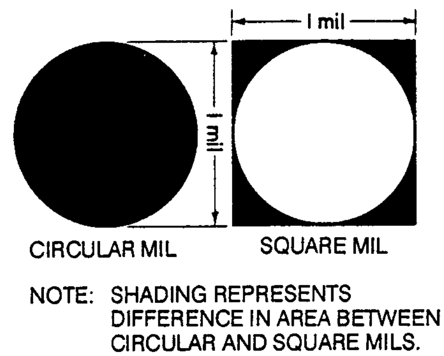


FIGURE 2-28. Square and Circular Mil.

Conductor Length. The length of a conductor is also a factor that determines the resistance of a conductor. If the length of a conductor is increased, the amount of energy given up increases. As free electrons move from atom to atom, some energy is given off as heat. The longer a conductor is, the more energy is lost to heat. The additional energy loss subtracts from the energy being transferred through the conductor, resulting in a decrease in current flow for a given applied voltage. A decrease in current flow indicates an increase in resistance, since voltage was held constant. Therefore, if the length of a conductor is increased the resistance increases. The resistance of a conductor is directly proportional to its length.

Effect of Temperature

Temperature changes affect the resistance of materials in different ways. In some materials, an increase in temperature causes an increase in resistance. In others, an increase in temperature causes a decrease in resistance. The amount of change of resistance per unit change in temperature is the temperature coefficient. If for an increase in temperature the resistance of a material increases, it has a positive temperature coefficient. A material whose resistance decreases with an increase in temperature has a negative temperature coefficient. Most conductors used in electronic applications have a positive temperature coefficient. However, carbon, a frequently used material, is a substance with a negative temperature coefficient. Several materials, such as the alloys constantan and manganin, are considered to have a zero temperature coefficient because their resistance remains relatively constant for changes in temperature.

CONDUCTANCE

Electricity is often explained in terms of opposites. The opposite of resistance is conductance. Conductance is the ability of a material to pass electrons. The same factors that affect the magnitude of resistance affect conductance, but in the opposite manner. Conductance is directly proportional to area and inversely proportional to the length of the material. The temperature of the material is also a factor. With a constant temperature, the conductance of a material can be calculated.

The unit of conductance is the mho, which is ohm spelled backwards, or siemens. Whereas the symbol used to represent resistance (R) is the Greek letter omega (Ω), the symbol used to represent conductance is (G). The relationship between resistance and conductance is a reciprocal one. A reciprocal of a number is 1 divided by the number. In terms of resistance and conductance, $R = 1/G$ and $G = 1/R$.

ELECTRICAL RESISTORS

Resistance is a property of every electrical component. At times, its effects will be undesirable. However, resistance is used in many varied ways. Resistors are components manufactured in many types and sizes to possess specific values of resistance. In a schematic representation, a resistor is drawn as a series of jagged lines (Figure 2-29).

Composition of Resistors

One of the most common types of resistors is the molded composition, usually referred to as the carbon resistor. These resistors are manufactured in a variety of sizes and shapes. The chemical composition of the resistor. which is accurately controlled by the manufacturer. determines its ohmic value. Carbon resistors are made in ohmic values that range from 1 ohm to millions of ohms. The physical size of the resistor is related to its wattage rating. the resistor's ability to dissipate heat caused by the resistance.

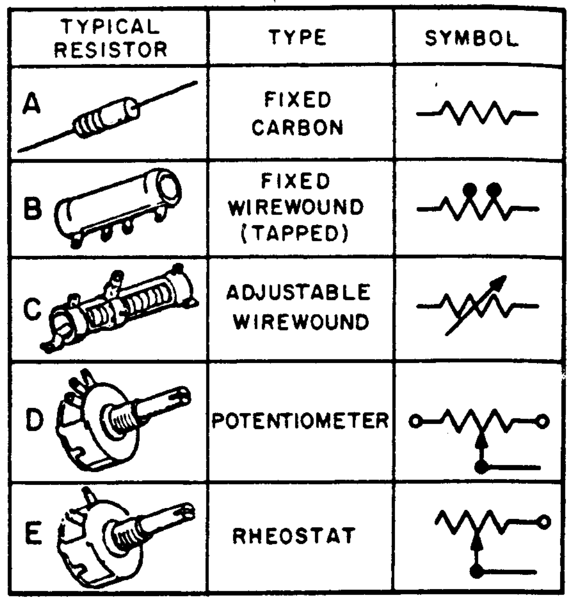


FIGURE 2-29. Types of Resistors.

Carbon is the main ingredient of carbon resistors. In their manufacture. fillers or binders are added to the carbon to obtain various resistor values. Examples of these fillers are clay. bakelite. rubber. and talc. These fillers are doping agents which change the overall conduction characteristics. Carbon resistors are the most common resistors because they are inexpensive and easy to manufacture. They also have an adequate tolerance for most electrical and electronic applications. Their prime disadvantage is that they tend to change value as they age. Another disadvantage is their limited power-handling capacity.

The disadvantage of carbon resistors can be overcome by using wirewound resistors (Figure 2-29 views B and C). These resistors have very accurate values and can handle higher current than carbon resistors. The material often used to manufacture wirewound resistors is German silver, composed of copper, nickel, and zinc. The qualities and quantities of these elements in the wire determine the resistivity of the wire, which is the measure or ability of the wire to resist current. Usually the percent of nickel in the wire determines the resistivity. One disadvantage of the wirewound resistor is that it takes a large amount of wire to manufacture a resistor of high ohmic value, thereby increasing the cost. A variation of the wirewound resistor provides an exposed surface to the resistance wire on one side. An adjustable tap is attached to this side. Such resistors, sometimes with two or more adjustable taps, are used as voltage dividers in power supplies and in other applications where a specific voltage needs to be tapped off.

Types of Resistors

The two kinds of resistors are freed and variable. The freed resistor will have one value and will never change, other than through temperature, age, and so forth. The resistors in views A and B are fixed resistors. The tapped resistor in view B has several fixed taps which make more than one resistance value available. The sliding cent act resist or in view C has an adjustable collar that can be moved to tap off any resistance within the ohmic value range of the resistor.

There are two types of variable resistors: the potentiometer and the rheostat (views D and E). An example of the potentiometer is the volume control on your radio. An example of the rheostat is the dimmer control for the dash lights in an automobile. There is a slight difference between them. Rheostats usually have two connections: one fixed and the other movable. Any variable resistor can properly be called a rheostat. The potentiometer always has three connections: two fixed and one movable. Generally, the rheostat has a limited range of values and high current-handling capability. The potentiometer has a wide range of values, but it usually has a limited current-handling capability. Potentiometers are always connected as voltage dividers.

WATTAGE RATING

When a current is passed through a resistor, heat develops within the resistor. The resistor must be able to dissipate this heat into the surrounding air. Otherwise, the temperature of the resistor rises causing a change in resistance or possibly causing the resistor to burn out.

The resistor's ability to dissipate heat depends on the design of the resistor. It depends on the amount of surface area exposed t o the air. A resistor designed to dissipate a large amount of heat therefore must be large. The heat dissipating capability of a resistor is measured in watts. Some of the more common wattage ratings of carbon resistors are 1/8 watt, 1/4 watt, 1/2 watt, 1 watt, and 2 watts. In some of the newer state-of-the-art circuits, much smaller wattage resistors are used. Generally, the type that can be physically worked with are of the values above. The higher the wattage rating of the resistor, the larger its physical size. Resistors that dissipate very large amounts of power (watts) are usually wirewound resistors. Wirewound resistors with wattage ratings up to 50 watts are not uncommon. Figure 2-30 shows some resistors with different wattage ratings.

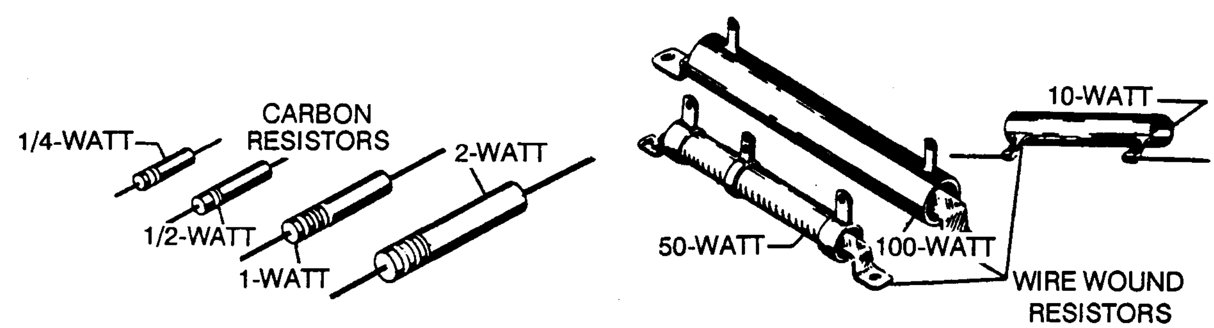


FIGURE 2-30. Resistors of Different Wattage Ratings.

CHAPTER 3

DIRECT CURRENT

INTRODUCTION

This chapter describes the basic direct current (DC) circuit and the basic schematic diagram of that circuit. The schematic diagram is used when working in electricity and electronics. This chapter also describes the series DC circuit and the parallel DC circuit. It explains how to determine the total resistance, current, voltage, and power in a series, parallel, or series-parallel network through the use of Ohm's and Kirchhoff's Laws.

BASIC ELECTRIC CIRCUIT

The flashlight is an example of a basic electric circuit. It contains a source of electrical energy (the dry cells in the flashlight), a load (the bulb) that changes the electrical energy into a more useful form of energy (light), and a switch to control the energy delivered to the load.

A load is any device through which an electrical current flows and which changes this electrical energy into a more useful form. The following are common examples of loads:

- A light bulb (changes electrical energy to light energy).
- An electric motor (changes electrical energy into mechanical energy).
- A speaker in a radio (changes electrical energy into sound).

A source is the device that furnishes the electrical energy used by the load. It may be a simple dry cell (as in a flashlight), a storage battery (as in an automobile), or a power supply (such as a battery charger). A switch permits control of the electrical device by interrupting the current delivered to the load.

SCHEMATIC REPRESENTATION

The engineer's main aid in troubleshooting a circuit in a piece of equipment is the schematic diagram. This is a picture of the circuit that uses symbols to represent the various circuit components. A relatively small diagram can show large or complex circuits. Before studying the basic schematic, review the appendix, which shows the symbols used in the schematic diagram. These symbols and others like them are used throughout the study of electricity and electronics.

The schematic in Figure 3-1 represents a flashlight. In the de-energized state, the switch (S1) is open. There is not a complete path for current (I) through the circuit, so the bulb (DS1) does not light. In the energized state, the switch (S1) is closed. Current flows from the negative terminal of the battery (BAT), through the switch (S1), through the lamp (DS1), and back to the positive terminal of the battery. With the switch closed, the path for current is complete. Current will continue to flow until the switch (S1) is moved to the open position or the battery is completely discharged.

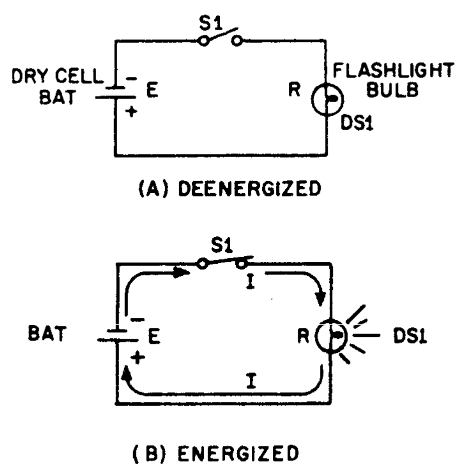


FIGURE 3-1. Schematic of a Flashlight.

OHM'S LAW

In the early part of the 19th century, George Simon Ohm proved by experiment that a precise relationship exists between current, voltage, and resistance. This relationship, called Ohm's Law, is stated as follows: The current in a circuit is directly proportional to the applied voltage and inversely proportional to the circuit resistance. Ohm's Law may be expressed as an equation.

Where:

I = current in amperes

E = voltage in volts

R = resistance in ohms

As stated in Ohm's Law, current is inversely proportional to resistance. As the resistance in a circuit increases, the current decreases proportionately.

In the equation I = E/R, if any two quantities are known, you can determine the third one. Refer to Figure 3-1 view B, the schematic of the flashlight. If the battery (BAT) supplies a voltage of 1.5 volts and the lamp (DS1) has a resistance of 5 ohms, then you can determine the current in the circuit by using these values in the equation:

If the flashlight were a two-cell flashlight, twice the voltage or 3.O volts would be applied to the circuit. You can determine the current in the circuit using this voltage in the equation

As the applied voltage is doubled, the current flowing through the circuit doubles. This demonstrates that the current is directly proportional to the applied voltage.

If the value of resistance of the lamp is doubled, you can determine the current in the circuit:

$$I = \frac{3.0 \text{ volts}}{10 \text{ ohms}}$$

$$I = .3 \text{ amp}$$

The current has been reduced to one-half of the value of the previous equation, or .3 ampere. This demonstrates that the current is inversely proportional to the resistance. Doubling the value of the resistance of the load reduces circuit current value to one-half of its former value.

Figures 3-2 and 3-3 are diagrams for determining resistance and voltage in a basic circuit, respectively.

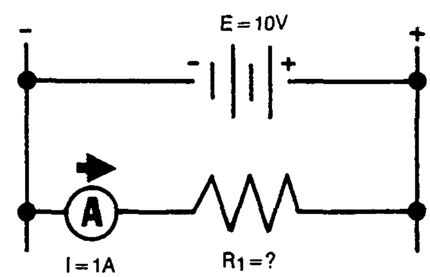


FIGURE 3-2. Determining Resistance in a Basic Circuit.

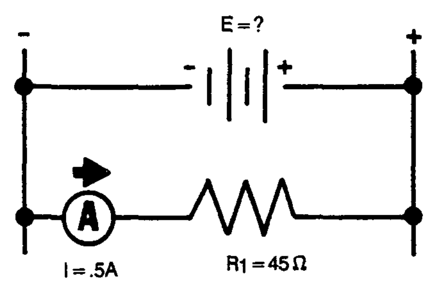


FIGURE 3-3. Determining Voltage in a Basic Circuit.

Using Ohms's Law, the resistance of a circuit can be determined knowing only the voltage and the current in the circuit. In any equation, if all the variables (parameters) are known except one, that unknown can be found. For example, using Ohm's Law, if current (I) and voltage (E) are known, you can determine resistance (R), the only parameter not known:

Basic formula: $I = \frac{E}{R}$

The formula may also be expressed as –

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

The Ohm's Law equation and its various forms may be obtained readily using Figure 3-4. The circle containing E, I, and R is divided into two parts, with E above the line and I and R below the line. To determine the unknown quantity, first cover that quantity with a finger. The position of the uncovered letters in the circle will indicate the mathematical operation to be performed.

For example, to find I, cover I with a finger. The uncovered letters indicate that E is to be divided by R, or –

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

To find the formula for E, cover E with your finger. The result indicates that I is to be multiplied by R, or –

$$E = IR$$

To find the formula for R, cover R. The result indicates that E is to be divided by I, or –

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

POWER

Power, whether electrical or mechanical, pertains to the rate at which work is being done. Work is done whenever a force causes motion. When a mechanical force is used to lift or move a weight, work is done. However, force exerted without causing motion, such as the force of a compressed spring acting between two freed objects, does not constitute work.

Voltage is an electrical force that forces current to flow in a closed circuit. However, when voltage exists but current does not flow because the circuit is open, no work is done. This is similar to the spring under tension that produced no motion. The instantaneous rate at which this work is done is called the electric power rate and is measured in watts.

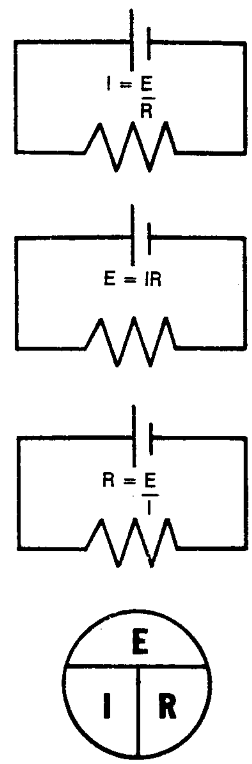


FIGURE 3-4. Ohm's Law in Diagram Form.

A total amount of work may be done in different lengths of time. For example, a given number of electrons may be moved from one point to another in 1 second or in 1 hour, depending on the rate at which they are moved. In both cases, total work done is the same. However, when the work is done in a short time, the wattage, or instantaneous power rate, is greater than when the same amount of work is done over a longer period of time.

The basic unit of power is the watt. Power in watts equals the voltage across a circuit multiplied by current through the circuit. This represents the rate at any given instant at which work is being done. The symbol P indicates electrical power. The basic power formula is–

P = I x E

Where:

I = current in the circuit

E = voltage

The amount of power changes when either voltage or current or both are changed.

In practice, the only factors that can be changed are voltage and resistance. In explaining the different forms that formulas may take, current is sometimes presented as a quantity that is changed. Remember, if current is changed it is because either voltage or resistance has been changed.

Four of the most important electrical quantities are voltage (E), current (I), resistance (R), and power (P). The relationships among these quantities are used throughout the study of electricity. Previously, P was expressed in terms of alternate pairs of the other three basic quantities (E, I, and R). In practice, any one of these quantities can be expressed in terms of any two of the others.

Figure 3-5 is a summary of 12 basic formulas. The four quantities E, I, R, and P are at the center of the figure. Next to each quantity are three segments. In each segment, the basic quantity is expressed in terms of two other basic quantities and no two segments are alike.

For example, you can use the formula wheel in Figure 3-5 to find the formula to solve this problem. A circuit has a source voltage of 24 volts and a measured current of 10 amperes. What would the power rate be? Find Pin the center of the wheel. IE or current multiplied by voltage fits the supplied information.

Given:

I = 10 amps

E = 24 volts

Solution:

P = IE

P = 10 x 24

P = 240 watts

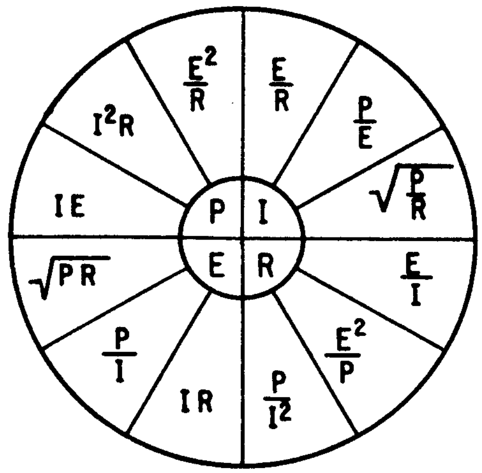


FIGURE 3-5. Summary of Basic Formulas.

Power Rating

Electrical components are often given a power rating. The power rating, in watts, indicates the rate at which the device converts electrical energy into another form of energy, such as light, heat, or motion. An example of such a rating is noted when comparing a 150-watt lamp to a 100-watt lamp. The higher wattage rating of the 150-watt lamp indicates it can convert more electrical energy into light energy than the lamp of the lower rating. Other common examples of devices with power ratings are soldering irons and small electric motors.

In some electrical devices, the wattage rating indicates the maximum power the device is designed to use rather than the normal operating power. A 150-watt lamp, for example, uses 150 watts when operated at the specified voltage printed on the bulb. In contrast, a device such as a resistor is not normally given a voltage or a current rating. A resistor is given a power rating in watts and can be operated at any combination of voltage and current as long as the power rating is not exceeded. In most circuits, the actual power a resistor uses is considerably less than the power rating of the resistor because a 50 percent safety factor is used. For example, if a resistor normally used 2 watts of power, a resistor with a power rating of 3 watts would be selected.

Resistors of the same resistance value are available indifferent wattage values. Carbon resistors, for example, are commonly made in wattage ratings of 1/8, 1/4, l/2, 1, and 2 watts. The larger the physical size of a carbon resistor, the higher the wattage rating. This is true because a larger surface area of material radiates a greater amount of heat more easily.

When resistors with wattage ratings greater than 5 watts are needed, wirewound resistors are used. Wirewound resistors are made in values between 5 and 200 watts, with special types being used for power in excess of 200 watts.

As with other electrical quantities, prefixes may be attached to the word "watt" when expressing very large or very small amounts of power. Some of the more common of these are the megawatt (1,000,000 watts), the kilowatt (1,000 watts), and the milliwatt (1/1,000 of a watt).

Power Conversion and Efficiency

The term "power consumption" is common in the electrical field. It is applied to the use of power in the same sense that gasoline consumption is applied to the use of fuel in an automobile.

Another common term is "power conversion." Power used by electrical devices is converted from one form of energy to another. An electrical motor converts electrical energy to mechanical energy. An electric light bulb converts electrical energy into light energy, and an electric range converts electrical energy into heat energy. Power electrical devices use is measured in watt-hours. This practical unit of electrical energy equals 1 watt of power used continuously for 1 hour. The term "kilowatt hour" (kWh), used more often on a daily basis, equals 1,000 watt-hours.

The efficiency (EFF) of an electrical device is the ratio of power converted to useful energy divided by the power consumed by the device. This number will always be less than one (1.00) because of the losses in any electrical device. If a device has an efficiency rating of .95, it effectively transforms 95 watts into useful energy for every 100 watts of input power. The other 5 watts are lost to heat or other losses that cannot be used.

To calculate the amount of power converted by an electrical device is simple. The length of time (t) the device is operated and the input power in horsepower (HP) rating are needed (1 horsepower equals 746 watts). Horsepower, a unit of work, is often found as a rating on electrical motors.

Example: A 3/4-HP motor operates 8 hours a day. How much power is converted by the motor per month? How many kWh does this represent?

Given:

$t = 8 \text{ hours} \times 30 \text{ days}$

$P = 3/4 \text{ HP}$

Solution: Convert horsepower to watts

$P = \text{HP} \times 746 \text{ watts}$

$P = 3/4 \times 746 \text{ watts}$

$P = 559 \text{ watts}$

Use the following to convert watts to watt-hours:

$P = \text{work} \times \text{time}$

$P = 559 \text{ watts} \times 8 \text{ hours} \times 30 \text{ days}$

$P = 134{,}000 \text{ watt-hours per month}$

NOTE: These figures are approximate.

Use the following to convert to kWh:

$$P = \frac{\text{Power in watt hours}}{1{,}000}$$

$$P = \frac{134{,}000 \text{ watt hours}}{1{,}000}$$

$P = 134 \text{ kWh}$

If the motor actually uses 137 kWh per month, what is the efficiency of the motor?

Given:

Power converted = 134 kWh per month

Power used = 137 kWh per month

Solution:

$$EFF = \frac{\text{Power converted}}{\text{Power used}}$$

$$EFF = \frac{\text{134 kWh per month}}{\text{137 kWh per month}}$$

EFF = .978 (rounded to three figures)

SERIES DC CIRCUITS

When two unequal charges are connected by a conductor, a complete pathway for current exists. An electric circuit is a complete conducting pathway. It consists of the conductor and the path through the voltage source. Inside the voltage source, current flows from the positive terminal, through the source, and emerges at the negative terminal.

Characteristics

A series circuit is a circuit that contains only one path for current flow. Figure 3-6 shows the basic circuit and a more complex series circuit. The basic circuit has only one lamp, and the series circuit has three lamps connected in series.

Resistance in a Series Circuit. The current in a series circuit must flow through each lamp to complete the electrical path in the circuit (Figure 3-6). Each additional lamp offers added resistance. In a series circuit, the total circuit resistance (Rt) equals the sum of the individual resistances (Rt = R1 + R2 + R3 + Rn).

> **NOTE:** The subscript n denotes any number of additional resistances that might be in the equation.

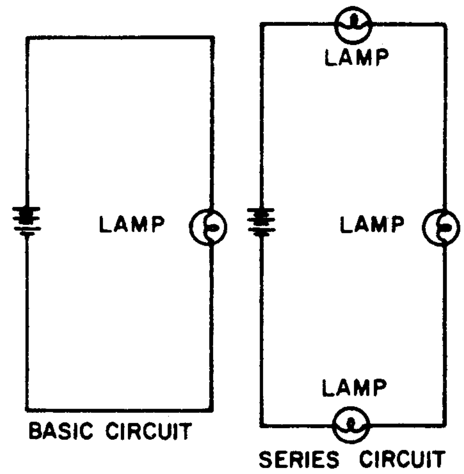


FIGURE 3-6. Comparison of Basic and Series Circuits.

Example: Figure 3-7 shows a series circuit consisting of three resistors (10 ohms, 1.5 ohms, and 30 ohms). What is the total resistance?

Given:

R1 = 10 ohms

R2 = 15 ohms

R3 = 30 ohms

Solution:

Rt = Rl + R2 + R3

Rt = 10 ohms + 15 ohms + 30 ohms

Rt = 55 ohms

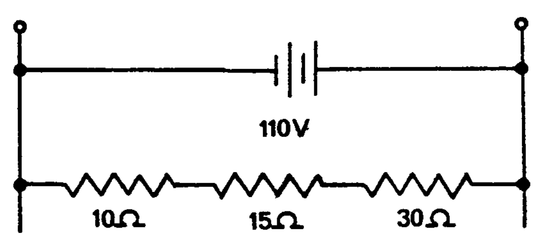


FIGURE 3-7. Calculating Total Resistance in a Series Circuit.

In some circuit applications, the total resistance is known and the value of one of the circuit resistors has to be determined. The equation Rt = R1 + R2 + R3 can be transposed to solve for the value of the unknown resistance (Figure 3-8).

Rt - Rl - R2 = R3

40 ohms - 10 ohms - 10 ohms = 20 ohms

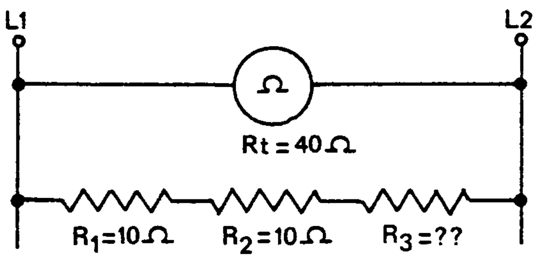


FIGURE 3-8. Calculating the Value of One Resistance in a Series Circuit.

Current in a Series Circuit. Since there is only one path for current in a series circuit, the same current must flow through each component of the circuit. To determine the current in a series circuit, only the current through one of the components need be known.

The fact that the same current flows through each component of a series circuit can be verified by inserting meters into the circuit at various points (Figure 3-9). If this were done, each meter would be found to indicate the same value of current.

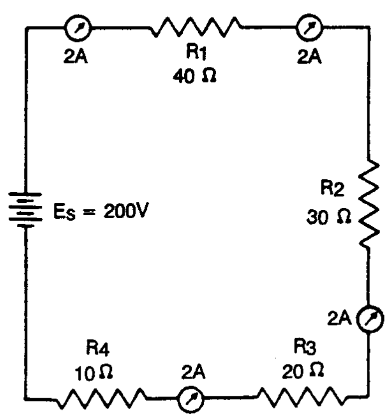


FIGURE 3-9. Current in a Series Circuit.

Voltage in a Series Circuit, The loads in a circuit consume voltage (energy). This is called a voltage drop. Voltage drop across the resistor in a circuit, consisting of a single resistor and a voltage source, is the total voltage across the circuit and equals the applied voltage. The total voltage across a series circuit that consists of more than one resistor is also equal to the applied voltage but consists of the sum of the individual resistor voltage drops. In any series circuit, the sum of the resistor voltage drops must equal the source voltage. An examination of the circuit in Figure 3-10 proves this. In this circuit, a source potential (Et) of 20 volts is consumed by a series circuit consisting of two 5-ohm resistors. The total resistance of the circuit (Rt) equals the sum of the two individual resistance or 10 ohms. Using Ohm's Law, calculate the circuit current (I) as follows:

Given:

Et = 20 volts

Rt = 10 ohms

Solution:

$$It = \frac{Et}{Rt}$$

$$It = \frac{20\ Volts}{10\ ohms}$$

It = 2 amps

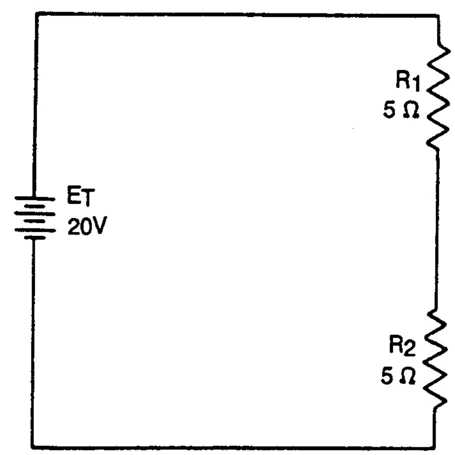


FIGURE 3-10. Calculating Individual Voltage Drops in a Series Circuit.

The value of the resistors is 5 ohms each, and the current through the resistors is 2 amperes. With these values known, you can calculate the voltage drops across the resistors. Calculate the voltage (El) across R1 as follows:

Given:

I1 = 2 amps

R1 = 5 ohms

Solution:

E1 = I1 x R1

El = 2 amps x 5 ohms

El = 10 volts

R2 is the same ohmic value as R1 and carries the same current. Therefore, the voltage drop across R2 is also equal to 10 volts. Adding these two 10-volt drops together gives a total drop of 20 volts, equal to the applied voltage. For series circuit, then –

Et = El + E2 + E3 + ...En

Example: A series circuit consists of three resistors having values of 20 ohms, 30 ohms, and 50 ohms, respectively. Find the applied voltage if the current through the 30-ohm resistor is 2 amperes. To solve the problem, first draw and label a circuit diagram (Figure 3-11).

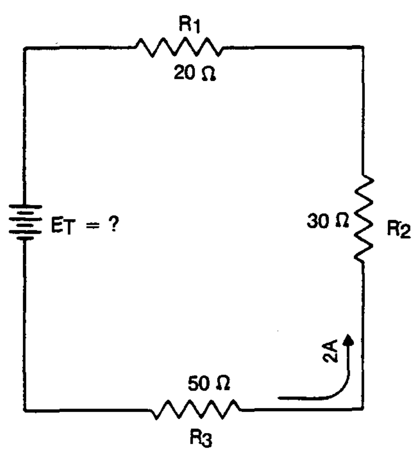


FIGURE 3-11. Calculating Applied Voltage in a Series Circuit.

Given:

R1 = 20 ohms

R2 = 30 ohms

R3 = 50 ohms

I = 2 amps

Solution:

Et = El + E2 + E3

El = R1 x I1 (I1 = the current through resistor R1)

E2 = R2 x I2

E3 = R3 x I3

Substituting:

Et = (Rl X I1) + (R2 X I2) + (R3 X I3)

Et = (20 ohms x 2 amps) + (30 ohms x 2 amps) + (50 ohms x 2 amps)

Et = 40 volts + 60 volts + 100 volts

Et = 200 volts

NOTE: When you use Ohm's Law, the quantities for the equation must be taken from the same part of the circuit. In the above example, the voltage across R2 was computed using the current through R2 and the resistance of R2.

The applied voltage determines the value of the voltage dropped by a resistor. It is in proportion to the circuit resistances. The voltage drops that occur in a series circuit are in direct proportion to the resistances. This is the result of having the same current flow through each resistor. The larger the ohmic value of the resistor, the larger the voltage drop across it.

Power in a Series Circuit. Each of the loads in a series circuit consumes power that is dissipated in the form of heat. Since this power must come from the source, the total power supplied must be equal to the power consumed by the circuit's loads. In a series circuit, the total power equals the sum of the power dissipated by the individual loads. Total power (Pt) equals —

Pt = Pl + P2 + P3 + ...Pn

Example: A series circuit consists of three resistors having values of 5 ohms, 10 ohms, and 15 ohms. Find the total power when 120 volts is applied to the circuit (Figure 3-12).

Given:

R1 = 5 ohms

R2 = 10 ohms

R3 = 15 ohms

Et = 120 volts

Solution: (The total resistance is found first.)

Rt = Rl + R2 + R3

Rt = 5 ohms + 10 ohms + 15 ohms

Rt = 30 ohms

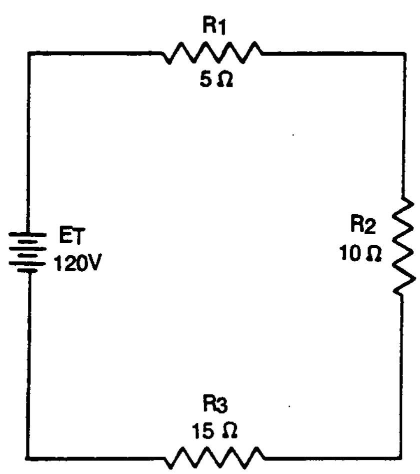


FIGURE 3-12. Calculating Total Power in a Series Circuit.

Calculate the circuit current by using the total resistance and the applied voltage

$$I = \frac{Et}{Rt}$$

$$I = \frac{120 \text{ volts}}{30 \text{ ohms}}$$

I = 4 amps

Calculate the power for each resistor using the power formulas:

For Rl–

$P1 = I^2 x R1$

$P1 = (4 amps)^2 x 5 ohms$

P1 = 80 watts

For R2 –

$P2 = I^2 x R1$

$P2 = (4 amps)^2 x 10 ohms$

P2 = 160 watts

For R3 –

$P3 = I^2 x R3$

$P3 = (4 amps)^2 x 15 ohms$

P3 = 240 watts

To obtain total power –

Pt = Pl + P2 + P3

Pt = 80 watts + 160 watts + 240 watts

Pt = 480 watts

To check the answer, calculate the total power delivered by the source:

P source = I source x E source

P source = 4 amps x 120 volts

P source = 480 watts

The total power equals the sum of the power used by the individual resistors.

Rules for Series DC Circuits

Listed below are the important factors governing the operation of a series circuit. For ease of study, they are set up as a group of rules. They must be completely understood before studying more advanced circuit theory.

1. The same current flows through each part of a series circuit.

   $I_t = I_1 = I_2 = I_3 = I_n$

2. The total resistance of a series circuit equals the sum of the individual resistances.

   $R_t = R_1 + R_2 + R_3 + R_n$

3. The total voltage across a series circuit equals the sum of the individual voltage drops.

   $E_t = E_1 + E_2 + E_3 + E_n$

4. The voltage drop across a resistor in a series circuit is proportional to the ohmic value of the resistor..

5. The total power in a series circuit equals the sum of the individual powers used by each circuit component.

   $P_t = P_1 + P_2 + P_3 + P_n$

Series Circuit Analysis

The following sample problems show the procedure for solving series circuits:

Example: Three resistors of 5 ohms, 10 ohms, and 15 ohms are connected in series with a power source of 90 volts (Figure 3-13).

a. What is the total resistance?

b. What is the circuit current?

c. What is the voltage drop across each resistor?

d. What is the power of each resistor?

e. What is the total power of the circuit?

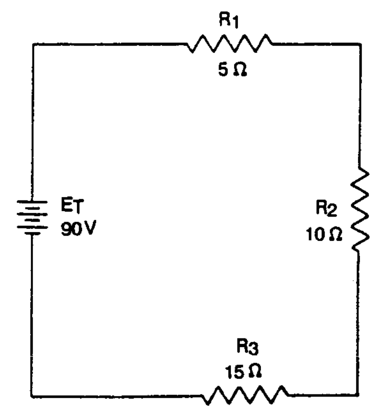


FIGURE 3-13. Solving for Various Values in a Series Circuit.

In solving the circuit, find the total resistance first. Next, calculate the circuit current. Once the current is known, calculate the voltage drops and power dissipations.

Given:

R1 = 5 ohms

R2 = 10 ohms

R3 = 15 Ohms

Et = 90 volts

Solution (a):

Rt = R1 + R2 + R3

Rt = 5 ohms + 10 ohms + 15 ohms

Rt = 30 ohms

Solution (b):

$$I = \frac{Et}{Rt}$$

$$I = \frac{90 \text{ volts}}{30 \text{ ohms}}$$

I = 3 amps

Solution (c):

El = (I)(R1)

El = 3 amps x 5 ohms

E1 = 15 volts

E2 = (I)(R2)

E2 = 3 amps x 10 ohms

E2 = 30 volts

E3 = (I)(R3)

E3 = 3 amps x 15 ohms

E3 = 45 volts

Solution (d):

P1 = (I)(E1)

P1 = 3 amps x 15 volts

P1 = 45 watts

P2 = (I)(E2)

P2 = 3 amps x 30 volts

P2 = 90 watts

P3 = (I)(E3)

P3 = 3 amps x 45 volts

P3 = 135 watts

Solution (e):

Pt = (Et)(I)

Pt = 90 volts x 3 amps

Pt = 270 watts

or

Pt = P1 + P2 + P3

Pt = 45 watts + 90 watts + 135 watts

Pt = 270 watts

Example: Four resistors (Rl = 10 ohms, R2 = 10 ohms, R3 = 50 ohms, and R4 = 30 ohms) are connected in series with a power source (Figure 3-14). The current through the circuit is 1/2 ampere.

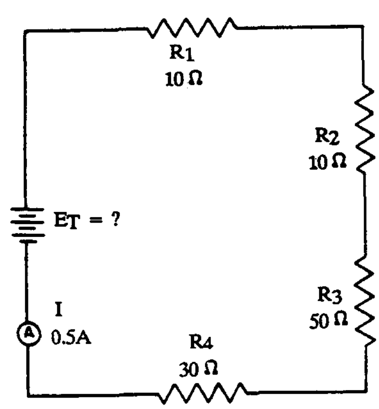


FIGURE 3-14. Computing Series Circuit Values.

a. What is the battery voltage?

b. What is the voltage across each resistor?

c. What is the power expended in each resistor?

d. What is the total power?

Given:

R1 = 10 ohms

R2 = 10 ohms

R3 = 50 ohms

R4 = 30 ohms

I = 0.5 amp

Solution (a):

Et = (I)(Rt)

Rt = Rl + R2 + R3 + R4

Rt = 10 ohms + 10 ohms + 50 ohms + 30 ohms

Rt = 100 ohms

Et = 0.5 amp x 100 ohms

Et = 50 volts

Solution (b):

El = (I)(R1)

El = 0.5 amp x 10 ohms

El = 5 volts

E2 = (I)(R2)

E2 = 0.5 amp x 10 ohms

E2 = 5 volts

E3 = (I)(R3)

E3 = 0.5 amp x 50 ohms

E3 = 25 volts

E4 = (I)(R4)

E4 = 0.5 amp x 30 ohms

E4 = 15 volts

Solution (c):

P1 = (I)(E1)

P1 = 0.5 amp x 5 volts

P1 = 2.5 watts

P2 = (I)(E2)

P2 = 0.5 amp x 5 volts

P2 = 2.5 watts

P3 = (I)(E3)

P3 = 0.5 amp x 25 volts

P3 = 12.5 watts

P4 = (I)(E4)

P4 = 0.5 amp x 15 volts

P4 = 7.5 watts

Solution (d):

$Pt = P1 + P2 + P3 + P4$

Pt = 2.5 watts + 2.5 watts + 12.5 watts + 7.5 watts

Pt = 25 watts

or

Pt = (I)(Et)

Pt = 0.5 amp x 50 volts

Pt = 25 watts

or

$$Pt = \frac{Et^2}{Rt}$$

$$Pt = \frac{(50 \text{ volts})^2}{100 \text{ ohms}}$$

$$Pt = \frac{2{,}500 \text{ volts}}{100 \text{ ohms}}$$

Pt = 25 watts

When applying Ohm's Law to a series circuit, consider whether the values used are component values or total values. When the information available enables the use of Ohm's Law to find total resistance, total voltage, and total current, total values must be inserted into the formula.

To find total resistance –

$$Rt = \frac{Et}{It}$$

To find total voltage –

Et = It x Rt

To find total current –

$$It = \frac{Et}{Rt}$$

NOTE: In a series circuit, It equals I. However, the distinction between It and I in the formula should be noted because future circuits may have several currents. Then it would be necessary to differentiate between It and other currents.

To compute any quantity (E, I, R, or P) associated with a single given resistor, obtain the values used in the formula from that particular resistor. For example, to find the value of an unknown resistance, use the voltage across and the current through that particular resistor.

To find the value of a resistor –

$$Rx = \frac{Ex}{Ix}$$

To find the voltage drop across a resistor –

Ex = (Ix)(Rx)

To find current through a resistor –

$$Ix = \frac{Ex}{Rx}$$

KIRCHHOFF'S VOLTAGE LAW

In 1847, G. R. Kirchhoff extended the use of Ohm's Law by developing a simple concept concerning the voltages contained in a series circuit loop. Kirchhoff's Law states, "The algebraic sum of the voltage drops in any closed path in a circuit and the electromotive forces in that path is equal to zero."

To state Kirchhoff's Law another way, the voltage drops and voltage sources in a circuit are equal at any given moment in time. If the voltage sources are assumed to have one sign (positive or negative) at that instant and the voltage drops are assumed to have the opposite sign, the result of adding the voltage sources and voltage drops will be zero.

NOTE: The terms "electromotive force" and "EMF" are used when explaining Kirchhoff's Law because Kirchhoff's Law is used in alternating current circuits (covered in later chapters). In applying Kirchhoff's Law to direct current circuits, the terms "electromotive force" and "EMF" apply to voltage sources such as batteries or power supplies.

Through the use of Kirchhoff's Law, circuit problems can be solved which would be difficult, and often impossible, with knowledge of Ohm's Law alone. When Kirchhoff's Law is properly applied, an equation can be set up for a closed loop and the unknown circuit values can be calculated.

Example: Three resistors are connected across a 50-volt source. What is the voltage across the third resistor if the voltage drops across the first two resistors are 25 volts and 15 volts?

The basic series voltage rule states –

Et = El + E2 + E3

Since the voltages of El and E2 as well as the voltage supply Et are given, the equation can be rewritten with the known values:

50 volts = 25 volts + 15 volts + Ex (the unknown factor)

Therefore –

Ex = 50 volts - 25 volts - 15 volts

Ex = 10 volts

Using this same idea, many electrical problems can be solved, not by knowing all the mysterious properties of electricity, but by understanding the basic principles of math. This algebraic expression can be used for all equations, not just for voltage, current, and resistance.

CIRCUIT TERMS AND CHARACTERISTICS

The following terms and characteristics used in electrical circuits are used throughout the study of electricity and electronics.

Open Circuit

A circuit is open when a break interrupts a complete conducting pathway. Although an open circuit normally occurs when a switch is used to de-energize a circuit, one may also develop accidentally. To restore a circuit to proper operation, the opening must be located, its cause determined, and repairs made.

Sometimes an open circuit can be located visually by close inspection of the circuit components. Defective components, such as burned out resistors, can usually be discovered by this method. Others, such as a break in wire covered by insulation or the melted element of an enclosed fuse, are not visible to the eye. Under such conditions, the understanding of the effect an open circuit has on circuit conditions enables a technician to use test equipment to locate the open component.

In Figure 3-15, the series circuit consists of two resistors and a fuse. Notice the effects on circuit conditions when the fuse opens. Current ceases to flow. Therefore, there is no longer a voltage drop across the resistors. Each end of the open circuit conducting path becomes an extension of the battery terminals and the voltage felt across the open circuit equals the applied voltage (Et).

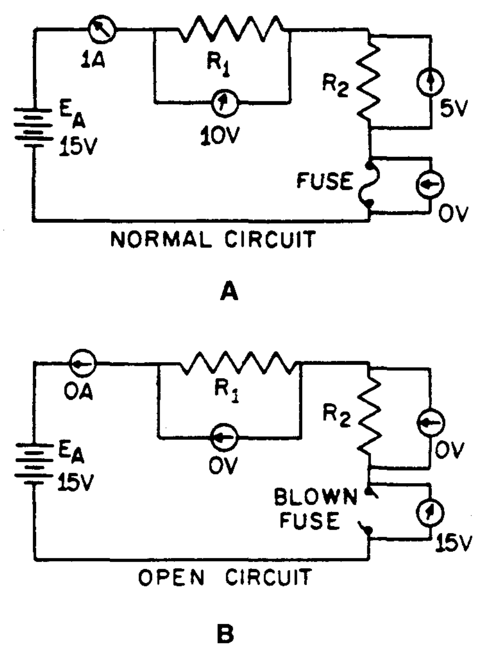


FIGURE 3-15. Normal and Open Circuit

An open circuit has infinite resistance. Infinity represents a quantity so large it cannot be measured. (The symbol for infinity is . In an open circuit, Rt = ∞. .)

Short Circuit

A short circuit is an accidental path of low resistance which passes an abnormally high amount of current. A short circuit exists whenever the resistance of a circuit or the resistance of a part of a circuit drops in value to almost 0 ohms. A short often occurs as a result of improper wiring or broken insulation.

In Figure 3-16, a short is caused by improper wiring. Note the effect on current flow. Since the resistor (Rl) has in effect been replaced with apiece of wire, practically all the current flows through the short and very little current flows through the resistor (R1). Electrons flow through the short (a path of almost zero resistance) and the remainder of the circuit by passing through the 10-ohm resistor (R2) and the battery. The amount of current flow increases greatly because its resistive path has decreased from 10,010 ohms to 10 ohms. Due to the excessive current flow, the 10-ohm resistor (R2) becomes heated. As it trys to dissipate this heat, the resistor will probably be destroyed. Figure 3-17 shows a pictorial wiring diagram, rather than a schematic diagram, to indicate how broken insulation might cause a short circuit.

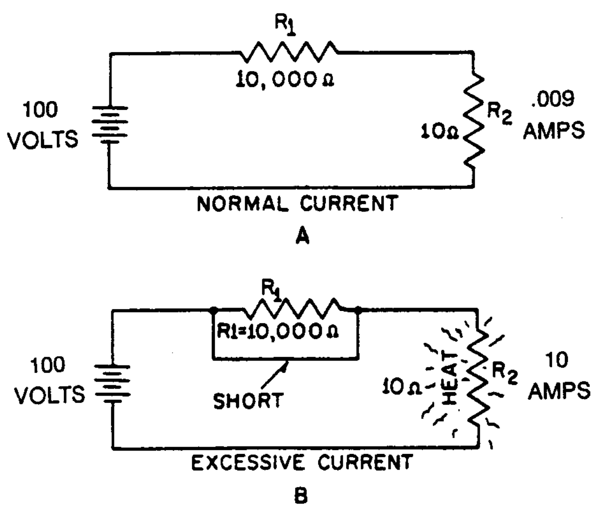


FIGURE 3-16. Normal and Short Circuit Conditions.

Source Resistance

A meter connected across the terminals of a good 1.5-volt battery reads about 1.5 volts. When the same battery is inserted into a complete circuit, the meter reading decreases to something less than 1.5 volts. This difference in terminal voltage is caused by the internal resistance of the battery (the opposition to current offered by the electrolyte in the battery). All sources of electromotive force have some form of internal resistance which causes a drop in terminal voltage as current flows through the source.

Figure 3-18 illustrates this principle, showing the internal resistance of a battery as Ri. In the schematic, the internal resistance is indicated by an additional resist or in series with the battery. With the switch open, the voltage across the battery terminals reads 15 volts. When the switch is closed current flow causes voltage drops around the circuit. The circuit current of 2 amperes causes a voltage drop of 2 volts across R1. The 1 ohm internal battery resistance thereby drops the battery terminal voltage to 13 volts. Internal resistance cannot be measured directly with a meter. An attempt to do this would damage the meter.

Power Transfer and Efficiency

Maximum power is transferred from the source to the load when the resistance of the load equals the internal resistance of the source. The table and the graph in Figure 3-19 illustrate this theory. When the load resistance is 5 ohms, matching the source resistance, the maximum power of 500 watts is developed in the load.

The efficiency of power transfer (ratio of output power to input power) from the source to the load increases as the load resistance is increased. The efficiency approaches 100 percent as the load's resistance approaches a relatively large value compared with that of the source, since less power is lost in the source. The efficiency of power transfer is only 50 percent at the maximum power transfer point (when the load resistance equals the internal resistance of the source). The efficiency of power transfer approaches zero efficiency when the load resistance is relatively small compared with the internal resistance of the source. This is also shown on the chart in Figure 3-19.

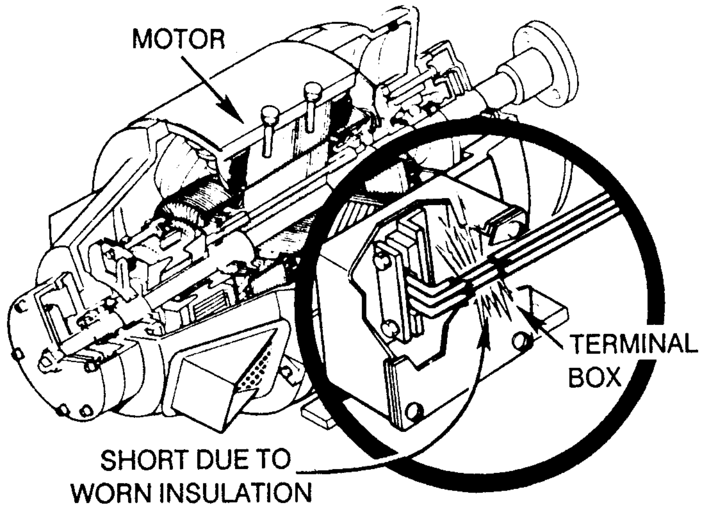


FIGURE 3-17. Short Due to Broken Insulation.

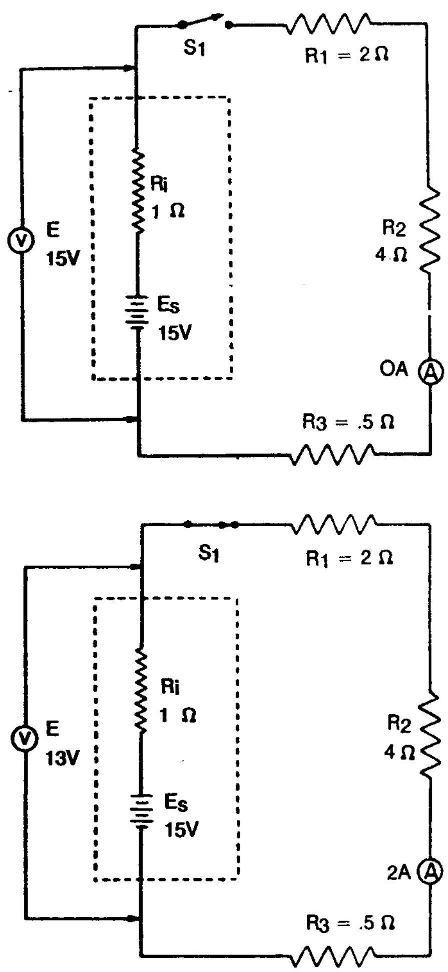


FIGURE 3-18. Effect of Internal Source

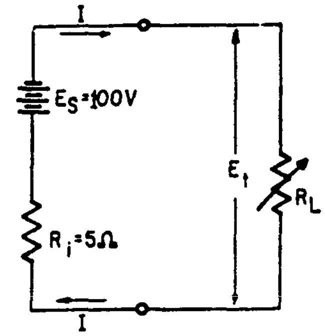
The problem of a desire for both high efficiency and maximum power transfer is resolved by a compromise between maximum power transfer and high efficiency. When the amount of power involved is large and the efficiency is important, the load resistance is made large relative to the source resistance so that the losses are kept small. In this case, the efficiency is high. When the problem of matching a source to a load is important, as in communications circuits, a strong signal may be more important than a high percentage of efficiency. In such cases, the efficiency of power transfer should be only about 50 percent. However, the power transfer would be the maximum the source is capable of supplying.

PARALLEL DC CIRCUITS

The series circuit has only one path for current. Another basic type of circuit is the parallel circuit. While the series circuit has only one path for current, the parallel circuit has more than one path for current. Ohm's Law and Kirchhoff's Law apply to all electrical circuits, but the characteristics of a parallel DC circuit are different than those of a series DC circuit.

Characteristics

A parallel circuit has more than one current path connected to a common voltage source. Parallel circuits, therefore, must contain two or more resistances that are not connected in series. Figure 3-20 shows an example of a basic parallel circuit.

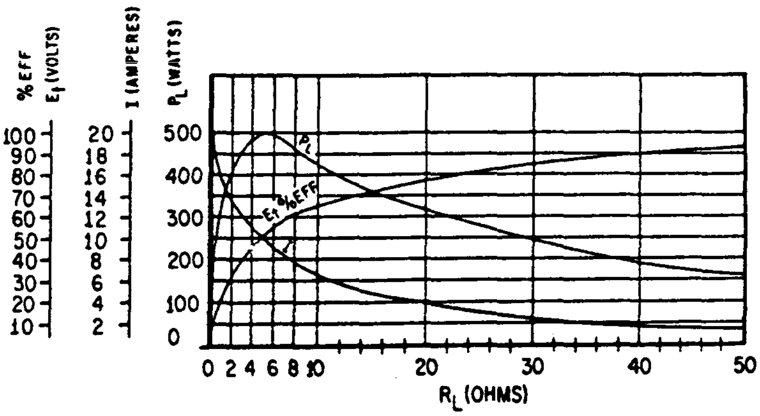


E_S = OPEN-CIRCUIT VOLTAGE OF SOURCE
R_i = INTERNAL RESISTANCE OF SOURCE
E_t = TERMINAL VOLTAGE
R_L = RESISTANCE OF LOAD
P_L = POWER USED IN LOAD
I = CURRENT FROM SOURCE
% EFF. = PERCENTAGE OF EFFICIENCY

(A)
CIRCUIT AND SYMBOL DESIGNATIONS

R_L	E_t	I	P_L	% EFF.
0	0	20	0	0
1	16.7	16.7	278.9	16.7
2	28.6	14.3	409	28.6
3	37.5	12.5	468.8	37.5
4	44.4	11.1	492.8	44.4
5	50	10	500	50
6	54.5	9.1	496.0	54.5
7	58.3	8.3	483.9	58.3
8	61.6	7.7	474.3	61.6
9	64.3	7.1	456.5	64.3
10	66.7	6.7	446.9	66.7
20	80	4	320	80
30	85.7	2.9	248.5	85.7
40	88.9	2.2	195.6	88.9
50	90.9	1.9	172.7	90.9

(B)
CHART



(C)
GRAPH

FIGURE 3-19. Effect of Source Resistance on Power Output.

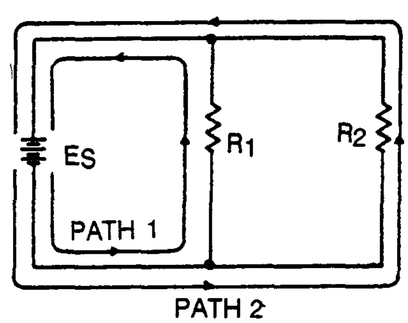


FIGURE 3-20. Example of a Basic Parallel Circuit.

Start at the voltage source (Et) and trace counterclockwise around the circuit in 'Figure 3-20. Two complete and separate paths can be identified in which current can flow. One path is traced from the source, through resistance R1, and back to the source. The other path is from the source, through resistance R2, and back to the source.

Voltage in a Parallel Circuit. The source voltage in a series circuit divides proportionately across each resistor in the circuit. In a parallel circuit, the same voltage is present in each branch (section of a circuit that has a complete path for current). In Figure 3-20, this voltage equals the applied voltage (Et). This can be expressed in equation form:

Et = El = E2 = En

Voltage measurements taken across the resistors of a parallel circuit verify this equation (Figure 3-21). Each meter indicates the same amount of voltage. Notice that the voltage across each resistor is the same as applied voltage.

Example: The current through a resistor of a parallel circuit is 12 amperes and the value of the resistor is 10 ohms. Determine the source voltage. Figure 3-22 shows the circuit.

Given:

R2 = 10 ohms

I2 = 12 amps

Solution:

E2 = (I2)(R2)

E2 = 12 amps x 10 ohms

E2 = 120 volts

Et = E2

Et = 120 volts

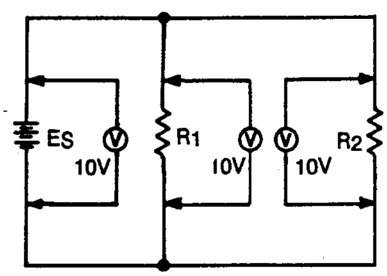


FIGURE 3-21. Voltage Comparison in a Parallel Circuit.

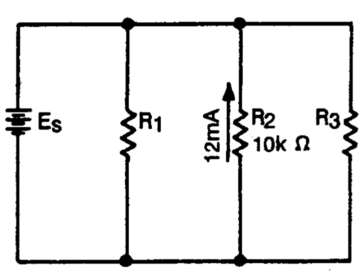


FIGURE 3-22. Example Problem of a Parallel Circuit.

Current in a Parallel Circuit. Ohm's Law states that the current in a circuit is inversely proportional to the circuit resistance. This is true in both series and parallel circuits.

There is a single path for current in a series circuit. The amount of current is determined by the total resistance of the circuit and the applied voltage. In a parallel circuit the source current divides among the available paths.

The following illustrations show the behavior of current in parallel circuits using example circuits with different values of resistance for a given value of applied voltage.

Figure 3-23 view A shows a basic series circuit. Here, the total current must pass through the single resistor. The amount of current can be determined as follows:

Given:

Et = 50 volts

R1 = 10 ohms

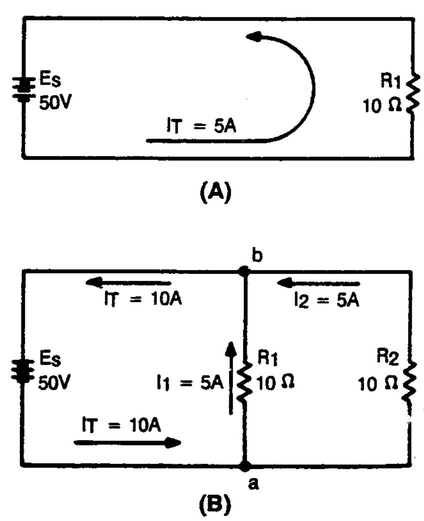


FIGURE 3-23. Analysis of Current in a Parallel Circuit.

Solution:

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

$$It = \frac{Et}{R1}$$

$$It = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

It = 5 amps

View B shows the same resistor (R1) with a second resistor (R2) of equal value connected in parallel across the voltage source. When Ohm's Law is applied, the current flow through each resistor is found to be the same as the current through the single resistor in view A.

Given:

Et = 50 volts

R1 = 10 ohms

R2 = 10 ohms

Solution:

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

Et = El = E2

$$I1 = \frac{E1}{R1}$$

$$I1 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

I1 = 5 amps

$$I2 = \frac{E2}{R2}$$

$$I2 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

I2 = 5 amps

If 5 amperes of current flow through each of the two resistors, there must be a total current of 10 amperes drawn from the source. The total current of 10 amperes leaves the negative terminal of the battery and flows to point a (view B). Point a, called anode, is a connecting point for the two resistors. At node a, the total current divides into two currents of 5 amperes each. These two currents flow through their respective resistors and rejoin at node b. The total current then flows from node b back to the positive terminal of the source. The source supplies a total current of 10 amperes, and each of the two equal resistors carries one-half of the total current.

Each individual current path in the circuit of view B is a branch. Each branch carries a current that is a portion of the total current. Two or more branches form a network.

The characteristics of current in a parallel circuit can be expressed in terms of the following general equation

It = I1 + I2 + ...In

Compare Figure 3-24 view A with the circuit in Figure 3-23 view B. Notice that doubling the value of the second branch resistor (R2) has no effect on the current in the first branch (I1). However, it does reduce the second branch current (I2) to one-half its original value. The total circuit current drops to a value equal to the sum of the branch currents. These facts are verified by the following equations

Given:

Et = 50 volts

R1 = 10 ohms

R2 = 20 ohms

Solution:

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

Et = El = E2

$$I1 = \frac{E1}{R1}$$

$$I1 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

I1 = 5 amps

$$I2 = \frac{E2}{R2}$$

$$I2 = \frac{50 \text{ volts}}{20 \text{ ohms}}$$

I2 = 2.5 amps

It = I1 + I2

It = 5 amps + 2.5 amps

It = 7.5 amps

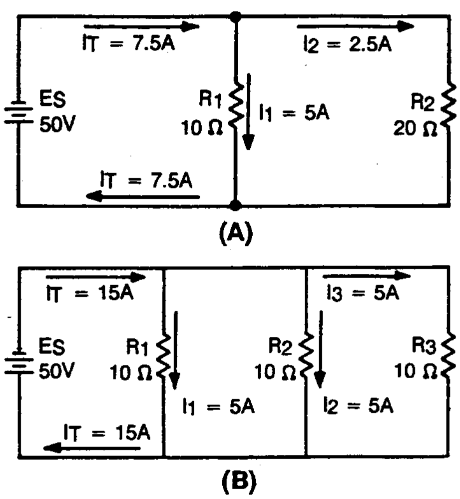


FIGURE 3-24. Current Behavior in a Parallel Circuit.

The amount of current flow in the branch circuits and the total current in the circuit in Figure 3-24 view B are determined by the following computations:

Given:

Et = 50 volts

R1 = 10 ohms

R2 = 10 ohms

R3 = 10 ohms

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

Es = E1 = E2 = E3

$$I1 = \frac{E1}{R1}$$

$$I1 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

I1 = 5 amps

$$I2 = \frac{E2}{R2}$$

$$I2 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

I2 = 5 amps

$$I3 = \frac{E3}{R3}$$

$$I3 = \frac{50 \text{ volts}}{10 \text{ ohms}}$$

I3 = 5 amps

It = I1 + I2 + I3

It = 5 amps + 5 amps + 5 amps

It = 15 amps

Notice that the sum of the ohmic values of the resistors in both circuits in Figure 3-24 is equal (30 ohms) and that the applied voltage is the same value (50 volts). However, the total current in Figure 3-24 view B (15 amperes) is twice the amount in Figure 3-24 view A (7.5 amperes). It is apparent, therefore, that the manner in which resistors are connected in a circuit, as well as their actual ohmic values, affect the total current.

The division of current in a parallel network follows a definite pattern. This pattern is described by Kirchhoff's Current Law which states, "The algebraic sum of the currents entering and leaving any node of conductors is equal to zero."

This law stated mathematically is –

Ia + Ib + ... In = 0

Where: Ia, Ib, . . . In = the current entering and leaving the node.

Currents entering the node are considered positive, and currents leaving the node are negative. When solving a problem using Kirchhoff's Current Law, the currents must be placed into the equation with the proper polarity signs attached.

Example: Solve for the value of 13 in Figure 3-25.

Given:

I1 = 10 amps

I2 = 3 amps

I4 = 5 amps

Solution:

Ia + Ib + ...In = 0

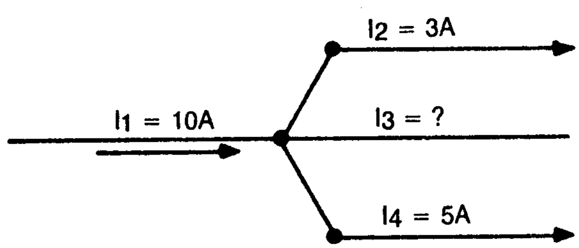


FIGURE 3-25. Circuit for Example Problem 1.

The currents are placed into the equation with the proper signs:

I1+I2+I3+I4=0

10 amps + (-3 amps) + 13 + (-5 amps) = 0

I2 + 2amps = 0

I2 = -2 amps

I2 has a value of 2 amperes. The negative sign shows it to be a current leaving the node.

Resistance in a Parallel Circuit. The example diagram (Figure 3-26) has two resistors connected in parallel across a 5-volt battery. Each has a resistance value of 10 ohms. A complete circuit consisting of two parallel paths is formed, and current flows as shown.

Computing the individual currents shows that there is 1/2 ampere of current through each resistance. The total current flowing from the battery to the node of the resistors and returning from the resistors to the battery equals 1 ampere.

The total resistance of the circuit is calculated using the values of total voltage (Et) and total current (It):

Given:

Et = 5 volts

It = 1 amp

Solution:

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

$$Rt = \frac{Et}{It}$$

$$Rt = \frac{5 \text{ volts}}{1 \text{ amp}}$$

$$Rt = 5 \text{ ohms}$$

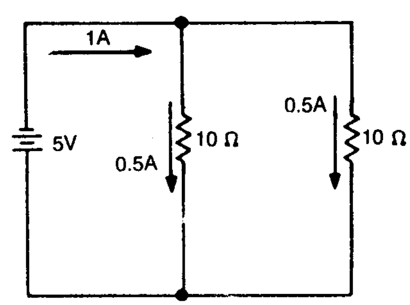


FIGURE 3-26. Two Equal Resistors Connected

This computation shows the total resistance to be 5 ohms, one-half the value of either of the two resistors.

The total resistance of a parallel circuit is smaller than any of the individual resistors. Thus, the total resistance of a parallel circuit is not the sum of the individual resistor values as was the case in a series circuit. The total resistance of resistors in parallel is also referred to as equivalent resistance (Req).

Several methods are used to determine the equivalent resistance of parallel circuits. The best method for a given circuit depends on the number and value of the resistors. For the circuit described above, where all resistors have the same value, the following simple equation is used:

$$Rt = \frac{R}{N}$$

Where: Rt = total parallel resistance

R = ohmic value of one resistor

N = number of resistors

This equation is valid for any number of parallel resistors of equal value.

Example: Four 40-ohm resistors are connected in parallel. What is their equivalent resistance?

Given

R1 = R2 = R3 = R4

R1 = 40 ohms

Solution:

$$Rt = \frac{R}{N}$$

$$Rt = \frac{40 \text{ ohms}}{4}$$

$$Rt = 10 \text{ ohms}$$

Figure 3-27 shows two resistors of unequal value in parallel. Since the total current is shown, the equivalent resistance can be calculated.

Given:

Et = 30 volts

It = 15 amps

Solution:

$$Rt = \frac{Et}{It}$$

$$Rt = \frac{30 \text{ volts}}{15 \text{ amps}}$$

$$Rt = 2 \text{ ohms}$$

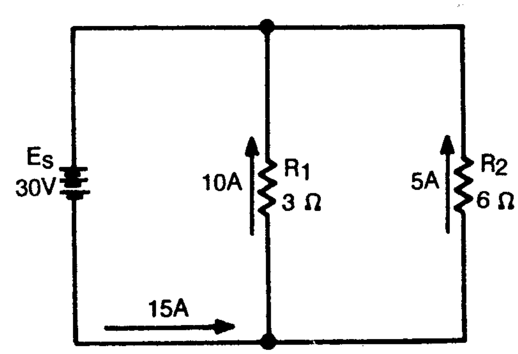


FIGURE 3-27. Example Circuit With Unequal Parallel Resistors.

The total resistance of the circuit in Figure 3-27 is smaller than either of the two resistors (R1, R2). An important point to remember is that the total resistance of a parallel circuit is always less than the resistance of any branch.

Reciprocal Method. This method is based on taking the reciprocal of each side of the equation. This presents the general formula for resistors in parallel as –

$$Rt = \frac{1}{\frac{1}{R1} + \frac{1}{R2} + \ldots \frac{1}{Rn}}$$

This formula is generally used to solve for the equivalent resistance of any number of unequal parallel resistors. Unlike the equal value or the product-over-the-sum method, the reciprocal method is the only formula that can be used to determine the equivalent resistance in any combination of parallel resistances. You must find the lowest common denominator in solving these problems.

Example: Three resistors are connected in parallel as shown in Figure 3-28. The resistor values are R1 = 20 ohms, R2 = 30 ohms, and R3 = 40 ohms. What is the equivalent resistance? Use the reciprocal method.

Given:

R1 = 20 ohms

R2 = 30 ohms

R3 = 40 ohms

Solution:

$$Rt = \frac{1}{\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3}}$$

$$Rt = \frac{1}{\frac{1}{20\text{ ohms}} + \frac{1}{30\text{ ohms}} + \frac{1}{40\text{ ohms}}}$$

$$Rt = \frac{1}{\frac{6}{120\text{ ohms}} + \frac{4}{120\text{ ohms}} + \frac{3}{120\text{ ohms}}}$$

$$Rt = \frac{1}{\frac{13}{120\text{ ohms}}}$$

$$Rt = \frac{120\text{ ohms}}{13}$$

$$Rt = 9.23\text{ ohms}$$

Product-Over-the-Sum Method. A convenient method for finding the equivalent, or total, resistance of two parallel resistors is by using the product-over-the-sum formula:

$$Rt = \frac{R1 \times R2}{R1 + R2}$$

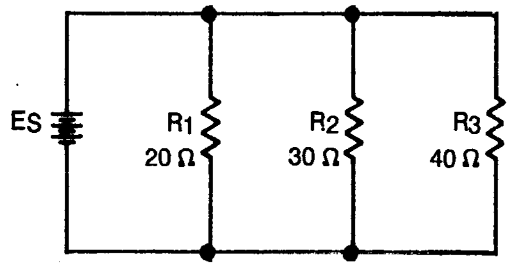


FIGURE 3-28. Example of a Parallel Circuit With Unequal Branch Resistors.

Example: What is the equivalent resistance of a 20-ohm and a 30-ohm resistor connected in parallel, as in Figure 3-29?

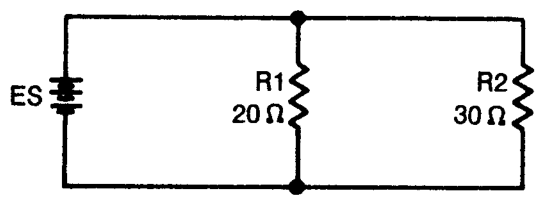


FIGURE 3-29. Parallel Circuit with Two Unequal Resistors.

Given:

R1 = 20

R2 =30

Solution:

$$Rt = \frac{R1 \times R2}{R1 + R2}$$

$$Rt = \frac{20\text{ ohms} \times 30\text{ ohms}}{20\text{ ohms} + 30\text{ ohms}}$$

$$Rt = \frac{600\text{ ohms}}{50\text{ ohms}}$$

$$Rt = 12\text{ ohms}$$

The product-over-the-sum method can only be used with two resistance values at a time. If three or more resistors are to be calculated, combine any two ohmic values into an equivalent resistance using the formula. Repeat the formula again, and this time, combine the remaining ohmic value with the recently derived equivalent resistance. Combining additional resistance values with equivalent resistance may be continued throughout the parallel circuit.

Power in a Parallel Circuit. Power computations in a parallel circuit are basically the same as those used for the series circuit. Since power dissipation in resistors consists of a heat loss, power dissipations are additive regardless of how the resistors are connected in the circuit. The total power equals the sum of the power dissipated by the individual resistors. Like the series circuit, the total power consumed by the parallel circuit is –

$Pt = Pl + P2 + ...Pn$

Example Find the total power consumed by the circuit in Figure 3-30.

Given:

R1 = 10 ohms

I1 = 5 amps

R2 = 25 ohms

I2= 2 amps

R3 = 50 ohms

I3 = 1 amp

Solution:

$P = I^2R$

$P1 = (I1)^2 x R1$

$P1 = (5 \text{ amps})^2 x 10 \text{ ohms}$

P1 = 250 watts

$P2 = (I2)^2 x R2$

$P2 = (2 \text{ amps})^2 x 25 \text{ ohms}$

P2 = 100 watts

$P3 = (I3)^2 x R3$

$P3 = (1 \text{ amp})^2 x 50 \text{ ohms}$

P3 = 50 watts

Pt = Pl + P2 + P3

Pt = 250 watts + 100 watts + 50 watts

Pt = 400 watts

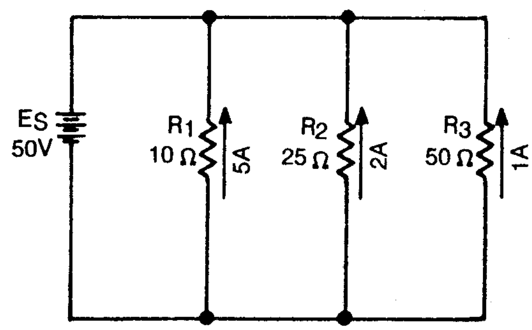


FIGURE 3-30. Example of a Parallel Circuit.

Since the total current and source voltage are known, the total power can also be computed

Given:

Et = 50 volts

It = 8 amps

Solution:

Pt = Et x It

Pt = 50 volts x 8 amps

Pt = 400 watts

Equivalent Circuits

In the study of electricity, it is often necessary to reduce a complex circuit into a simpler form. Any complex circuit consisting of resistances can be redrawn (reduced) to a basic equivalent circuit containing the voltage source and a single resistor representing total resistance. This process is called reduction to an equivalent circuit.

Figure 3-31 shows a parallel circuit with three resistors of equal value and the redrawn equivalent circuit. The parallel circuit in view A shows the original circuit. To create the equivalent circuit, first calculate the equivalent resistance:

Given:

R1 = 45 ohms

R2 = 45 ohms

R3 = 45 ohms

Solution:

$$Rt = \frac{R}{N}$$

$$Rt = \frac{45 \text{ ohms}}{3}$$

$$Rt = 15 \text{ ohms}$$

Once the equivalent resistance is known, a new circuit is drawn consisting of a single resistor (to represent the equivalent resistance) and the voltage source (Figure 3-31 view B).

The reduction of the electrical circuit from a complex parallel circuit to the simple single resistor series circuit may appear to drastically distort the original circuit and apply only to the mathematical electrical rules. However, this is the basic electrical schematic that a power source sees. The generator or battery only sees one single series electrical load. The load determines the total resistance (Rt) that the generator must deal with. Based on this, the generator supplies the current (It), pushed through the circuits by the voltage (Et). The electrical wiring system of series and parallel combinations and various electrical loads will require the current to be divided up effectively, as seen with Kirchhoff's Current Law.

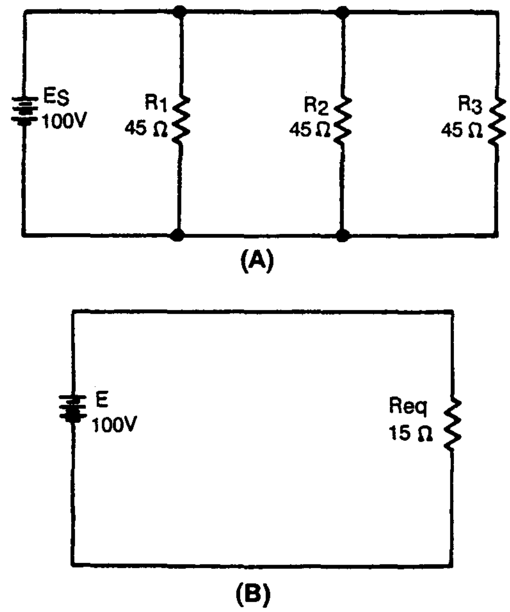


FIGURE 3-31. Parallel Circuit with Equivalent Circuit.

Rules for Parallel DC Circuits

The following are rules for parallel DC circuits

1. The same voltage exists across each branch of a parallel circuit and equals the source voltage.

   Et = El = E2 = E3 = En

2. The total current of a parallel circuit equals the sum of the individual branch currents of the circuit.

   It = I1 + I2 + I3 + In

3. The total resistance of a parallel circuit is found by the general formula (1/Rt = 1/Rl + 1/R2 + 1/R3 + 1/Rn) or one of the formulas derived from this general formula.

4. The total power consumed in a parallel circuit equals the sum of the power consumptions of the individual resistance.

Pt = P1 + P2 + P3 + Pn

Parallel Circuit Problems

Problems involving the determination of resistance, voltage, current, and power in a parallel circuit are solved as simply as in a series circuit. The procedure is the same:

1. Draw the circuit diagram.

2. State the values given and the values to be found.

3. Select the equations to be used in solving for the unknown quantities based on the known quantities.

4. Substitute the known values in the selected equation and solve for the unknown value.

Example: A parallel circuit consists of five resistors. The value of each resistor is known, and the current through R1 is known. Calculate the value for total resistance, total power, total current, source voltage, the power used by each resistor, and the current through resistors R2 R3, R4, and R5.

Given:

R1 = 20 ohms

R2 = 30 ohms

R3 = 18 ohms

R4 = 18 ohms

R5 = 18 ohms

Il = 9 amps

Find:

Rt, Et, It, Pt, I2, I3, I4, I5, P1, P2, P3, P4, P5

This may seem to be a large amount of mathematical manipulation. However, the step-by-step approach simplifies the calculation. The first step in solving this problem is to draw the circuit and indicate the known values (Figure 3-32).

There are several ways to approach this problem. With the given values, you could first solve for Rt, the power used by Rl, or the voltage across R1 which is equal to the source voltage and the voltage across each of the other resistors. Solving for Rt or the power used by R1 will not help in solving for the other unknown values.

Once the voltage across R1 is known, this value will help in calculating other unknowns. Therefore, the logical unknown to solve for is the source voltage (the voltage across R1).

Given:

R1 = 20 ohms

I1 = 9 amps

El = Et

Solution:

Et = Rl x Il

Et = 9 amps x 20 ohms

Et = 180 volts

Now that source voltage is known, you can solve for current in each branch:

Given:

Et = 180 volts

R2 = 30 ohms

R3 = 18 ohms

R4 = 18 ohms

R5 = 18 ohms

Solution:

$$I2 = \frac{Et}{R2}$$

$$I2 = \frac{180 \text{ volts}}{30 \text{ ohms}}$$

I2 = 6 amps

$$I3 = \frac{Et}{R3}$$

$$I3 = \frac{180 \text{ volts}}{18 \text{ ohms}}$$

I3 = 10 amps

Since R3 = R4 = R5 and the voltage across each branch is the same –

I4 = 10 amps

I5 = 10 amps

Solve for total resistance:

Given:

R1 = 20 ohms

R2 = 30 ohms

R3 = 18 ohms

R4 = 18 ohms

R5 = 18 ohms

Solution:

$$\frac{1}{Rt} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} + \frac{1}{R4} + \frac{1}{R5}$$

$$\frac{1}{Rt} = \frac{1}{20} + \frac{1}{30} + \frac{1}{18} + \frac{1}{18} + \frac{1}{18}$$

$$\frac{1}{Rt} = \frac{9 + 6 + 10 + 10 + 10}{180}$$

$$\frac{1}{Rt} = \frac{45}{180}$$

$$Rt = \frac{180}{45}$$

Rt = 4 ohms

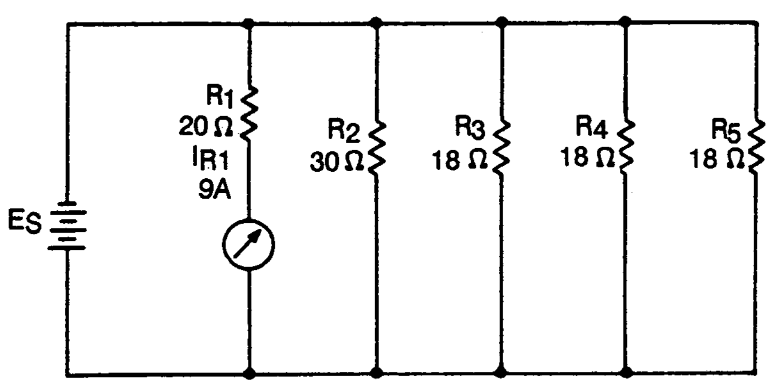


FIGURE 3-32. Parallel Circuit Problem.

An alternate method for solving Rt can be used. By observation, you can see that R3, R4, and R5 are equal ohmic value. Therefore, an equivalent resistor can be substituted for these three resistors in solving for total resistance.

Given:

R3 = R4 = R5 = 18 ohms

Solution:

$$R1 = \frac{R}{N}$$

$$R1 = \frac{18\text{ ohms}}{3}$$

$$R1 = 6\text{ ohms}$$

The circuit can now be redrawn using a resistor labeled Req 1 in place of R3, R4, and R5 (Figure 3-33).

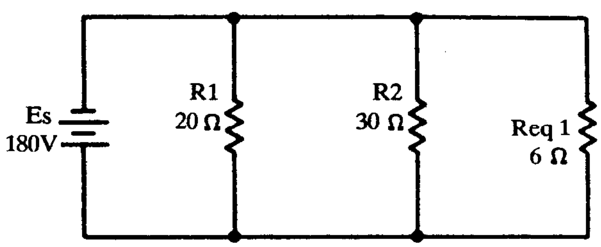


FIGURE 3-33. First Equivalent Parallel Circuit.

An equivalent resistor can be calculated and substituted for R1 and R2 by use of the product-over-the-sum formula

Given:

R1 = 20 ohms

R2 = 30 ohms

Solution:

$$R2 = \frac{R1 \times R2}{R1 + R2}$$

$$R2 = \frac{20 \times 30}{20 + 30}$$

$$R2 = \frac{600}{50}$$

$$R2 = 12\text{ ohms}$$

The circuit is now redrawn again using a resistor labeled Req 2 in place of R1 and R2 (Figure 3-34).

Two resistors are now left in parallel. The product-over-the-sum method can now be used to solve for total resistance:

Given:

R1 = 6 ohms

R2 = 12 ohms

Solution:

$$Rt = \frac{R1 \times R2}{R1 + R2}$$

$$Rt = \frac{R1 \times R2}{R1 + R2}$$

$$Rt = \frac{6\text{ ohms} \times 12\text{ ohms}}{6\text{ ohms} + 12\text{ ohms}}$$

$$Rt = \frac{72\text{ ohms}}{18\text{ ohms}}$$

Rt = 4 ohms

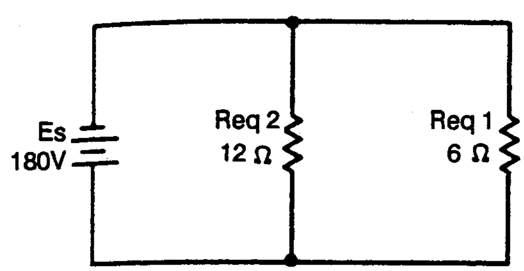


FIGURE 3-34. Second Equivalent Parallel Circuit.

This agrees with the solution found by using the general formula for solving for resistors in parallel.

The circuit can now be redrawn as shown in Figure 3-35, and the total current can be calculated.

Given:

Et = 180 volts

Rt = 4 ohms

Solution:

$$It = \frac{Et}{Rt}$$

$$It = \frac{180 \text{ volts}}{4 \text{ ohms}}$$

It = 45 amps

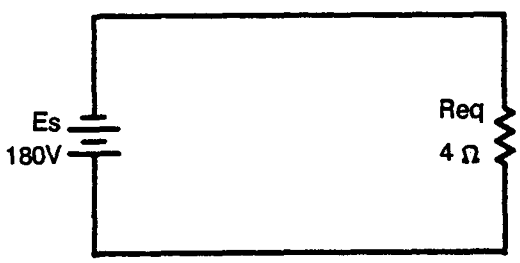


FIGURE 3-35. Parallel Circuit Redrawn to Final Equivalent Circuit.

This solution can be checked by using the values already calculated for the branch currents:

Given:

I1 = 9 amps

I2 = 6 amps

I3 = 10 amps

I4 = 10 amps

I5 = 10 amps

Solution:

It = I1 + I2 + ...In

It = 9 amps + 6 amps + 10 amps + 10 amps + 10 amps

It = 45 amps

Now that total current is known, the next logical step is to find total power.

Given:

Et = 180 volts

It = 45 amps

Solution

P = EI

Pt = Et x It

Pt = 180 volts x 45 amps

Pt = 8,100 watts = 8.1 KW

Solve for the power in each branch:

Given:

Et = 180 volts

I1 = 9 amps

I2 = 6 amps

I3 = 10 amps

I4 = 10 amps

I5 = 10 amps

Solution:

P = EI

Pl = Et x Il

P1 = 189 volts x 9 amps

P1 = 1,620 watts

P2 = Et x I2

P2 = 180 volts x 6 amps

P2 = 1,080 watts

P3 = Et x I3

P3 = 180 volts x 10 amps

P3 = 1,800 watts

Since I3= I4= I5, then P3 = P4 = P5 = 1,800 watts. The previous calculation for total power can now be checked:

Given:

P1 = 1,620 watts

P2 = 1,080 watts

P3 = 1,800 watts

P4 = 1,800 watts

P5 = 1,800 watts

Solution:

Pt = Pl + P2 + P3 + P4 + P5

Pt = 1,620 watts + 1,080 watts + 1,800 watts + 1,800 watts + 1,800 watts

Pt = 8,100 watts

Pt = 8.1 KW

SERIES-PARALLEL DC CIRCUITS

Engineers encounter circuits consisting of both series and parallel elements. This type of circuit is called a series-parallel network. Solving for the quantities and elements in a series-parallel network is simply a matter of applying the laws and rules discussed up to this point.

COMBINATION-CIRCUIT PROBLEMS

The basic technique used for solving DC combination-circuit problems is the use of equivalent circuits. To simplify a complex circuit to a simple circuit containing only one load, equivalent circuits are substituted (on paper) for the complex circuit they represent.

To demonstrate the method used to solve series-parallel networks problems, the network in Figure 3-36 view A will be used to calculate various circuit quantities, such as resistance, current, voltage, and power.

Examination of the circuit shows that the only quantity that can be computed with the given information is the equivalent resistance of R2 and R3.

Given:

R2 = 20 ohms

R3 = 30 ohms

Solution:

$$R2,3 = \frac{R2 \times R3}{R2 + R3} \text{ (product over the sum)}$$

$$R2,3 = \frac{20 \times 30}{20 + 30}$$

$$R2,3 = \frac{600}{50}$$

$$R2,3 = 12 \text{ ohms}$$

Now that the equivalent resistance for R2 and R3 has been calculated, the circuit can be redrawn as a series circuit (view B).

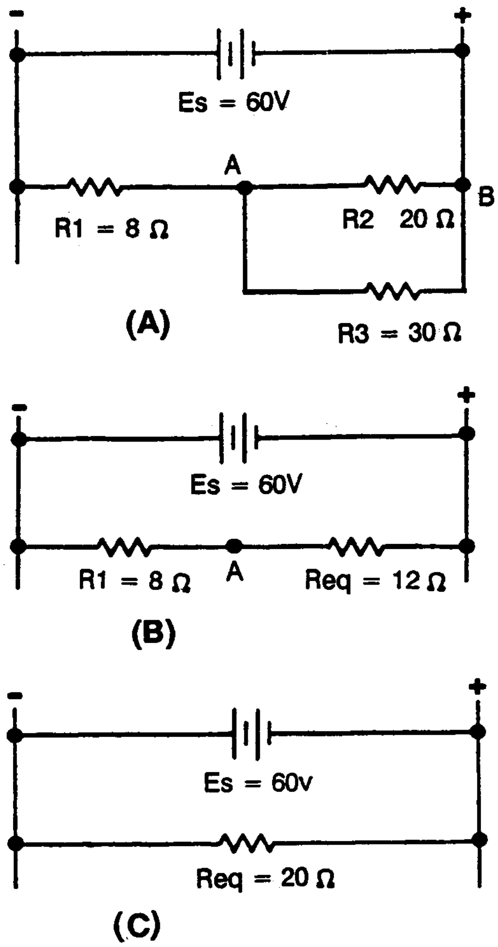


FIGURE 3-36. Example Series-Parallel Network.

The equivalent resistance of this circuit (total resistance) can now be calculated

Given

R1 = 8 ohms (resistors in series)

R2,3 = 12 ohms

Solution:

Rt = Rl + R2,3

Rt = 8 + 12

Rt = 20 ohms

The original circuit can be redrawn with a single resistor that represents the equivalent resistance of the entire circuit (view C).

To find total current in the circuit –

Given:

Et = 60 volts

Rt = 20 ohms

Solution:

$$It = \frac{Et}{Rt}$$

$$It = \frac{60 \text{ volts}}{20 \text{ ohms}} \quad \text{(Ohm's Law)}$$

It = 3 amps

To find total power in the circuit –

Given

Et = 60 volts

It = 3 amps

Solution

Pt = Et x It

Pt = 60 volts x 3 amps

Pt = 180 watts

To find the voltage dropped across Rl, R2, and R3, refer to Figure 3-36 view B. R2,3 represents the parallel network of R2 and R3. Since the voltage across each branch of a parallel circuit is equal, the voltage across R2,3 will be the same across R2 and R3.

Given:

It = 3 amps (current through each part of a series circuit equals total current.)

Rl = 8 ohms

R2,3 = 12 ohms

Solution:

E1 = I1 x R1

El = 3 amps x 8 ohms

El = 24 volts

E2 = E3 = E2,3

E2,3 = It x R2,3

E2,3 = 3 amps x 12 ohms

E2,3 = 36 volts

E2 = 36 volts

E3 = 36 volts

To find power used by Rl–

Given:

El = 24 volts

It = 3 amps

Solution:

Pl = El x Rt

P1 = 24 volts x 3 amps

PI = 72 watts

To find the current through R2 and R3, refer to the original circuit (Figure 3-35 view A). E2 and E3 are known from previous calculation.

Given:

E2 = 36 volts

E3 = 36 volts

R2 = 20 ohms

R3 = 30 ohms

Solution:

$$I2 = \frac{E2}{R2} \text{ (Ohm's Law)}$$

$$I2 = \frac{36 \text{ volts}}{20 \text{ ohms}}$$

I2 = 1.8 amps

$$I3 = \frac{E3}{R3}$$

$$I3 = \frac{36 \text{ volts}}{30 \text{ ohms}}$$

I3 = 1.2 amps

To find power used by R2 and R3, using values from previous calculations –

Given:

E2 = 36 volts

E3 = 36 volts

I2 = 1.8 amps

I3 = 1.2 amps

Solution:

P2 = E2 x I2

P2 = 36 volts x 1.8 amps

P2 = 64.8 watts

P3 = E3 x I3

P3 = 36 volts x 1.2 amps

P3 = 43.2 watts

After computing all the currents and voltages of Figure 3-36, a complete description of the operation of the circuit can be made. The total current of 3 amperes leaves the negative terminal of the battery and flows through the 8-ohm resistor (R1). In so doing, a voltage drop of 24 volts occurs across resistor R1. At point A, this 3-ampere current divides into two currents. Of the total current, 1.8 amperes flows through the 20-ohm resistor. The remaining current of 1.2 amperes flows from point A, down through the 30-ohm resistor to point B. This current produces a voltage drop of 36 volts across the 30-ohm resistor. (Notice that the voltage drops across the 20- and 30-ohm resistors are the same.) The two branch currents of 1.8 and 1.2 amperes combine at node B, and the total current of 3 amperes flows back to the source. The action of the circuit has been completely described with the exception of power consumed, which could be described using the values previously computed.

The series-parallel network is not difficult to solve. The key to its solution lies in knowing the order to apply the steps of the solution. First look at the circuit. From this observation, determine the type of circuit, what is known, and what must be determined.

CHAPTER 4

BATTERIES

INTRODUCTION

A battery consists of a number of cells assembled in a common container and connected together to function as a source of electrical power. This chapter introduces the basic theory and characteristics of batteries. The batteries discussed are representative of the many models and types used in the Army.

The cell is the building block of all batteries. This chapter explains the physical makeup of the cell and the methods used to combine cells to provide useful voltage, current, and power. The chemistry of the cell and how chemical action is used to convert chemical energy to electrical energy are also discussed. In addition, this chapter addresses the care, maintenance, and operation of batteries, as well as some of the safety precautions that should be followed while working around batteries.

Batteries are widely used as sources or direct current electrical energy in automobiles, boats, aircraft, shops, portable electric/electronic equipment, and lighting equipment. In some instances, batteries are used as the only source of power. In others, they are used as a secondary or emergency power source.

BATTERY COMPONENTS

The Cell

A cell is a device that transforms chemical energy into electrical energy. Figure 4-1 shows the simplest cell, known as a galvanic or voltaic cell. It consists of a piece of carbon (C) and a piece of zinc (Zn) suspended in a jar that contains a sulfuric acid solution (H_2SO_4), called the electrolyte.

The cell is the fundamental unit of the battery. A simple cell consists of two electrodes placed in a container that holds the electrolyte. In some cells, the container acts as one of the electrodes and is acted upon by the electrolyte.

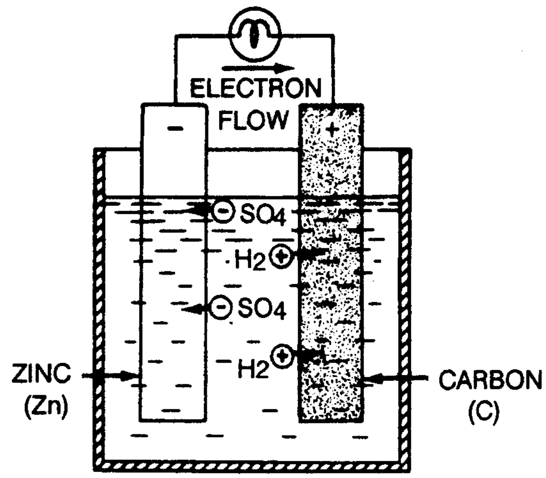


FIGURE 4-1. Simple Voltaic or Galvanic Cell.

Electrodes

The electrodes are the conductors by which the current leaves or returns to the electrolyte. In the simple cell, they are carbon and zinc strips placed in the electrolyte. In the dry cell (Figure 4-2), they are the carbon rod in the center and zinc container in which the cell is assembled.

Electrolyte

The electrolyte is the solution that reacts with the electrodes. The electrolyte provides a path for electron flow. It may be a salt, an acid, or an alkaline solution. In the simple galvanic cell, the electrolyte is a liquid. In the dry cell, the electrolyte is a paste.

Container

The container provides a means of holding (containing) the electrolyte. It is also used to mount the electrodes. The container may be constructed of one of many different materials. In the voltaic cell, the container must be constructed of a material that will not be acted upon by the electrolyte.

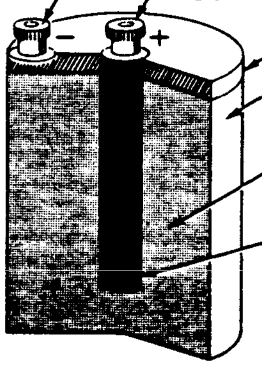


FIGURE 4-2. Dry Cell, Cross-Sectional View.

PRIMARY AND SECONDARY CELLS

Primary Cell

In a primary cell, the chemical action eats away one of the electrodes, usually the negative electrode. When this happens, the electrode must be replaced or the cell must be discarded. In a galvanic-type cell, the zinc electrode and the liquid electrolyte are usually replaced. It is usually cheaper to buy a new dry cell than it is to repair it.

Secondary Cell

In a secondary cell, the electrodes and electrolyte are altered by the chemical action that takes place when the cell delivers current. A secondary cell may be restored to its original condition by forcing an electric current through it in the direction opposite to that of discharge. The automobile storage battery is a common example of a secondary cell.

ELECTROCHEMICAL ACTION

When a load, a device that consumes electrical power, is connected to the electrodes of a charged cell, electrons will move from the cathode (negative electrode) toward the anode (positive electrode). The conversion of the cell's chemical energy to a productive electrical energy is called electrochemical action.

The voltage across the electrodes depends on the materials the electrodes are made of and the composition of the electrolyte. The current a cell delivers depends on the resistance of the entire circuit, including the cell itself. The internal resistance of the cell depends on the size of the electrodes, the distance between them in the electrolyte, and the resistance of the electrolyte. The larger the electrodes and the nearer their proximity in the electrolyte (without touching), the lower the internal resist ante of the cell. The lower the internal cell resistance, the smaller the voltage loss within the cell while delivering current.

Primary Cell Chemistry

When a current flows through a primary cell having carbon and zinc electrodes and a diluted solution of sulfuric acid and water (combined to form the electrolyte), the following chemical reaction takes place. The current flow through the load is the movement of electrons from the negative electrode (zinc) of the cell to the positive electrode (carbon). This causes fewer electrons in the zinc and an excess of electrons in the carbon. Figure 4-1 shows the hydrogen ions (H_2) from the sulfuric acid being attracted to the carbon electrode. Since the hydrogen ions are positively charged, they are attracted to the negative charge on the carbon electrode. The excess of electrons causes this negative charge. The zinc electrode has a positive charge because it has lost electrons to the carbon electrode. This positive charge attracts the negative ions (SO_4) from the sulfuric acid. The negative ions combine with the zinc to form zinc sulfate. This action causes the zinc electrode to be eaten away. Zinc sulfate is a grayish-white substance that is sometimes seen on the battery post of an automobile battery.

The process of the zinc being eaten away and the sulfuric acid changing to hydrogen and zinc sulfate causes the cell to discharge. When the zinc is used up, the voltage of the cell is reduced to zero.

In Figure 4-1, the zinc electrode is labeled negative, and the carbon electrode is labeled positive. This represents the current flow outside the cell from negative to positive.

The zinc combines with the sulfuric acid to form zinc sulfate and hydrogen. The zinc sulfate dissolves in the electrolyte (sulfuric acid and water), and the hydrogen appears as gas bubbles around the

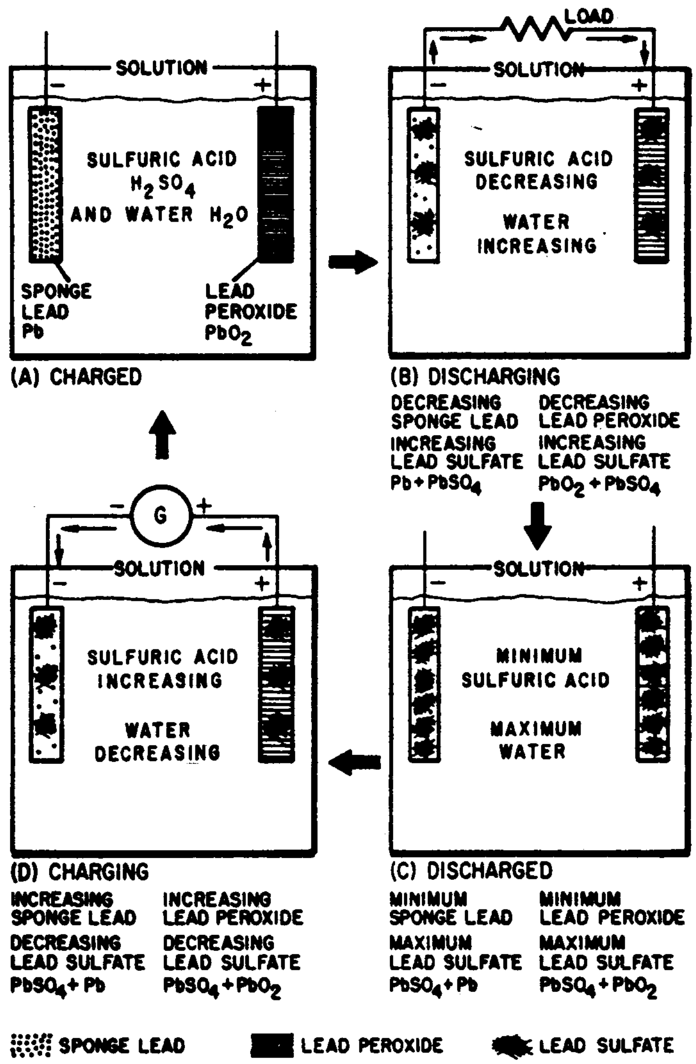


FIGURE 4-3. Secondary Cell.

carbon electrode. As current continues to flow, the zinc gradually dissolves, and the solution changes to zinc sulfate and water. The carbon electrode does not enter into the chemical changes taking place but simply provides a return path for the current.

Secondary Cell Chemistry

The secondary cell in Figure 4-3 uses sponge lead as the cathode and lead peroxide as the anode. This lead-acid cell is used to explain the general chemistry of the secondary cell. The materials that make up other types of secondary cells are different, but the chemical action is basically the same.

View A shows a fully charged, lead-acid secondary cell. The cathode is pure sponge lead. The anode is pure lead peroxide. The electrolyte is a mixture of sulfuric acid and water.

View B shows the secondary cell discharging. A load is connected between the cathode and anode. Current flows negative to positive. This current flow creates the same process found in the primary cell with the following exceptions. In the primary cell, the zinc cathode was eaten away by the sulfuric acid. In the secondary cell, the sponge-like construction of the cathode retains the lead sulfate formed by the chemical action of the sulfuric acid and the lead. In the primary cell, the carbon anode was not chemically acted on by the sulfuric acid. In the secondary cell, the lead peroxide anode is chemically changed to lead sulfate by the sulfuric acid.

View C shows a fully discharged Cell. The anode and cathode retain some lead peroxide and sponge lead, but the amounts of lead sulfate in each is maximum. The electrolyte has a minimum amount of sulfuric acid. With this condition, no further chemical action can take place within the cell.

A secondary cell can be recharged. This is the process of reversing the chemical action that occurs as the cell discharges. To recharge the cell, a voltage source, such as a generator, is connected (view D). The negative terminal of the voltage source is connected to the cathode of the cell, and the positive terminal of the voltage source is connected to the anode of the cell. This arrangement chemically changes the lead sulfate back to sponge lead in the cathode, lead peroxide in the anode, and sulfuric acid in the electrolyte. After all the lead sulfate is chemically changed, the cell is fully charged (view A). Then the discharge-charge cycle may be repeated.

POLARIZATION OF THE CELL

The chemical action that occurs in the cell while the current is flowing causes hydrogen bubbles to form on the surface of the anode. This action is called polarization. Some hydrogen bubbles rise to the surface of the electrolyte and escape into the air. Some remain on the surface of the anode. If enough bubbles remain around the anode, the bubbles form a barrier that increases internal resistance. When the internal resistance of the cell increases, the output current decreases and the voltage of the cell also decreases.

A cell that is heavily polarized has no useful output. There are several methods to prevent polarization or to depolarize the cell. One method uses a vent on the cell to let the hydrogen escape into the air. A disadvantage of this method is that hydrogen is not available to reform into the electrolyte during recharging. This problem is solved by adding water to the electrolyte, such as in an automobile battery. A second method uses a material rich in oxygen, such as manganese dioxide, to supply free oxygen to combine with the hydrogen and form water. A third method uses a material, such as calcium, to absorb the hydrogen. The calcium releases hydrogen during the charging process. All three methods remove enough hydrogen so that the cell is practically free from polarization.

LOCAL ACTION

When the external circuit is removed, the current ceases to flow, and theoretically, all chemical action within the cell stops. However, commercial zinc contains many impurities, such as iron, carbon, lead, and arsenic. These impurities form many small electrical cells within the zinc electrode in which current flows between the zinc and its impurities. Thus, the chemical action continues even though the cell itself is not connected to a load. Removing and controlling impurities in the cell greatly increases the life of the battery.

TYPES OF CELLS

The development of new and different types of cells in the past decade has been so rapid it is almost impossible to have a complete knowledge of all the various types. A few recent developments are the silver-zinc, nickel-zinc, nickel-cadmium, silver-cadmium, organic, inorganic, and mercury cells.

Primary Dry Cell

The dry cell is the most popular type of primary cell. It is ideal for simple applications where an inexpensive and noncritical source of electricity is all that is needed. The dry cell is not actually dry. The electrolyte is not in a liquid state, but it is a moist paste. If it should become totally dry, it would no longer be able to transform chemical energy to electrical energy.

Figure 4-4 shows the construction of a common type of dry cell. The internal parts of the cell are located in a cylindrical zinc container. This zinc container serves as the negative electrode (cathode) of the cell. The container is lined with a nonconducting material, such as blotting paper, to separate the zinc from the paste. A carbon electrode in the center serves as the positive terminal (anode) of the cell. The paste is a mixture of several substances, such as ammonium chloride, powdered coke, ground carbon, manganese dioxide, zinc chloride, graphite, and water. It is packed in the space between the anode and the blotting paper. The paste also serves to hold the anode rigid in the center of the cell. When the paste is packed in the cell, a small space is left at

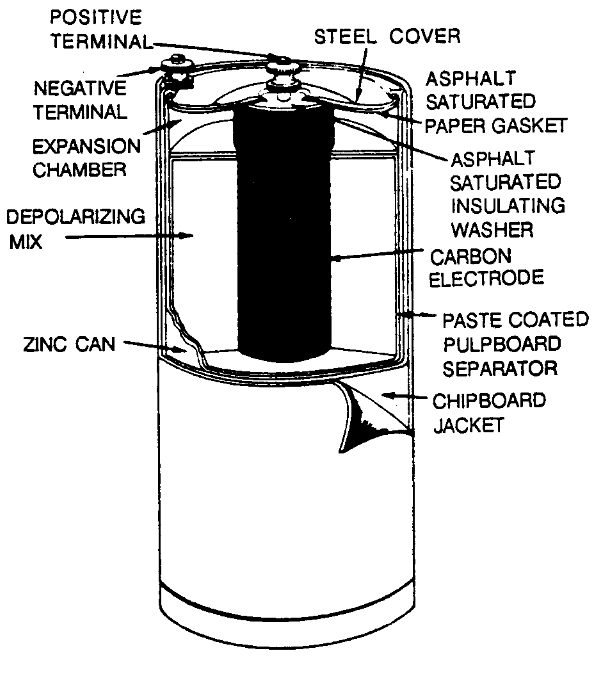


FIGURE 4-4. Cutaway View of the General-Purpose Dry Cell.

the top for expansion of the electrolytic paste caused by the depolarization action. The cell is than sealed with a cardboard or plastic seal.

Since the zinc container is the cathode, it must be protected with some insulating material to be electrically isolated. Therefore, it is common practice for the manufacturer to enclose the cells in the cardboard and metal containers.

The dry cell (Figure 4-4) is basically the same as the simple voltaic cell (wet cell) as far as its internal chemical action is concerned. The action of the water and the ammonium chloride in the paste, together with the zinc and carbon electrodes, produces the voltage of the cell. Manganese dioxide is added to reduce polarization when current flows, and zinc chloride reduces local action when the cell is not being used.

A cell that is not being used (sitting on the shelf) will gradually deteriorate because of slow internal chemical changes (local action). This deterioration is usually very slow if cells are properly stored. If unused cells are stored in a cool place, their shelf life will be greatly increased. Therefore, to minimize deterioration, they should be stored in refrigerated spaces.

The blotting paper (paste-coated pulpboard separator) serves two purposes:

- It keeps the paste from actually contacting the zinc container.
- It lets the electrolyte from the paste filter through to the zinc slowly.

The cell is sealed at the top to keep air from entering and drying the electrolyte. Care should be taken to prevent breaking this seal.

Secondary Wet Cells

Secondary cells are sometimes known as wet cells. There are four basic types of wet cells: lead-acid, nickel-cadmium, silver-zinc, and silver-cadmium. Different combinations of materials are used to form the electrolyte, cathode, and anode of different cells. These combinations provide the cells with different qualities for many varied applications.

Lead-Acid Cell. The lead-acid cell is the most widely used secondary cell. The previous explanation of the secondary cell describes how the lead-acid cell provides electrical power. The discharging and charging action presented in Electrochemical Action describes the lead-acid cell. The lead-acid cell has an anode of lead peroxide, a cathode of sponge lead, and an electrolyte of sulfuric acid and water.

Nickel-Cadmium Cell. The nickel-cadmium (NICAD) cell is far superior to the lead-acid cell. In comparison to lead-acid cells, these cells generally require less maintenance throughout their service life regarding the addition of electrolyte or water. The major difference between the nickel-cadmium cell and the lead-acid cell is the material used in the cathode, anode, and electrolyte. In the nickel-cadmium cell, the cathode is cadmium hydroxide; the anode is nickel hydroxide; and the electrolyte is potassium hydroxide and water.

The nickel-cadmium and lead-acid cells have capacities that are comparable at normal discharge rates. However, at higher discharge rates, the nickel-cadmium cell can deliver a large amount of power. Also, the nickel-cadmium cell can –

- Be charged in a shorter time.
- Stay idle longer in any state of charge and keep a full charge when stored for a longer period of time.
- Be charged and discharged any number of times without any appreciable damage.

Because of their superior capabilities, nickel-cadmium cells are used extensively in many military applications that require a cell with a high discharge rate. A good example is in the LACV-30 storage battery.

Silver-Zinc Cells. The silver-zinc cell is used extensively to power emergency equipment. However, it is relatively expensive and can be charged and discharged fewer times than other types of cells. When compared to lead-acid or nickel-cadmium cells, these disadvantages are outweighed by the light weight, small size, and good electrical capacity of the silver-zinc cell. The silver-zinc cell uses the same electrolyte as the nickel-cadmium cell (potassium hydroxide and water), but the anode and cathode differ. The anode is made of silver oxide, and the cathode is made of zinc.

Silver-Cadmium Cell. The silver-cadmium cell is a recent development for use in storage batteries. The silver-cadmium cell combines some of the better features of the nickel-cadmium and silver-zinc cells. It has more than twice the shelf life of the silver-zinc cell and can be recharged many more times. The disadvantages of the silver-cadmium cell are high cost and low voltage production. The electrolyte of the silver-cadmium cell is potassium hydroxide and water as in the nickel-cadmium and silver-zinc cells. The anode is silver oxide as in the silver-zinc cell, and the cathode is cadmium hydroxide as in the NICAD cell.

BATTERIES AS POWER SOURCES

A battery is a voltage source that uses chemical action to produce a voltage. The term "battery" is often applied to a single cell, such as the flashlight battery. In a flashlight that uses a battery of 1.5 volts, the battery is a single cell. The flashlight that is operated by 6 volts uses four cells in a single case. This is a battery composed of more than one cell. Cells can be combined in series or in parallel.

In many cases, a battery-powered device may require more electrical energy than one cell can provide. The device may require a higher voltage or more current, or, in some cases, both. To meet the higher requirements, a sufficient number of cells must be combined or interconnected. Cells connected in series provide a higher voltage, while cells connected in parallel provide a higher current capacity.

Series-Connected Cells

Assume that a load requires a power supply of 6 volts and a current capacity of 1/8 ampere. Since a single cell normally supplies a voltage of only 1.5 volts, more than one cell is needed. To obtain the higher voltage, the cells are connected in series, as shown in Figure 4-5. Figure 4-5 view B is a schematic representation of the circuit in view A. The load is shown by the lamp symbol, and the battery is indicated by one long and one short line per cell.

In a series hookup, the negative electrode (cathode) of the first cell is connected to the positive

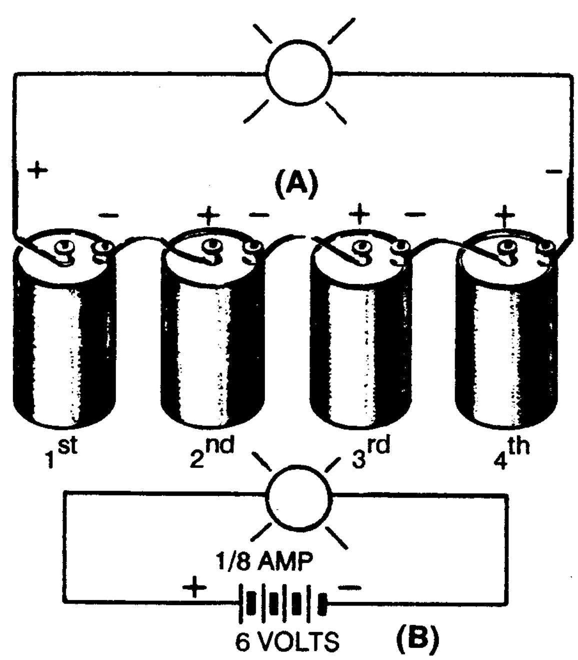


FIGURE 4-5. Series-Connected Cells.

electrode (anode) of the second cell, the negative electrode of the second to the positive of the third, and so on. The positive electrode of the first cell and negative electrode of the last cell then serve as the terminals of the battery. In this way, the voltage is 1.5 volts for each cell in the series line. There are four cells, so the output terminal voltage is 1.5 x 4 or 6 volts. When connected to the load, 1/8 ampere flows through the load and each cell of the battery. This is within the capacity of each cell. Therefore, only four series-connected cells are needed to supply this particular load.

WARNING

When connecting cells in series, there MUST ALWAYS he two unconnected terminals remaining. These two terminals must be connected to each side of a load. NEVER connect the final two remaining terminals together unless a load is placed between them. Physical harm or equipment damage will result.

Parallel-Connected Cells

Assume an electrical load requires only 1.5 volts but will require 1/2 ampere of current. (Assume that a single cell will supply only 1/8 ampere.) To meet this requirement, the cells are connected in parallel, as shown in Figure 4-6 view A and schematically represented in view B. In a parallel connection, all positive cell electrodes are connected to one line, and all negative electrodes are connected to the other. No more than one cell is connected between the lines at any one point, so the voltage between the lines is the same as that of one cell, or 1.5 volts. However, each cell may contribute its maximum allowable current of 1/8 ampere to the line. There are four cells, so the total line current is 1/8 x 4, or 1/2 ampere. In this case, four cells in parallel have enough capacity to supply a load requiring 1/2 ampere at 1.5 volts.

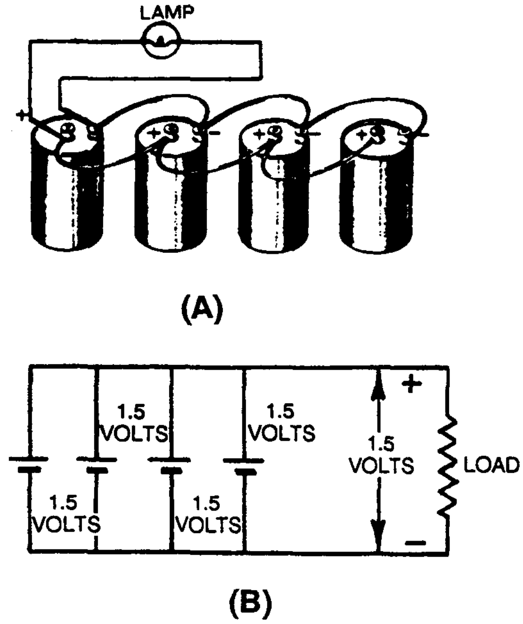


FIGURE 4-6. Parallel-Connected Cells.

BATTERY CONSTRUCTION

Secondary cell batteries are constructed using the various secondary cells already described. The lead-acid battery, one of the most common batteries, will be used to explain battery construction. The nickel-cadmium battery, which is being used with increasing frequency, will also be discussed.

Figure 4-7 shows the makeup of a lead-acid battery. The container houses the separate cells. Most containers are hard rubber, plastic, or some other material that is resistant to the electrolyte and mechanical shock and can withstand extreme temperatures. The container (battery case) is vented through vent plugs to allow the gases that form within the cells to escape. The plates in the battery are the cathodes and anodes. In Figure 4-8, the negative plate group is the cathode of the individual cells, and the positive plate group is the anode. The plates are interlaced with a terminal attached to each plate group. The terminals of the individual cells are connected together by link connectors, as shown in Figure 4-7. The cells are connected in series in the battery and the positive terminal of the battery. The negative terminal of the opposite end cell becomes the negative terminal of the battery.

The terminals of a lead-acid battery are usually identified from one another by their size and markings. The positive terminal, marked (+), is sometimes colored red and is physically larger than the negative terminal, marked (-). The individual cells of the lead-acid battery are not replaceable; so if one cell fails, the battery must be replaced.

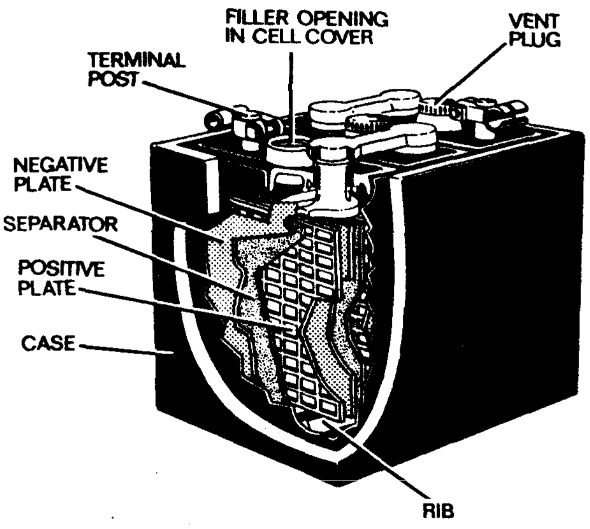


FIGURE 4-7. Lead-Acid Battery Construction.

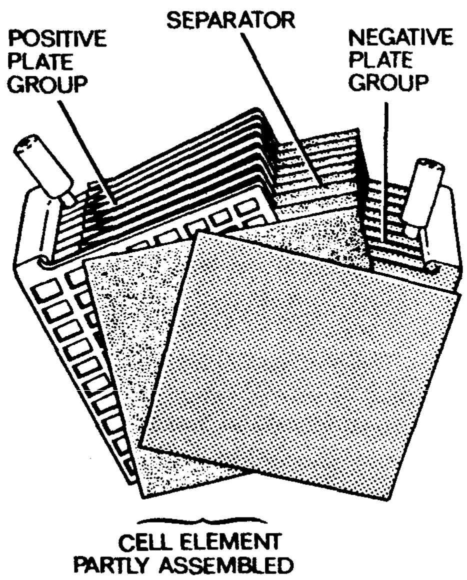


FIGURE 4-8. Lead-Acid Battery Plate Arrangement.

The nickel-cadmium battery is similar in construction to the lead-acid battery, except that it has individual cells that can be replaced. Figure 4-9 shows the cell of the NICAD battery.

The construction of secondary cell batteries is so similar that it is difficult to distinguish the type of battery by simply looking at it. The type of battery must be known to properly check or recharge the battery. Each battery should have a nameplate that gives a description of its type and electrical characteristics.

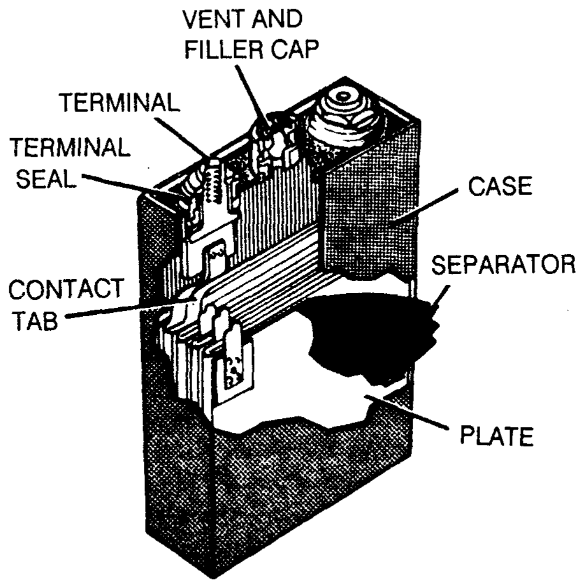


FIGURE 4-9. Nickel-Cadmium Cell.

BATTERY MAINTENANCE

The transportation field relies on the battery's ability to store electrical power until such time as the power is needed. Army watercraft personnel use the battery not only for diesel starting, but as an emergency source of power on watercraft during an electrical casualty. The general information below concerns the maintenance of secondary-cell batteries, in particular the lead-acid battery. Refer to the appropriate technical manual before engaging in any other battery maintenance.

Leak Test

Cleanliness of the lead-acid battery is a primary concern because moisture and dirt are conductors. Batteries that are allowed to gas excessively add additional conductive liquid to the top and sides of the battery. Damp battery surfaces retain conductive dirt and debris.

A simple test, known as the leak test, provides a visual and authoritative point of view for battery cleanliness. Figure 4-10 illustrates the procedure.

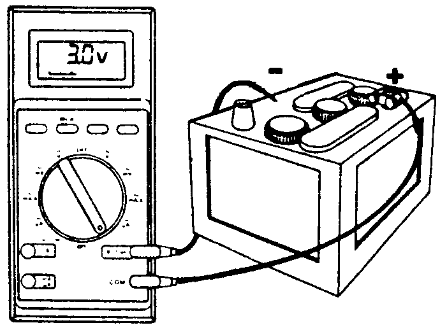


FIGURE 4-10. Leak Test.

(1) Select a DC voltage scale at or above battery voltage.

(2) Connect the negative meter lead to the negative battery post (the smaller battery post).

(3) Use the positive meter lead to probe the housing of the battery.

(4) Measure the voltage leaking across the two battery terminals using the multimeter.

In effect, electrolyte, dirt, and other foreign matter become a parallel circuit that continuously discharges the battery. Grease is not an acceptable battery terminal preservative. The heat from the battery compartment often melts the grease, which in turn covers the top and sides of the battery with a thin coating of lubricant. Dirt and dust adhere easily to this surface.

Idle Winter Batteries

Battery maintenance becomes even more critical during the winter months. The cold weather increases the already difficult task of starting diesel engines. Since the starter motor rotates slower than normal, less counter EMF is developed, and the current to the starter motor remains high. This increased current depletes the storage batteries rapidly. Problems are readily observed after extended winter weekends. To ensure the batteries are maintained at a high state of readiness –

- Always service and charge batteries thoroughly whenever the batteries are to enter an idle period. A discharged battery will freeze at about 18 degrees Fahrenheit. A frozen battery greatly increases the chance of a battery detonation. Detonation occurs during excessive charging or prolonged efforts to jump start equipment under these severe conditions.

- After the batteries are serviced and charged, disconnect the cables. Always disconnect the negative battery post first. Many small electrical problems in the starting or charging system can conduct current and discharge the batteries. When the equipment is operated regularly, small electrical deficiencies may not be noted. However, when equipment is left idle, even for a short time, these electrical deficiencies become apparent.

Battery Maintenance Tools

The most acceptable manner to clean battery terminals and clamps is to use the cutter or straightedge type of battery terminal and clamp cleaner. Wire-type battery terminal and clamp cleaners can damage the battery posts and clamps. Figure 4-11 shows the physical differences between the two cleaners.

Figure 4-12 view A shows a battery terminal in dire need of cleaning. The main concern for cleaning is to provide a large, clean contact surface area for the unimpeded flow of current. In view B, a cutter-type terminal cleaner is used. The cutter-type cleaner ensures a concentric post surface uniform in

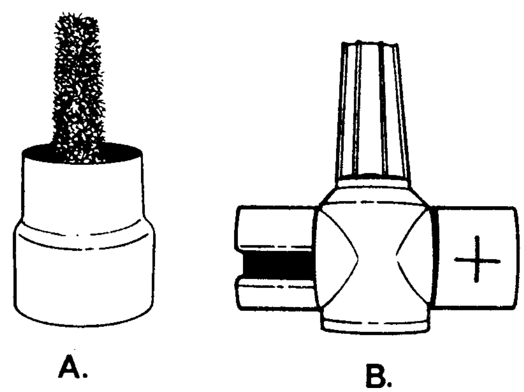


FIGURE 4-11. Battery Terminal and Clamp Cleaners.

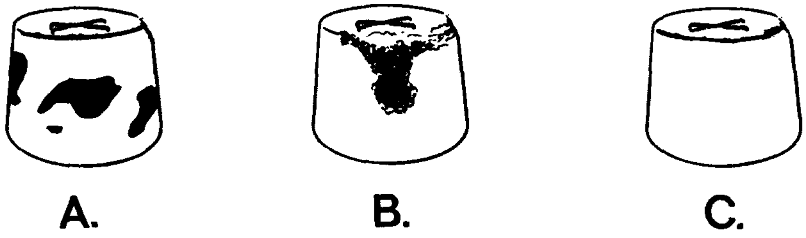


FIGURE 4-12. Cleaning a Dirty Battery Terminal.

contact area. The cutter leaves some of the surface area soiled and dull because it is designed to maintain the original taper of both the post and the clamp. The cutter can only remove a small amount of the outer post surface area each time. The low pitted areas grow smaller in dimension as the tool is used.

(A) Dirty Battery Terminal.

(B) Battery Terminal Partly Cleaned With Cutter-Type Terminal Cleaner.

(C) Battery Terminal Cleaned With Cutter-Type Terminal Cleaner.

When the inside of the terminal clamp is cleaned with the cutter-type cleaner, a similar condition results (Figure 4-13). Pits are visible and continually reduced in size. The cutting can continue until a uniform and properly tapered clean surface results.

(A) Dirty Battery Clamp.

B) Partly Cleaned Battery Clamp With Cutter-Type Cleaner.

(C) Cleaned Battery Clamp With Cutter-Type Cleaner.

The wire-type cleaner cannot restore the surface of the post or clamp. It will clean the entire area, but it cannot restore any irregularities in the surfaces. It actually increases the surface distortions. Pits get bigger, and the necessary contact surface area is decreased. The original taper is lost. The surface area is eventually reduced to a point where excessive heat from current flow can melt the post and clamp. A spark may result, detonating the battery. As Figure 4-14 shows, reduced contact area equals increased heating.

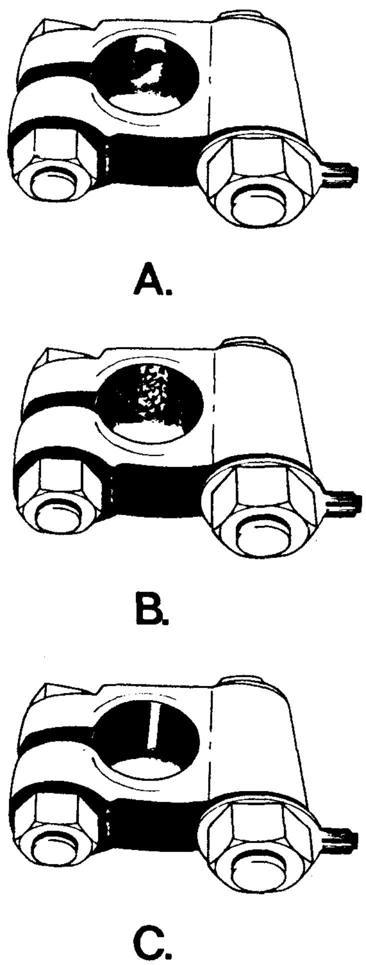


FIGURE 4-13. Cleaning a Dirty Battery Clamp.

Use a battery terminal clamp puller to remove battery clamps from the terminals. Prying the clamp from the terminal with a screwdriver will damage the terminal.

Battery Log

Keep weekly specific gravity readings and overall battery bank voltage readings in a battery logbook. This will provide an accurate and complete operational status of each battery to forecast any cells that are becoming deficient. Figure 4-15 is an example of a battery logbook.

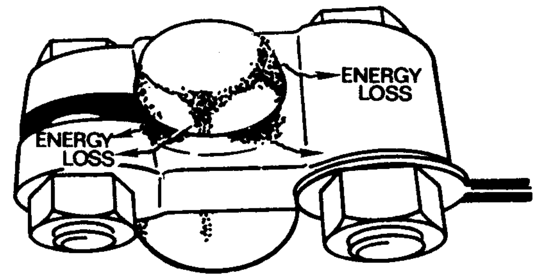


FIGURE 4-14. Reduced Contact Area Equals Increased Heating.

Date Serviced:

Battery No. 1:		Battery No. 2:	
Date Installed:		Date Installed:	
Specific Gravity Readings (negative to positive terminal)			
Cell 1: ______	Cell 4: ______	Cell 1: ______	Cell 4: ______
Cell 2: ______	Cell 5: ______	Cell 2: ______	Cell 5: ______
Cell 3: ______	Cell 6: ______	Cell 3: ______	Cell 6: ______
Battery No. 3:		Battery No. 4:	
Date Installed:		Date Installed:	
Cell 1: ______	Cell 4: ______	Cell 1: ______	Cell 4: ______
Cell 2: ______	Cell 5: ______	Cell 2: ______	Cell 5: ______
Cell 3: ______	Cell 6: ______	Cell 3: ______	Cell 6: ______
Battery No. 5:		Battery No. 6:	
Date Installed:		Date Installed:	
Cell 1: ______	Cell 4: ______	Cell 1: ______	Cell 4: ______
Cell 2: ______	Cell 5: ______	Cell 2: ______	Cell 5: ______
Cell 3: ______	Cell 6: ______	Cell 3: ______	Cell 6: ______

FIGURE 4-15. Battery Logbook.

The Hydrometer

A hydrometer is the instrument that measures the amount of active ingredients in the electrolyte of the battery. The hydrometer measures the specific gravity of the electrolyte. Specific gravity is the ratio of the weight of the electrolyte to the weight of the same volume of pure water. The active ingredient, such as sulfuric acid or potassium hydroxide, is heavier than water. Therefore, the more active ingredient there is in the electrolyte, the heavier the electrolyte will be. The heavier the electrolyte is, the higher the specific gravity will be.

WARNING

Never mix lead-acid and nickel cadmium servicing tools together. Never store or transport nickel-cadmium and lead-acid batteries together. The combination of potassium hydroxide and sulfuric acid electrolytes generate a toxic gas that can kill!

A hydrometer (Figure 4-16) is a glass syringe with a float inside it. The float is a hollow glass tube weighted at one end and sealed at both ends, with a scale calibrated in specific gravity marked on the side. The electrolyte to be tested is drawn into the hydrometer by using the suction bulb. Enough electrolyte should be drawn into the hydrometer so that the float will rise. However, the hydrometer should not be filled to the extent that the float rises into the suction bulb. Since the weight of the float is at its base, the float will rise to a point determined by the weight of the electrolyte. If the electrolyte contains a large concentration of active ingredient, the float will rise higher than if the electrolyte has a small concentration of active ingredient.

To read the hydrometer, hold it in a vertical position and take the reading at the level of the electrolyte. Refer to the manufacturer's technical manual for battery specifications for the correct specific gravity ranges.

WARNING

Care must be taken to prevent electrolytes from entering the eyes or from splashing on the skin.

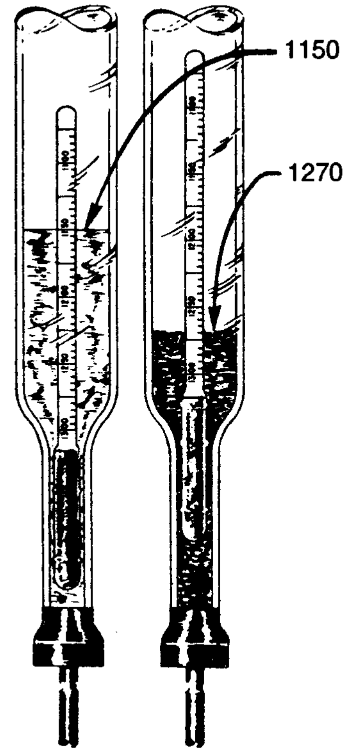


FIGURE 4-16. Hydrometer.

NOTE: Hydrometers should be flushed with fresh water after each use to prevent inaccurate readings. Storage battery hydrometers must not be used for any other purpose.

State of Charge

Table 4-1 provides a general guidance for the specific gravity of the lead-acid battery.

All testing of battery-powered equipment must be conducted with fully charged batteries. The manufacturer's technical data is based on the assumption that the power supply (batteries) is fully operational. Any deviation from the fully charged condition will change the testing results. If the batteries are not fully charged, the test results will be erroneous and inconclusive.

Unless otherwise specified, the specific gravity readings between cells should be no greater that 30

TABLE 4-1. Specific Gravity of the Lead -Acid Battery

Specific Gravity Temperate Climates	Specific Gravity Tropical Climates	State of Charge
1.260 - 1.280	1.225	Fully Charged
1.230 - 1.250	1.195	75 Percent Charged
1.200 - 1.220	1.165	50 Percent Charged
1.170 - 1.190	1.135	25 Percent Charged
1.110 - 1.130	1.075	Discharged

points (.030). Any variations outside the specifications indicate an unsatisfactory condition, and the battery should be replaced.

Gassing

When a battery is being charged, a portion of the energy breaks down the water in the electrolyte. Hydrogen is released at the negative plates and oxygen at the positive plates. These gases bubble up through the electrolyte and collect in the air space at the top of the cell. If violent gassing occurs when the battery is first placed on charge, the charging rate is too high. If the rate is not too high, steady gassing develops as the charging proceeds, indicating that the battery is nearing a fully charged condition.

Avoid excessive gassing. The by-products are hazardous and explosive. Any lost liquid from the battery cell is a combination of water and sulfuric acid. Since the specific gravity changes as the batteries increase in charge, it is impossible to anticipate the exact content of sulfuric acid removed from the cell. Every time the maintenance technician replenishes the cell with water, he is actually reducing the percentage of sulfuric acid within that cell. Eventually the chemical action will become deficient.

Battery Caps

When taking hydrometer readings, avoid contaminating battery cap undersides by placing them upside down on the battery case. This will help keep debris from falling into the cell.

Troubleshooting Battery-Powered Systems

Troubleshooting battery-powered systems can become complex. Unlike many mechanical systems, numerous electrical problems can be identified with a good initial inspection. Burned out electrical components have a distinctive electrical smell, and charred wires and connections are readily identified. Once these areas are identified and corrected, further tests are needed to determine the reason for this condition.

Check all connections, from the battery throughout the entire electrical system, regularly. All connections must be clean and tight. Army vessels operating in the salt air environment are especially prone to oxidation. All mobile units are prone to vibration. Together, vibration and oxidation account for a large percentage of electrical malfunctions.

Any increase in resistance in the circuit reduces the current throughout the entire circuit. When current is reduced, the magnetic properties of the circuit are reduced. Current is a quantity of electrons (with their magnetic field) passing a point in the circuit in a period of time. With fewer electrons, there is a reduction in the magnetic properties available to the circuit components. With a reduction of electrons (and their magnetic influence), motors, solenoids, and other electrical components will function irregularly. Some of the more obvious resistance increases are due to improper or dirty connections and corroded cable ends.

To understand how a small amount of additional resistance can reduce the capability of the electrical system, suppose that a resistance of 1 ohm exists in a poorly made connection in a diesel engine starting system. The 24-volt battery starting system normally provides 240 amps to a starting system with a resistance of .1 ohms. The 24 volts must now supply a starting system with 1.1 ohms resistance.

The additional 1 ohm resistance will consume power (power = amps x volts). The current will be reduced because the total resistance (Rt) is increased. The total amperage for the system is reduced as shown in the following equation:

$$It = \frac{Et}{Rt}$$

$$It = \frac{24\ \text{volts}}{1.1\ \text{ohm}}$$

$$It = 21.8\ \text{amps}$$

The 240 amps required to turn the starter motor has been reduced to 21.8 amps. The starter cannot turn.

Battery Voltage

A fully charged lead-acid battery has 2.33 volts per cell. It is quite common for a 24-volt battery bank to actually have a voltage of 26.5 volts. The technical manual specifies the term "battery voltage" instead of 24 volts because the actual battery terminal voltage must be observed throughout the entire electrical testing procedure. The manufacturer is concerned with the actual battery bank voltage.

A charged battery that shows an extremely high voltage is suspect of being deficient. Individual 12-volt batteries should not exceed 15.5 volts, and 6-volt batteries should not exceed 7.8 volts. If these voltages are exceeded, the battery is unsatisfactory and probably sulfated. These higher voltage values indicate only a superficial charge and are incapable of delivering the current capacity designed for the battery.

Test result standards are based on a fully functioning power supply. Always start troubleshooting the battery-powered electrical system at the batteries. The batteries must be fully operational and completely charged before testing any other electrical component. Charge the existing battery bank or substitute the batteries when other circuit components are suspect.

Other Maintenance

Perform routine maintenance of batteries regularly. Check terminals periodically for cleanliness and good electrical connections. Inspect the battery case for cleanliness and evidence of damage. Check the level of electrolyte. If the electrolyte is low, add distilled water to bring the electrolyte to the proper level. Maintenance procedures for batteries are normally determined by higher authority. Each command will have detailed procedures for battery care and maintenance.

Safety Precautions With Batteries

Observe the following safety precautions when working with batteries:

- Handle all types of batteries with care.
- Never short the terminals of a battery.
- Use carrying straps when transporting batteries.
- Wear chemical splash-proof safety glasses when maintaining batteries.
- Wear protective clothing, such as a rubber apron and rubber gloves when working with batteries. Electrolyte will destroy everyday clothing such as the battle dress uniform.
- Do not permit smoking, electric sparks, or open flames near charging batteries.
- Take care to prevent spilling the electrolyte.
- Never install alkaline and lead-acid batteries in the same compartment.
- Do not exchange battery tools to include hydrometers between lead-acid batteries and nickel-cadmium batteries.

In the event electrolyte is splashed or spilled on a surface, such as the deck or table, immediately dilute it with large quantities of water and clean it up.

If the electrolyte is spilled or splashed on the skin or eyes, immediately flush the area with large quantities of fresh water for a minimum of 15 minutes. If the electrolyte is in the eyes, be sure the upper and lower eyelids are pulled out sufficiently to allow the fresh water to flush under the eyelids. Notify the medical department of the type of electrolyte and the location of the accident as soon as possible.

CAPACITY AND RATING OF BATTERIES

The capacity of a battery is measured in ampere-hours. The ampere-hour capacity equals the product of the current in amperes and the time in hours during which the battery will supply this current. The ampere-hours capacity varies inversely with the discharge current. For example, a 400 ampere-hour battery will deliver 400 amperes for one hour or 100 amperes for four hours.

Storage batteries are rated according to their rate of discharge and ampere-hour capacity. Most batteries are rated according to a 20-hour rate of discharge. That is, if a fully charged battery is completely discharged during a 20-hour period, it is discharged at the 20-hour rate. Thus, if a battery can deliver 20 amperes continuously for 20 hours, the battery has a rating of 20 amperes x 20 hours, or 400 ampere-hours. Therefore, the 20-hour rating equals the average current that a battery can supply without interruption for an interval of 20 hours.

All standard batteries deliver 100 percent of their available capacity if discharged in 20 hours or more, but they will deliver less than their available capacity if discharged at a faster rate. The faster they discharge, the less ampere-hour capacity they have.

The low-voltage limit, as specified by the manufacturer, is the limit beyond which very little useful energy can be obtained from a battery. This low-voltage limit is normally a test used in battery shops to determine the condition of a battery.

BATTERY CHARGING

Adding the active ingredient to the electrolyte of a discharged battery does not recharge the battery. Adding the active ingredient only increases the specific gravity of the electrolyte. It does not convert the plates back to active material, and so does not bring the battery back to a charged condition. A charging current must be passed through the battery to recharge it.

WARNING

A mixture of hydrogen and air can be dangerously explosive. No smoking, electric sparks, or open flames should be permitted near charging.

Types of Charges

The following types of charges may be given to a storage battery, depending on the condition of the battery

- Initial charge.
- Normal charge.
- Equalizing charge.
- Floating charge.
- Fast charge.

Initial Charge. When a new battery is shipped dry, the plates are in an uncharged condition. After the electrolyte has been added, it is necessary to charge the battery. This is done by giving the battery a long low-rate initial charge. The charge is given according to the manufacturer's instructions, which are shipped with each battery. If the manufacturer's instructions are not available, refer to the detailed instructions for charging batteries found in TM 9-6140-200-14.

Normal Charge. A normal charge is a routine charge given according to the nameplate data during the ordinary cycle of operation to restore the battery to its charged condition.

Equalizing Charge. An equalizing charge is a special extended normal charge that is given periodically to batteries as part of maintenance routine. It ensures that all sulfate is driven from the plates and that all the cells are restored to a maximum specific gravity. The equalizing charge is continued until the specific gravity of all cells, corrected for temperature, shows no change for a four-hour period.

Floating Charge. In a floating charge, the charging rate is determined by the battery voltage rather than by a definite current value. The floating charge is used to keep a battery at full charge while the battery is idle or in light duty. It is sometimes referred to as a trickle charge and is done with low current.

Fast Charge. A fast charge is used when a battery must be recharged in the shortest possible time. The charge starts at a much higher rate than is normally used for charging. It should be used only in an emergency, as this type charge may harm the battery.

Charging Rate

Normally, the charging rate of storage batteries is given on the battery nameplate. If the available charging equipment does not have the desired charging rates, use the nearest available rates. However, the rate should never be so high that violent gassing occurs.

Charging Time

Continue the charge until the battery is fully charged. Take frequent readings of specific gravity during the charge and compare with the reading taken before the battery was placed on charge.

CHAPTER 5

CONCEPTS OF ALTERNATING CURRENT

INTRODUCTION

Thus far this text has dealt with direct current (DC); that is, current that does not change direction. However, a coil rotating in a magnetic field actually generates a current that regularly changes direction. This current is called alternating current (AC).

AC AND DC

Alternating current is current that changes constantly in amplitude and which reverses direction at regular intervals. Direct current flows only in one direction. The amplitude of current is determinedly the number of electrons flowing past a point in a circuit in one second. If, for example, a coulomb of electrons moves past a point in a wire in one second and all of the electrons are moving in the same direction, the amplitude of DC in the wire is 1 amp. Similarly, if half a coulomb of electrons moves in one direction past a point in the wire in half a second, then reverses direction and moves past the same point in the opposite direction during the next half-second, a total of 1 coulomb of electrons passes the same point in the wire. The amplitude of the AC is 1 ampere. Figure 5-1 shows this comparison of DC and AC. Notice that one white arrow plus one striped arrow comprises 1 coulomb.

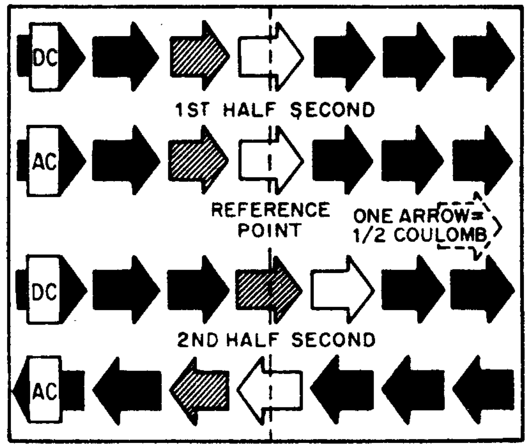


FIGURE 5-1. Comparing DC and AC Current Flow in a Wire.

DISADVANTAGES OF DC COMPARED TO AC

When commercial use of electricity became widespread in the United States, certain disadvantages in using DC became apparent. If a commercial DC system is used, the voltage must be generated at the level (amplitude or value) required by the load. To properly light a 240-volt lamp, for example, the DC generator must deliver 240 volts. If a 120-volt lamp is to be supplied power from a 240-volt generator, a resistor or another 120-volt lamp must be placed in series with the 120-volt lamp to drop the extra 120 volts. When the resistor is used to reduce the voltage, an amount of power equal to that consumed by the lamp is wasted.

Another disadvantage of the DC system becomes evident when the direct current (I) from the generating station must be transmitted a long distance over wires to the consumer. When this happens, a large amount of power is lost due to the resistance (R) of the wire. The power lost equals I^2R. However, this loss can be greatly reduced if the power transmitted over the lines is at a very high voltage level and a low current level. This is not a practical solution in the DC system since the load would then have to be operated at a dangerously high voltage. Because of the disadvantages related to transmitting and using DC, practically all modern commercial electric power companies generate and distribute AC.

Unlike direct voltages, alternating voltages can be stepped up or down in amplitude by a device called a transformer. Use of the transformer permits efficient transmission of electrical power over long distance lines. At the electrical power station, the transformer output is at high voltage and low current levels. At the consumer end of the transmission lines, the voltage is stepped down by a transformer to the value required by the load. Due to its inherent advantages and versatility, AC has replaced DC in all but a few commercial power and vessel applications.

ELECTROMAGNETISM

The sine wave is used to illustrate the change in current direction of the AC system. Although there are several ways of producing this current, the method based on the principles of electromagnetic induction is by far the easiest and most common method in use.

Chapter 2 discussed the fundamental theories concerning simple magnets and magnetism, but it only briefly mentioned how magnetism can be used to produce electricity. This chapter presents a more in-depth study of magnetism. The main points are how magnetism is affected by an electric current and, conversely, how electricity is affected by magnetism. This general subject area is called electromagnetism. The following relationships between magnetism and electricity must be understood to become proficient in the electrical field:

- An electric current always produces some form of magnetism.
- The most commonly used means for producing or using electricity involves magnetism.
- The peculiar behavior of electricity under certain conditions is caused by magnetic influences.

MAGNETIC FIELDS

In 1819, Hans Christian Oersted, a Danish physicist, found that a definite relationship exists between magnetism and electricity. He discovered that an electric current is always accompanied by certain magnetic effects and that these effects obey certain laws.

MAGNETIC FIELD AROUND A CURRENT-CARRYING CONDUCTOR

If a compass is placed near a current-carrying conductor, the compass needle will align itself at right angles to the conductor. This indicates the presence of a magnetic force. The presence of this force can be demonstrated by using the arrangement in Figure 5-2. In views A and B, current flows in a vertical conductor through a horizontal piece of cardboard. The direction of the magnetic field produced by the current can be determined by placing a compass at various points on the cardboard and noting the compass needle deflection. The direction of the magnetic force is assumed to be the direction in which the north pole of the compass points.

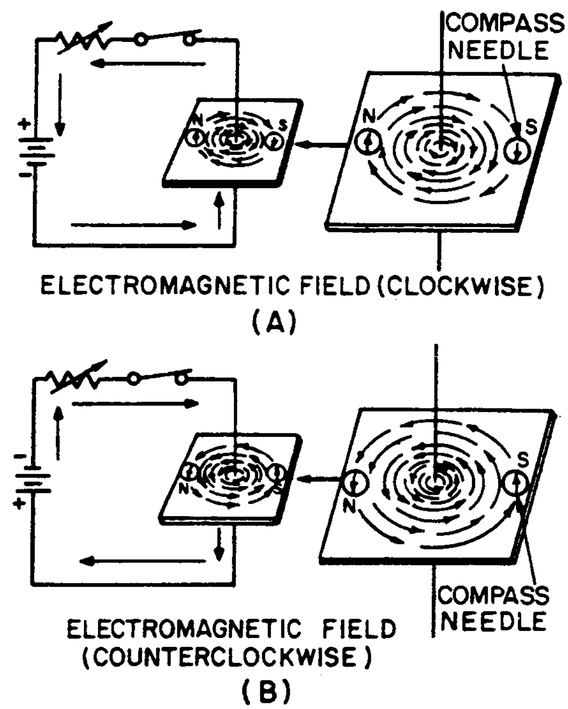


FIGURE 5-2. Magnetic Field Around a Current-Carrying Conductor.

In view A, the needle deflections show that a magnetic field exists in a circular form around a conductor. When the current flows upward (view A), the direction of the field is clockwise as viewed from the top. However, if the polarity of the battery is reversed so that the current flows downward (view B), the direction of the field is counterclockwise.

The relation between the direction of the magnetic lines of force around a conductor and the direction of the current in the conductor may be determined by means of the left-hand rule for a conductor. If you visualize the conductor in the left hand with your thumb extended in the direction of the electron flow (current: - to +), your finger will point in the direction of the magnetic lines of force. Now apply this rule to Figure 5-2. Note that your fingers point in the direction that the north pole of the compass points when it is placed in the magnetic field surrounding the wire.

An arrow is generally used in electrical diagrams to denote the direction of current in a length of wire (Figure 5-3 view A). Where across section of wire is shown, an end view of the arrow is used. View B shows a cross-sectional view of a conductor carrying current toward the observer. The direction of current is indicated by a dot, representing the head of an arrow. View C shows a conductor carrying current away from the observer. The direction of current is indicated by a cross, representing the tail of the arrow. The magnetic field around the current-carrying conductor is perpendicular to the conductor, and the magnetic lines of force are equal along all parts of the conductor.

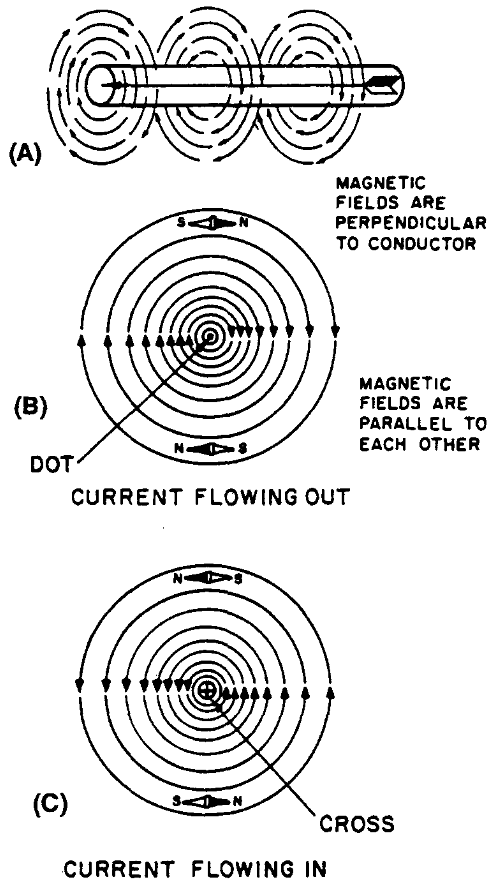


FIGURE 5-3. Magnetic Field Around a Current-Carrying Conductor, Detailed View.

When two adjacent parallel conductors are carrying current in the same direction, the magnetic lines of force combine and increase the strength of the magnetic field around the conductors (Figure 5-4 view A). View B shows two parallel conductors carrying currents in opposite directions. The field around one conductor is opposite in direction to the field around the other conductor. The resulting lines of force oppose each other in the space between the wires, thus deforming the field around each conductor. This means that if two parallel and adjacent conductors are carrying currents in the same direction, the fields about the two conductors aid each other. Conversely, if the two conductors are carrying currents in opposite directions, the fields about the conductors repel each other.

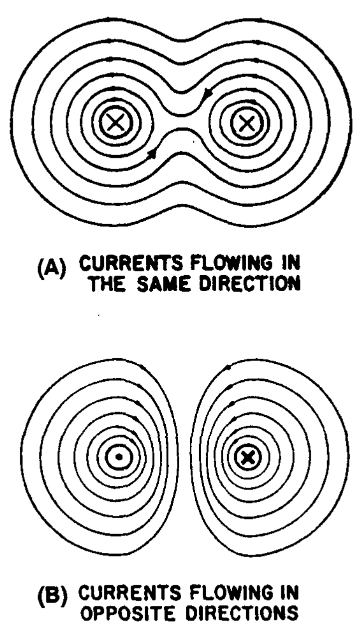


FIGURE 5-4. Magnetic Field Around Two Parallel Conductors.

MAGNETIC FIELD OF A COIL

Figure 5-3 view A shows that the magnetic field around a current-carrying wire exists at all points along the wire. Figure 5-5 shows that when a straight wire is wound around a core, it forms a coil, and the magnetic field about the core assumes a different shape. Figure 5-5 view A is actually a partial cutaway view showing the construction of a simple coil. View B shows a cross-sectional view of the same coil. The two ends of the coil are identified as X and Y.

When current is passed through the coil, the magnetic field about each turn of wire links with the fields of the adjacent turns (Figure 5-4). The combined influence of all the turns produces a two-pole field similar to that of a simple bar magnet. One end of the coil is a north pole and the other a south pole.

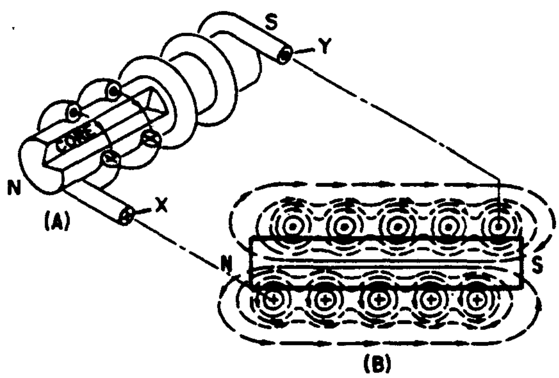


FIGURE 5-5. Magnetic Field Produced By a Current-Carrying Coil.

Polarity of an Electromagnetic Coil

The direction of the magnetic field around a straight wire depends on the direction of current in that wire, as shown in Figure 5-2. Thus, a reversal of current in a wire causes a reversal in the direction of the magnetic field that is produced. It follows that a reversal of the current in a coil also causes a reversal of the two-pole magnetic field about the coil.

When the direction of the current in a coil is known, the magnetic polarity of the coil can be determined by using the left-hand rule for coils. This rule, illustrated in Figure 5-6, is stated as follows:

> Grasp the coil in your left hand, with your fingers wrapped around in the direction of the current. Your thumb will then point toward the north pole of the coil.

Strength of an Electromagnetic Field

The strength or intensity of a coil's magnetic field depends on a number of factors. The main factors are as follows:

- The number of turns of wire in the coil.
- The amount of current flowing in the conductor.
- The ratio of the coil length to the coil width.
- The type of material in the core.

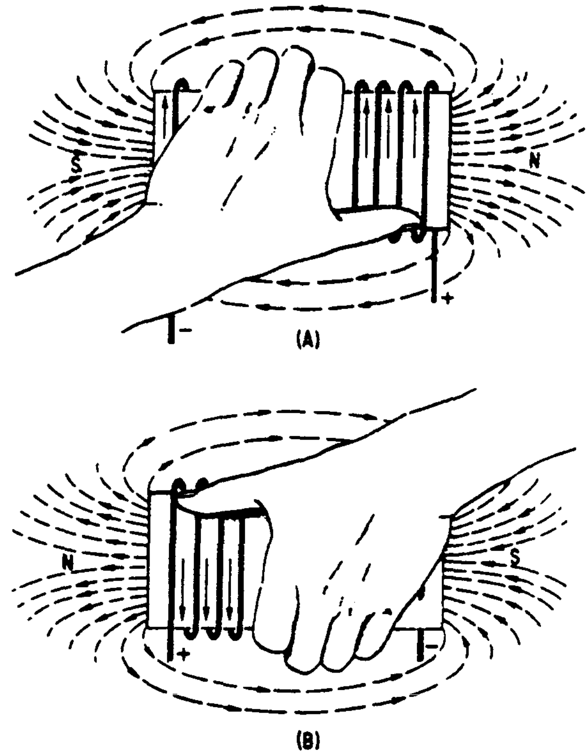


FIGURE 5-6. Left-Hand Rule for Coils.

Losses in an Electromagnetic Field.

When current flows in a conductor, the atoms line up in a definite direction, producing a magnetic field. When the direction of current changes, the direction of the atom's alignment also changes, causing the magnetic field to change direction. To reverse all the atoms requires that power be expended, and this power is lost. This loss of power (in the form of heat) is called hysteresis loss. Hysteresis loss is common to all AC equipment. However, it causes few problems except in motors, generators, and transformers.

BASIC AC GENERATION

A current-carrying conductor produces a magnetic field around itself. Chapter 2 discussed how a changing magnetic field produces an EMF in a conductor. If a conductor is placed in a magnetic field and either the field or the conductor moves in such a manner that lines of force are interrupted, an EMF is induced in the conductor. This effect is called electromagnetic induction.

CYCLE

Figure 5-7 shows a suspended loop of wire (conductor) being rotated (moved) in a clockwise direction through the magnetic field between the poles of a permanent magnet. For easy explanation, the loop has been divided into a dark half and a light half. In Figure 5-7 view A, the dark half is moving along (parallel to) the lines of force. As a result, it is cutting no lines of force. The same is true of the light half, which is moving in the opposite direction. Since the conductors are cutting no lines of force, no EMF is induced.

As the loop rotates toward the position in Figure 5-7 view B, it cuts more and more lines of force per second (inducing an ever-increasing voltage) because it is cutting more directly across the field (lines of force). At view B, the conductor has completed one-quarter of a complete revolution (90 degrees) of a complete circle. Because the conductor is now cutting directly across the field, the voltage induced in the conductor is maximum. If the induced voltages at various points during the rotation from views A to B are plotted on a graph (and the points connected), a curve appears as shown in Figure 5-8.

As the loop continues to be rotated toward the position in Figure 5-7 view C, it cuts fewer and fewer lines of force. The induced voltage decreases from its peak value. Eventually, the loop is again moving in a plane parallel to the magnetic field, and no EMF is induced in the conductor.

The loop has now been rotated through half a circle (an alternation or 180 degrees). If the preceding quarter-cycle is plotted, it appears as shown in Figure 5-8.

When the same procedure is applied to the second half of the rotation (180 degrees through 360 degrees), the curve appears below the horizontal time line. The only difference is in the polarity of the induced voltage. Where previously the polarity was positive, it is now negative.

The sine curve shows the induced voltage at each instant of time during the rotation of the loop. This curve contains 360 degrees, or two alternations. Two alternations represent one complete cycle of rotation.

Assuming a closed circuit is provided across the ends of the conductor loop, the direction of current in the loop can be determined by using the left-hand rule for generators (Figure 5-9). The left-hand rule is applied as follows:

- First, place your left hand near the illustration with the fingers as shown.
- Your thumb will point in the direction of rotation (relative movement of the wire to the magnetic field). The forefinger will point in the direction of the magnetic flux (north to south). The middle finger (pointing out of the paper) will point in the direction of current flow.

When applying the left-hand rule to the dark half of the loop in Figure 5-8 view B, the current flows in the direction indicated by the heavy arrow. Similarly, when applying the left-hand rule on the light half of the loop, the current flows in the opposite direction. The two induced voltages in the loop add together to form one total EMF. This EMF causes the current in the loop.

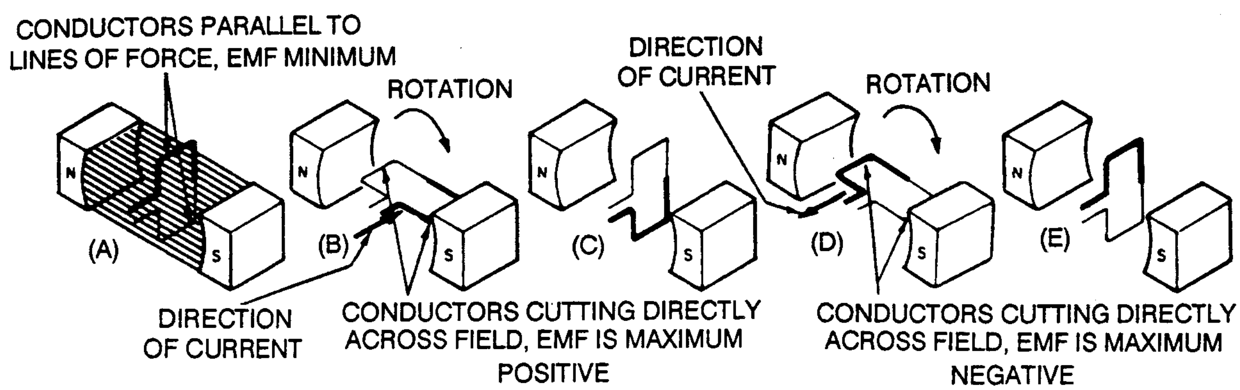


FIGURE 5-7. Simple Alternating Current Generator.

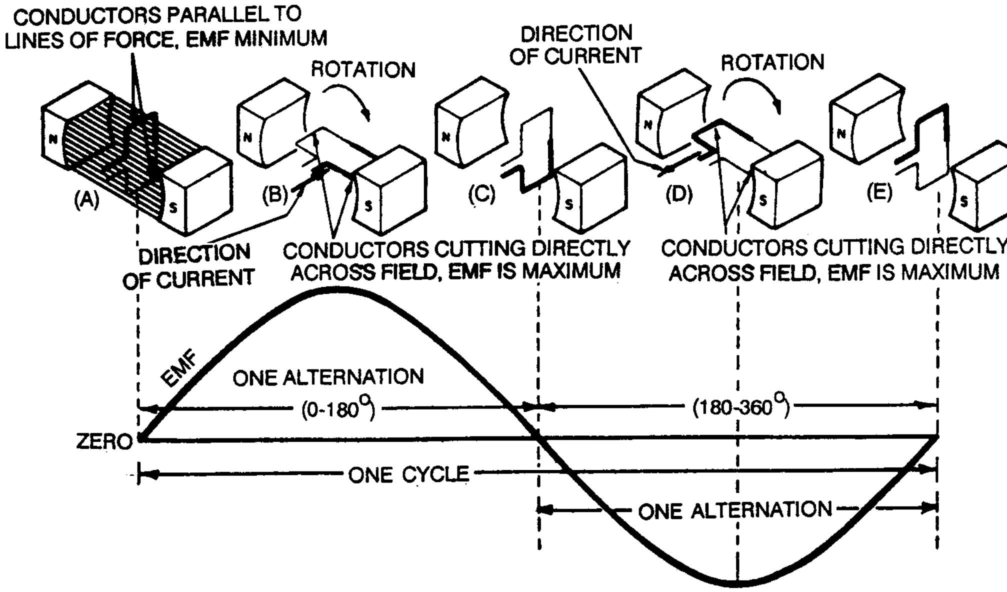
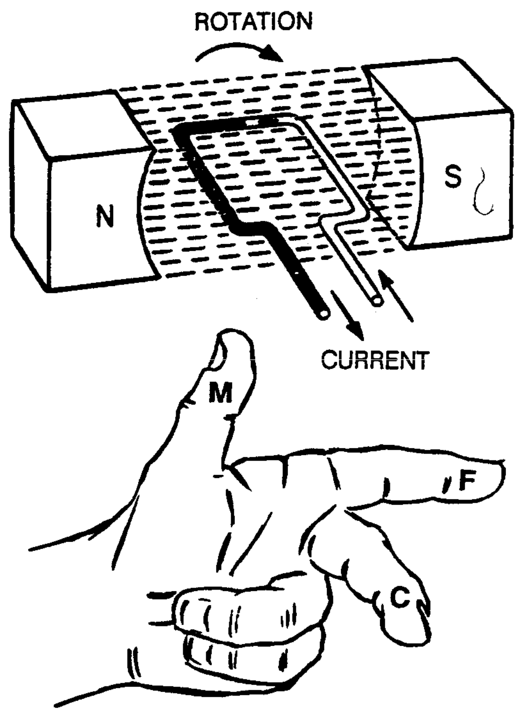


FIGURE 5-8. Basic Alternating Current Generator.

When the loop rotates to the position of view D, the action reverses. The dark half is moving up instead of down, and the light half is moving down instead of up. By applying the left-hand rule once again, the total induced EMF and its resulting current have reversed direction. The voltage builds up to maximum in this new direction, as shown by the sine curve. The loop finally returns to its original position, view E, at which point voltage is again zero. The sine curve represents one complete cycle of voltage generated by the rotating loop. These illustrations show the wire loop moving in a clockwise direction. In actual practice, either the loop or the magnetic field can be moved. Regardless of which is moved, the left-hand rule applies.

If the loop is rotated through 360 degrees at a steady rate and if the strength of the magnetic field is uniform, the voltage produced is a sine wave of voltage (Figure 5-8). Continuous rotation of the loop will produce a series of sine-wave voltage cycles or, in other words, AC voltage.

The cycle consists of two complete alternations in a period of time. The hertz (Hz) indicates one cycle per second. If one cycle per second is 1 hertz, then 100 cycles per second equal 100 hertz, and so on. This text uses the term "cycle" when no specific time element is involved and the term "hertz" when the time element is measured in seconds.



AN EASY WAY TO REMEMBER WHICH FINGER POINTS TO WHAT QUANTITY IS TO USE THE MEMORY AID: MY FINE CLOTHES.
MY = M, DIRECTION OF MOVEMENT
FINE = F, DIRECTION OF FLUX N → S
CLOTHES = C, DIRECTION OF CURRENT FLOW

FIGURE 5-9. Left-Hand Rule for Generators.

FREQUENCY

If the loop makes one complete revolution each second, the generator produces one complete cycle of AC during each second (1 Hz). Increasing the number of revolutions to two per second produces two cycles of AC per second (2 Hz). The number of complete cycles of AC or voltage completed each second is the frequency. Frequency is always measured and expressed in hertz.

PERIOD

An individual cycle of any sine wave represents a definite amount of time. Figure 5-10 shows two cycles of a sine wave that have a frequency of 2 hertz. Since two cycles occur each second, one cycle must require one-half second of time. The time required to complete one cycle of a waveform is the period of the wave. In the above example, the period is one-half second, The relationship between time (t) and frequency (f) is indicated by the following formulas:

$$t = \frac{1}{f} \quad \text{and} \quad f = \frac{1}{t}$$

Where: t = period in seconds
f = frequency in hertz

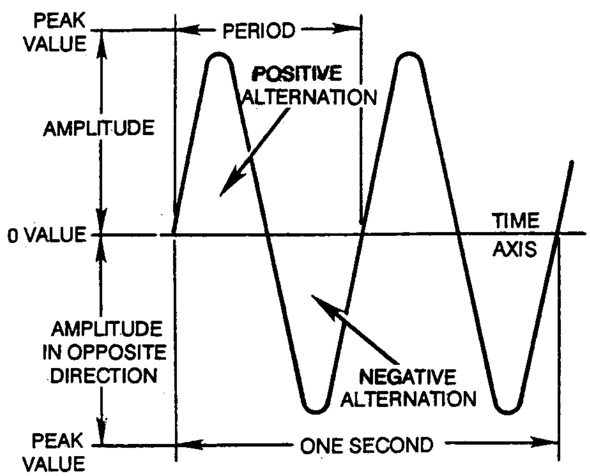


FIGURE 5-10. Period of a Sine Wave.

Each cycle of the sine wave in Figure 5-10 consists of two identically shaped variations in voltage. The variations that occur during the time considered the positive alternation (above the horizontal line) indicate current movement in one direction. The direction of current movement is determined by the generated terminal voltage polarities. The variations that occur during the time considered the negative alternation (below the horizontal line) indicate current movement in the opposite direction because the generated voltage terminal polarities have reversed.

The distance from zero to the maximum value of each alternation is the amplitude. The amplitude of the positive alternation and the amplitude of the negative alternation are the same.

WAVELENGTH

The time it takes for a sine wave to complete one cycle is defined as the period of the waveform. The distance traveled by the sine wave during this period is the wavelength. Wavelength, indicated by the Greek symbol lambda, is the distance along the wave from one point to the same point on the next cycle. Figure 5-11 shows this relationship. The point where waveform measurement of wavelength begins is not important as long as the distance is measured to the same point on the next cycle (Figure 5-12).

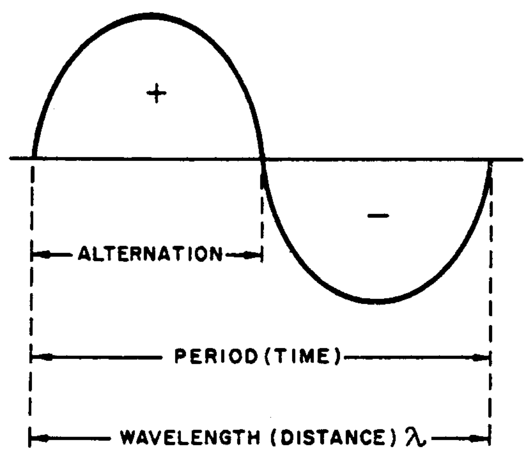


FIGURE 5-11. Wavelength.

The sine wave is usually expressed on a scale in degrees, Rather than express the time involved in minute portions of a second, it is more effective to express the single recurring sine wave by how many degrees it takes to complete a wavelength. Remember how the sine wave was developed. The conductor had to rotate 180 degrees to create the positive alternation and 180 degrees more to create the negative alternation (Figure 5-9). This produced 360 degrees or one complete revolution for a definite period of time. The amount of times this sine wave is repeated every second corresponds to the frequency (cycles per second) and to the speed of the moving conductor (revolutions per minute). This is the beginning of understanding the relationship between frequency, cycles, and the speed of the prime mover.

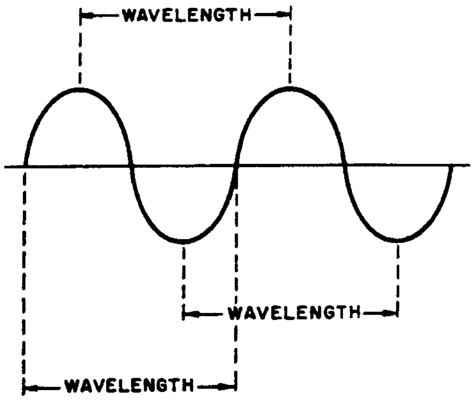


FIGURE 5-12. Wavelength Measurement.

ALTERNATING CURRENT VALUES

AC and voltage are often expressed in terms of maximum or peak values, peak-to-peak values, effective values, average values, or instantaneous values. Each of these values describes a different amount of the current or voltage.

Peak and Peak-to-Peak Values

Figure 5-13 shows the positive alternation of a sine wave (a half-cycle of AC) and a DC waveform that occur simultaneously. The DC starts and stops at the same moment as the positive alternation, and both waveforms rise to the same maximum value. However, the DC values are greater than the corresponding AC values at all points except the point at which the positive alternation passes through its maximum value. At this point, the DC and the AC values are equal. This point on the sine wave is referred to as the maximum or peak value.

During each complete cycle of AC, there are always two maximum or peak values: one for the positive half-cycle and the other for the negative half-cycle. The difference between the peak positive value and the peak negative value is the peak-to-peak value of the sine wave. This value is twice the maximum or peak value of the sine wave and is sometimes used to measure AC voltages. Figure 5-14 shows the difference between peak and peak-to-peak values. Usually, alternating voltage and current are expressed in effective values rather than in peak-to-peak values.

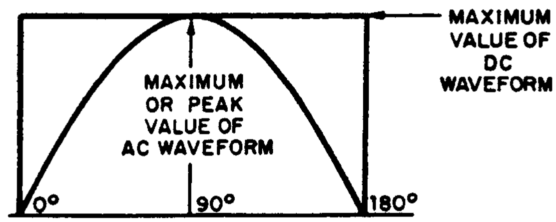


FIGURE 5-13. Maximum or Peak Value.

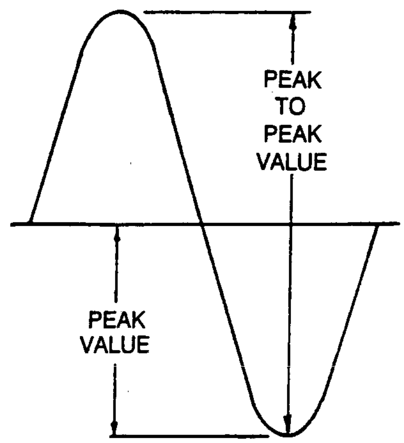


FIGURE 5-14. Peak and Peak-to-Peak Values.

Effective Value

The voltage and current values commonly displayed on multimeters and discussed by technicians is called the effective value. Although AC changes in value constantly, a value closely resembling a like value of DC can be expressed. The effective value of alternating current or voltage has the same effect as a like value of DC. To convert the effective value to a peak value, multiply the effective value by 1.414.

Example:

(450-volt generator effective value) x 1.414 = peak value

(450 volts) x 1.414 = 636.3 volts peak

Conversely, to change the peak value into the effective value, multiply the peak value by .707.

Example:

(636 volt peak value) x .707 = effective value

(636 volts) x .707 = 450 volts effective value

The effective value of alternating current or voltage is also referred to as root mean square or RMS. The RMS value is derived from the power formula. The RMS value turns out to be 70.7 percent of the peak value.

Figure 5-15 shows various values used to indicate sine wave amplitude.

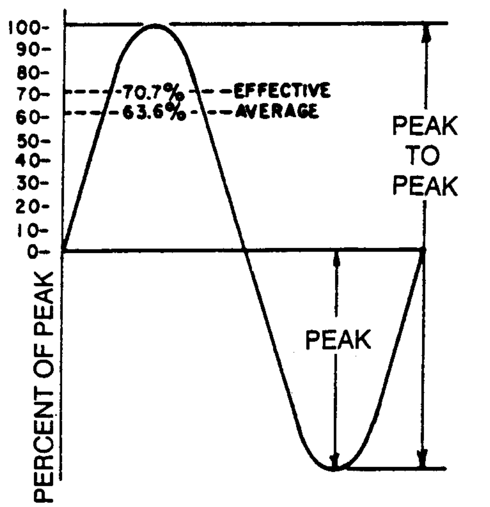


FIGURE 5-15. Various Values Used To Indicate Sine Wave Amplitude.

Instantaneous Value

The instantaneous value of an alternating voltage or current is the value of voltage or current at one particular instant in time. The value may be zero if the particular instant is the time in the cycle at which the polarity of the voltage is changing. It may also be the same as the peak value, if the selected instant is the time in the cycle at which the voltage or current stops increasing and starts decreasing. There are actually an infinite number of instantaneous values between zero and peak value.

Average Value

The average value of an alternating current or voltage is the average of all the instantaneous values during one alternation. Since the voltage increases from zero to peak value and decreases back to zero during one alternation, the average value must be some value between those two limits. The average value can be determined by adding together a series of instantaneous values of the alternation (between 0 and 180 degrees) and then dividing the sum by the number of the instantaneous values used. The computation would show that one alternation of a sine wave has an average value equal to 0.636 times the peak value.

Do not confuse the above definition of an average value with that of the average value of a complete cycle. Because the voltage is positive during one alternation and negative during the other alternation, the average value of the voltage values occurring during the complete cycle is zero.

SINE WAVES IN PHASE

When a sine wave of voltage is applied to a resistance, the resulting current is also a sine wave. This follows Ohm's Law which states that current is directly proportional to the applied voltage. In Figure 5-16, the sine wave of voltage and the resulting sine wave of current are superimposed on the same time axis. As the voltage increases in the positive alternation, the current also increases. When two sine waves, such as those in Figure 5-16, are precisely in step with one another, they are in phase. To be in phase, the two sine waves must go through their maximum and minimum points at the same time and in the same direction.

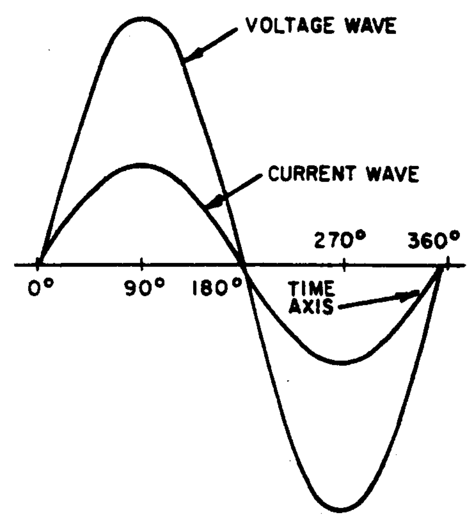


FIGURE 5-16. Voltage and Current Waves in Phase.

This action can only occur in a circuit containing a purely resistive load. A resistive load is any device that consumes all power in the form of heat and/or light. Resistors, light bulbs, and some heating elements are examples of these loads. All the power that arrives at the load is consumed at the load. There is no power left over to be returned to the circuit.

SINE WAVES OUT OF PHASE

Figure 5-17 shows voltage wave El which is considered to start at 0 degrees (time one). As voltage wave El reaches its positive peak, voltage wave E2 starts its rise (time two). Since these voltage waves do not go through their maximum and minimum points at the same instant in time, a phase difference exists between the two waves. The two waves are out of phase. For the two waves in Figure 5-17, the phase difference is 90 degrees.

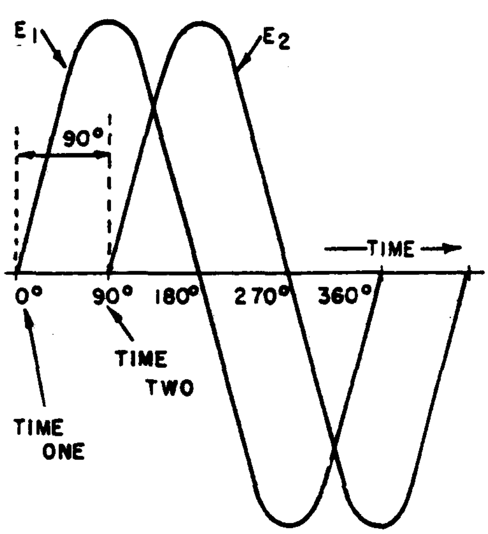


FIGURE 5-17. Voltage Waves 90 Degrees Out of Phase.

The terms "lead" and "lag" further describe the phase relationship between two sine waves. The amount by which one sine wave leads or lags another sine wave is measured in degrees. In Figure 5-17, wave E2 starts 90 degrees later in time than does wave El. Wave El leads wave E2 by 90 degrees, and wave E2 lags wave El by 90 degrees.

One sine wave can lead or lag another sine wave by any number of degrees, except 0 or 360. When the latter condition exists, the two waves are said to be in phase. Thus, two sine waves that differ in phase by 45 degrees are actually out of phase with each other; whereas two sine waves that differ in phase by 360 degrees are considered to be in phase with each other.

Figure 5-18 shows a common phase relationship. The two waves illustrated differ in phase by 180 degrees. Although the waves pass through their maximum and minimum values at the same time, their instantaneous voltages are always of opposite polarity.

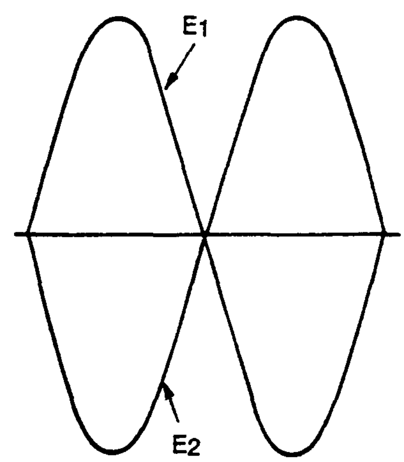


FIGURE 5-18. Voltage Waves 180 Degrees Out of Phase.

To determine the phase difference between two sine waves, locate the points where the two waves cross the time axis traveling in the same direction. The number of degrees between the crossing points is the phase difference. The wave that crosses the axis at the later time (to the right on the time axis) is said to lag the other wave.

OHM'S LAW IN AC CIRCUITS

Few shipboard circuits contain resistance only. For those circuits that contain purely resistive loads, the same rules apply to these circuits as apply to DC circuits. Ohm's Law for purely resistive circuits can be stated as follows

$$I_{eff} = \frac{E_{eff}}{R} \text{ or } I = \frac{E}{R}$$

Unless otherwise stated, all AC voltage and current values are given as effective values. Do not mix AC values. When solving for effective values, all values used in the formulas must be effective values. Similarly, when solving for average values, all values must be average values.

There are many other factors affecting the mathematical values of AC electrical systems. Even with these other outside variables, the marine engineer can use Ohm's Law to understand the relationship between voltage, current, and resistance.

CHAPTER 6

INDUCTANCE

INTRODUCTION

The study of inductance is a very challenging but rewarding segment of electricity. It is challenging because at first it seems that new concepts are being introduced. However, these new concepts are merely extensions of the fundamental principles in the study of magnetism and electron physics. The study of inductance is rewarding because a thorough understanding of it will enable you to acquire a working knowledge of electrial circuits more rapidly. The Army marine engineer field is the only military occupational speciality that requires an individual to show a working knowledge of electricity, from the production and supply, through the maintenance and overhaul, to the user-end operation.

CHARACTERISTICS OF INDUCTANCE

Inductance is the characteristic of an electrical circuit that opposes the starting, stopping, or changing of current flow. The symbol for inductance is L. The basic unit of inductance is the henry(H); 1 henry equals the inductance required to induce 1 volt in an inductor by a change of current of 1 ampere per second.

An analogy of inductance is found in pushing a heavy load, such as a wheelbarrow or car. It takes more work to start the load moving than it does to keep it moving. Once the load is moving, it is easier to keep the load moving than to stop it again. This is because the load possesses the property of inertia. Inertia is the characteristic of mass that opposes a change in velocity. Inductance has the same effect on current in an electrical circuit as inertia has on the movement of a mechanical object. It requires more energy to start or stop current than it does to keep it flowing.

ELECTROMOTIVE FORCE

Electromotive force is developed whenever there is relative motion between a magnetic field and a conductor. EMF is a difference of potential or voltage which exists between two points in an electrical circuit. In generators and inductors, the EMF is developed by the action between the magnetic field and the electrons in a conductor. (An inductor is a wire that is coiled, such as in a relay coil, motor, or transformer.) Figure 6-1 shows EMF generated in an electrical conductor.

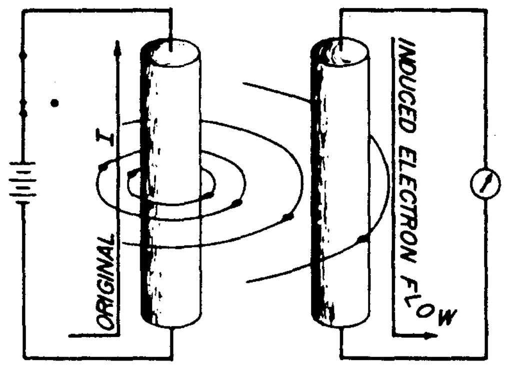


FIGURE 6-1. Generation of an EMF in an Electrical Conductor

When a magnetic field moves through a stationary conductor, electrons are dislodged from their orbits. The electrons move in a direction determined by the movement of the magnetic lines of flux (Figure 6-2).

The electrons move from one area of the conductor into another area (view A). The area that the electrons moved from has fewer negative charges (electrons) and becomes positively charged (view B). The area the electrons move into becomes negatively charged. The difference between the charges in the conductor equals a difference of potential (or voltage). This voltage caused by the moving magnetic field is called electromotive force.

In simple terms, compare the action of a moving magnetic field on a conductor to the action of a broom. Consider the moving magnetic field to be a moving broom (view C). As the magnetic broom moves along (through) the conductor, it gathers up and pushes loosely bound electrons before it.

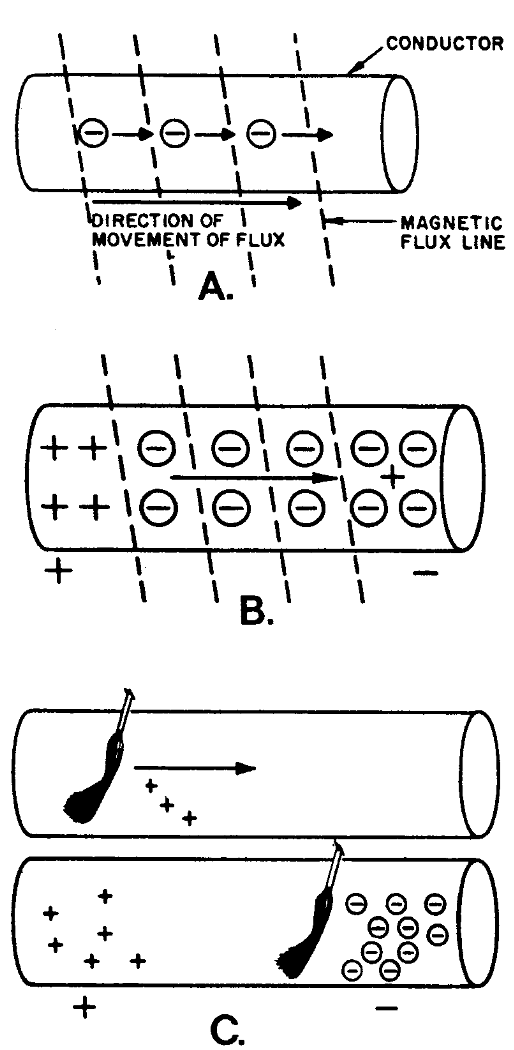


FIGURE 6-2. Current Movement and Flux Direction Relationship.

The area from which electrons are moved becomes positively charged, while the area into which electrons are moved becomes negatively charged. The potential difference between these two areas is the electromotive force.

SELF-INDUCTANCE

Even a perfectly straight length of conductor has some inductance. Current in a conductor produces a magnetic field surrounding the conductor. When the current changes direction, the magnetic field changes. This causes relative motion between the magnetic field and the conductor, and an EMF is induced in the conductor. This EMF is called a self-induced EMF because it is induced in the conductor carrying the current. It is also called counter electromotive force (CEMF).

COUNTER ELECTROMOTIVE FORCE

To understand what CEMF is and how it develops, first review a basic requirement for. the production of voltage. To magnetically produce a voltage or electromotive force, there must be —

- A conductor.
- A magnetic field.
- Relative motion.

Next, review some of the properties of an electrical circuit. If the ends of a length of wire are connected to a terminal of an AC generator, there would be an electrical short, and maximum current would flow. (Do not do this.) Excessive current would flow because there would be only the minimal resistance of the wire to hold back the current. This will damage the electrical system. Figure 6-3 illustrates self-inductance.

If the length of wire is rolled tightly into a coil, the coil would become an inductor. Whenever an inductor is used with AC, a form of power generation occurs. An EMF is created in the inductor because of the close proximity of the coil conductors and the expanding and contracting AC magnetic fields. The inductor creates its own EMF. Since this inductor generator follows the rules of inductance, opposing a change in current, the EMF developed is actually a counter EMF opposing the power source creating it. This CEMF pushes back on the electrical system as a form of resistance to the normal power source. CEMF is like having another power source connected in series and opposing.

This is an example of an inductive load. Unlike the resistive load, all the power in the circuit is not consumed. This effect is summarized in Lenz's Law which states that the induced EMF in any circuit is always in a direction to oppose the effect that produced it.

The direction of this induced voltage may be determined by applying the left-hand rule for generators. This rule is applied to a portion of conductor 2 that is enlarged for this purpose in Figure 6-3 view A. This rules states that if you point the thumb of your left hand in the direction of relative motion of the conductor and your index finger in the direction of the magnetic field, your middle finger, extended as shown, will indicate the direction of the induced current which will generate the induced voltage (CEMF) as shown.

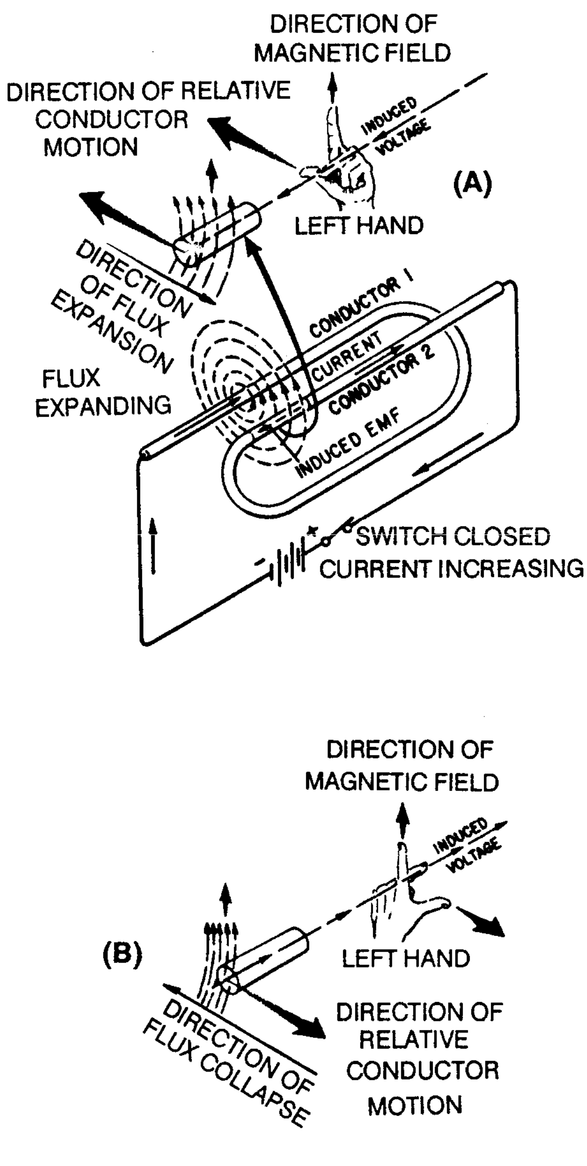


FIGURE 6-3. Self-Inductance.

View B shows the same section of conductor 2 after the switch has been opened. The flux field is collapsing. Applying the left-hand rule in this case shows that the reversal of flux movement has caused a reversal in the direction of the induced voltage. The induced voltage is now in the same direction as the battery voltage. The self-induced voltage opposes both changes in current. That is, when the switch is closed, this voltage delays the initial buildup of current by opposing the battery voltage. When the switch is opened, it keeps the current flowing in the same direction by aiding the battery voltage.

Thus, when a current is building up, it produces a growing magnetic field. This field induces an EMF in the direction opposite to the actual flow of current. This induced EMF opposes the growth of the current and the growth of the magnetic field. If the increasing current had not set up a magnetic field, there would have been no opposition to its growth. The whole reaction, or opposition, is caused by the creation or collapse of the magnetic field, the lines of which as they expand or contract cut across the conductor and develop the counter EMF (Figure 6-4).

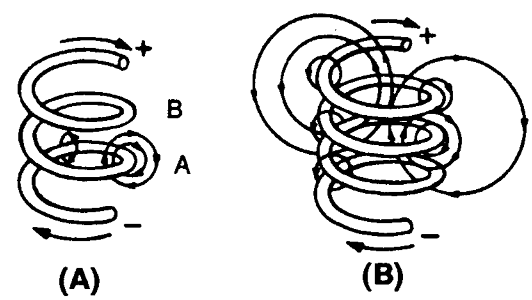


FIGURE 6-4. Inductance.

Inductors are classified according to core type. The core is the center of the inductor just as the core of an apple is the center of the apple. The inductor is made by forming a coil of wire around a core. The core material is normally one of two types: soft iron or air. Figure 6-5 view A shows an iron core inductor and its schematic symbol (represented with lines across the top of the inductor to indicate the presence of an iron core). The air core inductor may be nothing more than a coil of wire, but it is usually a coil formed around a hollow form of some nonmagnetic material such as cardboard. This material serves no purpose other than to hold the shape of the coil. View B shows an air core inductor and its schematic symbol.

FACTORS AFFECTING COIL INDUCTANCE

Several physical factors affect the inductance of a coil. They are the number of turns, the diameter, the length of the coil conductor, the type of core material, and the number of layers of winding in the coil. Inductance depends entirely on the physical construction of the circuit. It can only be measured with special laboratory instruments.

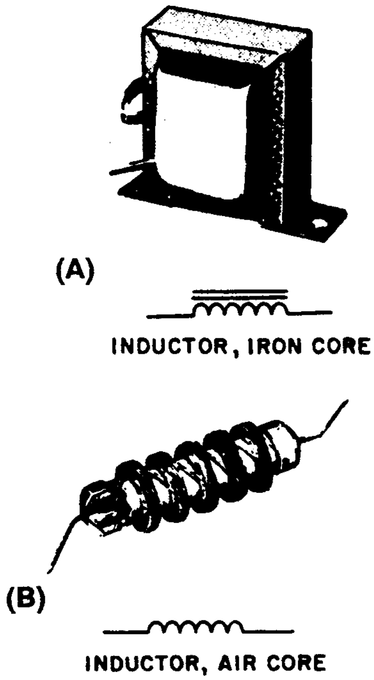


FIGURE 6-5. Inductor Types and Schematic Symbols.

The first factor that affects the inductance of the coil is the number of turns. Figure 6-6 shows two coils. Coil A has two turns, and coil B has four turns. In coil A, the flux field setup by one loop cuts one other loop. In coil B, the flux field setup by one loop cuts three other loops. Doubling the number of turns in the coil will produce a field twice as strong; if the same current is used. A field twice as strong, cutting twice the number of turns, will induce four times the voltage. Therefore, inductance varies by the square of the number of turns.

The second factor is the coil diameter. In Figure 6-7, coil B has twice the diameter of coil A. Physically, it requires more wire to construct a coil of larger diameter than one of smaller diameter with an equal number of turns. Therefore, more lines of force exist to induce a counter EMF in the coil with the larger diameter. Actually, 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 squared. Doubling the radius of a coil increases the area by a factor of four.

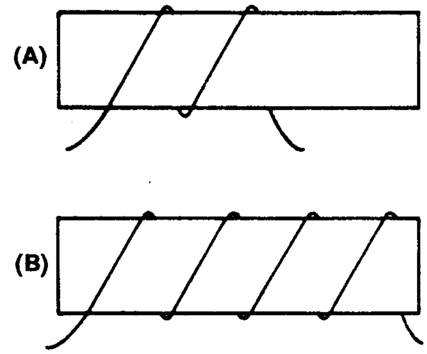


FIGURE 6-6. Inductance Factor (Turns).

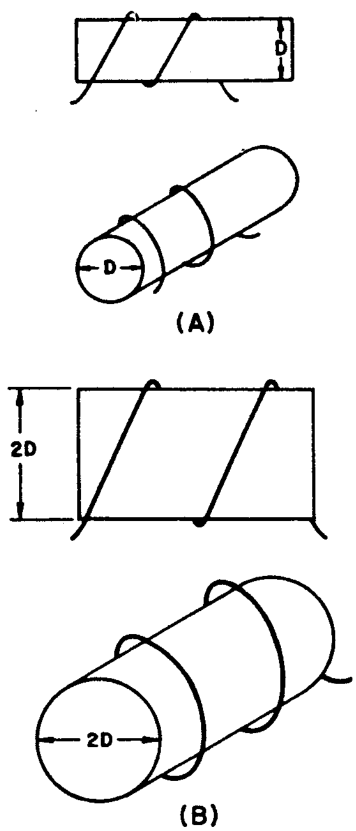


FIGURE 6-7. Inductance Factor (Diameter).

The third factor that affects the inductance of a coil is the length of the coil. Figure 6-8 shows two examples of coil spacings. Coil A has three turns, rather widely spaced, making a relatively long coil. A coil of this type has fewer flux linkages due to the greater distance between each turn. Therefore, coil A has a relatively low inductance. Coil B has closely spaced turns, making a relatively short coil. This close spacing increases the flux linkage, increasing the inductance of the coil. Doubling the length of a coil while keeping the number of turns of a coil the same halves the inductance.

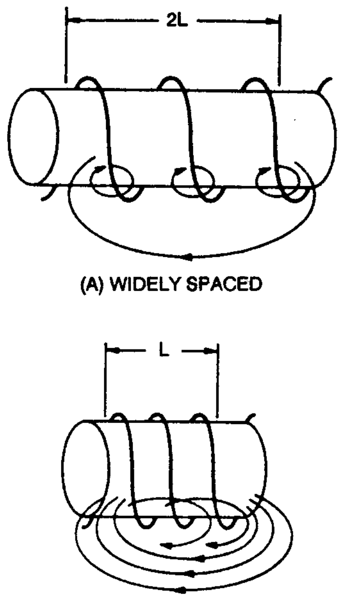


FIGURE 6-8. Inductance Factor (Coil Length).

The fourth factor is the type of core material used with the coil. Figure 6-9 shows two coils: coil A with an air core and coil B with a soft-iron core. The magnetic core of coil B is a better path for magnetic lines of force than the nonmagnetic core of coil A. The soft-iron magnetic core's high permeability has less reluctance to the magnetic flux, resulting in more magnetic lines of force. This increase in the magnetic lines of force increases the number of lines of force cutting each loop of the coil, thus increasing the inductance of the coil. The inductance of a coil increases directly as the permeability of the core material increases.

The fifth factor is the number of layers of windings in the coil. Inductance is increased by winding the coil in layers. Figure 6-10 shows three cores with different amounts of layering. Coil A is a poor inductor compared to the others in Figure 6-10 because its turns are widely spaced with no layering. The flux movement, indicated by the dashed arrows, does not link effectively because there is only one layer of turns. Coil B is a more inductive coil. The turns are closely spaced, and the wire has been wound in two layers. The two layers link each other with greater number of flux loops during all flux movements. Note that nearly all the turns, such as X, are next to four other turns (shaded). This causes the flux linkage to be increased.

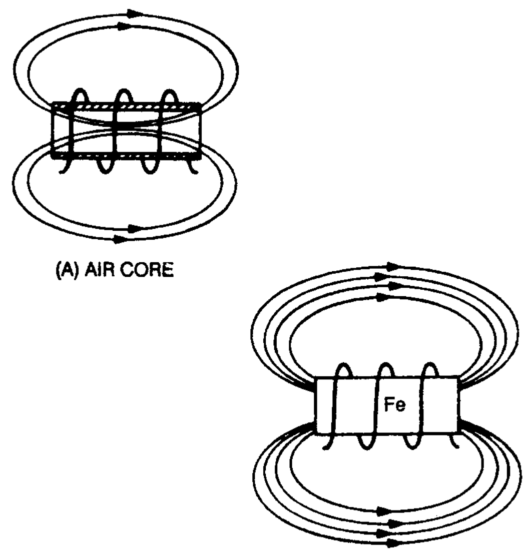


FIGURE 6-9. Inductance Factor (Core Materials).

A coil can be made still more inductive by winding it in three layers (coil C). The increased number of layers (cross-sectional area) improves flux linkage even more. Some turns, such as Y, lie directly next to six other turns (shaded). In actual practice, layering can continue on through many more layers. The inductance of a coil increases with each layer added.

The factors that affect the inductance of a coil vary. Many differently constructed coils can have the same inductance. Inductance depends on the degree of linkage between the wire conductors and the electromagnetic field. In a straight length of conductor, there is very little flux linkage between one part of the conductor and another. Therefore, its inductance is extremely small. Conductors become much more inductive when they are wound into coils. This is true because there is maximum flux linkage between the conductor turns, which lie side by side in the coil.

UNIT OF INDUCTANCE

As stated before, the basic unit of inductance (L) is the henry (H). An inductor has an inductance of 1 henry if an EMF of 1 volt is inducted in the inductor when the current through the inductor is changing at the rate of 1 ampere per second.

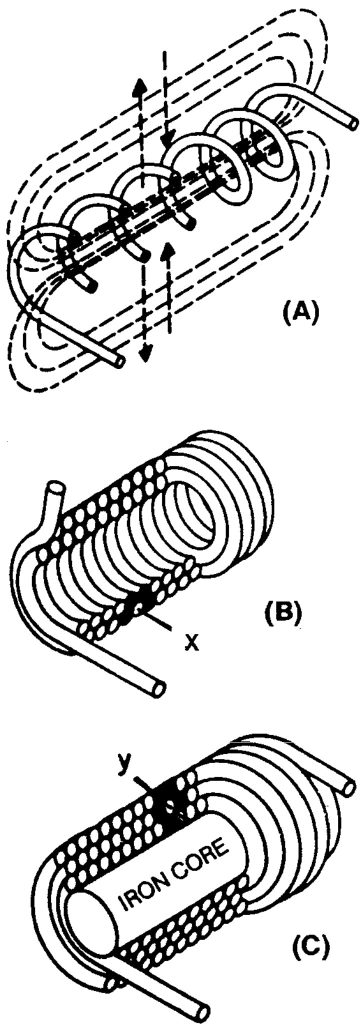


FIGURE 6-10. Coils of Various Inductances.

POWER LOSS IN AN INDUCTOR

Since an inductor (coil) consists of a number of turns of wire and since all wire has some resistance, every inductor has a certain amount of resistance. Normally, this resistance is small. It is usually neglected in solving various types of AC circuit problems because the reactance of the inductor (the opposition to alternating current) is so much greater than the resistance that the resistance has a negligible effect on current.

However, since some inductors are designed to carry relatively large amounts of current, considerable power can be dissipated in the inductor even though the amount of resistance in the inductor is small. This is wasted power called copper loss. The copper loss of an inductor can be calculated by multiplying the square of current in the inductor by the resistance of the winding (I^2R).

In addition to copper loss, an iron-core coil (inductor) has two iron losses. These are hysteresis loss and eddy-current loss. Hysteresis loss is due to power that is consumed in reversing the magnetic field of the inductor core each time the direction of current in the inductor changes. Eddy-current loss is due to currents that are induced in the iron core by the magnetic field around the turns of the coil. These currents are called eddy currents and flow back and forth in the iron core.

All these losses dissipate power in the form of heat. Since this power cannot be productively consumed in the electrical circuit, it is lost power.

MUTUAL INDUCTANCE

Whenever two coils are located so that the flux from one coil links with the turns of another coil, a change of flux in one causes an EMF to be induced into the other coil. This allows the energy from one coil to be transferred or coupled to the other coil. The two coils are coupled or linked by the property of mutual inductance. The amount of mutual inductance depends on the relative positions of the two coils (Figure 6-11). If the coils are separated a considerable. distance, the amount of flux common to both coils is small, and the mutual inductance is low. Conversely, if the coils are close together so that nearly all the flux of one coil links the turns of the other, the mutual inductance is high.

The mutual inductance can be increased greatly by mounting the coils on a common core. Two coils are placed close together (Figure 6-12). Coil 1 is connected to a battery through switch S, and coil 2 is connected to an ammeter (A). When switch S is closed (view A), the current that flows in coil 1 sets up a magnetic field that links with coil 2, causing an induced voltage in coil 2 and a momentary deflection of the ammeter. When the current in coil 1 reaches a steady value, the ammeter returns to zero. If switch S is now opened (view B), the ammeter (A) deflects momentarily in the opposite direction, indicating a momentary flow of current in the opposite direction of coil 2. This current in coil 2 is produced by the collapsing magnetic field of coil 1.

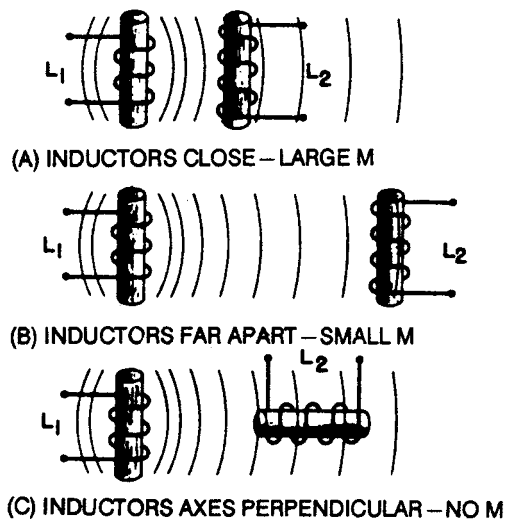


FIGURE 6-11. The Effect of Position of Coils on Mutual Inductance.

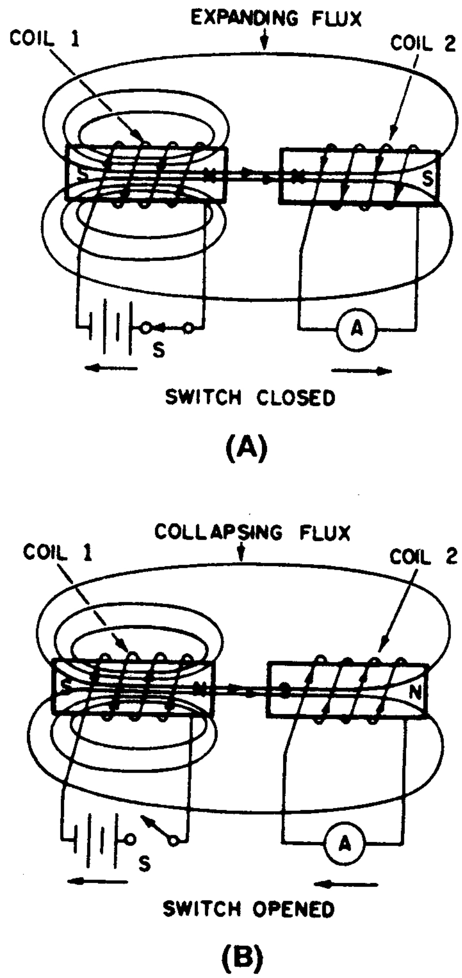


FIGURE 6-12. Mutual Inductance.

CHAPTER 7

CAPACITANCE

INTRODUCTION

Inductance is the property of a coil that causes energy to be stored in a magnetic field about the coil. The energy is stored so as to oppose any change in current. Capacitance is similar to inductance because it also causes a storage of energy. A capacitor is a device that stores energy in an electrostatic field. The energy is stored so as to oppose any change in voltage. This chapter explains the principles of an electrostatic field as it is applied to capacitance and how capacitance opposes a change in voltage.

ELECTROSTATIC FIELD

Opposite charges attract each other, while like electrical charges repel each other. The reason for this is the existence of an electrostatic field. Any charged particle is surrounded by invisible lines of force, called electrostatic lines of force. These lines of force have some interesting characteristics:

- They are polarized from positive to negative.
- They radiate from a charged particle in straight lines and do not form closed loops.
- They have the ability to pass through any known material.
- They have the ability to distort the orbits of tightly bound electrons.
- An electrostatic charge can only exist in an insulator.

Figure 7-1 represents two unlike charges surrounded by their electrostatic field. Because an electrostatic field is polarized positive to negative, arrows are shown radiating away from the positive charge and toward the negative charge. Stated another way, the field from the positive charge is pushing, while the field from the negative charge is pulling. The effect of the field is to push and pull the unlike charges together.

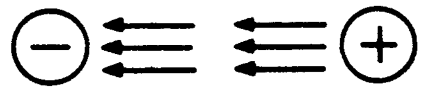


FIGURE 7-1. Electrostatic Lines of Force Surrounding Two Unlike Charged Particles.

Figure 7-2 shows two like charges with their surrounding electrostatic field. The effect of the electrostatic field is to push the charges apart.

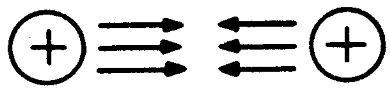


FIGURE 7-2. Electrostatic Lines of Force Surrounding Two Like Charged Particles.

If two unlike charges are placed on opposite sides of an atom whose outermost electrons cannot escape their orbits, the orbits of the electrons are distorted. Figure 7-3 view A shows the normal orbit. View B shows the same orbit in the presence of charged particles. Since the electron is a negative charge, the positive charge attracts the electrons, pulling the electrons closer to the positive charge. The negative charge repels the electrons, pushing them further from the negative charge. It is this ability of an electrostatic field to attract and to repel charges that allows the capacitor to store energy.

SIMPLE CAPACITOR

A simple capacitor consists of two metal plates separated by an insulating material called a dielectric (Figure 7-4). One plate is connected to the positive terminal of a battery. The other plate is connected to the negative terminal of the battery. An insulator is a material whose electrons cannot easily escape their orbits. Due to the battery voltage, plate A is charged positively, and plate B is charged negatively. Thus, an electrostatic field is set up between the positive and negative plates. The electrons on the negative plate (plate B) are attracted to the positive charges on the positive plate (plate A).

The orbits of the electrons are distorted in the electrostatic field. This distortion occurs because the electrons in the dielectric are attracted to the top plate while being repelled from the bottom plate. When switch S1 is opened, the battery is removed from the circuit, and the charge is retained by the capacitor. This occurs because the dielectric material is an insulator, and electrons in the bottom plate (negative charge) have no path to reach the top plate (positive charge). The distorted orbits of the atoms of the dielectric plus the electrostatic force of attraction between the two plates hold the positive and negative charges in their original position. Thus, the energy that came from the battery is now stored in the electrostatic field of the capacitor. Figure 7-5 shows the symbol for capacitor. The symbol is composed of two plates separated by a space that represents the dielectric. The curved plate of the symbol represents the plate that should be connected to a negative polarity.

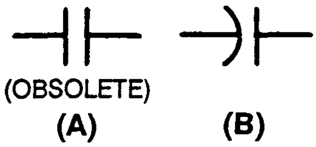


FIGURE 7-5. Circuit Symbols for Capacitors.

The Farad

Capacitance is measured in units called farads. A 1-farad capacitor stores 1 coulomb (a unit of charge [Q] equal to 6.242 times 10 to the 18th electrons) of charge when a potential of 1 volt is applied across the terminals of a capacitor. This can be expressed by the formula:

$$C \text{ (farads)} = \frac{Q \text{ (coulombs)}}{E \text{ (volts)}}$$

The farad is a very large unit of measurement of capacitance. For convenience, the microfarad or the picofarad is used. Capacitance is a physical property of the capacitor. It does not depend on circuit characteristics of voltage, current, and resistance. A given capacitor always has the same value

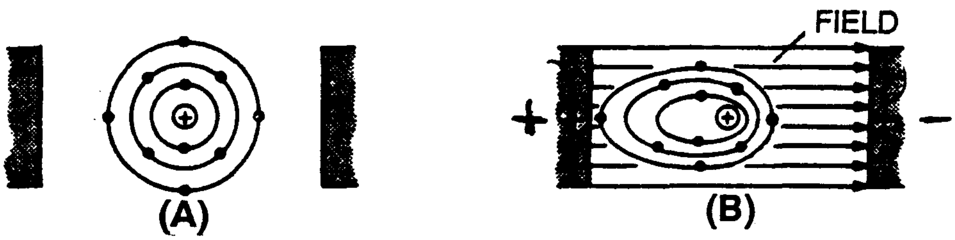


FIGURE 7-3. Distortion of an Electron's Orbit Due to Electrostatic Force.

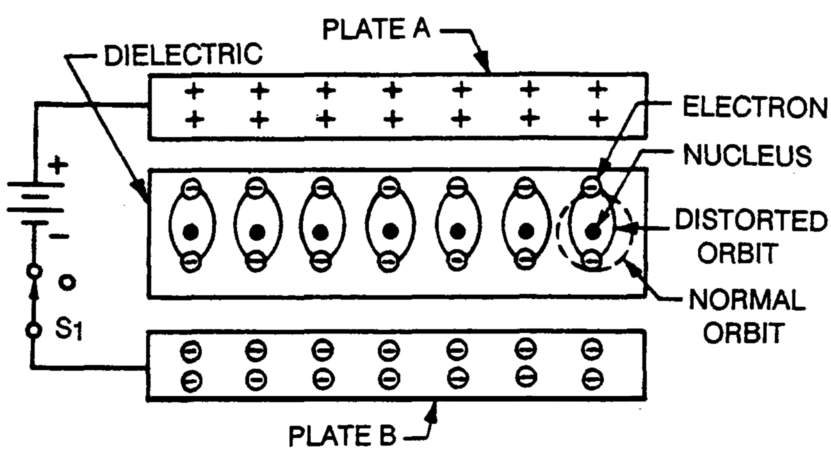


FIGURE 7-4. Distortion of Electron Orbits in a Dielectric.

of capacitance (farads) in one circuit as in any other circuit in which it is installed.

FACTORS AFFECTING THE VALUE OF CAPACITANCE

The value of capacitance of a capacitor depends upon three factors:

- The area of the plates.
- The distance between the plates.
- The dielectric constant of the material between the plates.

Plate area affects the value of capacitance in the same way that size of a container affects the amount of liquid that can be held by the container. A capacitor with a large plate area can store more charges than a capacitor with a small plate area. Simply stated, the larger the plate area, the larger the capacitance.

The second factor affecting capacitance is the distance between the plates. Electrostatic lines of force are strongest when the charged particles that create them are close together. When the charged particles are moved further apart, the lines of force are weakened, and the ability to store a charge decreases.

The third factor affecting capacitance is the dielectric constant of the insulating material between the plates of a capacitor. The various insulating materials used as the dielectric in a capacitor differ in their ability to respond to (or pass) electrostatic lines of force. A dielectric material, or insulator, is rated as to its ability to respond to electrostatic lines of force in terms of a figure called the dielectric constant. A dielectric material with a high dielectric constant is a better insulator than a dielectric material with a low dielectric constant. Dielectric constants for some common materials are listed in Table 7-1.

Since a vacuum is the standard reference, it is assigned a dielectric constant of one. The dielectric constants for all other materials are compared to that of a vacuum. Since the dielectric constant for air has been determined to be about the same as for a vacuum, the dielectric constant of air is also considered to be equal to one.

TABLE 7-1. Dielectric Constants for Common Materials.

MATERIAL	CONSTANT
Vacuum	1.0000
Air	1.0006
Paraffin paper	2.5 - 3.5
Transformer oil	4
Glass	5 - 10
Mica	3 - 6
Rubber	2.5 - 35
Wood	2.5 - 8
Porcelain	6
Glycerine (15 C)	56
Petroleum	2
Pure water	81

CAPACITOR RATING

In selecting or substituting a capacitor for use, consideration must be given to the value of capacitance desired and the amount of voltage to be applied across the capacitor. If the voltage applied across the capacitor is too great, the dielectric will break down, and arcing will occur between the capacitor plates. When this happens, the capacitor becomes a short circuit, and the flow of current through it causes damage to other electrical components. A capacitor is not a conductor. It is used as a power source that delivers current to the circuit at a different time than it would have originally received it. Each capacitor has a voltage rating (a working voltage) that should never be exceeded.

The working voltage of a capacitor is the maximum voltage that can be steadily applied without danger of breaking down the dielectric. The working voltage depends on the type of material used as the dielectric and on the thickness of the dielectric. (A high-voltage capacitor that has a thick dielectric must have a relatively large plate area to have the same capacitance as a similar low-voltage capacitor having a thin dielectric.) The working voltage also depends on the applied frequency because losses and the resultant heating effect increase as the frequency increases.

EXPEDIENT REPLACEMENT

In the event of an electrical casualty on a single-phase motor, certain expedient capacitor replacements can be made. The following is a guide for capacitor replacement when the exact replacement part is unavailable:

- A start capacitor can be replaced with another capacitor equal to but not greater than 20 percent of the original microfarad rating. The voltage rating must be equal to or greater than the original capacitor voltage rating.
- A run capacitor can be replaced with another capacitor within plus or minus 10 percent of the original microfarad rating. The voltage rating must be equal to or greater than the original capacitor voltage rating.

Remember, as with all expedient repairs, Army marine equipment must be returned to its original, like new, condition upon arrival at port.

A capacitor that may be safely charged to 500 volts DC cannot be safely subjected to an alternating voltage or a pulsating direct voltage having the same effective value of 500 volts. In practice, select a capacitor so that its working voltage is at least 50 percent greater than the highest effective voltage applied to it.

CAPACITOR LOSSES

Power loss in a capacitor may be attributed to dielectric hysteresis and electric leakage. Dielectric hysteresis is an effect in a dielectric material similar to the hysteresis found in a magnetic material. It is the result of changes in orientation of electron orbits in the dielectric because of the rapid reversals of the polarity of the line voltage. The amount of power loss due to dielectric hysteresis depends on the type of dielectric used. A vacuum dieletric has the smallest power loss.

Dielectric leakage occurs in a capacitor as the result of leakage of current through the dielectric. Normally, it is assumed that the dielectric will effectively prevent the flow of current through the capacitor. Although the resistance of the dielectric is extremely high, a minute amount of current does flow. Ordinarily this current is so small that for all practical purposes it is ignored. However, if the leakage through the dielectric is abnormally high, there will be a rapid loss of charge and an overheating of the capacitor.

The power loss of a capacitor is determined by loss in the dielectric. If the loss is negligible and the capacitor returns the total charge to the circuit, it is considered to be a perfect capacitor with a loss of zero.

CHARGING AND DISCHARGING A CAPACITOR

Charging

To better understand the action of a capacitor in conjunction with other components, the charge and discharge actions of a purely capacitive circuit are analyzed first. For ease of explanation, the capacitor and voltage source in Figure 7-6 are assumed to be perfect (no internal resistance), although this is impossible in practice.

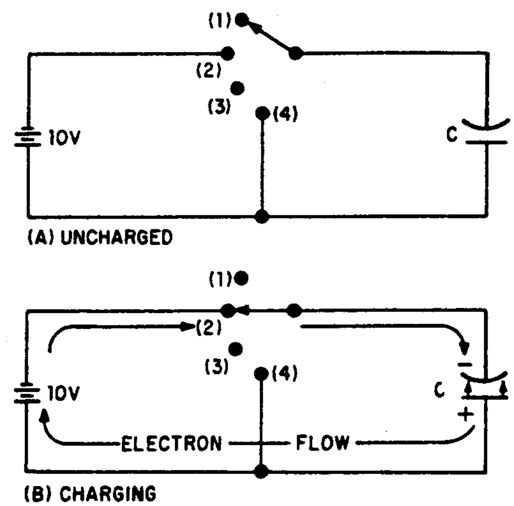


FIGURE 7-6. Charging a Capacitor.

View A shows an uncharged capacitor connected to a four-position switch. With the switch in position 1, the circuit is open, and no voltage is applied to the capacitor. Initially, each plate of the capacitor is a neutral body. Until a difference in potential is impressed (or a voltage applied) across the capacitor, no electrostatic field can exist between the plates.

To charge the capacitor, the switch must be thrown to position 2, which places the capacitor across the terminals of the battery. Under the assumed perfect conditions, the capacitor would reach full charge instantaneously. However, in the following discussion, the charging action is spread out over a period of time for a step-by-step analysis.

At the instant the switch is thrown to position 2 (view B), a displacement of electrons occurs simultaneously in all parts of the circuit. This electron displacement is directed away from the negative terminal and toward the positive terminal of the source (the battery). A brief surge of current will flow as the capacitor charges.

If it were possible to analyze the motion of individual electrons in this surge of charging current, the action described below would be observed (Figure 7-7).

At the instant the switch is closed, the positive terminal of the battery extracts an electron from the bottom conductor. The negative terminal of the bat-

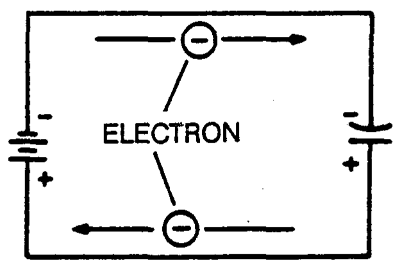


FIGURE 7-7. Electron Motion During Charge.

tery forces an electron into the top conductor. At this same instant, an electron is forced into the top plate of the capacitor, and another is pulled from the bottom plate. Thus, in every part of the circuit, a clockwise displacement of electrons occurs simultaneously.

As electrons accumulate on the top plate of the capacitor and others depart from the bottom plate, a difference of potential develops across the capacitor. Each electron forced onto the top plate makes that plate more negative, while each electron removed from the bottom causes the bottom plate to become more positive. The polarity of the voltage that builds up across the capacitor is such as to oppose the source voltage. The source voltage (EMF) forces current around the circuit of Figure 7-7 in a clockwise direction. The EMF developed across the capacitor, however, has a tendency to force the current in a counterclockwise direction, opposing the source EMF. As the capacitor continues to charge, the voltage across the capacitor rises until it is equal to the source voltage. Once the capacitor voltage equals the source voltage, the two voltages balance one another, and current ceases to flow in the circuit.

In the charging process of a capacitor, no current flows through the capacitor. The material between the plates of the capacitor is an insulator. Hwoever, to an observer stationed at the source or along one of the circuit conductors, the action appears to be a true flow of current, even though the insulating material between the plates of the capacitor prevents the current from having a complete path. The current that appears to flow through a capacitor is called displacement current.

When a capacitor is fully charged and the source voltage is equaled by the counter EMF across the capacitor, the electrostatic field between the plates of the capacitor is maximum (Figure 7-4). Since the electrostatic field is maximum, the energy stored in the dielectric field is maximum.

If the switch is now opened (Figure 7-8 view A), the electrons on the upper plate are isolated. The electrons on the top plate are attracted to the charged bottom plate. Because the dielectric is an insulator, the electrons cannot cross the dielectric to the bottom plate. The charges on both plates will be effectively trapped by the electrostatic field, and the capacitor will remain charged. However, the insulating dielectric material of a practical capacitor is not perfect, so small leakage current will flow through the dielectric. This current will eventually dissipate the charge. However, a high quality capacitor may hold its charge for a month or more.

To review briefly, when a capacitor is connected across a voltage source, a surge of charging current flows. This charging current develops a CEMF across the capacitor which opposes the applied voltage. When the capacitor is fully charged, the CEMF equals the applied voltage, and charging current ceases. At full charge, the electrostatic field between the plates is at maximum intensity, and the energy stored in the dielectric is maximum. If the charged capacitor is disconnected from the source, the charge will be retained for some time. The length of time the charge is retained depends on the amount of leakage current present. Since electrical energy is stored in the capacitor, a charged capacitor can act as a source EMF.

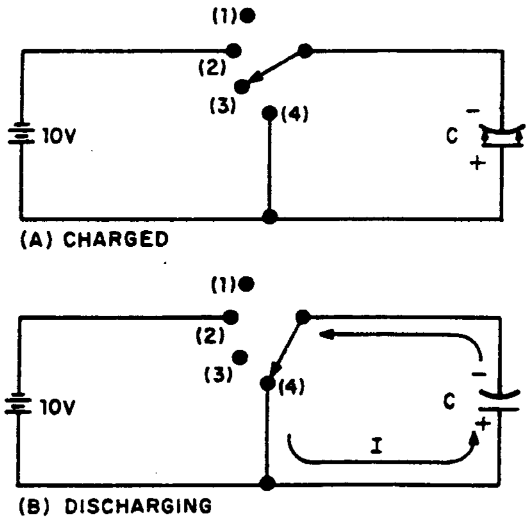


FIGURE 7-8. Discharging a Capacitor.

Discharging

To discharge a capacitor, the charges on the two plates must be neutralized. This is done by providing a conducting path between the two plates (Figure 7-8 view B). With the switch in position (4), the excess electrons on the negative plate can flow to the positive plate and neutralize its charge. When the capacitor is discharged, the distorted orbits of the electrons in the dielectric return to their normal positions, and the stored energy is returned to the circuit. A capacitor does not consume power. The energy the capacitor draws from the source is recovered when the capacitor is discharged.

CHARGE AND DISCHARGE OF A CAPACITOR

Ohm's Law states that the voltage across a resistance is equal to the current through the resistance times the value of the resistance. This means that a voltage is developed across a resistance only when current flows through a resistance.

A capacitor can store or hold a charge of electrons. When uncharged, both plates of the capacitor contain essentially the same number of free electrons. When charged, one plate contains more free electrons than the other plate. The difference in the number of electrons is a measure of the charge on the capacitor. The accumulation of this charge builds up a voltage across the terminals of the capacitor, and the charge continues to increase until this voltage equals the applied voltage. The charge in a capacitor is related to the capacitance and voltage as follows:

$$Q = CE$$

Where:

Q = charge in coulombs
C = capacitance in farads
E = EMF across the capacitor in volts

CAPACITORS IN SERIES AND IN PARALLEL

Capacitors may be connected in series or in parallel to obtain a resultant value that may be either the sum of the individual values (in parallel) or a value less than that of the smallest capacitance (in series).

Capacitors in Series

The overall effect of connecting capacitors in series is to move the plates of the capacitor farther apart. A capacitor is NOT a conductor. The dielectric is influenced by a magnetic field, and the polarity that creates the electrostatic field can only effectively exist at the outside plates of both capacitors. The magnetic field's influence is reduced (Figure 7-9). The junction between C1 and C2 is essentially neutral. The total capacitance of the circuit is developed between the leftmost plate of C1 and the rightmost plate of C2. Because these outside plates are so far apart, the total value of the capacitance in the circuit is decreased. Solving for the total capacitance (Ct) of capacitors connected in series is similar to solving for the total resistance (Rt) of resistors connected in parallel.

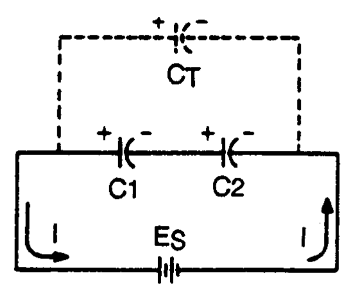


FIGURE 7-9. Capacitors in Series.

Note the similarity between the formulas for Rt and Ct:

$$Rt = \frac{1}{\frac{1}{R1} + \frac{1}{R2} + \ldots \frac{1}{Rn}}$$

$$Ct = \frac{1}{\frac{1}{C1} + \frac{1}{C2} + \ldots \frac{1}{Cn}}$$

If the circuit contains more than two capacitors, use the above formula. If the circuit contains only two capacitors, use the following formula:

$$Ct = \frac{(C1) \times (C2)}{C1 + C2}$$

> **NOTE:** All values for Ct, C1, C2, C3,...Cn should be in farads. It should be evident from the above formulas that the total capacitance of capacitors in series is less than the capacitance of any of the individual capacitors.

Capacitors in Parallel

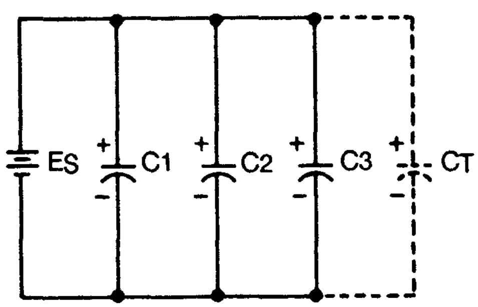


FIGURE 7-10. Parallel Capacitive Circuit.

When capacitors are connected in parallel, one plate of each capacitor is connected directly to one terminal of the source, while the other plate of each capacitor is connected to the other terminal of the power source. Figure 7-10 shows all the negative plates of the capacitors connected together and all the positive plates connected together. Ct, therefore, appears as a capacitor with a plate area equal to the sum of all the individual plate areas. Capacitance is a direct function of plate area. Connecting capacitors in parallel effectively increases plater area and thereby increases total capacitance.

For capacitors connected in parallel, the total capacitance is the sum of all the individual capacitors. The total capacitance of the circuit may be calculated using this formula:

$$Ct = C1 + C2 + C3 + \ldots Cn$$

Where AU capacitances are in the same units.

FIXED CAPACITOR

A freed capacitor is constructed so that it possesses a freed value of capacitance and cannot be adjusted. A fixed capacitor is classified according to the type of the material used as its dielectric, such as paper, oil, mica, or electrolyte. Two capacitors commonly found in the marine field are the electrolytic capacitor and the paper capacitor.

Electrolytic Capacitor

The electrolytic capacitor is used where a large amount of capacitance is required. As the name implies, an electrolytic capacitor contains electrolyte. This electrolyte can be in the form of a liquid (wet electrolytic capacitor). The wet electrolytic capacitor is no longer in popular use because of the care needed to prevent spilling of the electrolyte.

A dry electrolytic capacitor consists essentially of two metal plat es separated by the electrolyte. The capacitance values and the voltage ratings of the capacitor are generally printed on the side of the case.

Internally, the electrolytic capacitor is constructed similarly to the paper capacitor. The positive plate consists of aluminum foil covered with an extremely thin film of oxide. This thin oxide film, which is formed by an electrochemical process, acts as the dielectric of the capacitor. Next to and in contact with the oxide strip is paper or gauze that has been impregnated with a paste-like electrolyte. The electrolyte acts as the negative plate of the capacitor. A second strip of aluminum foil is then placed against the electrolyte to provide electrical contact to the negative electrode. When the three layers are in place, they are rolled up into a cylinder (Figure 7-11).

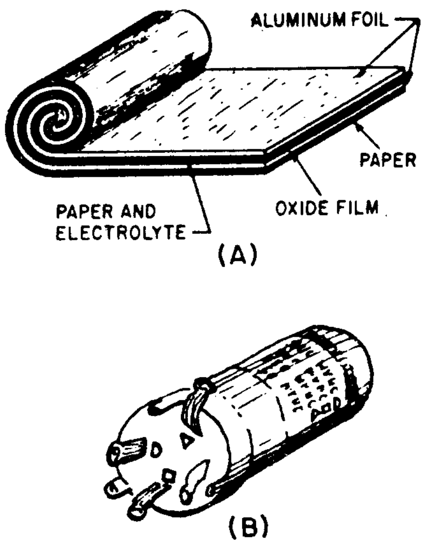


FIGURE 7-11. Construction of an Electrolytic Capacitor.

The DC electrolytic capacitor has two disadvantages compared to a paper capacitor. The electrolyte type is polarized and has a low-leakage resistance. This means that should the positive plate be accidentally connected to the negative terminal of the source, the thin oxide film dielectric will dissolve, and the capacitor will become a conductor. That is, it will short. These electrolytic capacitors are very comon in DC systems. DC electrolytic capacitors have the polarity indicated on the casing or capacitor terminals. They should never be connected into an AC circuit. The polarity must be observed. The electrolytic capacitor could explode if these precautions are not observed.

The AC electrolytic capacitor has been specially developed for single-phase AC motors. These capacitors, which **are** generally encased in plastic, are called start capacitors. They have 20 times the capacitance of motor-run capacitors. The start capacitors are small in size and high in capacitance. Not intended for constant use, the start capacitor can be readily removed from the motor's starting circuit after a short time.

These AC capacitors effectively provide a two-phase current to the single-phase motor. This is done by allowing the initial source current to arrive in one winding before it arrives in the other single-phase motor windings. Chapter 17 discusses the operation of this capacitor at length.

Paper Capacitor

A paper capacitor is made of flat thin strips of metal foil conductors that are separated by waxed paper (the dielectric material). Paper capacitors usually range in value from about 300 picofarads to about 4 microfarads. The working voltage of a paper capacitor rarely exceeds 600 volts. Paper capacitors are sealed with wax to prevent corrosion, leakage, and the harmful effects of moisture.

Many different kinds of outer coverings are used on paper capacitors. The simplest is a tubular cardboard covering. Some paper capacitors are encased in very hard plastic. These types are very rugged and can be used over a much wider temperature range than can the tubular cardboard type. Figure 7-12 shows the construction of a tubular paper capacitor.

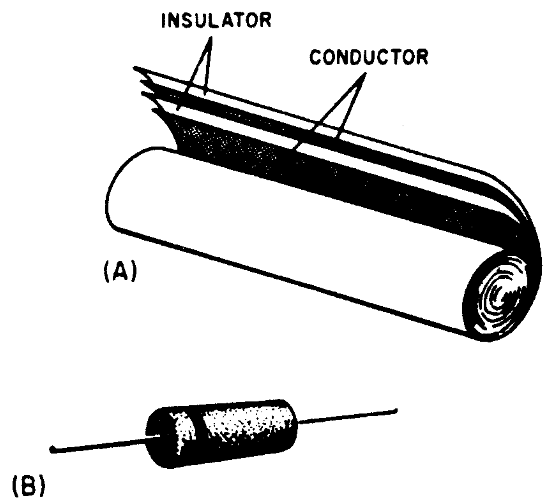


FIGURE 7-12. Paper Capacitor.

Paper capacitors are generally used for run capacitors in single-phase motors. These capacitors are metal-cased and have a low capacitance for constant operation in the AC circuit. The larger size and lower capacitance is necessary for effective heat transfer.

Oil capacitors are often used in high-power electrical equipment. An oil-filled capacitor is nothing more than a paper capacitor immersed in oil. Since oil-impregnated paper has a high dielectric constant, it can be used to produce capacitors with a high capacitance value. Many capacitors will use oil with another dielectric material to prevent arcing between plates. If arcing should occur between the plates of an oil-filled capacitor, the oil will tend to reseal the hole caused by the arcing. Such a capacitor is called a self-healing capacitor.

Polychlorinated biphenyl or PCBs were commonly used to impregnate capacitors. This oil is used as a lubricant, for heat transfer, and as a fluid for a tire-resistant application. PCBs are toxic. If a capacitor is leaking, remove it from the circuit immediately. Personnel should not come in contact with the liquid. Treat it as if it is a very hazardous material, and dispose of it according to local regulations.

CAPACITIVE AND INDUCTIVE REACTANCE

When the voltage and current values are changing through a cycle together so that the values begin, peak, and change direction together, they are in phase. When these same values fail to stay in phase because one value leads or lags the other value, the circuit is said to be out of phase. The deviation from the simultaneous starting, peaking, and directional change of in-phase values is a direct result of the effects capacitance and inductance have on the circuit.

A circuit having pure resistance (if such a circuit could exist) would have the alternating current and voltage rising, falling, and changing direction together. Figure 7-13 view A shows the sine waves for current and voltage in a purely resistive AC circuit. The voltage and current do not have the same amplitude, but they are in phase.

In the case of a circuit having inductance, the opposing force of the counter EMF would be enough to prevent the current from remaining in phase with the applied voltage. In a DC circuit containing pure inductance, the current took time to rise to a maximum even though the full applied voltage was immediately at maximum. View B shows the waveforms for a purely inductive AC circuit in steps of quarter-cycles.

With an AC voltage, in the first quarter-cycle (0 to 90 degrees), the applied AC voltage is continually increasing. If there was no inductance in the circuit, the current would also increase during the first quarter-cycle. This circuit does have inductance. Since inductance opposes any change in current flow, no current flows during the first quarter-cycle. In the next quarter-cycle (90 to 180 degrees), the voltage decreases back to zero. Current begins to flow in the circuit and reaches a maximum value at the same instant the voltage reaches zero. The applied voltage now begins to buildup to a maximum in the other direction, to be followed by the resulting current. When the voltage again reaches its maximum at the end of the third quarter-cycle (270 degrees), all values are exactly opposite to what they were during the first half-cycle. The applied voltage leads the resulting current by one quarter-cycle or 90 degrees. To complete the full 360-degree cycle of the voltage, the voltage again decreases to zero, and current builds to a maximum value.

These values do not stop at a particular instant. Until the applied voltage is removed, current and voltage are always changing in amplitude and direction.

The sine wave can be compared to a circle (Figure 7-14). Just as a circle can be marked off into 360 degrees, the time of one cycle of a sine wave can be marked off into 360 degrees. Figure 7-14 shows how the current lags the voltage, in a purely inductive circuit, by 90 degrees. Figures 7-13 view A and 7-14 also show how the current and voltage are in phase in a purely resistive circuit. In a circuit having resistance and inductance, the current lags voltage by an amount somewhere between 0 and 90 degrees.

INDUCTIVE REACTANCE

When the current flowing through an inductor continuously reverses itself, as in the case of an AC system, the inertia of the CEMF is greater than with DC. The greater the amount of inductance, the greater the opposition from this inertia effect. Also, the faster the reversal of current, the greater this inertia opposition. This opposing force that an inductor presents to the flow of alternating current cannot be called resistance, since it is not the result of friction within a conductor. The name given to it is inductive reactance because it is the reaction of the inductor to alternating current. Inductive reactance is measured in ohms, and its symbol is XL.

The induced voltage in a conductor is proportional to the rate at which magnetic lines of force cut the conductor. The greater the rate (the higher the frequency), the greater the CEMF. Also, the induced voltage increases with an increase in inductance; the more ampere-turns, the greater the CEMF. Reactance then increases with an increase of inductance.

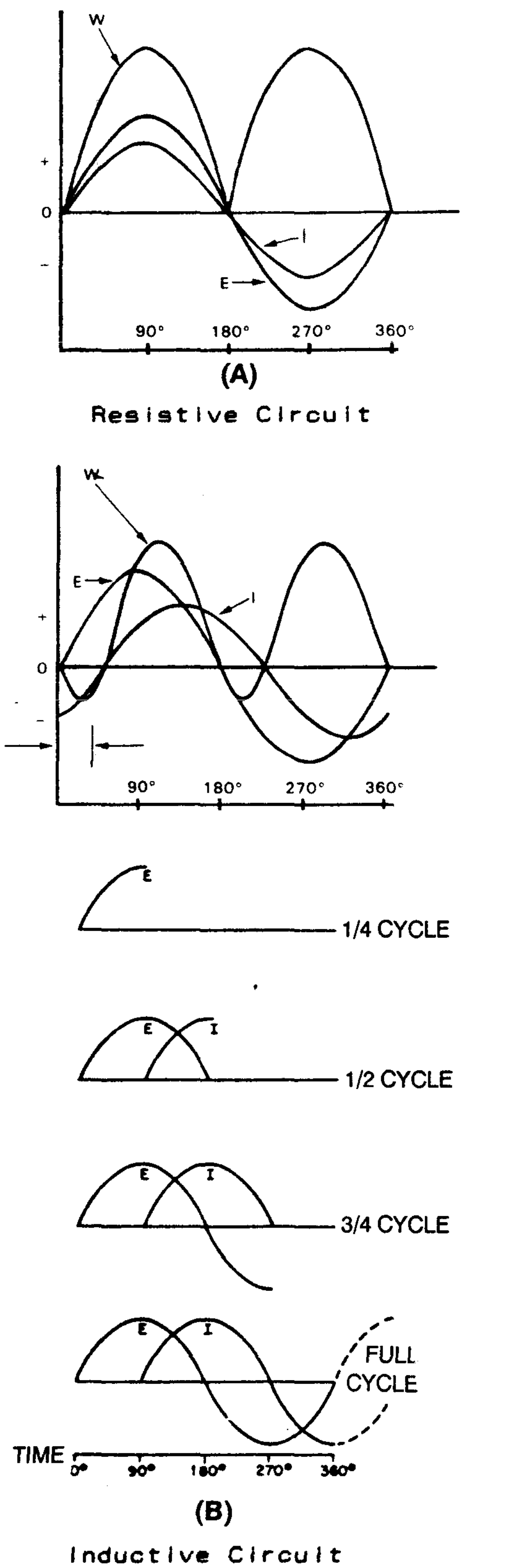


FIGURE 7-13. Voltage and Current Waveforms.

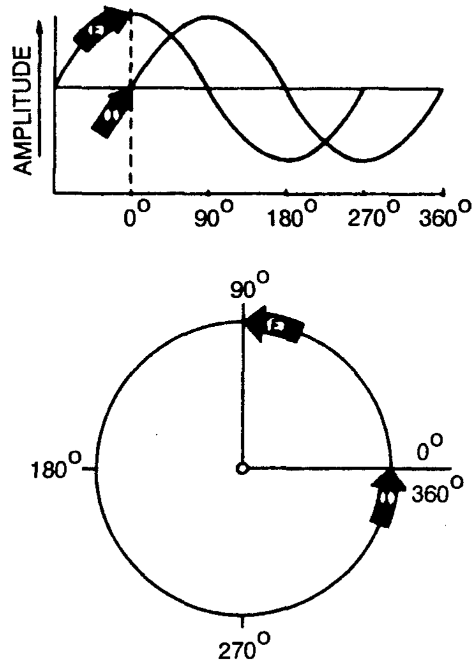


FIGURE 7-14. Comparison of Sine Wave and Circle in an Inductive Circuit.

CAPACITORS AND ALTERNATING CURRENT

The four parts of Figure 7-15 show the variation of the alternating voltage and current in a capacitive circuit for each quarter of one cycle. The solid line represents the voltage across the capacitor, and the dotted line represents the current. The line running through the center is the zero, or reference point, for voltage and current. The bottom line marks off the time of the cycle in terms of electrical degrees. Assume that the AC voltage has been acting on the capacitor for some time before the time represented by the starting point of the sine wave in the figure.

At the beginning of the first quarter-cycle (0 to 90 degrees), the voltage has just passed through zero and is increasing in the opposite direction. Since the zero point is the steepest part of the sine wave, the voltage is changing at its greatest rate. The charge on a capacitor varies directly with the voltage. Therefore, the charge on the capacitor is also changing at its greatest rate at the beginning of the first quarter-cycle. In other words, the greatest number of electrons are moving off one plate and onto the other plate. Thus, the capacitor current is at its maximum value (Figure 7-15 view A).

As the voltage proceeds toward maximum at 90 degrees, its rate of change becomes less and less. Hence, the current must decrease toward zero. At 90 degrees, the voltage across the capacitor is maximum, and the capacitor is fully charged. There is no further movement of electrons from plate to plate. That is why the current at 90 degrees is zero.

At the end of the first quarter-cycle, the alternating voltage stops increasing in the positive direction and starts to decrease. It is still a positive voltage, but to the capacitor, the decrease in voltage means that the plate that has just accumulated an excess of electrons must lose some electrons. The current flow must reverse its direct ion. Figure 7-15 view B shows the current to be below the zero line (negative current direction) during the second quarter-cycle (90 to 180 degrees).

At 180 degrees, the voltage has dropped to zero. This means that for a brief instant the electrons are equally distributed between the two plates. The current is maximum because the rate of change of voltage is maximum. Just after 180 degrees, the voltage has reversed polarity and starts building up its maximum negative peak, which is reached at the end of the third quarter-cycle (180 to 270 degrees). During this third quarter-cycle, the rate of voltage change gradually decreases as the charge builds to a maximum at 270 degrees. At this point, the capacitor is fully charged and carries the full impressed voltage. Because the capacitor is fully charged, there is no further exchange of electrons. Therefore, the current flow is zero at this point. The conditions are exactly the same as at the end of the first quarter-cycle (90 degrees), but the polarity is reversed.

Just after 270 degrees, the impressed voltage once again starts to decrease, and the capacitor must lose electrons from the negative plate. It must discharge, starting at a minimum rate of flow and rising to a maximum. This discharging action continues through the last quarter-cycle (270 to 360 degrees) until the impressed voltage has reached zero. At 360 degrees, it is back at the beginning of the entire cycle, and everything starts over again.

Figure 7-15 view D shows that the current always arrives at a certain point in the cycle 90 degrees ahead of the voltage because of the charging and discharging action. This time and place relationship between the current and voltage is called the phase relationship. The voltage-current phase relationship in a capacitive circuit is exactly opposite to that of an inductive circuit. The current through a capacitor leads voltage across the capacitor by 90 degrees.

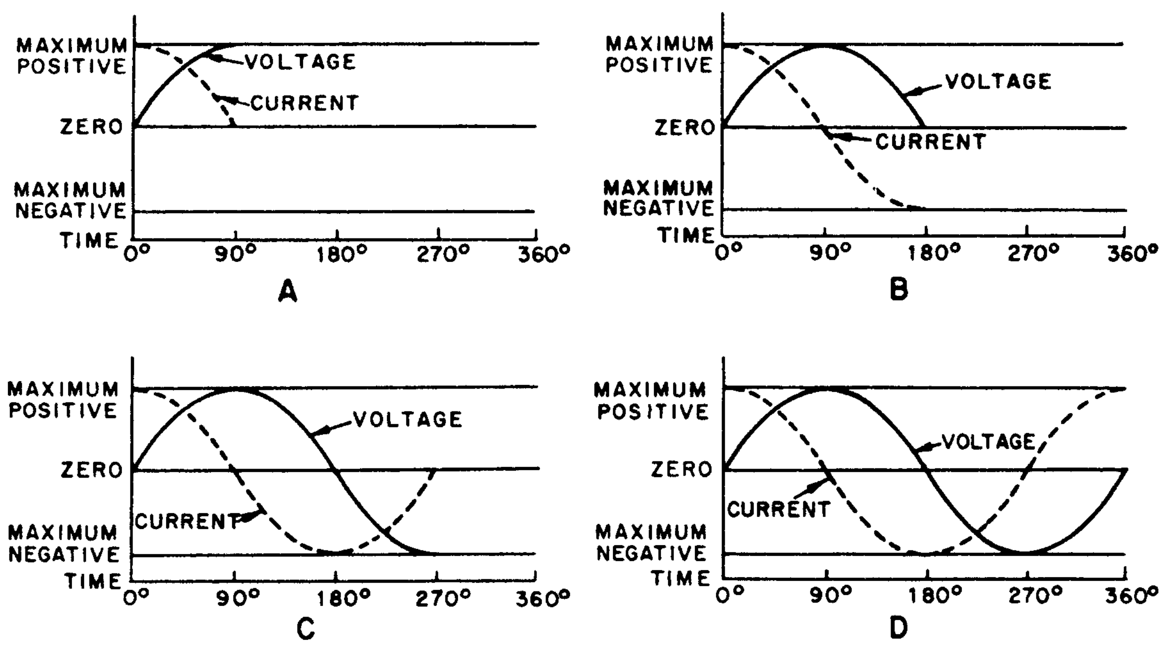


FIGURE 7-15. Phase Relationship of Voltage and Current in a Capacitive Circuit.

The current and voltage are going through their individual cycles at the same time during the period the AC voltage is impressed. The current does not go through part of its cycle (charging or discharging), stop, and wait for the voltage to catch up. The amplitude and polarity of the voltage and the amplitude and direction of the current are continually changing. Their posit ions with respect to each other and to the zero line at any electrical instant (any degree between 0 and 360) can be seen by reading vertically from the time-degree line. The current swing from the positive peak at 0 degrees to the negative peak at 180 degrees is not a measure of the number of electrons or the charge on the plates. It is a picture of the direction and strength of the current relationship to the polarity and strength of the voltage appearing across the plates.

Since the plates of the capacitor are changing polarity at the same rate as the AC voltage, the capacitor seems to pass an alternating current. Actually, the electrons do not pass through the dielectric, but their rushing back and forth from plate to plate causes a current flow in the circuit. It is convenient to say that the alternating current flows through the capacitor. This is not true, but the expression avoids a lot of trouble when speaking of current flow in a circuit containing a capacitor.

IMPEDANCE

Inductive reactance and capacitive reactance act to oppose the flow of current in an AC circuit. However, another factor, the resistance, also opposes the flow of current. Since in practice AC circuits containing reactance also contain resistance, the two combine to oppose the flow of current. This combined opposition by the resistance and the reactance is called the impedance and is represented by the symbol Z.

Since the values of resistance and reactance are given in ohms, it might at first seem possible to determine the value of the impedance by simply adding them together. However, it cannot be done so easily. In an AC circuit that contains only resistance, the current and voltage will be in step (in phase) and will reach their maximum values at the same instant. Also, in an AC circuit containing only reactance, the current will either lead or lag the voltage by 90 degrees. When reactance and resistance are combined, the value of the impedance will be greater than either. It is also true that the current will not be in phase with the voltage nor will it be exactly 90 degrees out of phase with the voltage. It will be somewhere between the in-phase and the 90 degree out-of-phase condition. The larger the reactance compared with the resistance, the more nearly the phase angle will approach 90 degrees. The larger the resistance compared to the reactance, the more nearly the phase difference will approach 0 degrees.

CHAPTER 8

TRANSFORMERS

INTRODUCTION

A transformer is a device that transfers electrical energy from one circuit to another by electromagnetic induction (also called transformer action). It is most often used to step up or step down voltage. Occasionally, it is used as an isolating device to eliminate a direct mechanical electrical connection between the power source and the loads. The electrical energy is always transferred without a change in frequency but may involve changes in the effective value of voltage and current. Because a transformer works on the principle of electromagnetic induction, it must be used with an input source that varies in amplitude.

Examining a very unusual transformer will show power is transferred through the use of electromagnetic induction. This direct current transformer will demonstrate the actions of a step-up transformer and provide stop-action analysis of the moving magnetic field. Figure 8-1 shows a one-fine diagram of the primary and secondary automobile ignition system. The primary circuit, or power source side, includes the battery positive terminal, the ignition switch, the primary winding to the ignition points, and the battery negative terminal. The secondary circuit starts with the secondary winding wire and connects the distributor rotor and the spark plug.

When both the ignition switch and the points are closed, there is a complete circuit through the 12-volt battery terminals and the primary windings. As a current initially moves through the conductor, an expanding magnetic field is created. As the magnetic field from the primary winding expands across the secondary windings, a type of generator is created which produces an EMF in the secondary windings. Through electromagnetic induction, the secondary winding has all the necessities for generating an EMF a conductor (the secondary winding), the magnetic field (from the current flow through the primary winding), and the relative motion between the expanding magnetic field and the secondary winding.

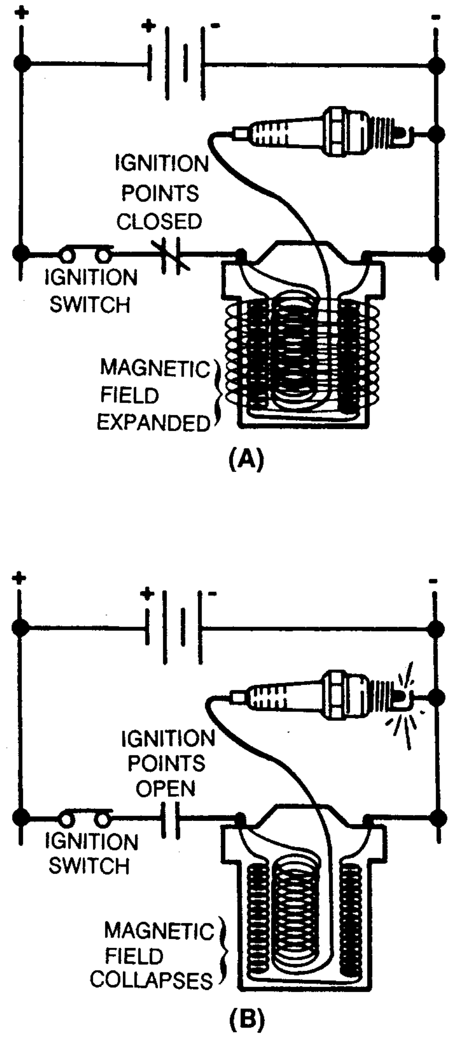


FIGURE 8-1. Automobile Step-Up Transformer.

As the contact points open, the primary field collapses. With this collapse, there is again relative motion between the magnetic field and the secondary windings. This motion and the increased number of conductors in the secondary windings allow the coil to step up voltage from the original 12 volts to the 20,000 volts necessary to fire this type of ignition system.

The distributor, ignition points, and condenser that comprise this DC switching device are very costly. It is not very practical to use DC to step up voltage. AC has certain advantages over DC because it changes direction readily and has a constantly moving magnetic field. One important advantage is that when AC is used, the voltage and current levels can be increased or decreased by means of a transformer.

BASIC OPERATION OF A TRANSFORMER

The transformer circuit in Figure 8-2 shows basic transformer action. The primary winding is connected to a 60 hertz AC source. The magnetic field (flux) expands and collapses about the primary winding. The expanding and contracting magnetic field around the primary winding cuts the secondary winding and induces an EMF into the winding. When a circuit is completed between the secondary winding and a load, this voltage causes current to flow. The voltage may be stepped up or down depending on the number of turns of conductor in the primary and secondary windings.

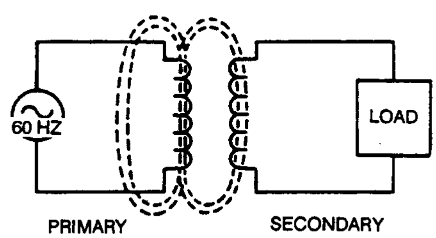


FIGURE 8-2. Basic Transformer Action.

The ability of a transformer to transfer power from one circuit to another is excellent. For marine engineering applications, the power loss is negligible. Power into the transformer is considered equal to power out. It is possible to increase, or step up, the voltage to loads with a subsequent reduction in current. The power formula (P = I x E) demonstrates this phenomenon. The transformer is rated by power or VA for volts times amps. Transformers are rated more often in kVA for thousands of volt amps. The terms “step up” or “step down” refer to the actions of the voltage. A step-down transformer means that the voltage of the source has been reduced to a lesser value for the loads.

Examples of step-down transformers can be found on most Army watercraft. The ship service generator provides 450 VAC to the distribution system. The lighting panels and smaller motors require 115 VAC for a power supply. The ship’s transformers step down the 450 volts to 115 volts. Although there is a lesser voltage in the load side than in the power supply side, the current in the load side will be greater than the current provided from the source side.

For example, if the ship service generator provides 450 VAC at 20 amperes to the primary winding of the transformer, the secondary winding of the transformer will provide 115 VAC at 78 amperes to the loads.

Primary (generator) side:

$$P = I \times E$$

$$P = 20 \text{ amps} \times 450 \text{ volts}$$

$$P = 9{,}000 \text{ VA (or 9 kVA)}$$

Secondary (load) side:

$$P = I \times E \text{ or } I = \frac{P}{E}$$

$$I = \frac{9{,}000 \text{ VA}}{115 \text{ volts}}$$

$$I = 78 \text{ amps}$$

The conventional constant-potential transformer is designed to operate with the primary connected across a constant-potential source, such as the AC generator. It provides a secondary voltage that is substantially constant from no load to full load.

Transformers require little care and maintenance because of their simple, rugged, and durable construction.

APPLICATIONS

Various types of small single-phase transformers are used in electrical equipment. In many installations, transformers are used in switchboards to step down the voltage for indicating lights. Low-voltage transformers are included in some motor control panels to supply control circuits or to operate contractors and relays.

Instrument transformers include potential, or voltage, transformers and current transformers. Instrument transformers are commonly used with AC instruments when high voltages or large currents are to be measured.

TRANSFORMER COMPONENTS

The principle parts of a transformer and their functions are –

- The core, which provides a path for the magnetic lines of flux.
- The primary winding, which receives power from the AC power source.
- The secondary winding, which receives power from the primary winding and delivers it to the load.
- The enclosure, which protects the above components from dirt, moisture, and mechanical damage.

CORE CHARACTERISTICS

The composition of a transformer core depends on such factors as voltage, current, and frequency. Size limitations and construction costs are also factors to be considered. Commonly used core materials are air, soft iron, and steel. Each of these materials is suitable for particular applications and unsuitable for others. Generally, air-core transformers are used when the voltage source has a high frequency (above 20 kHz). Iron-core transformers are usually used when the source frequency is low (below 20 kHz). A soft-iron-core transformer is useful when the transformer must be physically small, yet efficient. The iron-core transformer provides better power transfer than does the air-core transformer. A transformer whose core is constructed of laminated sheets of steel dissipates heat readily, providing efficient transfer of power. Most transformers in the Army marine field contain laminated steel cores. These steel laminations (Figure 8-3) are insulated with a nonconducting material, such as varnish, and then formed into a core. It takes about 50 such laminations to make a core an inch thick.

The laminations reduce certain losses which will be discussed later. The most effective transformer core is one that offers the best path for the most lines of flux with the least magnetic and electrical energy loss.

Two main shapes of cores are used in laminated steel-core transformers: the hollow core and the shell core.

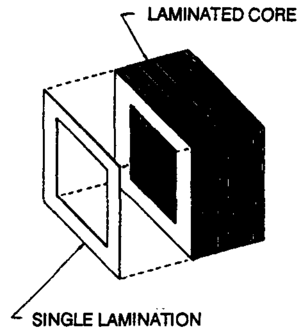


FIGURE 8-3. Hollow-Core Construction.

The hollow core is shaped with a square through the center (Figure 8-3). The core is made up of many laminations of steel. Figure 8-4 shows how the transformer windings are wrapped around both sides of the core.

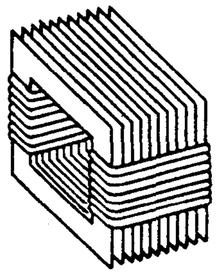


FIGURE 8-4. Windings Wrapped Around Laminations.

The shell core is the most popular and efficient transformer (Figures 8-5 through 8-7).

As shown, each layer of the core consists of E- and I-shaped sections of metal. These sections are butted together to form laminations. The laminations are insulated from each other and then pressed together to form a core.

TRANSFORMER WINDINGS

Two wires called windings are wound around the core. Each winding is electrically insulated from the other. The terminals are marked according to the voltage: H indicates the higher voltage, and X indicates the lesser voltage. Figure 8-8 shows examples of this.

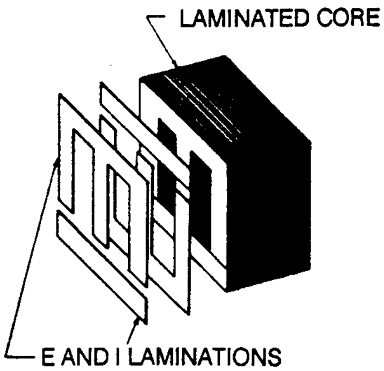


FIGURE 8-5. Shell-Type Core Construction.

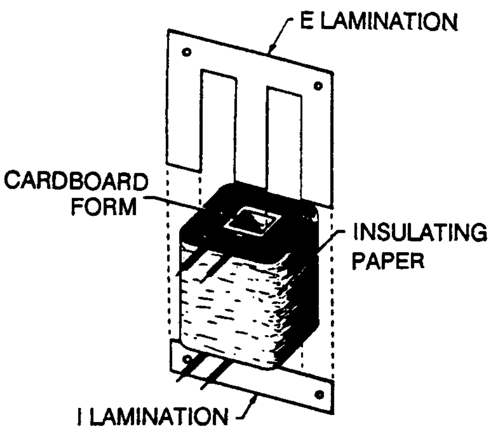


FIGURE 8-6. Exploded View of Shell-Type Transformer Construction.

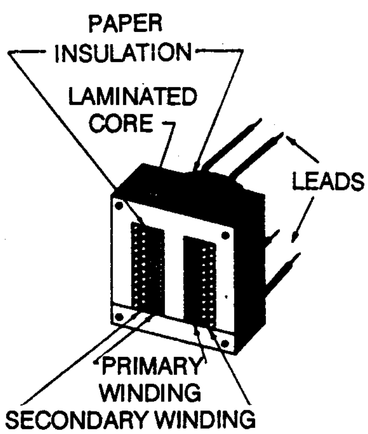


FIGURE 8-7. Cutaway View of Shell-Type Core With Windings.

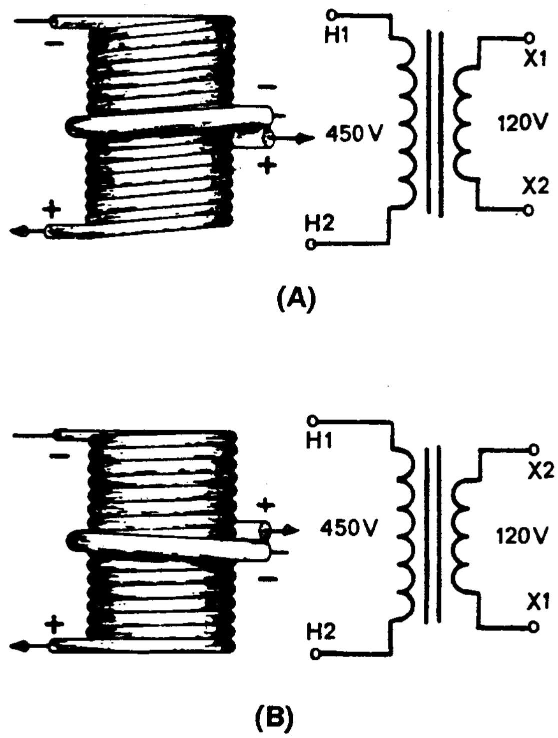


FIGURE 8-8. 450/120 Volt Step-Down Transformer.

Additionally, H1 and X1 indicate polarity. Since AC is constantly changing polarity, the H1 and X1 indicate that the polarities at both these terminals are identical during the same instant in time. At the same moment H1 has current moving through it in a given direction, the induced current through terminal X1 is moving in the same direction. When H1 and Xl are directly opposite each other, a condition known as subtractive polarity is formed (Figure 8-9 view B). When the H1 and the X1 are diagonally positioned, a condition known as additive polarity is formed (view A).

Another form of polarity marking is through the use of dots. Dot notation is used with diagrams to express which terminals are positive at the same instant in time (Figure 8-10).

M1 transformers are not wired the same way, and improper connections can damage the entire electrical circuit. The terms "additive polarity" and "subtractive polarity" come from the means of testing unmarked transformers. Do not connect a transformer opposite to its intended purpose. Do not connect a step-down transformer for step-up application because the internal stresses set up within the transformer may damage it.

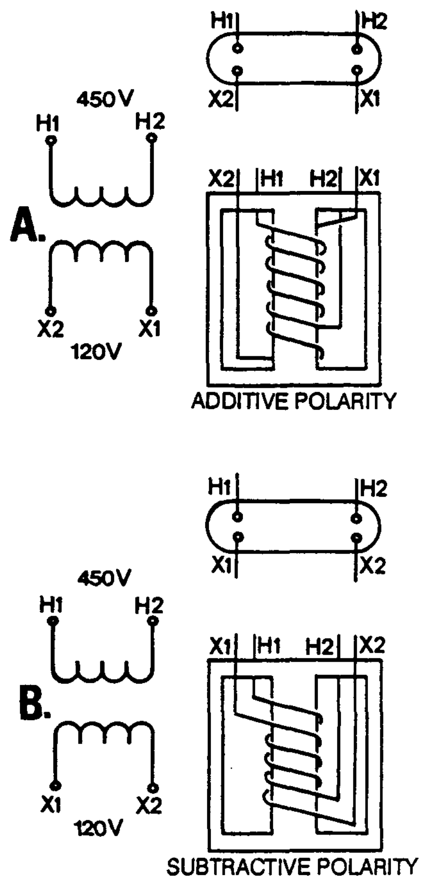


FIGURE 8-9. Polarity Markings for Large Transformers.

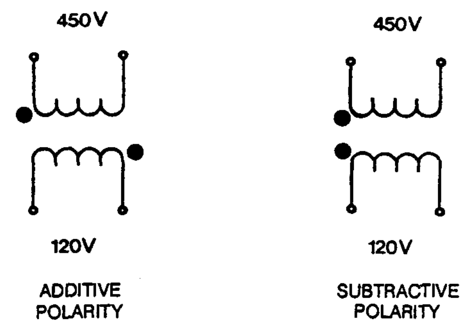


FIGURE 8-10. Instantaneous Polarity.

SCHEMATIC SYMBOLS FOR TRANSFORMERS

Figure 8-11 shows typical schematic symbols for transformers. View A shows the symbol for an air-core transformer. Views B and C show iron-core transformers. The bars between the windings indicate an iron core. Frequently, additional connections are made to the transformer windings at points other than the ends of the windings. These additional connections are called taps. When a tap is connected to the center of the winding, it is called center tap. View C shows the schematic representation of a center-tapped iron-core transformer.

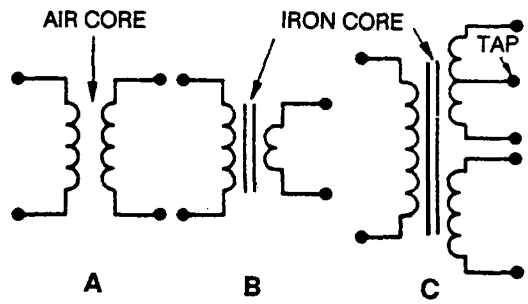


FIGURE 8-11. Schematic Symbols for Various Types of Transformers.

NO-LOAD CONDITION

A transformer can supply voltages that are usually higher or lower than the source voltage. This is done through mutual induction, which takes place when the changing magnetic field produced by the primary voltage cuts the secondary winding.

A no-load condition exists when a voltage is applied to the primary, but no load is connected to the secondary (Figure 8-12). Because of the open switch, there is no current flowing in the secondary winding. With the switch open and an AC voltage applied to the primary, there is, however, a very small amount of current, called exciting current, flowing in the primary. The exciting current “excites” the winding of the primary to create a magnetic field.

The amount of the exciting current is determined by three factors, which are all controlled by transformer action:

- The amount of voltage applied.
- The resistance of the primary winding’s wire and core losses.
- The inductive reactance which depends on the frequency of the exciting current.

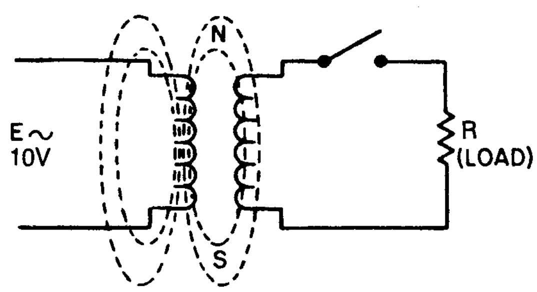


FIGURE 8-12. Transformer Under No-Load Conditions.

This very small amount of exciting current serves two functions:

- Most of the exciting energy is used to support the magnetic field of the primary.
- A small amount of energy is used to overcome the resistance of the wire and core. This is dissipated in the form of heat (power loss).

Exciting current will flow in the primary winding at all times to maintain this magnetic field, but no transfer of energy will take place as long as the secondary circuit is open.

WARNING

The open secondary leads provide a potential hazard to personnel. Should a path between the secondary leads develop, current will result. The soldier should never come in contact with the exposed secondary leads when the primary leads are energized.

COUNTER ELECTROMOTIVE FORCE

When an AC flows through a primary winding, a magnetic field is established around the winding. As the lines of flux expand outward, relative motion is present, and a counter EMF is induced in the winding. Flux leaves the primary at the north pole and enters the primary at the south pole. The CEMF induced in the primary has a polarity that opposes the applied voltage, thus opposing the flow of current in the primary. It is the CEMF that limits the exciting current to a very low value.

VOLTAGE IN THE SECONDARY

Figure 8-12 shows a voltage is induced into the secondary winding of a transformer. As the exciting current flows through the primary, magnetic lines of force are generated. During this time, while current is increasing in the primary, magnetic lines of force expand outward from the primary and cut the secondary. A voltage is induced into a winding when magnetic lines cut across it. Therefore, the voltage across the primary causes a voltage to be induced across the secondary.

TURNS AND VOLTAGE RATIOS

The total voltage induced into the secondary winding of a transformer is determined mainly by the ratio of the number of turns in the primary to the number of turns in the secondary and by the amount of voltage applied to the primary. Figure 8-13 view A shows a transformer whose primary consists of 10 turns of wire and whose secondary consists of a single turn of wire. As lines of flux generated by the primary expand and collapse, they cut both the 10 turns of the primary and the single turn of the secondary. Since the length of the wire in the secondary is about the same as the length of the wire in each turn of the primary, CEMF induced into the secondary will be the same as the EMF induced into each turn in the primary. This means that if the voltage applied to the primary winding is 10 volts, the CEMF in the primary is almost 10 volts. Thus, each turn in the primary will have an induced CEMF of about 1/10th of the total applied voltage, or 1 volt. Since the same flux lines cut the turns in both the secondary and the primary, each turn will have an EMF of 1 volt induced into it. The transformer in Figure 8-13 view A has only one turn in the secondary thus, the EMF across the secondary is 1 volt.

The transformer in view B has a 10-turn primary and a 2-turn secondary. Since the flux induces 1 volt per turn, the total voltage across the secondary is 2 volts. The volts per turn are the same for both the primary and secondary windings. Since the CEMF in the primary is equal (or almost equal) to the applied voltage, a proportion may be set up to express the value of the voltage induced in terms of the voltage applied to the primary and the number of turns in each winding. This proportion also shows the relationship between the number of turns in each winding and the voltage across each winding.

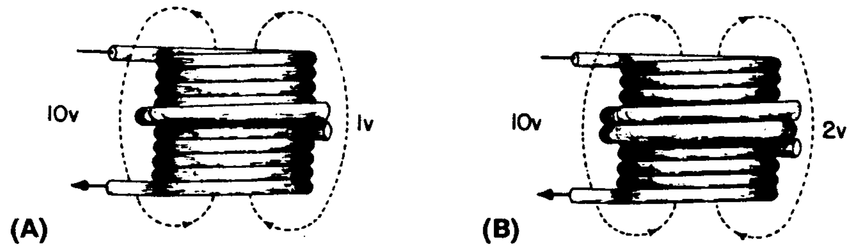


FIGURE 8-13. Transformer Turns and Voltage Ratios.

This proportion is expressed by the following equation:

$$\frac{Es}{Ep} = \frac{Ns}{Np}$$

Where: Np = number of turns in the primary

Ep = voltage applied to the primary

Es = voltage induced in the secondary

Ns = number of turns in the secondary

The equation shows that the ratio of secondary voltage to primary voltage equals the ratio of secondary turns to primary turns. The equation can be written as —

$$(Ep) \times (Ns) = (Es) \times (Np)$$

The following formulas are derived from the above equation:

Transposing for Es: $Es = \frac{(Ep) \times (Ns)}{Np}$

Transposing for Ep: $Ep = \frac{(Es) \times (Np)}{Ns}$

If any three quantities in the above formulas are known, the fourth quantity can be calculated.

Example: A transformer has 200 turns in the primary, 50 turns in the secondary, and 120 volts applied to the primary. What is the voltage across the secondary (Es)?

Given:

Np = 200 turns

Ns = 50 turns

Ep = 120 volts

Es = ?

Solution:

$$Es = \frac{(Ep) \times (Ns)}{Np}$$

Substitution:

$$Es = \frac{(120 \text{ volts}) \times (50 \text{ turns})}{200 \text{ turns}}$$

Es = 30 volts

The transformer in the above problem has fewer turns in the secondary than the primary. As a result, there is less voltage across the secondary than across the primary. A transformer in which the voltage across the secondary is less than the voltage across the primary is called a step-down transformer. The ratio of a four-to-one step-down transformer is written 4:1. A transformer that has fewer turns in the primary than in the secondary will produce a greater voltage across the secondary than the voltage applied to the primary. A transformer in which the voltage across the secondary is greater than the voltage applied to the primary is called a step-up transformer. The ratio of a one-to-four step-up transformer is written as 1:4. In the two ratios, the value of the primary winding is always stated first.

EFFECT OF A LOAD

When an electrical load is connected across the secondary winding of a transformer, current flows through the secondary and the load. The magnetic field produced by the current in the secondary interacts with the magnetic field produced by the current in the primary. This interaction results from the mutual inductance between the primary and secondary windings.

POWER RELATIONSHIP BETWEEN PRIMARY AND SECONDARY WINDINGS

The turns ratio of a transformer affects current as well as voltage. If voltage is doubled in the secondary, current is halved in the secondary. Conversely, if voltage is halved in the secondary, current is doubled in the secondary. In this manner, all the power delivered to the primary by the source is also delivered to the load by the secondary (minus whatever power is consumed by the transformer in the form of losses). In the transformer shown in Figure 8-14, the turns ratio is 20:1. If the input to the primary is 10 amperes at 450 volts, the power in the primary is 4,500 watts (P = IxE). If the transformer has no losses, 4,500 watts is delivered to the secondary. The secondary steps down the voltage to 22.5 volts and will increase the current to 200 amperes. Thus, the power delivered to the load by the secondary is P = E x I = 22.5 volts x 200 amps = 4,500 watts.

The reason for this is that when the number of turns in the secondary is decreased, the opposition to the flow of the current is also decreased. Hence, more current will flow in the secondary. If the turns ratio of the transformer is increased to 1:2 (step up), the number of turns on the secondary is twice the number of turns on the primary. This means the opposition to current is doubled. Thus, voltage is doubled, but current is halved due to the increased opposition to current in the secondary. With the exception of the power consumed within the transformer, all power delivered to the primary by the source will be delivered to the load. The form of the power may change, but the power in the secondary almost always equals the power in the primary. This can be expressed in the formula:

Ps = Pp - Pl

Where: Ps = powered delivered to the load by the secondary

Pp = power delivered to the primary by the source

Pl = power losses in the transformer

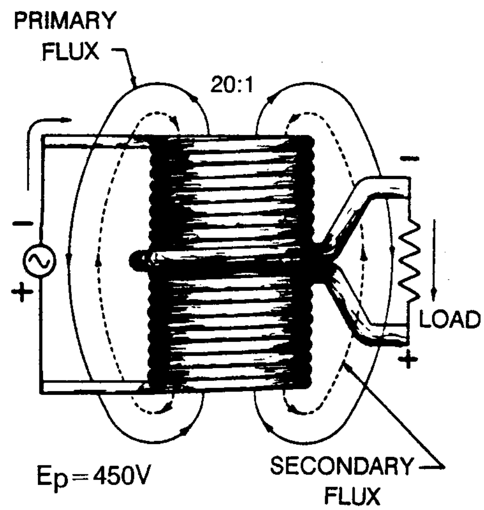


FIGURE 8-14. Simple Transformer Indicating Primary and Secondary Winding Flux Relationship.

ACTUAL TRANSFORMER LOSSES

Practical power transformers, although highly efficient, are not perfect devices. Small power transformers used with electrical components have an 80 to 90 percent efficiency range, while large distribution system transformers may have efficiencies exceeding 98 percent.

The total power loss in a transformer is a combination of losses. One loss is due to the resistance in the conductors of the primary and secodary windings. This loss is called copper loss or I^2R loss. As current increases through the resistance of the conductor, there is a drop in voltage proportional to the increase in current flow. This phenomenon is found wherever there is a resistance. Ohm's Law shows this.

Example: The initial electrical load demands 10 amperes. The resistance in the transformer winding conductor is .4 ohms. The voltage drop across the winding conductor is 4 volts.

$E = I \times R$

$E = 10 \text{ amps} \times .4 \text{ ohms}$

$E = 4 \text{ volts}$

If the electrical demand is increased and a current of 70 amperes is now required, the voltage drop across the winding conductor will increase.

$E = I \times R$

$E = 70 \text{ amps} \times .4 \text{ ohms}$

$E = 28 \text{ volts}$

As current flow increases, there is a resulting increase in heat. The resistance of copper increases as current and temperature increase. This further affects the voltage drop. This makes secondary voltage decrease as load is applied.

Whenever current flows in a conductor, power is dissipated in the resistance of the conductor in the form of heat. The amount of power dissipated by the conductor is directly proportional to the resistance of the wire and to the square of the current through it.

The greater the value of either the current or the resistance, the greater the power dissipated.

$P = I \times E$

$P = 70 \text{ amps} \times 28 \text{ volts}$

$P = 1{,}960 \text{ watts}$

or

$P = I^2 \times R$

$P = 70^2 \text{ amps} \times .4 \text{ ohms}$

$P = 4{,}900 \text{ amps} \times .4 \text{ ohms}$

$P = 1{,}960 \text{ watts}$

This is the power consumed or lost due to the resistance of the conductor.

The resistance of a given conductor or winding is a function of the diameter of the conductor and its length. Large diameter, lower resistance wire is required for high-current-carrying applications whereas small diameter, higher resistance wire can be used for low-current-carrying applications.

Two other losses are due to eddy currents and hysteresis in the core of the transformer. Copper loss, eddy current loss, and hysteresis loss result in undesirable conversion of electrical energy to heat energy.

Eddy Current Loss

The core of a transformer is usually constructed of some type of ferromagnetic material because it is a good conductor of magnetic lines of flux.

Whenever the primary of an iron-core transformer is energized by an AC source, a fluctuating magnetic field is produced. This magnetic field cuts the conducting core material and induces a voltage into it. The induced voltage causes random currents to flow through the core which dissipate power in the form of heat. These undesirable currents are eddy currents.

To minimize the loss resulting from eddy currents, transformer cores are laminated. Since the thin, insulated laminations do not provide an **easy** path for current, eddy current losses are greatly reduced.

Hysteresis Loss

When a magnetic field is passed through a core, the core material becomes magnetized. To become magnetized, the domains within the core must align themselves with the external field. If the direction of the field is reversed, the domains must turn so that their poles are aligned with the new direction of the external field.

Transformers normally operate at 60 hertz. Each tiny atomic particle domain must realign itself twice each cycle or a total of 120 times a second. The energy used to turn each domain is dissipated as heat within the iron core. This is hysteresis loss, which results from molecular friction. Hysteresis loss can be held to a small value by proper choice of core materials during the manufacturing process.

TRANSFORMER EFFICIENCY

To compute the efficiency of a transformer, the input power and the output power from the transformer must be known. The input power equals the product of the voltage applied to the primary and the current in the primary. The output power equals the product of the voltage across the secondary and the current in the secondary. The difference between the input power and the output power represents a power loss. This percentage of efficiency of a transformer is calculated using the standard efficiency formula

$$\text{Efficiency (in percentage)} = \frac{\text{power out}}{\text{power in}} \times 100$$

TRANSFORMER RATINGS

When a transformer is to be used in a circuit, more than just the turns ratio must be considered. The voltage, current, and power-handling capabilities of the primary and secondary windings must be considered as well.

The maximum voltage that can safely be applied to any winding is determined by the type and thickness of the insulation used. When a better (and thicker) insulation is used between the windings, a higher maximum voltage can be applied to the windings.

The maximum current that can be carried by a transformer winding is determined by the diameter of the wire used for the winding. If current is excessive in a winding, a higher than ordinary amount of power will be dissipated by the winding in the form of heat. This heat may become sufficiently high to cause the insulation around the wire to break down. If this happens, the transformer will become permanently damaged.

The power-handling capability of a transformer depends on its ability to dissipate heat. If the heat can be safely removed, the power-handling capability of the transformer can be increased. This is sometimes done by immersing the transformer in oil or by using cooling fins. The power-handling capability of distribution system transformers is measured in the volt-ampere unit (kVA). Smaller units generally used in resistive circuits are measured in the watt unit (KW).

DISTRIBUTION TRANSFORMERS

Step-down and isolation distribution transformers supply voltages to the various circuits in the electrical system. Distribution transformers are rated at 500 kVA or less. These are the type found on Army vessels. They are the dry type and are air-cooled and drip-proof. They can operate at 30-degree inclinations. They are designed for ambient temperature operation of 40C and 50C.

The high- and low-voltage windings in a distribution transformer can usually be distinguished by observing the diameter of the conductor. Since most transformers located on board ship are the step-down type, the low-voltage winding will have the larger diameter conductor. This is because the power is not changed. The reduction in voltage means an increase of current. Current determines the diameter of the conductor.

ISOLATION TRANSFORMERS

Isolation transformers do not change either the power or the voltage and current levels. Instead, they provide an extra degree of protection to the distribution system for those circuits that are set aside for access by other than engineering personnel and the circuits that are available for unspecified electrical apparatus.

Should one of these circuits have a catastrophic electrical casualty that prevents local circuit breakers and overloads from operating properly, the isolation transformer prevents a mechanical connection of the circuit with the rest of the distribution system. A catastrophic electrical problem will damage the transformer and allow time for the rest of the distribution system to react to the electrical problem. The isolation transformers effectively isolate these problem circuits from the rest of the single-phase distribution system. The areas under the added protection of the isolation transformer include galley equipment and “hotel” services (120-volt electrical outlets).

TRANSFORMER TAPS

Typical transformers used for electrical components and control circuits have several primary and/or secondary windings. Figure 8-15 shows the schematic symbol for a typical multitap transformer. For any given voltage across the primary, the voltage across each of the secondary windings is determined by the number of turns in each secondary. A winding may be center-tapped like the secondary 350-volt winding in Figure 8-15. To center-tap a winding means to connect a wire to the center of the coil, so that between this tap and either terminal of the winding there appears one-half of the voltage developed across the entire winding.

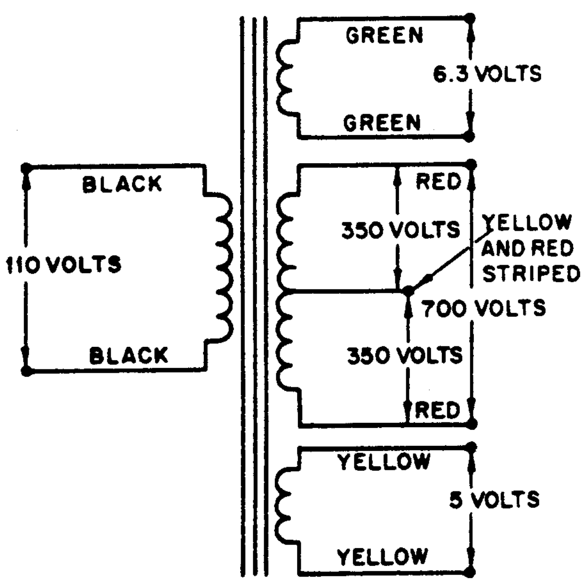


FIGURE 8-15. Schematic Diagram of a Typical Transformer.

AUTOTRANSFORMERS

It is not always necessary to have two or more separate and distinct windings in a transformer. Figure 8-16 is a schematic diagram of an autotransformer. A single winding is tapped to produce what is electrically a primary and secondary winding.

Through inductance, the magnetic field from the power supply can produce a CEMF into the primary winding as well as an EMF into the secondary winding. Voltage is self-induced into every coil of wire.

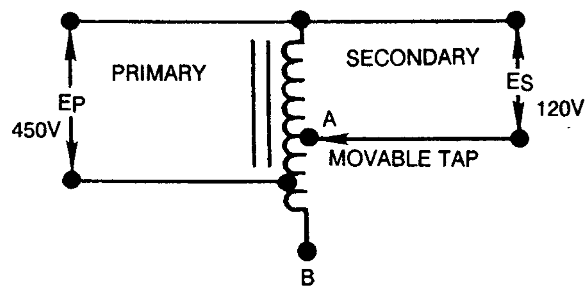


FIGURE 8-16. Schematic Diagram of an Autotransformer With a Movable Tap.

Example: *Assume that 208 volts is applied to the autotransformer in Figure 8-17. The primary includes all the turns, but the secondary includes only half the turns. The turns ratio is 21. Secondary voltage is —

$$Es = \frac{208 \text{ volts}}{2}$$

$$Es = 104 \text{ volts}$$

There is a 10.4-ohm resistive load. Load current is —

$$Is = \frac{104 \text{ volts}}{10.4 \text{ ohms}}$$

$$Is = 10 \text{ amps}$$

Primary current is –

$$Ip = \frac{10 \text{ amps}}{2}$$

$$Ip = 5 \text{ amps}$$

It may be hard at first to understand how the secondary can have twice the primary current. After all, the primary and secondary are the same coil. Secondary current, however, is the sum of two separate currents. One is primary current which also flows in the secondary circuit. The other is produced by the back-voltage (CEMF), which is self-induced in the secondary part of the coil.

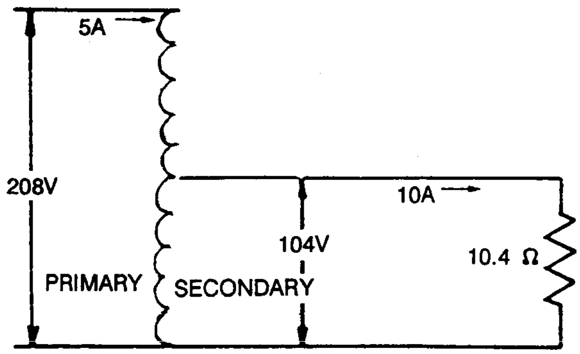


FIGURE 8-17. Step-Down Transformer.

The primary current of 5 amperes is conducted to the secondary current. The other 5 amperes is transformed in the transformer.*

The autotransformer is used extensively for reduced voltage starting of larger motors, such as the fire pump. This is one of the most effective ways to hold the line current and voltage to a minimum when a maximum current (or torque per line ampere) is required at the motor.

The autotransformer is used for motor starting. It is never used to supply feeders or branch circuits in the distribution system. Figure 8-18 view B shows a damaged autotransformer. If this type of casualty took place, the voltage to the load would increase to the value available at the primary side. This could be electrically devastating to all the electrical loads connected to the secondary side.

TRANSFORMER SAFETY

If transformers are being worked on or inspected, the following additional rules apply:

- Remove the transformer from all power sources in the primary and secondary circuitry.
- Remove all the fuses from the power source.
- Trip circuit breakers and take action to prevent their accidental resetting.
- Short out transformer secondaries before connecting and disconnecting equipment.
- To prevent potentially high voltage and current levels, always connect a load to the secondary side of the transformer before energizing the primary. The voltmeter is an excellent high-resist ante load when connected with alligator clips.

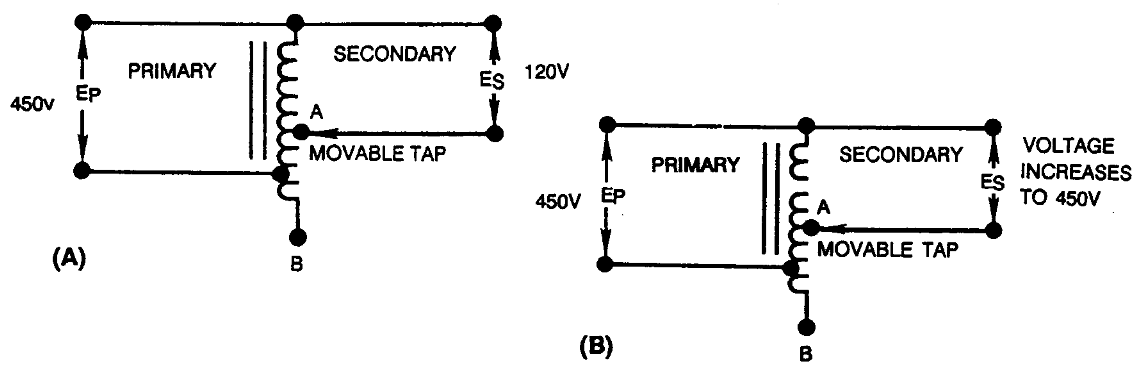


FIGURE 8-18. Damaged Autotransformer Winding.

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CHAPTER 9

CIRCUIT MEASUREMENT

INTRODUCTION

This chapter explains the basics of circuit measurement. It covers devices used to measure volt age, current, resistance, power, and frequency. This chapter does not cover all the available testing instruments. Instead, it describes those instruments most commonly found on Army watercraft.

Because of the high cost of repair and replacement parts, the marine engineman/engineer must correctly diagnose and repair defects in electrical equipment. With the correct choice of meters, it is possible to determine any circuit values needed to troubleshoot the electrical system.

This chapter uses schematic symbols and schematic diagrams to explain terms. Many of these schematic diagrams represent a meter in the circuit, as shown in Figure 9-1.

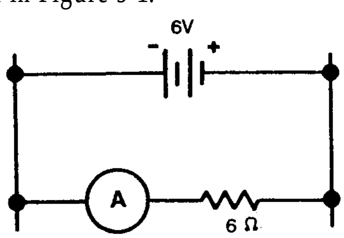


FIGURE 9-1. A Simple Representative Circuit.

The current in a DC circuit with 6 volts across a 6-ohm resistor is 1 ampere. The circled A in Figure 9-1 is the symbol of the ammeter. An ammeter is a meter used to measure current in amperes. Thus, it is an ampere meter, or ammeter. The ammeter in Figure 9-1 is measuring a current of 1 ampere with the voltage and resistance values given.

The quantities in an electrical circuit (voltage, current, and resistance) are important. By measuring the electrical quantities in a circuit, it is easier to understand what is happening in that circuit. This is especially true when troubleshooting defective circuits. By measuring the voltage, current, and resistance, the reason the circuit is not doing what it is supposed to do can be determined.

IN-CIRCUIT METERS

Some electrical devices have meters built into them. These are in-circuit meters, which monitor the operation of the circuit in which they are installed. Some examples of in-circuit meters are the generator or alternator meter on some automobiles; the voltage, current, and frequency meters on ship switchboards; and the electrical power meter that records the amount of power consumed in a building.

It is not practical to install an in-circuit meter in every circuit. However, it is possible to install an in-circuit meter in each critical or representative circuit to monitor the operation of a piece of equipment. A mere glance at an in-circuit meter on a control board is often sufficient to tell if the equipment is working properly. It is important to become familiar with in-circuit meter values during all facets of the system operation. Only after observing familiar “normal” readings can an engineer readily identify abnormal system operation.

An in-circuit meter will indicate when an electrical device is not functioning properly. The cause of the malfunction is determined by troubleshooting, the process of locating and repairing faults in equipment after they have occurred.

OUT-OF-CIRCUIT METERS

In troubleshooting, it is usually necessary to use an out-of-circuit meter that can be connected to the electrical equipment at various testing points. Out-of-circuit meters may be moved from one piece of equipment to another. They are generally portable and self-contained.

BASIC METER MOVEMENTS

There are many different types of meter movements. The first discussed below is based on the principle of interaction of magnetic fields.

Compass and Conducting Wire

An electrical conductor in which current flows has a magnetic field generated around it. If a compass is placed close to the conductor, the compass will react to that magnetic field (Figure 9-2).

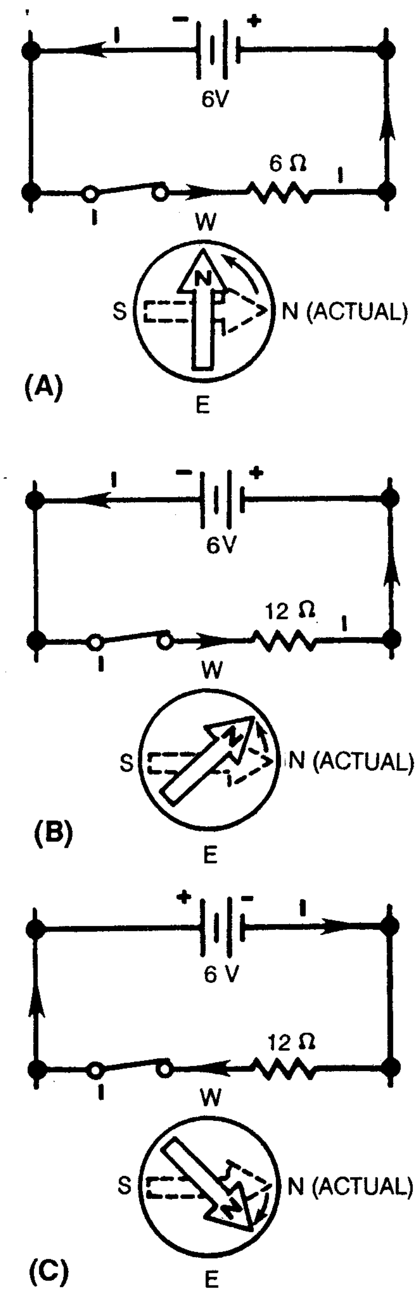


FIGURE 9-2. Compass and Conductor With Direct Current.

If the battery is disconnected, the north end of the compass will point to the south magnetic pole (located at the north geographic pole [Figure 2-10]). This is indicated by the broken line compass needle pointing to the right. When a battery is connected, current flows through the circuit, and the compass needle aligns itself with the magnetic field of the conductor, as indicated by the solid compass needle. The strength of the magnetic field created around the conductor depends on the amount of current. Because of the magnetic principle that unlike poles attract, a compass incorrectly identifies the North Pole as magnetic north. The North Pole of the earth is, in fact, the magnetic south pole.

In Figure 9-2 view A, the resistance in the circuit is 6 ohms. With the 6-volt battery shown, current in the circuit is 1 ampere. In view B, the resistance has been changed to 12 ohms. With the 6-volt battery shown, current in the circuit is l/2 or .5 ampere. The magnetic field around the conductor in view B is weaker than the magnetic field around the conductor in view A. The compass needle in view B does not move as far from magnetic south.

If the direction of the current is reversed, the compass needle will move in the opposite direction because the polarity of the magnetic field has reversed. In view C, the battery connections are reversed; the compass needle now moves in the opposite direction.

A crude meter to measure current can be made using a compass and a piece of paper. To make a simple meter, use resistors of known values and mark the paper to indicate a numerical value (Figure 9-3). The first galvanometers were developed this way. A galvanometers is an instrument that measures small amounts of current. It is based on the electromagnetic principle.

The meter in Figure 9-3 is not very practical for electrical measurement. The amount the compass needle swings depends on the closeness of the compass to the conductor carrying the current, the direction of the conductor in relation to magnetic south, and the influence of other magnetic fields. In addition, very small amounts of current will not overcome the magnetic field of the earth, and the needle will not move.

The compass and conducting wire meter is a fixed conductor moving magnet device since the compass is, in reality, a magnet that can move. The basic principle of this device is the interaction of magnetic fields: the field of the compass (a permanent magnet) and the field around the conductor (a simple electromagnet).

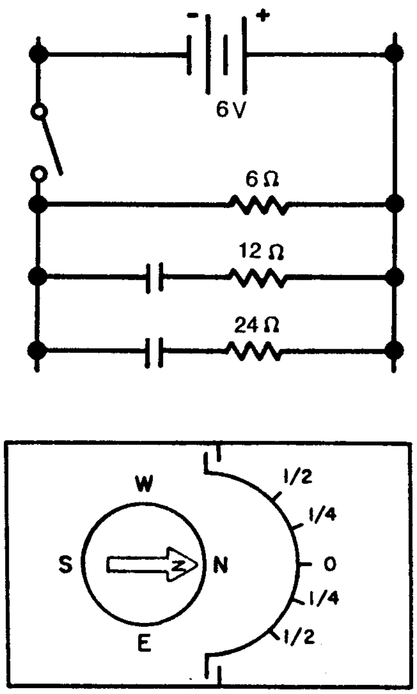


FIGURE 9-3. A Simple Meter From a Compass.

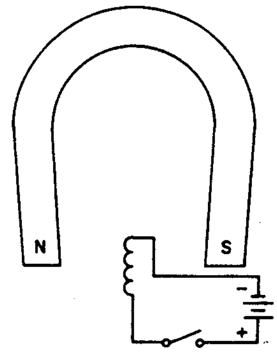


FIGURE 9-4. A Movable Coil in a Magnetic Field (No Current).

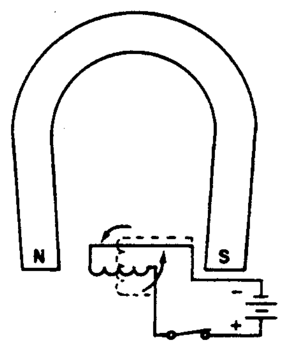


FIGURE 9-5. A Movable Coil in a Magnetic Field (With Current).

Permanent Magnet Moving Coil Movement

A permanent magnet moving coil movement is based upon a freed permanent magnet and a coil of wire that can move, as in Figure 9-4. When the switch is closed, causing current through the coil, the coil will have a magnetic field that will react to the magnetic field of the permanent magnet. The bottom portion of the coil in Figure 9-4 will be the north pole of this electromagnet. Since opposite poles attract, the coil will move to the position shown in Figure 9-5.

The coil of wire is wound on an aluminum frame or bobbin. The bobbin is supported by jeweled bearings that let it move freely (Figure 9-6).

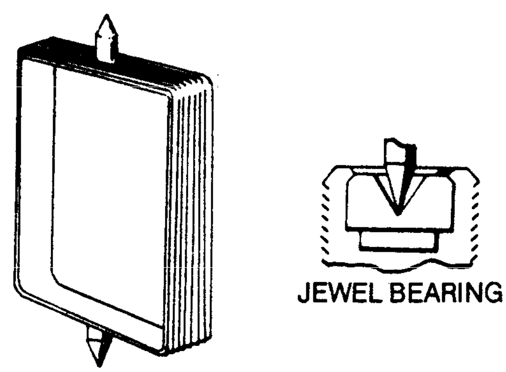


FIGURE 9-6. A Basic Coil Arrangement.

To use this permanent magnet moving coil device as a meter, two problems must be solved. First, a way must be found to return the coil to its original position when there is no current through the coil. Second, a method is needed to indicate the amount of coil movement.

The first problem is solved by attaching hairsprings to each end of the coil (Figure 9-7). These hairsprings can also be used to make the electrical connections to the coil. By using hairsprings, the coil will return to its initial position when there is no current. The springs will also tend to resist the movement of the coil when there is current through the coil. When the attraction between the magnetic fields (from the permanent magnet and the coil) exactly equals the force of the hairsprings, the coil will stop moving toward the magnet.

As the current through the coil increases, the magnetic field generated around the coil increases. The stronger the magnetic field around the coils, the farther the coil will move. This is a good basis for a meter.

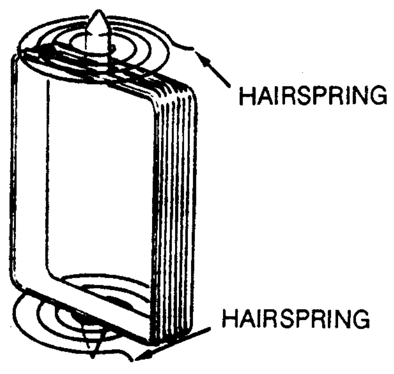


FIGURE 9-7. Coil and Hairsprings.

The second problem is solved using a pointer attached to the coil and extended out to a scale. The pointer will move as the coil moves. The scale can be marked to indicate the amount of current through the coil (Figure 9-8).

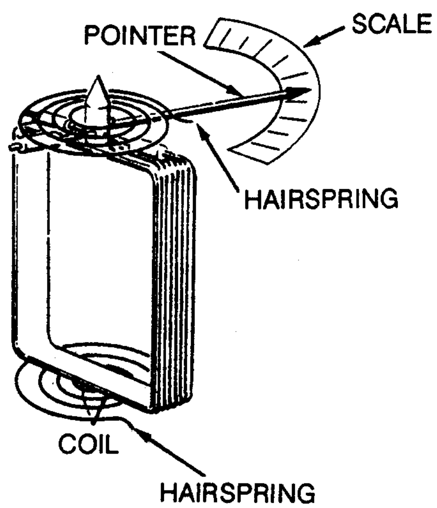


FIGURE 9-8. A Complete Coil.

Two other features are used to increase the accuracy and efficiency of this meter movement. First, an iron core is placed inside the coil to concentrate the magnetic fields. Second, curved pole pieces are attached to the magnet to ensure the turning force on a coil increases steadily as the current increases. These same curved pole pieces are found in a motor.

Figure 9-9 shows the meter movement as it appears when fully assembled.

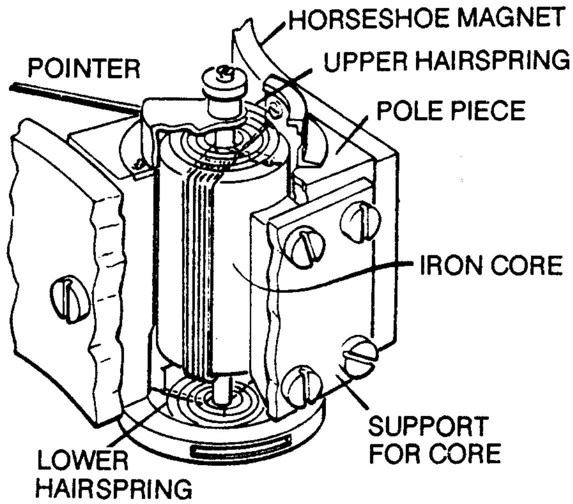


FIGURE 9-9. Assembled Meter Movement.

This permanent magnet moving coil meter movement is the basic movement in most analog (meter with a pointer indicator hand) measuring instruments. It is commonly called d'Arsonval movement because it was first employed by the Frenchman d'Arsonval in making electrical measurements. Figure 9-10 is a view of the d'Arsonval meter movement used in a meter.

Compass and Alternating Current

Up to this point, only DC examples have been used. Figure 9-11 illustrates what happens when AC is used. It shows a magnet close to a conductor carrying AC at a frequency of 1 hertz. The compass needle swings toward the east part of the compass (down) as the current goes positive (view A). (The lower portion of the figure shows the sine wave of the current.) In view B, the current returns to zero, and the compass needle returns to magnetic south (right). As the current goes negative (view C), the compass needle swings toward the west portion of the compass (up). The compass needle returns to magnetic south as the current returns to zero (view D).

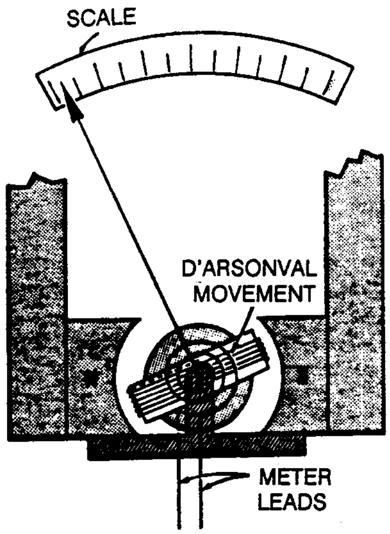


FIGURE 9-10. A Meter Using d'Arsonval Movement.

This cycle of current going positive and negative and the compass swinging back and forth will continue as long as AC is in the conductor.

If the AC frequency is increased, the compass needle will swing back and forth at a higher rate of speed. At a high enough frequency, the compass needle will not swing back and forth, but simply vibrate around the magnetic north position. This happens because the needle cannot react fast enough to the very rapid current alternation. The compass (a simple meter) will indicate the average value of the AC as zero. A device known as a rectifier is needed to let the compass react to the AC in a way that can be useful in measuring the current.

A rectifier is a device that changes AC to a form of DC. Figure 9-12 shows that an AC passing through a rectifier will come out as a pulsating DC.

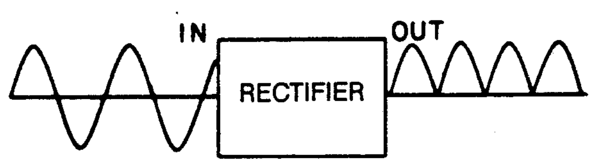


FIGURE 9-12. Rectifier Action.

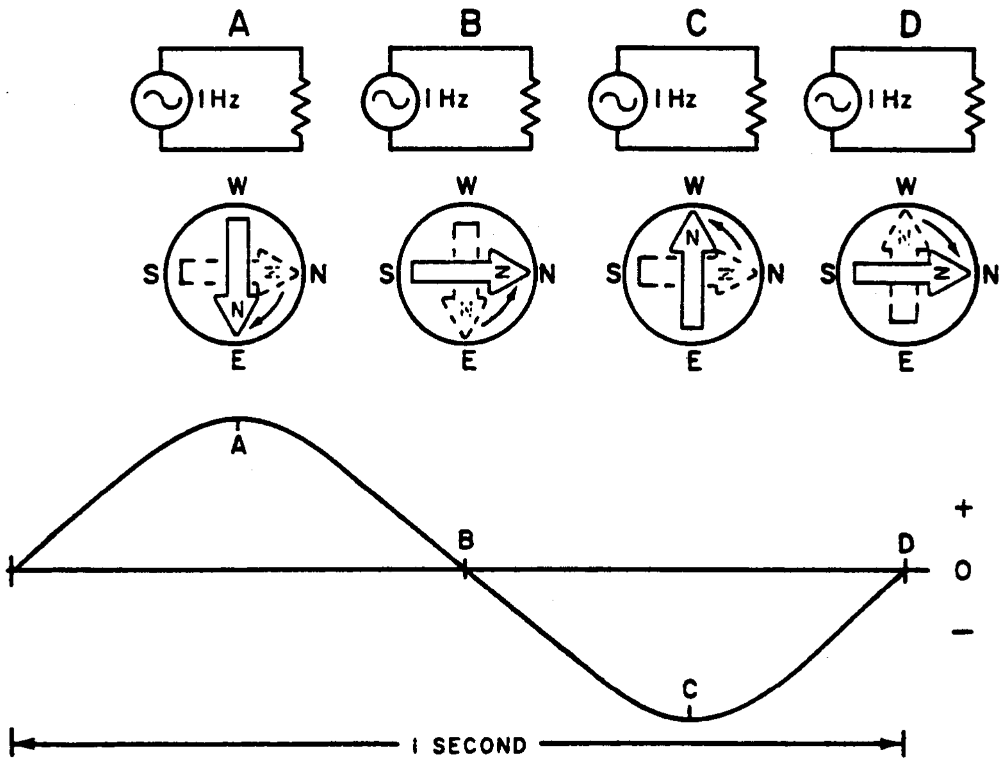


FIGURE 9-11. Compass and Conductor With Alternating Current.

Figure 9-13 shows what happens to the compass. When the compass is placed close to a wire and the frequency of the AC is high enough, the compass will vibrate around a point that represents the average value of the pulsating DC.

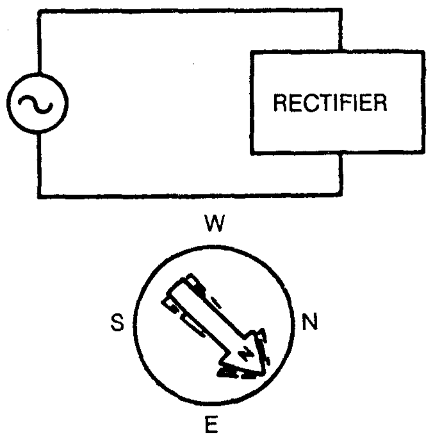


FIGURE 9-13. Compass and Conductor, Rectified AC.

Connecting a rectifier to a d'ArsonvaI meter movement creates an AC measuring device. When AC is converted to DC, the d'Arsonval movement will react to the average value of the pulsating DC, which is the average value of one-half of the AC sine wave. A d'Arsonval meter movement can indicate current in only one direction. If the d'Arsonval meter movement were used to indicate AC without a rectifier or DC of the wrong polarity, the movement would be severely damaged. The pulsating DC is current in a single direction, so the d'Arsonval meter movement can be used as long as proper polarity is observed.

Another problem encountered in measuring AC is that the meter movement reacts to the average value of AC. The value used when working with AC is the effective value (rms value). Therefore, a different scale is used on an AC meter. The scale is marked with the effective value, even though it is the average value to which the meter is reacting. That is why an AC meter will give an incorrect reading if used to measure DC.

OTHER METER MOVEMENTS

The d'Arsonval meter movement (permanent magnet moving coil) is only one type of meter movement. Many other mechanical devices react to electrical movement. The electrodynamics meter movement and the moving-vane meter movements also work on the principle of magnetism.

THERMOCOUPLES

Chapter 2 described how an EMF could be developed from heat. As the dissimilar metals increased in temperature, the EMF increased proportionally. When an external circuit was connected to the dissimilar metals, current flow was established. During this process the thermocouple monitors temperature.

Many Army vessels use the thermocouple to monitor the main propulsion engine cylinder firing temperatures. Rather than have the meter face calibrated in current or voltage values, the meter face is calibrated in degrees Fahrenheit. As the cylinder temperature increases, there is an increase in current flow through the thermocouple. The current flow and temperature are directly proportional and will increase and decrease together.

AMMETERS

An ammeter is a device that measures current. Since all meter movements have some resistance, a resistor will be used to represent a meter in the following explanations. DC circuits will be used for simplicity of explanation.

Multimeter Ammeters Connected in Series

In Figure 9-14 view A, R1 and R2 are in series. The total circuit current flows through both resistors. The total circuit resistance Rt is —

$$Rt = R1 + R2$$

In view B, R1 and R2 are in parallel. The total circuit current does not flow through either circuit. The total circuit resistance Rt is —

$$Rt = \frac{R1 \times R2}{R1 + R2}$$

If R1 represents an ammeter, the only way in which total current will flow through the meter (and thus be measured) is to have the meter (R1) in series with the circuit load (R2), as shown in view A.

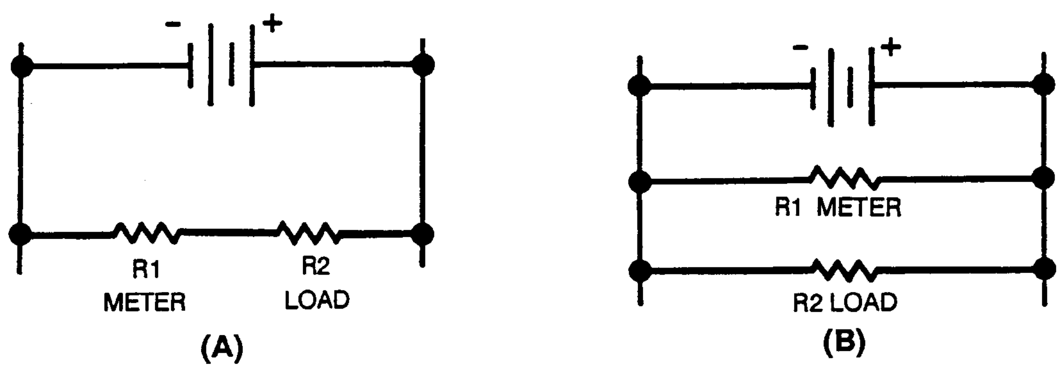


FIGURE 9-14. A Series and a Parallel Circuit.

In complex electrical circuits, you are not always interested in the total circuit current. You may be interested in the current through a particular component. In any case, an ammeter is always connected in series with the circuit that will be tested. Figure 9-15 shows various circuit arrangements with ammeters properly connected for measuring current in various portions of the circuit.

Connecting a multimeter ammeter in parallel with one of many electrical loads would give an incorrect reading. In this situation, current would be divided between the resistance in the loads and the very low resistance in the ammeter. It would not give the true total current moving through that section of the circuit.

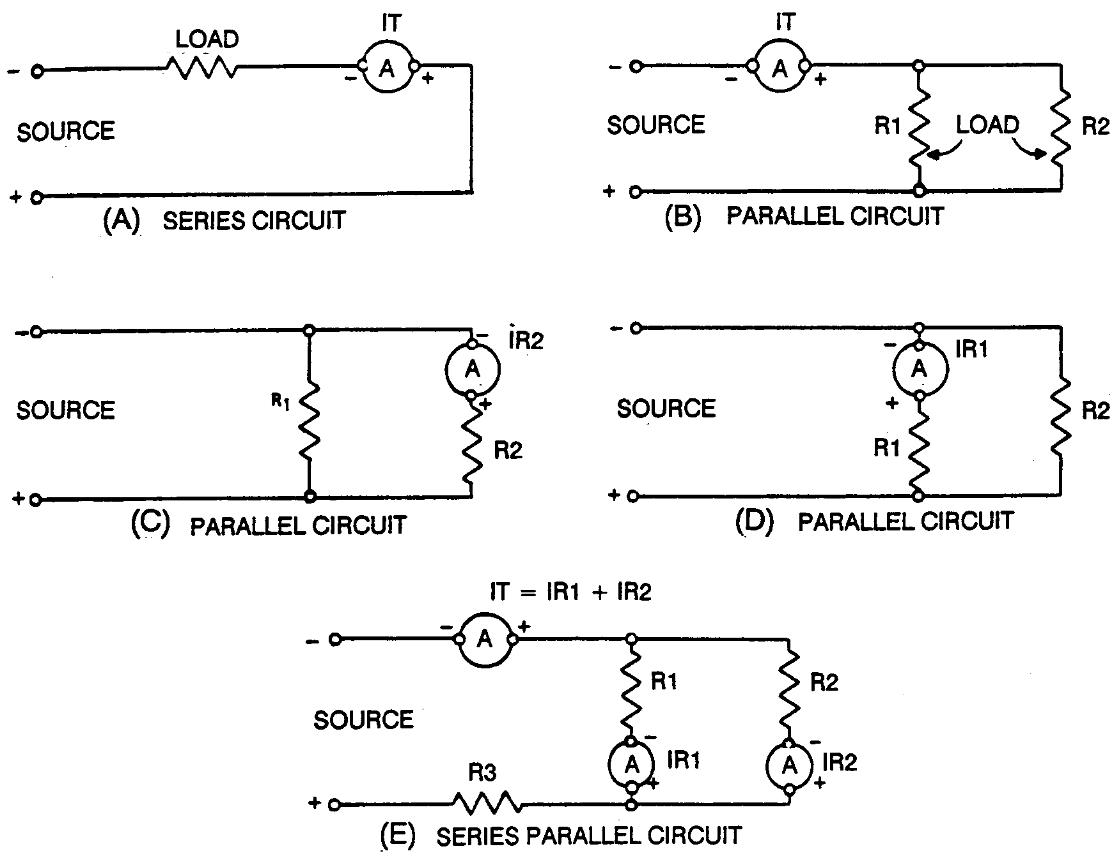


FIGURE 9-15. Proper Ammeter Connections.

Should the multimeter ammeter be connected across a constant potential source, such as the generator terminals, the minimal resistance in the ammeter would not be sufficient to restrict the majority of the generator's total current. This would be the equivalent of a shorted circuit. The excessive current draw through the meter movement would damage the meter. It may not be apparent at first, but if the ammeter is connected in parallel, across a higher resistance electrical load, a shorting situation results. Figure 9-16 shows a circuit. Figure 9-17 shows what happens when a meter is connected across the high-resistance load. Even though current is proportionally divided between the meter and the load in a parallel circuit, the extreme difference in resistance will put most of the generator's available current through the meter. The total resistance (Rt) in a parallel circuit is always less than the smallest resistor. With less resistance in the circuit, an increased current will be delivered. Note the change in total current (It) from the initial circuit in Figure 9-16 to the total current in Figure 9-17 with the addition of the improperly placed meter.

FIGURE 9-16. Initial Circuit.

Et = 450 volts

Rt = ?

It = ?

E1 = 450 volts

R1 = 500 ohms

I1 = ?

(R1 represents the electrical system loads. There is no meter connected in the circuit above.)

Rt = R1

Rt = 500 ohms

$$It = \frac{Et}{Rt} = \frac{450 \text{ volts}}{500 \text{ ohms}}$$

It = .9 amps

The high circuit resistance keeps current from the generator down. Figure 9-17 shows the ammeter placed <u>improperly</u> in the circuit.

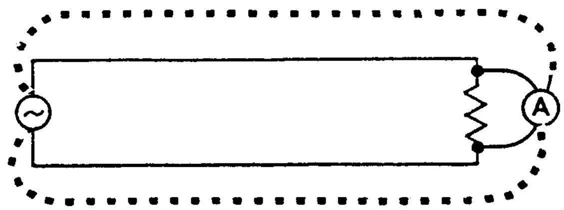


FIGURE 9-17. Improperly Placed Ammeter in Circuit.

Et = 450 volts

Rt = ?

It = ?

E1 = 450 volts

R1 = 500 ohms

I1 = ?

Ea = 450 volts

Ra = 4 ohms

Ia = ?

Figure 9-17 shows the meter incorrectly connected across a constant potential source. To say that the meter is connected only in parallel with the load can be misleading. For all electrical purposes, the meter is connected directly to the generator terminals (dotted lines). Current takes the path of least resistance. In this situation, the generator current flow will respond to the minimal resistance of the meter and increase its current output.

The new total resistance (Rt) of the circuit is found as follows:

$$Rt = \frac{R1 \times Ra}{R1 + Ra}$$

$$Rt = \frac{500 \text{ ohms} \times 4 \text{ ohms}}{500 \text{ ohms} + 4 \text{ ohms}}$$

$$Rt = 3.97 \text{ ohms}$$

The total resistance of this circuit has changed from 500 ohms to 3.97 ohms. With this drastic change in circuit resistance, generator current flow will increase accordingly:

$$It = \frac{Et}{Rt}$$

$$It = \frac{450 \text{ volts}}{3.97 \text{ ohms}}$$

$$It = 113.4 \text{ amps}$$

Use the circuit rules and Ohm's Law to determine how this new current is divided between the load and the meter:

The load:

$$I1 = \frac{E1}{R1}$$

$$I1 = \frac{450 \text{ volts}}{500 \text{ ohms}}$$

$$I1 = .9 \text{ amps}$$

The current through the load has not changed.

The ammeter:

$$Ia = \frac{Ea}{Ra}$$

$$Ia = \frac{450 \text{ volts}}{4 \text{ ohms}}$$

$$Ia = 112.5 \text{ amps}$$

There is an excessive current flow through the meter.

Whenever you connect the ammeter portion of the multimeter, always break the circuit and connect your meter in series with the load. The small resistance of the meter is now added to the total electrical system loads (Rt) and will only serve to slightly decrease the total generator current output.

In-Circuit Ammeters Connected in Parallel

This section explains how in-circuit meters are connected in parallel for correct meter readings. This is another example of real-life applications of electrical circuit rules.

The ammeter in the instrument panel of the landing craft mechanized and the ammeters of many larger vessels are not designed to interrupt the electrical system they are monitoring. A device known as a shunt or parallel path is used. Physically small meters, monitoring hundreds of amperes, could not withstand that amount of current without burning up their meter movements. The shunt is a calibrated parallel path that allows the majority of current to bypass the meter. A shunt is a relatively heavy-gauge copper bar (Figure 9-18), readily able to conduct a great amount of current flow. The meter and the shunt are calibrated to each other so that the meter reacts to changes in current accurately. The shunt is always of a lesser resistance than the meter. Figure 9-18 shows how the shunt and ammeter are connected in the circuit.

If either the meter or the shunt are replaced separately, a component with the exact characteristics and ohmic value must be ensured. If an ammeter or shunt of a differing value is installed, the meter reading would not be accurate. It would change the relationship between the meter and its parallel path. Otherwise, the meter may actually show a system charging properly when, in actuality, the system is deficient.

Ammeters are also connected to current transformers so that the current through the meter maybe reduced accordingly. The same rules apply for replacing these current transformers and their meters that apply to the ammeter and its shunt.

Chapter 8 discusses the principles of current and voltage transformation.

Effects on Circuit Being Measured

The ammeter affects the operating characteristics of the circuit. When the meter is installed, the generator's total current (It) changes accordingly.

The current and voltage potential produced in the vessel's ship service generators are of such a large and deadly amplitude that a meter normally has minimal overall effects on the distribution system. However, like all components, devices, or conductors in the system, accumulative effects can be achieved. Conductor length, improper or corroded connections, and the introduction of meters (all otherwise insignificant loads) can contribute to an increased circuit resistance overall. For this reason, meter connections, as well as all device connections, must be made correctly to ensure conclusive troubleshooting practices. Under normal circumstances, the introduction of meters into a circuit is only a concern when printed circuitry is addressed.

Ammeter Sensitivity

Ammeter sensitivity is the amount of current necessary to cause full-scale deflection (maximum reading) of the ammeter. The smaller the amount of current, the more sensitive the ammeter. For example, an ammeter with a maximum current reading of 1 milliampere would have a sensitivity of 1 milliampere. It would be more sensitive than an ammeter with a maximum reading of 1 ampere and a sensitivity of 1 ampere. Sensitivity ears be given for a meter movement, but ammeter sensitivity usually refers to the entire ammeter and not just the meter movement.

Range Selection

Today's meters are extremely sensitive to the ranges and types of currents tested. Before any range selection is ever made, determine whether the circuits are alternating or direct current circuits. If the incorrect type of current is chosen, the meter will become damaged, or its fuse will open (blow). In either case, the meter will be rendered ineffective.

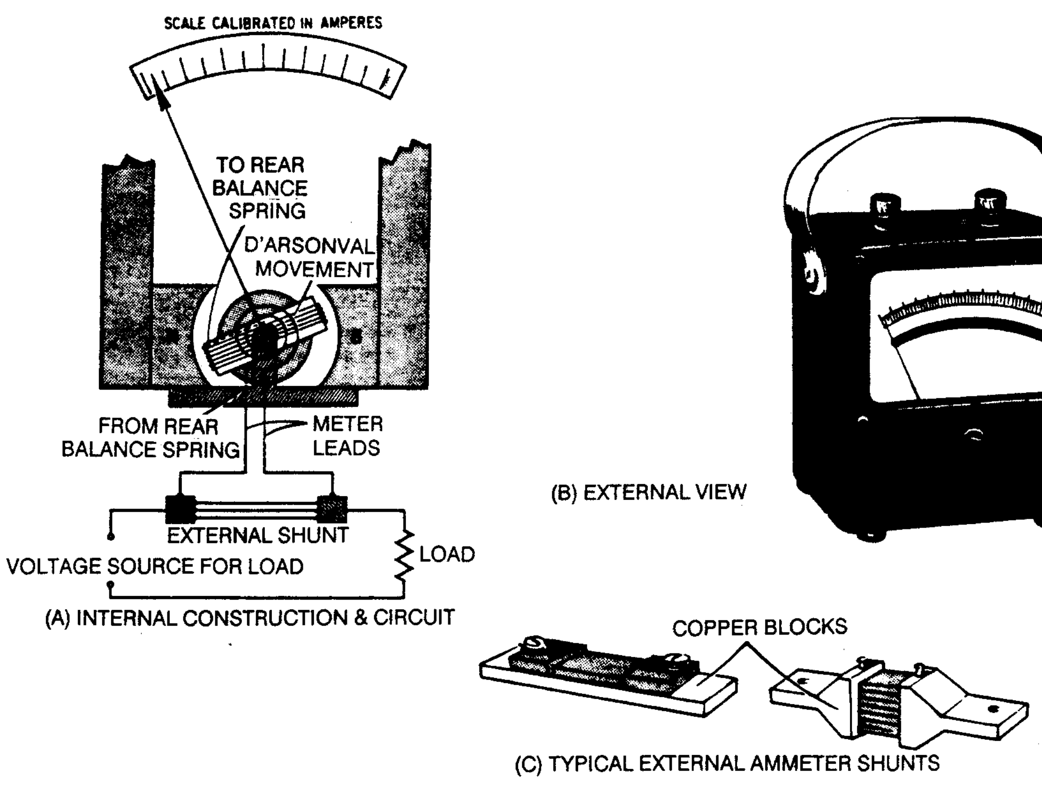


FIGURE 9-18. An Ammeter Using the External Shunt.

The range switch is another very important part of the meter. To use the meter correctly, the range must be properly selected. If the current to be measured is larger than the meter scale selected, the meter movement will have excessive current and may become damaged. Therefore, it is important to always start with the highest range when using any meter.

If current can be measured on several ranges, use the range that results in a reading near the middle of the scale (Figure 9-19). This is important enough for digital meters to use bar graphs to indicate what percentage of the meter scale is in use.

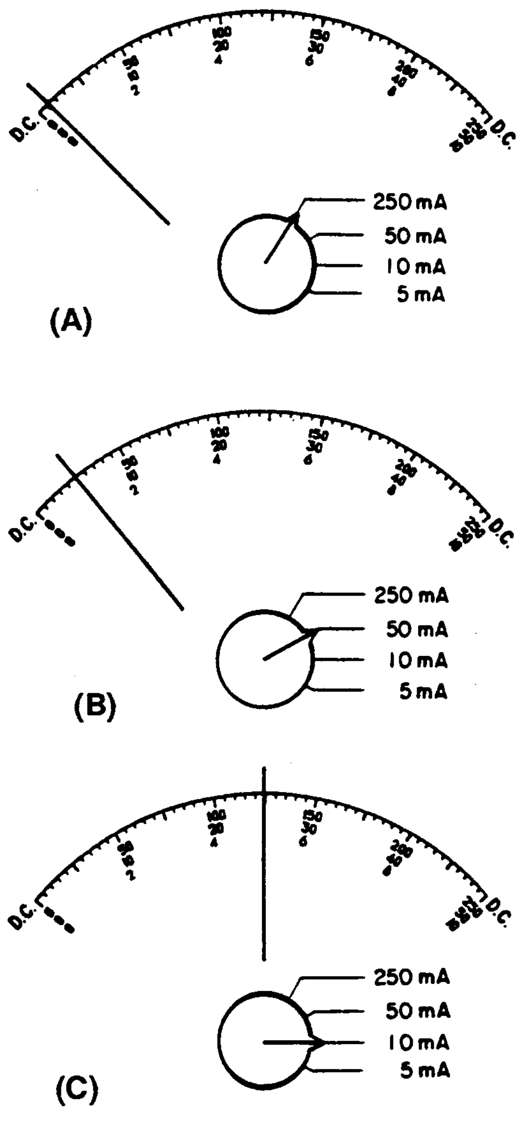


FIGURE 9-19. Reading an Ammeter at Various Ranges.

Clamp-on Ammeter

The clamp-on ammeter (Figure 9-20) may be of the digital or the analog (movable needle) type. This meter is restricted to AC circuits. At the top of the meter is a set of jaws used to surround the wire being tested. The beneficial part of this meter is its ability to operate by detecting the magnetic field generated by the current moving in the conductor. This ability prevents the circuit from being opened and having to physically insert the meter. Current readings can also be taken from easily accessible locations in the circuit.

The clamp-on ammeter operates on the same principle that the transformer uses. The jaws of the ammeter are clamped around the conductor. The current-carrying conductor of the circuit being tested represents the primary winding. The jaws of the ammeter are the secondary winding. The current moving through the circuit generates its own magnetic field that surrounds the conductor. This AC magnetic field can induce a voltage and resulting current flow in the jaws of the ammeter.

The greater the current through the circuit conductor, the greater the magnetic field surrounding that conductor. Increased induction between the conductor and the ammeter means a greater current reading on the ammeter.

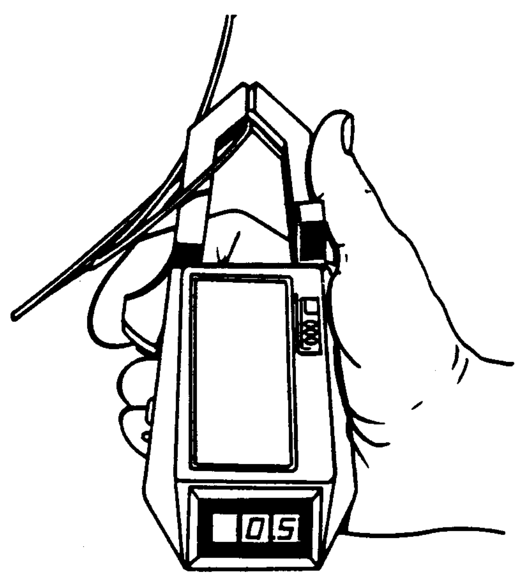


FIGURE 9-20. Clamp-On Ammeter or Induction Ammeter.

The conductor does not need to have the insulation stripped back. The only requirements for clamp-on ammeters are –

- The induction ammeter may only be used on AC systems. The DC electrical system does not have a constantly changing field. Therefore, without relative motion between the magnetic field of the conductor and the jaws of the induction ammeter, it is impossible to induce an EMF in the meter movement.

- The ammeter must measure one conductor at a time. If the ammeter jaws are encircling both wires of a two-wire electrical system, there will be no reading. The current traveling from the power source to the load sets up a magnetic field in one direction. The same current returning to the power supply from the load creates a magnetic field in the opposite direction. These two magnetic fields cancel each other out.

Digital clamp-on ammeters, or induction ammeters, are provided with a peak hold setting. This lets the user have the highest transient current reading displayed and maintained for a period of time. This becomes very important in electrical systems because of the fluctuating currents when motors are started.

When checking a circuit where the value of current is far below the lowest reading on the meter scale, the wire can be looped around the jaws of the ammeter. Doubling the conductor passes through the meter jaws doubles the magnetic field strength (Figure 9-21). Since only one wire is used, the current is traveling in the same direction and the magnetic field is doubled. Divide the meter reading by two. This also applies when looping the conductor any number of times through the jaws of the ammeter. Simply divide the current reading by the number of loops for the actual conductor current. This is an important concept because this type of setup is used in the current transformers of switchboards in Army Ships.

Ammeter Safety Precautions

When using an ammeter, certain precautions must be observed to prevent injury to yourself and others and to prevent damage to the ammeter or the equipment being serviced. The following list contains the minimum safety precautions for using an ammeter:

- Always connect multimeter ammeters in series with the circuit under test.

- Always start with the highest range on an ammeter (or any meter).

- De-energize and discharge the circuit completely before connecting or disconnecting the ammeter.

- In DC ammeters, observe the proper circuit polarity to prevent the meter from being damaged.

- Never use a DC ammeter to measure AC.

- Observe the general safety precautions of electricity.

- Ground all metal case meters to the hull of the ship. Many old metal case meters provide a grounding jack for this purpose.

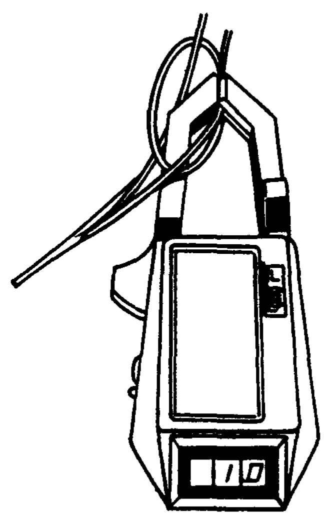


FIGURE 9-21. Ammeter Induction Effects Increased.

VOLTMETERS

The voltmeter measures the voltage in a circuit or any EMF-producing component. The meter more accurately measures any difference in potential between any two places to which the meter leads are connected.

Voltmeters Connected in Parallel

Ammeters or their shunts are always connected in series with the electrical load. Voltmeters are always connected in parallel. Figure 9-22 and the following figures use resistors to represent the voltmeter movement. Since a meter movement can be considered as a resistor, the concepts shown are true for voltmeters and resistors. For simplicity, DC circuits are shown, but the principles apply to both AC and DC voltmeters.

When a voltmeter is connected across or parallel to a load, the measurement value indicates how much of the voltage was used up pushing current through the electrical load. Voltage is easily referred to as difference in potential here. Connecting the voltmeter across the terminals of a generator measures the difference in potential or the difference between the area where negative electrons are, as opposed to the area where they are not (the area of positive ions). If the same combination of negative electrons and positive ions were at each terminal of the generator, then there would be no difference in potential, or zero voltage.

To have a difference in potential, there must be an electron imbalance somewhere. When a generator is operating properly, negative electrons are excited. The negative electrons leave their atoms and accumulate atone terminal of the generator. Positive ions accumulate at the other terminal. Both these electrical particles have opposite magnetic polarities. As long as the generator keeps operating, the only way these negative electrons can recombine with the positive ions is through the electrical distribution system. Voltage is a measurement of how great the difference in potential is. The greater the difference in potential, the greater the force available to push the electrons to the positive ions.

When a load is placed in the circuit, its resistance determines how many electrons will be able to leave the negative terminal during any given period of time. Since a quantity of electrons exists on each side of the load, the difference between them is the difference in potential dropped from the original generator voltage source. If there is a high resistance, such as an open condition, then there would be maximum electrons on one side of the load, and no electrons on the other side of the load. This would be a maximum voltage reading. A negligible resistance, such as a good fuse, would have the same amount of electrons on each side of the fuse element. There would then be no difference in potential and 0 voltage reading.

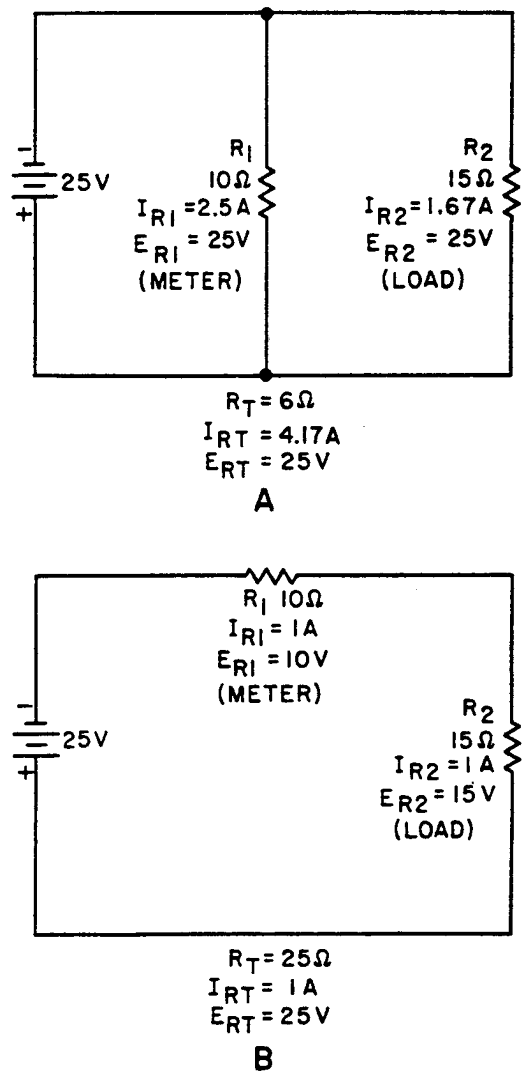


FIGURE 9-22. Current and Voltage in Series and Parallel Circuits.

A good example of this is the series circuit in Figure 9-23, which shows two loads in series with the generator. Place a voltmeter across the R2 load. Measure the difference in potential between the negative side of the R2 load and the positive side of the R2 load.

Et = 120 volts

Rt = ?

It = ?

R1 = 10 ohms

I1 = ?

E1 = ?

R2 = 20 ohms

I2 = ?

E2 = ?

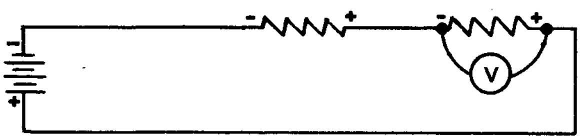


FIGURE 9-23. Voltage Drops.

To determine the electrical values, find the total resistance of the circuit (Rt):

Rt = R1 + R2

Rt = 10 ohms + 20 ohms

Rt = 30 ohms

Since this is a series circuit and current is constant, find the total current (It) allowed to flow through the circuit in one second:

$$It = \frac{Et}{Rt}$$

$$It = \frac{120\ volts}{30\ ohms}$$

It = 4 amps

Do not be concerned with the minimal influence the meter has on the circuit, but transcribe the current value to 11 and 12.

Using the voltmeter, there is a reading of 80 volts across the R2 resistance. By using Ohm's Law, verify this reading:

E2 = I2 x R2

E2 = 4 amps x 20 ohms

E2 = 80 volts

This is the difference in potential across the R2 resistance. When the meter is repositioned to read the voltage across R1, a difference in potential between the negative side and the positive side of the resistance is registered. In this case, there are 40 volts. Figure 9-24 effectively shows the differences in potential.

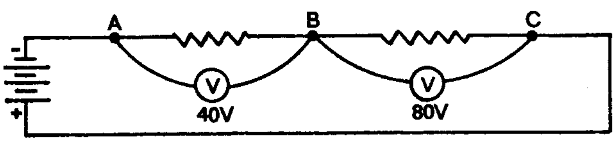


FIGURE 9-24. Differences in Potential.

SOURCE	**120 V**	**80 V**	**0 V**
VOLTAGE	**A**	**B**	**C**

R1	**R2**
120 - 80 = 40	**80 - 0 = 80**

At point A, there is full generator voltage available (120 volts). At point B, 80 volts are left. This means that the R1 resistance was sufficient enough to use up, or drop out of the circuit, 40 volts when moving 4 coulombs of electrons through the 10-ohrn resistance in one second. At point C, no voltage is left after completing all the work pushing electrons through the resistances. The voltmeter does not read the points A or B or C, but rather a difference between points A and B as well as between points B and C. Since voltage is the potential force and a difference between each side of a resistor exists, a difference in the potential (or voltage) is recorded.

Sensitivity of Voltmeters

Voltmeter sensitivity is expressed in ohms per volt (ohms/volt). It is the resistance of the voltmeter at full-scale reading in volts. Since the voltmeter's resistance does not change with the position of the pointer, the total resistance of the meter is the sensitivity multiplied by the full-scale reading. The higher the sensitivity of a voltmeter, the higher the voltmeter's resistance. Since high-resistance voltmeters have less loading effects on circuits, a high-sensitivity meter will provide a more accurate voltage reading.

Voltmeter Safety Precautions

Just as with ammeters, voltmeters require safety precautions to prevent injury to personnel and damage to the voltmeter or equipment. The following is a list of the minimum safety precautions for using a voltmeter:

- Always connect voltmeters in parallel.
- Always start with the highest range of a voltmeter.
- In DC voltmeters, observe the proper circuit polarity to prevent damage to the meter.
- Never use a DC voltmeter to measure AC voltage.
- Observe the general safety precautions of electricity.

OHMMETERS

The two instruments most commonly used to measure resistance are the ohmmeter and the megohmmeter (megger).

The ohmmeter is widely used to measure resistance and check the continuity of electrical circuits and components. Using an ohmmeter to determine continuity provides the engineer with information on the circuit's ability to conduct current. The ohmmeter is inaccurate below the 3- to 5-ohm level. Its range usually extends to only a few megohms.

The megger is widely used for measuring insulation resistance, such as between a wire and another surface on the other side of the insulation. The range of a megger extends to more than 1,000 megohms.

The ohmmeter consists of a DC ammeter, with a few added features. The added features are a DC source of potential (usually a 9-volt battery) and one or more resistors (one of which is variable). Figure 9-25 shows a simple ohmmeter circuit.

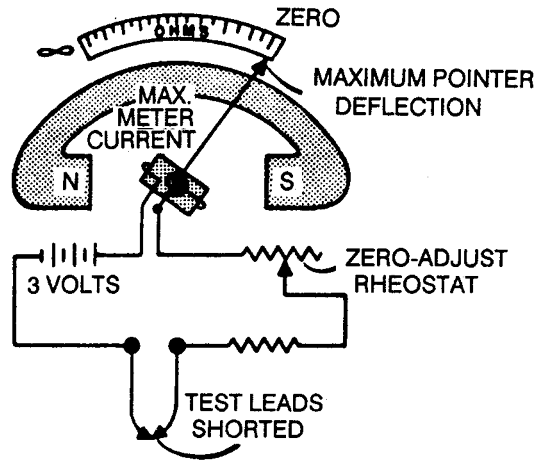


FIGURE 9-25. Simple Ohmmeter Circuit.

The ohmmeter's pointer deflection is controlled by the amount of battery current passing through the moving coil. Before measuring the resistance of an unknown resistor or component, the test leads of the ohmmeter are first shorted together (Figure 9-25), With the leads shorted, the meter is calibrated for proper operation on the selected range. Whale the leads are shorted, meter current is maximum, and the pointer deflects a maximum amount, somewhere near the zero on the ohms scale. Consult the manufacturer's manual to zero the ohmmeter. The AN/PSM-45 and AN/PSM-45A digital multimeter calibrates automatically when the test leads are shorted together. Analog meters have a variable resistor (rheostat) that requires manual adjustment to zero (with the test leads shorted together). When the test leads are separated, the meter should indicate infinity, or the meter's maximum resistance reading. Always turn the ohmmeter off when it is not in use to prevent the leads from accidentally discharging the meter battery.

Ohmmeter Use

After the ohmmeter is adjusted for zero reading, it is ready to be connected in a circuit to measure resistance. Figure 9-26 shows a typical circuit and ohmmeter arrangement.

The circuit must always be de-energized. This prevents the source voltage from being applied across the meter, which could damage the meter movement.

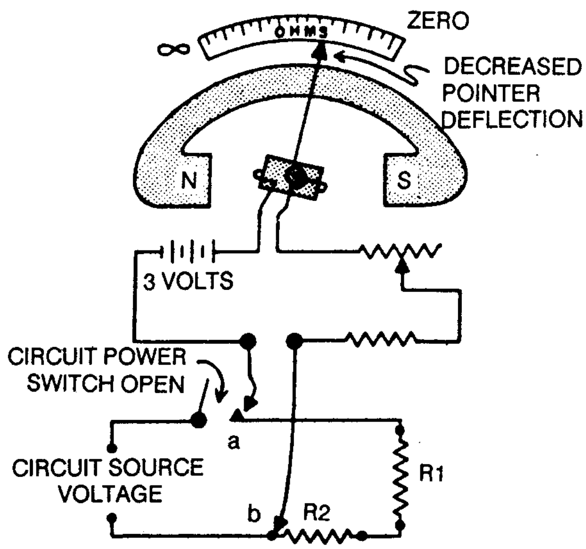


FIGURE 9-26. Measuring Circuit Resistance With an Ohmmeter.

The test leads of the ohmmeter are connected in series with the circuit to be measured (Figure 9-26). This causes the current produced by the 9-volt battery of the meter to flow through the circuit being tested. Assume that the meter test leads are connected at points a and b of Figure 9-26. The amount of current that flows through the meter coil will depend on the total resistance of resistors R1 and R2 and the resistance of the meter. Since the meter has been preadjusted (zeroed), the amount of coil movement now depends entirely on the resistance of R1 and R2. The inclusion of R1 and R2 raises the total series resistance, decreasing the current, and thus decreasing the pointer deflection. The pointer will now come to rest as a scale figure indicating the combined resistance of R1 and R2. If R1 and R2, or both, were replaced with resistors having a larger value, the current flow in the moving coil of the meter would be decreased further. The deflection would also be further decreased, and the scale indication would read a still higher circuit resistance. Movement of the moving coil is proportional to the amount of current flow.

When using an ohmmeter in complicated circuits, the circuit must be disconnected at the component being checked. If other parallel paths are accidentally measured with the ohmmeter, the resistance reading will be less than the smallest resistance, providing an incorrect interpretation of the test results.

Ohmmeter Ranges

The amount of circuit resistance to be measured may vary over a wide range. In some cases, it may only be a few ohms; in others, it may be as great as 1,000,000 ohms (1 megohm). To enable the meter to indicate any value being measured with the least error, scale multiplication features are used in most ohmmeters. There are various scale indicators for checking diodes and capacitors as well. The many different meters require the specific information attained from their technical manual. TM 11-6625-3199-14 is the reference for the AN/PSM-45A multimeter. This is required reading before trying to operate this multimeter.

Ohmmeter Safety Precautions

The following safety precautions and operating procedures for ohmmeters are the minimum necessary to prevent injury and damage:

- Be certain the circuit is de-energized and discharged before connecting an ohmmeter.
- Do not apply power to a circuit while measuring resistance.
- When finished using the ohmmeter, switch it to the OFF position.
- Always adjust the ohmmeter for zero after you change ranges and before making resistance measurement.

MEGOHMMETER

An ordinary ohmmeter cannot be used for measuring resistance of multimillions of ohms, such as in conductor insulation. To adequately test for insulation breakdown, it is necessary to use a much higher potential than is furnished by the battery of an ohmmeter. An instrument called a megohmmeter (megger) is used for these tests. The megger is the most useful engineering tool for determining the condition of electrical insulation. Thus, it determines the condition of the electrical component and possible future operational readiness of the vessel.

In catastrophic cases, the insulation is burned off the conductor by excessive current heat. In this case, the component requires replacement. More often, the component insulation resistance is slowly reduced over a period of months. Proper monitoring of the major electrical components will provide information on the expected servicing requirements for the device. In this manner, major component maintenance can be projected ahead of time, instead of managed by crisis.

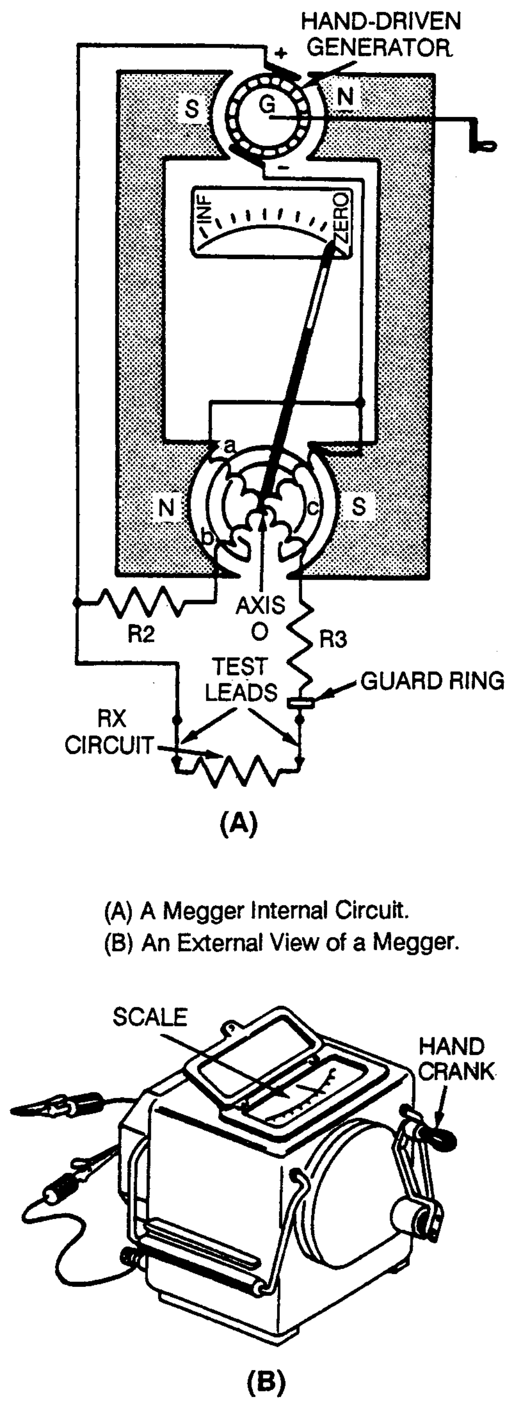
Megger Construction

The megger (Figure 9-27) is a portable instrument that consists of two primary elements:

- A hand- or electric-driven DC generator (G). This supplies the necessary voltage for making the measurement.
- The instrument portion, which indicates the value of the resistance being measured.

The instrument portion is the opposed coil type, as shown in view A. Coils a and b are mounted on the movable member c, with a fixed relationship to each other, and are free to turn as a unit in a magnetic field. Coil b tends to move the pointer counterclockwise, and coil a tends to move the pointer clockwise.

Coil a is connected in series with R3 and the unknown resistance, Rx, to be measured. The combination of coil, R3, and Rx forms a direct series path between the positive (+) and negative (-) brushes of the DC generator. Coil b is connected in series with R2, and this combination is also connected across the generator. There are no restraining springs on the movable member of the instrument portion of the megger. Therefore, when the generator is not operated, the pointer floats freely and may come to rest at any position of the scale. When checking the megger for proper operation, isolate the two megger leads from each other. Crank or operate the megger. There should be a maximum resistance or infinite resistance reading. Next, connect the two megger test leads to each other and operate the megger. The meter should indicate zero resist ante. Do not touch the megger leads when the megger is being operated.



(A) A Megger Internal Circuit.
(B) An External View of a Megger.

FIGURE 9-27. Megohmmeter.

Megger Ratings

Army meggers are rated at 500 and 1,000 volts. To avoid excessive test voltages, most meggers are equipped with friction clutches. When the megger is cranked faster than its rated speed, the clutch slips, and the generator speed and output voltage are not allowed to exceed their rated value. When extremely high resistances (for example, 10,000 megohms or more) are to be measured, a high voltage is needed to cause sufficient current to flow to actuate the meter movement. For extended ranges, a 1,000-volt megger is available. Usually, meggers are only used on circuits with a normal voltage of 100 volts and up. When testing insulation, always refer to the appropriate TM or the manufacturer's recommendations.

Megger Use

Motor windings and components are tested to ensure that the conductors are not coming in direct contact with their housing, frame, or other individual conductor turns because the insulation has been damaged. The difference in potential, provided by the 9-volt ohmmeter battery, may not be substantial enough to correctly indicate an insulation problem in a 450-volt electrical system. The 9-volt push may not be sufficient to bridge some damaged insulation. There would then bean indication of infinite (maximum ohms) resistance. What appears to be an acceptable insulation reading would, in fact, be inconclusive. The higher voltage of the 450-volt electrical system would have no trouble bridging the gap in the damaged insulation. The megger, available in 500- and 1,000-volt power supplies, would detect this damage in the insulation and measure the resistance required when pushing the current past the damaged section of insulation. The megger provides an accurate indication of electrical insulation under system operating conditions.

The ohmmeter does not allow a conclusive test for conductor insulation. This is because the small potential in the ohmmeter is not sufficient to force electrons across small distances or high-resistance insulation. For this same reason, the megger is not suitable for testing the continuity of a conduct or. The higher potential of the megger would allow completed circuit readings where the low potential ohmmeter would detect defects in conductor continuity. The megger and the ohmmeter should always be used together when substantiating the condition of electrical components.

Megger Testing

Many regulatory texts require the periodic testing of insulation. The Institute of Electrical and Electronic Engineers requires the additional testing of idle apparatus. A log book will be maintained for these megger resistance readings. As equipment ages and becomes contaminated with grease and dirt, the resistance of the insulation decreases. When these decreases in resistance are noted, preventive maintenance can be planned. Sometimes, cleaning alone will restore the insulation dielectric strength and return the component to operational condition. It is recommended that all major electrical components over 100 volts be megger tested every two years. Generators and critical electric motors can be megged before missions to evaluate and project their future operating condition.

As with the ohmmeter, the megger is never used on an energized circuit. Additionally, the megger is never used on a circuit in which solid state components cannot be isolated. The high potential of the megger will destroy rectifiers, voltage regulators, radio equipment, and other electronic equipment. Make sure that the electrical component undergoing testing is completely isolated from the rest of the circuit.

One megger test lead is connected to the de-energized conductor. The other megger test lead is connected to the noncurrent-carrying conductive material adjacent to the conductor's insulation. To test a cable, one test lead would go to the de-energized normally current-carrying copper conductor of a cable, and the other test lead would be connected to the noncurrent-carrying armor shielding. In another example, a megger lead could be connected to a motor winding lead, and the other megger test lead could be connected to the motor housing. In both of these cases, there should be no continuity. There should be a great deal of resistance between the current-carrying conductor and the housing with which the engineer is likely to come in contact.

The megger is then operated for a period of at least 30 seconds. Refer to the component manufacturer's information for the specific results of a test. However, if these specifications are no longer available, any change in the insulation resistance must be considered suspect.

Megger Safety Precautions

When using a megger, observe the following minimum safety precautions to prevent injury to personnel or damage to the equipment:

- Use meggers on high-resistance measurements only, such as insulation measurements.
- Never touch the test leads when the megger is being operated.
- De-energize and discharge the circuit before connecting a megger.
- Disconnect the component being checked from other circuitry before using the megger.
- Use only on circuits with a normal voltage of 100 volts or greater.

MULTIMETER

A multimeter is the most common measuring device in the Army. The name multimeter comes from multiple meter, and that is exactly what it is. It combines a DC ammeter and voltmeter, an AC ammeter and voltmeter, and an ohmmeter.

Digital Multimeters

Several models of digital multimeters have been fielded for use in the Army. Always follow instructions for use in the applicable TMs. Digital multimeters have a display screen and give their readings as numerals on the screen, usually using liquid crystal display (LCD).

Analog Multimeters

Analog multimeters are those with d'Arsonval movements using a needle and scale. Most analog multimeters have been replaced by digital multimeters, but the marine engineman/engineer may still be issued analog multimeters.

Parallax Error

Analog multimeters have a mirror built into the scale to aid in reducing parallax error (Figure 9-28).

Parallax can be a problem when reading analog meters. To prevent improper meter value recognition, a mirror is placed just above the scale. When properly viewing the meter, the reflection of the pointer will not be seen. Although portable analog meters are being phased out, in-circuit analog meters are not. The problem of parallax is nowhere more evident than when paralleling AC generators. Even though some switchboard meters do not have a mirror, a perfect match of the voltage for each generator is required. Each of the two (or more) voltmeters must be viewed directly from the front to confirm exact voltage readings.

FREQUENCY METERS

All AC sources are generated at a set frequency or range of frequencies. A frequency meter provides a means of measuring this frequency. Two common types of frequency meters are the vibrating reed frequency meter and the moving disc frequency meter.

Vibrating **Reed Frequency Meter**

The vibrating reed frequency meter is one of the simplest devices for indicating the frequency of an AC source. It is used on power panels to monitor the frequency of AC. Figure 9-29 is a simplified diagram of one type of vibrating frequency meter.

The current, whose frequency is to be measured, flows through the coil and exerts maximum attraction on the soft iron armature twice during each cycle (Figure 9-29). The armature is attached to the bar, which is mounted on a flexible support. Reeds having natural vibration frequencies of 110, 112, 114 and so on up to 130 hertz are mounted on the bar (view B). The reed having a frequency of 110 herlz is marked 55 hertz. The one with 112 hertz is marked 56 hertz. The one with 120 hertz is marked 60 hertz, and so forth.

When the coil is energized with a current having a frequency between 55 and 65 hertz, all the reeds are vibrating slightly. But the reed having a natural frequency closest to that of the energized current whose frequency is to be measured vibrates more. The frequency is read from the scaled value opposite the reed having the greatest vibration.

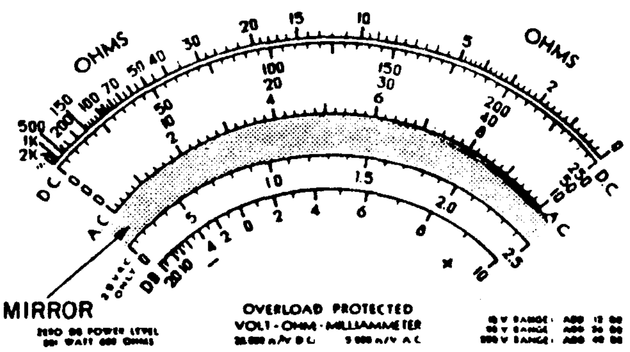


FIGURE 9-28. Analog Multimeter Scale With Mirror.

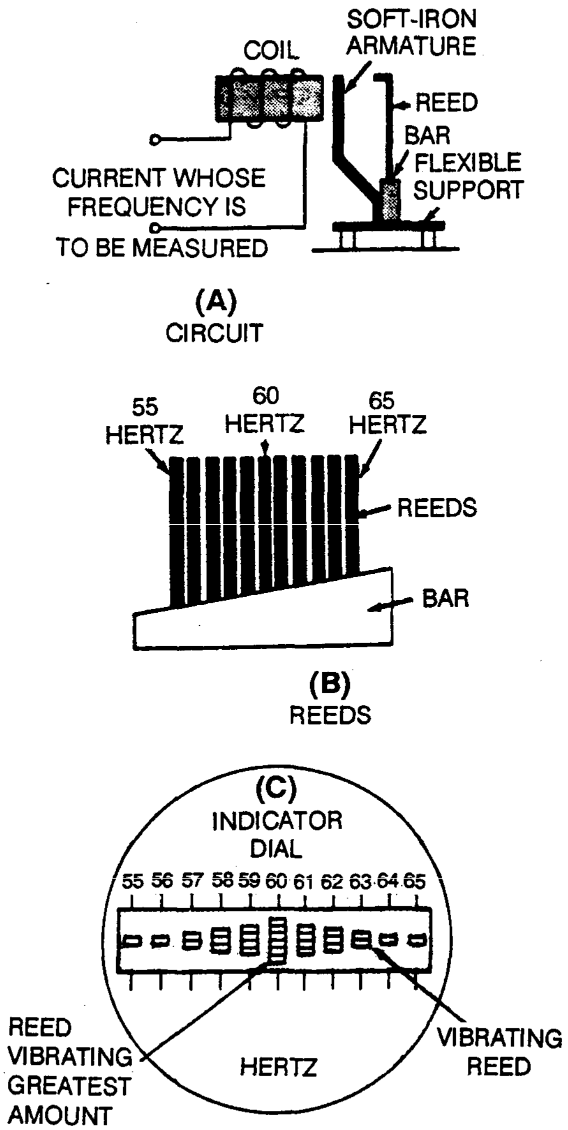


FIGURE 9-29. Simplified Diagram of a Vibrating Reed Frequency Meter.

In some instruments, the reeds are the same lengths but are weighted by different amounts at the top so that they will have different natural rates of vibration.

The indicator dial of Figure 9-29 view C shows an end view of the reeds. If the current has a frequency of 60 hertz, the reed marked 60 hertz will vibrate the greatest amount, as shown.

Moving Disc Frequency Meter

Moving disc frequency meters can be found in out-of-circuit meters as well as in-circuit meters. Figure 9-30 shows a moving disc frequency meter. One coil tends to turn the disk clockwise, and the other, counterclockwise. Magnetizing coil A is connected in series with a large value of resistance. Coil B is connected in series with a large inductance, and the two circuits are supplied in parallel by the source.

For a given voltage, the current through coil A is almost constant. However, the current through coil B varies with frequency. At a higher frequency, the inductive reactance is greater, and the current through coil b is less. The reverse is true at a lower frequency. The disc turns in the direction determined by the stronger coil.

A perfectly circular disc would tend to turn continuously. This is not desirable. Therefore, the disc is constructed so that it will turn only a certain amount clockwise or counterclockwise about the center position, which is commonly marked 60 hertz. To prevent the disk from turning more than the desired amount, the left half of the disk is mounted so that when motion occurs, the same amount of disc area will always be between the pole of coil A.

Therefore, the force produced by coil A to rotate the disk is constant for a constant applied voltage. The right half of the disc is offset, as shown in the Figure 9-30. When the disk rotates clockwise, an increasing area will come between the poles of coil B. When it rotates counterclockwise, a decreasing area will come between the poles of coil B. The greater the area between the poles, the greater will be the disc current and the force tending to turn the disk.

If the frequency applied to the ammeter should decrease, the reactance offered by L would decrease, and the field produced by coil B would increase. The field produced by coil A would remain the same. Thus, the force produced by coil B would tend to move the disk and the pointer counterclockwise until the area between the poles was reduced enough to make the two forces equal. The scale is calibrated to indicate the correct frequency.

If the frequency is constant and the voltage is changed, the currents in two coils, and therefore the opposing forces, change by the same amount. Thus, the indication of the instrument is not affected by a change in voltage amplitude.

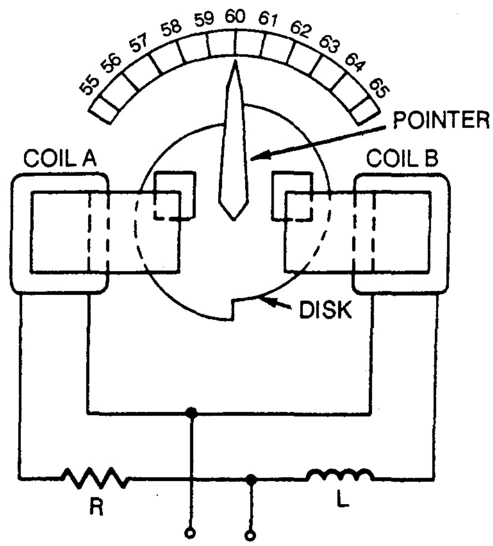


FIGURE 9-30. Simplified Diagram Of a Moving Disk Frequency Meter.

CHAPTER 10

CIRCUIT PROTECTION DEVICES

INTRODUCTION

An electrical unit is built with great care to ensure that each separate electrical circuit is fully insulated from all the others. This is done so that the current in a circuit will follow its intended path. Once the unit is placed into service, many things can happen to alter the original circuitry. Some of these changes can cause serious problems if they are not detected and corrected in time. While circuit protection devices cannot correct the abnormal current condition, they can indicate that an abnormal condition exists and protect personnel and circuits from that condition. This chapter explains circuit conditions that require protection devices and the type of protection devices used.

A circuit protection device is used to keep an undesirable current, voltage, or power surge out of a given part of an electrical circuit. Some of the components protected by circuit breakers and fuses follow

- Wiring - general reference used for the conductor that forms the link between the switchboard and the loads or any portion of that link.

- Bus bars - the copper or aluminum bars located inside the main or emergency switchboard. These heavy, rugged metallic conductors are usually insulated with a nonconducting paint and are used to carry the large generator loads within the switchboard (Figure 10-1). Smaller versions of these bus bars are located in power and lighting distribution panels and the motor control center (MCC) controllers.

- Feeders - the cables that extend from the main switchboard to a secondary distribution panel or switchboard. In some cases, these feeders will provide power directly to a load.

- Bus tie - a special cable that extends from the main switchboard to a second main or emergency switchboard. A bus tie between generator and distribution switchboard, including one between main and emergency switchboards, is never considered a feeder.

- Feeder, branch, or connecting boxes - watertight boxes that permit the joining of two or more continuous electrical wires or feeders.

- Distribution panels - panels that receive power from a distribution switchboard and distribute this power to power-consuming devices, other distribution panels, or panel boards.

- Branch circuits - that portion of wiring extending beyond the final overcurrent device protecting the circuit. Branch circuits are cables that extend from the distribution panel to the loads.

- Nonmotor loads - circuits that contain mostly resistive loads, such as lighting systems.

CIRCUIT CONDITIONS REQUIRING PROTECTION DEVICES

Many unwanted things can happen to the electrical circuits after they are in use. Previous chapters contained information on how to measure circuit values. Some changes in circuit values can cause conditions that are dangerous to the circuit itself or to people working near the circuits. Potentially dangerous conditions that require circuit protection are direct shorts, excessive current, and excessive heat.

Direct Shorts

One of the most serious troubles that can occur in a circuit is a direct short. Another term for this condition is a short circuit. These terms describe a situation in which full system voltage comes in direct contact with the ground or return side of the circuit bypassing the load. This establishes a path for current flow that contains only the negligible resistance present in the wires carrying the current. This is an unintentional path of current flow. In certain situations, a direct short can terminate part of the vessel's power supply.

According to Ohm's Law, if the resistance in a circuit is extremely small, the current will be extremely large. Therefore, when a direct short occurs, there will be a very large current through the wires. Suppose, for instance, that the two opposite polarity leads from a battery came in contact with each other. If the leads were uninsulated at the point of contact, there would be a direct short. Any other electrical component that could have received current from the battery is now shunted out. Shunting a component out means that there is a parallel path around the component. The minimal resistance of the direct short calls for the maximum current available from the batteries. In addition, the other high-resistance electrical loads that would have received current from the batteries now become inoperative. A direct short of this kind could result in a battery explosion.

The battery cables in this example would be very large conductors capable of carrying very high currents. Most wires used in electrical circuits are much smaller, and their current-carrying capacity is quite limited. The size of the wire used in any given circuit is determined by ambient temperature, cost, and the amount of current the wire is expected to carry under normal operating conditions. Therefore, any current flow in excess of normal would cause a rapid generation of heat in the wire.

If the excessive current flow caused by the direct short is left unchecked, the heat in the wire will continue to increase until a part of the circuit burns. Perhaps part of the wire will melt and open the circuit. In this case, only the original casualty is damaged. However, much greater damage may result. The heat in the wire can char and burn the insulation of the wire and that of other wires bundled wit h it. This can cause more shorts. Figure 10-2 shows the close proximity of groups of electrical cables. If fuel or oil is near any of these hot wires, a disastrous fire will be started.

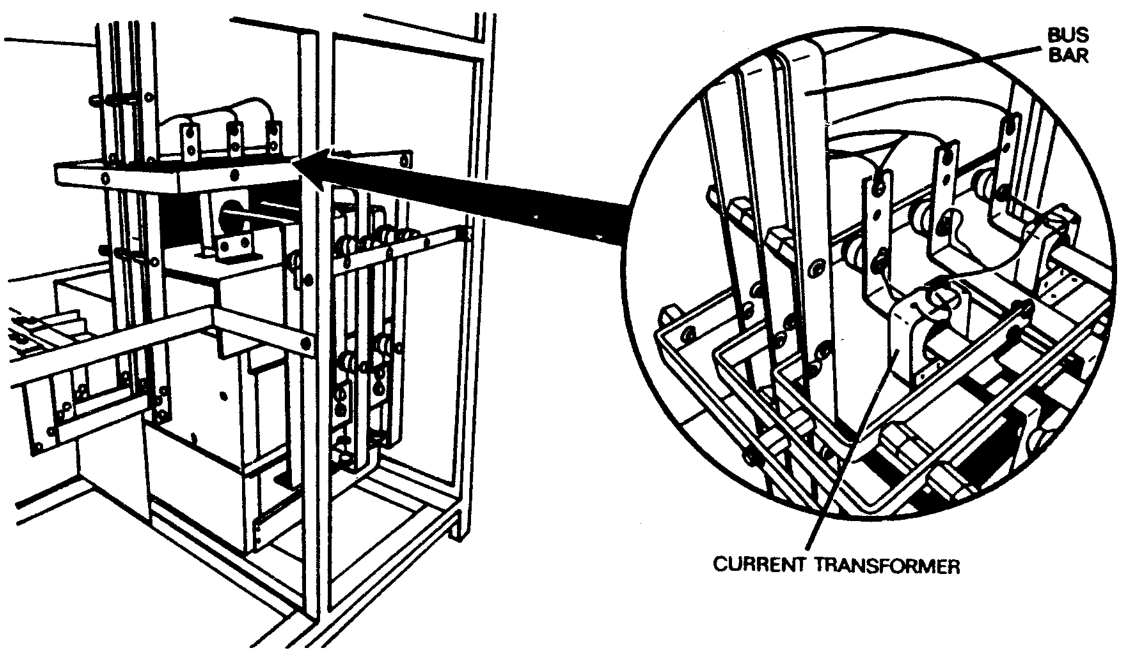


FIGURE 10-1. Switchboard Bus Bars.

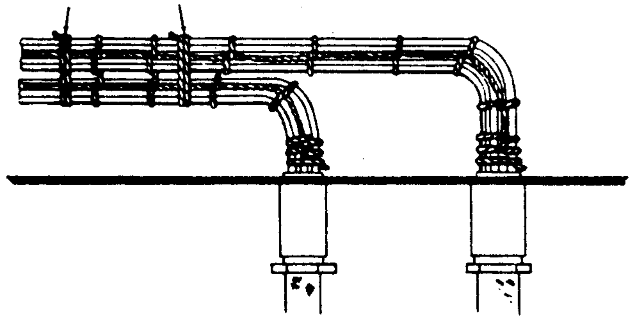


FIGURE 10-2. Bundled Electrical Cables Within a Motor Controller.

Excessive Current

The circuit current can increase without a direct short. If a resistor, capacitor, or inductor changes value, the total circuit impedance will also change in value. The impedance, which is the combined opposition to AC flow, can come from many sources. If a resistor decreases in ohmic value, the total circuit resistance (Rt) decreases. If a capacitor has a dielectric leakage, the capacitive reactance decreases. If an inductor has a partial short in its windings, inductive reactance decreases. Any of these conditions will increase circuit current (It). Since the circuit wiring and components are designed to withstand normal circuit current, an increase in current would cause overheating, just as in the case of the direct short. Therefore, excessive current without a direct short will cause the same problems as a direct short.

Excessive Heat

Excessive heat destroys electrical insulation and contact surfaces and reduces component longevity. In addition to the presence of amperage and its relationship with temperature, two other problems generate the heat that causes electrical malfunctions:

- Motor cleanliness. Dirty and oily machine windings and ventilation screens prevent the transfer of heat from the current-carrying conductors. The heat accumulates and eventually deteriorates the insulating material destroying the component.
- Excessive ambient temperatures. Electrical devices and components are selected according to the environment of their placement. A component designed for 40°C applications cannot be placed in an engine room (50°C environment) without detrimental effects. Excessive ambient temperatures cause the same electrical casualty as the heat from excessive current.

CIRCUIT PROTECTION

All of the above conditions are potentially dangerous and require the use of circuit protection devices. Circuit protection devices are used to stop current flow by opening the circuit. To do this, a circuit protection device must always be connected in series with the circuit it is protecting.

A circuit protection device operates by opening and interrupting current to the circuit. The opening of a protective device shows that something is wrong in the circuit and should be corrected before the power is restored. When a problem exists and the protection device opens, the device should isolate the faulty circuit from the other unaffected circuits in time to protect unaffected components in the faulty circuit. The protection device should not open during normal circuit operation.

Two types of circuit protection devices are fuses and circuit breakers.

A fuse is a simple circuit protection device. It derives its name from the Latin word “fusus,” meaning to melt. Fuses have been employed since the invention of electricity. The earliest type of fuse was simply a bare wire between two connections. The wire was smaller than the conductor it was protecting and, therefore, would melt before the conductor it was protecting was damaged. Some copper fuse link types are still in use, but most fuses no longer use copper as the element (the part of the fuse that melts). After changing from copper to other metals, tubes or enclosures were developed to hold the melting metal. The enclosed fuse made possible the addition of filler material, which helps contain the arc that occurs when the element melts.

WARNING

Never take anything for granted on board a vessel. There are many possible circumstances of which you are not yet aware. Never work on a live circuit and never "tempt fate."

WARNING

When servicing electrical circuits, always remove all fuses in that circuit.

While a fuse protects a circuit, it is destroyed in the process of opening the circuit. Once the problem that caused the increased current or heat is corrected, a new fuse must be placed in the circuit. A circuit protection device that can be used more than once solves the problem of replacement fuses. Such a device is safe, reliable, and tamperproof. It is also resettable, so it can be reused without replacing any parts. This device is called a circuit breaker because it breaks, or opens, the circuit (Figure 10-3).

FUSES

Fuses are manufactured in many shapes and sizes. In addition to the copper fuse link, Figure 10-4 shows other fuse types. Although there is a variety of fuses, there are basically only two types: plug-type fuses and cartridge fuses. Both types use either a single wire or a ribbon as the fuse element (the part of the fuse that melts). The condition (good or bad) of some fuses can be determined by visual inspection. The condition of other fuses can only be determined with a meter.

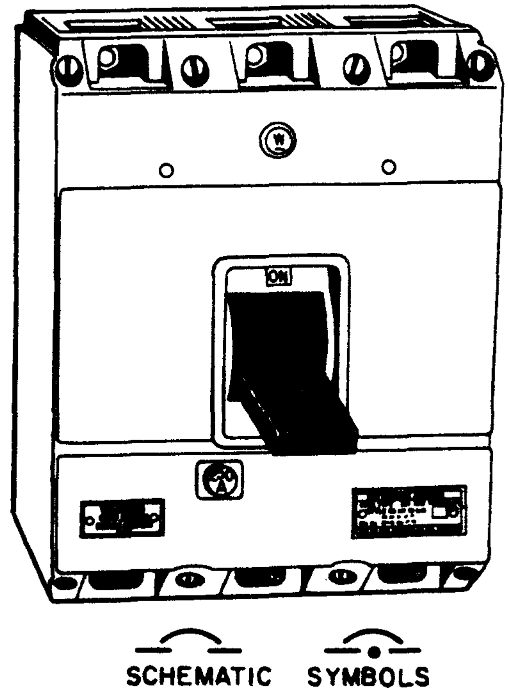


FIGURE 10-3. Typical Circuit Breaker and Schematic Symbols.

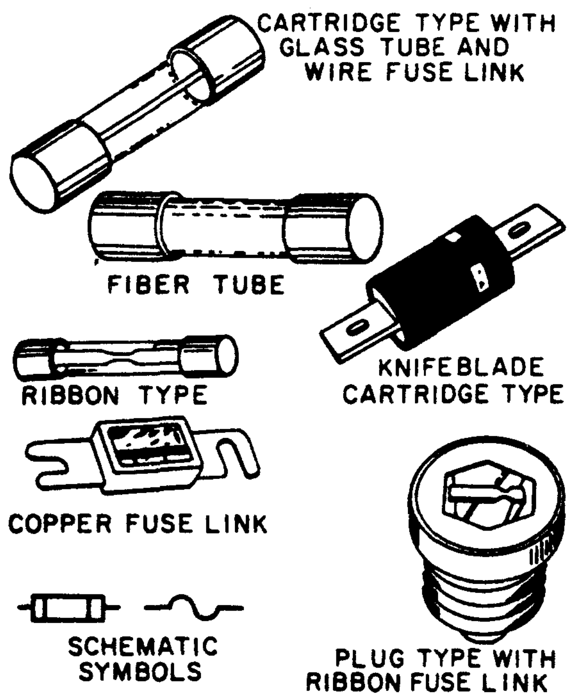


FIGURE 10-4. Typical Fuses and Schematic Symbols.

The only fuses used on Army watercraft are the cartridge, nonrenewable type conforming to the Underwriters' Laboratories standard. The threaded plug-type fuses tend to vibrate out of place on board a ship, leaving the electrical circuit de-energized.

In the cartridge fuse, the fuse link is enclosed in a tube of insulating material with metal ferrules at each end (for contact with the fuse holder). Some common insulating materials are glass, bakelite, or a fiber tube filled with insulating powder.

Figure 10-5 shows a glass tube fuse. View A shows the fuse link and the metal ferrules. View B shows a glass tube fuse that is open. The open fuse link could appear either of the ways shown in view B.

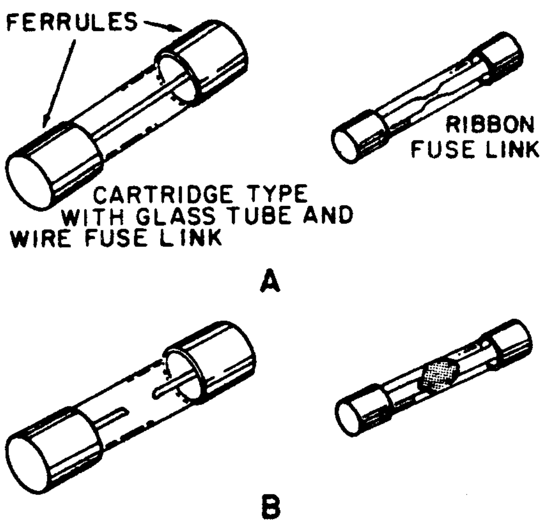


FIGURE 10-5. Cartridge-Type Fuse.

Cartridge fuses are available in a variety of physical sizes. They are used in many different circuit applications. They can be rated at voltages up to 10,000 volts and have a current rating from .002 ampere to more than 10,000 amperes. Cartridge fuses may also be used to protect against excessive heat and open at temperatures from 165 to 410 F.

All circuits protected by fuses must have a fuse for each current-carrying conductor. Even though one break in the electrical circuit is sufficient to stop all current flow to the equipment, a difference in potential exists between the wire connected to the power supply and the vessel hull. Although the hull is not an intentional current carrier, the potential from the generator will complete a path to a natural ground.

Rating Fuses

The physical size and type of a fuse can be determined by looking at it. However, to select the proper fuse, other conditions must be known. Fuses are rated by current, voltage, and time-delay characteristics.

To select the proper fuse, consult the applicable technical, regulatory, or manufacturer's manuals. Do not take for granted that the fuse being removed is in fact the type of fuse that should be reinstalled. An example of this is the 24-volt battery-powered general alarm system. The fuse used, regardless of the system voltage, must be rated for 250 volts. The general alarm system is greatly overrated for operation during marine casualty. When the current is finally sufficient to open the fuse, the system has achieved an excessive current so great that the general alarm system itself may become an additional factor working against the crew. The 250-volt rating prevents the lower voltages from arcing across the open fuse, re-energizing an already endangered circuit.

Current Rating. The current rating of a fuse is a value expressed in amperes. It represents the current that the fuse will carry without opening. The current rating of a fuse is always indicated on the fuse ferrules. Fuses rated up to 200 amperes are commonly found on board vessels. The 200-ampere fuses are generally restricted to special system applications such as emergency lighting battery cables. Otherwise, circuit breakers should be used in place of 200-ampere or greater fuses.

Voltage Rating. The voltage rating of a fuse is not an indication of the voltage the fuse is designed to withstand while carrying current. The voltage rating indicates the ability of the fuse to quickly extinguish the arc after the fuse element melts and the maximum voltage the open fuse will block. In other words, once a fuse has opened, any voltage less than the voltage rating of the fuse will not be able to jump the gap of the open fuse. Because of the way the voltage rating is used, it is a maximum rms voltage value. Always select a fuse with a voltage rating equal to or greater than the voltage in the circuit to be protected.

Time-Delay Rating. Many types of electrical circuits and components require customized protection. Some components are very current-sensitive and require fast-acting protection. In other instances, it is unnecessary and impractical to provide a close tolerance overcurrent protection when the circuit normally experiences momentary current increases without a time delay. A time delay prevents nuisance fuse openings and protects the circuit after the specified time limit has elapsed. The three time-delay ratings are delay, standard, and fast.

Figure 10-6 shows the differences between delay, standard, and fast fuses. It shows that if a l-ampere rated fuse has 2 amperes of current through it (200 percent of the rated value), a fast fuse would open in about .7 second. A standard fuse would open in about 1.5 seconds, and a delay fuse would open in about 10 seconds. In each of the fuses, the time required to open the fuse decreases as the rated current increases.

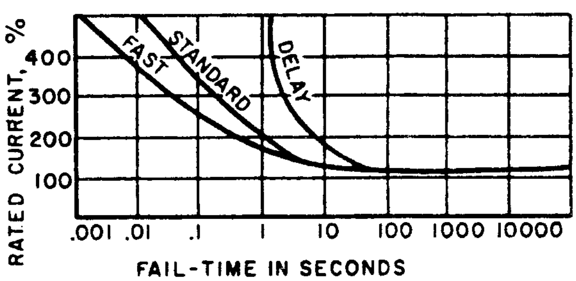


FIGURE 10-6. Time Requirement for Fuse to Open.

A delay, or slow blowing, fuse has a built-in delay that is activated when the current through the fuse is greater than the current rating of the fuse. This fuse will allow temporary increases in current (surge) without opening. Some delay fuses have two elements, which allow a very long time delay. If the overcurrent condition continues, a delay fuse will open, but it will take longer to open than the standard or fast fuse. Delay fuses are used for circuits with high surge or starting currents such as solenoids and transformers.

Standard fuses have no built-in time delay. Also, they are not designed to be very fast acting. Standard fuses are sometimes used to protect against direct shorts only. They may be wired in series with a delay fuse to provide faster direct short protection. For example, in a circuit with a l-ampere delay fuse, a 5-ampere standard fuse may be used in addition to the delay fuse to provide faster protection against a direct short.

A standard fuse can be used in any circuit where surge currents are not expected, and a very fast opening of the fuse is not needed. A standard fuse opens faster than a delay fuse, but slower than a fast rated fuse. Standard fuses can be used for automobiles, lighting circuits, and some electrical power circuits.

Fast fuses open very quickly when current through the fuse exceeds the current rating of the fuse. Fast fuses protect components that are sensitive to increased current. A fast fuse will open faster than a delay or standard fuse. Fast fuses are used to protect delicate equipment and solid state devices.

Identifying Fuses

Fuses have identifications printed on them. The printing on the fuse identifies the physical size and type of the fuse and the fuse ratings. There are four different systems used to identify fuses. The systems are the old military designation, the new military designation, the old commercial designation, and the new commercial designation.

All four systems are described below, so you can identify a fuse no matter which designation is printed on the fuse. You may have to replace an open fuse that is identified by one system with a good fuse that is identified by another system. You may find a fuse coded in one of the commercial designations because Army vessels are often repaired in commercial shipyards. The designation systems are fairly simple to understand and cross-reference once you are familiar with them.

Old Military Designation. Figure 10-7 shows a fuse with an old military designation. The tables in the lower part of the figure show the voltage and current codes used in this system. The upper portion of the figure is the explanation of the old military designation. The numbers and letters in parentheses are the coding for the fuse shown in Figure 10-7.

The old military designation always starts with F, which stands for fuse. Next, the set of numbers (02) indicates the style, which is the construction and dimensions of the fuse. Following the style is a letter that represents the voltage rating of the fuse (G). The voltage code table in Figure 10-7 shows each voltage rating letter and its meaning in volts. In the example shown, the voltage rating is G, which means the fuse should be used in a circuit suitable for a

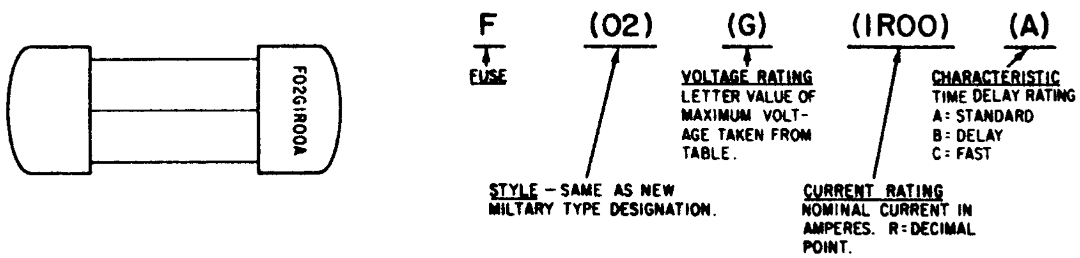
250-volt fuse. After this is a set of three numbers and the letter R, which represent the current rating of the fuse.

The R indicates the decimal point. In the example shown, the current rating is lR00 or 1.00 ampere. The final letter in the old military designation (A) indicates the time-delay rating of the fuse.

While the old military design is still found on some fuses, the voltage and current ratings must be translated, since they use letters to represent numerical values. The military developed the new military designations to make fuse identification easier.

New Military Designation. Figure 10-8 is an example of a fuse coded in the new military designation. The fuse in Figure 10-8 is the same type as the fuse used as an example in Figure 10-7.

The new military designation always starts with the letter F, for fuse. The set of numbers (02) next to this indicates the style. The style numbers are identical to the ones used in the old military designations and indicate the construction and dimensions of the fuse. Following the style designation is a single letter (A) that indicates the time-delay rating of the fuse. This is the same time-delay rating code as indicated in the old military designation, but the position of this letter in the coding is changed to avoid confusing the A for standard time delay with the A for ampere. Following the time-delay rating is the voltage rating for the fuse (250V). In the old military designation, a letter was used to indicate the voltage rating. In the new military designation, the voltage is indicated by numbers followed by a V, which stands for voltage. After the voltage rating, the current rating is given by numbers followed by the letter A. The current rating may be a whole number (1A), a fraction (1/500 A),



VOLTAGE CODE LETTER	VOLTAGE (VOLTS OR LESS)
A	32
B	52
C	90
D	125
G	250
H	500
J	1,000
K	2,500
N	5,000
P	10,000

VOLTAGE CODE (OLD)

CURRENT CODE	CURRENT (AMPERES)
R002	.002 = 1/500
R005	.005 = 1/200
R010	.010 = 1/100
R031	.031 = 1/32
R750	.750 = 3/4
1R50	1.500 = 1 1/2

CURRENT CODE (OLD)

FIGURE 10-7. Old Military Fuse Designation.

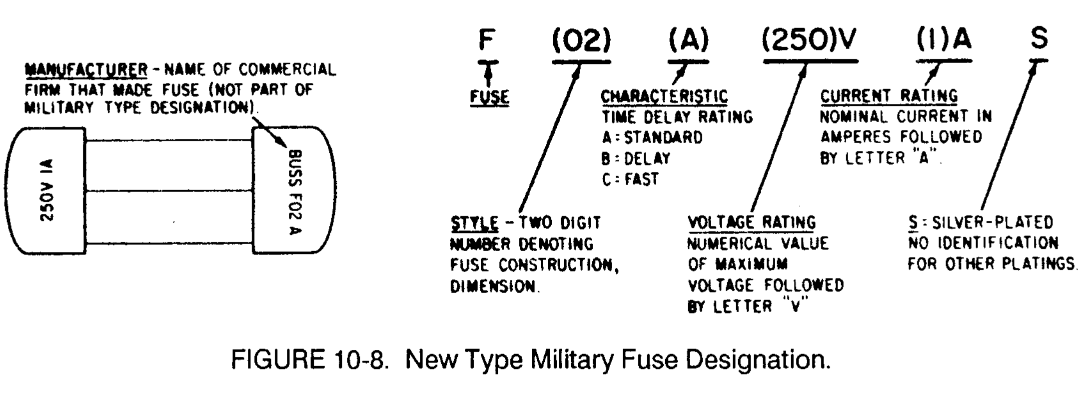


FIGURE 10-8. New Type Military Fuse Designation.

or a decimal (1.5 A). If the ferrules of the fuse are silver-plated, the current rating will be followed by the letter S. If any other plating is used, the current rating will be part of the fuse identification. The new military designation is much easier to understand than the old military designation.

Old Commercial Designation. Figure 10-9 shows the old and new commercial designations for the same type of fuse that was used in Figures 10-7 and 10-8.

Figure 10-9 view A shows the old commercial designation for a fuse. The first part of the designation is a combination of letters and numbers (three in all) that indicates the style and time-delay characteristics. This part of the designation (3AG) is the information contained in the style and time-delay rating portions of military designations. In the example shown, the code 3AG represents the same information as the underlined portions of F02 G lROO A from Figure 10-7 (old military designation) and F02A 250V1AS from Figure 10-8 (new military designation). The only way to know the time-delay rating of this fuse is to look it up in the manufacturer's catalog or a cross-reference listing to find the military designation. The catalog will give the physical size, the material from which the fuse is constructed, and the time-delay rating of the fuse. A 3AG fuse is a glass-bodied fuse, 1/4 inch x 1 1/4 inch, with a standard time-delay rating.

Following the style designation is a number that is the current rating of the fuse (l). This could be a whole number, a fraction, or a decimal. Following the current rating is the voltage rating, which is followed by the letter V, which stands for voltage (250V).

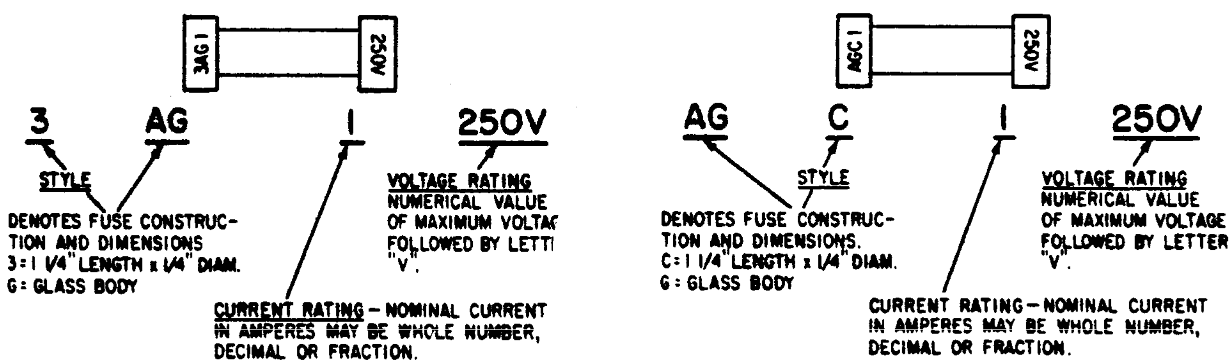
New Commercial Designation. Figure 10-9 view B shows the new commercial designation for fuses. It is the same as the old commercial designation except for the style portion of the coding. In the old commercial system, the style was a combination of letters and numbers. In the new commercial system, only letters are used. In the example shown, 3AG in the old system becomes AGC in the new system. Since C is the third letter of the alphabet, it is used instead of 3. Once again, the only way to find out the time-delay rating is to look up this coding in the appropriate manuals. The remainder of the new commercial designation is exactly the same as the old commercial designation.

Identifying Fuse Holders

For a fuse to be useful, it must be connected to the circuit it will protect. Some fuses are wired in or soldered to the wiring of circuits, but most marine applications use the fuse holder. A fuse holder is a device that is wired into the circuit and allows easy replacement of the fuse.

Fuse holders are made in many shapes and sizes, but most fuse holders are either a clip- or post-type. Figure 10-10 shows typical clip- and post-type fuse holders.

Clip-Type Fuse Holders. The clip-type fuse holder is used for cartridge fuses. The ferrules or knife blade of the fuse are held by the spring tension of the clips. These clips provide the electrical circuit connection between the fuse and the circuit. If a glass-bodied fuse is used, the fuse can be inspected visually for an opening without removing the fuse from the fuse holder. The clips may be made for



A. OLD COMMERCIAL DESIGNATIONS   B. NEW COMMERCIAL DESIGNATIONS

FIGURE 10-9. Commercial Designations for Fuses.

ferrules or knife blade cartridge fuses. While the base of a clip-type fuse holder is made from insulating material, the clips themselves are conductors. The current through the fuse goes through the clips. Therefore, be careful not to touch the clips when power is applied or else a severe shock or short circuit will occur.

Post-Type Fuse Holders. Post-type fuse holders are made for cartridge fuses. The post-type fuse holder is much safer because the fuse and fuse connections are covered with insulating material. The post-type fuse holder has a cap that screws onto the body of the fuse holder. The fuse is held in this cap by a spring-type connector. As the cap is screwed on, the fuse makes contact with the body of the fuse holder. When the cap and fuse are removed from the circuit, there is no danger of shock or short circuit from touching the fuse.

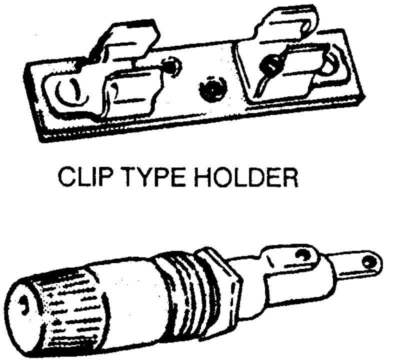


FIGURE 10-10. Typical Fuse Holders.

Post-type fuse holders are usually mounted on the chassis of the equipment they are protecting. After wires are connected to the fuse holder, insulating sleeves are placed over the connections to reduce the possibility of a short circuit. Figure 10-10 shows two connections on a post-type fuse holder. The terminal on the right is called the center connector. The other connector is called the outside connector. The outside connector will be closer to the equipment chassis. (The threads and nut shown are used to fasten the fuse holder to the chassis.) The possibility of the outside connector coming in contact with the chassis (causing a direct short) is much greater than the possibility of the center connector contacting the chassis. The power source should always be connected to the center connector so that the fuse will open if the outside connector contacts the chassis. If the power source were connected to the outside connector and the outside connector contacted the chassis, there would be a direct short, but the fuse would not open.

Checking and Replacing Fuses

A fuse, if properly selected, should not open unless something is wrong in the circuit the fuse is protecting. When a fuse is found open, the reason the fuse is open must be determined. Replacing the fuse is not enough.

Before looking for the cause of an open fuse, determine if the fuse is open. There are several ways of checking for an open fuse. Some fuses and fuse holders have indicators built in. Also, a multimeter can be used to check fuses.

Using a Fuse Indicator. Some fuses and fuse holders have built-in indicators to show when a fuse is open. Figure 10-11 shows examples of open fuse indicators. View A shows a cartridge-type fuse with an open fuse indicator. The indicator is spring-loaded and held by the fuse link. If the fuse link opens, the spring forces the indicator out. Some manufacturers color the indicator so it is easier to see in the open fuse position.

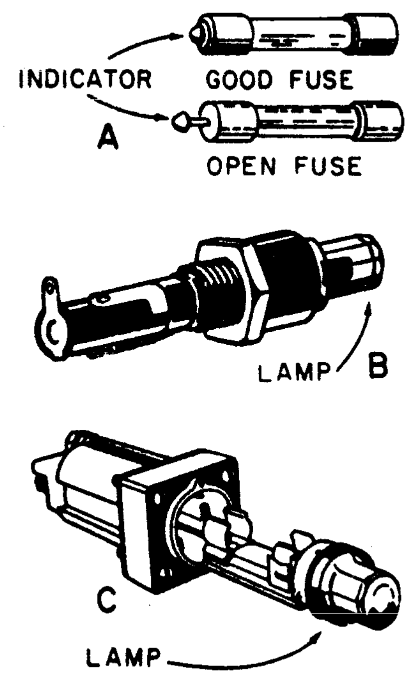


FIGURE 10-11. Open Fuse Indicators.

View B shows a plug-type fuse holder with an indicating lamp in the fuse cap. If the fuse opens, the lamp in the fuse cap will light. View C shows a clip-type fuse holder with an indicating lamp.

Using a Meter. The only sure method of determining if a fuse is open is to use a meter. An ohmmeter can be used to check for an open fuse by removing the fuse from the circuit and checking for continuity (O ohm) through the fuse. If the fuse is not removed from the circuit and the fuse is open, the ohmmeter may measure the circuit resistance. A low resistance might lead you to think the fuse is good.

A voltmeter can also be used to check for an open fuse. The measurement is taken between each end of the fuse and the power supply end of another fuse. If voltage is present on both sides of the fuse (from the voltage source and to the load), the fuse is not open. Another method commonly used is to measure across the fuse with the voltmeter. If no voltage is indicated on the meter, the fuse is good (not open). There is no voltage drop unless there is a resistance. An open fuse has a great deal of resistance.

To check for voltage on a clip-type fuse holder, check each of the clips. The advantage of using a voltmeter to check for an open fuse is that the circuit does not have to be de-energized, and the fuse does not have to be removed.

Observing Safety Precautions. Since a fuse has current through it, be very careful when checking for an open fuse to avoid being shocked or damaging the circuit. The following safety precautions and prudent maintenance practices will protect you and the equipment you are using

- Turn power off and discharge the circuit before removing the fuse.
- Use a fuse puller (Figure 10-12) when removing a fuse from a fuse holder.
- When checking a fuse with a voltmeter, be careful to avoid shocks and short circuits.

Replacing Open Fuses

After an open fuse is found and the trouble that caused the fuse to open has been corrected, the fuse must be replaced. Before replacing the fuse, be certain that the replacement fuse is the proper type and that it fits correctly.

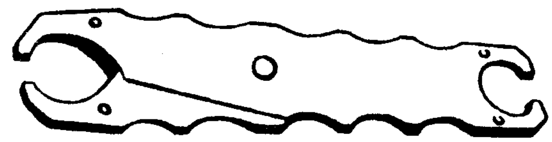


FIGURE 10-12. Fuse Puller.

To be certain a fuse is the proper type, consult the technical manual for the equipment. The parts list gives the proper fuse identification for a replacement fuse. Obtain and use the exact fuse specified.

If a direct replacement cannot be obtained, use the following guidelines:

- Never use a fuse with a higher current rating, a lower voltage rating, or a slower time-delay rating than the specified fuse.
- Use the best substitution for a fuse with the same current and time-delay ratings and a higher voltage rating. (If a lower current rating or a faster time-delay rating is used, the fuse may open under normal circuit conditions.)
- Use substitute fuses that have the same style (physical dimensions) as the specified fuse.
- Regularly inspect the circuit and substitute fuse during operation.
- Return the circuit to a like-new condition when arriving in the next port.

When a proper replacement fuse has been found, make certain it will fit correctly in the fuse holder. If the fuse holder is corroded, the fuse will not conduct current properly and will increase resistance or heating. Clean corroded terminals with fine sand paper so that all corrosion is removed. Do not lubricate the terminals. If the terminals are badly pitted, replace the fuse holder.

If the fuse clips do not make complete contact with the fuse (Figure 10-13), try bending the clips back into shape. If the clips cannot be repaired by bending, replace the fuse holder or clip clamps.

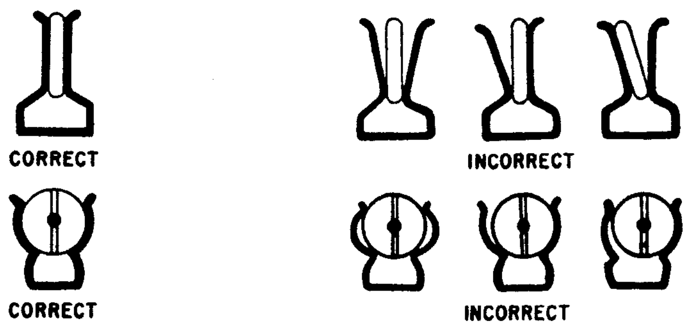


FIGURE 10-13. Contact Between Clips and Fuses.

CIRCUIT BREAKERS

A circuit breaker is a circuit protection device that, like the fuse, will stop current in the circuit if there is a direct short, excessive current, or excessive heat. Unlike a fuse, a circuit breaker is reusable. The circuit breaker does not have to be replaced after it has opened and broken the circuit. Instead of replacing the circuit breaker, it is reset.

Circuit breakers can also be used as circuit control devices. By manually opening and closing the contacts of a circuit breaker, the power can be selectively switched on and off. This is of practical use when trying to isolate a circuit ground.

Circuit breakers are available in a great variety of sizes and types. Army marine circuit breakers are of the molded case, trip-free type. They must be arranged so that they can be removed without disconnecting the copper or cable connections or de-energizing the power supply to the circuit breaker. The circuit breaker rating should be the value of current the breakers will carry continuously without exceeding the specific temperature rise.

CIRCUIT BREAKER COMPONENTS

Circuit breakers have five main components (Figures 10-14 and 10-15). The components are the frame, the operating mechanism, the arc extinguishers, the terminal connectors, and the trip elements.

The Frame. The frame provides an insulated housing and is used to mount the circuit breaker components (Figure 10-14). The frame determines the physical size of the circuit breaker and the maximum allowable voltage and current.

The Operating Mechanism. The operating mechanism provides a means of opening and closing the breaker contacts (turning the circuit on and off). The toggle mechanism in Figure 10-15 is the quick-make, quick-break type, which means the contacts snap open or closed quickly, regardless of how fast the handle is moved. In addition to indicating whether the breaker is on or off, the operating mechanism handle indicates when the breaker has opened automatically (tripped) by moving to a position between on and off. To reset the circuit breaker, first move the handle to the OFF position, then to the ON position.

Arc Extinguishers. The arc extinguisher confines, divides, and extinguishes the arc drawn between the contacts each time the circuit breaker interrupts current. The arc extinguisher is actually a series of contacts that open gradually, dividing the arc and making it easier to confine and extinguish. This is shown in Figure 10-16. Arc extinguishers are generally used in circuit breakers that control a large amount of power, such as those found in distribution switchboards. Small power circuit breakers, such as those found in lighting panels, may not have arc extinguishers.

Terminal Connectors. Terminal connectors are used to connect the circuit breaker to the power source and the load. They are electrically connected to the contacts of the circuit breaker and provide the means of connecting the circuit breaker to the circuit.

Trip Element. The trip element is the part of the circuit breaker that senses the overload condition and causes the circuit breaker to trip or break the circuit. Thermal, magnetic, and thermal magnetic trip units are used by most circuit breakers. Some circuit breakers use solid state trip units with current transformers and solid state circuitry.

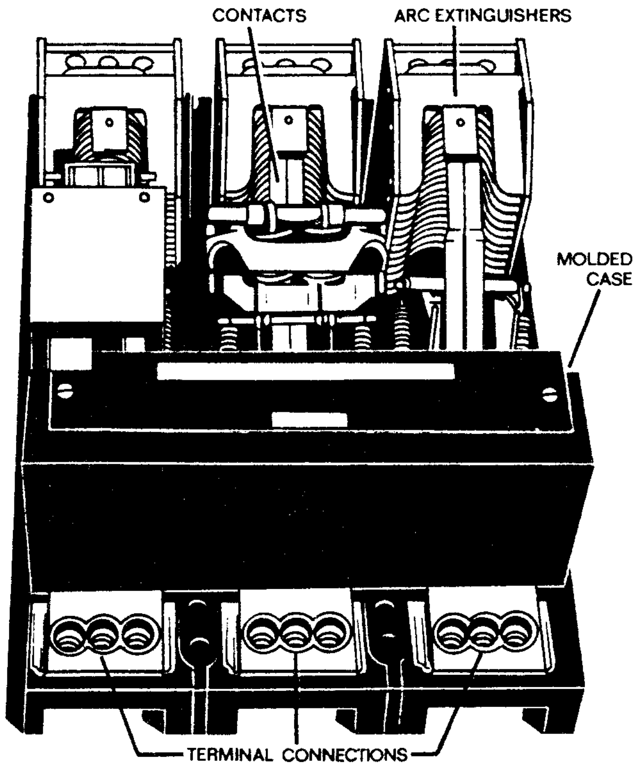


FIGURE 10-14. Circuit Breaker Components.

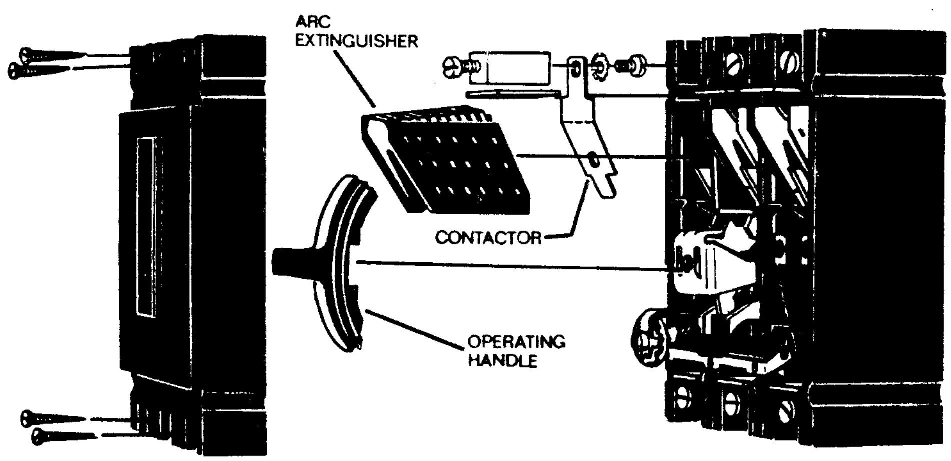


FIGURE 10-15. Circuit Breaker Construction.

Thermal trip element. A thermal trip element circuit breaker uses a bimetallic element that is heated by the load current. The bimetallic element is made from strips of two different metals bonded together. The metals expand at different rates as they are heated. This causes the bimetallic element to bend as it is heated. Figure 10-17 shows how this can be used to trip a circuit breaker.

Figure 10-17 view A shows the trip element with normal current. The bimetallic element is not heated excessively and does not bend. If the current increases (or the ambient temperature around the circuit breaker increases), the bimetallic element bends, pushes against the trip bar, and releases the latch. Then the contacts open (Figure 10-16 view B).

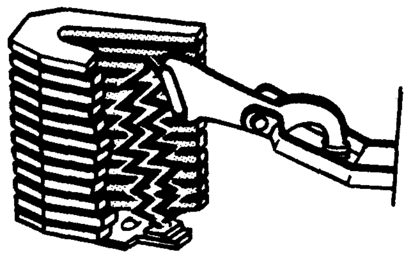


FIGURE 10-16. Arc Extinguisher Action.

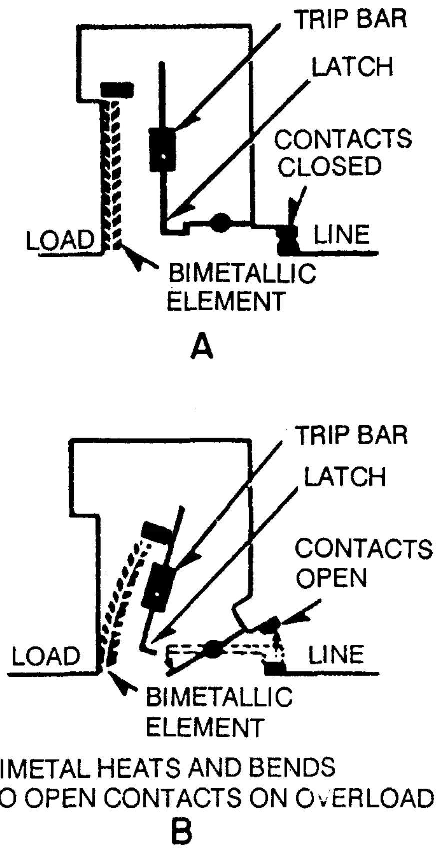


FIGURE 10-17. Thermal Trip Element Action.

The amount of time it takes for the bimetallic element to bend and trip the circuit breaker depends on the amount the element is heated. A large overload will heat the element quickly. A small overload will require a longer time to trip the circuit breaker.

Magnetic trip element. A magnetic trip element circuit breaker uses an electromagnet in series with the circuit load (Figure 10-18). With normal current, the electromagnet will not have enough magnetic force on the trip bar to move it, and the contacts will remain closed (view A). The strength of the magnetic field of the electromagnet increases as current through the coil increases. As soon as the current in the circuit becomes large enough, the trip bar is pulled toward the magnetic element (electromagnet). The contacts are opened, and the current stops (view B).

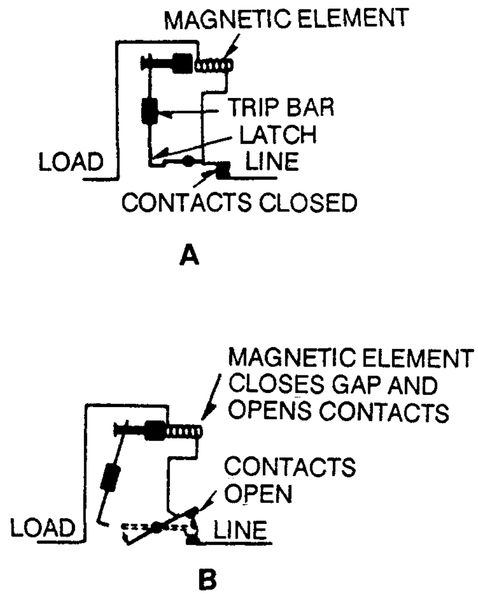


FIGURE 10-18. Magnetic Trip Element Action.

The amount of current needed to trip the circuit breaker depends on the size of the gap between the trip bar and the magnetic element. On some circuit breakers, this gap (and therefore the trip current) is adjustable.

Thermal-magnetic trip element. The thermal-magnetic trip element circuit breaker, like a delay fuse, will protect a circuit against a small overload for a long period of time. The larger the overload, the faster the circuit breaker will trip. The thermal element portion will protect the circuit against ambient temperature rises. The magnetic element portion will trip instantly when the preset current is present. In some applications, both types of protection are desired. Rather than using two separate circuit breakers, a single trip element combining thermal and magnetic trip elements is used. Figure 10-19 shows a thermal-magnetic trip element.

In the thermal-magnetic trip element circuit breaker, a magnetic element (electromagnet) is connected in series with the circuit load, and a bimetallic element is heated by the load current. With normal circuit current, the bimetallic element does not bend, and the magnetic element does not attract the trip bar (view A).

If the temperature or current increases over a sustained period of time, the bimetallic element will bend, push the trip bar, and release the latch. The circuit breaker will trip as shown in view B.

If the current suddenly or rapidly increases enough, the magnetic element will attract the trip bar, release the latch, and trip the circuit breaker (view C). (This circuit breaker has tripped even though the thermal element has not had time to react to the increased current.)

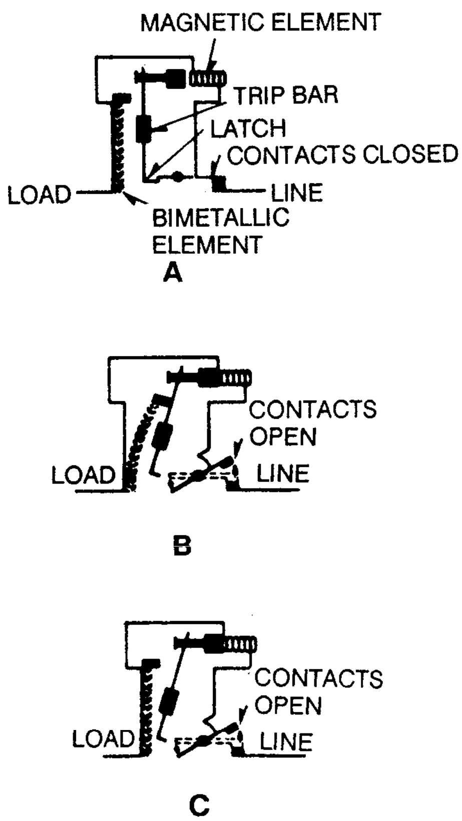


FIGURE 10-19. Thermal-Magnetic Trip Element Action.

CIRCUIT BREAKER CLASSIFICATIONS

Circuit breakers are classified as being trip-free or nontrip-free. A trip-free circuit breaker will trip (open) even if the operating mechanism (on-off switch) is held in the ON position. A nontrip-free circuit breaker can be reset and/or held on even if an overload or excessive heat condition is present. In other words, a nontrip-free circuit breaker will remain closed by holding the operating mechanism on.

Trip-free circuit breakers are used on circuits that cannot tolerate overloads and on nonemergency circuits. Examples of trip-free applications include precision or current-sensitive circuits, non-emergency lighting circuits, and nonessential equipment circuits.

TIME-DELAY RATINGS

Circuit breakers, like fuses are rated by the amount of time delay. In circuit breakers, the ratings are instantaneous, short time delay, and long time delay. The delay times of circuit breakers can be used to provide selective tripping.

Selective tripping is used to cause the circuit breaker closest to the faulty component to trip. This will remove power from the faulty circuit without affecting other, nonfaulty circuits.

Figure 10-20 shows a power distribution system using circuit breakers for protection. Circuit breaker 1 (CB1) has the entire current for all seven loads feed through it. CB2 feeds loads 1, 2, 3, and 4 (through CB4, CB5, CB6, and CB7), and CB3 feeds loads 5, 6, and 7 (through CB8, CB9, and CB10). If all the circuit breakers were rated with the same time delay, an overload on load 5 could cause CB1, CB3, and CBS to trip. This would remove power from all seven loads, even though load 5 was the only circuit with an overload.

Selective tripping would have CB1 rated as long time delay, CB2 rated as short time delay, and CB4 through CB10 rated as instantaneous. With this arrangement, if load 5 had an overload, only CBS would trip. CB8 would remove the power from load 5 before CB1 and CB3 could react to the overload. In this way, only 5 would be affected, and the other circuits would continue to operate.

PHYSICAL TYPES OF CIRCUIT BREAKERS

All the circuit breakers described above have been physically large, controlling large amounts of power, and using a type of toggle operating mechanism. Not all circuit breakers are of this type. The circuit breaker in Figure 10-21 is physically large and controls large amounts of power, but the operating mechanism is not a toggle. Except for the difference in the operating mechanism, this circuit breaker is identical to the circuit breakers already presented.

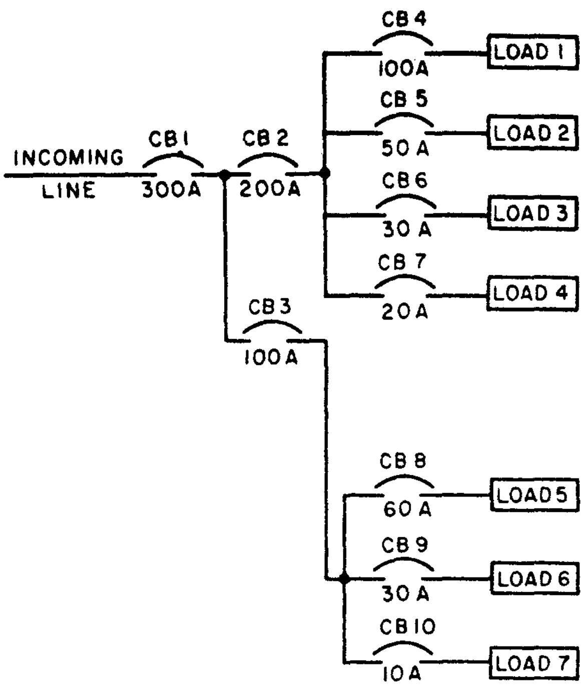


FIGURE 10-20. Use of Circuit Breakers in a Power Distribution System.

Circuit breakers used for low-power protection, such as 28 volt DC, 30 amperes, can be physically small. With low-power use, arc extinguishers are not required and so are not used in the construction of these circuit breakers. Figure 10-22 shows a low-power circuit breaker. This circuit breaker has a thermal trip element (the bimetallic disk) and is nontrip-free.

There are other physical types of circuit breakers. They are found in power distribution systems, lighting panels, and even on individual pieces of equipment. Regardless of the physical size and the amount of power through the circuit breaker, the basic operating principles of circuit breakers apply.

CIRCUIT BREAKER MAINTENANCE

Circuit breakers require careful inspection and cleaning at least once a year. Before working on circuit breakers, check the applicable technical manual carefully. Before working on shipboard circuit breakers, obtain the approval of the electrical officer. Be certain to remove all power to the circuit breaker before working on it. Tag the switch that removes the power to the circuit breaker to ensure that power is not accidentally applied while working on it.

Once approval has been obtained, the incoming power removed, the switch tagged, and the technical manual checked, you may begin to check the circuit breaker. Manually operate the circuit breaker several times to be sure the operating mechanism works smoothly. Inspect the contacts for pitting caused by arcing or corrosion.

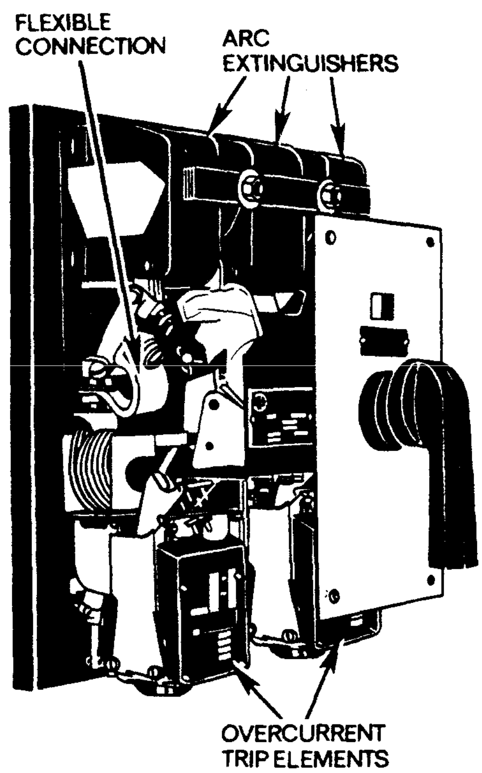


FIGURE 10-21. Circuit Breaker With Operating Handle.

Under normal circumstances, replace the damaged or worn out circuit breaker as an assembly. Follow the contact servicing section in Chapter 11 if the circuit breaker must be reused. Before installing any item that has been reconditioned, ensure the chief engineer or the electrical officer has made a final inspection of the component.

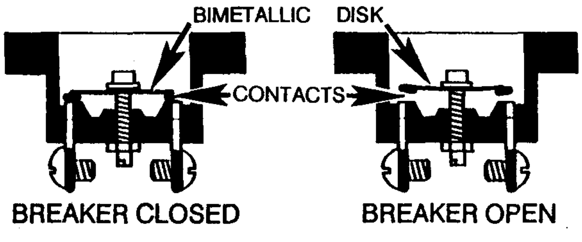


FIGURE 10-22. Circuit Breaker.

Check the connections at the terminals to be certain the terminals and wiring are tight and free from corrosion. Check all mounting hardware for tightness and wear. Check all components for wear. Clean the circuit breaker completely.

When you have finished working on the circuit breaker, restore power and remove the tag from the switch that applies power to the circuit.

CHAPTER 11

CIRCUIT CONTROL DEVICES

INTRODUCTION

Circuit control, in its simplest form, is the application and removal of power. It can also be expressed as turning a circuit on and off or closing and opening a circuit.

If a circuit develops problems that could damage equipment or endanger personnel, it must be possible to remove the power from the circuit. The circuit protection devices discussed in Chapter 10 will remove power automatically if current or temperature increases sufficiently. Even with this protection, a manual means of control is needed so the operator can start and stop electrical equipment as he chooses.

When working on a circuit, it is often necessary to de-energize the circuit to install test equipment or replace components. When power is removed from a circuit for servicing, be sure to tag out that circuit breaker that supplies power to those components. When work has been completed, restore power to the circuit. Check the circuit for proper operation before placing it back in service. After the circuit has been checked for proper operation, remove the tag and log the work.

Many electrical devices are used only part of the time. These controlling devices can allow a programed sequence of events to take place or to repeat cycles of specific operations. The air conditioner is a good example. The compressor motor cycles on and off automatically, controlled by the thermostat switch. As the temperature increases, the thermostat switch closes the circuit, and the air conditioner starts. When the temperature drops to the predetermined level, the thermostat opens the circuit and shuts the compressor off.

Multimeters and televisions use circuit control devices to select a specific function or circuit. The separate control of a specific part of a circuit can be made either automatically or manually by the operator.

TYPES OF CIRCUIT CONTROL DEVICES

Circuit control devices have many different shapes and sizes (Figures 11-1 and 11-2). There are three basic groups of circuit control devices: manual, magnetic, and electronic.

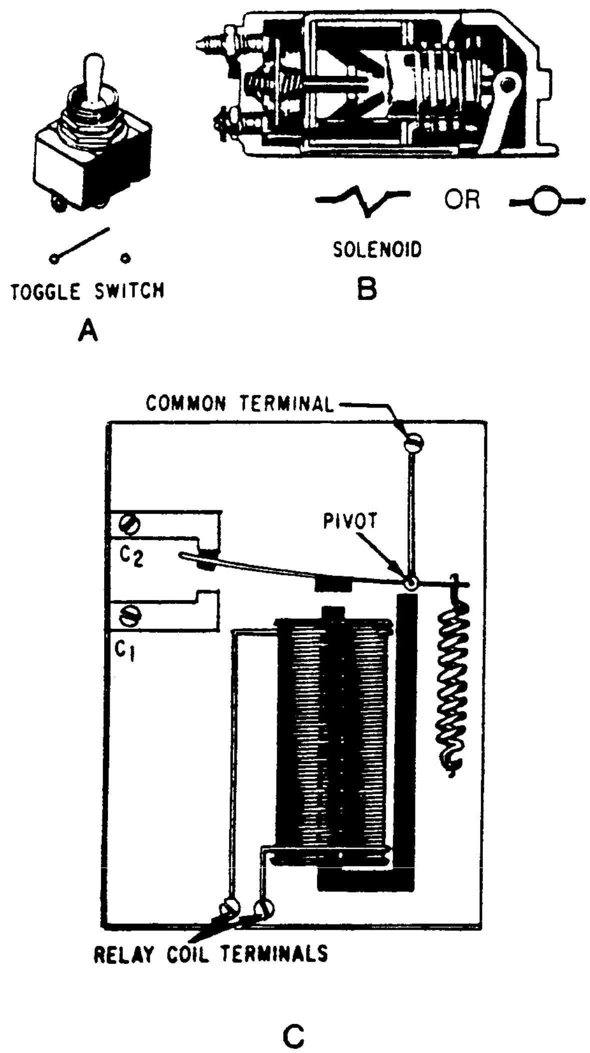


FIGURE 11-1. Typical Circuit Control Devices.

There are many ways of physically positioning electrical control devices. The toggle switch and push button comprise the largest concentration of manual controls. Other manually activated controls are those operated by an outside physical force, such as pressure operating a pressure switch or a water level operating a float switch. Even with the varied number of switching devices, all have one thing in common. They all have contacts.

CONTACTS

Copper and silver alloy are the two most common types of contact materials. A contact is usually a circular or rectangular surface designed to carry and interrupt the flow of current. Figure 11-3 shows contacts both normally closed (view A) and normally open (view B). Contacts are found in pairs. One contact is permanently fixed in position. The other contact is affixed to a movable arm or plunger. When the switch is closed, both contacts come together and complete the circuit. When the switch is opened, the contacts are separated, and the circuit is broken. The contacts and their terminal connections are insulated from the switch housing and actuator handle. The contacts are always in series with the components they control.

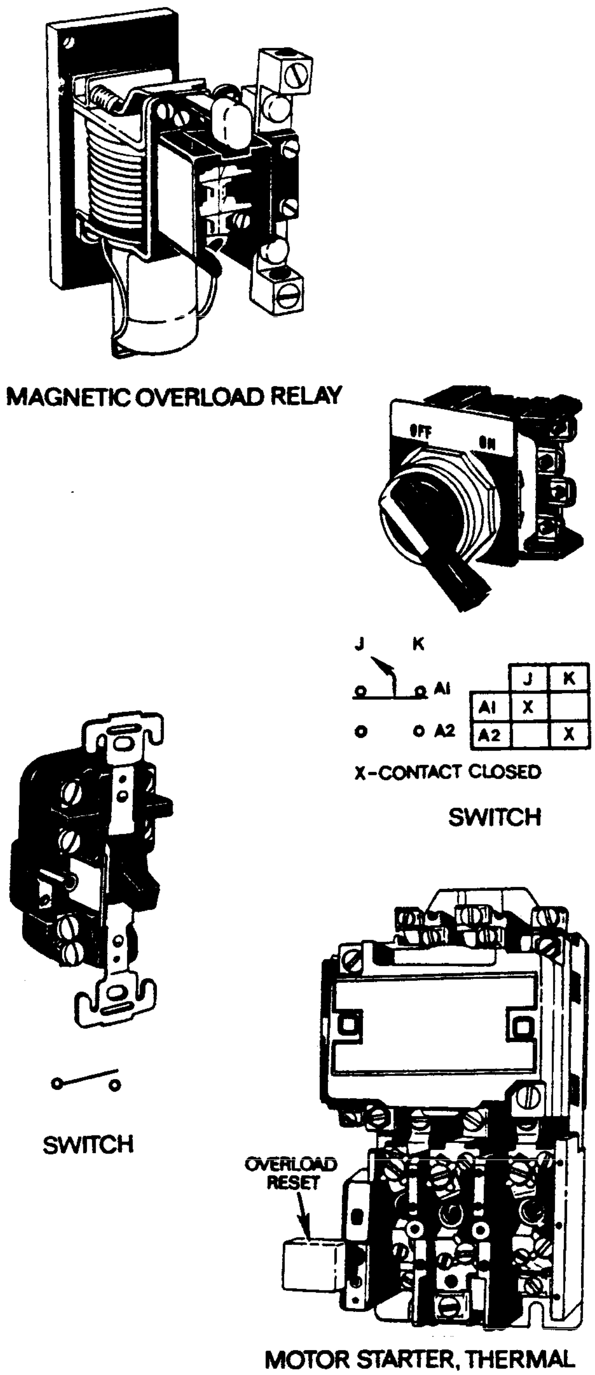


FIGURE 11-2. Types of Circuit Controls.

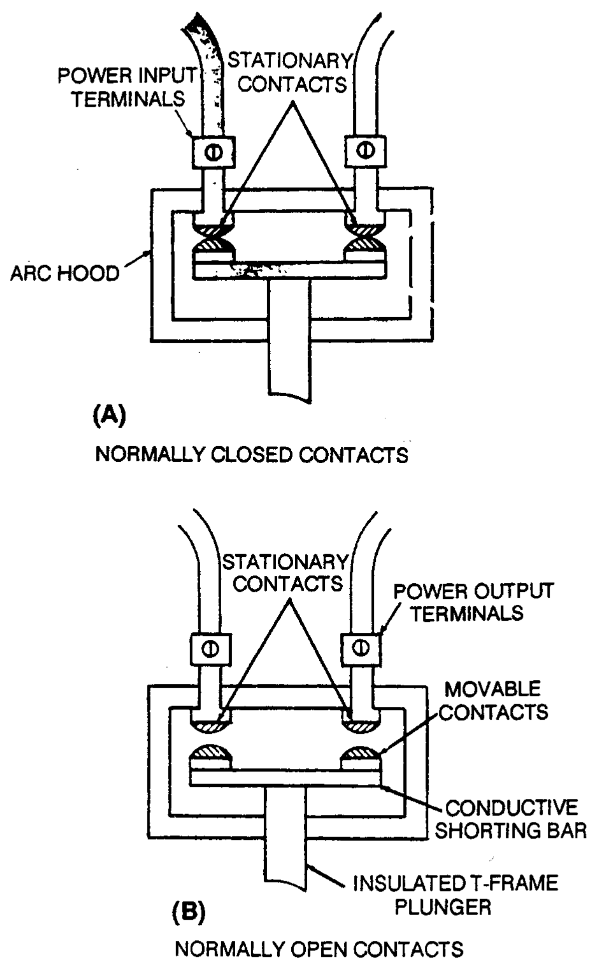


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FIGURE 11-3. Contacts.

Inspect and clean copper contact surfaces of any black-oxide film. This copper oxide film is a partial insulator. Large copper contacts are designed to open and close with a wiping action. That helps eliminate the copper black-oxide that prevents good continuity (contact) between the contact surfaces.

Newer contacts are composed of silver alloy materials. During normal circuit operation, arcing causes a blackened condition on the silver alloy contact faces as well. However, this silver oxide has been found to improve contact operation. It minimizes the tendency of one contact to weld to another. The silver oxide also inhibits the transfer of material from one contact face to the other contact face. It is not recommended to remove this film from silver alloy contacts.

Any buildup of film on the contact surface is a cause for concern. Normal oxidation will form a film on the contacts because of the action of the atmosphere and other surrounding gases. This cannot be avoided. The film caused by grease is particularly detrimental to good contact operation. Normal arcing causes grease and other petroleum products to burn. Carbon rings form on the contact surfaces, and eventually the contacts are prevented from operating properly. Grease contamination is often caused by service technicians who ignore the need for cleanliness. Cleanliness must be second nature to all engineers.

When current flows in only one direction through a set of contacts, a problem known as cone and crater may develop. The crater is formed by the transfer of metal from one contact to the other contact. Figure 11-4 view A shows this condition. If this condition is present, replace the contacts.

Some contacts are formed in a ball shape. In many applications, this type of contact is superior to a flat surface. View B shows a set of ball-shaped contacts. Dust or other substances are not easily deposited on a ball-shaped surface. Also, a ball-shaped contact penetrates film more easily than a flat contact. When cleaning or servicing ball-shaped contacts, be careful to avoid flattening or otherwise altering the rounded surfaces. The contacts can be damaged by using sandpaper or emery cloth. Only a burnishing tool should be used for this purpose (Figure 11-5). Do not touch the surfaces of the burnishing tool. After the burnishing tool is used, it should be cleaned with alcohol.

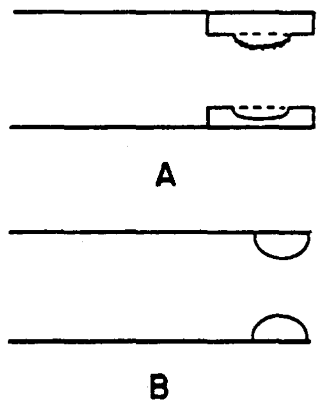

FIGURE 11-4. Relay Contacts.

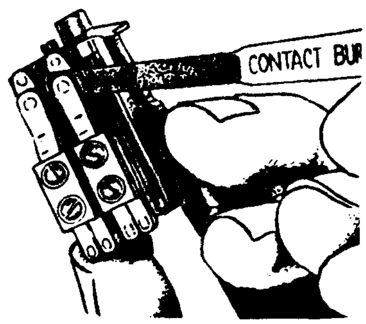

FIGURE 11-5. Burnishing Tool.

Never use finishing papers that are conductive. Conductive particles fall from the paper during servicing and can short across parts of the circuit. When these particles are dropped into the equipment, an engineer's first response is to blow the equipment out with compressed air. Never blow particles deeper into an electrical device. Always use a vacuum cleaner to pull the particles back out the way they went in, rather than trying to drive them through the component.

Maintain contact clearances or gap settings according to the operational specifications of the component. If the contact gap needs to be adjusted, bend the contact arm with a point bender (Figure 11-6). Any other tool can cause the relationship between the two mating contact surfaces to distort. This would necessitate the replacement of the entire relay assembly.

FIGURE 11-6. Point Bender.

Cleanliness is important when servicing semi-sealed relays. When these relays are installed in a compartment where there is a possibility of contact with explosive fumes, take extra care with the cover gasket. The gaskets must be free of grease and defects. The housing gasket surfaces must be free of burrs. Any damage to or incorrect seating of the gasket increases the possibility of igniting the vapors.

After servicing the contacts, verify their operation with an ohmmeter. Ensure the circuit is de-energized. Disconnect at least one of the leads to the contact surfaces. This is necessary to ensure that other parallel circuits are not read by the ohmmeter. Connect one lead of the ohmmeter to one side of the contacts. Connect the other ohmmeter lead to the other contact (Figure 11-7). Physically open and close the contacts and observe the ohmmeter readings. The ohmmeter should read zero resistance when the contacts are closed and an infinite resistance when the contacts are open.

SWITCH RATING

Chapter 10 discussed how the contacts open the electrical circuit during overcurrent conditions. Circuit breakers, circuit control devices, and switches have contacts of either copper or silver alloy materials. The National Electrical Manufacturers Association (NEMA) rates contractors according to the size and type of load. How contacts are rated and what they are made of depend on their physical size, current, voltage capacities, and particular application.

Table 11-1 lists some common ratings for AC contractors.

TABLE 11-1. Common Size and Rating of AC Contactors.

Size	Three-Phase 230/460V	Single-Phase 115V
00	2 HP	1/3 HP
0	5 HP	1 HP
1	10 HP	2 HP
2	25 HP	3 HP
3	50 HP	

The overall size of a single-break contact device can be reduced by making it a double-break contact. Figure 11-8 shows a single- and double-break switch. A double-break contact can carry a much higher current in a smaller space because it interrupts the circuit in two places at the same time. It can further be reduced by making it out of silver alloy. Silver alloy is an excellent conductor with better mechanical strength. Contacts made of silver alloy will allow many more operations than a contact of copper construction. Copper is a good choice for large contacts because it is a good conductor and is relatively inexpensive.

The current rating of the switch refers to the maximum current the switch is designed to carry. The current rating of a switch should never be exceeded. Excessive currents will weld the contacts together making it impossible to open the circuit.

The voltage rating of a switch refers to the maximum voltage allowable in the circuit in which the switch is used. The voltage rating will be given as AC, DC, or both. If the voltage rating of the switch is exceeded, the voltage may jump the open contacts of the switch, energizing the circuit.

Application is very important because both AC and DC are found on Army watercraft. Direct current sends electrons in one direction constantly. As long as the circuit is complete, the current will be sustained at the maximum source level. For this, larger, heavier contacts are needed. Alternating current, by its nature, sends current through the circuit in two directions alternately. For 60 hertz, the AC shuts itself off 120 times a second. This characteristic allows AC to be interrupted without as great an arcing as a DC produces.

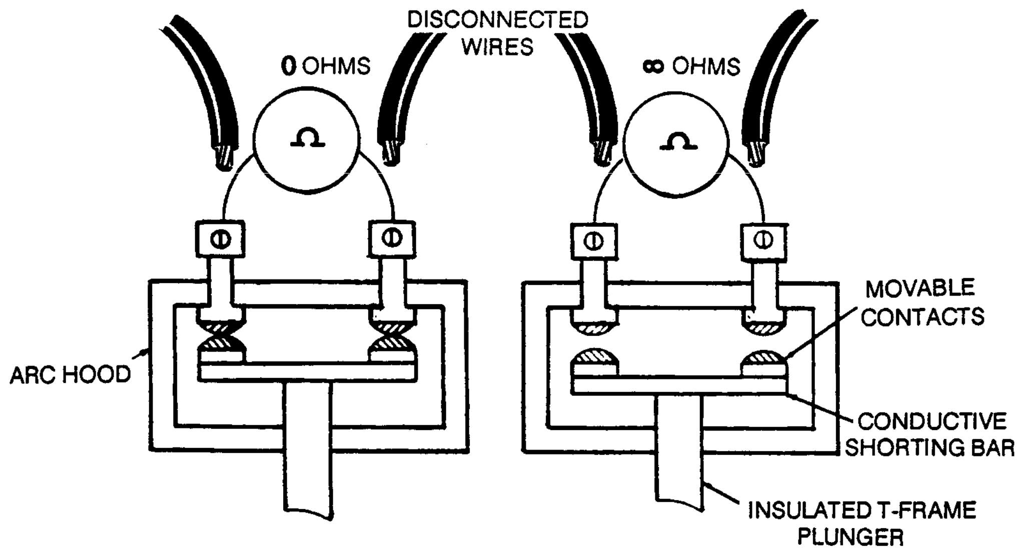

FIGURE 11-7. Checking Contacts With an Ohmmeter.

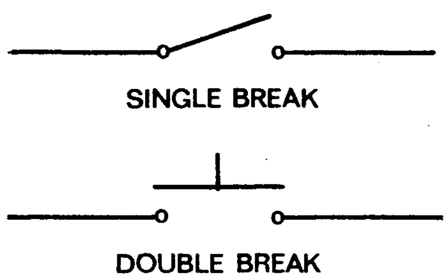

FIGURE 11-8. Single- and Double-Break Contacts.

The following rules apply to switch and contact symbols:

- The position that the switch is in when placed in an electrical diagram is its normal position. This means that unless acted on by an outside force, such as a finger or a mechanical pressure, this switch will remain in that position. The switch can be either normally open (NO) or normally closed (NC).

- Relays and contractors follow the same rules as switches. These devices have electromagnets (coils) that control the position of their contacts. When the coil is not energized, the contacts will be in the same position as shown by their symbol on the diagram. This is their normal position, either NO or NC. When the coil is energized, the contacts change their position. Normally open contacts close, and normally closed contacts open.

- Pole refers to the number of terminals at which current can enter the switch. The single-pole switch has only one terminal for current to enter. The three-pole switch has three terminals in which current can enter.

- Throw refers to the number of additional circuits that can be controlled by physically repositioning the pole or poles. The double-throw switch provides a choice of two possible circuits.

The number of poles can be determined by counting the number of points where current enters the switch (from the schematic symbol or the switch itself). By counting the number of different points each pole can connect with, the number of throws can be determined.

For example, Figure 11-9 shows some of the symbols for a toggle switch. View B shows a double-pole, single-throw (DPST) switch. This means that when the toggle switch is moved, two paths for current to flow will be completed. The dotted lines connecting the two poles indicates that they are mechanically connected. They are both activated with a single motion. This is known as mechanical interlocking.

Figure 11-10 view A shows a DPST normally open switch. View B shows the same configuration except that the switch is normally closed. View C shows a symbol for the double-pole, double-throw (DPDT) switch. In this situation, there is a possibility of four paths for current to flow. This type of switch has contacts that are normally opened and normally closed. At any given time, at least two circuits will have power available.

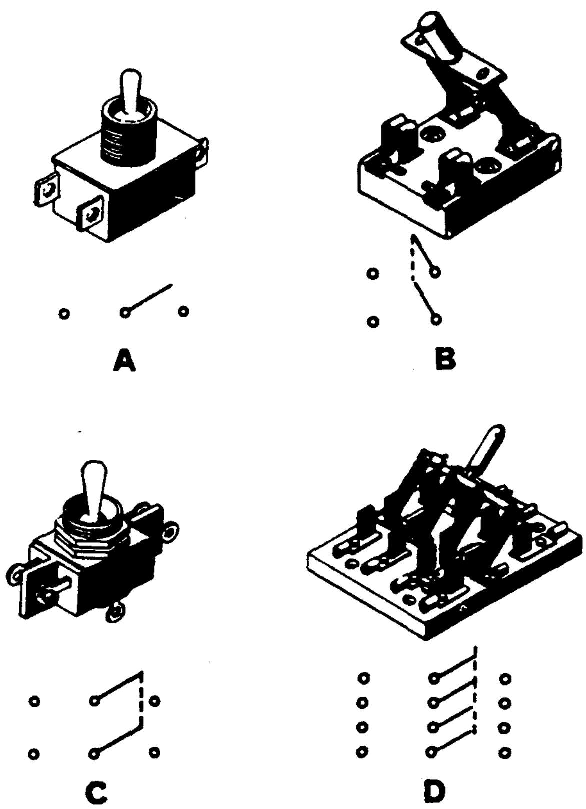

FIGURE 11-9. Multicontact Switches.

TYPES OF SWITCHES

Push Button

A common manual switch is the push button (Figure 11-11). The push button, like all the schematic symbols, has a standard that governs its drawn position on diagrams:

- The position it is drawn on the diagram represents the position it maintains until acted on by an outside force. It is maintained in the normal position by spring pressure.
- The position will always be structurally natural. That is, if you could physically touch the diagramed switch and make it move, it will move only as the picture will let it move.

Figure 11-11 view B shows the symbol for the normally open, double-break push button. This switch, normally used for a start push button, can be physically depressed to touch the contacts or circles. When the finger is removed, the push button is spring-loaded and returns to its NO position.

Figure 11-11 view A shows the normally closed push button in contact below the contacts. This normally closed switch is generally used for a stop push button. When pressure is applied to the button, the pole moves away from the contacts. This push button is also spring-loaded and will return to its normally closed position.

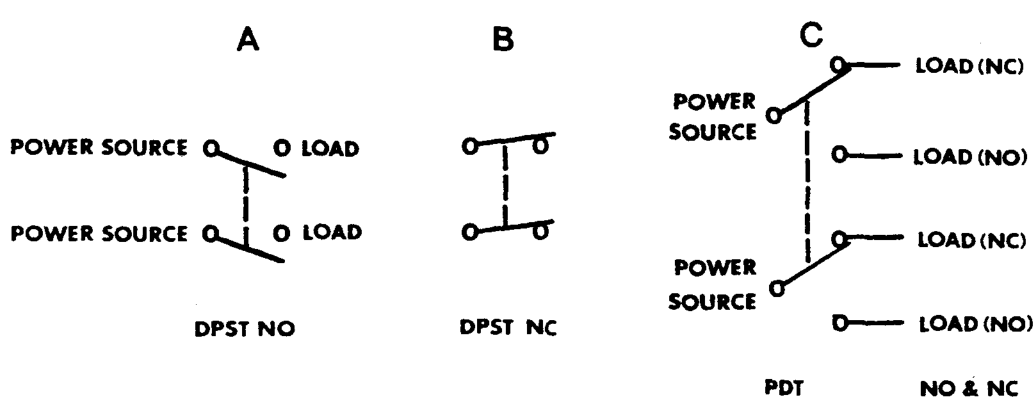

FIGURE 11-10. Normally Open and Normally Closed Switches.

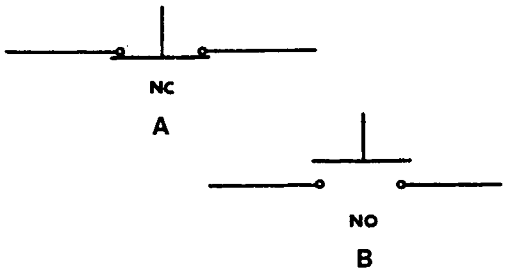

FIGURE 11-11. Push Buttons.

If the stop push button's pole was placed above the contacts (circles), it would be impossible to imagine pushing the electrical diagram out of the way to open the circuit. This is a very important concept when dealing with more complex symbols. The way the switch is illustrated represents the manner in which the switch is constructed.

Selector Switches

A selector switch is rotated by the operator to a desired position to energize a specific circuit. Figures 11-12 and 11-13 show a two- and three-position selector switch positioned in a diagram. The target table used to determine the exact switch position and the circuit combination is in Figure 11-12. Each contact position on the line diagram is identified. The contacts are lettered, and the switch positions are numbered. The target table is identically marked.

The position column has a place for every switch position. The position identification usually corresponds to the positions labeled on the switch in the component. The contacts column indicates when each lettered circuit is completed. The boxes indicate whether the switch is opened or closed when the switch handle is pointing to the switch position number. If an X is in the block, then the contacts are closed on that letter circuit. Closing the contacts completes that circuit.

In Figure 11-12 view A, the selector switch is in position 1. In the target table, position 1 has an X under the contact column a. This indicates that the circuit labeled "a" now can energize coil number 1.

Another way to indicate the position of the selector switch is to use differentiating lines. Figure 11-13 uses solid, circular, and dashed lines to indicate the three positions of the selector switch. In the solid line configuration, the selector points to the 1 position, and the topmost circuit is energized. In the circle configuration, the OFF position selection is made, and the pole is positioned between the top and bottom circuit contacts. This position leaves Ml and M2 de-energized. In the 2 position, M2 is energized, and Ml is de-energized.

Snap-Action Switches

A snap-action switch keeps the movement of the contacts independent from the physical activation of the switch. In a toggle switch, for example,

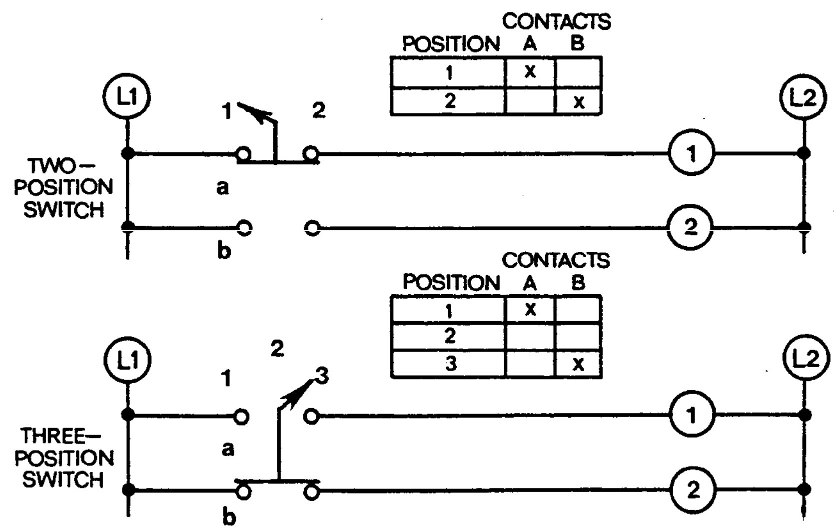

FIGURE 11-12. Use of a Target Table.

no matter how fast or how slow the toggle is moved, the actual switching of the circuit takes place at a fixed speed. The snap-action switch is constructed by making the switch mechanism a leaf spring so that it snaps between positions. Increasing the contact closing speed decreases the time arcing can take place. A snap-action switch cannot be between positions.

Microswitch

A microswitch is a precision snap-action switch in which the operating point is preset and very accurately determined (Figure 11-14). The operating point is the point at which the plunger causes the switch to switch.

The microswitch in Figure 11-14 is a two-position, single-pole, double-throw, single-break, momentary-contact, precision, snap-action switch. The terminals are marked "C" for common, "NO" for normally open, and "NC" for normally closed.

In Figure 11-15, the common terminal is connected through the NC contact terminal. In this position, with this simple wiring circuit, bulb Alights.

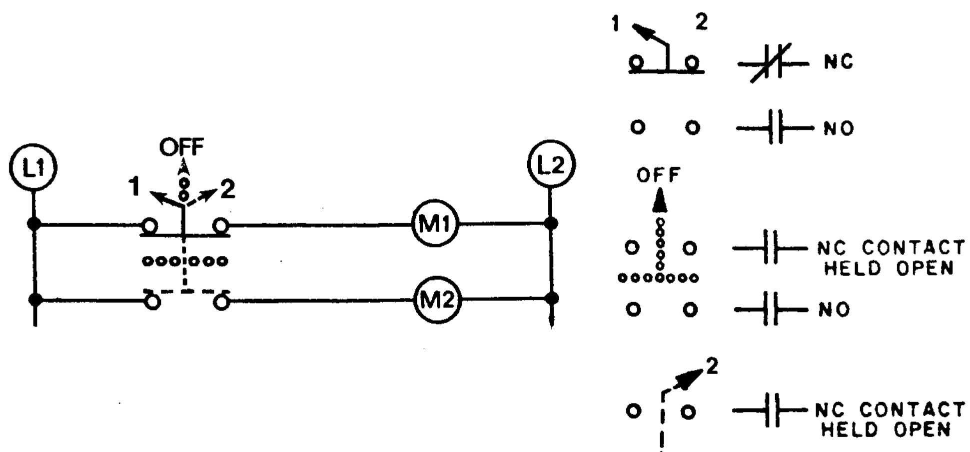

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FIGURE 11-13. The Operation of a Maintained Three-Position Selector Switch.

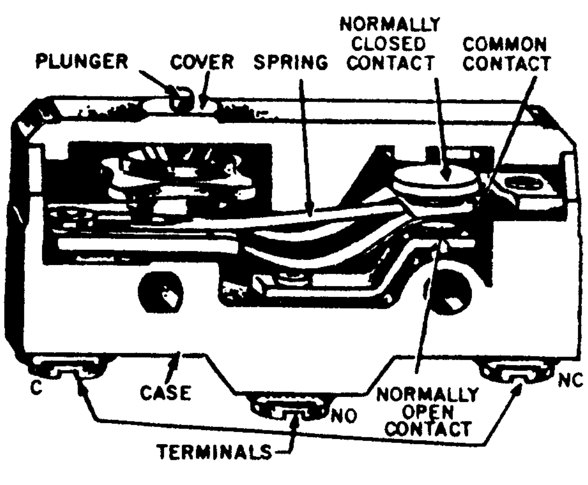


FIGURE 11-14. Precision Snap-Action Switch (Microswitch).

When the plunger is depressed, the spring will snap into the momentary position, and the common terminal will be connected to the NO terminal. In this position, the NC contact opens, and bulb A is off. The NO contact closes, and bulb B is lit. As soon as the plunger is released, the spring will snap back to the original NC position.

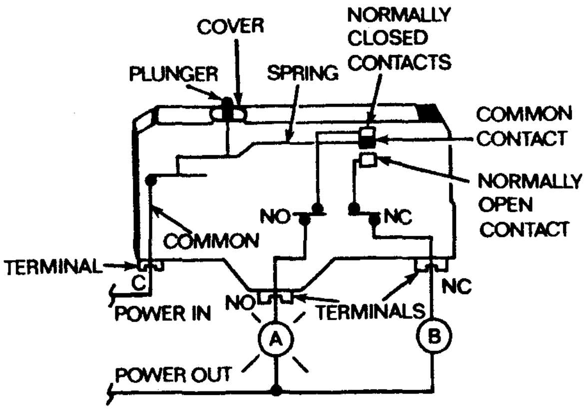


FIGURE 11-15. The Common Connection.

Other Switches

There are hundreds of switches that require some type of activation by other than human interaction. The following are a sampling to serve as a guide in understanding the operation of circuit control devices and their symbol relationships.

Limit Switch. The Army's fleet is based on the assumption that there will be few, if any, ports left in the areas of military confrontation. The LCM, the 1466 and 1600 class LCU, and the 2000 series LCUs are to unload their cargo on undeveloped beaches. This requires the use of a hinged ramp. A common concern to all these vessels is the prevention of excessive ramp cable slack. Excessive slack can cause tangling that will cut the cable. A ramp slack safety switch prevents the cables from coming off their drums when the ramps are operated. This switch is a limit switch. As long as cable tension is acting on the limit switch, the circuit can be energized. If, however, switch pressure is removed because of cable slack, the switch will open the circuit and prevent the cable drum from turning.

The switch is made up of two parts. The lever, or the actuator, is physically moved by an outside source (or the cable as mentioned above). The lever physically changes the position of the contacts from NO to NC or NC to NO.

This switch can be used in four ways: normally open, normally open held closed, normally closed, or normally closed held open. Figure 11-16 shows the four limit switch positions. By arranging them according to the circuit and the response wanted from the circuit, this two-position switch will provide a wide range of safety options.

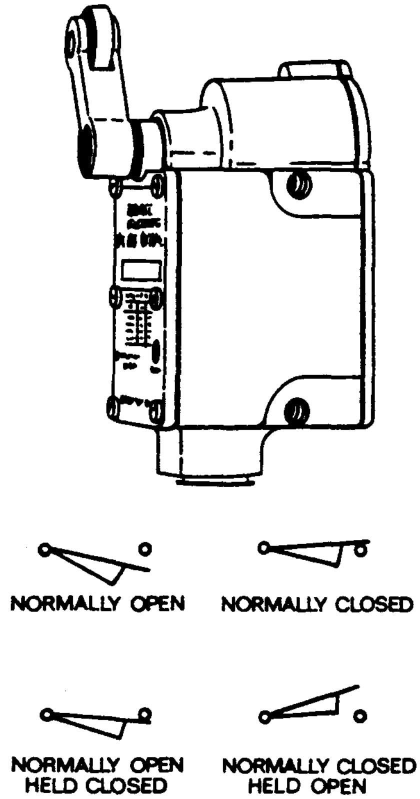


FIGURE 11-16. Common Type of Limit Switch and Symbols.

NOTE. Manufacturers require strict compliance in observing polarity when installing limit switches in DC circuits. If the limit switch is connected incorrectly, metal transfer between the switch contacts will occur. Possible welding of the contacts can take place.

Pressure Switch. Pressure switches are control devices that react to pressure changes in water, oils, gases, and so forth. Figure 11-17 shows a cutaway portion of the pressure switch. A normally closed pressure switch is used to maintain the correct water pressure in a potable water system (view A). As the pressure from the pump increases, the pressure switch contacts will open and disconnect the pump motor from the circuit. As the water is used and the pressure drops, the switch closes, and the pump starts to replenish the reservoir.

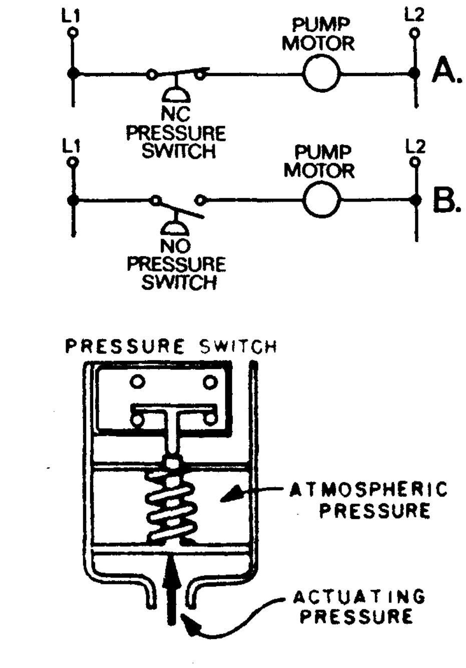


FIGURE 11-17. Pressure Switch and Symbol.

The normally open switch in view B cannot be used in this situation. With water pressure at below acceptable standards, the pump would continue to remain idle because there was no outside force acting on it to close the contacts. If the contacts could be held closed until they stayed closed under pressure, then the pump would not shut off. The NO pressure switch is used to maintain inches of mercury (vacuum) in the sewage systems. When the vacuum is lost, the pressure increases (toward atmospheric pressure of 14.7 psia). This increase in pressure (or loss of vacuum) closes the switch. The vacuum pumps then pull out the air to maintain the correct pressure in inches of mercury.

An NO pressure switch needs an outside force to close its contacts. An NC pressure switch needs an outside force to open the contacts.

Temperature Switch. A bimetallic control device responds to changes in temperature. Two dissimilar metal stripes are attached together. The fusion of two dissimilar metals, one material on top of the other material, is called a bimetallic strip. The bimetallic strip has a contact surface at one end. As long as the bimetallic strip remains cool, the contacts remain together, completing a circuit. As the temperature increases, each of these two metal strips expand at a different rate. The faster expanding metal curves toward the slower expanding material. When the bimetallic strip distorts sufficiently, it curves away from the other contact, opening the circuit (Figure 11-18).

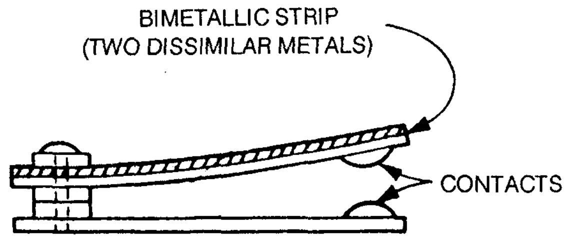


FIGURE 11-18. Bimetallic Strip.

This type of bimetallic device is affected by heat. Heat can be from the ambient temperature around the switch or from the current flowing through the strip. When current is used to create the heat that can distort the bimetallic strip, it can be used in an overload protection device.

Figure 11-19 illustrates a capillary tube control device. The temperature switch is far removed from the bulb sensor, separated by a long capillary tube. The temperature switch can be placed in a convenient location, while the sensing bulb is positioned for the most effective temperature measurement. A volatile liquid or gas within the bulb and capillary tube reacts proportionally to temperature changes. As the ambient temperature surrounding the bulb rises, the bulb's internal volative gas expands with a resulting increase in pressure. The pressure within the bulb is transmitted through the capillary tube acting on the remotely located switch. As the temperature surrounding the bulb is reduced, so is the internal pressure of the volatile gas.

MAINTENANCE AND REPLACEMENT OF SWITCHES

Switches are usually very reliable electrical devices. Most switches are designed to operate 100,000 times or more without failure if the voltage and current ratings are not exceeded. Even so, switches do fail. The following information will help you in troubleshooting switches.

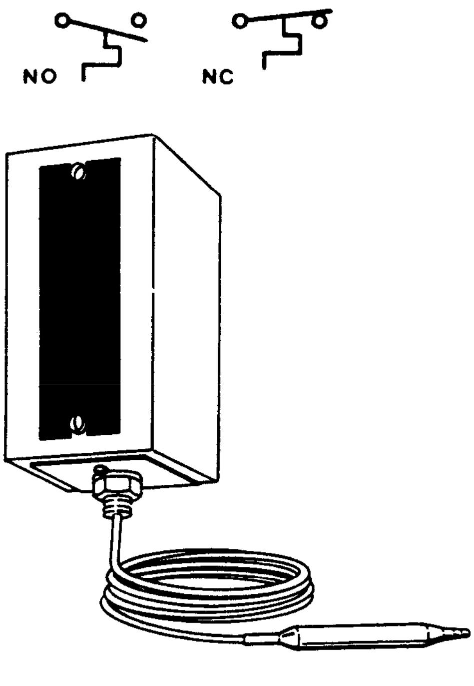


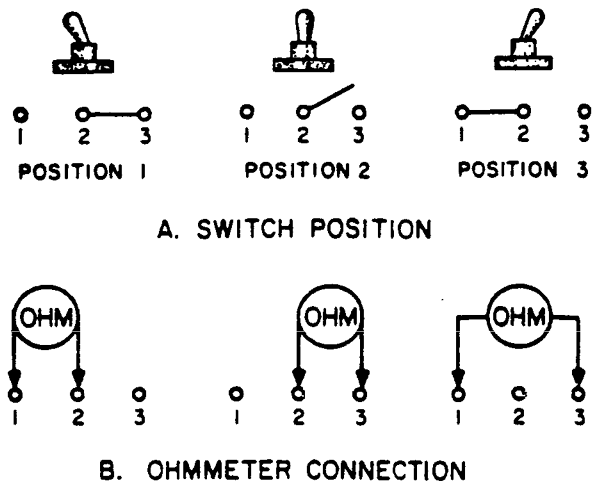
FIGURE 11-19. NO and NC Temperature-Actuated Switch.

Checking Switches

Two meters can be used to check a switch: an ohmmeter or a voltmeter. The method employing these meters is explained below using a single-pole, double-throw, single-break, three-position, snap-acting toggle switch.

Figure 11-20 shows the method of using an ohmmeter to check a switch. View A shows the toggle switch positions and schematic diagrams for the three-switch positions. View B shows the ohmmeter connections used to check the switch while the toggle switch is in position 1. View C is a table showing the switch position, ohmmeter connection, and correct ohmmeter reading for those conditions.

Before the ohmmeter is used, remove power from the circuit and isolate the suspected switch from the circuit. The best way to isolate it from the circuit is to remove it from the circuit entirely. This is not always practical, and it is sometimes necessary to check a switch while there is power applied to it. In these cases, an ohmmeter cannot be used to check the switch, but a voltmeter can.



SWITCH POSITION	OHMMETER CONNECTION	CORRECT READING
1	1-2	∞
1	2-3	0
1	1-3	∞
2	1-2	∞
2	2-3	∞
2	1-3	∞
3	1-2	0
3	2-3	∞
3	1-3	∞

C. TABLE OF CORRECT READINGS

FIGURE 11-20. Checking a Switch With an Ohmmeter.

Figure 11-21 shows the method of using a voltmeter to check a switch. View A shows a switch connected between a power source (battery) and two loads. View B shows a voltmeter connected between the battery terminal negative node and each of the three-switch terminals while the switch is in position 1. View C is a table showing the switch position, voltmeter connection, and the correct voltmeter reading.

With the switch in position 1 and the voltmeter connected between the battery terminal negative node and terminal 1, the voltmeter should indicate no voltage (0V). When the voltmeter is connected to terminal 2, the voltmeter should indicate the source voltage. With the voltmeter connected to terminal 3, the source voltage should also be indicated. The table in view C shows the correct readings with the switch in position 2 or 3.

Replacing Switches

When a switch is faulty, it must be replaced. The technical manual for the equipment will specify the exact replacement switch. If it is necessary to use a substitute switch, it must have all of the following characteristics:

- At least the same number of poles.
- At least the same number of throws.
- At least the same number of breaks.
- At least the same number of positions.
- The same configuration in regard to momentary or locked positions.
- A voltage rating equal to or higher than the original switch.
- A current rating equal to or higher than the original switch.
- A physical size compatible with the mounting.

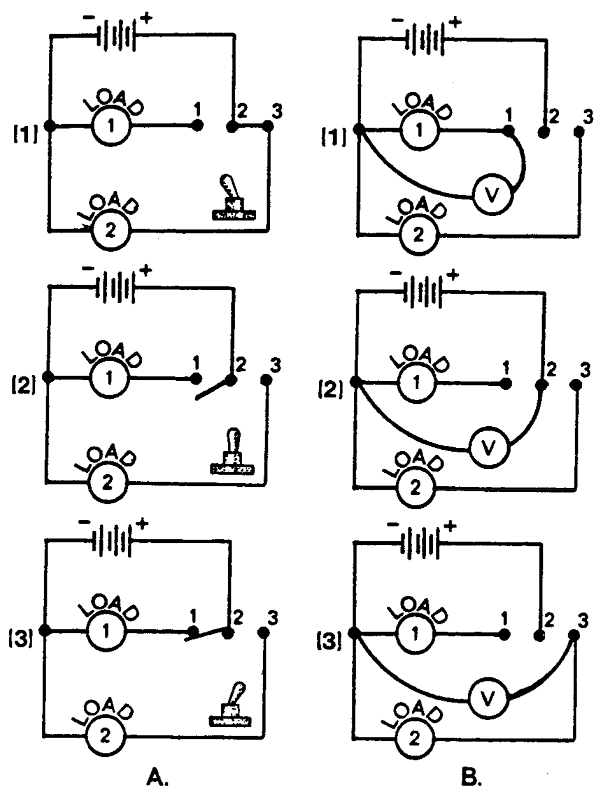
The number of poles and throws of a switch can be determined from markings on the switch itself. The switch case will be marked with a schematic diagram of the switch or letters, such as SPST for single pole, single throw. The voltage and current ratings will also be marked on the switch. The number of breaks can be determined from the schematic marked on the switch or by counting the terminals after the number of poles and throws have been determined. The type of actuator and the number of positions of the switch can be determined by looking at the switch and switching it between positions.

Whenever component substitutions are made, the correct replacement must be installed as soon as possible. Vessel configuration must be maintained, and unauthorized modifications are prohibited.

Performing Preventive Maintenance of Switches

Switches do not fail very often. However, there is still a need for switch preventive maintenance. Switches should be checked periodically for corrosion at the terminals, smooth and correct operation, and physical damage. Any problems found need to be corrected immediately.

Most switches can be inspected visually for corrosion and damage. The operation of the switch may be checked by moving the actuator. When the actuator is moved, you can feel whether the switch operation is smooth or seems to have a great deal of friction. To check the actual switching, observe the operation of the equipment or check the switch with a meter.



SWITCH POSITION	VOLTMETER CONNECTION	CORRECT READING
1	1	OV
1	2	VOLTAGE
1	3	VOLTAGE
2	1	OV
2	2	VOLTAGE
2	3	OV
3	1	VOLTAGE
3	2	VOLTAGE
3	3	OV

TABLE OF CORRECT READINGS

C.

FIGURE 11-21. Checking a Switch With a Voltmeter.

CHAPTER 12

ELECTRICAL CONDUCTORS

INTRODUCTION

Many factors determine the type of electrical conductor to be used to connect components. Some of these factors are the physical size of the conductor, the type of material used for the conductor, and the electrical characteristics of the insulation. Other factors that can determine the choice of a conductor are the weight, the cost, and the environment where the conductor is to be used.

CONDUCTOR SIZES

To compare the resistance and size of one conductor with that of another, a standard or unit must be established. A convenient unit of measurement for the diameter of a conductor is the mil (0.001 or one-thousandth of an inch). A convenient unit of conductor length is the foot. The standard unit of size in most cases is the mil-foot. A wire will have a unit size if it has a diameter of 1 mil and a length of 1 foot.

Square Mil

The square mil is a unit of measurement used to determine the cross-sectional area of a square or rectangular conductor (Figure 12-1 views A and B). A square mil is the area of a square whose sides are each 1 mil. To obtain the cross-sectional area of any square conductor, multiply the dimensions of any side of the conductor by itself. For example, with a square conductor with a side dimension of 3 mils, multiply 3 mils by itself (3 mils x 3 mils). This gives a cross-sectional area of 9 square mils.

To determine the cross-sectional area of a rectangular conductor, multiply the length times the width of the end face of the conductor (in mils). For example, if one side of the rectangular cross-sectional area is 6 mils and the other side is 3 mils, nultiply 6 mils x 3 mils. The cross-sectional area is 18 square mils.

The following is another example of how to determine the cross-sectional area of a rectangular conductor. Assume a bus bar is 3/8 inch thick and 4 inches wide. The 3/8 inch expressed in decimal form is .375 inch. Since 1 mil equals .001 inch, the thickness of the conductor is 375 mils. The width is 4 inches. Since there are 1,000 mils per inch, the width is 4,000 mils.

To determine the cross-sectional area, multiply the length by the width, or 375 mils x 4,000 mils. The area (A) equals 1,500,00 square mils.

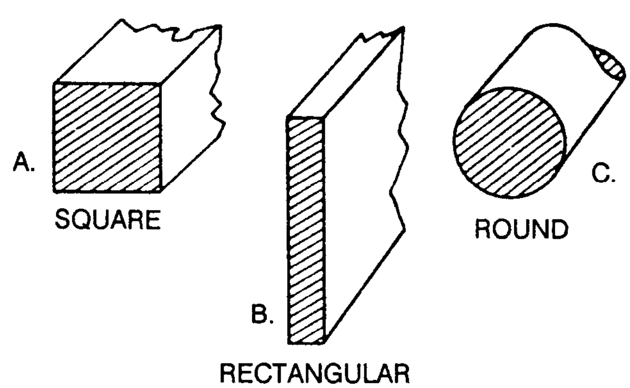


FIGURE 12-1. Cross-Sectional Area of Conductors.

Circular Mil

The circular mil is the standard unit of measure of the cross-sectional area of a wire. This unit of measurement is found in American and English wire tables. The diameter of a round conductor used to conduct electricity may be only a fraction of an inch. Therefore, it is convenient to express this fraction in mils to avoid using decimals. For example, the diameter of a wire is expressed as 25 mils instead of 0.025 inch, A circular mil is the area of a circle whose diameter is 1 mil, as shown in Figure 12-2 view B. The area in circular mils of a round conductor is obtained by squaring the diameter, which is measured in mils. Thus a wire having a diameter of 25 mils has an area of 25^2 or 625 circular mils.

To determine the number of square mils in the same conductor, apply the conventional formula for determining the area o a circle (area [A] = pi x radius squared = pi x r^2. In this formula, A is the unknown. It equals the cross-sectional area in square mils. Pi is the constant 3.1416. Letter r is the radius of the circle, or half the diameter. Through substitution A = 3.1416 $(12.5)^2$. Therefore, 3.1416 x 156.25 = 490.625 square mils. The cross-sectional area of the wire has been shown to have 625 circular mils, while it has only 490.625 square mils. Therefore, a circular mil represents a smaller unit of area than the square mil. If a wire has a cross-sectional diameter of 1 mil, by definition he circular mil area (CMA) is $A = D^2$,or $A = 1^2$, or A = 1 circular mil. To determine thes are mil area of the same wire, the form a A = pir^2 is applied. Therefore, A = 3.1416 x $(.5)^2$. When the formula is carried forward, A = 3.1416 x .25, or A = .7854 square mils. From this, it can be concluded that 1 circular mil equals .7854 square mil. This becomes important when square conductors (Figure 12-2 view A) and round conductors (view B) are compared. View C shows the comparison. When the square mil area is given, divide the area by 0.7854 to determine the circular mil area. When the circular mil area is given, multiply the area by 0.7854 to determine the square mil area.

Example: The American wire gauge (AWG) No. 12 wire has a diameter of 80.81 mils:

a. What is the area in circular mils?

b. What is the area in square mils?

Solution:

a. $A = D^2 = (80.81)^2$ = 6,530 circular mils.

b. A = 0.7854 x 6,530 = 5,128.7 square mils.

A wire in its usual form is a slender rod or filament of drawn metal. In larger sizes, wire is difficult to handle. To increase flexibility, it is stranded. Strands are usually single wires twisted together in sufficient numbers to make up the necessary cross-sectional area of the cable. The total area in circular mils is determined by multiplying the area in circular mils of one strand by the number of strands in the cable.

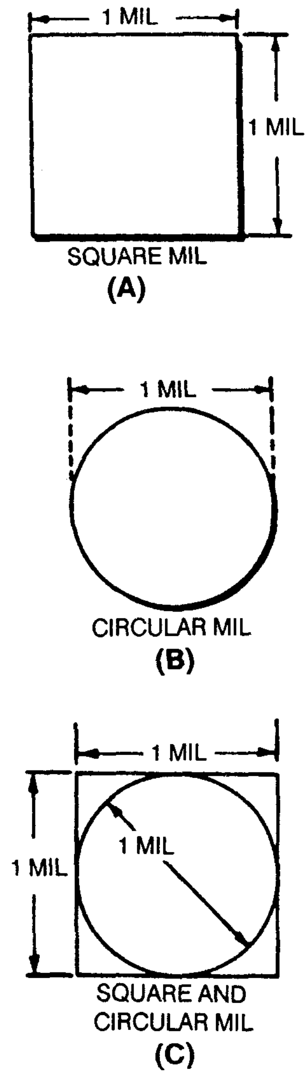


FIGURE 12-2. A Comparison of Circular and Square Mils.

Circular Mil-Foot

A circular mil-foot is a unit of volume (Figure 12-3). It is a unit conductor 1 foot in length with across-sectional area of 1 circular mil. Because it is considered a unit conductor, the circular mil-foot is useful in making comparisons between wires that are made of different metals. For example, a basis of comparison of the resistivity (to be discussed later) of various substances may be made by determining the resistance of a circular mil-foot of each of the substances.

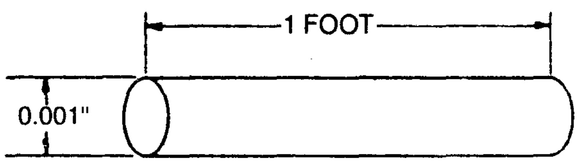


FIGURE 12-3. Circular Mil-Foot.

In working with square or rectangular conductors, such as ammeter shunts and bus bars, it is sometimes more convenient to use a different unit volume. Bus bars are to be used when a large current capacity is required. Accordingly, unit volume may also be measured as the centimeter cube. Specific resistance, therefore, becomes the resistance offered by a cube-shaped conductor 1 centimeter in length and 1 square centimeter in cross-sectional area. The unit volume to be used is given in tables of specific resistances.

SPECIFIC RESISTANCE OR RESISTIVITY

Specific resistance, or resistivity, is the resistance in ohms offered by a unit volume (the circular mil-foot or the centimeter cube) of a substance to the flow of electric current. Resistivity is the reciprocal of conductivity. A substance that has a high resistivity will have a low conductivity and vice versa.

Thus, the specific resistance of a substance is the resistance of a unit volume of that substance. Many tables of specific resistance are based on the resistance in ohms of a volume of a substance 1 foot in length and 1 circular mil in cross-sectional area. If the kind of metal of which a conductor is made is known, the specific resistance of the metal may be obtained from one of these tables. These tables also specific the temperature at which the resistance measurement is made. Table 12-1 gives the specific resistance of some common substances.

The resistance of a conductor of a uniform cross section varies directly as the product of the length and the specific resistance of the conductor and inversely as the cross-sectional area of the conductor. Therefore, the resistance of a conductor may be calculated if the length, cross-sectional

TABLE 12-1. Specific Resistance to Common Substances.

Substance	Specific resistance at 20° C.	
	Centimeter cube (microhms)	Circular-mil-foot (ohms)
Silver	1.629	9.8
Copper (drawn).	1.724	10.37
Gold	2.44	14.7
Aluminum . . .	2.828	17.02
Carbon (amorphous.)	3.8 to 4.1	. . . .
Tungsten	5.51	33.2
Brass	7.0	42.1
Steel (soft) . . .	15.9	95.8
Nichrome . . .	109.0	660.0

area, and specific resistance of the substance is known. Expressed as an equation, the resistance (R) in ohms of a conductor is —

$$R = \frac{p\,L}{A}$$

Where: p (Greek rho) = the specific resistance in ohms per circular mil-foot (refer to Table 12-1)

L = the length in feet
A = the cross-sectional area in circular mils

Example: What is the resistance of 1,000 feet of copper wire having a cross-sectional area of 10,400 circular mils (No. 10 AWG wire) at a temperature of 20C?

Given

p = 10.37 ohms/circular mil-foot
L = 1,000 feet
A = 10,400 circular mils

Solution:

$$R = \frac{p\,L}{A} = 10.37\,\frac{(1{,}000)}{10{,}400} = 1 \text{ ohm (approximately)}$$

RELATIONSHIP BETWEEN WIRE SIZES

Wires are manufactured in sizes numbered according to a table known as the American wire gauge (AWG). The National Bureau of Standards publishes tables for various conductors either solid or stranded and the material they are made from, such as copper or aluminum. Table 12-2 is one example of such a table. The wire diameters become smaller as the gauge numbers become larger. (Numbers are rounded off for convenience but are accurate for practical application.) The largest wire in Table 12-2 is 0000, and the smallest is number 22. Larger and smaller sizes are manufactured but are not commonly used by the Army. The tables show the diameter, circular mil area, and area in square inches of the different AWG wire sizes. It also shows the resistance per thousand feet of the various wire sizes at 25C.

STRANDED WIRES AND CABLES

A wire is a slender rod or filament of drawn metal. The definition restricts the term to what would ordinarily be understood as solid wire. The word “slender” is used because the length of a wire is usually’ large in comparison with the diameter. If a wire is covered by insulation, it is called an insulated wire. Although wire properly refers to the metal, it is generally understood to include the insulation.

A conductor is a wire suitable for carrying an electric current. A stranded conductor is composed of a group of wires or of any combination of groups of wires. The wires in a stranded conductor are usually twisted together and not insulated from each other.

A cable is either a stranded conductor (a single conductor cable) or a combination of conductors insulated from one another (multiple conductor cable). The term “cable” is a general one, and in practice, it usually applies only to larger sizes of conductors. A small cable is more often called a stranded wire. The insulated cables may be sheathed (covered) with lead or protective armor.

Figure 12-4 shows some of the different types of wire and cable used in the military.

Conductors are stranded mainly to increase their flexibility. The wire strands in cables are arranged in the following order. The first layer of strands around the center conductor are made of 6 conductors. The second layer is made up of 12 conductors. The third layer is made up of 18 conductors, and so on. Thus, standard cables are composed of 7, 19, and 37 strands, in continuing fixed increments.

The overall flexibility may be increased by further stranding of the individual strands. All Army marine electrical wires and cables will be of the stranded type. The excessive vibration of a vessel prohibits solid conductor wires.

Figure 12-5 shows a typical cross section of a 37-strand cable. It also shows how the total circular mil cross-sectional area of a stranded cable is determined.

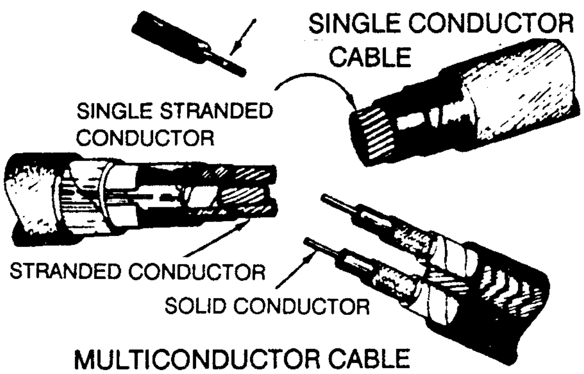


FIGURE 12-4. Conductors.

SELECTION OF WIRE SIZE

Several factors must be considered in selecting the size wire to be used for transmitting and distributing electric power. There are military specifications that cover the installation of wiring of ships and electrical/electronic equipment. These specifications describe the technical requirements for material which is to be purchased from manufacturers by the Department of Defense. One important reason for these specifications is to reduce the danger of fires caused by the improper selection of wire sizes. Wires can carry only a limited amount of current safely. If the current flowing through a wire exceeds the current-carrying capacity of the wire, excess heat is generated. This heat may be great enough to burn off the insulation around the wire and continue to do much greater damage by starting a fire.

TABLE 12-2. Construction and Resistances of Standard Class B Concentric Conductors.

Conductor Size		Class B Stranding			Nominal dc Resistance ohms/1000 ft at 25 °C	
Area in Circular Mils	Gauge, AWG Size	Number of Wires	Diameter of wires (mils)	Conductor Diameter (inches)	Bare	Alloy Coated or Tinned
2 000 000		127	125.5	1.632	0.00539	0.00555
1 500 000		91	128.4	1.412	0.00719	0.00740
1 250 000		91	117.2	1.289	0.00863	0.00883
1 000 000		61	128.0	1.152	0.0108	0.0111
750 000		61	110.9	0.998	0.0144	0.0148
600 000		61	99.2	0.893	0.0180	0.0187
500 000		37	116.2	0.813	0.0216	0.0222
400 000		37	104.0	0.728	0.0270	0.0278
350 000		37	97.3	0.681	0.0308	0.0320
300 000		37	90.0	0.630	0.0360	0.0374
250 000		37	82.2	0.573	0.0431	0.0449
211 600	0000	19	105.5	0.528	0.0510	0.0525
167 800	000	19	94.0	0.470	0.0643	0.0669
133 100	00	19	83.7	0.418	0.0811	0.0843
105 600	0	19	74.5	0.373	0.102	0.106
83 690	1	19	66.4	0.332	0.129	0.134
66 360	2	7	97.4	0.292	0.163	0.169
52 620	3	7	86.7	0.260	0.205	0.213
41 740	4	7	77.2	0.232	0.258	0.269
33 090	5	7	68.8	0.206	0.326	0.339
26 240	6	7	61.2	0.184	0.411	0.427
20 820	7	7	54.5	0.164	0.518	0.539
16 510	8	7	48.6	0.146	0.653	0.679
10 380	10	7	38.5	0.116	1.04	1.08
6 530	12	7	30.5	0.092	1.65	1.72
4 110	14	7	24.2	0.073	2.63	2.73
2 580	16	7	19.2	0.058	4.18	4.44
1 620	18	7	15.2	0.046	6.64	7.05
1 020	20	7	12.1	0.036	9.97	10.6
643	22	7	10.0	0.030	16.1	16.7

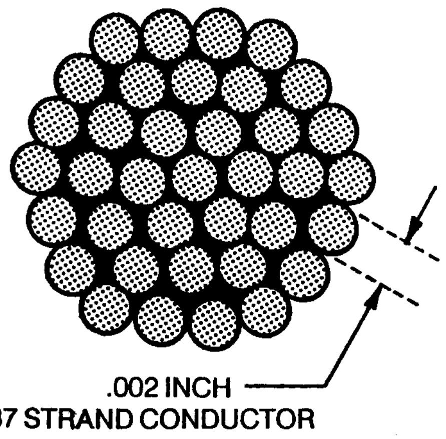


FIGURE 12-5. Stranded Conductor.

FACTORS AFFECTING THE CURRENT RATING

The current rating of a cable or wire indicates the current capacity that the wire or cable can safely carry continuously. If this limit, or current rating, is exceeded for a length of time, the heat generated may bum the insulation. The current rating of a wire is used to determine what size is needed for a given electrical load.

The following factors determine the current rating of a wire:

- The conductor size.
- The material of which the conductor is made.
- The location of the wire.
- The type of insulation used.
- Ambient temperature.

Some of these factors affect the resistance of a wire carrying current.

An increase in the diameter or cross section of a conductor decreases its resistance and increases its capability to carry current. An increase in the specific resistance of a conductor increases its resistance and decreases its capacity to carry current.

The location of a conductor determines the temperature under which it operates. A cable may be located in a row of other cables (banked) or placed alongside other cables in one of two rows (double-banked). Therefore, it operates at a higher temperature than if it is open to the free air. The higher the temperature under which a wire is operating, the greater its resistance. Its capacity to carry current is also lowered. In each case, the resistance of a wire determines its current-carrying capacity. The greater the resistance, the more power it dissipates in the form of heat energy. Electrical conductors may also be installed in locations where the ambient temperature is relatively high. When this is the case, the heat generated by external sources constitutes an appreciable part of the total conductor heating. This will be explained further under *Temperature Coefficient*. Due allowances must be made for the influence of external heating on the allowable conductor current. Each case has its own specific limitations. Table 12-3 gives the maximum current-carrying capacity for distribution cable. Table 12-4 shows control cable ampacities. Table 12-5 specifies the maximum allowable operating temperature of insulated conductors. It varies with the type of conductor insulation being used.

The insulation of a wire does not affect its resistance. It does, however, determine how much heat is needed to burn the insulation. The limit of current that an insulated conductor can withstand depends on how hot the conductor can get before it burns the insulation. Different types of insulation will burn at different temperatures. Therefore, the type of insulation used is a factor that determines the current rating of a conductor. Polyvinyl chloride (PVC) insulation will begin to deteriorate at relatively low temperatures. Silicon rubber retains its insulating properties at much higher temperatures.

TABLE 12-3. Distribution Cable Maximum Current-Carrying Capacity.

(Types T, E, X, S, and GTV — 45 °C Ambient)

			Single-Conductor Cable			Two-Conductor Cable			Three-Conductor Cable		
AWG	mm²	Circular Mils	T 75 °C	E, X 90 °C	S, GTV 100 °C	T 75 °C	E, X 90 °C	S, GTV 100 °C	T 75 °C	E, X 90 °C	S, GTV 100 °C
14	2.1	4410	28	34	37	24	29	31	20	24	25
12	3.3	6530	35	43	45	31	36	40	24	29	31
10	5.3	10 400	45	54	58	38	46	49	32	38	41
8	8.4	16 500	56	68	72	49	60	64	41	48	52
7	10.6	20 800	65	77	84	59	72	78	48	59	63
6	13.3	26 300	73	88	96	66	79	85	54	65	70
5	16.8	33 100	84	100	109	78	92	101	64	75	82
4	21.1	41 700	97	118	128	84	101	110	70	83	92
3	26.7	52 600	112	134	146	102	121	132	83	99	108
2	33.6	66 400	129	156	169	115	137	149	93	111	122
1	42.4	83 700	150	180	194	134	161	174	110	131	143
1/0	53.5	106 000	174	207	227	153	183	199	126	150	164
2/0	67.4	133 000	202	240	262	187	233	242	145	173	188
3/0	85.0	168 000	231	278	300	205	245	265	168	201	218
4/0	107.2	212 000	271	324	351	237	284	307	194	232	252
	127	250 000	300	359	389	264	316	344	217	259	282
	152	300 000	345	412	449	296	354	385	242	290	316
	177	350 000	372	446	485	324	387	421	265	317	344
	203	400 000	410	489	533	351	419	455	286	342	371
	253	500 000	469	560	609	401	479	520	329	393	428
	271	535 000	485	579	630	415	496	538	340	407	443
	304	600 000	521	623	678	450	539	585	368	440	478
	327	646 000			715						
	380	750 000	605	723	786	503	602	656	413	494	537
	394	777 000			804						
	507	1 000 000	723	867	939						
	562	1 110 000			1003						
	633	1 250 000	824	990	1072						
	706	1 500 000	917	1100	1195						
	1013	2 000 000	1076	1292	1400						

	DC Ratings		
	75	90	100
750 000	617	738	802
1 000 000	747	896	964
1 250 000	865	1038	1126
1 500 000	980	1177	1276
2 000 000	1195	1435	1557

NOTES: (1) Current ratings are for ac or dc except for sizes one-conductor 750 000 circular mils and larger.

(2) For service voltage 601 V to 5000 V, Type T should not be used.

(3) Current-carrying capacity of four-conductor cables where one conductor is neutral, is the same as three-conductor cables listed in Table A6.

(4) The above values are based on ambient temperatures of 45 °C and maximum conductor temperatures not exceeding 75 °C for type T insulated cables, 90 °C for types X and E insulated cables, and 100 °C for types GTV and S insulated cables.

(5) If ambient temperatures differ from 45 °C the values shown above should be multipled by the following factors:

Ambient Temperature	40 °C	50 °C	60 °C	70 °C
Type T insulated cables	1.08	0.91	—	—
Type X and E insulated cables	1.05	0.94	0.82	—
Type GTV and S insulated cables	1.04	0.95	0.85	0.74

(6) The above current-carrying capacities are for marine installations with cables arranged in a single bank per hanger and are 85% of the ICEA calculated values [see Note (7)]. Double banking of distribution-type cables should be avoided. For those instances where cable must be double banked, the current-carrying capacities in the above table should be multiplied by 0.8.

(7) The ICEA calculated current capacities of these cables are based on cables installed in free air, that is, at least one cable diameter spacing between adjacent cables. See IEEE Std-135-1962 [31].

TABLE 12-4. Control Cable Ampacities.

Dimensions, Weights, and Ampacities
Multiconductor Control Cable 600 V

	Conductor Size AWG 14				Conductor Size AWG 16				Conductor Size AWG 18			
			Ampacity				Ampacity				Ampacity	
Number of Conductors	Max Diam (in)	Weight (lbs per 1000 ft)	Type T Conductors 75 °C	Type X or E Conductors 90 °C	Max Diam (in)	Weight (lbs per 1000 ft)	Type T Conductors 75 °C	Type X or E Conductors 90 °C	Max Diam (in)	Weight (lbs per 1000 ft)	Type T Conductors 75 °C	Type X or E Conductors 90 °C
2	0.50	155	13	17	0.46	140	11	14	0.44	115	8	11
3	0.52	175	11	14	0.48	145	8	11	0.46	125	7	9
4	0.56	200	9	11	0.52	170	7	9	0.49	145	6	7
7	0.68	295	8	10	0.60	225	6	8	0.56	190	5	7
10	0.82	410	8	10	0.75	330	6	8	0.71	280	5	7
14	0.89	500	8	10	0.81	395	6	8	0.76	325	5	7
19	1.02	670	8	10	0.89	485	6	8	0.83	395	5	7
24	1.16	815	8	10	1.06	640	6	8	0.94	485	5	7
30	1.22	945	7	8	1.11	735	5	7	1.04	600	4	6
37	1.31	1120	7	8	1.19	860	5	7	1.11	690	4	6
44	1.46	1300	6	7	1.31	1000	4	6	1.22	805	4	5
61	1.61	1680	6	7	1.47	1270	4	6	1.34	1010	4	5

Notes: (1) Weights given are for cables with Type T insulated conductors. Those with Type X or E insulated conductors will be from three to five percent lighter depending on the number of conductors.
(2) Ampacities are average current capacities for all conductors in the cables. No individual conductor should be permitted to carry more than 1.5 times these values.
(3) All ampacities are for double-banked cables in trays, 45 °C ambient temperature.
(4) For ambient temperatures other than 45 °C, the ampacity values shown should be multiplied by the factors in Table A6, Note (5).

TABLE 12-5. Maximum Allowable Operating Temperature of Insulated Conductors.

Insulation Type Designation		Maximum Conductor Temperature
T	Polyvinyl chloride	75C
E	Ethylene propylene rubber	90C
X	Cross-linked polyethylene	90C
M	Mineral (MI)	85C
S	Silicone rubber	100C
GTV	Impregnated glass, varnished cloth	100C

COPPER VERSUS ALUMINUM CONDUCTORS

Although silver is the best conductor, its cost limits its use to special circuits. It is used where a substance with high conductivity or low resistivity is needed.

Copper has high conductivity. It is more ductile (can be drawn out). It has relatively high tensile strength (the greatest stress a substance can bear along its length without tearing apart). It can also be easily soldered. US Army vessels use only soft annealed copper wire. The copper conductor is tinned or alloy-coated to ensure compatibility with insulation.

TEMPERATURE COEFFICIENT

The resistance of pure metals, such as silver, copper, and aluminum, increases as the temperature increases. The resistance of some alloys, such as constantan and manganin, changes very little as the temperature changes. Measuring instruments use these alloys because the resistance of the circuits must remain constant to achieve accurate measurements. The amount of increase in the resistance of a l-ohm sample of the conductor per degree rise in temperature above 0C is called the temperature coefficient of resistance. For copper, the value is about 0.00427 ohm. This and more is taken into account when designing the electrical distribution system of the vessel. A wire is not just any wire. There is a reason and a purpose for the entire electrical system. The only changes in the electrical system should be for expedient repairs and approved modifications. Do not modify electrical systems without proper authority.

CONDUCTOR INSULATION

To be useful and safe, electric current must be forced to flow only where it is needed. It must be channeled from the power source to a useful load. In general, current-carrying conductors must not be allowed to come in contact with one another, their supporting hardware, or personnel working near them. To accomplish this, conductors are coated or wrapped with various materials. These materials have such a high resistance that they are, for all purposes, nonconductors. They are generally referred to as insulators or insulating material.

Only the necessary minimum of insulation is applied to any particular type of conductor designed to do a particular job. This is done because of several factors. The expense, stiffening effect, and variety of physical and electrical conditions under which the conductors are operated must be considered. Therefore, a wide variety of insulated conductors is available to meet the requirements of any job.

Two fundamental properties of insulating materials, such as rubber, glass, asbestos, and plastic, are insulation resistance and dielectric strength. These are two entirely different and distinct properties.

Insulation resistance is the resistance to current leakage through the insulation materials. Insulation resistance can be measured by means of a megger without damaging the insulation. Information so obtained serves as a useful guide in appraising the general condition of the insulation. Clean, dry insulation having cracks or other faults may show a high resistance but would not be suitable for use. Megger testing does not damage the cable. This is one form of nondestructive testing.

Dielectric strength is the ability of the insulation to withstand potential difference. It is usually expressed in terms of the voltage at which the insulation fails because of the electrostatic stress. Maximum dielectric strength values can be measured only by raising the voltage of a test sample until the insulation breaks down. When the dielectric strength is tested, the cable insulation is damaged. This is an example of destructive testing.

Figure 12-6 shows two types of insulated wire. One is a single, solid conductor. The other is a two-conductor cable with each stranded conductor covered with a rubber-type insulation. In each case, the rubber serves the same purpose: to confide the current to its conductor.

Materials

Marine cable insulation should be one of the following materials:

- Polyvinyl chloride (designated T). This is the most common type of insulation currently used on modern vessels. It is a form of polymerized vinyl compound, resin, or plastic. The maximum conductor temperature that the insulation can handle is 75C. The voltage range is a maximum of 600 volts. The maximum allowable ambient temperature is 50C. It is of thermoplastic construction. This means it becomes soft when heated and rigid when cooled and cured. Polyvinyl chloride-protected cable provides a nonmetallic rigid sheathed cable. It is commonly called PVC.

WARNING

This product produces extremely toxic vapors when ignited. When selecting this type of cable, a designation of "LS" (low smoke) indicates insulation modifications have been made to reduce these toxic gases.

- Ethylene propylene rubber (designated E). This insulation is thermosetting (not reshapeable). The maximum conductor temperature that the insulation can handle is 90C. The maximum allowable ambient temperature is 60C. It is normally used for up to 2,000 volts. For special applications, a maximum of 5,000 volts may be used.
- Cross-linked polyethylene (designated X). This insulation is thermosetting. The maximum conductor temperature it can handle is 90C. The maximum allowable ambient temperature is 60C. It is used from 2,001 to 5,000 volts.

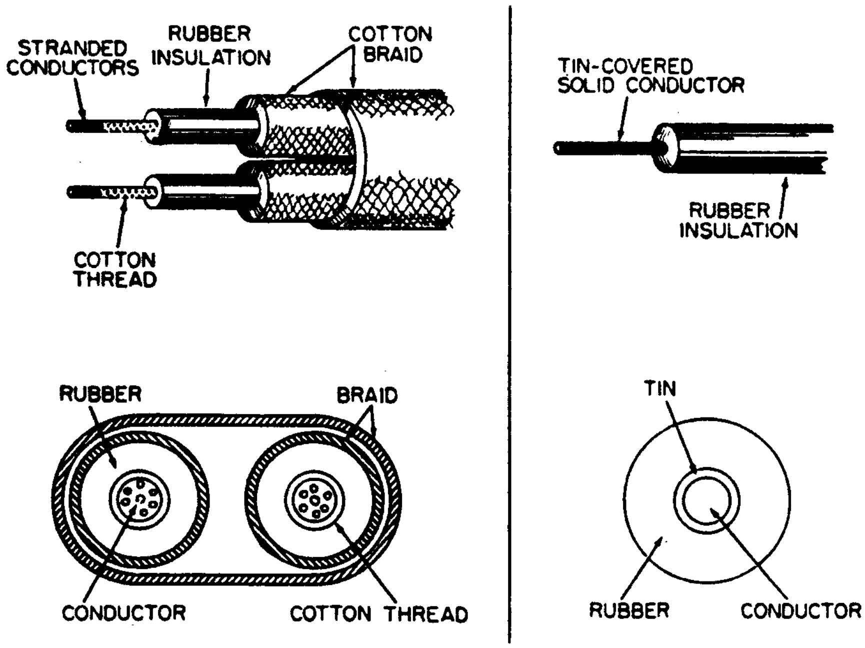


FIGURE 12-6. Conductor Insulation.

- Mineral (MI) (designated M). This is a refactory material made of magnesium oxide that is highly compressed to provide the properties needed for insulation. The maximum conductor temperature that the insulation can handle is 85C. The ambient temperature is specified by distinct design only. Some special applications allow a maximum conductor temperature of 250C. Care must be taken when considering cable end fittings. See IEEE Standard 45, Table A-21, for ampacity.

- Silicon rubber (designated S). The maximum conductor temperature that the insulation can handle is 100C. The maximum allowable ambient temperature is 70C. It may be used in specific applications up to 5,000 volts.

- Impregnated glass, varnished cloth (designated GTV). The outside covering consists of a composite wall of glass or varnished cloth layers. Figure 12-7 shows the insulation helically wound around the cable. The maximum conductor temperature that the insulation can handle is 100C. The maximum allowable ambient temperature is 70C.

Moisture-Resistant Jackets

An additional cable identification designation of I will be displayed on all cables with a moisture-resistant jacket. The jacket will be composed of one of the following:

- Thermoplastic type T.

- Thermoplastic type T covered with a nylon coating, which changes the designator to type N.

- Thermosetting chlorosulfonated polyethylene (type CP).

Separators and Fillers

Separators may be provided inside the insulation to allow free stripping of cable conductors. Fillers eliminate air spaces in the cable (Figure 12-8). Marine cables will not permit the passage of water along the inside of a cable, nor will they support conductor oxidation.

Additional insulating coding and specifications may be found in the Recommended Practice for Electrical Installations on Shipboard, the

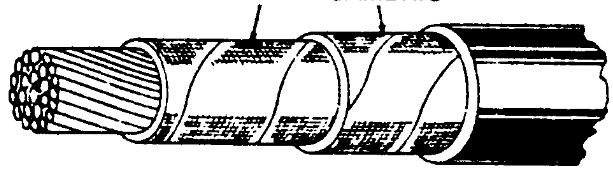


FIGURE 12-7. Varnished Cambric Cloth.

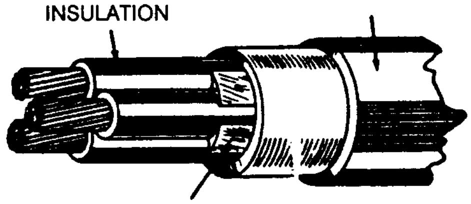


FIGURE 12-8. Separators and Fillers.

Institute of Electrical and Electronics Engineers, Inc. (IEEE Standard 45).

Enamel Coating

The wire used on the coils of meters, relays, small transformers, motor windings, and so forth is called magnetic wire. It is insulated with an enamel coating. The enamel is a synthetic compound of cellulose acetate (wood pulp and magnesium). In the manufacturing process, the bare wire is passed through a solution of hot enamel and then cooled. This process is repeated until the wire acquires from 6 to 10 coatings. Enamel has a higher dielectric strength than rubber, thickness for thickness. It is not practical for large wires because of the expense and because the insulation is readily fractured when large wires are bent. Do not handle any enamel-covered conductors in a rough manner. Never set a disassembled component down on its enamel-coated wires.

Figure 12-9 shows an enamel-coated wire. Enamel is the thinnest insulating coating that can be applied to wires. Hence, enamel-insulated magnetic wire makes smaller coils. Enameled wire is sometimes covered with one or more layers of cotton to protect the enamel from nicks, cuts, or abrasions.

CONDUCTOR PROTECTION

Wires and cables are generally subject to abuse. The type and amount of abuse depends on how and where they are installed and the manner in which they are used. Generally, except for overhead transmission lines, wires or cables are protected by some form of covering. The covering may be some type of insulator like rubber or plastic. Over this, an outer covering of fibrous braid may be applied. If conditions require, a metallic outer covering may be used. The type of outer covering used depends on how and where the wire or cable is to be used.

Metallic armor provides a tough protective covering for wires or cables. The type, thickness, and kind of metal used to make armor depends on three factors:

- The use of the conductors.
- The circumstances under which the conductors are to be used.
- The amount of rough treatment that is expected.

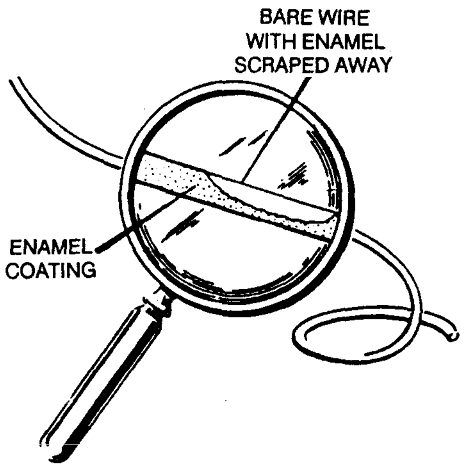


FIGURE 12-9. Enamel Insulation.

Figure 12-10 shows an armored cable. Basket-weave wire-braid armor is used wherever a light and flexible protection is needed. In the past, this type of armor covering has been used almost exclusively on-board ships. Wire braid is still used for special purposes in the engineering spaces. The individual wires that are woven together to form the braid are made out of aluminum or bronze. Besides mechanical protection, the wire braid also provides a static shield. This is important in radio work aboard ship to prevent interference from stray magnetic fields.

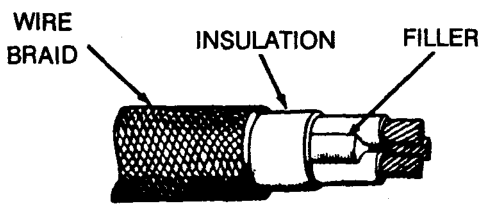


FIGURE 12-10. Armored Cable.

CAUTION

The armor braid must be grounded directly or indirectly to the hull

In this situation, grounding does not mean that current will be carried through the armor braid under normal conditions. Rather, it means that an electrical path will be provided to the hull should an abnormal electrical fault cause current to flow in the armor.

For additional information and specifications, refer to IEEE Standard 45-1983, Section 20.2, and Code of Federal Regulations, Title 46, Subpart 111.05-7.

Cables should not be painted. Only when cables carry a potential of 5,000 volts or greater is yellow color-coding permissible.

For general use, polyvinyl chloride-protected cable is replacing armor cable.

WIRING TECHNIQUES

Wire connections should be made inside the electrical component or inside watertight feeder, branch, or connection boxes. These boxes are generally brass or bronze. Watertight integrity is maintained by using stuffing tubes and gaskets. All the wire ends should be provided with lugs for connecting to bus terminals or for bolting and insulating individual wires together. During the course of normal electrical servicing, splicing wires is not authorized.

Electrical cables must be continuous between the terminals except as outlined below:

- Component subassemblies may be spliced together. Splices may not be made to the subassembly power supply cables or branch circuits.
- Cables may be spliced to extend a circuit when a vessel is receiving authorized alterations.
- An extremely long cable may be spliced to allow its proper and efficient installation as explained above.
- Splicing is authorized for repair of damaged cables if the remainder of the cable is in good mechanical and electrical condition. The cable must be replaced in its entirety at the most opportune time.

When electrical casualty requires expedient repairs, it is absolutely necessary that the repairs be made properly. A poor repair can prevent the operation of emergency equipment or develop into a tire. Any electric circuit is only as good as its weakest link. The basic requirement of any splice or connection is that it is both mechanically and electrically sound.

Quality workmanship and materials must be used to ensure lasting electrical contact, physical strength, and proper insulation. The most common methods of making splices and connections in electrical cables are explained below.

Splicing

Splices should be located in an area that is easily accessible and inspect able. The splice should consist of the following components:

- A conductor connector (terminal lugs, splice bolts, or splices) (Figure 12-11).
- A replacement jacket for the insulation.
- A shunt or suitable conductor to maintain the electrical continuity between two severed pieces of the armor braid.

WARNING

Continuity must be maintained between the armor covering and the vessel's hull at all times.

Removing Insulation

The preferred method of removing insulation is with the use of a wire-stripping tool. The calibrated hand wire stripper in Figure 12-12 is excellent for even the most intricate electrical wire work.

Hand Wire Stripper. The procedure for stripping wire with the hand wire stripper is as follows:

- Confirm the stripper's operation. Use a spare wire to ensure the conductor is not marred by the cutting blades of the wire stripper. If the wire strippers have been used or abused, consult the manufacturer's instructions to adjust the depth of the insulation cut.
- Insert the wire into the exact center of the correct cutting slot for the wire size to be stripped (Figure 12-13). Keep the wire perpendicular to the stripper.
- Close the handles together until the wire is held firmly by the jaws of the wire stripper.
- Continue to close the handles only until the insulation starts to separate. Do not use the stripper to pull the insulation from the conductor.
- Remove the wire from the wire stripper.
- Gently unwind the insulation so that the natural lay of the conductors is not disturbed.

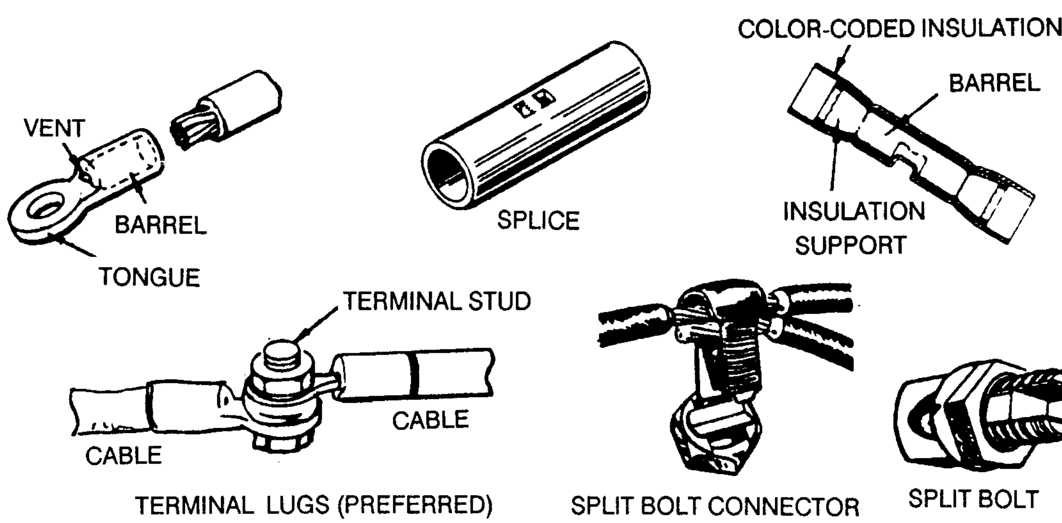


FIGURE 12-11. Expedient Splices.

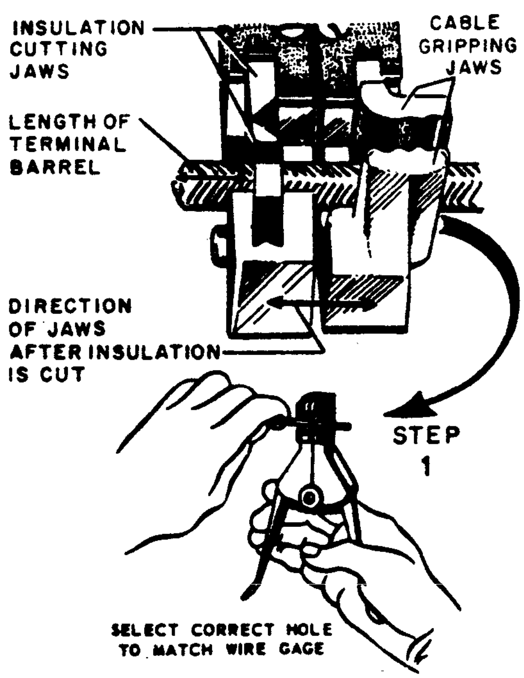


FIGURE 12-12. Hand Wire Strippers.

NOTE: If you are going to solder the conductor, do not touch the conductor with your hands. The contamination from your hands will start to oxidize the conductor, and proper tinning and soldering will become more difficult.

Knife Stripping. This is not recommended because it cuts into the conductor and effectively reduces the circular mil area at the fault. Nicks and cuts also reduce the mechanical strength of the conductor at a point that is naturally weaker then the section of cable where it is protected by insulation.

However, the very nature of a vessel requires it to be placed in situations that must be satisfactorily managed until a more advantageous time arrives. In emergencies, the following procedure will keep conductor damage to a minimum.

A sharp knife can be used to strip the insulation from a conductor. The procedure is much the same as sharpening a pencil. The knife should be held at a 60-degree angle to the conductor. Use extreme care to avoid cutting into the conductor. This procedure produces a taper on the cut insulation (Figure 12-14). Should the connection require solder, the tapered insulation will fuse more readily to the conductor. This fusion increases mechanical strength at the weak point and prevents the entrance of moisture.

WIRE STRIPPING CAUTIONS

The following minimum precautions are necessary when preparing conductors for repair:

- Ensure power is off before connecting or removing wires.
- Do not touch any conductor you intend to solder.
- Ensure the wire strippers are held perpendicular to the wire.
- Make sure the insulation is clean-cut with no frayed or ragged edges. Trim if necessary. This is particularly important when stripping armored cable. If the frayed armor insulation is allowed to chafe the replacement insulation at the spliced area, current may accidentally energize the exterior armor of the cable. This can be deadly.
- Ensure all insulation is removed from the conductor. Some wires are provided with a transparent layer between the conductor and the insulation. This must be removed.

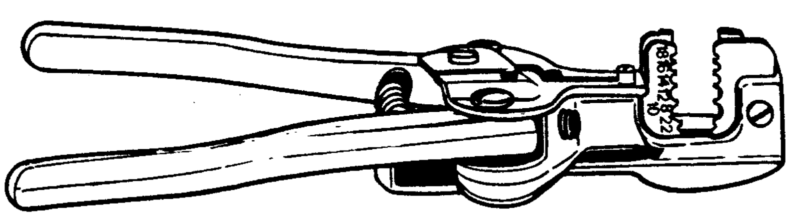


FIGURE 12-13. Cutting Edge Slots.

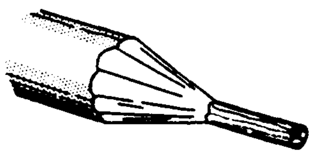


FIGURE 12-14. Knife Stripping.

WESTERN UNION SPLICE

Figure 12-15 shows the steps to make a Western Union splice. First, prepare the wires for splicing. Remove enough insulation to make the splice and then clean the conductor. Next, bring the wires to a crossed position and make a long twist or bend in each wire. Then wrap one of the wire ends four or five times around the straight portion of the wire. Wrap the other end of the wire in a similar manner. Finally, press the ends of the wire down as close as possible to the straight portion of the wire. This prevents the sharp ends from puncturing the tape covering that is wrapped over the splice.

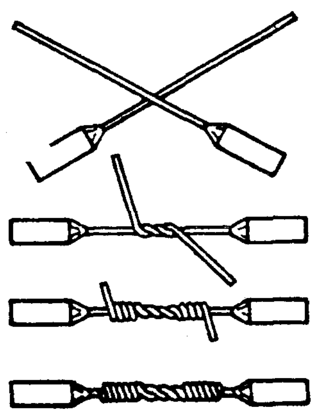


FIGURE 12-15. Western Union Splice.

STAGGERED SPLICES

Joining small, multiconductor cables together presents somewhat of a problem. Each conductor must be spliced and taped. If the splices are contiguous to each other, the size of the joint becomes large and bulky. A smoother and less bulky joint may be made by staggering the splices.

Figure 12-16 shows how a two-conductor cable is joined to a similar size cable by means of staggering the splices. Take care to ensure that a short wire from one side of the cable is connected to a long wire from the other side of the cable being spliced. Then clamp the sharp ends firmly down on the conductor. Figure 12-16 shows a Western Union splice being staggered. Each conductor is insulated separately.

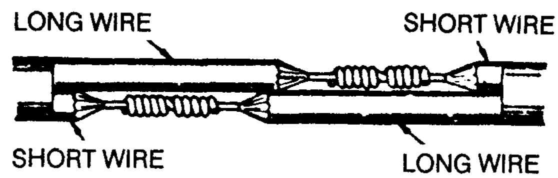


FIGURE 12-16. Staggering Splices.

SPLICE INSULATION

The splices discussed above are those usually insulated with tape. The tape used to insulate a splice should be centered over the splice and should overlap the existing insulation by at least 2 inches on each side. The characteristics of rubber, friction, and plastic electrical tape are described below.

Rubber Tape

Latex (rubber) tape is a splicing compound. It is used where the original insulation was of a rubber compound. The tape is applied to the splice with a light tension so that each layer presses tightly against the one beneath it. This pressure causes the rubber tape to blend into a solid mass. Care must be taken to keep the spliced area watertight. Upon completion, insulation similar to the original is restored.

WARNING

Some rubber tapes are made for special applications. These types are semiconducting and will pass current that presents a shock hazard. These types of tape are packaged similar to the latex rubber tape. Take care to insulate splices only with latex rubber insulation tape.

In roll form, a layer of paper or treated cloth is between each layer of rubber tape. This layer prevents the latex from fusing while still on the roll. The paper or cloth is peeled off and discarded before the tape is applied to the splice.

Apply the rubber splicing tape smoothly and under tension so that no air exists between the layers. Start the first layer near the middle of the joint instead of the end. The diameter of the completed insulated joint should be somewhat greater than the overall diameter of the original wire, including the insulation.

Friction Tape

Putting rubber over the splice means that the insulation has been restored to a great degree. It is also necessary to restore the protective covering. Friction tape is used for this purpose.

WARNING

Some friction tapes may conduct electrical current.

Friction tape is a cotton cloth that has been treated with a sticky rubber compound. It comes in rolls similar to rubber tape, except that no paper or cloth separator is used. Friction tape is applied to rubber; however, it does not stretch.

Start the friction tape slightly back on the original insulation. Wind the tape so each turn overlaps the one before it. Extend the tape over onto the insulation at the other end of the splice. From this point, wind a second layer back along the splice until the original starting point is reached. To complete the job, cut the tape and firmly press down the end.

Plastic Electrical Tape

Plastic electric tape has come into wide use in recent years. It has certain advantages over rubber and friction tape. For example, it withstands higher voltages for a given thickness. Single layers of certain plastic tapes will withstand several thousand volts without breaking down. In practice, however, several layers of tape are used to equal or slightly exceed the original thickness of the insulation. Additional layers of plastic electrical tape add the protection normally furnished by friction tape. Plastic electrical tape usually has a certain amount of stretch so that it easily conforms to the contour of the splice.

TERMINAL LUGS

Since marine cables are stranded, it is necessary to use terminal lugs to hold the stranded wires together to help fasten the wires to terminal studs (Figure 12-17). This is the preferred method for connecting wires to terminals or to other wire ends. Generally, distribution system cable connectors will not use solder. The terminals used in electrical wiring are either of the soldered or crimped type. Terminals used in repair work must be of the size and type specified on the electrical wiring diagram for the particular equipment.

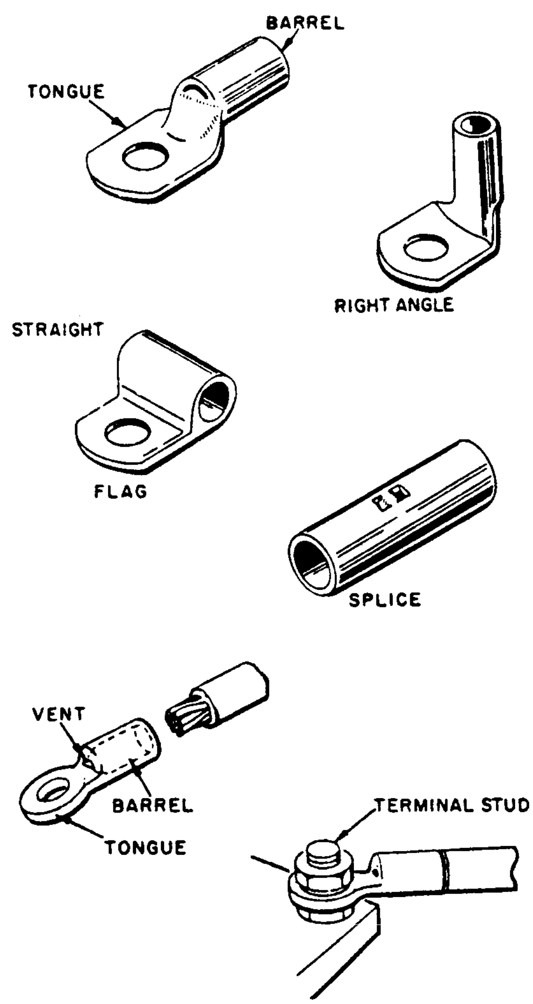


FIGURE 12-17. Terminal Lugs and Splices.

The increased use of crimp on terminals is a result of the limitations of soldered terminals. The quality of soldered connections depends mostly on the operator's skill. Other factors, such as temperature, flux, cleanliness, oxides, and insulation damage due to heat, also add to defective connections.

An advantage of crimp on solderless terminal lugs is that they require relatively little operator skill to use. Another advantage is that the only tool needed is the crimping tool. This allows terminal lugs to be applied with a minimum of time and effort. The connections are made more rapidly and are cleaner and more uniform in construction. Because of the pressures exerted and the material used, the crimped connection or splice, properly made, is both mechanically and electrically sound. Figure 12-17 shows some of the basic types of terminals. There are several variations of these basic types, such as the use of a slot instead of a terminal hole, three- and four-way splice type connectors, and insulation covering.

Figure 12-18 shows how to determine the amount of insulation to remove from the wire.

Solderless terminals may be of the insulated type. The barrel of the terminal or splice is enclosed in an insulating material. The insulation is compressed along with the terminal barrel when it is crimped, but it is not damaged in the process (Figure 12-19).

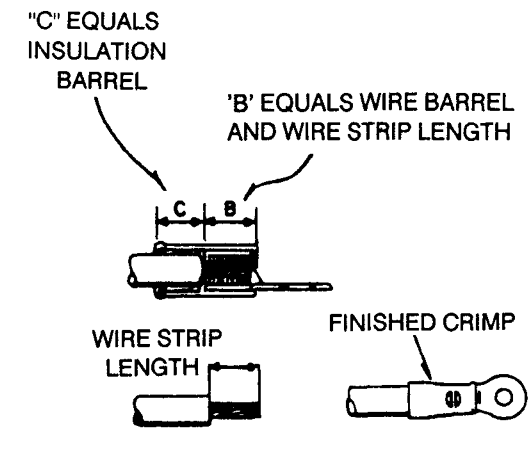


FIGURE 12-18. Proper Insertion of Stripping Wire in Insulated Terminal Lug for Crimping.

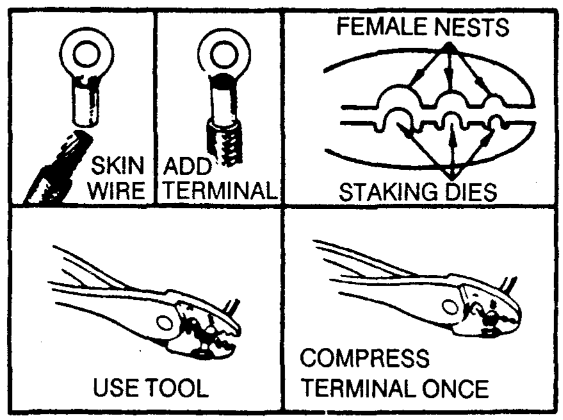


FIGURE 12-19. Crimping Small Copper Terminals.

Aluminum Terminals and Splices

Do not use aluminum terminals, connectors, or wires interchangeably with copper wires and connectors. Copper and aluminum expand at different rates and will become loose over a period of time. Electrolysis also takes place. The two dissimilar metals and the salt air will create a chemical reaction that will eat away the materials. Also, never use an aluminum crimping tool for compressing copper hardware.

Preinsulated Terminal Lugs

The use of preinsulated terminal lugs and splices has become the most common method for copper wire termination and splicing in recent years. It is by far the best and easiest method. Many tools are used for crimping terminal lugs and splices.

Small diameter copper wires are terminated with solderless, preinsulated copper terminal lugs. As Figure 12-20 shows, the insulation is part of the terminal lug. It extends beyond the barrel so that it covers a portion of the wire insulation. This makes the use of spaghetti or heat shrink tubing unnecessary. Preinsulated terminal lugs also have an insulation support (a metal reinforced sleeve) beneath the insulation for extra supporting strength of the wire insulation. Some preinsulated terminals fit more than one size of wire. The insulation is color-coded, and the range of wire sizes is marked on the tongue. This identifies the wire sizes that can be terminated with each of the terminal lug sizes (Table 12-6).

For crimping small copper terminal lugs, the MS90413 hand crimping tool is used for wire sizes

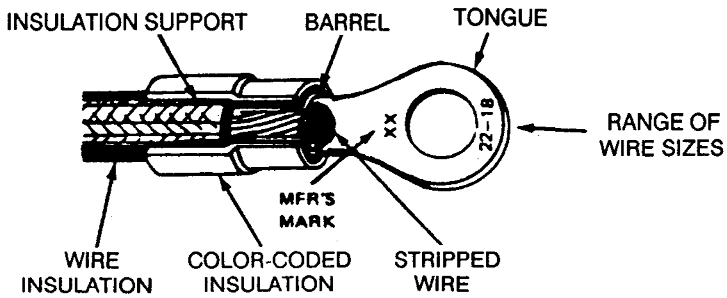


FIGURE 12-20. Preinsulated Straight Copper Terminal Lug.

AWG 26 to 14. The MS3316 tool is used for wire sizes 12 and 10. Figure 12-21 shows these tools. These hand crimping tools have a self-locking ratchet that prevents the tool from opening until the crimp is completed. These and other one-cycle compression tools (as outlined in ANSI/UL 4S6-1975[25]) are the preferred method of compression.

After completing the compression, visually inspect the terminal or splice. Check for the following conditions:

- Indent centered on the terminal barrel.
- Indent in line with the barrel.
- Terminal lug not cracked.
- Terminal lug insulation not cracked.
- Insulation grip crimped.

SOLDERING

The following discussion on basic soldering skills provides information needed when soldering wires to electrical connectors, splices, and terminals.

TABLE 12-6. Color Coding of Copper Terminal Lug or Splice Insulation

Color of Terminal Lug or Splice Insulation	To Be Used On Wire Sizes
Yellow (Bright)	#26-#24
Red	#22-#20, #18
Blue	#16-#14
Yellow (Dull)	#12-#10

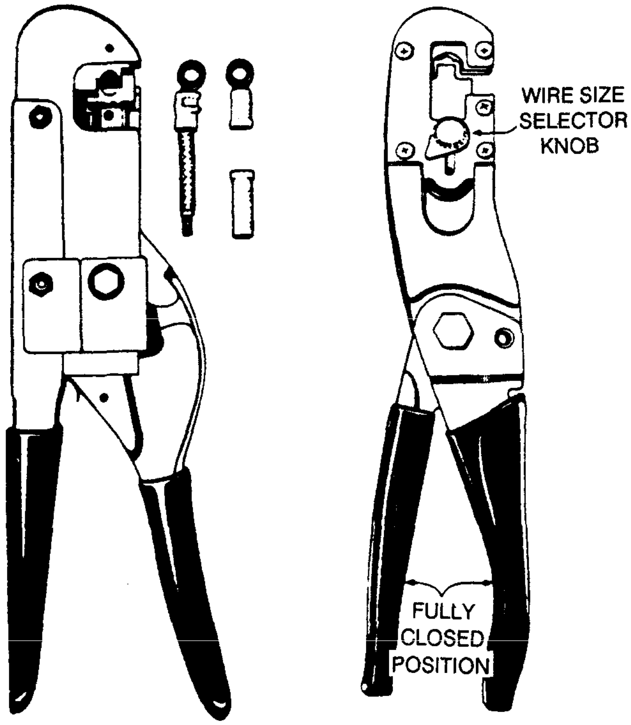
Soldering Tools

Many types of soldering tools are in use today. Some of the more common types are the soldering iron, soldering gun, resistance soldering set, and pencil iron. The main concern when selecting a soldering tool is the selection of the wattage. Table 12-7 provides a guide for determining the correct wattage for the size wire.

TABLE 12-7. Approximate Soldering Iron Size for Tinning.

Wire Size (AWG)	Soldering Iron Size (Heat Capacity)
#20-#16	65 Watts
#14 & #12	100 Watts
#10 & #8	200 Watts

Soldering Iron. Figure 12-22 shows some types of common soldering irons. All high-quality soldering irons operate in the temperature range of 500 to 600F. Even the little 25-watt midget irons produce this temperature. The important difference in iron sizes is not the temperature, but the wattage. The wattage, or thermal inertia, is the capacity of the iron to generate and maintain a satisfactory temperature while giving up heat to the joint to be soldered. Although it is not practical to solder large conductors with a 25-watt iron, this iron is suitable for replacing a half-watt resistor in an electronic circuit or soldering a miniature connector. One advantage of using a small iron for small work is that it is light and easy to handle and has a small tip which is easily used in close places. Even though its temperature is high enough, it does not have the thermal energy to solder a large conductor.



A. TOOL MS3316 B. TOOL MS90413

FIGURE 12-21. One-Cycle Compression Tools.

A well-designed iron is self-regulating. The resistance of its element increases with rising temperature, thus limiting the flow of current. Figure 12-23 shows some tip shapes of the soldering irons in common use in the Army.

An iron is always tinned prior to soldering a component in a circuit. After extended use, the tip tends to become pitted due to oxidation. Pitting indicates the need for retinning, as shown in Figure 12-24. Melt a piece of clean solder dipped in rosin flux over the soldering iron tip until all cavities are gone and the tip is completely shiny and silver-coated Figure 12-25). Use a lint-free paper towel to wipe the solder away. Do not shake the solder off.

The larger soldering irons used exclusively for large conductors may require the tip to be filed first. The tip must then be tinned.

Never clean the tip of an iron by dipping it into the flux container. All this does is contaminate the flux and add impurities to the next soldering project.

Soldering Gun. The soldering gun (Figure 12-26) has gained popularity in recent years

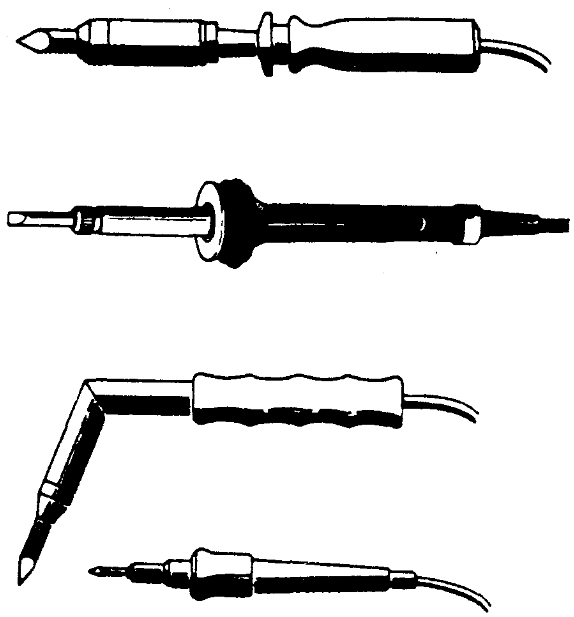


FIGURE 12-22. Types of Hand Soldering Irons.

because it heats and cools rapidly. It is especially well-adapted to maintenance and troubleshooting work where only a small part of the technician's time is spent soldering.

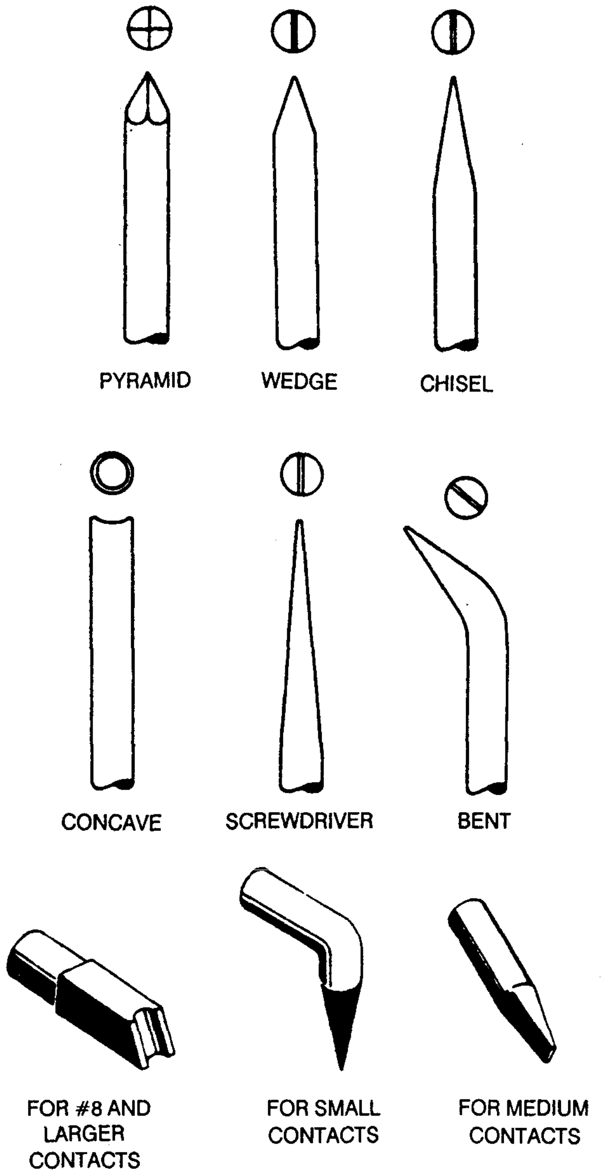


FIGURE 12-23. Soldering Iron Tip Shapes.

A transformer in the soldering gun supplies about a volt at high current to a loop of copper, which acts as the soldering tip. It heats to soldering temperature in 3 to 5 seconds. However, it may overheat to the point of incandescence if left on more than 30 seconds. This should be avoided because excess heat will burn the insulation of the wiring and damage the soldering gun. The gun is operated by a finger switch. The gun heats only while the switch is depressed. For most jobs, depress the trigger for no more than 10 seconds. Regulate the tip temperature by pulsating the gun on and off with the trigger.

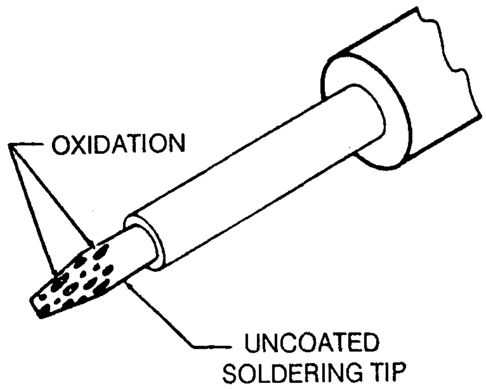


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FIGURE 12-24. Soldering Tip Oxidation.

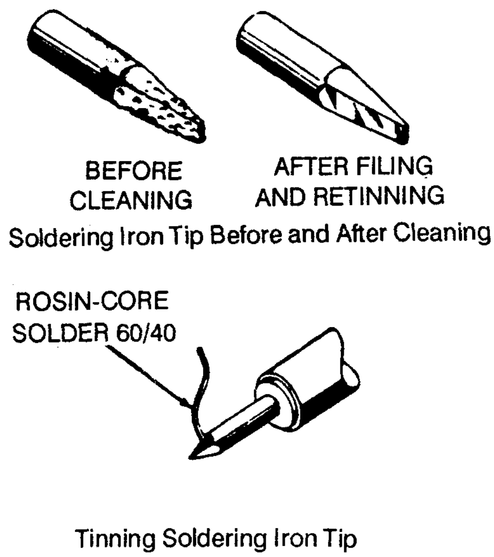

FIGURE 12-25. Reconditioning Pitted Soldering Tip Iron.

The gun or iron should always be kept tinned to permit proper heat transfer to the connection to be soldered. Tinning also provides adequate control of the heat to prevent solder from building up on the tip. This reduces the chance of the solder spilling over to nearby components and causing short circuits.

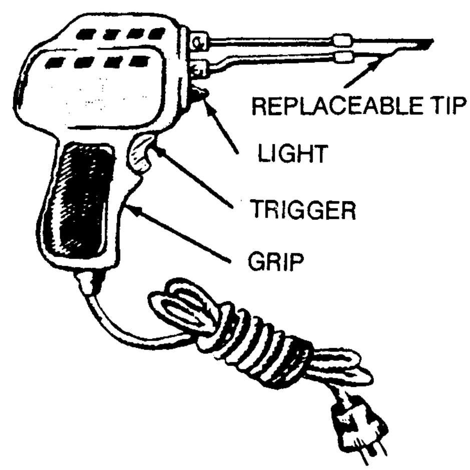

FIGURE 12-26. Soldering Gun.

When the soldering gun or iron is used, heating and cooling cycles tend to loosen the nuts or screws that hold the replaceable tips. When the nut on the gun becomes loose, the resistance of the tip increases. The temperature of the connection is increased and reduces the heat at the tip. Continued loosening may even cause an open circuit. Therefore, the tip should be tightened before and during operations as needed.

CAUTION

Never use soldering guns to solder solid state electronic components, such as resistors, capacitors, and transistors, because the heat generated can destroy the components.

Solder

Ordinary soft solder is a fusible alloy consisting chiefly of tin and lead. It is used to join together two or more metals at temperatures below their melting point, A good general solder for electrical work is 60/40 solder; 60/40 represents the tin-to-lead ratio (percentage) of the solder. Eutectic solder (63/37) is an ideal solder combination. Eutectic solder goes from a solid to a liquid state without entering a mushy condition. The eutectic solder is used in electrical and electronic soldering processes.

Solder comes on rolls. Many times the solder is hollow and contains a rosin or acid core. The rosin or acid flux cleans and prevents oxidation of the materials to be soldered. Never use acid core solder in soldering electronic components. Acid core flux causes corrosion and leads to shorts or open conditions. Avoid acid core solder whenever possible when soldering electrical components. Rosin is the only acceptable electrical soldering flux.

Soldering Process

Cleanliness is necessary for efficient, effective soldering. Solder will not adhere to dirty, greasy, or oxidized surfaces. Heated metals tend to oxidize rapidly, so the oxide must be removed before soldering. Remove oxides, scale, and dirt by mechanical means, such as scraping and cutting with an abrasive cloth, or by chemical means. Remove grease or oil films with a suitable solvent (alcohol). Clean the connections to be soldered just before the actual soldering operation.

Items to be soldered should normally be tinned before making a mechanical connection. Tinning is coating the material to be soldered with a light coat of solder (Figure 12-27). When the surface has been properly cleaned, place a thin, even coating of flux over the surface to be tinned. This will prevent oxidation while the part is being heated to soldering temperature. Rosin core solder is usually preferred in electrical work. However, a separate rosin flux may be used instead. Separate rosin flux is often used when wires in cable fabrication are tinned.

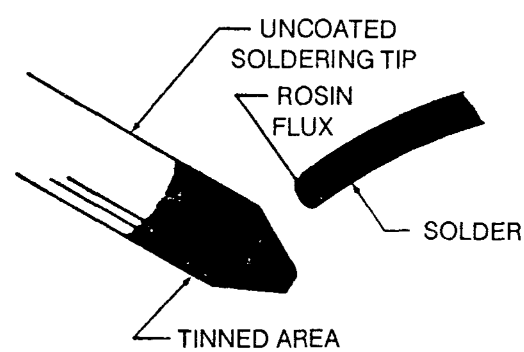

FIGURE 12-27. Tinned Tip Area.

Placing a very thin coating of solder on the copper conductor is called tinning the wire. This is done before soldering the conductor to a terminal or other component. First, strip the insulation from the wire. Do not touch the copper conductor with your hands or any other oily objects. Apply heat from the soldering iron under the copper conductor. Then apply the solder to the top of the copper conductor.

Starting at either the insulation end of the conductor or at the bitter end of the conductor, move the soldering iron as the solder melts and coat the entire length of the conductor. There is to be a complete, yet very fine solder coating. Every layer of the conductor should be easily defined underneath the bright solder coating.

If the tinned lead is to be connected to a shaped device, such as a turret or post, then form the tinned portion to exactly match the shape. Ensure no open space is between the tinned wire and the point of connection. Figure 12-28 shows the exact relationship the stripped conductor maintains with the terminal post. The insulation is stripped back far enough to be one conductor diameter from the post. The bitter end of the conductor never goes farther around the post terminal than its widest point. This is the only way to ensure the best current flow.

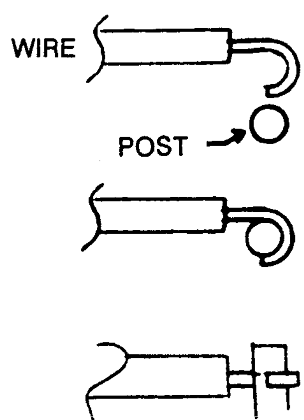

FIGURE 12-28. Conductor Formed to Post Diameter.

In earlier years, tinning was not extended to the insulation because the wire was thought to provide better performance when it was allowed to flex at the insulation. However, actual performance is improved when this weakened portion is not allowed to flex. Proper strength is maintained when there is a slight fusing between the soldier and the insulation. This gives more protection from vibration and maintains the conductor more steadily in application. Tinning to the insulation eliminates the small movement that causes the conductor to break near the insulation.

Do not tin wires that are to be crimped to solderless terminals or splices.

Once the conductor has been tinned, start to prepare the terminal for soldering. Clean all oils and foreign material from the terminal. Remove all remaining solder and any leftover broken conductors. Use a soldering wick to remove old solder expeditiously. Place the wick on the old solder and the soldering tool on top of the wick (Figure 12-29). Capillary action draws the old solder off the terminals and into the wick. Clean the area with denatured alcohol and a white pencil-type typist eraser.

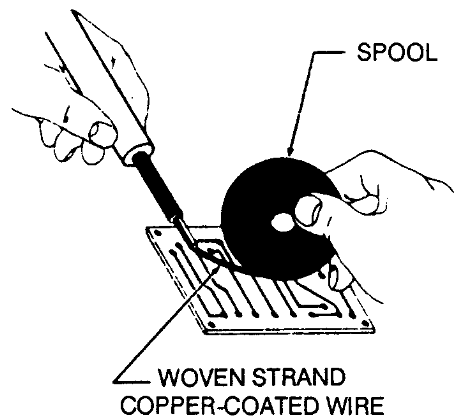

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FIGURE 12-29. Old Solder Removal.

Connect the tinned conductor to the terminal without placing your hands on either prepared surface. Apply heat and solder. Never apply the solder to the tip of the soldering iron. Always apply solder to the opposite side of the component lead. There should be just enough solder to penetrate and surround the terminal and conductor connection. There should not be so much solder that there is a bulge at the connection.

If the conductor or terminal is moved while the solder is solidifying, a cold solder joint will result. This poor joint has a dull, grainy appearance. If there is any bridging, dimples, or holes, then the joint has been improperly made and must be remade. A properly soldered joint will be bright and shiny.

CHAPTER 13

BELT-DRIVEN ALTERNATORS

INTRODUCTION

A generator is a machine that converts mechanical energy into electrical energy using the principle of magnetic induction. This principle is based on the fact that whenever a conductor is moved within a magnetic field so that the conductor cuts across magnetic limes of force, voltage is generated in the conductor.

Earlier chapters discussed the three requirements to produce an electromotive force or EMF. The requirements are a conductor, a magnetic field, and a relative motion between the conductor and the magnetic field.

The generator uses these three essential conditions to separate the valence electron from the atom. Once this is done and a suitable negative electron potential is at one terminal and a suitable positive ion potential is at the other terminal, an external circuit can be connected to use this subatomic imbalance. The electrons from the negative terminal will seek out the positive ions at the positive terminal and return to an equilibrium. In the process, the negative electron gives us an electrical current flow through the circuit. The circuit is the way the electron's magnetic charge is directed to operate motors, solenoids, and light lamps.

The amount of voltage generated depends on—

- The strength of the magnetic field.
- The speed at which the conductor is moved.
- The length of the conductor in the magnetic field.

The polarity of the voltage depends on the direction of the magnetic field (or flux) and the direction of the movement of the conductor. To determine the direction of current movement in the conductor, the left-hand rule for generators was developed. The rule is explained as follows:

- Extend the thumb, forefinger, and middle finger of your left hand at right angles to one another (Figure 13-1).
- Point your thumb in the direction the conductor is going to be moved.
- Position your forefinger in the direction of the magnetic flux (from north to south, knuckle to nail). Your middle finger will then point in the direction of current flow when an external circuit is connected. At the end of your fingernail is the area where the electrons are gathering. This is the negative terminal at this instant in time.

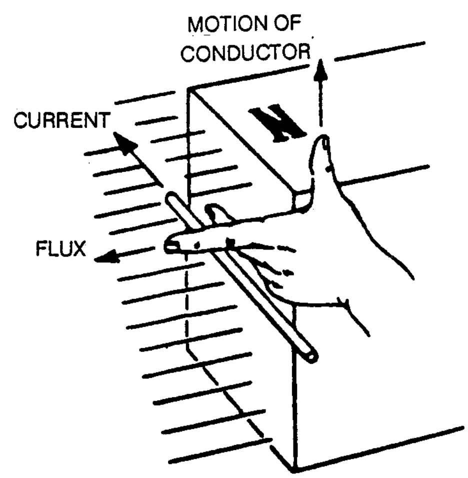

Figure 13-1. Left-Hand Rule for Generators.

THE ELEMENTARY GENERATOR

An elementary revolving armature AC generator (Figure 13-2) consists of a wire loop that can be rotated in a stationary magnetic field. This will produce an induced EMF in the loop. Sliding contacts (brushes and slip rings) connect the loop to an external circuit.

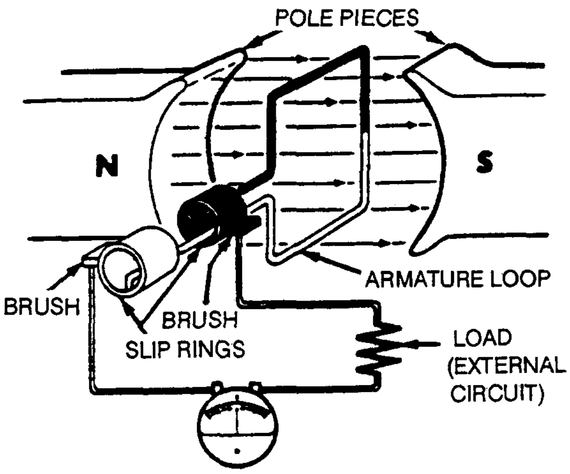

FIGURE 13-2. The Elementary Generator.

The pole pieces (marked N and S) provide the magnetic field. They are shaped and positioned to concentrate the magnetic field as close as possible to the wire loop. The loop of wire that rotates through the field is called the rotor. The ends of the rotor are connected to slip rings, which rotate with the rotor. The stationary brushes, usually made of carbon, maintain contact with the revolving slip rings. The brushes are connected to the external circuit.

The elementary generator produces a voltage in the following manner (Figure 13-3). The rotor (or armature in this example) is rotated in a clockwise direction. Figure 13-3 position A shows its initial or starting position. (This will be considered the 0-degree position.) At 0 degrees, the armature loop is perpendicular to the magnetic field. The black and white conductors of the loop are moving parallel to the field. At the instant the conductors are moving parallel to the magnetic field, they do not cut any lines of force. There is no relative motion between the magnetic lines of force and the conductor when both the conductor and the magnetic lines of force move in the same direction. Therefore, no EMF is induced in the conductors, and the meter in position A indicates 0.

As the armature loop rotates from position A to B, the conductors cut through more and more lines of flux at a continually increasing angle. At 90 degrees (B), they are cutting through a maximum number of magnetic lines of flux and at a maximum angle. The result is that between 0 and 90 degrees, the induced EMF in the conductors builds up from 0 to a maximum value. Observe that from 0 to 90 degrees, the black conductor cuts down through the magnetic field (or flux). At the same time, the white conductor cuts up through the magnetic field. The induced EMF in the conductors is series-aiding. This means the resultant voltage across the brushes (the terminal voltage) is the sum of the two induced voltages. The meter at position B reads maximum value.

As the armature loop continues rotating from position B (90 degrees) to position C (180 degrees), the conductors that were cutting through a maximum number of lines of flux at position B now cut through fewer lines of flux. At C, they are again moving parallel to the magnetic field. They no longer cut through any lines of flux. As the armature rotates from 90 to 180 degrees, the induced voltage will decrease to 0 in the same reamer as it increased from 0 to 90 degrees. The meter again reads 0. From 0 to 180 degrees, the conductors of the rotor armature loop have been moving in the same direction through the magnetic field. Therefore, the polarity of the induced voltage has remained the same. This is shown by A through C on the graph. As the loop starts rotating beyond 180 degrees, from C through D to A, the direction of the cutting action of the conductors (of the loop) through the magnetic field reverses. Now the black conductor cuts up through the field. The white conductor cuts down through the field. As a result, the polarity of the inducted voltage reverses. Following the sequence shown in C through D and back to A, the voltage will be in the direction opposite to that shown from positions A, B, and C. The terminal voltage will be the same as it was from A to C except for its reversed polarity, as shown by meter deflection in D. The graph in Figure 13-3 shows the voltage output wave form for the complete revolution of the loop.

ROTOR AND STATOR

An alternator has two separate coils (or windings) of wire. One coil will carry DC and produce a magnetic field for use inside the generator. This coil of wire is wrapped around an iron core pole piece to concentrate its magnetic effects. This coil is always called the field. The other coil, usually called the stator, will have an EMF induced into it from the rotor's field and produce an AC flow for use by the electrical system. Thi is the conductor used in cutting the magnetic field. This coil is always called the armature.

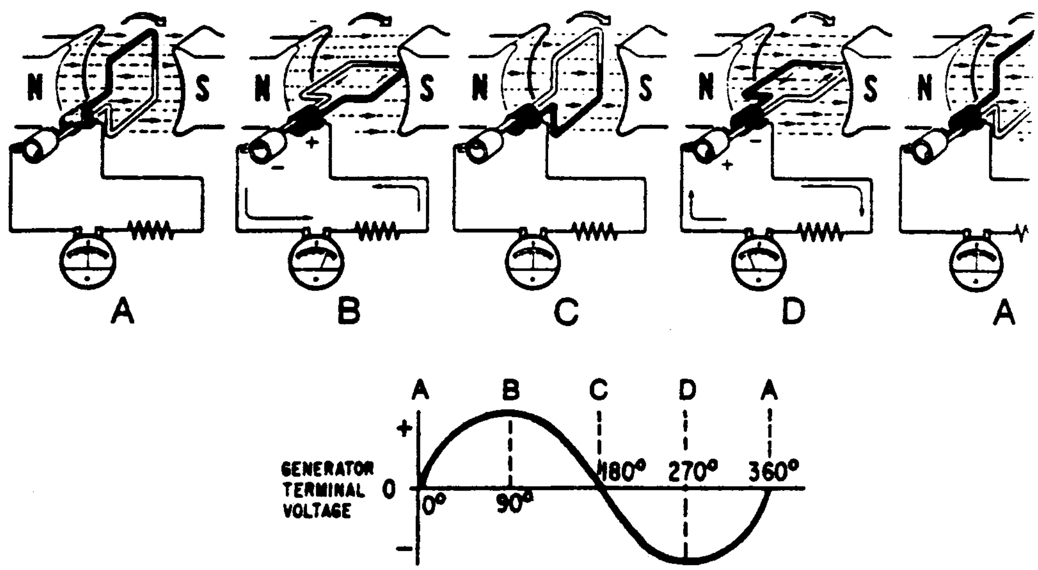

FIGURE 13-3. Output Voltage of a Single-Phase Elementary Generator During One Revolution.

Two of the three requirements for producing an EMF in an alternator have now been identified. Some form of relative motion between the magnetic field and the conductor is still necessary. By rotating one of these coils, an EMF can be developed. The item that moves a generator coil is called a prime mover. The prime mover can be a diesel engine or turbine.

The coil of wire that is rotating can be called the rotor. The coil of wire that is permanently fixed to the alternator housing can be called the stator. This text will not use these terms. The reasons will become apparent as multistator and multirotor machines are discussed.

ARMATURE AND FIELD

In an AC generator, the conductor coil does not always have to rotate. Often it is the field (the coil with the DC applied magnetic field) that rotates. As long as relative motion exists between the magnetic field and the conductor, an EMF will be produced. Since either the rotor or the stator can be the conductor or the field, it is necessary to further distinguish between the two fields. The coil connected to the electrical system to supply the system's voltage and current requirements is the armature. The armature is the stationary winding found on Army watercraft belt-driven alternators.

By definition, the armature is the conductor that has an EMF induced into it. The coil of wire that provides the magnetic field for the generator to develop an EMF is called the field. This field must always be supplied with DC.

The explanation in *The* ***Elementary Generator*** describes the rotating armature type. This is not common to small generators. The electromagnetic flux (or magnetism) produced in the field coil requires a very small current to sustain it. On the other hand, the current produced in the armature, for use by the electrical system, can be enormous. It is not in the best interests of the electrical system to have a high current connection that is not fixed.

ROTATING ARMATURE ALTERNATORS

A rotating armature alternator requires slip rings and brushes to connect the high output voltage and current from the armature to the load. The armature, brushes, and slip rings are difficult to insulate. Arc-over and short circuits can result at high voltages. For this reason, high-voltage alternators are usually of the rotating field type. Army applications of this type alternator are extremely limited.

ROTATING FIELD ALTERNATORS

The rotating field alternator has a stationary armature winding and a rotating field winding

(Figure 13-4 view B). This is the most common type of small generator in use today. The advantage of having a stationary armature is that the generated current can be connected directly and permanently to the load. There are no sliding connections (slip rings and brushes) to carry the heavy output current.

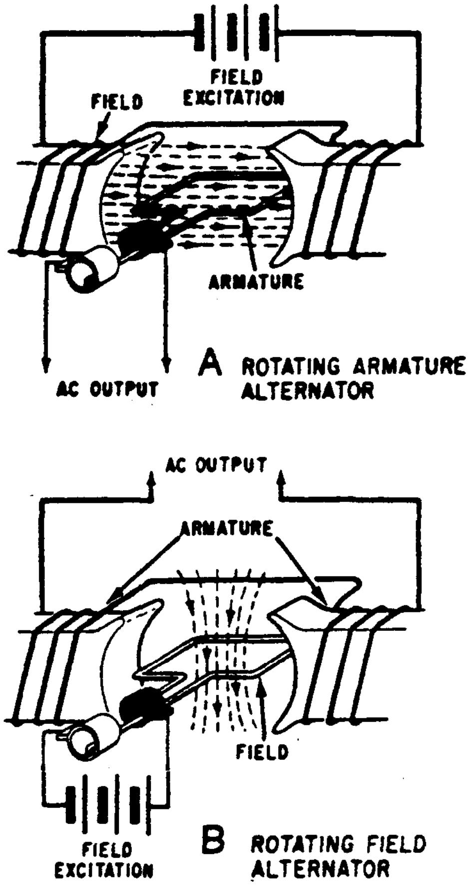

FIGURE 13-4. Types of AC Generators.

Field

Figure 13-5 shows the motorola field. The rotating field consists of one fine wire wrapped a multitude of times around its core. This wire terminates at two slip rings where DC is applied through brushes. Direct current is necessary to produce AC because of the need to maintain a magnetic field much the same way that a revolving bar magnet would if it were rotated by its center. Figure 13-6 shows how the direction of current flow is reversed when the magnetic field changes. The small DC needed for the magnetic field can be supplied by the battery or the alternator's own rectified output.

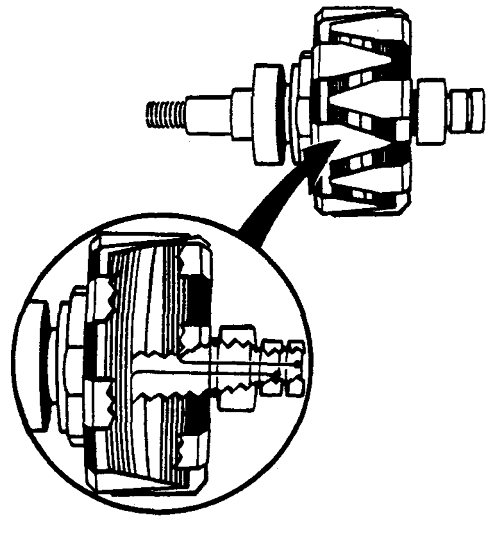

FIGURE 13-5. Alternator Field.

Multiple Magnetic Polarities in the Field

Alternate north and south field polarities are necessary to produce the AC desired from AC generators. By increasing the number of magnetic north and south poles, the efficiency of the alternator can be increased. As these alternate polarities sweep past the armature conductors, the current is forced to change directions.

Many AC and DC machines require the use of multiple north and south poles. How the field develops many north and south poles from only one wire is very simple. When the single field wire is wrapped around an iron core (clockwise, for example), it produces a given magnetic polarity. If the same wire is then wrapped around another iron core in a different direction (counterclockwise), the poles of this iron core are opposite to those in the clockwise-wrapped iron core. Figure 13-7 shows one wire wrapped around two iron cores in different directions. The north polarity of the left coil is up, and the south polarity of the right coil is up. This is determined by the left-hand rule for coil polarity (Figure 13-8).

Multiple Alternator Fields

The alternator field uses only a single wire on a solid core. When direct current goes through the conductor, a fixed polarity is established in the core. The ends of the core branch out into fingers. These pointed fingers direct and concentrate the magnetic field from the core. All the fingers at the north polarity end maintain a north polarity. The same is true for the south polarity end. Figure 13-9 clearly shows the positioning of the north and south fingers alternately positioned around the outside of the magnetic core. It also shows the end view of the south pole field. Notice the alternate north and south polarities available at the circumference of the rotor. Notice also how the magnetic lines of flux are extended outward toward the armature windings.

Armature

The rotating field alternator is the most common type found in the Army. The armatures of all rotating field alternators appear the same. The armature consists of a laminated iron core with the armature windings embedded in this core (Figure 13-10). The core is secured to the generator housing.

The armature in Figure 13-10 has the stationary conductors that are cut by the revolving magnetic field. There are three conductors (or windings) connected together in the armature. This allows three separate circuits that are overlapped and spaced apart 120 electrical and mechanical degrees from one another. These three windings, positioned accordingly, act as three separate single-phase armatures. The three independent windings act together to provide three-phase AC. View A of Figure 13-11 shows the three windings and their combined sine waves.

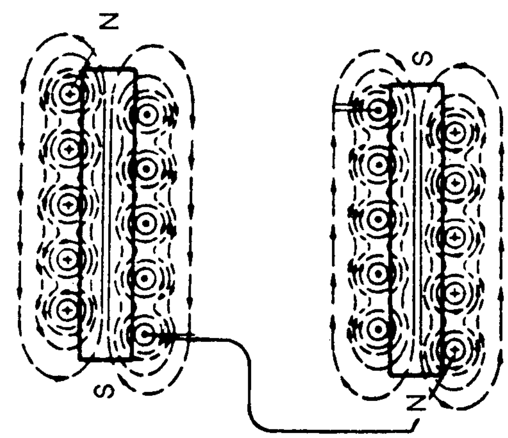

FIGURE 13-7. Multiple Coil Polarities With a Single Conductor.

Numerous coils are used for each of the three armature windings (Figure 13-10). This provides an effective use of conductors by placing them in close proximity to all the rotor field poles. The armature coils are not wrapped in opposite directions. They are merely placed strategically around the circumference of the alternator housing to be in close proximity to the field's magnetic field. The closer the conductor is to the magnetic field's origin, the greater the induced EMF in the armature windings.

Rather than have six individual leads coming out of the three-phase generator, two internal wiring configurations are available. One end of each winding may be connected together to form a wye connection

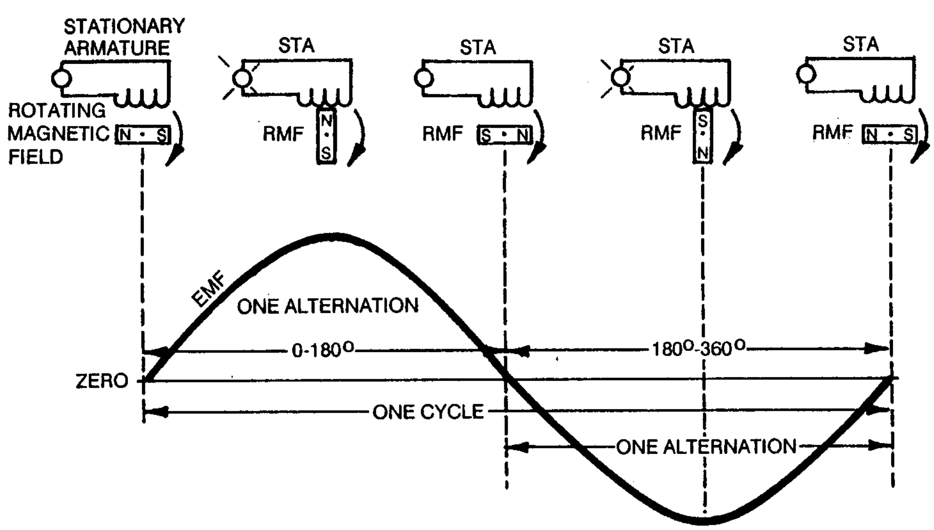

FIGURE 13-6. Rotating Bar Magnet Effect.

(Figure 13-11 view B). If every end of a an armature winding is connected to another armature winding, the resulting configuration is a delta-connected armature (view C). The delta connection is seldom used in today's marine field.

The voltage and current generated in the armature, as a result of induction, are the AC and voltage that are applied to the loads.

The three-wire armature can be easily distinguished from the two-wire DC field by merely counting the wire ends and observing the overlapping of the armature coils.

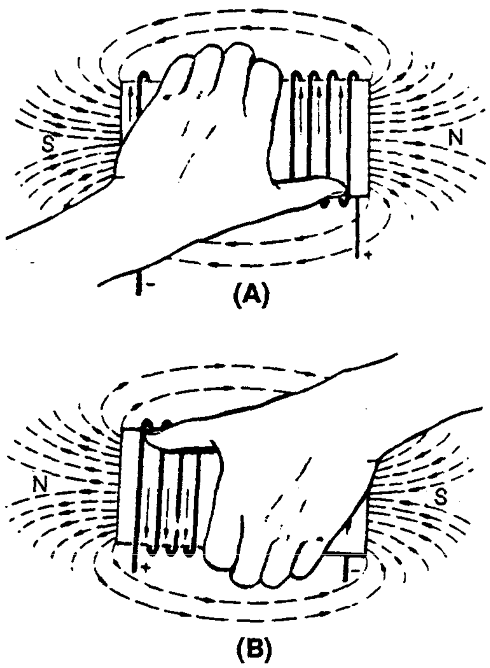

FIGURE 13-8. Left-Hand Rule for Coil Polarity.

RECTIFIED ALTERNATING CURRENT GENERATORS

Induction has made AC the power of today. Alternating current can be transmitted at high voltages and changed to a low voltage through the use of transformers. Alternating current also saves money in the construction of large motors. The efficiency of AC generators has all but eliminated the DC generator. This is not to say that it is possible to eliminate all DC systems. The automobile electrical system is an example. The starting systems and emergency battery systems on most Army watercraft will still be DC. To take advantage of the properties and efficiency of AC and the requirements of a DC electrical system, a compromise has been found in the rectified AC generator.

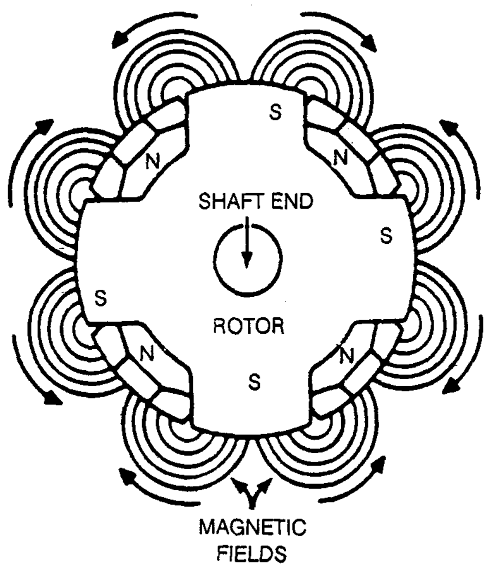

FIGURE 13-9. Rotor End View.

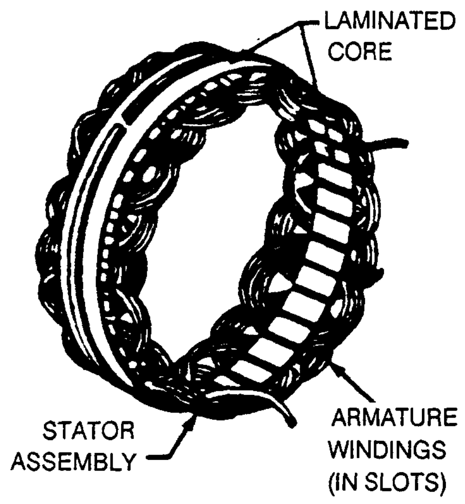

FIGURE 13-10. Stationary Armature Windings.

DIRECT CURRENT OUTPUT FROM ALTERNATORS

The alternators on small Army watercraft produce a DC. These vessels do not have large AC power requirements, and the electrical needs of these vessels are best served through the use of DC. The DC generators were very inefficient. They could not meet the growing electrical needs of the Army.

The alternator was the obvious choice. The AC output had to be modified in some way so that a constant polarity could be established and current flow would be maintained in one direction only. The use of diodes in a full-wave bridge rectifier is used to do this. The full-wave bridge rectifier consists of six diodes: three positive and three negative.

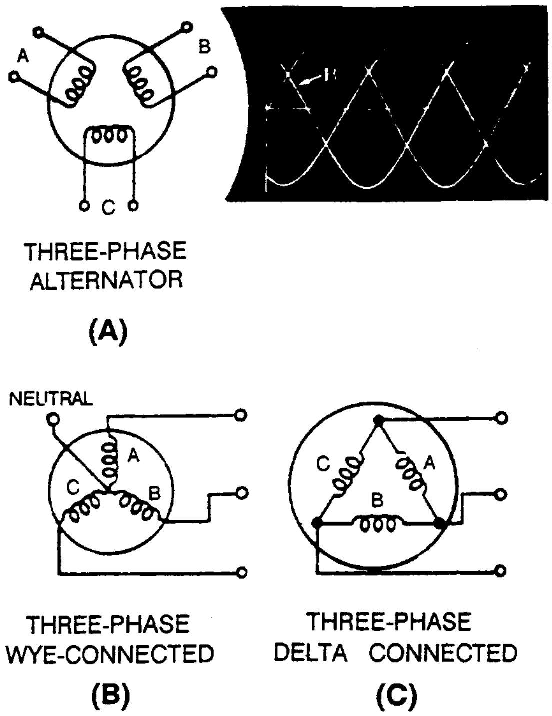

FIGURE 13-11. Three-Phase Alternator Connections.

Diodes

Semiconductor diodes are an electrical check valve (Figure 13-12). Current can readily travel through a diode in one direction only. Diodes are commonly made from silicon and germanium. By adding certain impurities to these two materials, called doping, a diode will become conductive only when a current moving in the proper direction is applied.

Some diodes have wires for terminals. Most of our diodes used for rectifying AC to DC have only one wire for a terminal. The other terminal is the diode housing.

Forward and Reverse Bias

Current conducts through the diode when the proper difference in potential (voltage) is applied across its terminals. When the proper difference in potential exists and current does conduct, this is called forward bias. When the wrong polarity exists and current is restricted, this is called reverse bias.

The diode has a relatively low resistance in one direction and a relatively high resistance in the other direction. This is determined through the use of a multimeter. Figure 13-13 shows the symbol of a diode. The straight line is called the cathode. The triangle is called the anode. Current (electrons) always flows against the triangle in electron flow theory.

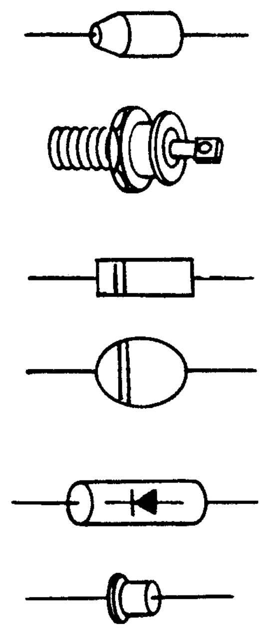

FIGURE 13-12. Various Diodes.

Diode Testing

The ohmmeter can be used to test a diode (Figure 13-14). Since the ohmmeter has a battery and a battery has a predetermined polarity, the direction in which current will move through a diode can be established. Whether or not there is continuity can be determined by connecting the leads of the ohmmeter to each end of a diode.

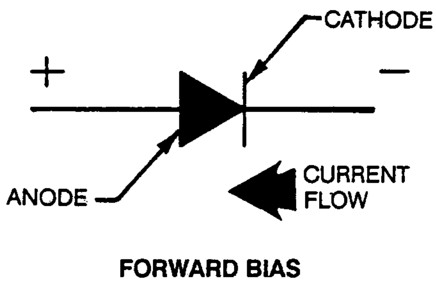

FIGURE 13-13. Diode Schematic Symbol.

When the meter is connected across a diode, it should read high resistance and low resistance. If the meter indicates a low resistance in both directions, the diode is shorted. If the meter indicates a high resistance in both directions, the diode is open. Neither condition is acceptable. Consult the manufacturer's manuals for specific information.

Diode Polarity

Belt-driven alternators use diodes that look exactly alike. This makes maximumuse of the limited internal space. However, the diodes operate in two distinct manners. The negative diode passes current in the opposite direction that the positive diode passes current. Black coloring or writing indicates a negative diode; red coloring or writing indicates a positive diode (Figure 13-15). This can be further verified by the multimeter.

The polarity of the ohmmeter is indicated by the colored leads or jack polarity markings on the meter. Identifying the diode terminals can be done as follows:

- Connect the ohmmeter for forward bias. The ohmmeter will read a low resistance. If the ohmmeter reads a high resistance, reverse the ohmmeter leads.

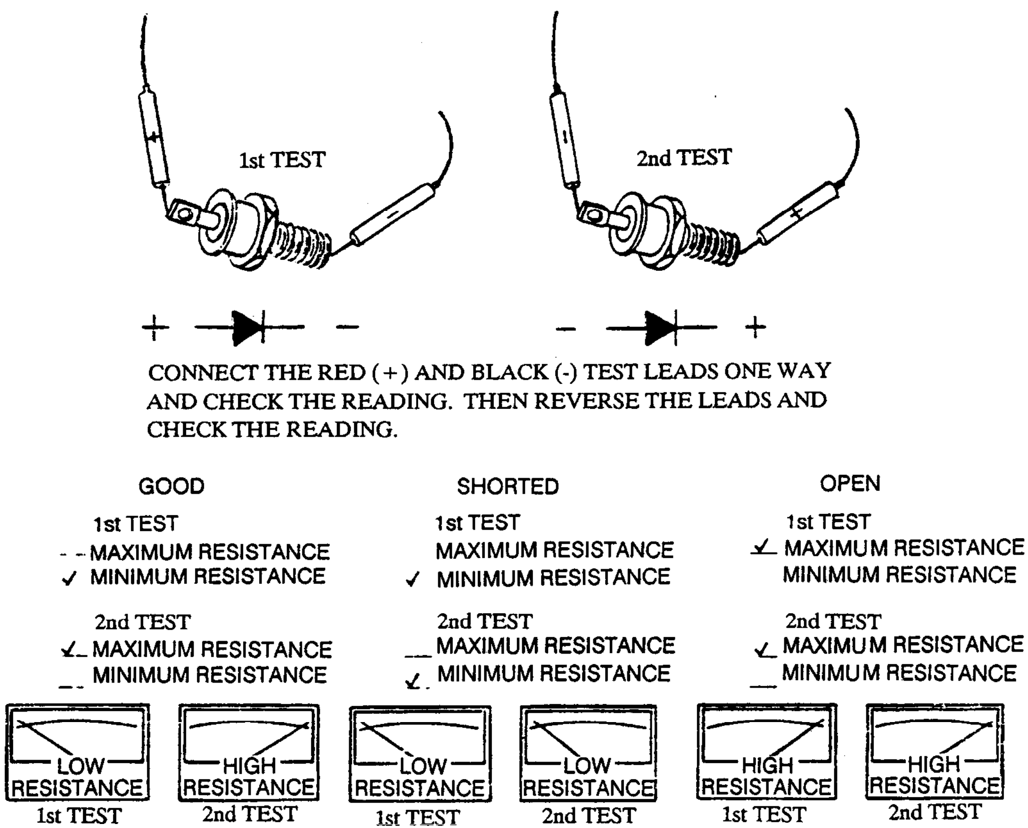

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FIGURE 13-14. Diode Testing.

- In forward bias, the negative meter lead determines the diode's cathode terminal.
- The positive meter lead now determines the anode.
- When the ohmmeter has the negative lead on the diode terminal, the positive ohmmeter lead on the diode housing, and the diode is forward bias, then the diode is considered negative.
- When the ohmmeter has the positive lead on the diode terminal, the negative ohmmeter lead on the diode housing, and the diode is forward bias, then the diode is considered positive.

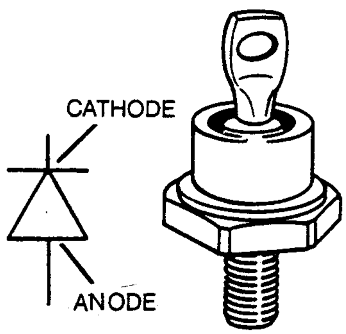


FIGURE 13-15. Positive and Negative Diode Markings.

In forward bias, the ohmmeter is correctly connected to the diode and indicates a low resistance (Figure 13-16). The negative (black) lead is connected to the diode cathode, and the positive (red) lead is connected to the diode anode. Current is leaving the ohmmeter's battery by the negative terminal and completing a circuit through the diode, to the red lead, and back to the meter battery. In reverse bias, the ohmmeter is incorrectly connected to the diode. Current flow is restricted and the ohmmeter reads a high resistance. Remember, there are two different diodes in alternators that look physically identical.

RECTIFIED ALTERNATING CURRENT GENERATOR OPERATION

The Army's small alternators are made by a variety of manufacturers. A generic system will be used as an example (Figures 13-17 and 13-18). This produces approximately 70 amperes at 24 volts.

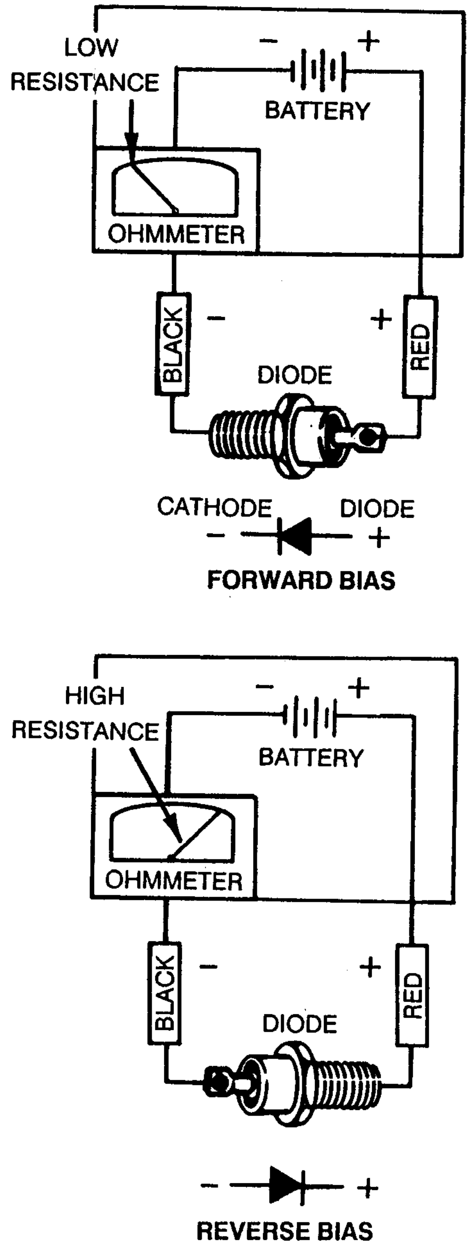


FIGURE 13-16. Forward and Reverse Bias.

There are three basic elements to the belt-driven alternators:

- The rotor which provides the magnetic field.
- The armature which has the EMF induced in it.
- A full-wave bridge rectifier assembly which converts the AC to DC.

Direct current is supplied to the alternator from the vessel's starting batteries via the voltage regulator. The DC enters the alternator through a set of carbon brushes and slip rings. Constant contact between the battery supply and the alternator is maintained through the sliding brush and slip ring connections.

Direct current flows through the slip rings directly to the rotor. The DC flowing through the field windings establishes a magnetic field around the rotor poles. The rotor is turned through a belt and pulley assembly by the prime mover. This provides the revolving magnetic field necessary to develop the three-phase AC needed for efficiency.

The revolving magnetic field from the rotor sweeps past the stationary conductors of the armature. The rotor field sweeps by the armature's conductors with alternating magnetic polarities that change the direction of current flow in the stationary conductors.

As a positive magnetic polarity sweeps past the armature conductor in Figure 13-19 view A coil 1, an EMF is induced, and current flow in the armature conductor moves in one direction.

As the rotor turns a little further, no magnetic field cuts the armature conductor, and current flow stops (view B). The rotor turns a little further. Now the negative magnetic polarity of the rotor sweeps past the same armature conductor, and current flow is again established. This time it is in the opposite direction (view C).

The armature has three windings connected together to form a wye. Each winding produces a separate EMF. The rotor and armature interaction from these three single-phase windings produces a three-phase AC. This three-phase AC must be rectified to DC before it can be used to charge batteries or operate the DC electrical system.

One end of each armature winding is connected together to form the wye armature winding (Figure 13-20). The other end of each winding is connected to a pair of diodes. Each pair contains a positive and a negative diode. There are six diodes in the alternator full-wave bridge rectifier assembly. Since AC flow moves in both directions in each winding, the pair of diodes are employed to restrict current flow to one direction only. Figures 13-21 through 13-23 show how the current flow out of the armature is conducted through one of the diodes, and

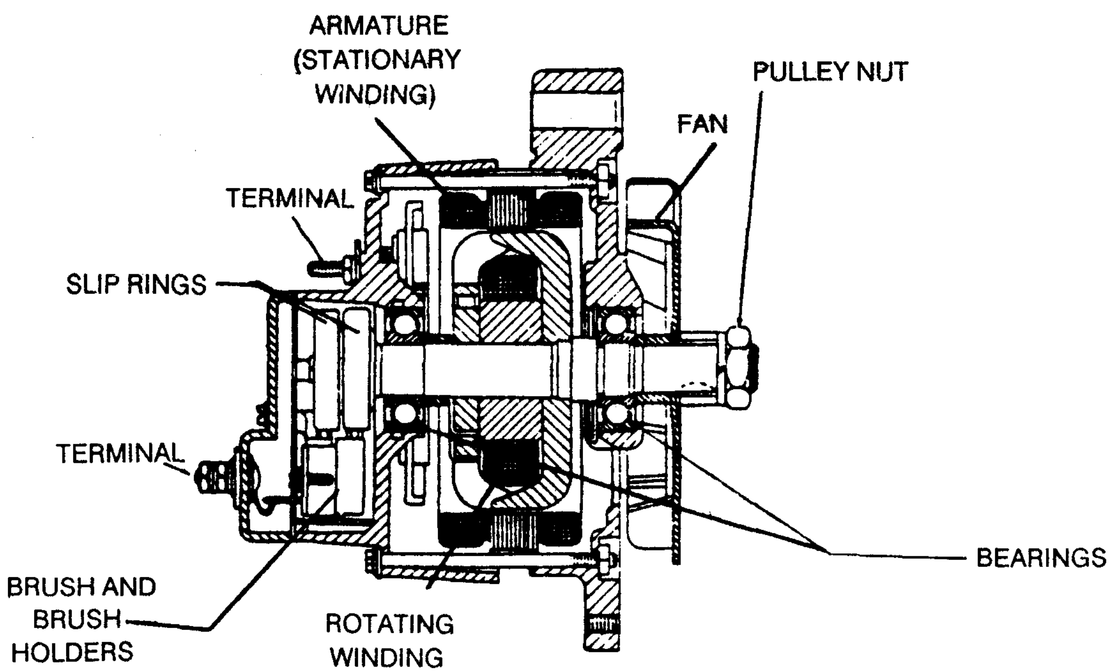


FIGURE 13-17. The Rectified Alternating Current Generator.

current flow into the armature is conducted by the other diode. In this manner, current is prevented from leaving the diode assembly in any other direction than that required for DC vessel operation.

Figures 13-21 through 13-23 illustrate the completed circuits through the alternator armature. These circuits include the A-B, B-C, and C-A winding combinations. The figures are very elementary

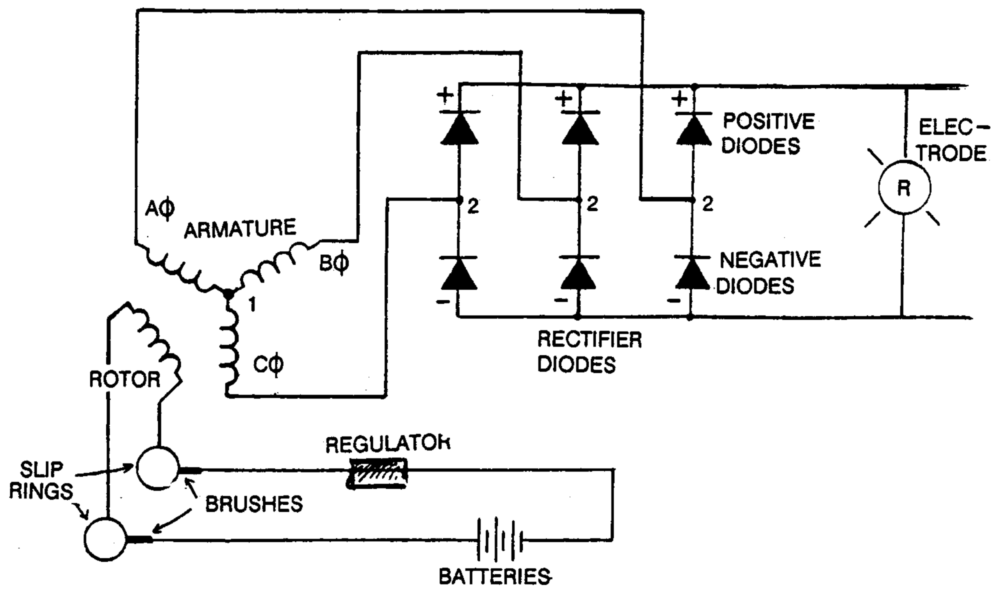


FIGURE 13-18. Basic Rectified Alternating Current Generator Wiring Diagram.

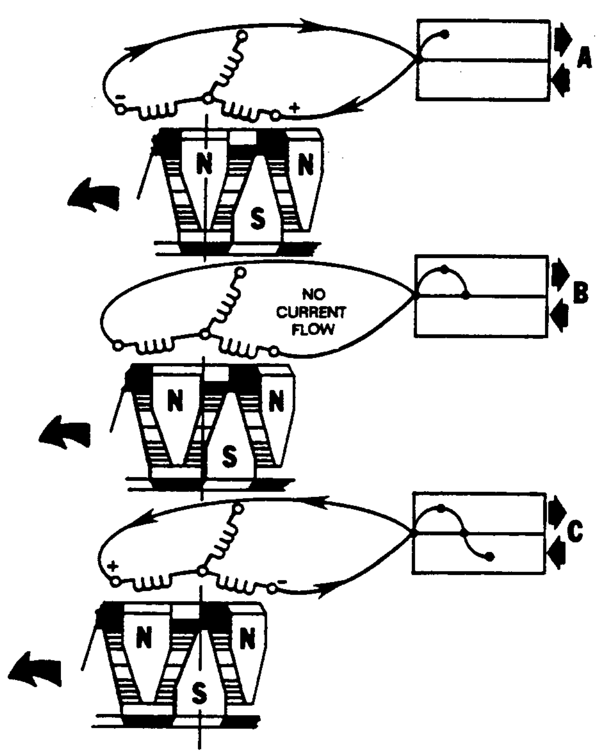


FIGURE 13-19. Alternating Current Flow in the Rectified Alternating Current Generator.

diagrams showing the rotor field moving within the armature, influencing a current flow in a given direction.

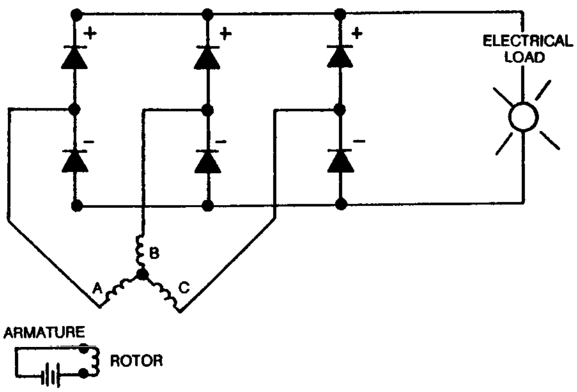


FIGURE 13-20. Full-Wave Bridge Rectifier.

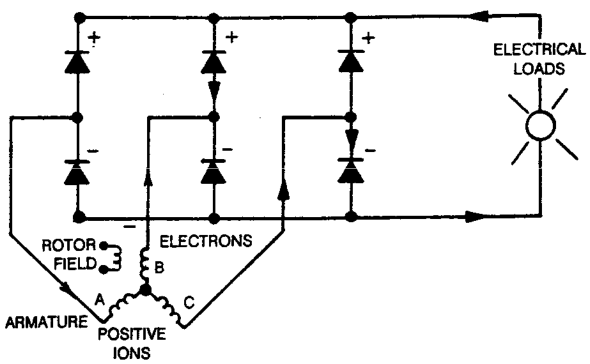


FIGURE 13-21. Current Flow From A Phase, Circuit A-B.

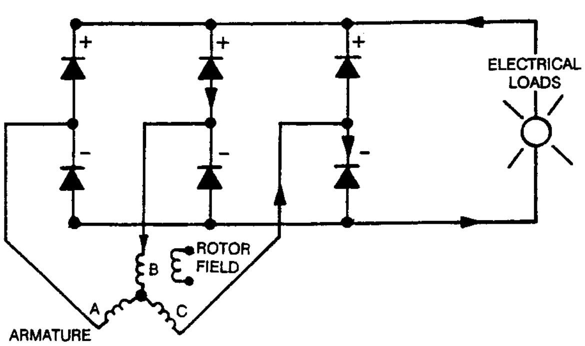


FIGURE 13-22. Current Flow From B Phase,

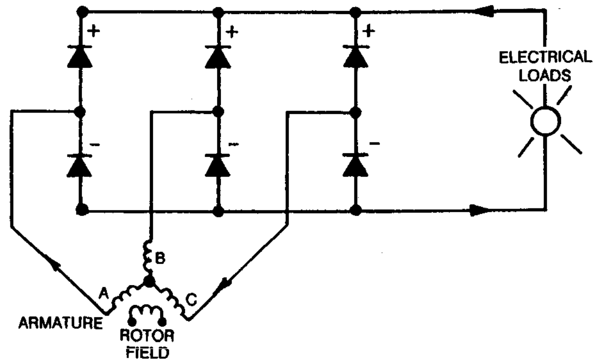


FIGURE 13-23. Current Flow From C Phase, Circuit C-A.

A completed circuit is required for current to flow. The three-phase AC from the armature acts more like three independent single-phase EMFs. In Figure 13-21, the field rotor develops an EMF in the A-B combination of armature windings. To produce an EMF, the valance electron must go to one armature terminal, and the positive ion must go to the other armature terminal. These electrons will naturally seek out the positive ion again. Because the field is exciting the electrons away from the positive ions, the only path back to the positive armature terminal is through the electrical circuit. Electrons are afforded one path out the negative diode (in the center pair of diodes) to the electrical loads (in this case a light bulb). The electrons pass through the light bulb and return through the only positive diode that is connected to the strong positive polarity of the A phase armature winding. There is no stronger positive polarity at this point in time to attract the negative electron.

Figures 13-21 through 13-23 illustrate three independent circuits. These independent circuits, however, overlap each other during operation. This is because the armature windings are physically displaced from each other by 120 electrical degrees. The north and south pole of the revolving field affects the induced individual armature EMF in different amplitudes and current directions, all at the same time.

Pulsating Direct Current

The diodes direct the three separate armature EMFs to deliver their AC to the electrical system in a single direction only. This is known as rectified or pulsating DC. Three-phase AC is necessary to prevent large gaps in current delivery to the electrical system. The rectified DC is relatively stable because of the three EMFs supplying it. Figure 13-24 shows an initial three-phase AC before it is rectified to pulsating DC. Figure 13-25 shows the three-phase AC rectified to DC by the diodes. Notice how the DC amplitude rises and falls slightly with the AC peaks.

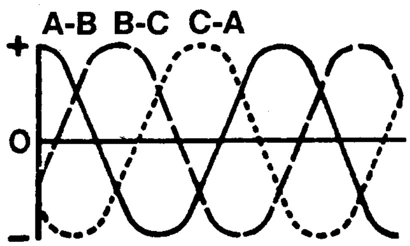


FIGURE 13-24. Three-Phase AC to Rectified DC.

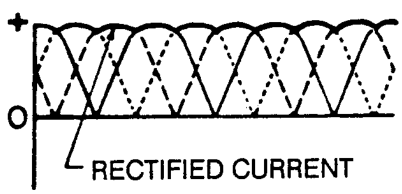


FIGURE 13-25. Single-Phase AC to Rectified DC.

Voltage Regulation

To regulate the output of the alternator, the input to the alternator's field must be regulated. Initially, the field is established with battery voltage. As the alternator comes up to speed and starts to develop an output, a portion of the DC output is redirected to the rotor field. The voltage regulator senses the alternator's output and increases or decreases the current to the field as necessary to maintain the proper output voltage. By increasing the DC in the field windings, a stronger magnetic field is developed. This stronger magnetic field induces a greater EMF in the armature. This increases alternator output. Conversely, by decreasing the current flow through the field, thus reducing the magnetic field of the rotor, less EMF is induced in the armature, and output is similarly reduced.

Some voltage regulators are separate units mounted alongside the alternator. These regulators can be easily replaced. Other voltage regulators are part of the alternator. These integral regulators can not be serviced at the unit level.

Additional Diodes

Additional diodes may be found in the belt-driven alternators. The isolation diode is one. This diode allows current to leave the alternator only. As long as the alternator output is greater than the batteries, the batteries will charge. If, however, the battery EMF becomes greater than the EMF produced in the alternator, then the isolation diode prevents the battery from discharging itself through the alternator.

The three cylindrical diodes connected in parallel to the positive rectifier diodes are called the field diode assembly. These supply continued power to the field windings after the initial battery field excitement when the alternator was initially started.

CHAPTER 14

SHIP SERVICE GENERATORS (AC)

INTRODUCTION

All generators change mechanical energy into electrical energy. This is the easiest way to transfer power over distances. Fuel is used to operate the diesel or prime mover. The fuel is converted into energy to turn the generator. The generator's movement, magnetic field, and associated wiring change this mechanical energy into electrical energy. Wires and cables deliver this power to the electrical loads. The motor is designed to change electrical energy back into mechanical energy to do work.

Chapter 13 describes the rectified AC generator which produced a DC output to operate small DC electrical systems. This chapter describes the three-phase AC brushless generator which delivers three-phase AC to the ship's main electrical distribution system. Most of the large generators used to provide AC to ships' electrical systems are of the brushless type. The brushless generator eliminates the weak link (brushes and slip rings) in the generating system and reduces the maintenance required. There are revolving field and revolving armature brush and slip ring generators in use today. However, brushless AC generators are used exclusively as the Army's ship service power source.

BRUSHLESS ALTERNATING CURRENT GENERATOR CONSTRUCTION

Figure 14-2 illustrates the brushless generator. The main frame or housing (7) is a strong metallic structure surrounding and retaining the stationary windings (6). The main frame is, in turn, supported by mounts. These mounts are not rigid. Rubber composition or springs are incorporated into the mounts as shock absorbers called resilient mounts.

One end of the generator main frame is bolted to the prime mover's flywheel housing. The other end of the generator main frame is bolted to the bell end or end frame (12). The bell end contains a bearing (17) that supports the internal rotor shaft.

The other end of the rotor shaft connects to a flexible drive disc (29) and fan (15) assembly. The drive disc assembly, in turn, is bolted to the flywheel of the prime mover. When the prime mover turns, the drive disc turns, and the fan pulls cooling air into the housing to dissipate heat created in the generator windings.

The fan can disturb high bilge water and pass particulate of oil over the windings. When oil-covered windings become incapable of transferring sufficient heat to the air stream, the winding insulation becomes damaged. It is imperative that low bilge levels be maintained, and the diesel air box ventilation exhausts away from the fan's air flow.

Generator Windings

There are four different sets of windings in the brushless generator (Figure 14-2). Two windings (6 and 10) are connected to the generator main frame, and two windings (8 and 9) are fitted to the rotor shaft. There are no direct mechanical electrical connections between the rotating and stationary windings of the generator.

Winding Contamination

Inspect the stationary and rotating winding periodically for cleanliness. The chief engineer or his appointed representative will supervise internal inspection of the ship service generator. Never inspect internal generator components while the prime mover is operating or the generator is connected to the switchboard bus. Always secure the prime mover fully and ensure other power sources, such as the emergency generator or shore power, cannot feed the generator being serviced.

Textbook maintenance practices call for removal of dirt by vacuuming and removal of grease and oil through wiping with lint-free rags. These methods rarely serve the purpose intended. Contamination prevention is the key. Inspect the generator prime mover for gasket and seal leaks. Check also adjacent piping and deck plates for liquids and particles. Once the windings become contaminated, there is no thorough and safe method to clean the generator windings on board the vessel. The only effective recourse requires the removal of the generator, its complete disassembly, chemical cleaning, and baking by the DS/GS maintenance activity.

When contamination is found, use the megger to check the insulation values. Always disconnect the rotating rectifier, voltage regulator, and any other components that house semiconductors. Compare readings with the appropriate technical manual, with other known good generator readings, or against megger historical documentation.

Exciter Field

The exciter field is a stationary DC energized winding. This is the winding where the DC magnetic field is initially developed. Even before any voltage regulation takes place, a residual magnetic field exists in the poles. During voltage regulation, DC in the exciter field induces an EMF and resulting current flow in the exciter armature. This winding can be found mounted toward the bell end section of the generator.

Exciter Armature

The exciter armature is a three-conductor, three-phase rotating winding. The exciter armature is located directly inside the exciter stator. A three-phase EMF is induced in the exciter armature as it rotates inside the fixed magnetic field of the exciter field.

Together, the exciter field and exciter armature develop a three-phase AC. In effect, this is a rotating armature generator. This portion of the generator is used to provide the excitation necessary for the main field portion. The exciter field and armature operate in the same manner described in Chapter 13. The exciter portion is the generator that develops the power necessary to develop the magnetic field in the main generator portion. Since current is induced into the armature without the aid of wires, brushes and slip rings are eliminated.

Rotating Rectifier

The output developed from the exciter portion of the generator is AC. To produce the enhanced three-phase output from the main armature of the generator (necessary for the large power requirements of the distribution system), the main field must be provided a direct current source. To change (or rectify) the exciter portion output from AC to DC, the rotating rectifier is used. The rotating rectifier provides the same conversion of AC to DC as the diode combination discussed in Chapter 13 for the belt-driven alternator.

Main Rotating Field

The main rotating field (8 in Figure 14-2) can consist of four to eight individual coils or pole pieces keyed to the rotor shaft. The coils are connected in series and consist of only one wire. The direction that the wire is wound around the pole piece determines the magnitude polarity of each individual field coil. Rectified DC, from the rotating rectifier (11), develops the revolving magnetic field inside the main

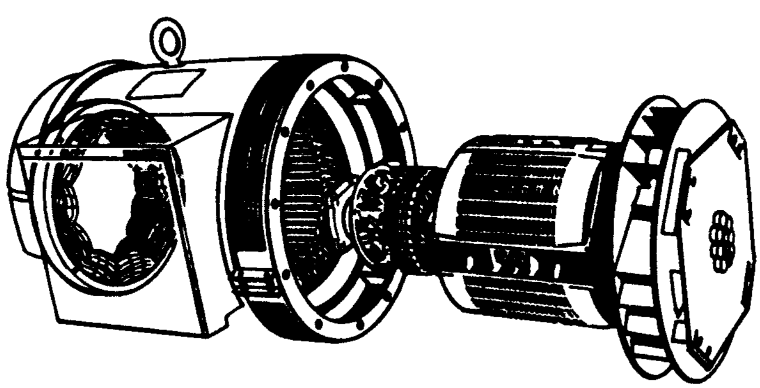
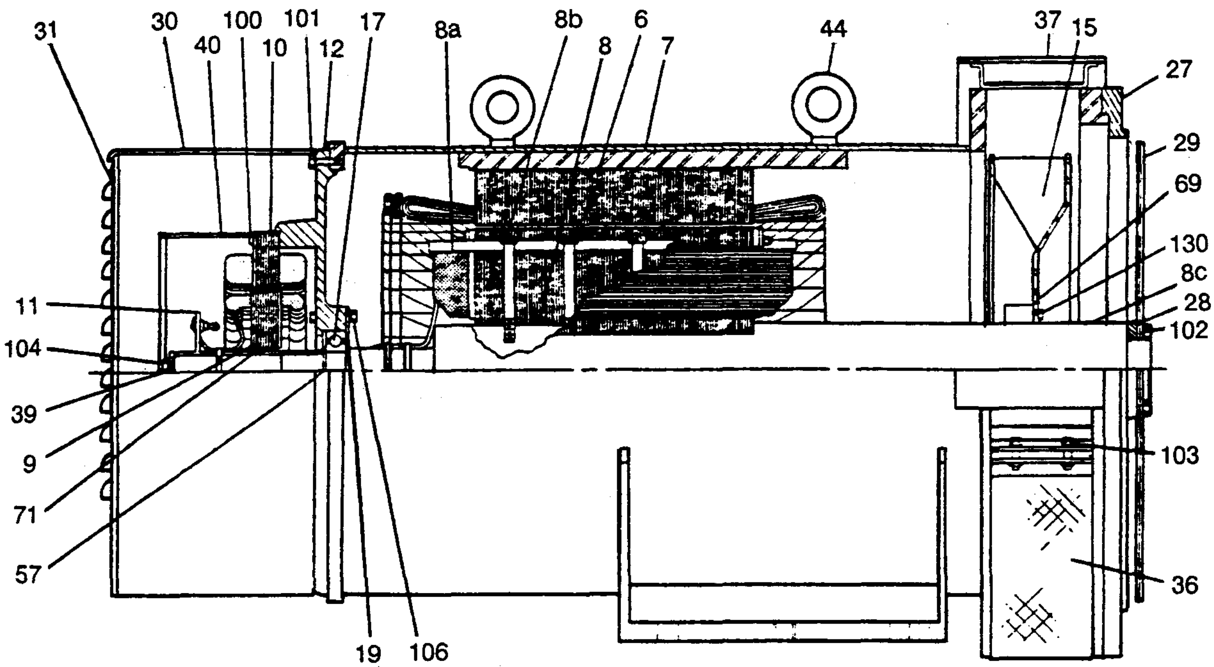


FIGURE 14-1. AC Brushless Generator.



ITEM	NAME	ITEM	NAME	ITEM	NAME
6	Stator & Coil	18	Bearing, Drive End	44	Eyebolt
7	Main Frame	19	Bearing Cap, Inside, Exciter End	57	Snap Ring
8	Rotor	21	Bearing Cap, Inside, Drive End	69	Fan Hub
8a	Rotating Coil	22	Bearing Cap, Outside, Drive End	71	Key, Exciter Armature
8b	Bolt Rotating Coil	27	Spacer Housing	73	Key, Drive End, Shaft
8c	Shaft	28	Spacer, Shaft	100	Bolt, Exciter Field
9	Exciter Armature	29	Driving Disc Assm.	101	Bolt, End Frame, Exc. End
10	Exciter Field	30	Connection Box	102	Bolt, Drive Disc
11	Rotating Rectifier Assm.	31	Connection Box Cover	103	Bolt, Cover Band
12	End Frame, Exciter End	36	Cover Band, Screen, Exhaust	104	Bolt, End Cap
13	End Frame, Drive End	37	Cover Band, Dripproof, Exhaust	106	Bolt, Bearing Cap, Exc. End
15	Fan	39	End Cap	130	Bolt, Fan Mounting
17	Bearing, Exciter End	40	Lead Protection Cover	137	Bolt, End Frame, Drive End
				138	Bolt, Bearing Cap, Drive End

FIGURE 14-2(A). Generator Components.

field generator portion providing alternate fixed field polarities.

Amortisseur or Damper Winding

Embedded in the face of each main field pole piece is the Amortisseur or damper windings. These are necessary for generators that operate in parallel. These become very important when dealing with frequency. The frequency of an AC generator must not change. These damper windings prevent hunting during parallel operation. Damper windings are copper or aluminum conductors embedded just below the surface of the rotor. They are short-circuited at each end to allow currents to circulate so that a magnetic field can be produced to oppose any change in prime mover motion.

Main Armature

The main armature (6 in Figure 14-2 view B) is bolted to the inside of the main frame. There are three windings, each of which are spaced 120 mechanical and electrical degrees apart. They may be connected in either wye or delta configurations as required for the application. The main armature windings are connected directly to the electrical system through the switchboard.

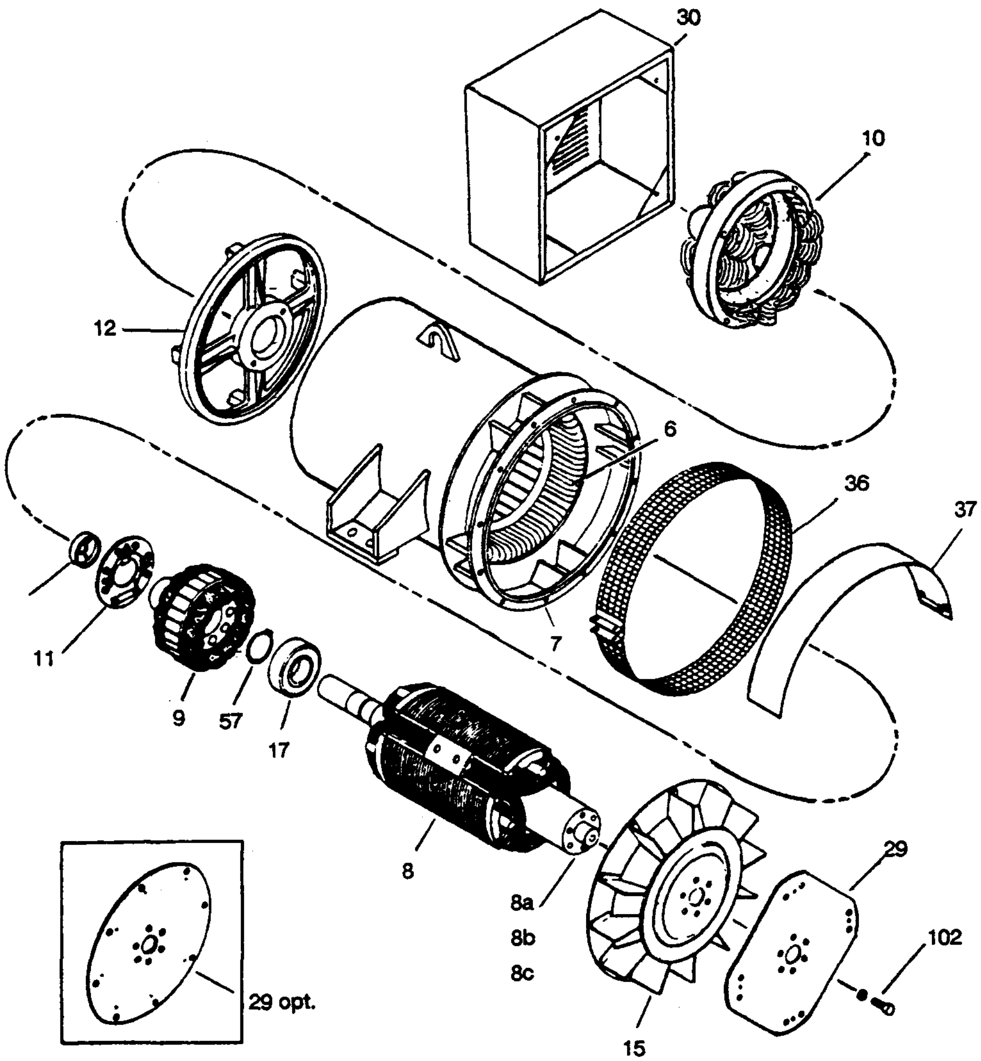


FIGURE 14-2(B). Generator Components.

BRUSHLESS ALTERNATING CURRENT GENERATOR OPERATION

The brushes and slip rings used by many small generators become intense maintenance problems. This area is extremely prone to contamination. As the brush slides over the slip ring, a certain amount of arcing may take place. To eliminate brushes, two generators are coupled together in a single housing. A rectified rotating armature generator, similar to the one discussed in Chapter 13, provides a direct current source for the rotating field of the main generator. Putting these two generators together eliminates the need for any physical mechanical connection between the moving and the stationary parts of the generator. Figure 14-4 is a pictorial diagram of the electrical circuits in the generic brushless AC generator.

Generator Residual Magnetism

Residual magnetism exists in all ferrous metal that has had a current carried around it. In many generators, there is not enough material to provide a substantial residual magnetic field to use in creating an EMF. The ship service generator has a lot of metal. The material mass maintains enough of a residual magnetic field in the exciter field to induce an EMF in the exciter armature when there is motion.

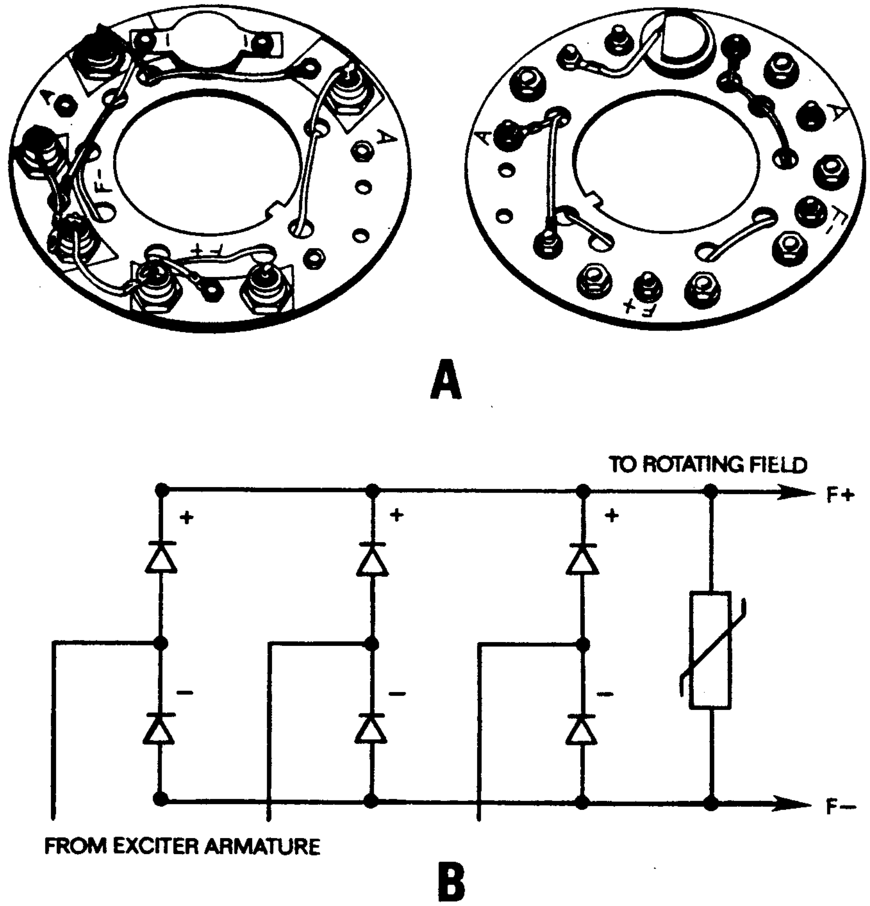


FIGURE 14-3. Typical Rotating Rectifier Assembly and Electrical Diagram.

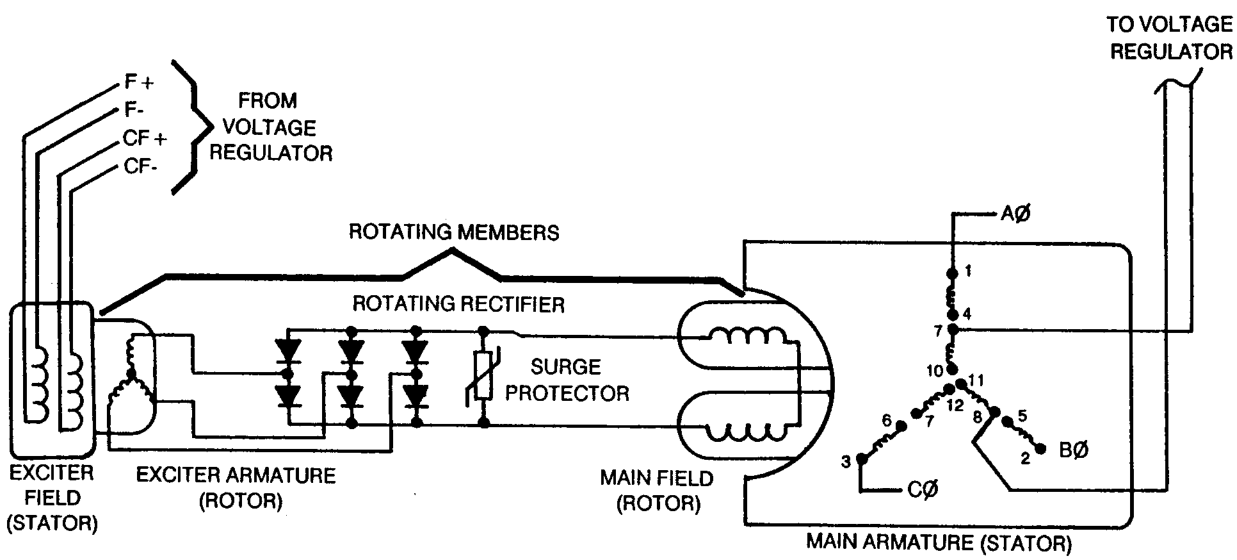


FIGURE 14-4. Pictorial Diagram of the Brushless Generator.

Outline of Operation

The following is a basic outline of the brushless generator operation:

- The prime mover starts. The prime mover crankshaft revolves, and the generator shaft is moving. This turns the exciter armature, the main field, and the rotating rectifier.

- The exciter initiates an EMF. The rotating exciter armature cuts the residual magnetic field left over in the exciter field pole pieces. A small EMF is induced in the wye-wound rotating exciter armature windings. The exciter portion of the machine operates as a revolving armature generator.

- Exciter AC is rectified to DC. The small exciter three-phase AC is directed to the rotating rectifier. The diodes rectify the AC to a pulsating DC. Five wires are connected to the rotating rectifier. Three wires are from the three-phase exciter armature, and two wires direct the DC output to the main field winding.

- The main field induces an EMF into the main armature. Direct current enters the rotating main field. As the rotor shaft turns the main field, the alternating polarities induce an EMF of alternating potentials in the main armature windings.

- Three-phase AC is produced from the main armature. The main armature has three windings producing three-phase AC. The main portion of the generator is operating as a revolving field generator. Initially, only a small three-phase EMF is produced.

- Voltage control takes over. The voltage regulator senses an undervoltage condition and diverts the current flow back to the stationary exciter field. In this case, the CF exciter field winding is used for the initial voltage buildup and some short-circuited conditions. The current flow through the exciter field winding increases its magnetic field. The exciter armature conductors now cut through a greater magnetic field, and the induced EMF in the exciter armature is increased.

- The process is repeated until satisfactory voltage is achieved. The increased exciter armature current is rectified by the rotating rectifier and directed again to the rotating main field. The increased magnetic field, of the rotating main field, sweeps past the conductors in the stationary main armature. This produces a greater three-phase EMF. Normal voltage control is maintained by the regulator controlling current to the exciter field.

Permanent Magnet Generator (PMG)

Newer Army generators employ six separate windings. The additional two windings are identical in operation to any pair of field and armature windings described above. These extra windings provide external excitation for the generator in the same way the four winding generator provided for its own self-excitation.

On Cummins generators and some Caterpillar generators, a permanent magnet generator has been added to the generator assembly. The magnet is mounted on the rotor and is located inside the permanent magnet armature. When the generator is running, the PMG magnet generates an EMF in the PMG armature, providing current directly to the automatic voltage regulator for control of the exciter field. The permanent magnet provides definite voltage output on start-up and greater voltage control under extreme load conditions.

GENERATOR VOLTAGE CONTROL

The voltage regulator (Figure 14-5) controls the output of the generator by controlling the magnetic field in the stationary exciter field winding. The voltage regulator senses the generator's output voltage directly from the generator's main armature windings or indirectly through generator cable connections within the switchboard. The voltage regulator may monitor only a portion of the single phase (Figure 14-6) from the main armature's three-phase or each phase directly from the switchboard.

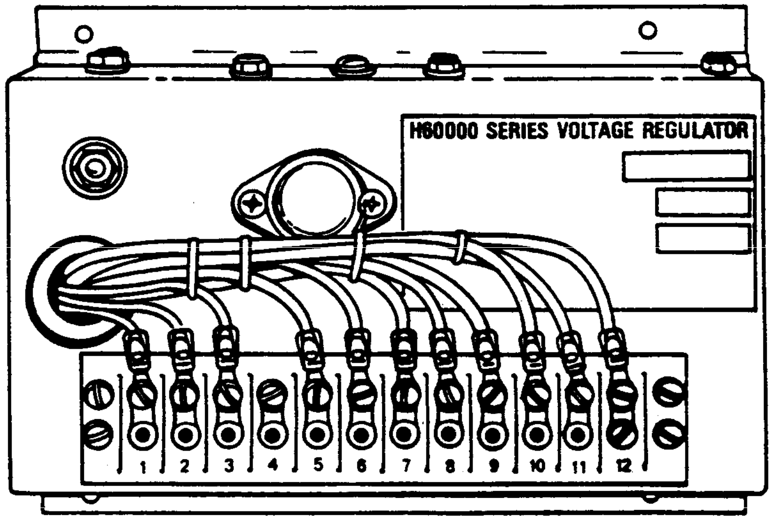


FIGURE 14-5. Voltage Regulator.

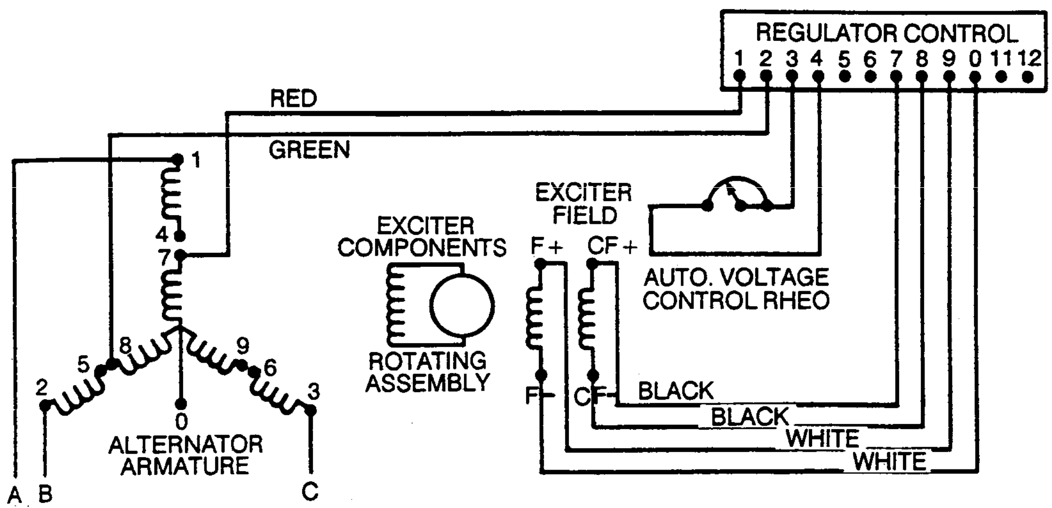


FIGURE 14-6. Input Voltage Sensed From the Generator Armature.

The generator output voltage is controlled by controlling the current in the exciter field windings. Self-excited generators redirect part of their main armature AC output to the voltage regulator. Inside the voltage regulator, the armature AC is rectified to DC. The voltage regulator applies the DC to the exciter field to increase or decrease the magnetic field. When the exciter field magnetic strength is great, the generator's output is improved. With a decrease in the exciter field strength, the output of the generator is reduced.

Separately excited generators sense the output voltage in the same manner as self-excited generators but derive the current for exciter field control directly from a permanent magnet generator designed exclusively for that purpose. In each case, changes in the magnetic exciter field strength is derived from DC supplied from the voltage regulator.

FLASHING THE FIELD

Initially, self-excited ship service generators may need to have the fields flashed to establish the residual magnetism necessary to start the exciter induction process.

> **NOTE:** Read the manufacturer's recommendations carefully. Damage to the generator or voltage regulator will result if proper procedures are not correctly followed.

Generally, flashing the field is done by connecting a battery to the exciter field terminals. By allowing directing current to flow through the exciter field windings, a residual magnetic field is established. The direct current source must be connected correctly. Failure to do so can damage the voltage regulator semiconductors. Observe the field and battery polarity. Ensure the connections are positive to positive and negative to negative.

MAIN ARMATURE THREE-PHASE CONNECTIONS

Brushless generators are usually 240- or 450-volt three-phase AC machines. They are rated in kVA at a specified power factor. Many generator manufacturers produce a basic unit with a variety of voltage and current possibilities.

The main armature consists of six individual windings. Two windings, as a pair, are connected to each other in series or parallel. Each armature winding pair is then connected to the other two armature winding pairs to form the common wye or delta combination. The actual connection between each winding is completed outside of the generator's frame in the attached terminal connector box. In this manner, the user can connect the individual armature winding pairs in series or parallel and the pairs in the delta or wye configuration. The configuration is selected for the type of voltage and current requirements that best fit the application.

PHASES

Only a single-phase EMF (voltage) can be induced (produced) in a single pair of the armature windings. Since there are three such pairs of windings, three separate single-phase EMF values are induced. It is the development of each of the three single-phase values that together produce the three-phase output from the armature windings (Figure 14-7).

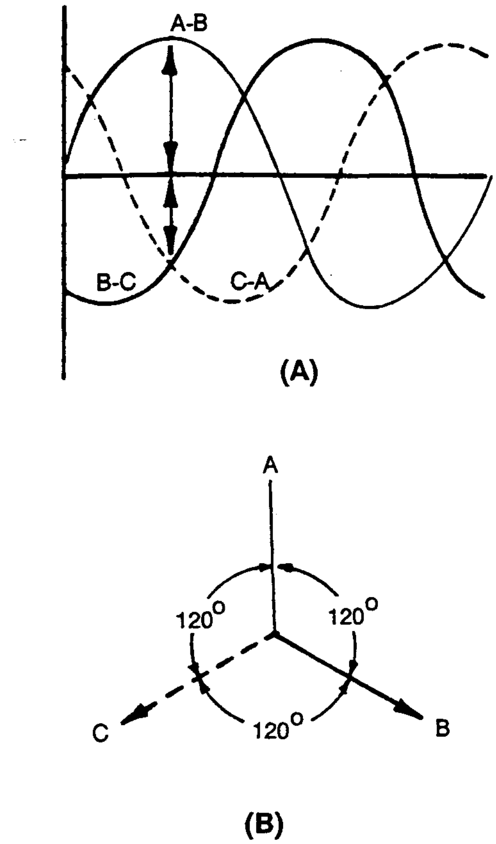


FIGURE 14-7. Three Individual Sine Waves Overlapped in Time for Three-Phase AC.

Phases are often referred to in the following manners:

- Three-phase: phase to phase to phase, A-B-C.
- Single-phase high voltage: phase to phase, A-B, B-C, A-C.
- Single-phase low voltage: phase to neutral, A-N, B-N, or C-N.

Single-phase connections using the neutral are the least common combination on commercial or Army watercraft. The neutral connection is eliminated on all Army watercraft ship service generators but retained on some three-phase delta-wye-connected transformers.

Figure 14-8 illustrates the three-phase winding combination of the wye-connected armature.

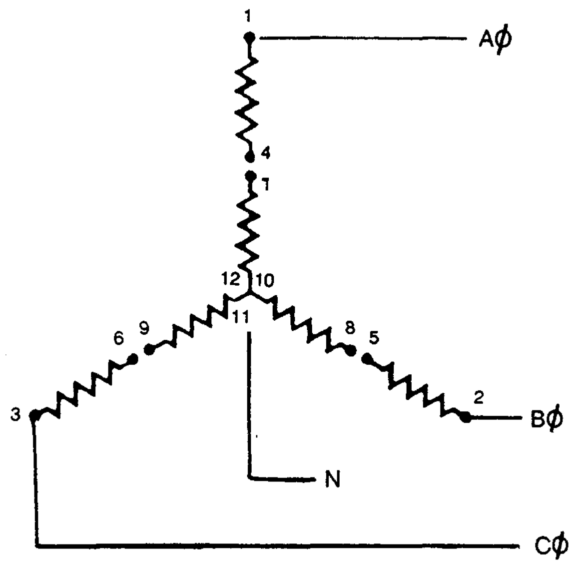


FIGURE 14-8. Wye-Connected Armature.

The three-phase condition is the culmination of all the windings, A-B-C. This produces the highest voltage and current for a given period of time in the electrical system. The three-phase condition takes advantage of three independent electrical circuits almost simultaneously. Figure 14-9 shows how one circuit (between the generator armature and the motor stator windings) at a time is completed. Armature windings A to B and the motor's equivalent A (T1) to B (T2) windings complete one circuit (view A). After 120 degrees of generator rotor rotation, the B to C circuit starts (view B) in the same manner as the A to B circuit; 240 rotor degrees after the A to B circuit started, the C to A circuit is starting (view C). In effect, three single-phase currents are delivered to three motor windings in various amplitudes over the same period of time.

> **NOTE:** For clarity, three different periods of time are used to reflect a current at a maximum amplitude in one specific direction per completed circuit. In reality, current is moving in various amplitudes and directions at any point in time as illustrated by the three-phase sine wave.

A phase is the reoccurring electrical event, or value, found between any combination of the generator's armature terminals. In other words, a phase is the voltage and current found between terminals A to B, B to C, C to A, A to N, B to N, C to N, or terminals A, B, and C (Figure 14-10).

The electrical value found between any two terminals is a single-phase event. The electrical value found between three terminals is a three-phase event. There cannot be a two-phase value derived from these terminals. The single-phase circuit has an electrical load between two of the generator terminals. This is the only way to provide for the complete circuit required for current flow. The armature winding has the difference in potential required to attract the electron back. For example, terminals A and B complete one phase.

The three-phase circuit uses three such combinations in varying amplitudes at the same time (Figure 14-11). Although each sine wave is usually identified as A, B, or C, each sine wave is a combination of a completed circuit. A better representation of the three-phase sine waves would identify each wave as the circuit it completes, such as A-B, B-C, or C-A. In this manner, it is easy to see the three single phases, operating out of phase by 120 electrical and mechanical degrees. It also becomes apparent that with the loss of anyone winding (A for example), only one complete circuit phase is left. Without phase A, there cannot be a completed circuit between A-B or C-A. This leaves only B-C and a single-phase event. This electrical three-phase malfunction is called single phasing.

The following terms describe the operation of the generator and the transformer:

- Phase to phase to phase. This is a three-phase event using all the available voltage and current values in the entire generator armature over a period of time.
- Phase to phase. This is a single-phase event, providing the total available voltage and current value from two individual phases. This is a high voltage single phase. There is no difference in voltage between phase-phase and phase-phase-phase values in the same machine.
- Phase to neutral. This is a single-phase event using any voltage and current that can be induced into one armature winding alone. This is a low voltage single-phase value.

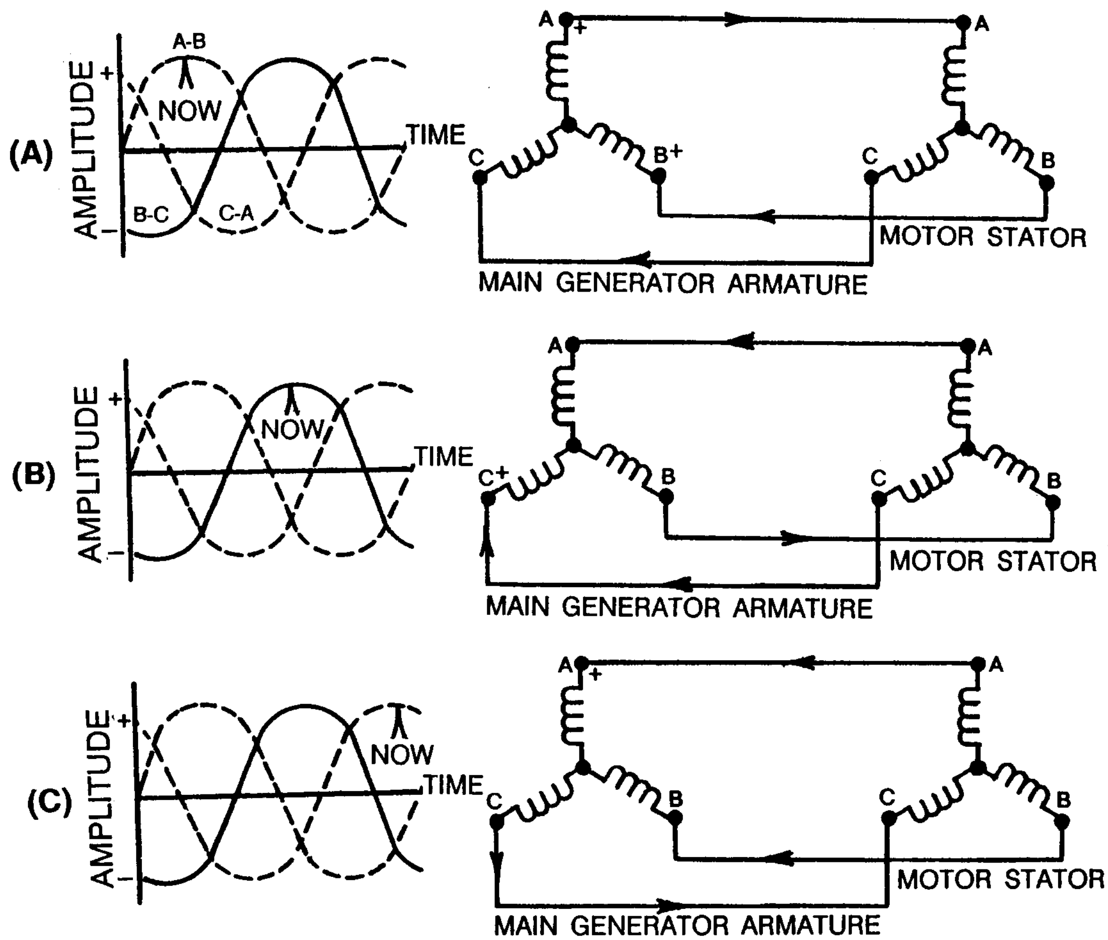


FIGURE 14-9. Three Independent Single Phases Equates to a Three-Phase Condition.

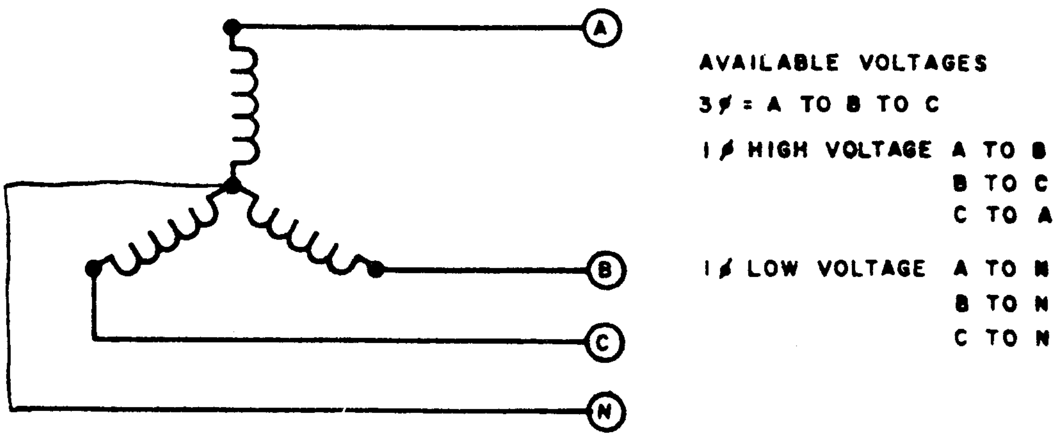


FIGURE 14-10. The Wye-Connected Armature Winding.

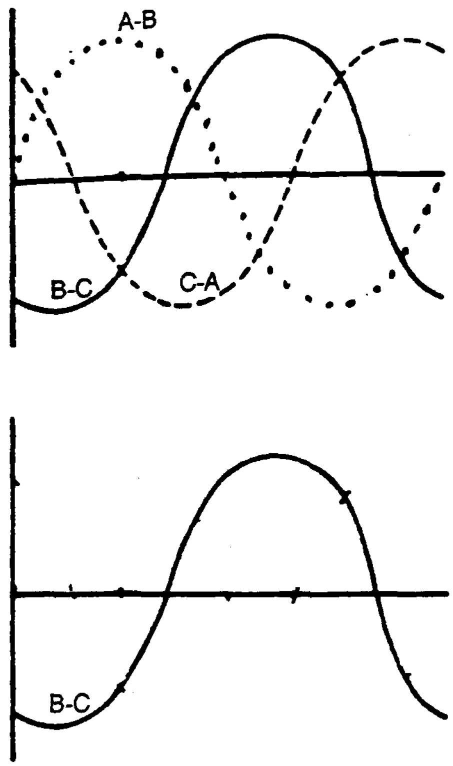


FIGURE 14-11. Loss of Phase A Produces Only Single Phase.

WINDING COMBINATIONS

The generator main armature has six individual windings (Figure 14-12). Two windings are for use in each phase-to-neutral combination. Each of the two leads from each winding may be brought out of the armature to a connection box for connecting externally. How these windings are wired together will determine the current and voltage characteristics of the generator output terminals. Although this chapter deals primarily with ship service operations, the combinations of windings remain pertinent to transformers and motors alike.

The neutral is used as a reference point when dealing with the Army's AC generators. Currently, the neutral is isolated within the connector box and left unconnected. However, it is necessary to understand the neutral conductor and its effects on the electrical system. The LSV uses the neutral lead from delta-wye transformers. The transformer's primary side receives three conductors from the generator armature. The secondary side of the LSV three-phase transformer uses the neutral terminal and provides four leads and an extra low voltage capability. Whether windings are connected in an armature, in a single three-phase transformer, or in three single-phase transformers, the wye and delta combinations all apply equally.

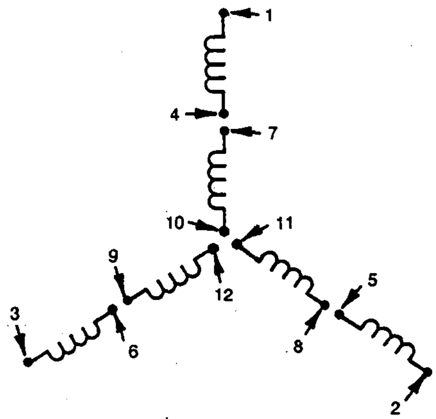


FIGURE 14-12. Armature Winding Cables.

WYE-CONNECTED ARMATURE

Marine generators are almost exclusively wye-connected. The wye is a series winding because any completed circuit, A-B, B-C, or C-A, has only one path for current to flow. The neutral (N) represents the common connection point where one end of each of the individual phase windings are connected. The other end of the phase windings deliver power to the electrical system as terminals: A, B, or C.

In the wye armature (Figure 14-13), the series connection is the key to the voltage and current output. If each phase winding can develop a specific number of amperes and volts, then the generator's total output characteristics can be calculated. For example, the phase winding A-N, B-N, or C-N can develop an induced EMF at 260 volts with a maximum resulting current of 100 amperes.

Basic series circuit rules apply. In a series circuit, amperage remains constant. Therefore, current available to the electrical system from any phase-to-phase combination, A-B, B-C, or C-A, is 100 amperes.

Line current = phase current = 100 amperes

Phase-to-phase (or line) voltage, as described in the series circuit rules, is the sum of the individual phase winding voltages. In this case, 260 volts from A-N, for example, cannot be added to 260 volts from B-N because the same magnetic flux of the generator's main field does not affect them equally. The phase windings are displaced in time and space by 120 degrees. Instead, a constant has been developed through vector mathematics as 1.732. This figure will always hold true for basic electrical needs. Figure 14-14 shows the connection between voltage in a series circuit and the 1.732 multiplication factor.

The total voltage in a series circuit equals the sum of the voltages. However, Figure 14-14 shows that the north magnetic polarity is influencing one armature winding in its entirety. The second overlapping armature winding is being affected to a great extent, but not fully. The third overlapping armature winding is not affected at all by the north field pole polarity. The magnetic influence of the single pole cannot affect each physically displaced winding equally. Think of the 1.732 multiplication factor as the following:

Voltage total = one complete armature winding + 73 percent of the other armature winding

Et = 260 volts + (.73)(260 volts)

Et = 260 volts + 190 volts (approximate)

Et = 450 volts

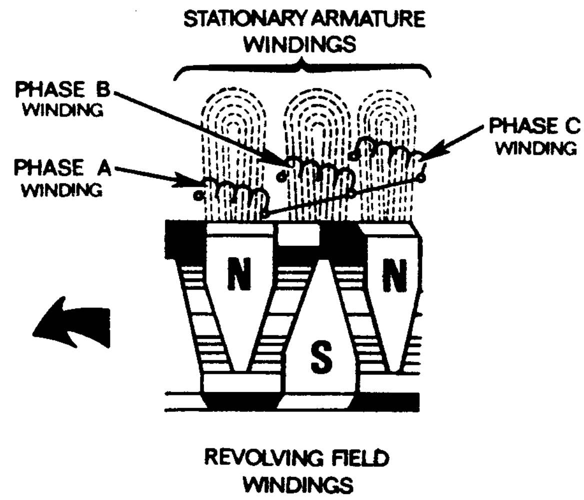


FIGURE 14-14. The Magnetic Field Affecting the Armature Windings.

NOTE: This is an oversimplification of the entire electrical process. These armature winding effects happen to all three windings by two different polarities constantly in various degrees at any given time.

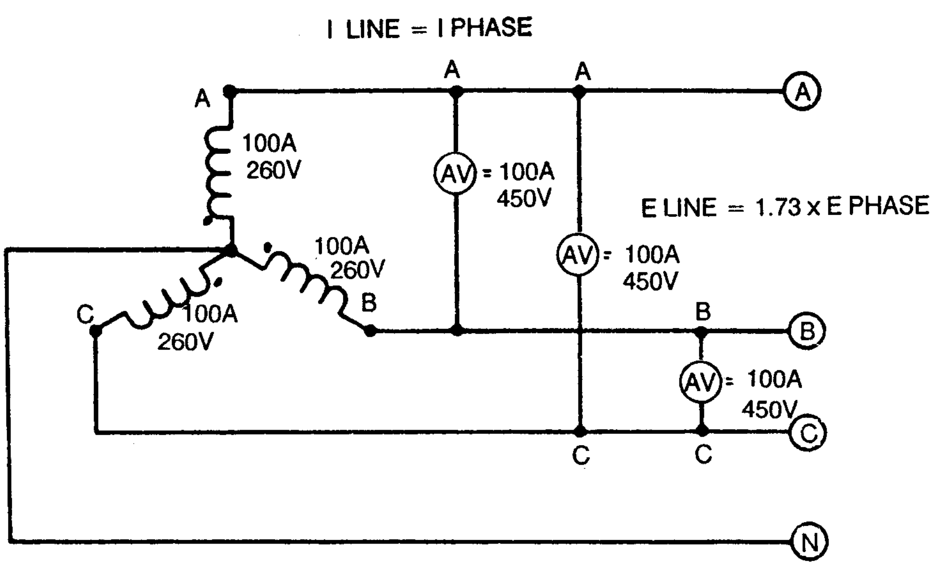


FIGURE 14-13. WYE-Connected Winding Values.

Multiplying the voltage by 1.732 gives the voltage supplied to the electrical system by phase A-B (or B-C or C-A):

(Phase-to-neutral voltage) x (1.732) = line voltage

(260 volts) X (1.732) = 450 volts

Should an additional single-phase voltage value be desired, the wye can be tapped at the neutral connection. This provides the phase-to-neutral voltage. In this case, A-N, B-N, or C-N would provide another voltage value possibility of 260 volts (Figure 14-15).

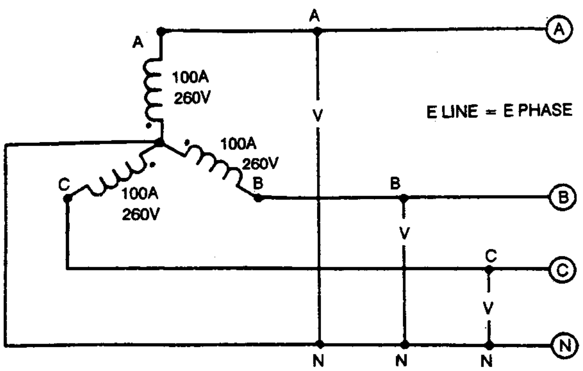


FIGURE 14-15. Phase-to-Neutral Voltage.

DELTA-CONNECTED ARMATURE

The delta connects the windings in parallel (Figure 14-16). The positive end of each winding is connected to the negative end of another winding. The terminals are labeled A, B, and C.

The delta connection in Figure 14-17 shows that a complete circuit between any phase provides two paths for current to flow. For example, current may leave armature terminal A, go through the motor stator, and return to armature terminal B to complete the A-B circuit). The current in the C-A and the B-C phases are also affected by the rotor field in various degrees. Notice that there is no single common connection. All phases in the armature are connected together in parallel during any single-phase complete circuit. The parallel circuit rules, therefore, are the key to understanding the delta connection.

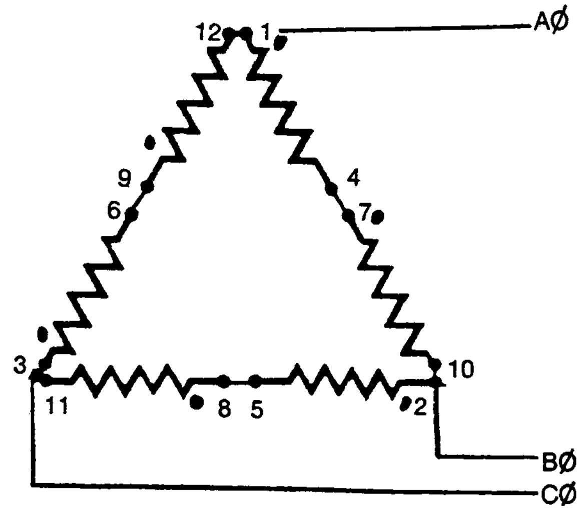


FIGURE 14-16. Delta-Connected Windings.

The same example values that were used with the wye-connected windings are used for the delta. Each phase winding can develop an induced EMF of 260 volts with a maximum current value of 100 amperes (Figure 14-18). The basic parallel rule states that voltage remains constant. Therefore—

Line voltage = phase voltage = 260 volts

Line current is the sum of the individual currents developed in the generator. Since the magnetic field of the rotor cannot affect all the phase windings equally, the constant 1.732 must be used for the calculations.

Line current = (phase current) x (1.732)

Line current = (100 amps) x (1.732)

Line current = 173 amperes

POWER CONSIDERATIONS

Both the wye- and the delta-wound generator have approximately the same power capability. The wye generator is the most favorable generator for the application. By using the higher voltage and lower current (450 volts and 100 amperes), smaller diameter conductors, contacts, and circuit breakers can be used in the electrical system. Dual voltage motors will run cooler and last longer with the lower current value.

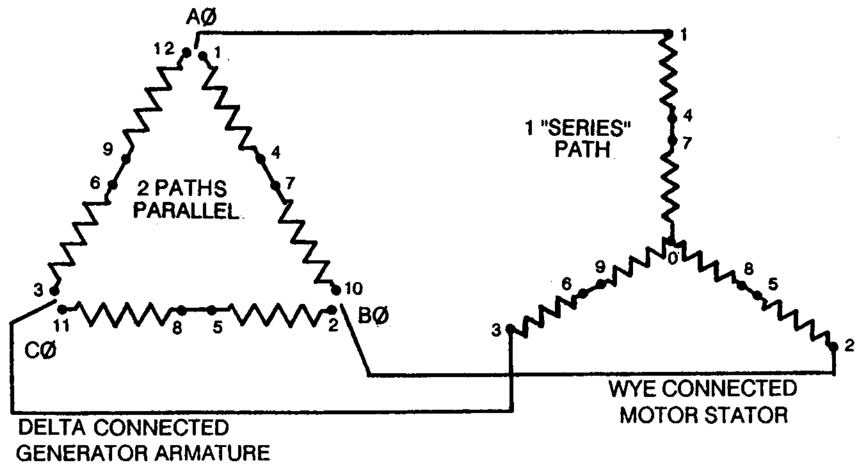


Figure 14-17. Delta Parallel Paths.

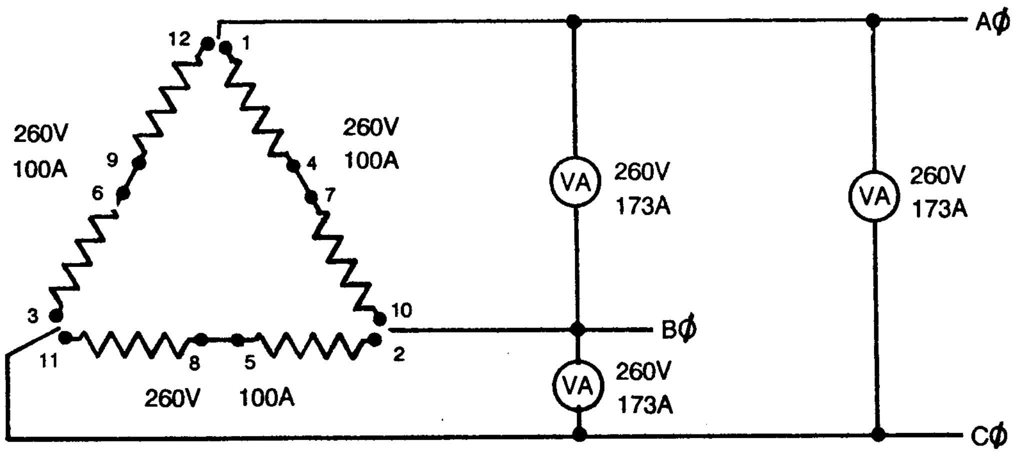


FIGURE 14-18. Delta-Connected Armature.

The delta generator uses 260 volts at 173 amperes to provide the same power needs to the electrical distribution system. Increased current means increased heat. Heat is the element of destruction to electrical components. The increase in current requires increased cable, contactor, and motor protective size. Any increase in size is an increase in cost.

Figure 14-19 details some of the possible configurations for wiring ship service generators. The many options let the manufacturer keep costs low by reducing the number of different generators that must be built and stocked. This lets the consumer determine what application of the generator best serves him.

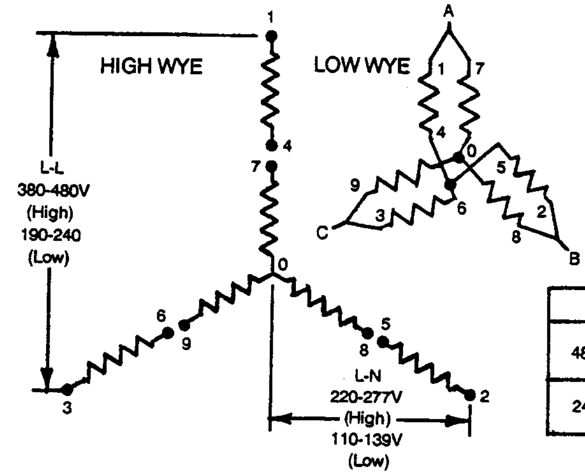
WYE-DELTA VOLTAGES

When using identical windings, the high delta is the same voltage as the low wye and half the voltage of the high wye (Table 14-1). The parallel delta is half the voltage of the high delta and low wye and one-fourth the voltage of the high wye.

TABLE 14-1. Wye-Delta Voltages.

HIGH WYE	416 - 480 volts
LOW WYE	208 - 240 volts
HIGH DELTA	240 volts
PARALLEL DELTA or LOW DELTA	120 volts

10 LEAD HIGH-LOW WYE 1600 Series LCU



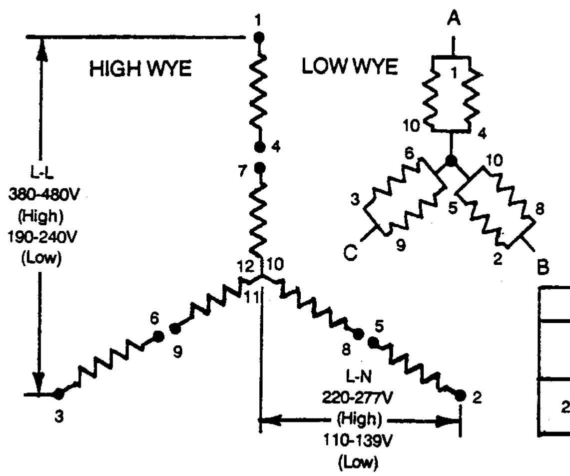
Ten lead generators are dual voltage generators with six coils. One end of the three coils is connected together. There are 10 or 20 leads coming out of the generator.

CAUTION: Some generators have multiple, identically marked, conductors for each lead. Connect all identically marked conductors together when making connection to load. L-N/L-L

Voltages: 60 Hz 240/416V through 277/480V
(High) 50 Hz 220/380V through 240/416V
Voltages: 60 Hz 120/208V through 139/240V
(Low) 50 Hz 110/190V through 120/208V

VOLTAGE	CONNECT	L1	L2	L3	NEUTRAL
480-416 WYE	4-7 5-8 6-9	1	2	3	0
240-208 WYE	1-7 2-8 3-9 4-5-6-0	1	2	3	4-5-6-0

12 LEAD HIGH-LOW WYE



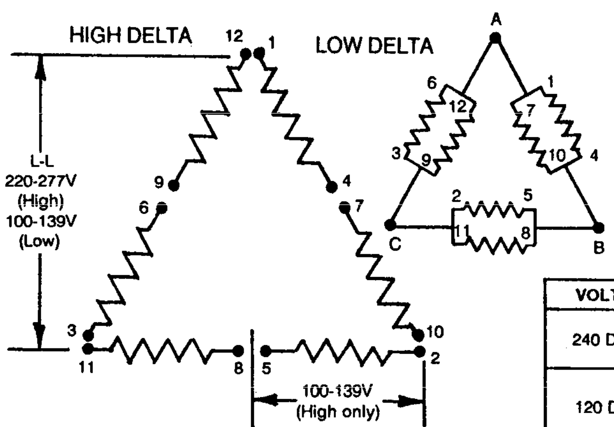
Twelve lead generators are dual voltage generators with six coils which don't have the connection of the three inner coils. There are 12 or 24 leads coming out of the generator.

CAUTION: Some generators have multiple, identically marked, conductors for each lead. Connect all identically marked conductors together when making connection to load. L-N/L-L

Voltages: 60Hz 240/416V through 277/480V
(High) 50 Hz 220/380V through 240/416V
Voltages: 60Hz 120/208V through 139/240V
(Low) 50 Hz 110/190V through 120/208V

VOLTAGE	CONNECT	L1	L2	L3	NEUTRAL
480-416	10-11-12 4-7 5-8 6-9	1	2	3	10-11-12
240-208 WYE	10-11-12 1-7 2-8 3-9 4-5-6	1	2	3	10-11-12 4-5-6

12 LEAD HIGH-LOW DELTA



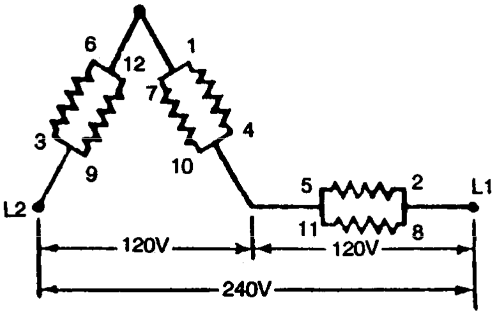
Delta Connection with 12 lead generators only.

Voltages: 60 Hz 120/240V through 138/277V
(High) 50 Hz 110/220V through 120/240V
Voltages: 60Hz 120V through 139V
(Low) 50 Hz 100V through 120V

VOLTAGE	CONNECT			L1	L2	L3
240 DELTA	4-7	5-8	6-9	1	2	3
	1-12	2-10	3-11			
120 DELTA	1-7-6-12			1	2	3
	2-8-4-10					
	3-9-5-11					

FIGURE 14-19. Various Armature Configurations.

12 LEAD ZIG-ZAG



ZIG-ZAG connection with 12 lead machine only.
Voltages: 60 Hz 120/240V single phase.

VOLTAGE	CONNECT		L1	L2
240 SINGLE PHASE	3-9	2-8	2-8	3-9
	1-6-7-12			
	4-10-5-11			

FIGURE 14-19. Various Armature Configurations (Continued).

GENERATOR PHASE BALANCE

The ship's distribution system has been specifically designed with certain conditions in mind. Your specific involvement with the actual design is unlikely. However, the marine engineer's direct influence on the electrical system is evident on each vessel. The Army requires that all the military inventory in its possession be maintained by configuration control standards. This means that all equipment will not be modified, added to, or altered in any manner without the proper approval of appropriate commands.

Phase-to-neutral, phase-to-phase, and three-phase relationships were discussed earlier. A vessel is designed to accommodate electrical growth of approximately 10 percent. When three-phase equipment is added to the distribution system, within the system's capabilities, few problems are encountered. The three-phase motor current draw is distributed over all three generator armature phases equally. There is no unbalanced condition.

However, if a single-phase device is added to the distribution system, an additional electrical load will be imposed on one phase of the generator's armature only. The lowered resistance, from another resistance in parallel, means that more current will be delivered by the generator's armature phase that is involved. This also creates a voltage drop due to the internal resistance within that generator phase and increases the inductive reactance within that phase. This unbalances the generator. If too many single-phase loads are added to the same generator armature phase, overheating will occur. Moreover, if three-phase equipment is improperly replaced with a single-phase component, the entire generator overall three-phase current demand is reduced and replaced by an equal current demand on one phase alone. This is extremely detrimental to the generator.

Generators function adequately within certain parameters of electrical imbalance. However, this is not for the marine engineer to determine. Any changes must be submitted in writing through the vessel maintenance office. Changes and additions to the electrical system, both approved and expedient, must be logged in the engineering logbook indicating the circuit, the phases involved, and the starting kVA if the component is a motor.

Every time you turn on a blender in the galley, turn your bunk lights off, or start the coffee pot, a single-phase circuit has been individually changed. These changes are considered and taken into account when the distribution system is designed. Improper component substitutions and unauthorized additions and modifications have not been considered in the design of the electrical system.

FREQUENCY

The frequency of a generator must never change. If the frequency of the generator changes, the speed of the motors and the contactor operation will be adversely affected. Frequency is measured in cycles per second or hertz. The equipment on board Army vessels operates at a frequency of 60 hertz. Frequency is concerned with how frequently the rotor's magnetic field sweeps past the armature winding and induces a usable EMF. Each time a north and south pair of poles rotates one complete revolution, one cycle of AC is developed. If a rotor with one north and one south pole, called a two-pole machine, is revolved 60 times a second, it will produce a frequency of 60 hertz (cycles per second). Rotor revolutions, however, are not measured in cycles per second They are measured in revolutions per minute (RPM).

Prime mover speed is an important factor in frequency. The other factor is generator construction. Generators are classified by the number of poles. For example, a two-pole generator has one pair of main field poles. A north and south pole constitute a pair. They are connected to the rotor shaft. A four-pole generator has two pairs of poles on the rotor and two pairs of poles in each phase in the armature.

The number of poles determines the speed the prime mover must turn the rotor to maintain a frequency of 60 hertz. A four-pole generator must have a prime mover turn the rotor at 1,800 RPM to attain a frequency of 60 hertz (cycles per second).

$$\text{Frequency} = \frac{(\text{number of poles}) \times (\text{RPM})}{(2 \text{ poles per pair*}) \times (60 \text{ seconds per minute**})}$$

$$\text{Frequency} = \frac{(4 \text{ poles}) \times (1{,}800 \text{ RPM})}{(2 \text{ poles per pair*}) \times (60 \text{ seconds per minute**})}$$

$$\text{Frequency} = \frac{7{,}200}{120}$$

Frequency = 60 revolutions (or cycles) per second

*2 poles per pair is a constant used to account for the requirement of two poles of one north and one south polarity for each individual cycle of events.

**6O seconds per minute is a constant used to convert events per minute to cycles per second.

Poles and Frequency Relationships

Table 14-2 lists some of the more common speed and rotor pole relationships of the AC generator for 60 hertz operation.

TABLE 14-2. Common Speed and Rotor Pole Relationships.

NUMBER OF POLES	PRIME MOVER SPEED (RPM)
2	3,600
4	1,800
6	1,200
8	900

Factors Affecting Frequency

When a large conductor motor is first started (connected to the line), the resistance of the distribution system is reduced. This reduction in resistance is because the loads in the distribution system are connected in parallel (Rt is always less than the smallest resistance in a parallel circuit). As distribution system resistance decreases, current from the generator increases through the main armature windings. This results in the following braking action Within the generator:

- Large main armature currents react with an increased main field magnetic flux (initiated by the voltage regulator to maintain voltage as the high current moves through the main armature windings to the load).
- Both strong magnetic fields, produced by increased current flow through the windings, slow the rotation of the generator shaft just as effectively as if a friction brake is applied. A form of this, known as electric braking, is commonly used in large motors to bring rotation to a rapid halt.
- The magnetic braking effect makes generator rotation by the prime mover most difficult. To help the prime mover overcome this difficulty, several components are used:
  - The diesel governor maintains precise engine speed control.
  - The diesel flywheel has stored energy which tends to keep the diesel moving at the same speed.

– The damper windings are required for all generators that operate in parallel. These damper windings are short-circuited bars embedded in the main field (rotor) windings.

Damper Winding Construction

Figure 14-20 view A shows the damper windings. These windings are nothing more than metal bars parallel to the rotor shaft (view B). The forward ends of these bars are connected together by shorting rings. The aft ends of these bars are connected in a like manner. When the magnetic fields from the main field and the main armature change in respect to each other, an EMF is induced in the damper bars. A resulting current flows, and a magnetic field is established because the bars are short-circuited at each end. The magnetic field that develops in the damper windings is a result of any change in the magnetic flux between the field and the armature windings. The magnetic field in the damper windings opposes the effects that created it.

Damper Winding Operation

When the rotor is turning at the required speed and there is no change in the current demands on the generator armature, then the rotor field, induced armature field, and the damper windings all move together. The two fields and the damper windings are magnetically linked together. However, there is no relative movement between them and no induced EMF in the damper windings.

If the prime mover changes speed, resulting in a speed change of the rotor, there is a change in the magnetic field link between the rotor field, the induced armature field, and the short-circuited damper windings. This provides a relative motion between the magnetic fields and the damper windings. A voltage is induced with a resulting current flow in the damper windings. This current flow sets up its own magnetic field. This magnetic field is governed by the property of induction and Lenz's Law, which states, "An induced effect is always such as to oppose the cause that produced it."

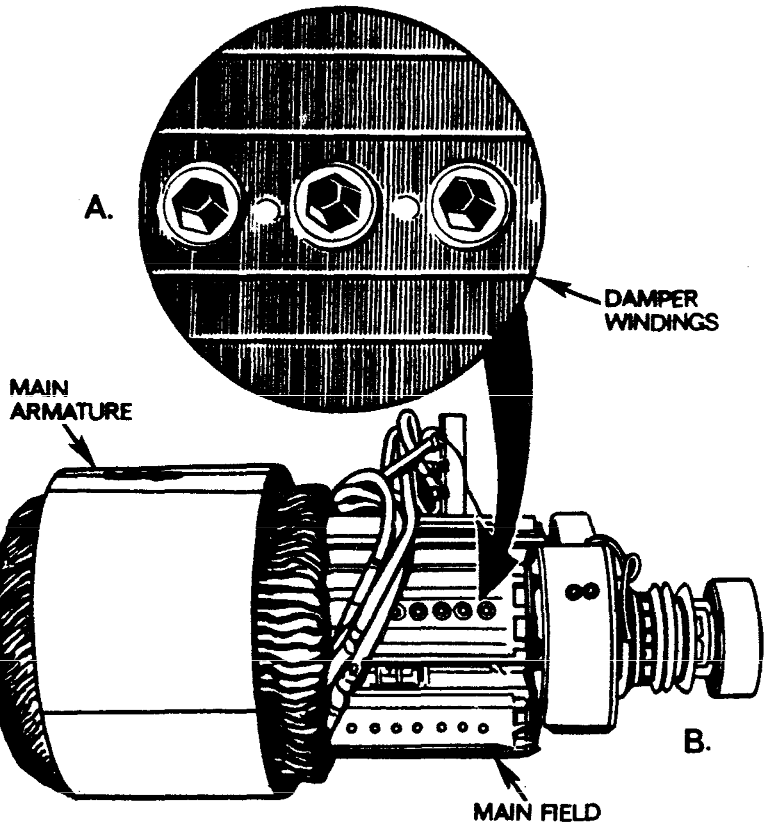


FIGURE 14-20. Damper Windings.

This means that the speed decrease of the rotor is opposed magnetically by the damper windings. The magnetic field of the damper windings tries to push the rotor along and maintain speed. If the rotor would speed up, the induced EMF in the damper windings would develop a magnetic field that would oppose this speed increase, slowing the rotor to its original speed.

VOLTAGE VARIATIONS UNDER LOAD

When the generator is disconnected from the electrical system, no load is applied. Then the terminal voltage is exactly the same as the generated voltage. There is no current flow without a complete circuit.

When the electrical circuit is completed and current flow is established in the armature, then certain phenomena take place. This is called the internal impedance of the generator. These factors affect the terminal voltage of the generator.

Resistance of the Armature Conductors

This is the IR drop so often mentioned. As current flows through the wire in the armature, it encounters resistance. The resistance of copper increases as its temperature increases. Any time current encounters resistance, a certain amount of force is necessary to overcome this resistance. The force that is used is voltage. Voltage is lost driving current through the armature windings of the generator. Although this voltage drop is small because of the small resistance encountered, the terminal voltage decreases as the current increases in response to the electrical system demands. The higher the current through the armature winding resistance, the greater the voltage consumed.

Armature Reaction

This is the combined effects of the rotor's magnetic field and the field developed in the armature as current is delivered to the electrical system. As long as the generator is not supplying current to the electrical system, the rotor's field is distributed evenly across the air gap to the main armature.

When the generator supplies inductive loads, the current developed in the armature opposes the rotor's field and weakens it. This develops the lagging power factor and decreases terminal voltage. This is extremely common to Army watercraft.

When current leads voltage out of the armature conductors (because of capacitor banks and synchronous motors), then a leading power factor develops. The armature current flow actually strengthens the magnetic field across the air gap and combines with the rotor field. This increases terminal voltage.

Inductive Reactance

This is encountered when an EMF is induced in a conductor. Induction produces a counter EMF. The current moving through the conductor and the magnetic fields cutting the adjacent turns of the conductor are all that is necessary to produce an EMF in the opposite direction. Inductive reactance in the armature may be as great as 30 to 50 times that of armature resistance. Two effects can be encountered with inductive reactance:

- When the load current is in phase with the terminal voltage or when the load current lags the terminal voltage (due to inductive reactance from motor loads), then additional voltage must be generated to overcome the armature's inductive reactance (Figure 14-21).

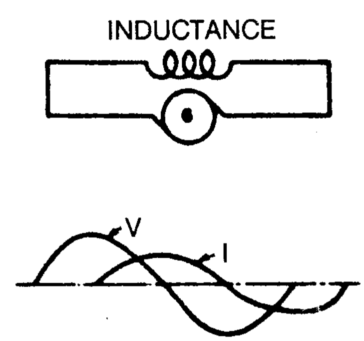


FIGURE 14-21. Lagging Power Factor (More Voltage is Required).

- When the current leads the terminal voltage, as is the case with capacitors or synchronous motors, then the inductive reactance in the armature aids the generated voltage. Less voltage must be generated than when resistance was the only consideration (Figure 14-22).

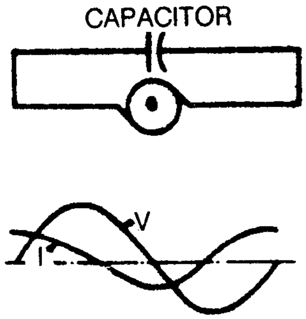


FIGURE 14-22. Leading Power Factor (Less Voltage is Necessary).

VOLTAGE REGULATION

The voltage regulation of an AC generator is the change of voltage from full load to no load, expressed in percentage of full-load volts. This information is necessary to determine how much change to expect in the terminal voltage between no load and full load.

$$\text{Percent regulation} = \frac{(\text{no-load volts}) - (\text{full-load volts}) \times 100}{(\text{full-load volts})}$$

$$\text{Percent regulation} = \frac{465 \text{ volts} - 450 \text{ volts} \times 100}{450 \text{ volts}}$$

Percent regulation = 3.33 percent

EFFECTIVE ALTERNATING CURRENT VALUES

Voltage and current are often expressed in specific values. Alternating current changes not only in direction, but in constantly changing amplitudes. The value most commonly expressed is the generator's effective value.

For instance, the 450-volt AC generator produces a 450-volt output with the same effect as the 450-volt DC generator. The effective value of the voltage or current is computed as follows:

- Square the instantaneous values.
- Determine the mean average.
- Extract the square root.

The effective value is also called the root mean squared (RMS) value. Mathematically, it is determined to be a factor of .707 of the peak value.

POWER FACTOR

The DC generator output can be measured easily in watts. To calculate DC power, multiply the current by the voltage (review *Power* in Chapter 2). Unlike DC, AC does not maintain a constant amplitude. Further, the current and voltage are influenced by the very nature of the reversing current flow characterized by AC (Figure 14-23). To understand how these circumstances affect the actual generator output, the actual values available at the generator terminals must be understood.

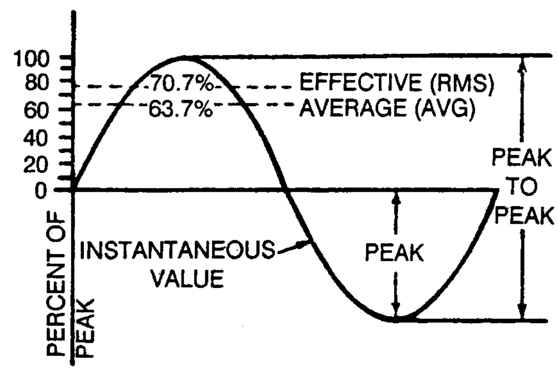


FIGURE 14-23. AC Voltage and Current Values.

Inductance was discussed in Chapter 6. Every motor, generator, and transformer has a coil of wire called an inductor. By the very nature of AC and its effects on the inductors in the circuit, current often lags voltage. The average current lag is represented by a decimal known as the power factor (PF). Unity power factor indicates that current and voltage arrive together and are in phase with each other. Unity power factor has a decimal representation of 1.0. Unity is the best use of electrical power. This condition results when all the power is consumed in the circuit. The ratio of unity to current lag is approximately 80 percent or .8 PF.

The inductors in the motors actually become their own miniature generators, inducing an EMF that opposes a change in current.

The current from the generator must overcome the resistance in the wires of the motor as well as overcome this counter EMF. The extra current developed by the generator, necessary to overcome the CEMF, is not consumed by the motor. It is considered to be a shuttle power, existing in the electrical system moving between the generator and the motor. This condition also results between two generators when they are improperly paralleled.

When AC is applied only to resistors, lights, and heaters, all the power is consumed in the circuit. The power consumed in the resistive AC circuit can be computed the same as in the DC system. This is the true power (or active power) that has been consumed and is expressed in kilowatts (KW).

Figure 14-24 view A shows that the current and voltage rise and fall together. Only when the peak current and voltage are in phase is the product of voltage and amperage the same as the power consumption of the load in watts.

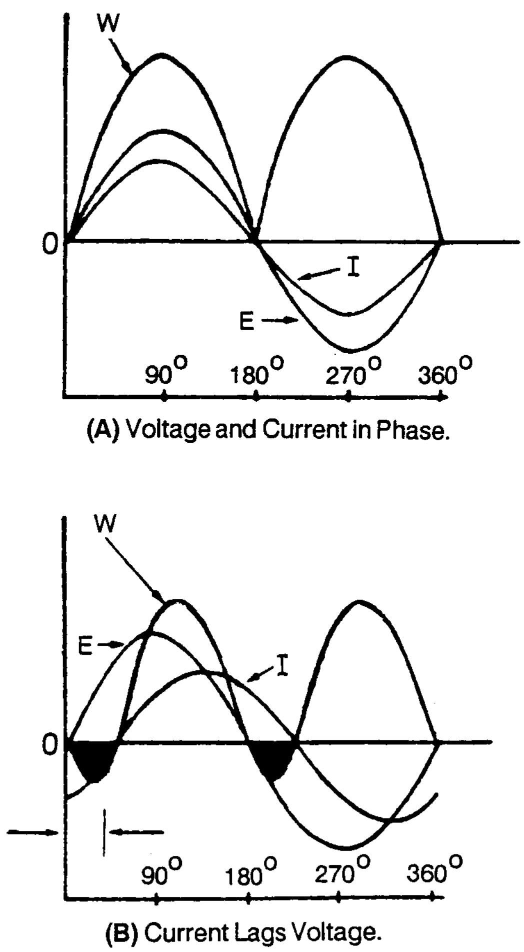


FIGURE 14-24. Voltage and Current.

This situation is inconceivable on board a vessel. The current held momentarily suspended in time by the CEMF generated by the action of the inductive coils cannot be successfully multiplied together to determine the power consumption of the electrical system. In view B, the current is delayed behind the voltage. The apparent power (power that the generator apparently sees that must be added to compensate) is represented by kVA.

Power factor is the percentage of the true power to apparent power or –

$$PF = \frac{KW \text{ (true power)}}{kVA \text{ (apparent power)}}$$

$$PF = \frac{125\ KW}{156\ kVA}$$

$$PF = .80$$

The electrical system must be designed to operate on the apparent power of the system, not the true power of the system. Apparent power is always greater than true power when there is a power factor less than 1.0 (unity).

The following are some additional formulas that may be useful:

(Three-phase applications)

$$KW = \frac{(1.732) \times E \times I \times PF}{1{,}000}$$

$$kVA = \frac{(1.732) \times E \times I}{1{,}000}$$

$$HP = \frac{(1.732 \times E \times I \times 100 \times PF}{746 \times \text{efficiency}}$$

$$RPM = \frac{2 \times 60 \times \text{frequency}}{\text{poles}}$$

CHAPTER 15

WIRING AND ELECTRICAL DISTRIBUTION

INTRODUCTION

The distribution system is an extension of the generator. All electrical loads are connected in parallel with the generator terminals through connection points (nodes) at the switchboards and distribution panels. Through proper design, large cables (feeders) provide power to bus bars inside the switchboards and each distribution panel (Figure 15-1). The use of a single feeder cable will eliminate dozens of individual parallel cables that would have otherwise been needed for the connection between the generator and each load.

The distribution system is also designed to protect the overall electrical environment from electrical component casualties. Circuit breakers and fuses are installed in switchboards and distribution panels to separate abnormally operating electrical apparatus from the rest of the system. Each circuit protective device, from the generator to the load, is set at decreasingly smaller ampacity increments. When all overcurrent and short circuit protective devices are properly selected and correctly adjusted, selective tripping can be provided. Selective tripping allows an abnormal circuit to be separated from the electrical distribution system very close to the fault.

The switchboard receives power directly from the generators. In turn, feeders extend from the switchboard circuit breakers to the power distribution panels, lighting distribution panels, or large motor circuits. Branch circuits leave the distribution panel circuit breakers and provide power to individual loads.

GROUNDING

To understand the type of electrical system used by the Army's marine field, the term "grounding" must be understood. This is the most misunderstood term in electricity today. For the most part, Army vessels have an entirely ungrounded current-carrying system. However, every electrical device is grounded.

The term "ground" refers solely to physical connections between conductive materials and the earth. Whether or not this conducting connection

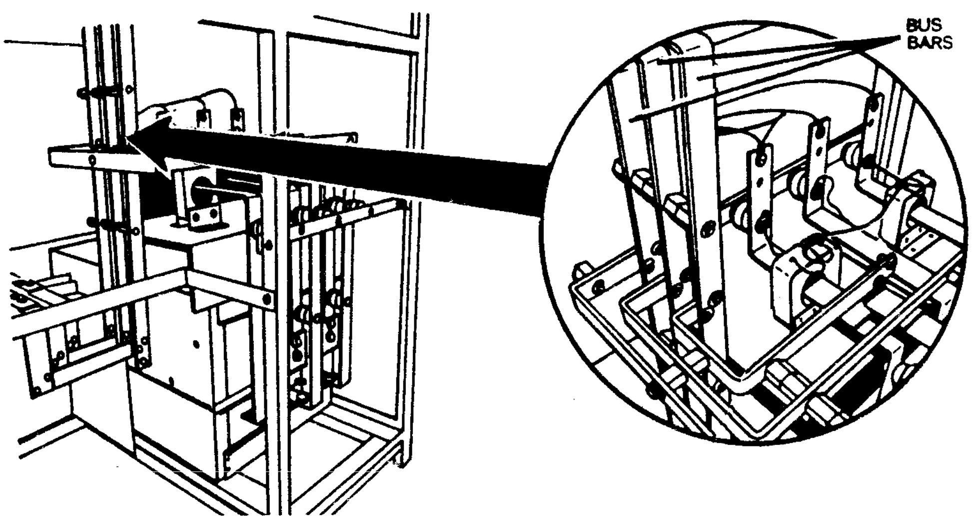


FIGURE 15-1. Switchboards and Distribution Panels.

carries current is irrelevant. To help understand this term, start with these definitions from the National Electrical Code, Article 100:

- Ground - a conducting connection, whether intentional or accidental, between an electrical circuit or equipment and the earth or to some conducting body that serves in place of earth.
- Grounded - connected to earth or to some conducting body that serves in place of earth.
- Grounded conductor - a circuit conductor that is intentionally grounded (connected to earth).
- Grounding conductor, equipment - the conductor used to connect the noncurrent-carrying metal parts of equipment, raceways, and other enclosures to the system grounded conductor. In the case of Army watercraft, the hull of the vessel is the grounded conductor.

WARNING

All electrical component enclosures, switchboards, motor housings, generator frames, and so forth must be grounded for safety.

The definitions of ground and grounded do not state whether or not the conductive material carries current. Engineers ground components for two reasons:

- To carry current through a structural component to complete a circuit under normal operating conditions.
- To carry current through a structural component only under abnormal electrical conditions. This is not designed to complete a circuit for normal electrical operations.

A ground can be either a current carrier under normal operating conditions or a current carrier for abnormal operating conditions. This depends on the application of the hull connection.

The “grounded” system of the automobile has current traveling through the chassis, engine block, and all connected metal. The body of the car represents the negative conductors of its electrical system. All circuits are completed from the negative battery terminal through the chassis, the electrical loads, positive wires, and back to the positive battery terminal. The ground symbol (⏚) identifies the point in the electrical circuit that connects to the metallic structure. All the ground symbols in Figure 15-2 are connected like a node, as if the entire automobile frame was a giant connector. This system is in fact insulated from earth by tires and is <u>not</u> a grounded system.

Current-Carrying Grounds

The emergency generator used on the 2K series LCU is an example of a current-carrying grounded electrical system. The 24-volt DC battery starting and charging system is connected normally as a current-carrying ground. The main AC power production portion, however, retains the insulated conductors and does not use a current-carrying ground for normal operations. Grounded current-carrying electrical systems are avoided whenever possible on watercraft because of the galvanic corrosion and electrical shock hazards. In this situation, hazards and corrosion are minimized through strict adherence to Subchapter J, Subpart 111.05-11(a)(2), Title 46, Code of Federal Regulations.

The DC part of the emergency generator prime mover and power generation controls incorporate the metal structure as a current-carrying structural assembly of the generator. It is connected to the hull (grounded), and the automobile chassis is not. See Figure 20-4 for the diagram of this circuit.

Noncurrent-Carrying Grounds

The AC current-carrying conductors of the ship service generator are not designed to come in contact with the structural components of the equipment. Instead, only the structure and metallic enclosures are connected together and connected to the hull. All conductive equipment that surrounds electrical current-carrying conductors must be grounded; that is, connected to earth.

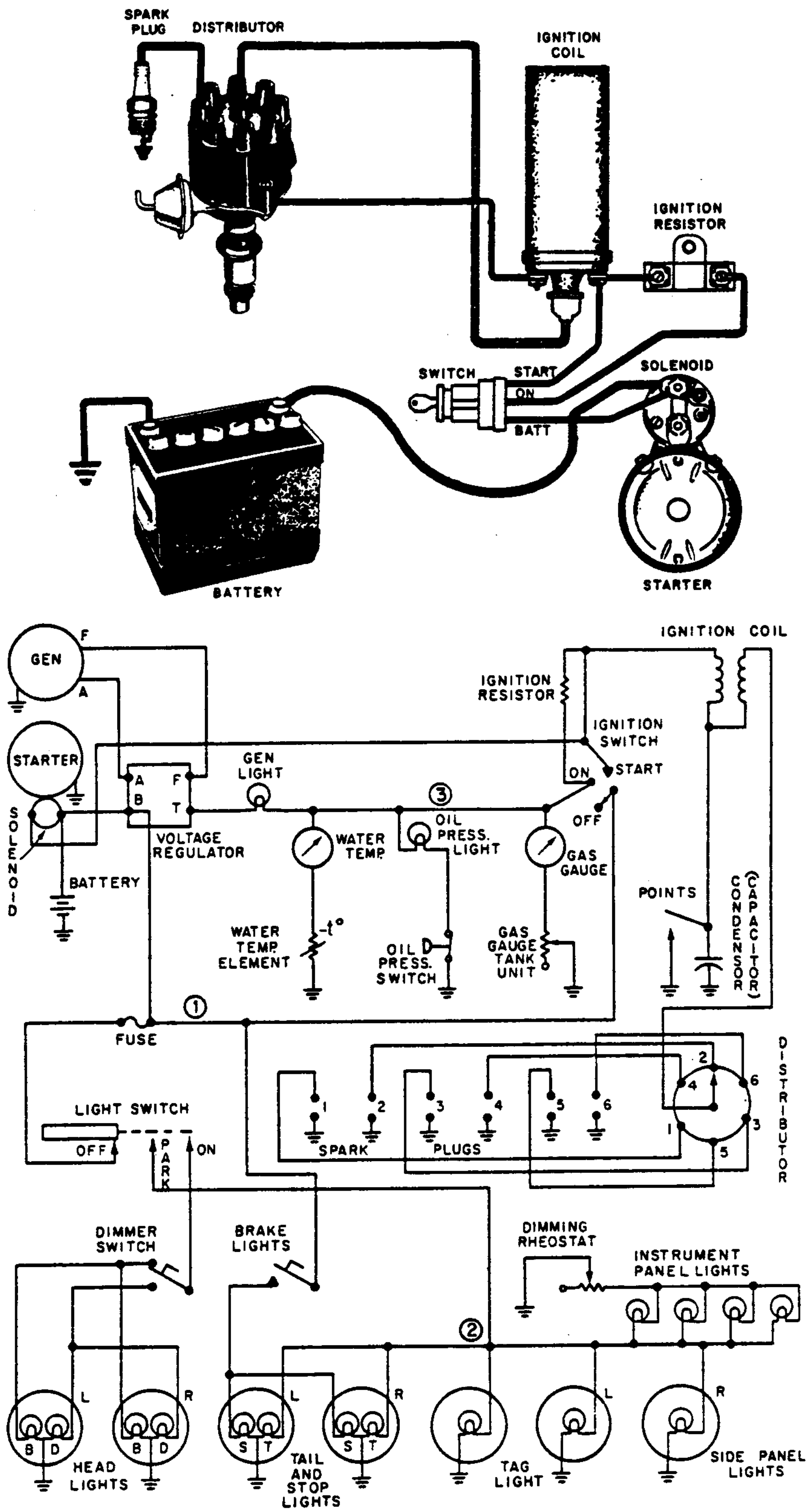


FIGURE 15-2. Wires and Structures Can Carry Current.

Figure 15-3 shows the generator housing physically connected to the prime mover's block. The prime mover may be directly bolted to the engine bed. The engine bed is connected to the hull and the hull to the water.

A break in this normal metal-to-metal contact, from the generator housing to the vessel hull, may come from the diesel generator set mountings. To eliminate excessive generator vibrations during normal operation, modern vessels do not have the prime mover rigidly connected to the engine bed. A resilient mount, not electrically conductive, acts as a shock absorber. A grounding strap or flexible shunt is attached from the generator housing to the engine bed. This connects the diesel generator set to the engine bed with a conductive path. In normal operation, this is not a current-carrying ground.

This type of ground is used for safety. Should an abnormal electrical situation develop within the generator, a low-resistance conductive path is provided for winding current to move to earth through to the vessel's hull. This is necessary to prevent current from using a human host as a conductor. Stray current will go to earth when provided a path to do so. The metallic connection between the generator and the engine bed must not have any resistance. If enough resistance is placed between electrical equipment and the vessel's hull, a condition can exist where the soldier will conduct current because he has less resistance to ground than the equipment.

A low-resistance path is necessary to allow current to flow to earth when an abnormal electrical condition exists. This means a clean, unpainted metal-to-metal contact surface. If vibration dampening is necessary, a grounding strap or flexible shunt is mandatory to complete the connection. Additional information is in the Code of Federal Regulations, Title 46, Subpart 111.05.

The electrical component housing that is properly grounded will not become a deadly device to a soldier under abnormal electrical conditions. The current will travel from the damaged generator windings, for example, to the generator housing. From the generator housing, the current will go through the shunt to the hull and earth. The current developed from the abnormal condition will bypass the soldier. The soldier still provides more resistance than the correctly grounded components in the system. Current will take the path of least resistance, around the soldier, through the metal-to-metal connections, to the mounting, to the hull and water, returning to earth.

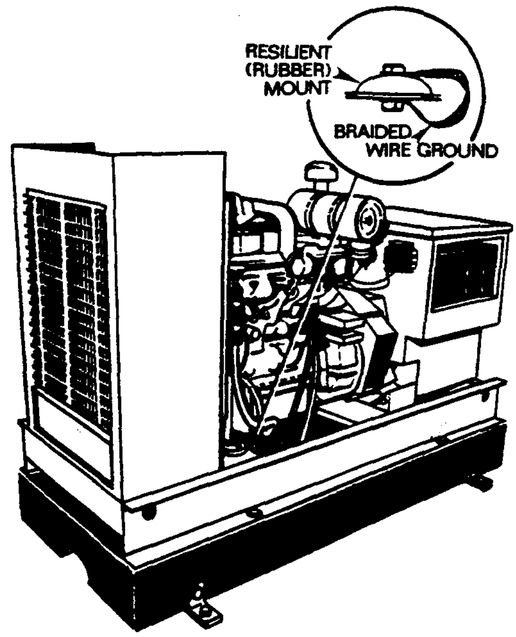


FIGURE 15-3. Metal-to-Metal Contact for Abnormal Conditions.

THE EARTH

To properly understand how these different grounds fit into the vessel's electrical system, the word "ground" must be understood as it was originally used. Decades ago, when DC tugboats were designed, the term "earth" was used instead of ground. Still later, the tugboats were called positive ground systems. (Foreign cars used to be termed positive earth systems). Over the years, many individuals and contractors mistook the term "ground" for a negative ground (as referred to on today's automobiles). Eventually all types of grounds were incorporated into the tugboats, and the true meaning of the term "ground" was lost. Both earth and ground have their original roots in terra firma. However, today the importance of the earth's electrical potential as a safety factor is realized.

Nikola Tesla, the father of alternating current, discovered the rotating magnetic field and developed the Tesla coil used in radio and television today. In

1900, he made one of his most important discoveries. He found that the earth could be used as a conductor and would respond to electrical vibrations. He called this terrestrial stationary waves. In one experiment, he lighted 200 lamps without wires from a distance of 25 miles.

The earth has a continuous electrical current that flows in, over, and around itself. This current seeks out equilibrium. In this way, it tries to establish a balance in its magnetic field. The potential of the earth is due to the transient electric currents that are electromagnetically induced within the earth itself. The electrical potential (voltage) of the earth has been measured. It is possible because of the conditions that form an electric cell-like device due to the electrochemical differences in local conditions.

In effect, the earth is its own low-voltage generator. The current produced is called telluric current. Telluric current, some believe, is caused by the motion of our sphere or the magma, the electrically conductive sphere itself, and the presence of the geomagnetic field. The earth is itself a generator and produces its own difference in potential.

Therefore, it is advantageous to maintain our very precise current-carrying electrical systems separate from the earth. When there is current flow between one electrical terminal and the hull, it is usually due to an unintentional ground, carrying current within our own electrical system.

US ARMY VESSEL SYSTEMS

The Institute of Electrical and Electronics Engineers (IEEE) Standard 45, *Recommended Practice For Electrical Installations on Shipboard,* recommends a dual voltage AC system of 450/120 volts AC ungrounded. Army ports, Naval ports, and Coast Guard facilities have 450 volts readily available for shore power hookups. The second voltage (120 volts) should be obtained through the use of transformers. This system is found in many Army watercraft.

An ungrounded current-carrying system means that all the current-carrying conductors are insulated from other conductors, other structures, and earth. Each electrical component has a complete circuit from the generator to itself and back to the generator through the use of these insulated wires. Each current-carrying conductor has an overcurrent protection device. This is because each of the circuits to the electrical component is a different potential than that of the hull (and the earth).

Even though Army vessels use the ungrounded current-carrying system, all electrical components must be grounded. The housings of all motors, generators, and motor controller housings must be directly connected to the hull. The switchboard housings, the distribution panels, the armor wrapping surrounding the electrical cables, and the electrical appliance casings must have a low-resistance connection to the hull. Any metal device that houses a current-carrying conductor must have its enclosure grounded. This direct connection allows the flow of current to the hull and not through the engineer in the event of an abnormal electrical condition.

THE NEUTRAL

The neutral is a ground system that uses an insulated current-carrying conductor and a direct wiring connection to the earth. Onshore facilities, for example, the receptacle outlet, has three conductor orifices: the neutral, a safety ground, and the phase conductor. The phase conductor is insulated throughout its circuit and retains the circuit breaker protection. The neutral conductor is insulated throughout the circuit, normally without a circuit breaker. Both the neutral and the phase conductor are current carriers under normal conditions. The ground wire is the safety circuit designed specifically to carry current during an abnormal condition to protect the operator.

The neutral, although an insulated current-carrying conductor, retains a single connection to earth. By connecting the neutral to earth, the earth's potential is locally stabilized as a neutral potential. This provides safety on shore because two of the three wires in every outlet receptacle will not create an electrical shock. The neutral and the ground are the same potential as earth; hence there is no difference in potential. There is no shock hazard between the neutral, the ground, and the earth. There remains only one "hot" wire even though the neutral is a current carrier.

A very real danger would exist on shore if the earth was a very good conductor and had the potential to encourage great current values to move between the phase and earth. Since the earth is not capable of this current encouragement, electrocution from accidental contact with the phase wire is reduced (although not eliminated).

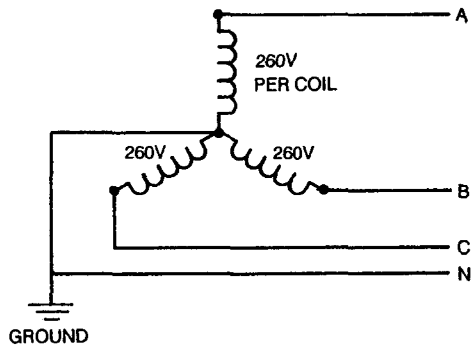
Watercraft generators or transformers can use the center tap of a wye winding combination to derive a separate low voltage potential cheaply. The trouble with using a neutral current-carrying conductor as a potential stabilizing device is the connection to earth, directly through the hull. Army watercraft make limited use of this low voltage potential. Since the vast majority of conductors on board the craft are insulated current-carrying conductors, limited safety can be derived from such a current.

Danger exists when a neutral is connected to the hull because A, B, and C are always a difference in potential to the neutral. When the neutral is connected to the hull, the generator's center is extended as a node throughout the entire length of the ship incorporating all conductive materials connected to the hull. Unlike the earth's feeble ability to encourage current movement, the potential developed in the neutral connection will encourage any current from a difference in potential. Any accidental contact between any current-carrying conductor becomes potentially fatal. Unlike shore facilities that make extensive use of the neutral conductor to carry current, watercraft rarely employ such a circuit. All Army watercraft, with the exception of a few branch circuits on the LSVs, have a difference is potential between any current-carrying conductor (A, B, C, L1, L2, or L3) and the neutral point of a generator or transformer. There is no gain in safety by grounding a neutral conductor unless the neutral can limit the number of current-carrying conductors that maintain an aboveground voltage.

Army watercraft no longer use the center-tapped neutral from the generator. Only the LSV uses the neutral connection from the wye transformer to obtain this inexpensive low voltage value (Figure 15-4).

Figure 15-5 shows the optimum setup for vessels. It shows three single-phase transformers connected for three-phase power. Remember, it is the manner in which windings are connected, not the housing that encases them, that provides the desired voltage and current values. Three single-phase transformers can be wired in the same manner that the ship service armature windings were wired in Chapter 7 to produce a given three-phase output.

The LSV using one three-phase transformer is wired identically.



AVAILABLE VOLTAGES

3Ø = A TO B TO C 450V
1Φ HIGH VOLTAGE
450V —— A TO B
450V —— B TO C
450V —— C TO A
1Φ LOW VOLTAGE
260V —— A TO N
260V —— B TO N
260V —— C TO N

FIGURE 15-4. The Wye Tap From a Three-Phase Winding.

Notice the neutral going to the hull from the secondary transformer side. Note further that there are no circuit protective devices in the neutral conductors.

As long as the neutral conductor, carrying the current to the electrical component, is the same potential as the earth (or hull) that a soldier is in contact with, then there will be no difference in potential between the soldier and the neutral conductor to cause injury. Without a difference in potential, there is no current flow. However, extra care must be exercised when working between a phase and the hull.

WARNING

Never change the relationship of the circuit overcurrent protective device and the neutral conductor.

The neutral wire must not have an independent overcurrent protective device installed unless the device can open the neutral and all the associated phases in that circuit simultaneously.

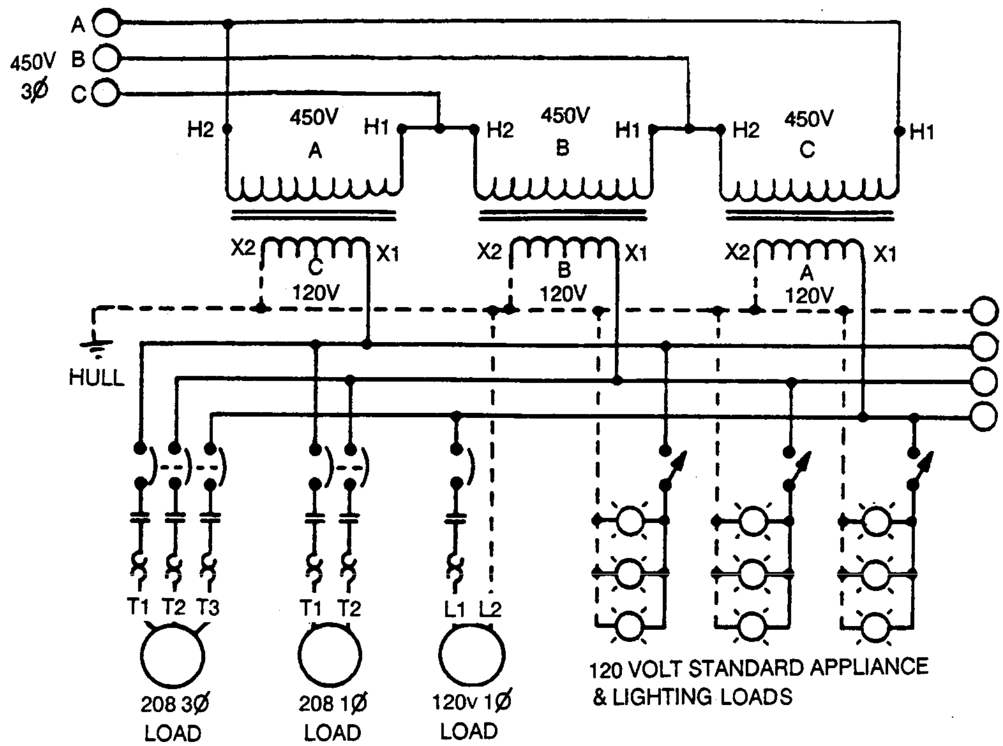


FIGURE 15-5. The Neutral Connection to the Hull and the Component.

If the neutral opened and the other power supply lead did not open, the motor would stop. There would no longer be a completed circuit to the motor. But there would be a difference in potential at the faulty component housing and a difference in potential in the hull the soldier contacts. If someone touches the faulty motor housing, current would take the only available path back to the earth – through him and the hull.

This is of such importance that neutrals will be stressed again when your understanding of the distribution system is complete.

ELECTROLYSIS

In addition to safety reasons, the generator is not connected electrically to the hull as a current-carrying conductor to prevent electrolysis. Electrolysis is the chemical process in which a substance loses or gains electrons. Recall the operation of a battery. The battery developed an EMF by chemical means. Oxidation, or rust, is a chemical process that reduces the number of electrons in a substance because the electrons migrate to other areas. Salt water and dissimilar metals connected together for vessel construction create a very large chemical reaction. Electrons lost by the oxidizing materials are taken up by other metals lower down the oxidation scale.

Some of these metals are called noble metals. Noble metals have an outstanding resistance to oxidation. Some noble metal oxidation rates in descending order are gold, silver, and platinum. When electrons leave a metal, oxidation reduces the material. Hull and piping would deteriorate rapidly if this condition were not properly addressed.

The steel hull is not one of the noble metals. However, steel is less easily oxidized than zinc. Zinc sacrificial anodes are attached to the hull of the vessel. Electrons leave the zinc for the steel hull during electrolysis. This provides a good degree of protection to the hull. For the zinc and steel to properly provide protection, the zinc anode should not be painted and retained at a size no smaller than 50 percent of the original.

Electrolysis in the hull cannot be completely eliminated, but it can be reduced. When stray currents are allowed to exist in the vessel's hull, electrolysis, called galvanic corrosion, is greatly increased. Years ago, the 1466 class LCU was incorrectly wired to the hull. The first indication of an extensive electrical problem was the hull's unusual deterioration. Electrically energizing the vessel's hull created a very large battery. The zinc anodes dissolved quickly, and the entire aft third of the hull bottom excessively deteriorated. After appropriate documentation was completed, the situation was corrected.

VESSEL DISTRIBUTION SYSTEM COMPONENTS

A vessel has an extensive electrical system designed to carry out more functions than can be found in a small community. Lighting, instrument panels, steering systems, stoves, and so forth are spread throughout the vessel. Every electrical item must be serviced regularly. Locating the electrical wires can be frustrating. In an emergency situation, restoring electrical power for the dewatering and fire pumps can mean the difference between life and death.

Chapter 10 discussed circuit breakers and fuses for the protection of electrical circuits. It briefly mentioned the parts making up the circuit. To understand the electrical distribution system, the different system components need to be examined in closer detail.

Distribution Center

The distribution center controls the ship service generated power and shore power. Automatic overcurrent protective devices connected to the bus monitor and protect the feeders and branch circuits.

Feeder

The feeder consists of the cables that extend from the main switchboard to the distribution panels. In some cases, the feeder may provide power directly to a large motor.

Bus Tie

The bus tie is the electrical connection between the main and emergency switchboard bus bars. It is not considered a feeder.

Emergency Switchboard

The emergency switchboard is a smaller version of the main distribution switchboard. Power is received either from the emergency generator or the main switchboard through a bus tie. This switchboard provides power to vital services, including the fire main, communications, emergency lighting, steering, and so forth. When the ship's main power is lost, emergency power is automatically provided by the emergency generators through the emergency switchboard by an automatic bus transfer (ABT) switch.

Motor Control Center (MCC)

The motor control center consolidates all the motor controlling equipment for all the major motors on board the vessel. Overcurrent and overload protection is provided to the motor and immediate circuitry.

Distribution Panel

The distribution panel is an enclosed metal panel that supplies power to components for a localized section of the vessel (Figure 15-6). Circuit breakers or fuses are installed to protect the branch circuits. The distribution panel has three bus bars (there is a fourth when the neutral is used). When the distribution panel is used to provide three-phase power to loads, then each bus bar is connected to one terminal of a three-pole circuit breaker (Figure 15-7). The other side of the circuit breaker is connected to the loads.

If the distribution panel is used to supply single-phase power to loads, then only two of the bus bars are used, and a two-pole circuit breaker is employed (Figure 15-8).

> **NOTE:** The same two bus bars are NOT used to supply all the power to the loadsconnected in the single-phase distribution panel.

To keep the three-phase generator balanced with single-phase circuits, each phase (A-B, B-C, or C-A) is designed to carry a specific percentage of the load. The single-phase loads are equally divided between the three phases. Each distribution panel receives three-phase power. When single-phase loads are connected, the distribution panel divides up the three phases so that each single-phase circuit (A-B, B-C, or C-A) has one third of the total power available from that panel.

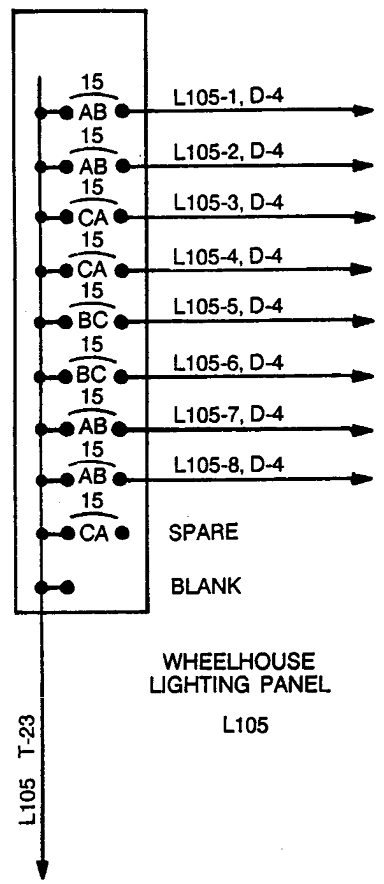


FIGURE 15-6. The LCU 2000 Distribution Panel.

This electrical balance is continued by equally dividing the load at each panel throughout the vessel. All the other panels are divided in the same manner because in the event of a distribution panel casualty, the overall generator load will be decreased evenly across the phases. The generator will still be electrically balanced.

Power Distribution Panel

This panel is generally dedicated as a source of power for operating other components, such as the power supplied to the emergency batteries or to other distribution panels. More often, it can be distinguished as a panel used to distribute three-phase power to three-phase components.

Branch Circuits

These are the conductors that exist between the final overcurrent protective device in the distribution panel and the load; for example, motors, lights, and receptacle outlets.

Lighting Branch Circuits

These conductors supply power to lighting systems, bracket fans, small heating appliances, circuits, and motors 1/4 HP or less.

Appliance Branch Circuits

These conductors supply power to the outlets for the use of portable or nonfixed electrical apparatus.

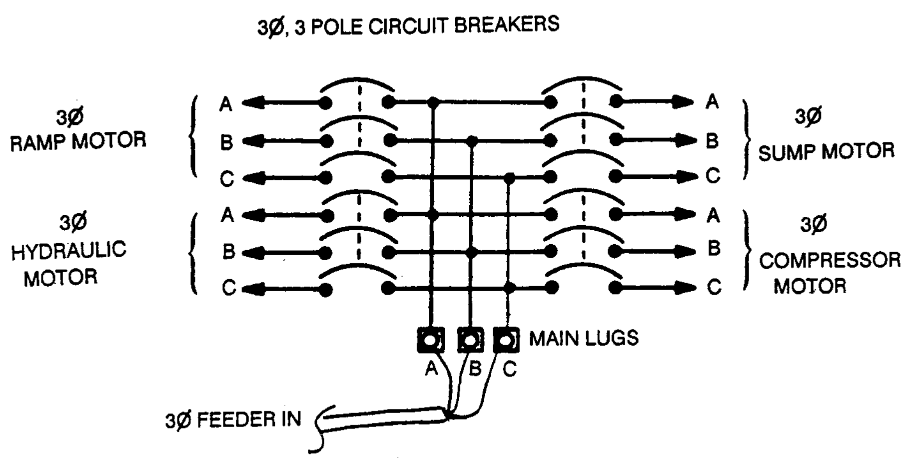


FIGURE 15-7. Internal Wiring and Circuit Breaker Connection.

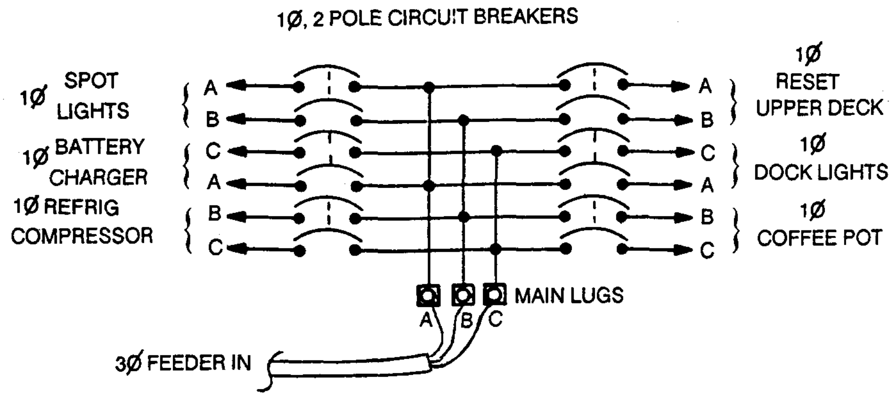


FIGURE 15-8. Single-Phase Power Supplied From Three-Phase Bus.

Communication Branch Circuits

These conductors supply power to communication, audio, and visual signaling devices.

Cables

These are heavy-duty conductors used to carry current between a source and a load. Alternating current cables should contain all three current- carrying conductors in a single cable to cancel out heating caused by inductive effects.

Distribution Cables

These cables are used for the power distribution up to the rated voltage and ampacity of the cable. Low-voltage (600-volt) cables are generally found on Army watercraft. They are used for most electrical connections.

Control Cables

These are multiple parallel conductor cables used for —

- Control circuits where an electrical signal energizes a magnetic control device to physically open or close the main contacts of a motor. The control cable does not carry the main motor operating current, but only the current used in energizing the coil of the magnetic control device.
- Indicating circuits in meters and other audio and visual indicating apparatus.
- Communication, electronic, and other similar circuits.

Signal Cables

Signal cables of twisted pairs of conductor cables are used for signal transmission. Each twisted pair of conductors will have a shield to prevent interference.

Portable Cords

Portable cords are used for the temporary connection of portable appliances. They are not to be used for fixed wiring. They must conform with NAVSEA 0981-052-8090 [40].

DISTRIBUTION CABLE AND WIRE MARKING SYSTEMS

Color coding allows the engineer/engineman to follow electrical circuits throughout a vessel without having to physically touch each cable. The color can be continuous throughout the length of the conductor, or the color noun-nomenclature, such as red, is printed every 24 inches on the insulation of the conductor.

The following are newer color designations for distribution cables:

- 2 conductors - black, red, or white.

- 3 conductors - black, red, blue, or white.
- 4 conductors - black, red, blue, orange, or white.

Older wire designations are as follows:

- Alternating current:

Phase A: black.
Phase B: white.
Phase C: red.

- Direct current:

2 wire DC: positive(+) black.
negative (-) white.

3 wire DC: positive (+) black.
negative (-) red.

Table 15-1 gives the newer color designations for control and signal cables.

TABLE 15-1. Color Code Control and Signal Wires.

Conductor Number	Base color	Tracer color	Tracer color
1	Black		
2	White		
3	Red		
4	Green		
5	Orange		
6	Blue		
7	White	Black	
8	Red	Black	
9	Green	Black	
10	Orange	Black	
11	Blue	Black	
12	Black	White	
13	Red	White	
14	Green	White	
15	Blue	White	
16	Black	Red	
17	White	Red	
18	Orange	Red	
19	Blue	Red	
20	Red	Green	
21	Orange	Green	
22	Black	White	Red
23	White	Black	Red
24	Red	Black	White
25	Green	Black	White
26	Orange	Black	White
27	Blue	Black	White
28	Black	Red	Green
29	White	Red	Green
30	Red	Black	Green
31	Green	Black	Orange
32	Orange	Black	Green
33	Blue	White	Orange
34	Black	White	Orange
35	White	Red	Orange
36	Orange	White	Blue
37	White	Red	Blue
38	Brown		
39	Brown	Black	
40	Brown	White	
41	Brown	Red	
42	Brown	Green	
43	Brown	Orange	
44	Brown	Blue	

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Cable Tags

Embossed metal tags are used to identify cables throughout the vessel. The tags are located at the distribution panel and the component. Tags are also attached to the cables where penetration of the bulkhead is necessary. The tag code will start with the type of circuit it is. Army vessels use P to indicate power distribution panel cables, L for lighting distribution panel cables, and E for emergency distribution cables. If there is a number preceding that letter, this identifies the cable in the distribution panel. The next numbers indicate the voltage carried in that cable, such as 400 or 200. Any additional numbers above the whole hundred value are used to distinguish the differences between two like voltage distribution panels. For example, in the cable tag 3P-401–

- 3 indicates the third wire in distribution panel P-401.
- P indicates that this cable acts as a power-supplying cable or that it provides three-phase AC to its loads.
- An L would indicate a lighting or single-phase AC supply panel cable.
- 4 with two additional digits means that there is 400 to 499 volts in that cable.. If there was only one additional digit, then the voltage in the cable would be what is actually printed. For example, 24 indicates 24 volts.
- 01 distinguishes the cable's source. This identifies the difference between the P-401 distribution panel and the P-400 distribution panel.

Wire Construction Details

With the addition of a set of prints, the engineer/engineman can locate all the necessary electrical components on his vessel. To make the most use out of the wiring construction details and to help distinguish between single and three-phase AC circuits, a basic understanding is needed. The wire construction detail is the code used for determining the current-carrying capacity, insulation material, shielding, application, and so forth. This information may be found in the IEEE Standard 45 manual However, it is not necessary to understand everything about these intricate codes. There are some basic rules that can be easily applied. The following details are found on the distribution system prints:

- 2SJ-14.
- DSGU-14.
- MSCU-10.
- TSGA-100.

This text will examine only the frost and last character and the numbers. The first character indicates the number of individual conductors in the cable; 2 obviously means that there are two conductors in the cable. D means that there is a double conductor in the cable, or the same as 2. M stands for multiple conductors, and there may be several unused conductors for future electrical growth. T stands for a triple conductor, so there will be three conductors in the cable. If the last letter is an A or B, then the cable is armor-shielded. The last numbers indicate the size of the conductor in thousands of circular roils (KC MIL). Thus, 14 indicates that the area is 14,000 circular roils. The 100 indicates that there is a 100,000-circular mil area. It would be easy to identify the difference between the two cables. The TSGA- 100 will be much larger than the 2SJ-14 cable.

This basic understanding is useful in locating the wire on the vessel after seeing it in the blueprints. Additionally, if there are two conductors in a cable, the cable cannot carry three-phase power. Wire size, application, and distribution panel location will help you locate components when troubleshooting.

Shipboard Electronic Equipment Wire Marking Systems

The following explanation is an example of the type of conductor marking used in shipboard electronic equipment. These conductors may be contained in cables within the equipment. Cables within equipment are usually numbered by the manufacturer. These numbers are found in the technical manual for the equipment. If the cables connect equipment between compartments on a ship, they will be marked by the shipboard cable numbering system previously described.

On the conductor lead, at the end near the point of connection to a terminal post, spaghetti sleeving is used as a marking material and insulator. The sleeve is marked with identifying numbers and letters and then slid over the conductor.

The marking on the sleeve identifies the conductor connections to and from by giving the following information (Figure 15-9):

- The terminal from.
- The terminal board to.
- The terminal to.

These designations on the sleeve are separated by a dash. The order of the markings is such that the first set of numbers and letters reading from left to right is the designation corresponding to the terminal from which the conductor runs. Following this is the number to the terminal board to which the conductor runs. The third designation is the terminal to which the conductor runs.

For example, as shown in Figure 15-9, the conductor is attached to terminal 2A of terminal board 101 (terminal from 2A on the spaghetti sleeving). The next designation on the sleeving is 401, indicating it is going to terminal board 401. The last designation is 7B, indicating it is attached to terminal 7B of TB 401. The spaghetti marking on the other end of the conductor is read the same way. The conductor is going from terminal 7B on terminal board 401 “to” terminal 2A on terminal board 101.

It may be necessary to run conductors to units which have no terminal board numbers; for example, a junction box. In this case, an easily recognizable abbreviation may be used in place of the terminal board number on the spaghetti sleeving. The designation JB2 indicates the conductor is connected to junction box 2 (Figure 15-10).

In the same manner, a plug would be identified as P. This P would be substituted for the terminal board number marking on the sleeve. A complete description of shipboard electronic equipment wire marking is in NAVSEA Publication 0967 LP 1470010, *Dictionary of Standard Terminal Designations for Electronic Equipment.*

POWER DISTRIBUTION

The wires and cables in the distribution system are expressed as a single line between the power supply source and the component. Instead of showing the actual number of conductors, only one line is illustrated. While the distribution wire diagram more closely resembles the actual cable runs, the complete circuits necessary for electrical operation are missing. The wire construction details become very informative now. The wire construction details state, rather than illustrate, the actual number of current paths in the component’s circuit.

As an example, Figures 15-11 through 15-21 illustrate the power distribution system from an LCU.

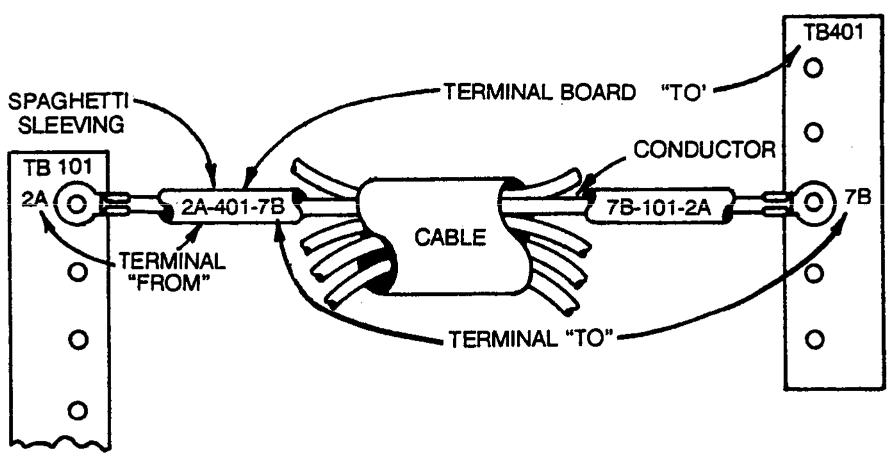

FIGURE 15-9. Designating Conductor Marking Between Unlike Terminals.

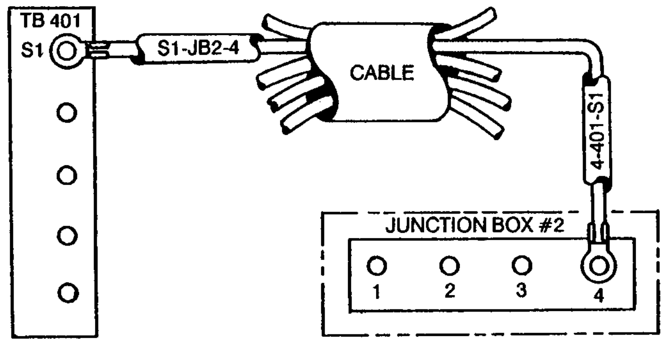

FIGURE 15-10. Marking Conductors Running to a Junction Box.

Three-phase AC is developed in the generators. The AC is fed to the switchboard through a TSGA-30 cable (Figure 15-11). The TSGA-30 indicates three large 30,000-circular mil conductors.

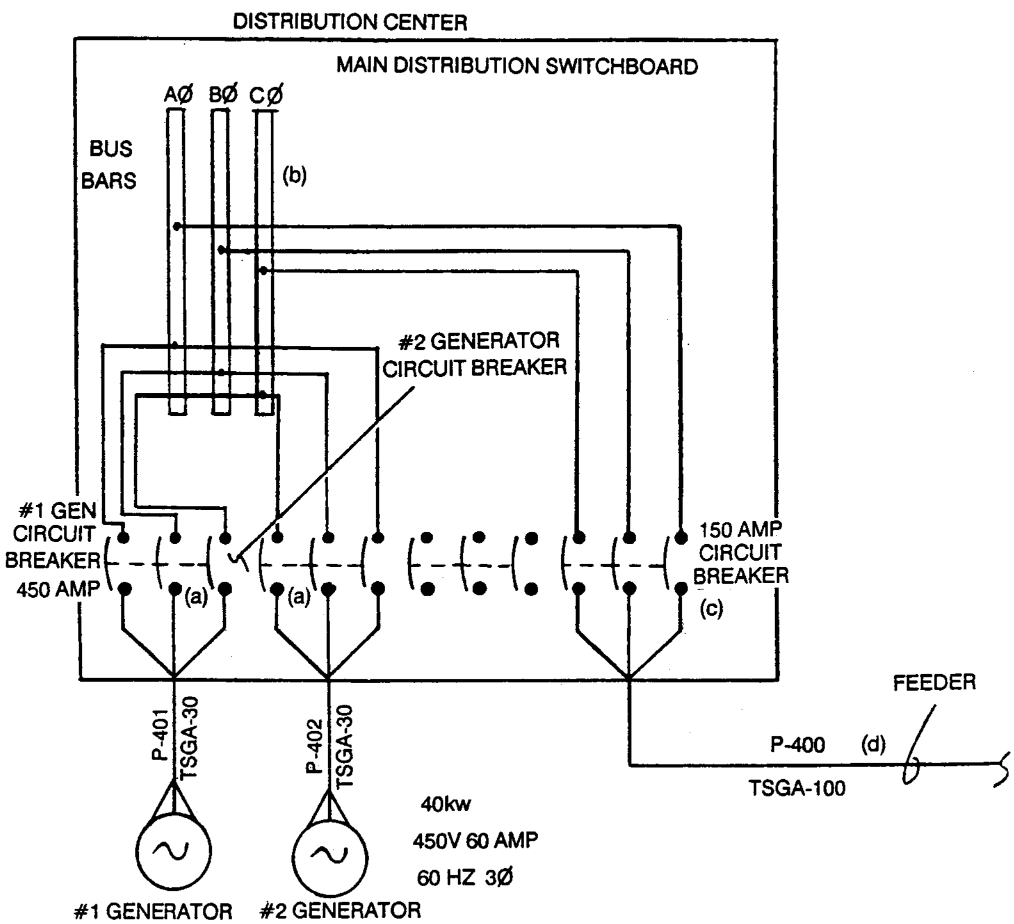

FIGURE 15-11. Main Distribution Switchboard.

Three-phase AC enters the distribution center's main switchboard through a three-pole circuit breaker (Figure 15-11 [a]). When this main circuit breaker is closed, power is provided to three bus bars inside the switchboard. Each bus bar (b) carries one phase of the generator's power. The bus bars are actually a mere connection point on this switchboard. The actual bus in Figure 15-11 has been expanded for clarity.

Current is available from the main distribution switchboard to the power distribution panel (P-400) through the three-pole circuit breaker (c) and TSGA-100 feeder (d).

A cable tag P-400 indicates that 450 volts are supplied to the power distribution panel number 400 (Figure 15-12). The feeder is protected by the circuit breaker in the main distribution switchboard (c). The TSGA-100 feeder is larger than the TSGA-30 generator cable because the TSGA-100 feeder must carry current from both generators when operating in parallel.

The power distribution panels do not have any circuit breakers for the entering feeder. The feeder is connected to three bus bars in the power distribution panel P-400. In this manner, current is available, through a common contact point, for all the three-phase branch cables and feeder cables. Current is connected to the cables through three-pole circuit breakers (e).

Where the cable goes can be determined by using the blueprints. In the same way, a defective motor can be identified, and then the source of its power (and circuit breaker) can be determined from the motor cable tag.

A three-phase 450-volt motor is connected to the feeder tagged P-408 (f). Refer to Figure 15-13.

After the cable passes through a disconnect switch (DS) (Figure 15-13 [g]) and enters a controller (C), the wire is branched into four directions.

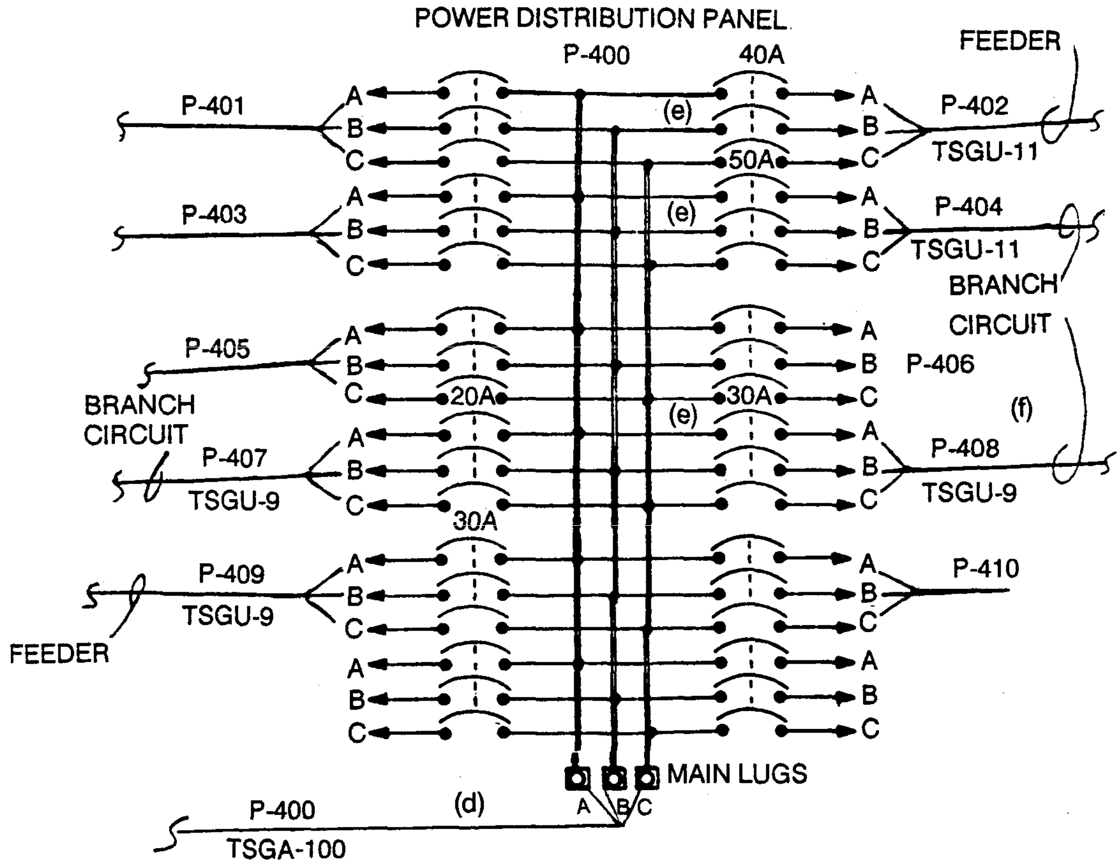

FIGURE 15-12. Power Distribution Panel P-400.

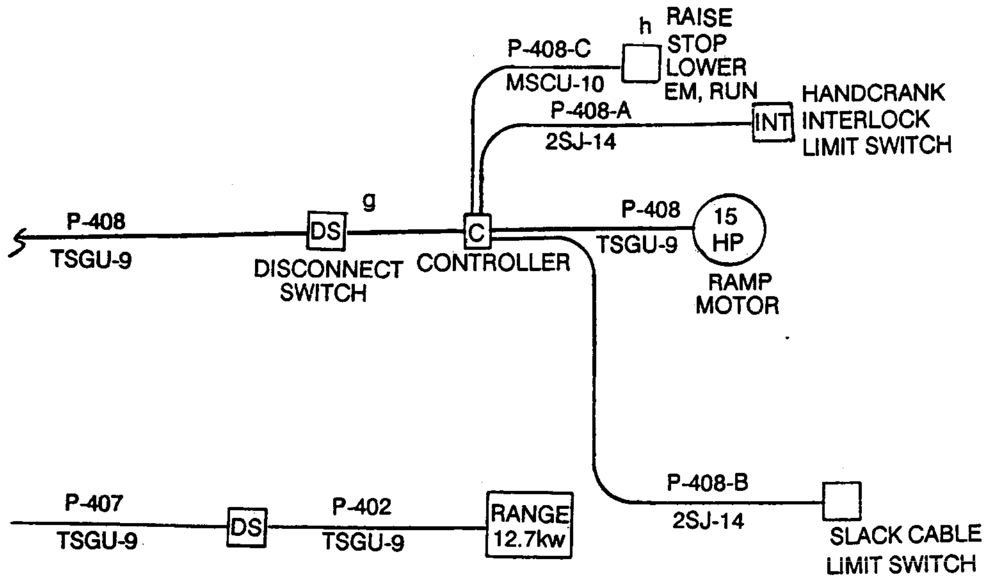

FIGURE 15-13. Ramp Motor and Range.

P-408-C indicates the first of three control circuits used with this motor. Each circuit is tagged with the controllers number and wire number P-408. This is followed by an alphabetical designation P-408-C. This wire is also a MSCU-10. This indicates that there are multiple conductors as would be expected from a station that controls the raise, stop, and lower of a ramp motor (h), unarmored, and of limited diameter.

P-408-A 2SJ-14 indicates that this handcrank interlock limit switch is part of a two-wire, single-phase circuit in the same way the slack cable limit switch (P-408-B) is connected.

The motor uses the same size cable as the feeder that powers the controller. This is necessary because of the high current draw from the motor.

Skip the elementary branch circuit P-407, and refer to feeder P-409, Figure 15-12, at the power distribution panel. P-409 TSGU-9 indicates a cable going to power distribution panel P-409 in the air conditioning compartment (Figure 15-14). This feeder also carries three-phase current to three bus bars inside the P-409 power panel.

Power is provided to all the three-phase branch circuits through three-pole circuit breakers. Individual branch circuits are designated by the first number on the tag, such as lP-409, 2P-409, and 3P-409. 4P-409 is a spare provided for future electrical growth. Note the location identification of the 3/4-HP motor vent (2-30-1) and the 7.5-KW heater (1-31-1) in the air conditioning compartment.

Now return to the P-400 power distribution panel and begin with feeder P-402. Feeder P-402 TSGU-14 is of special interest. This three-phase, 450-volt feeder is going to provide the 120-volt single-phase power necessary to operate the lighting and single-phase branch circuits. TSGU-14 enters three 10-kVA single-phase delta-delta connected step-down transformers (Figure 15-15). When three single-phase transformers are connected together delta-delta, this connection provides increased system reliability and the proper electrical three-phase relationship necessary to operate the lighting circuits.

The secondary side of the transformer bank is labeled L-100. This indicates that the cable will go to the lighting distribution panel using the TSGA-100 cable.

Notice that the secondary cable is larger in diameter than the primary cable (TSGU-14 versus TSGA-100). This is because a reduction in the voltage of a step-down transformer means an increase in the current on the secondary side of the transformers. With an increase in current, an increase in conductor size is necessary.

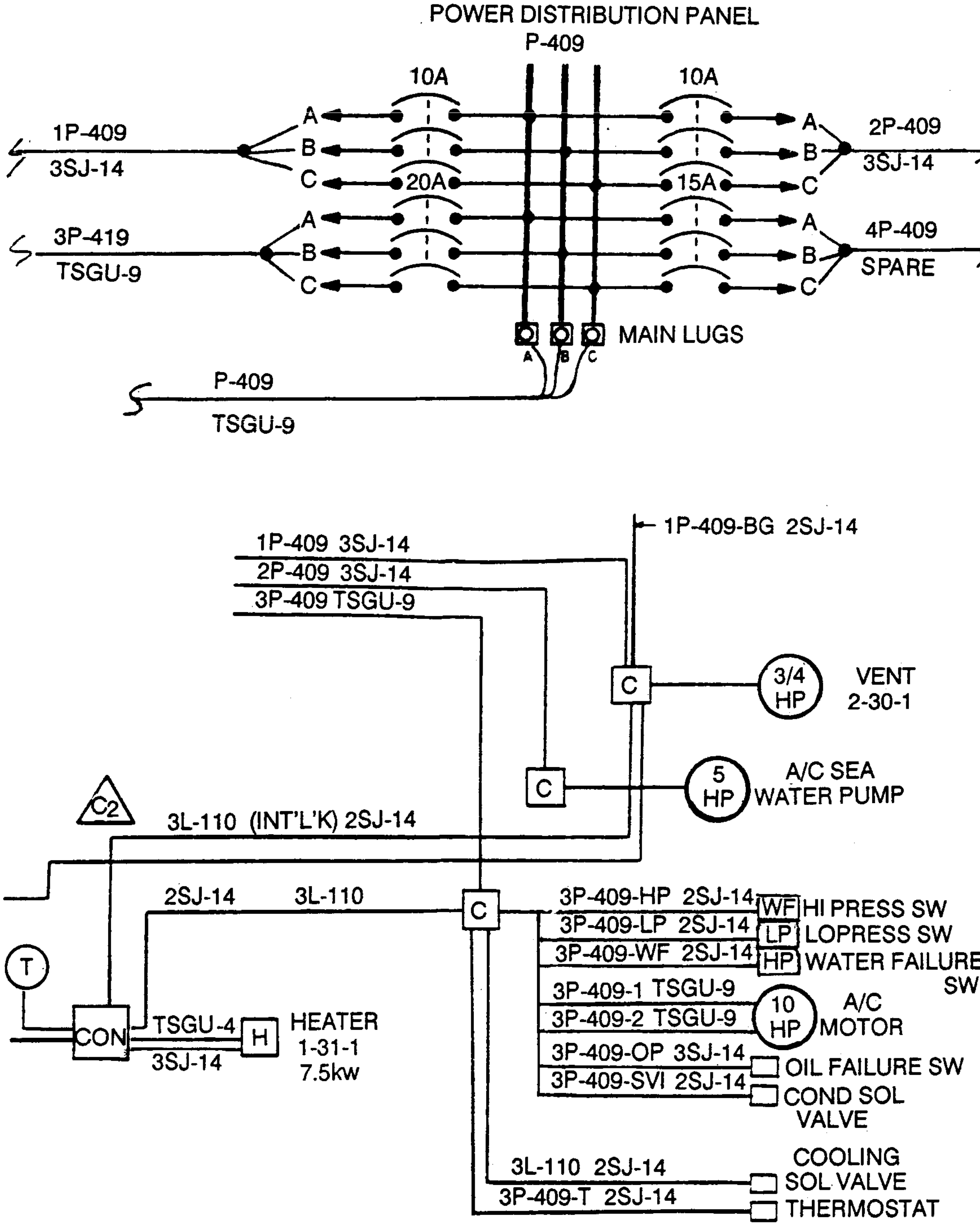

FIGURE 15-14. Power Panel P-409.

The L-100 TSGA-100 feeder enters the lighting distribution panel (L-100, Figure 15-16) and connects to three bus bars. Three-phase power is still maintained in the lighting distribution panel. Three-phase power is distributed to other lighting panels through the three-pole circuit breakers. Feeders L-101 and L-103 identify themselves as feeding three-phase current to lighting panels of like designations.

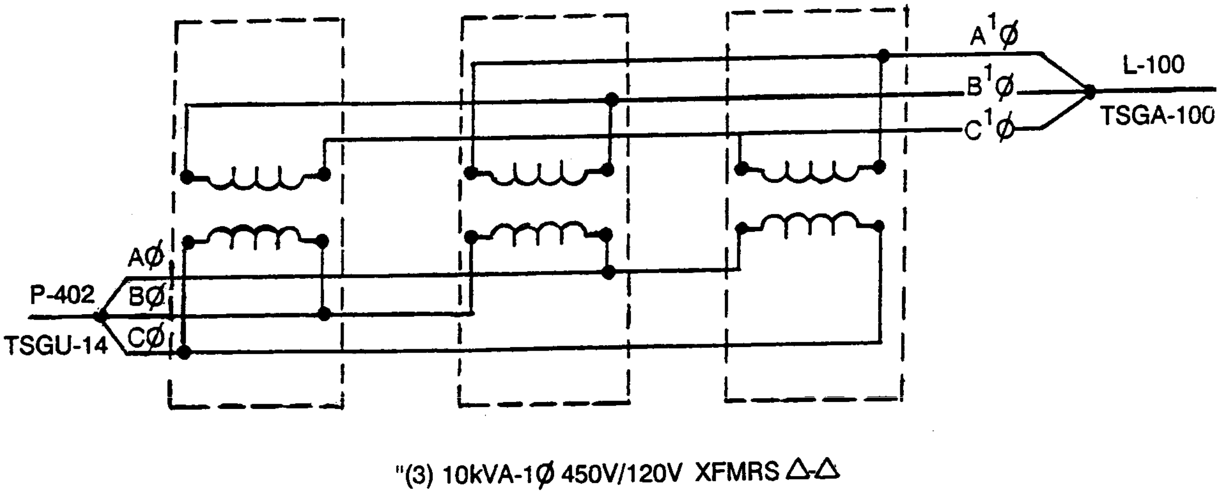

FIGURE 15-15. Step-Down Transformer Bank.

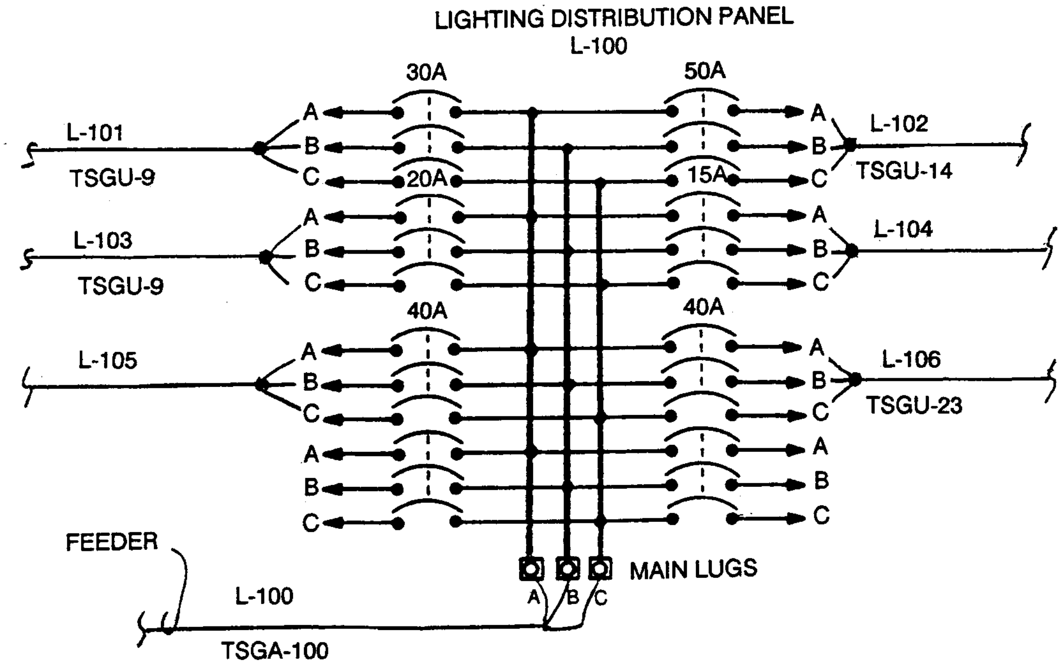

FIGURE 15-16. Panel L-100.

Tagged feeder L-101 TSGU-9 has three conductors entering lighting distribution panel L-101 (Figure 15-17). Each conductor connects to one of the three bus bars. Since lighting panel L-101 has only branch circuits distributing single-phase power to the loads, only two bus bars at a time are used. Figure 15-17 shows phases A and C (i) supplying current to the 1L-101 branch circuit. Branch 6L-101 is supplied by phases A and B (j). Branch 3L-101 is supplied with power from B and C (k). This keeps the load equally distributed across the distribution panel and the windings in the generator. Notice how all these branch circuits are two-conductor wires.

In this case, 1L-101/2SJ-14 and 2L-101/2SJ-14 supply the aft engine room lighting system. 3L-101/DSGU-14 provides power to the oil water separator motor and controls. The D in DSGU-14 indicates that there are only two wires. This means that the motor must be single phase.

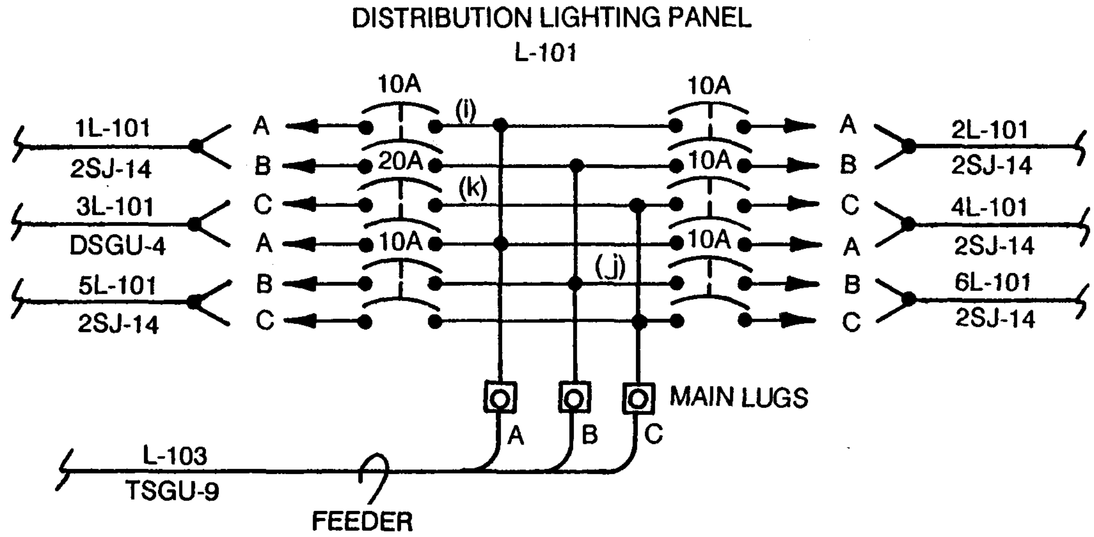

FIGURE 15-17. Panel L-101.

Return to the lighting distribution panel L-100 in Figure 15-16. The L-102 feeder provides power to the isolation transformer bank. Again, the most effective way to use the benefits derived from a transformer bank results when three single-phase transformers are connected delta-delta. In this situation, the transformers do not step up or step down the voltage. The diameter of the conductor is the same on the primary side as it is on the secondary side of the transformer (Figure 15-18). The transformers are not used to increase or decrease the voltage. In this situation, the isolation transformers provide a nonmechanical electrical connection between the L-100 lighting panel and the L-102 lighting distribution panel.

The branch circuits in the L-102 distribution panel example are very prone to abuse. This vessel's upper and lower deck receptacles receive their power from this panel. Receptacles are available for use by personnel not necessarily proficient in the electrical crafts. All types of equipment can be connected to receptacles. This is not to say that all types of equipment should be connected here, merely that improper conditions are likely to present themselves. All transformers prevent catastrophic

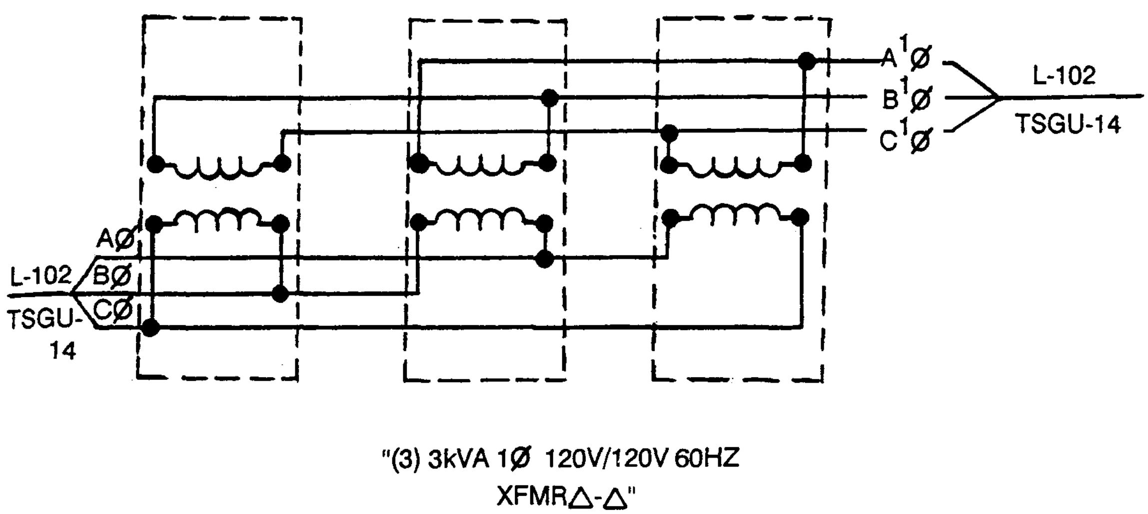

FIGURE 15-18. Isolation Transformer Bank.

electrical system damage by opening up on their secondary side before the short circuit condition can be passed throughout the distribution system. The isolation transformer bank exists for this sole purpose of protecting the electrical environment. The isolation bank neither steps down nor steps up the voltage. If this nonmechanical electrical link were not provided for, a short circuit condition can result in an electrical casualty of the L-100 lighting panel and end all single-phase power from the panel.

Should an electrical casualty damage one of the transformers, the other two can be connected open-delta. The number of phases does not change. With the loss of one of the three transformers, a power reduction to approximately 58 percent is necessary to prevent the open-delta from becoming overloaded.

In another example, three single-phase transformers are used to step down the 450 volts to 120 volts and provide the same protection to the P-400 power panel

Return to lighting panel L-100 (Figure 15-16) and locate feeder L106/TSGA-23. This feeder goes to lighting panel L-106 in the pilot house (Figure 15-19). From here, a very important system can be traced out – the emergency power supply.

From the lighting panel L-106, follow feeder 5L-106/DSGU-9 to the battery charger. From the battery charger to the loads, the cables will now be labeled as P for power. The batteries directly charged by the battery charger provide the power supply to the emergency power panel P-24. Notice how the circuit protective devices (fuses) are graphically represented in Figure 15-20. Each conductor has circuit protection.

Troubleshooting usually starts with the identification of a defective electrical component. The power supply will then be sought out. The tag on the wire of the component will indicate its source of power; for example, the lighting distribution panel L-101. This allows the engineer/engineman to work backwards from the component, isolating and de-energizing only the circuit needing service.

EMERGENCY POWER AND LIGHTING

Personal involvement with new state-of-the-art electrical equipment and their appropriate manuals will complete your knowledge of the electrical system. This field is undergoing major changes that preclude this text from encompassing all aspects of the distribution system. The emergency power and lighting system should be one of the first systems you become comfortable with.

If the power should fail on board a vessel, lives and property are jeopardized. Many vessels regain control of their electrical systems through the use of an emergency generator and emergency switchboard. The generator is provided with its own starting system. When power is lost, the emergency generator must be able to automatically start and provide power to the emergency switchboard within a few moments.

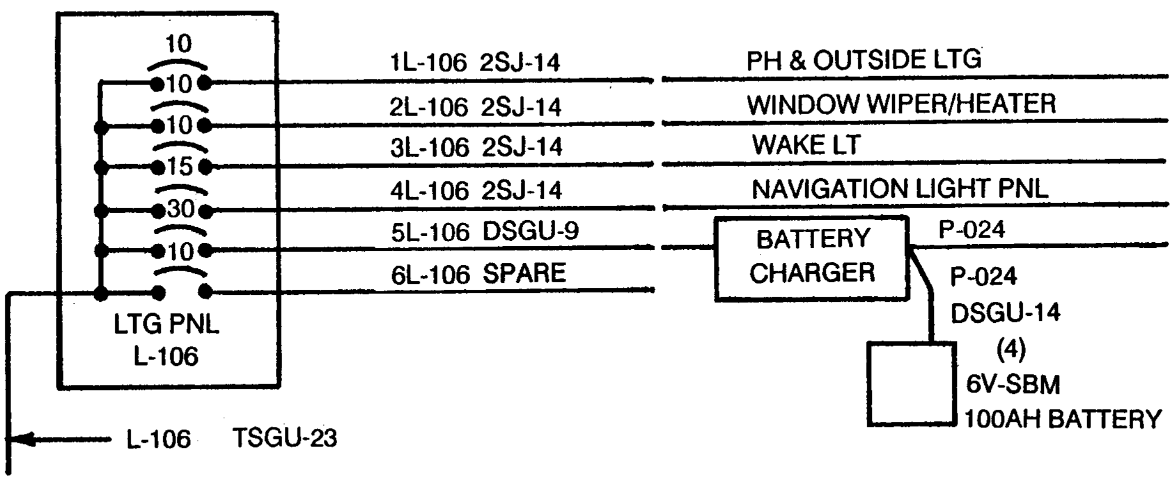

FIGURE 15-19. Lighting Panel L-106.

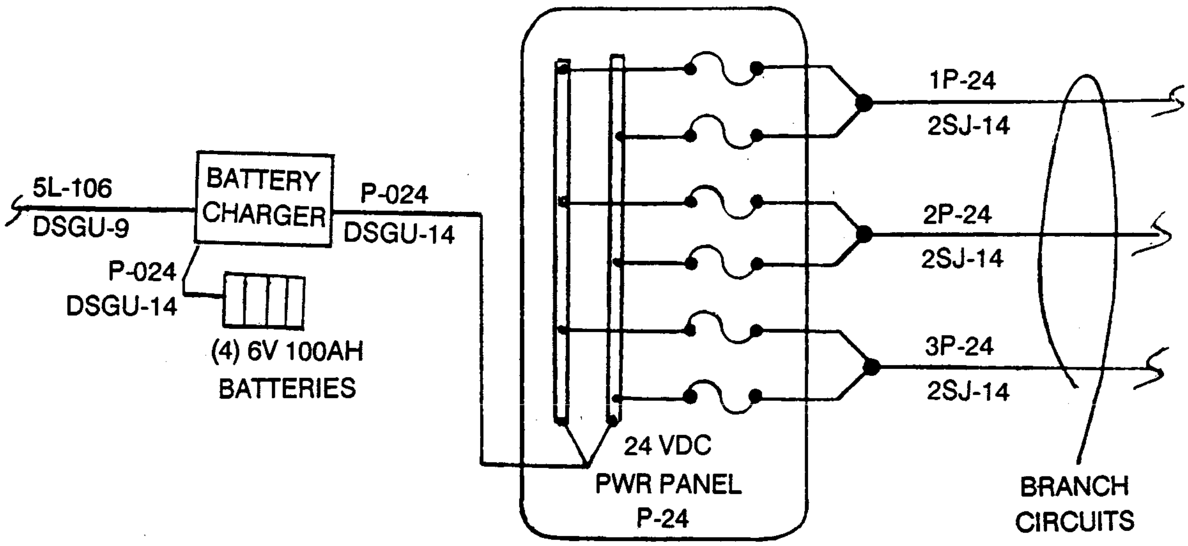

FIGURE 15-20. Emergency 24-Volt DC Power Panel P-24.

Transferring power from ship to shore requires the momentary interruption of ship's power because most Army vessels are not equipped to cogenerate (or run in parallel with) shore power utility companies. Make provisions to ensure the emergency generator will not start during this momentary interruption.

The emergency generator power supply is made available to either the main distribution center or the emergency distribution switchboard through an automatic bus transfer (ABT) switch and the bus tie. Normally, the ship service generators supply power to the emergency switchboard from the main distribution center through a circuit breaker and automatic bus transfer switch. When power is lost, the ABT switch automatically connects the emergency generator to the emergency switchboard. The ABT simultaneously disconnects the main distribution switchboard from the emergency switchboard. This allows all the emergency power to be supplied to the vital services connected to the emergency switchboard. For unusual conditions, manual switches may allow the emergency generator to provide power to the main distribution center. Care must be taken not to overload the emergency generator.

The circuits connected to the emergency switchboard are determined by the design of the vessel. Some of these vital services are the —

- Steering gear.
- Fire pump.
- Emergency lighting.
- Emergency bilge pump.
- Interior communications.
- Main and emergency radio.
- Loran and radar.

Additional information may be obtained in the IEEE Standard 45, Section 36.

SWITCH BOARDS

The operator monitors the power from the generators through the main power distribution switchboard. The marine engineer/engineman has the critical task of putting the generators on line. On line means that the generator is supplying power through the switchboard to the loads. If a generator is coming on line, this indicates that the generator is operating and waiting to furnish power to the switchboard.

The information below is provided as a general guide for the junior and senior marine engineman in the operation of the AC switchboard. In all cases, equipment should not be operated without first consulting the manufacturer's manuals and appropriate Army technical manuals. Look for additional information pertinent to the operation of the 2000-series LCU and logistics support vessel (LSV).

The following is based on the procedures necessary to operate and parallel the generic AC brushless generators. Every prime mover and generator manufacturer has its own specific needs and interrelated requirements for paralleling generators. Unlike many selective tasks you may have performed in the past, the act of paralleling generators depends on many outside influences.

Prime Mover

Currently, the Army vessel inventory uses the Cummins, Detroit, and Caterpillar diesels as the prime mover to provide the motion necessary to produce an electromotive force. To become a good electrician, you must first be a good mechanic. Nowhere is it more evident than when generators need to be paralleled. In order to parallel generators, the prime movers must be in proper working order. The diesels need to be mechanically sound and properly tuned. The governors must be set properly. Before you ever consider major adjustments on the distribution switchboard, you must consult the operator and maintenance manual of the prime mover. If the prime movers do not operate with the expected speed characteristics, then there is no possible way for you to compensate for their inaccuracies at the switchboard.

Speed Droop

The efficient operation of a generator is not enough. Both generators must operate with the same efficient characteristics. Each generator must be tuned up individually, but their speed droop setting must be collectively consistent. The reason the speed droop is set is to establish a defined engine speed at no load and full load.

When a large electrical load is suddenly placed on the generators, the speed of their prime mover drops. This is because it is harder for the diesel to turn the generator rotor with the stronger magnetic field. The magnetic field in the rotor had to increase to compensate for the increase in electrical demand. How spontaneously the two generator prime movers react to this decrease in speed depends on the speed droop setting of the individual governors. The increase infield strength and armature current acts as a magnetic break, reducing diesel RPM.

Speed droop allows a decrease in diesel speed as the load is applied. In keeping with the elementary basics of this manual, the electronic speed and voltage controls of the new 2K LCUs will not be directly addressed. Although all functions presented are comparable between all generator sets, consultation of the specific manufacturer's manual is mandatory. General understanding of speed droop is best presented by the basic PSG governor function found on the 1600 series LCUs. Much of the following information is reprinted with permission of the Woodward Governor Company.

Speed droop is increased by moving the external knurled knob forward on the governor and decreased (toward zero droop) by moving the knurled knob toward the back of the governor. The droop setting must be made by trial and error because there is no calibration point (on these models). If it has not been previously set, the engineer must move the knob back and forth until he achieves the proper droop setting between full load and no load.

The procedure below is recommended by the original manufacturer's manual, incorporated within the initial TMs (Figure 15-21).

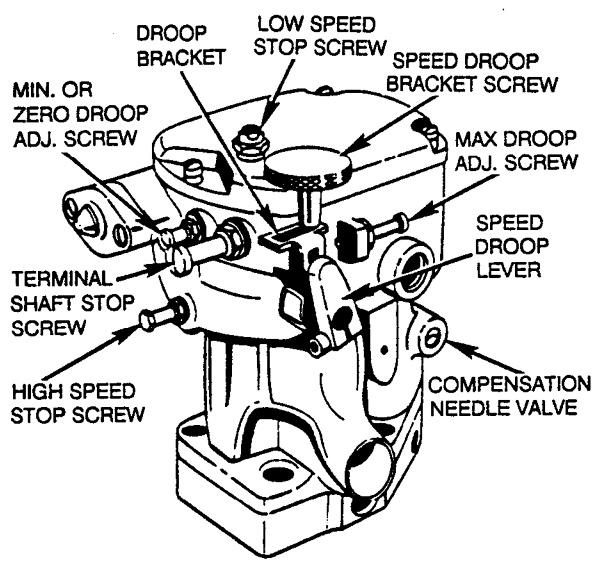

FIGURE 15-21. Speed Droop Adjustment.

> **NOTE:** A very accurate tachometer must be used to determine the speed drop. The same tachometer must be used for both generators. This will eliminate any calibration errors or erratic tachometer response.

The Detroit diesel manual for the speed droop adjustment on the 4/71, PSG governor is supplemented as follows:

- Operate the prime mover until the oil is up to operating temperature.
- Position the governor speed droop adjusting knob midway.
- With the throttle in the RUN position, adjust the engine speed 5 percent above the recommended full-load speed.
- Apply a full electrical load on the engine. Ensure that motors are providing the majority of the load. An inductive load demonstrates the current action in the AC system better than the resistive load from the stove, electric heaters, or lights.
- Remove the rated load. After the speed has stabilized, the diesel speed should be 5 percent higher for no load than for full load.
- Adjust the governor speed droop accordingly.
- Adjust both generators the same way.

If the speed droop is not accurately established between the two prime movers, balanced electrical distribution cannot be obtained.

Generator Voltage Droop

Voltage droop is the decrease in the normal generator voltage due to an increase in load current. The decrease in voltage from no load to full load is expressed as a percentage of the full-load voltage:

$$\text{Percent voltage droop} = \frac{(\text{no-load voltage} - \text{full-load voltage}) \times 100}{\text{full-load voltage}}$$

This is another adjustment that is necessary to properly parallel AC generators. The droop control should be set so that a given amount of reactive current applied separately to each generator will cause identical reductions in output voltage.

A large increase in current draw is followed by a slight decrease in voltage. This voltage drop needs to be compensated for accurately and consistently by both generators.

The procedure below is a general guidance to be used in accordance with appropriate technical and manufacturer's manuals. It is designed to clarify electrical procedures only.

Before adjusting for voltage droop, the droop control is initially set in the mid position. Shore power is secured. To adjust for voltage droop–

- Operate both prime movers at rated speed and voltage until the prime movers and the regulators have stabilized.
- Remove all electrical load from the main bus by opening the feeder circuit breakers and the main circuit breakers of any additional distribution panels connected to the main bus.
- Close one generator circuit breaker. With the voltmeter selector switch in the BUS position, adjust the automatic voltage control to 465 volts. Open the generator circuit breaker.

Repeat this procedure for the other generator, except do not open the generator circuit breaker after the last adjustment. Leave this generator on line. Then –

- Close enough circuit breakers to load the generator with reactive loads. Do not exceed the current or power factor rating of the generator.
- With the integral unit/parallel switch in the OFF position (ensure that the generators are not electrically linked for operation in parallel), adjust the droop control for the desired voltage droop percentage at the available reactive load. A voltage drop of three percent will generally result in

acceptable reactive load sharing without unacceptable voltage regulation. Consult your manufacturer's manual. If the available reactive current is less than the rated reactive current, set the droop control to give a proportionally higher bus voltage.

NOTE: The load should be motors. Motors provide the inductive reactance necessary for this setting.

- Open the generator circuit breaker of the generator adjusted instep 5. Repeat steps 4 and 5, and adjust the droop control of the second generator. The reactive load and the voltmeter selector switch (BUS position) must be the same as used for the first generator. Identical loads and meters are paramount in duplicating the droop characteristics necessary to perform the adjustment as properly as possible. The same voltmeter must be used for each machine.

- Record the dial position of each of the two droop controls. This will allow prompt correction of unintentional control disturbances. Once the voltage droop is set, minor changes in reactive load should be corrected by an adjustment of the automatic voltage control and not the droop control.

PLACING AN ALTERNATING CURRENT GENERATOR ON LINE

Before trying to start the generator, ensure the following:

- Make sure the associated generator circuit breakers are open. If a generator is started and the circuit breakers to both generators are closed, the voltage surge to the generator that is not operating will destroy the components in its rotating rectifier.

- Place the selector switch in a position that indicates an individual generator is operating, that is, unit or single unit operation.

- Place the voltage regulator in the automatic position.

NOTE: A complete understanding of the manufacturer's manual is necessary. Many generator electrical systems are not designed to be warmed up or operated at below rated speed with the voltage regulator in operation. Failure to comply with the manufacturer's recommendation will damage the voltage regulator.

NOTE: Many generator electrical systems are not designed to be operated with the voltage regulator field open.

To place one generator on line –

- Start the prime mover and bring the generator set up to speed.

- Adjust the generator for rated voltage.

- Adjust the frequency for 60 hertz by adjusting the speed of the prime mover.

- When it has been determined that the generator is operating at the required voltage and frequency, connect the bus to the feeders by closing the appropriate circuit breaker. The generator is now on line.

PARALLEL OPERATION OF ALTERNATING CURRENT GENERATORS

The voltage setting of AC generators is the most critical setting for paralleling. The voltage of each generator must be set exactly the same. Since a vessel is subjected to extensive vibration and salt air corrosion, it is advisable to check the calibration of all the meters regularly.

The voltmeter should always reflect the rated voltage of the machine. In a perfect scenario, both generators will reflect the exact rated voltage. However, this is not often the case. Voltage settings are critical because any voltage difference between the generators will increase the reactance between the two generators. This will require the generator to supply extra current to overcome this wasted power. (Review Chapter 6 on inductive reactance.) This means increased heat in the electrical system and extra demand from the generators.

An expedient way to check the calibration of the voltmeter is as follows:

- Start and operate number one generator only.
- With the number two generator off, turn the number two generator voltmeter to the BUS position.

Now the number one voltmeter and the number two voltmeter are reading the same voltage source. If everything is correctly calibrated, then both meters will read the same voltage from the number one generator.

If both generator voltmeters do not display the same voltage reading, then there is an inconsistency. If you adjust each generator according to its own meter readings, then the voltage difference still exists. As an expedient measure, you can maintain the voltage difference as noted above, when each voltmeter is monitoring its own generator. Even though the meters are not identical, the voltages will be. Final paralleling voltage adjustment will compensate for any inconsistency.

In paralleling, it is more effective to have both the voltages slightly below or both voltages slightly above the rated voltage than for one generator to be only 1 volt above and the other generator at exactly the rated voltage. Differences in voltage increase electrical system reactance. The increased current and subsequent increase in heat decrease the life expectancy of components. In any application, when an inconsistency is found with the equipment, correct it immediately or refer it to a higher echelon of maintenance.

PARALLEL OPERATION AND SYNCHRONIZING

Use the following sequence to parallel two generators:

- Make sure both generator sets are up to operating temperature and rated speed.
- Place one generator on line as earlier described.
- Set the voltage regulator to AUTO-MATIC.
- Set the voltage on each machine.
- Set the frequency of both machines. The frequency represents the speed of the generator prime mover. A change in the prime mover speed changes the frequency. The generator on line should indicate 60 hertz. The generator that will be placed on line should be slightly higher than 60 hertz. This is because the generator that will be placed on line will eventually be placed under load, reducing its speed slightly. One generator is operating at full load (with speed droop), and the other generator is operating at no load.
- Place the synchronizing switch in the incoming generator position. The synchronizing scope lets you see when the generators are operating in phase and to see the relationship between the differing speeds of the two prime movers. The synchronizing pointer must rotate in the FAST direction. This indicates that the generator that will be coming on line is operating faster (more revolutions per minute) than the generator online. If the synchronizing scope pointer rotates in the SLOW position, this indicates that the speed of the generator that will be placed on line is moving too slowly. Ensure that the pointer is moving slowly in the FAST direction at a speed where you can accurately close the incoming generator circuit breaker at the 12 o'clock position.
- When the synchronizing pointer is at the 12 o'clock position, close the incoming generator circuit breaker.
- Observe the kilowatt load at once. Adjust the kilowatt load by adjusting the speed of the prime movers. This is to balance the load between both generators. Each generator should share the kilowatt load evenly.
- Check the frequency of the generators and adjust both prime mover speeds together, if necessary, to maintain 60 hertz.
- Check the ammeters. Check the voltmeters. If you had 40 amperes on one ammeter

before you paralleled the generators and now you observe 25 amperes on each ammeter, then the voltage is not exact. This is because 25 amperes plus 25 amperes does not equal 40 amperes. The total power produced between the two generators is now 50 amperes, and therefore 10 extra amperes are being produced to overcome the increased reactance. Adjust one voltage in minute proportions until you have the lowest total current reading. This is how you will finally eliminate the extra reactive loads due to any inconsistencies in the voltmeters. Do not drop below rated voltage. Only one voltage needs to be adjusted.

- Place the integral unit/parallel switch in the position that indicates both generators are operating in parallel. This switch provides an electrical link between the two generator sets and helps maintain parallel operation.

- Recheck all meters. Adjust each ammeter and kilowatt meter so that they show an evenly distributed load.

FLOATING ON THE LINE

Once a generator is paralleled, its voltage and speed are determined by the bus. At the instant you throw the switch, the generator is connected to the bus, but it is not delivering power. It is said to be "floating" on the line. If you try to reduce the speed of the prime mover, the generator continues to run at rated speed. How is that possible? There is not enough mechanical power to drive the generator that fast. Therefore, the generator draws electrical power from the bus. It actually runs as a motor.

If you try to increase voltage by increasing DC excitation to the generator's field, terminal voltage will appear to remain the same. You have actually increased the generated voltage of one generator, but it does not show.

Why is it that the terminal voltage does not change? The extra generated voltage produces a reactive current flow into the bus. This current does not deliver any active (usable load) power. Only by increasing the prime mover speed will the generator accept its share of the load.

SHUTTING DOWN THE GENERATORS

To shut down the generators –

- Place the integral unit/parallel switch in a position that indicates which generator is to remain on line.

- Transfer the entire load to the generator to remain on line by simultaneously increasing the speed of the generator and decreasing the speed of the generator that will be shut down.

- When the transfer is almost complete (again check with applicable manuals), open the main circuit breaker of the generator to be secured.

- Recheck your voltage and frequency meters.

- Secure the prime mover as required.

Now you may continue to operate on one unit or continue to shut down the other generator as follows:

- Reduce the electrical load as much as possible by securing equipment and opening feeder circuit breakers to the electrical distribution system.

- Open the generator main circuit breaker.

- Shut down the prime mover as applicable.

Remember, never perform any maintenance, servicing, or operating without first consulting the appropriate technical manuals.

ELECTRONIC GOVERNORS

Newer vessels designed for the Army will be using the electronic fuel control (EFC) and governing system. The following information is provided as introductory information only. In-depth information will be made available at the junior and senior marine engineer levels. Specific information is available from the vessel technical manuals and manufacturer's manuals.

The EFC system will be made up of three basic units (Figure 15-22):

- Electronic speed sensor, magnetic pickup (MPU).
- Electronic control box, governor control.
- Electronic actuator, fuel delivery.

The elimination of most throttle controls and linkages means that the system is less maintenance-intensive than current fuel control systems.

The MPU is an electromagnetic component mounted through the flywheel housing (Figure 15-23). The MPU is a permanent magnet with the circuit from the governor control tightly wrapped around it. The MPU comes in close proximity with the teeth of the flywheel. As the teeth from the flywheel move past the magnetic field from the MPU, the MPU's magnetic field becomes distorted. The motion of the distorted magnetic field induces an EMF into the governor control circuit wrapped around the magnet. As the flywheel teeth move further past the MPU, another portion of the MPU field becomes distorted in a like but opposite manner. This magnetic field

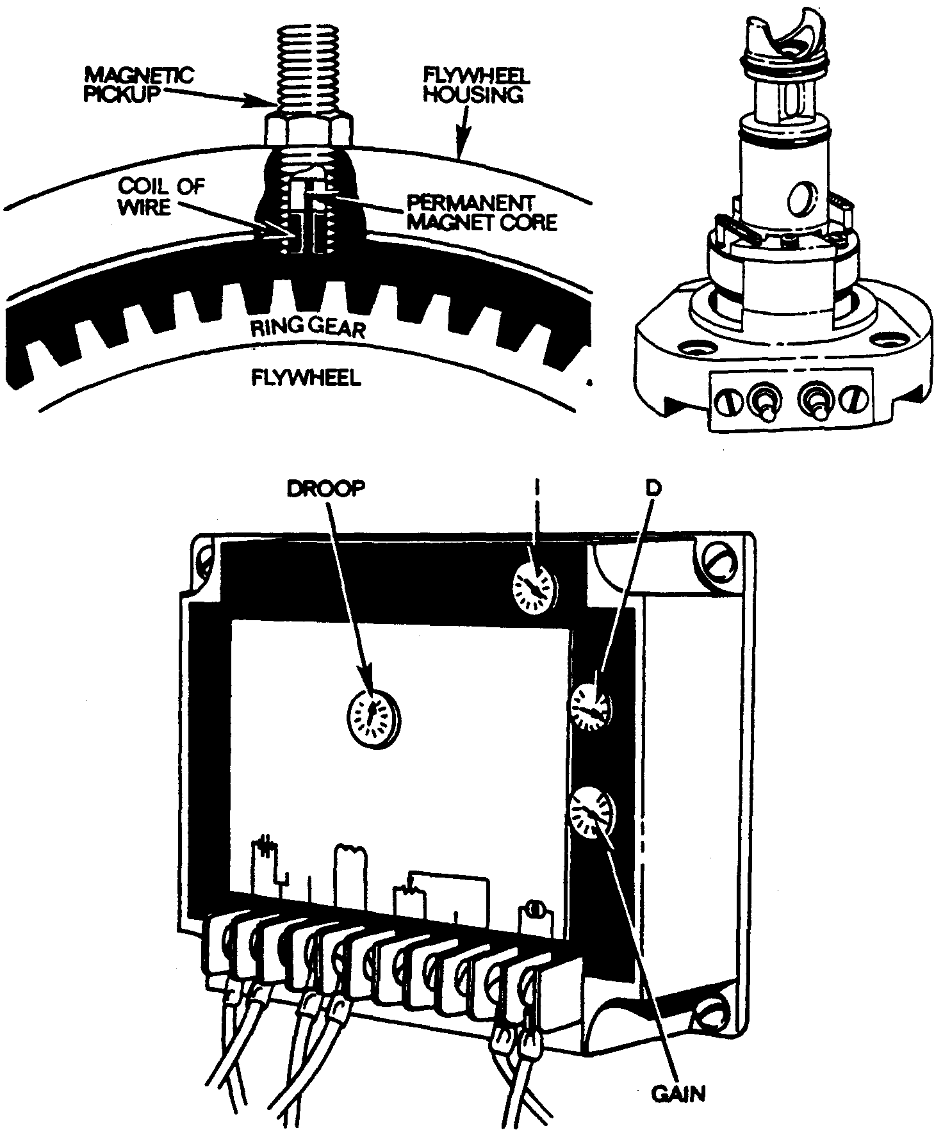

FIGURE 15-22. EFC System Components.

motion in the MPU induces an EMF in the opposite direction as previous. The single-phase AC developed in the MPU is sent to the governor control. The cycles per second can be easily converted to revolutions per minute. This provides the governor with an indication of prime mover speed. The faster the flywheel turns, the faster the induced EMF frequency. In this manner, the governor control senses the changes in speed.

The governor control interprets these speed changes and, depending on the setting of the controls, provides an electrical signal to the actuator port.

The actuator is basically a solenoid valve that admits fuel to the diesel in a quantity determined by the signal from the governor control. The slower the speed of the prime mover, the more the governor control electrically opens the fuel port. The faster the prime mover speed, the smaller the quantity of fuel delivered through the actuator port.

The most important information for the junior and senior marine engineman concerns the batteries. The batteries provide the voltage and current necessary for operating the electronic fuel control system. This equipment is set up so that the generator prime mover cannot function without the batteries fully operational. Although provided with manual means to override this system, normal operation is prohibited. Emergency generators will not start automatically nor will the ship service generators continue to operate should the batteries fail to provide the necessary power for the EFC control circuits.

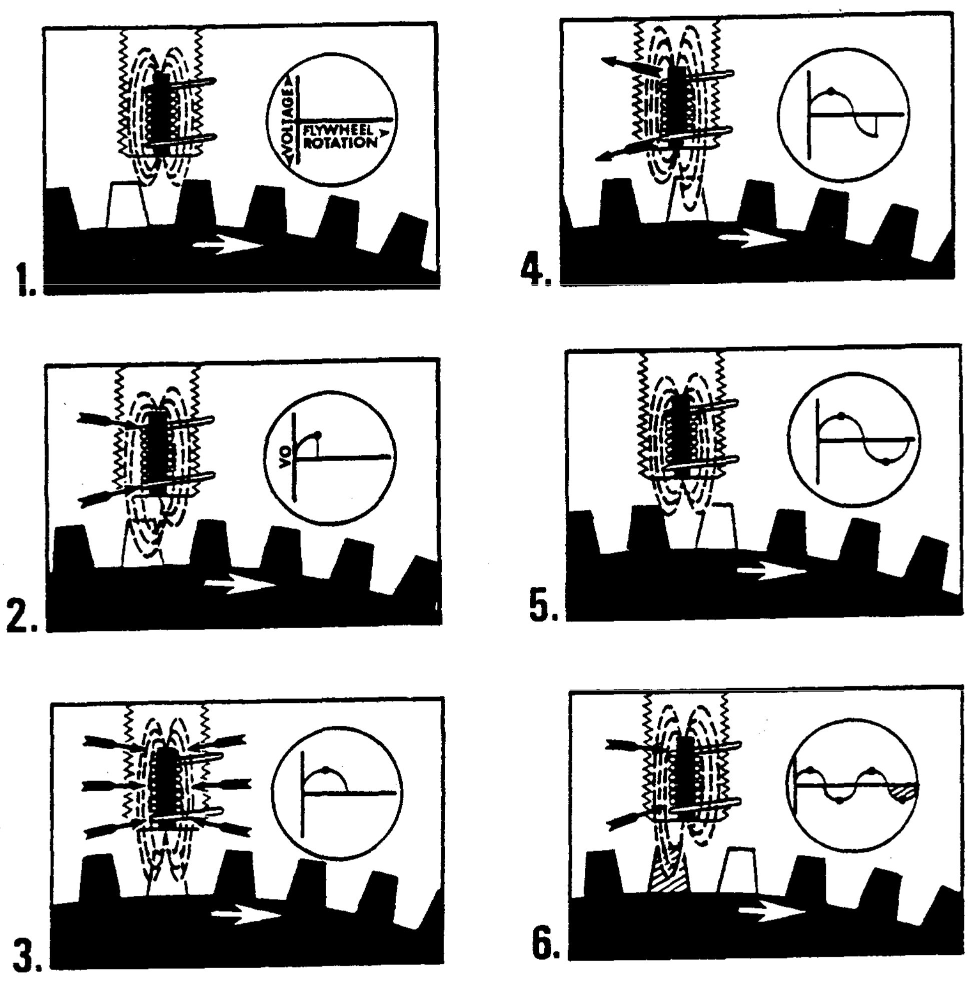

FIGURE 15-23. Representation of EFC System Cycle.

CHAPTER 16

THREE-PHASE ALTERNATING CURRENT MOTORS

INTRODUCTION

Most of the power-generating systems, ashore and afloat, produce AC. For this reason, a majority of the motors used throughout the Army operate on AC. There are other advantages to using AC. In general, AC motors are less expensive and easier to maintain than DC machines.

An AC motor is particularly well suited for constant speed operations. This is because its speed is determined by the frequency of the power source and the number of poles constructed in the motor.

Alternating current motors are built in different sizes, shapes, and ratings for many different jobs (Figures 16-1 and 16-2). It is impossible to address all forms of AC motors in this text. This chapter will address only the squirrel cage induction motor.

INDUCTION MOTOR PRINCIPLE

The principle of the revolving magnetic field is the key to the operation of the AC motor. Induction motors rely on revolving magnetic fields in their stators (stationary windings) to cause their rotors to turn. Stators themselves do not turn. Stators are permanently attached to the inside of the motor housing in the same manner that the stationary windings in the generator are connected to the main frame. The revolving magnetic fields created in the stator windings provide the necessary torque to move the rotor.

The idea is simple. A magnetic field in a stator can be made to appear to rotate electrically, around the inside periphery of the motor housing. This is done by overlapping several different stator windings. A magnetic field is developed in each different stator winding at a different time. Just before the magnetic field of one winding decays, the winding overlapping it develops the same magnetic polarity. As this second magnetic field decays in the second winding, another overlapping winding develops a magnetic field of the same polarity, and the sequence repeats itself. Successive stator windings develop magnetic fields in an orderly procession and appear to progressively move around the inside of the motor housing.

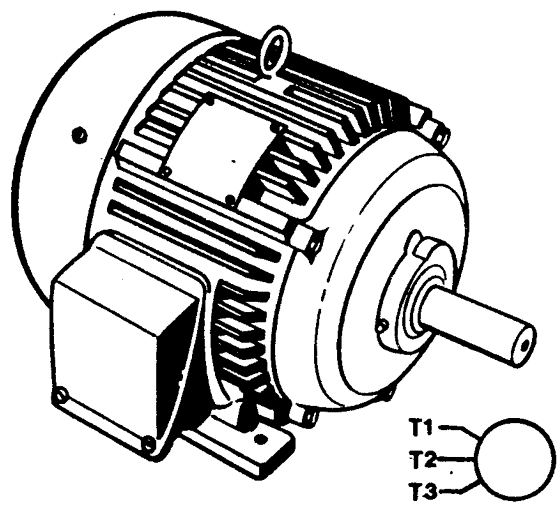

FIGURE 16-1. Three-Phase Motor Symbol.

These individual magnetic fields are the property of current flow in the motor stator. This current flow comes from the three individual phase currents of the three-phase generator output. In Chapter 14, Figure 14-8 shows the three single-phase voltages/currents that develop in the generator main armature completing individual circuits. Circuit A-B in the generator armature has a like A-B winding in the motor's stator. Each of the three circuit combinations (A-B, B-C, and C-A) are developed independently in the generator over a short period of time. The generator circuits are then completed through the motor's stator windings in a similar manner. As long as the current and magnetic field develops and decays in an orderly, progressive manner around the periphery of the motor frame, a revolving magnetic field exists.

A revolving magnetic field in the stator is only part of the operation. Another magnetic field needs to be created in the rotor so that the torque and rotation can develop using the principles of magnetic attraction and repulsion. The magnetic field developed in the rotor is a product of induction. As soon as the stator and the rotor windings develop their magnetic affiliation, torque will develop, and the rotor will turn.

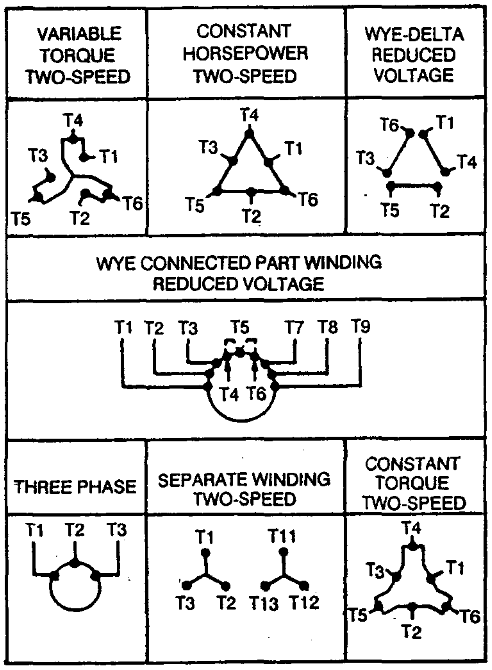

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FIGURE 16-2. Various Three-Phase Motor Stator Terminals.

REVOLVING FIELD OPERATION

The rotating field is set up by out-of-phase currents in the stator windings. Figure 16-3 shows the manner in which a rotating field is produced by stationary coils or windings when they are supplied by a three-phase current source. For the purpose of explanation, rotation of the field is developed in the figure by "stopping" it at six selected positions, or instants. These instants are marked off at 60-degree intervals on the sine waves representing currents in the three phases A, B, and C.

At instant 1, the current in phase B is maximum positive. (Assume plus 10 amperes in this example.) Current is considered to be positive when it is flowing out from a motor terminal. At the same time (instant 1), current flows into A and C terminals at half value (minus 5 amperes each in this case). These currents combine at the neutral (common connection) to supply plus 10 amperes out through the B phase.

The resulting field at instant 1 is established downward and to the right as shown by the arrow NS. The major part of this field is produced by the B phase (full strength at this time) and is aided by the adjacent phases A and C (half strength). The weaker parts of the field are indicated by the letters n ands. The field is a two-pole field extending across the space that would normally contain the rotor.

At instant 2, the current in phase B is reduced to half value (plus 5 amperes in this example). The current in phase C has reversed its flow from minus 5 amperes to plus 5 amperes, and the current in phase A has increased from minus 5 amperes to minus 10 amperes.

The resulting field at instant 2 is now established upward and to the right as shown by the arrow NS. The major part of the field is produced by phase A (full strength) and the weaker parts by phases B and C (half strength).

At instant 3, the current in phase C is plus 10 amperes, and the field extends vertically upward. At instant 4, the current in phase B becomes minus 10 amperes, and the field extends upward and to the left. At instant 5, the current in phase A becomes plus 10 amperes, and the field extends downward and to the left. At instant 6, the current in phase C is minus 10 amperes, and the field extends vertically downward. In instant, 7 (not shown), the current corresponds to instant 1 when the field again extends downward and to the right.

Thus, a full rotation of the two-pole field has been done through one full cycle of 360 electrical degrees of the three-phase currents flowing through the stator windings.

SYNCHRONOUS SPEED

The number of poles in the motor will determine how many times the magnetic field in the stator revolves for any given generated frequency. The term "pole" should bring to mind the terms used in Chapter 2 on magnetism. The following definition of a motor pole gives it a practical application value: A motor pole is the completed circuit of a motor stator winding that, when energized by a current, will produce a magnetic field concentration, or polarity.

The speed of the revolving stator field is called synchronous speed. The synchronous speed depends on two factors:

- The number of poles.
- The frequency of the power source.

The synchronous speed, in turn, determines the speed of the motor rotor. Just as with the generator prime mover speed, the generated frequency and rotor speed are directly related. The number of poles in the motor determines how fast the revolving field will move around the inside periphery of the motor housing at a given frequency. The more poles a motor has, the longer it takes to energize all the sets of poles and the slower the motor field will revolve at 60 hertz.

Table 16-1 shows the speed of the revolving field (or synchronous speed) for a 60-hertz generated power supply.

TABLE 16-1. Synchronous Speed for a 60-Hertz Generated Power Source.

Number of Poles in the Motor	Stator Revolving Field Speed (Synchronous Speed)
2 poles	3,600 RPM
4 poles	1,800 RPM
6 poles	1,200 RPM
8 poles	900 RPM

DIRECTION OF ROTATION

The direction of rotation of three-phase machines are determined by the phase sequence. Normal phase sequence on board Army vessels is A-B-C. This can be verified from the switchboard. A set of lights indicates the phase sequence from the power source.

As the generator rotates, current flow is induced in the armature. Each phase in the armature becomes electrically active. The order in which the phases become electrically active determines the

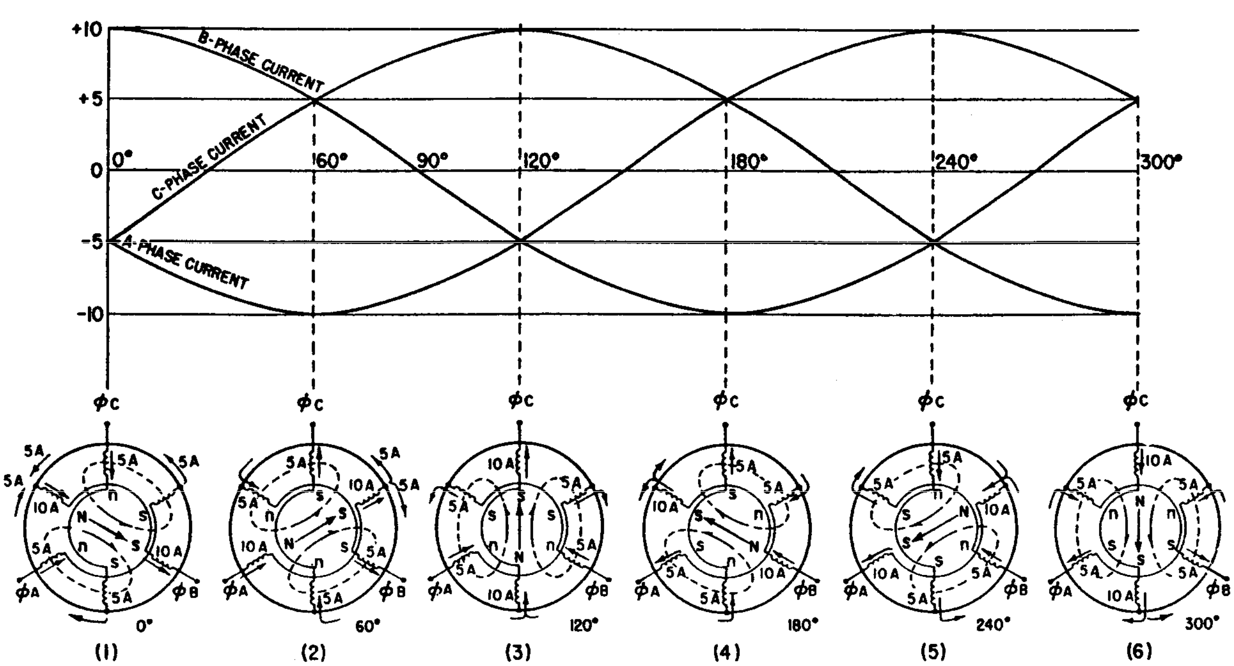

FIGURE 16-3. Developing a Resolving Magnetic Field.

order in which the motor's stator receives the current. The motor that receives current A-B-C-A-B-C will rotate in a given direction. If any two leads change places, then the two affected phases change their sequence of arrival. If phases B and C are exchanged, then phase C will follow phase A. This reverses the direction of the revolving magnetic field in the stator. Current arrives at the motor C-B-A-C-B-A. When the revolving field in the motor's stator changes direction, the motor's rotor changes direction. Reversing the generator's output will turn the motor's rotor in the opposite direction as well. If the generator's output is reversed, then it is known as C-B-A phase sequence.

By reversing any two phase wires, either at the generator's armature or the motor's terminals, the phase sequence will change at that point. Reversing any two leads, at the same point, will restore normal phase sequence. Industry standard dictates configuration control by identifying the conductors to be exchanged: the A and C phase for generators, P1 and P3 for feeders, L1 and L3 for branch circuits, or T1 and T3 for motor terminals.

CONSTRUCTION AND OPERATION

Figure 16-4 shows a cutaway view of a three-phase induction motor. There is very little difference between the AC motor and the AC generator. The rotor is supported by bearings at each end. The stator is freed in position to the inside of the motor frame. The frame encloses all the components of the motor.

Frame

The motor frame, among other considerations, is a determining factor in the placement of the motor. Each motor frame enclosure has certain characteristics and specific vessel applications. There are seven basic types of enclosures:

- In an open-type enclosure, the end bells are open and provide for maximum motor ventilation. This is the lowest cost motor enclosure.
- In a semiguarded enclosure, the end bells are open, but screens are provided to prevent objects from falling into the motor. There is no protection against water or liquids.
- In a guarded enclosure, screens and guards exist over any opening in the motor housing. Limited openings are provided to limit access to live and rotating components within the motor enclosure. Generally, the holes must prevent a 1/2-inch diameter rod from entering the enclosure.
- In a drip-proof enclosure, the end bells are covered to prevent liquid from entering the enclosure at an angle not greater than 15 degrees from the vertical.
- In a splash-proof enclosure, the motor openings are constructed to prevent liquid drops or solid particles from entering the motor at any angle not greater than 100 degrees from the vertical.
- A waterproof enclosure prevents any moisture or water leakage from entering the motor and interfering with its successful operation.
- A watertight enclosure prevents a stream of water from a hose (not less than 1 inch in diameter, under a head of 35 feet, from a distance of 10 feet) from any direction from entering the motor for a period of at least 15 minutes.

Electric equipment exposed to the weather or in a space where it is exposed to seas, splashing, or similar conditions must be watertight or in a watertight enclosure. Electric motors, however, must be either watertight or waterproof (Code of Federal Regulations, Title 46, Subpart 111.01-9).

Stator Windings

The motor stator is the stationary winding bolted to the inside of the motor housing. The stator windings have a very low resistance. The three-phase AC generator armature is built very similar to the three-phase AC motor stator. Each machine has the stationary conductor winding insulated its entire length to prevent turn-to-turn shorts. The winding is also insulated from the frame. The motor stator winding is identical to a generator armature that has a like amount of poles. Each winding is overlapped and is electrically and mechanically 120 degrees out of phase.

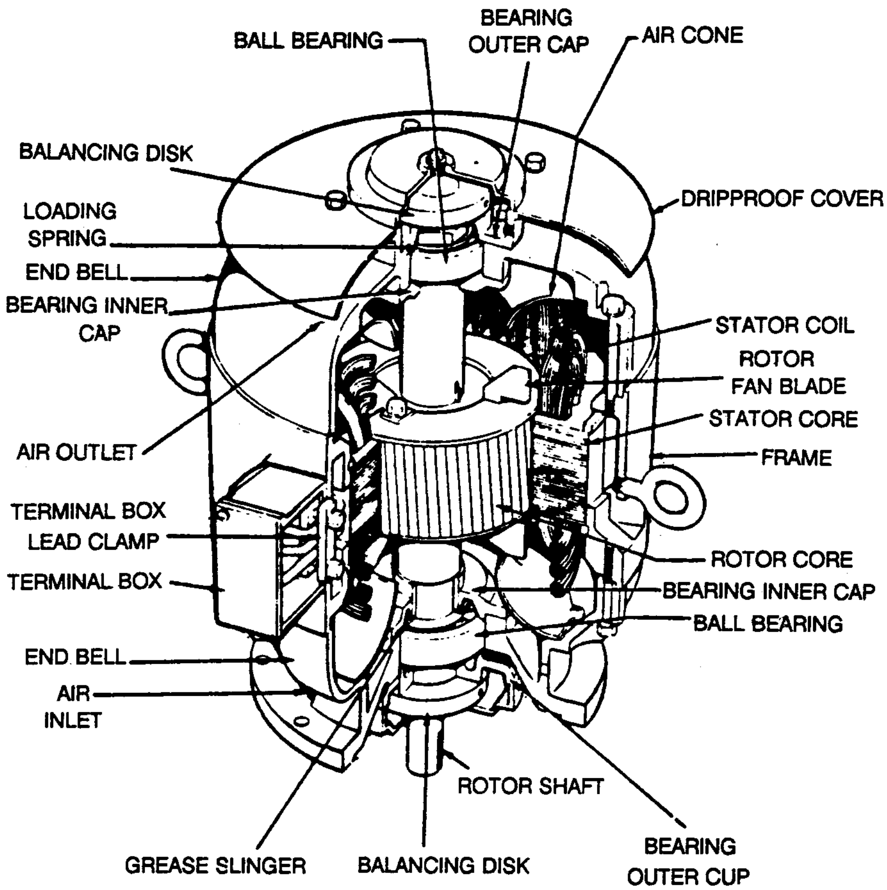

FIGURE 16-4. Three-Phase Induction Motor.

Figure 16-5 shows an end view of the stationary windings. Each of the three-phase windings are divided into many additional coils uniformly distributed throughout the stator. This even distribution allows more effective use out of the magnetic fields that will be developed within the stator windings when current is present. This also produces a more even torque (pulling and pushing by magnetic forces) for the rotor.

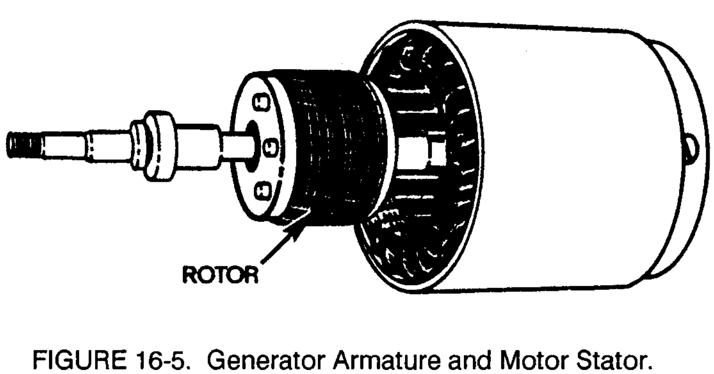

FIGURE 16-5. Generator Armature and Motor Stator.

Rotor Windings

The rotor looks like a solid cylinder supported at each end by bearings (Figure 16-6). Upon closer examination, you may see thin bars embedded in the laminated cylinder at an angle almost parallel to the rotor shaft. At each end of the cylindrical rotor core, there are shorting rings. Each end of a bar is connected to the shorting rings. These rotor windings are similar in construction to the amortisseur or damper windings found in the generator.

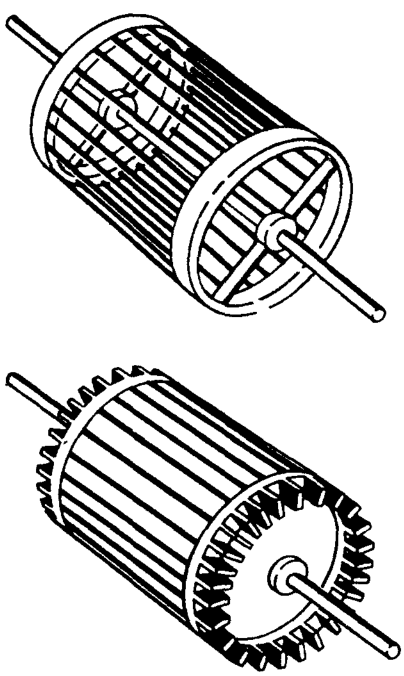

Figure 16-6. Induction Motor Rotor Windings.

Rotor Current

These short-circuited rotor bars become a transformer secondary. The magnetic field established in the stator induces an EMF in the rotor bars. The rotor bars and the shorting rings complete a circuit, and a current flow is then established in these rotor bars. Remember, whenever a current flow is established so is a magnetic field. Since this magnetic field is the property of induction and induction opposes that which creates it, the magnetic field pole in the rotor is of the opposite polarity of the stator field pole that generated it. Magnetism principles apply, and the rotor's polarity is attracted to the stator's opposite polarity. The revolving field of the stator, in effect the revolving magnetic polarity, pulls and pushes the initially established rotor field in the rotor. The pulling and pushing produces torque, and the motor rotor turns.

Short-Circuited Rotor Bars

Words often used to describe the solid bar windings found in the induction motor rotor are "short-circuited bars." A short circuit is a very low resistance situation that has very little restraint in reducing current flow. A short circuit condition can have devastating effects on the entire electrical environment. The rotor bars are designed for very low resistance to obtain certain motor operating characteristics. The rotor bars themselves are not entirely the cause for the short circuit condition. The great inrush of motor current is initiated because of the relative motion between the <u>stationary</u> rotor winding and the <u>revolving</u> stator field. This is part of the maximum current the motor will draw initially from the distribution system. Through transformer-like action, the great difference in relative motion induces a large EMF and resulting current flow in the rotor.

The inrush will be dramatically reduced as the rotor speed increases. The closer the rotor RPM is in relation to the speed of the revolving stator magnetic field, the less relative motion exists. Less relative motion means less induced EMF and a reduction in rotor and stator winding currents. Shortly after power is applied to the motor, the current is reduced to as little as 10 percent. Once the motor is operating at normal speed, the full-load current (FLC), stipulated on the data plate, is maintained (Figure 16-7). Large motors installed on Army watercraft can have an increase in current 6 to 12 times greater than the data plate FLC rating. Mechanically overloading a motor slows the rotor and increases current. It is the increase in current, no matter how little, that results in heating sufficient to destroy motors.

SLIP

If the rotor could turn at synchronous speed, then there would be no relative motion between the magnetic field of the stator and the rotor conductor bars. This would end the induction process in the rotor, and the rotor would lose its magnetic field.

This is not possible with an induction motor. If rotor speed equaled synchronous speed, the rotor would stop. However, as soon as the rotor slowed, even slightly, induced EMF and current would again flow in the rotor winding. Rotor speed would be maintained somewhere below synchronous speed. Slip is the difference between the synchronous speed and the actual speed of the rotor. Slip is more often expressed as a percentage:

$$\text{Percent slip} = \frac{(\text{synchronous speed} - \text{rotor speed}) \times 100}{\text{synchronous speed}}$$

$$\text{Percent slip} = \frac{(1{,}800 \text{ RPM} - 1{,}785 \text{ RPM}) \times 100}{1{,}800 \text{ RPM}}$$

$$\text{Percent slip} = \frac{15 \times 100}{1{,}800}$$

$$\text{Percent slip} = 0.8 \text{ percent}$$

An induction motor will always have a difference in speed between the rotor and the stator field. Without this difference, there would be no relative motion between the field and rotor and no induction or magnetic field in the rotor.

Rotor and therefore motor speed is determined by the number of poles, the frequency, and the percentage of slip.

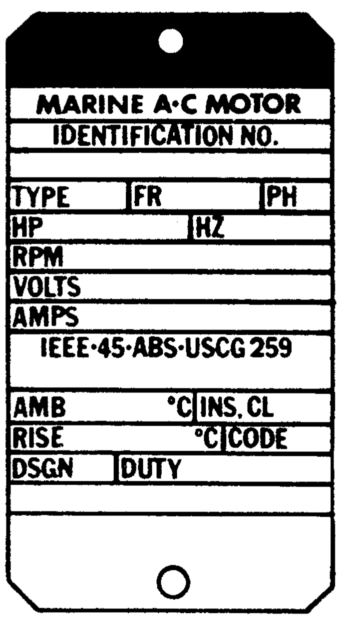

FIGURE 16-7. Typical Motor Data Plates.

ROTOR RESISTANCE

Induction motor rotors are designed to have a specific amount of resistance. The resistance in the rotor determines the comparative ease with which the magnetic field in the rotor becomes established. The motor starting current, slip, and torque are modified by the rotor resistance. By developing a motor with a high rotor resistance, a larger slip is developed because the magnetic field of the rotor cannot develop very quickly. A step-by-step sequence of events portrays the actions between the stator and rotor in a relatively high rotor resistance induction motor:

- Alternating current in the revolving stator field induces an EMF in the rotor bars.
- The high resistance in the rotor prevents the rapid building of the rotor's magnetic field.
- The inability of the rotor to rapidly build a magnetic field fails to allow the rotor to increase in speed rapidly.
- Because the rotor does not increase in speed rapidly, there is a greater relative motion between the revolving stator field and the slow-moving rotor.
- The greater relative motion, from a slow-moving rotor, increases the EMF into the rotor bars.
- The increased rotor EMF generates an increased current flow in the short-circuited rotor bars.
- The increased current increases the rotor's magnetic field.
- The increased magnetic field increases the magnetic attraction of the rotor to the stator's revolving field.
- The rotor develops a greater torque to operate heavier loads.

However, extra torque does not come without some complications. Increased torque means an increased current demand on the distribution system. There is also an increase in slip at full load. Higher resistance rotors are not acceptable for all applications. This is the reason for the many rotor designs.

The rotor resistances are identified by the National Electrical Manufacturers Association (NEMA) and designated by design.

MOTOR CHARACTERISTICS

The resistance of the stator windings is very low. The less resistance a component has, the greater the current from the generator. Motor current requirements can be, among others, attributed simply to size. The larger the stator winding diameter is, the larger the motor itself is constructed. A motor, with its low resistance stator windings, initially reacts as a short circuit. It is not until the expanding and contracting magnetic fields cut the many turns of wire adjacent to each conductor in the stator winding that the current is further reduced. This momentary inrush of current, combined with the transformer-like action, described in Short-Circuit Rotor Bars, accounts for the overall current needed for a motor.

When the vessel is initially started, a ship's electrical distribution system may have only lights in operation. There is very little current registering on the switchboard ammeters. This is because the resistance in the light bulbs is so high. The high resistance keeps current down.

As soon as a motor is connected to the line, the current draw becomes excessive. The ammeter will register more than six times the normal operating current of the motor. This is what happens: The motor's internal wiring is of negligible resistance. Since all electrical components are connected in parallel in the distribution system, the parallel circuit rules apply. Resistance in a parallel circuit is always less than the smallest resistor. (This is why the largest idle motor is of considerable concern when designing a ship's distribution system.) The motor wire resistance is now the only determining factor for the generator's current output. The current immediately supplied by the generator is called inrush current. If the rotor is mechanically prevented from moving, the current is then called locked rotor current.

Westinghouse developed a program to investigate motor circuit protection. A power source and cabling system was designed to handle LRC levels far in excess of that normally found on Army watercraft. The objectives of the test was to determine how much the fault current would exceed the normal full-load current if a rotor was mechanically prevented from rotating. Results show that lock rotor current progresses in steps. Approximately 44 cycles after the initial LRC, LRC almost doubled in value. This double LRC was maintained for an additional 42 cycles until the LRC increased again. This time the LRC was stepped up to three times initial LRC. The LRC continued to increase in steps of similar values with fewer cycles between steps. Test results hold little consolation in the knowledge that at no time did the fault current exceed 50 times the FLC. The test established that motor failures start at relatively low values (6 x FLC) and cascade quickly in mere seconds. A current draw of the observed magnitude would devastate the current-producing capacity of the generating system and effectively terminate the operation of the distribution system if not interrupted rapidly. Remember, all improperly protected circuits are tire hazards!

The induction motor poses many problems for the electrical system environment. The motor's great current draw can tax the electrical system to the extent that the generated voltage will drop. (There is internal resistance in the generator, too. The greater the current through the generator's conductors, the greater the voltage dropped in the entire electrical system, $E = IR$). When this generated voltage drops below a certain point, relays, contractors, and other electrical holding coils become de-energized, and their associated equipment stops operating.

A complete understanding of motor operating characteristics is necessary to understand the effects of the motor on the electrical system and the requirements for protecting a motor against overload conditions. The two most prominent effects from the motor are —

- Inductive reactance.
- High rotor EMF.

Inductive Reactance

The discussion on transformers explained the properties of induction on a coil of wire. Except for the minimal resistance of the wire itself, there appears to be nothing to prevent a power source from restricting the majority of its current. As it turns out, induction opposes a change in current. A back voltage or counter EMF (CEMF) is developed and pushes back on the power supply. In the DC system, the CEMF restricts current flow. In AC, the CEMF impedes current flow change. The AC system with its various amplitudes and current directions creates a generator out of any inductor. This shuttle power is inductor-generated and must be overcome by the generator. When the inductive reactance (shuttle power), the motor's load, and assorted losses are overcome, the generator supplies only enough additional current to keep the motor rotor turning. The only problem exists with the inductive reactance. This generated CEMF and its resulting current are there to be overcome. Inductive reactance, therefore, is not consumed.

Whenever inductance is involved in the electrical system, a lagging power factor results. The power factor is extremely poor when the motor is first started. The lower the power factor, the greater the increase in current needed to operate the motor. A power factor of .5 can be expected when a motor is first started. At the motor's rated speed, a power factor of .8 is normal. Unity or 1.0 is the best use of power. Not only does the generator have to supply current for overcoming the wire resistance, but it must overcome the inductive reactance from the motor itself.

Never select a motor that is overrated for its application. Contrary to popular belief, when a motor is not operated at its rated capacity, the electrical system efficiency is decreased. The power factor is decreased, goes further away from unity, and more power is required to operate the motor than would have normally been required for a motor operating at the designated rated capacity.

Never operate a motor above its rated capacity. It will not operate long. Motors and generators can easily operate at many times their normal current ratings for a short period of time. Even so, excess heat is generated. If this heat is not permitted to dissipate rapidly, insulation damage will result.

High Rotor EMF

Inductive reactance is always an important consideration when choosing motors for the electrical system. But the induction motor has another characteristic that influences the electrical environment even more. This is called the rotor EMF.

The motor acts much like a transformer. The stator winding becomes the primary winding, and the rotor becomes the secondary winding. If the secondary winding of a transformer becomes shorted out, the primary winding effectively becomes the generating source. The primary winding, an extension of the generator, provides as much current as possible according to the Maximum Power Transfer Theorem.

At the instant when the rotor has not yet begun to move and current is applied to the stator, there is a maximum slip. There is maximum relative motion between the stator and the rotor and a maximum induced voltage into the low-resistance rotor bars. These rotor bars act like a short circuit drawing very large currents from the source because there is negligible resistance to restrict the current flow.

The stator windings have extremely large currents because of the large induced rotor EMF. Both the rotor and the stator develop maximum magnetic fields from maximum current flows.

The rotor's magnetic field, from induction, is of the opposite polarity of the stator's magnetic field. The rotor starts to move. As the rotor speed increases, the relative motion between the two windings decreases. The decreasing relative motion decreases the EMF and the resulting current flow in the rotor bars. The power source demand decreases as does the current flow to the stator.

This phenomenon is readily observable by using an induction ammeter and an AC motor. Simply place the jaws of the ammeter around one insulated conduct or (not all). Start the motor and observe the meter readings. The current will start very high and then taper off quite rapidly as the motor increases in speed.

Load Changes

Counter electromotive force developed in the stator windings could restrict current flow to moderation, except for the overwhelming EMF induced in the rotor. Many other factors affect the operation of the motor, such as impedance, changes in torque, and the angle in degrees separating the stator and rotor magnetic fields. Table 16-2 is a simple reference to the factors affecting a motor and the electrical environment under three motor operations.

Table 16-2. Factors Affecting the Motor.

	STARTING UP	OPERATING SPEED	UNDER LOAD
Motor RPM	0	highest	dropping
CEMF	0	highest	dropping
Power factor	lowest	highest	droppong
Rotor EMF	highest	lowest	increasing
Current I	highest	lowest	increasing
Torque	highest	lowest	increasing

The following is a brief outline on the motor-operating characteristics under several conditions:

- When the motor is operating at no-load conditions, the rotor speed gets very close to synchronous speed. Very little EMF is induced in the rotor bars, just enough to overcome mechanical losses. Current draw is low.
- As the motor becomes increasingly more loaded, the slip increases, and relative motion increases. Induced rotor EMF increases and with it a resulting increase in current flow in both the rotor and stator windings. The increased magnetic fields increase torque and the ability of the motor to return to its proper speed. Current automatically increases as the rotor slows down.
- During an overload condition, the rotor is slowed excessively. The EMF induced in the rotor and its subsequent current flow in both the rotor and stator can burn up the insulation windings and destroy the motor. Current becomes destructive.

MOTOR PROTECTION

Motor requirements for current vary widely with the load. In addition, the current actually exceeds the normal operating range when the motor is first started. How then can the motor be protected against the excessive currents outside the normal parameters of operation and still be protected from small prolonged current increases?

Fuse Protection

Fuses have several disadvantages in protecting the motor. If a fuse is used to protect the motor for its full-load current rating, then the fuse would open during the initial inrush of current. A fuse designed to pass inrush current would not protect the motor against currents less than the inrush but greater than the normal full-load current. For every IC rise over normal ambient temperature ratings for insulation, it has been estimated that the life expectancy of a motor can be reduced almost a year. Current generates heat in a motor. Heat destroys the motor insulation.

Time-delay fuses have been used for motor protection in the past. However, another problem develops when using three fuses for the protection of the three-phase motor. Should only one of the three fuses open when the motor was operating, the motor would not stop immediately. It would continue to operate. The operation of three-phase motors on only two lines constitutes a single-phase condition. The three-phase motor cannot operate single phasing for long without internal damage. This would not become apparent until enough damage was incurred that the motor would be irreparable. The fuse was not the answer for protecting three-phase motors.

Magnetic Motor Starters

The magnetic motor starter is a magnetic contactor with an overload protection device (Figure 16-8). Unlike the fuse, the magnetic motor starter does not have to be replaced. It can be reset repeatedly.

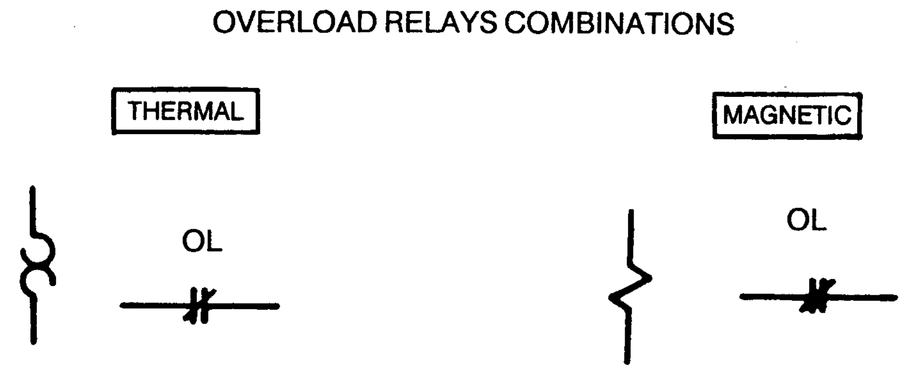

FIGURE 16-8. Thermal and Magnetic Motor Protection Symbols.

The Motor Circuits

Larger current-demanding motors use two circuits for operation. One circuit is the three-phase power circuit supplied from the distribution power panel. The other electrical circuit is the control circuit.

Figure 16-9 shows the magnetic motor starter and the power circuit from the distribution power panel. The heavy, dark lines provide the three-phase, high current-carrying power to the motor.

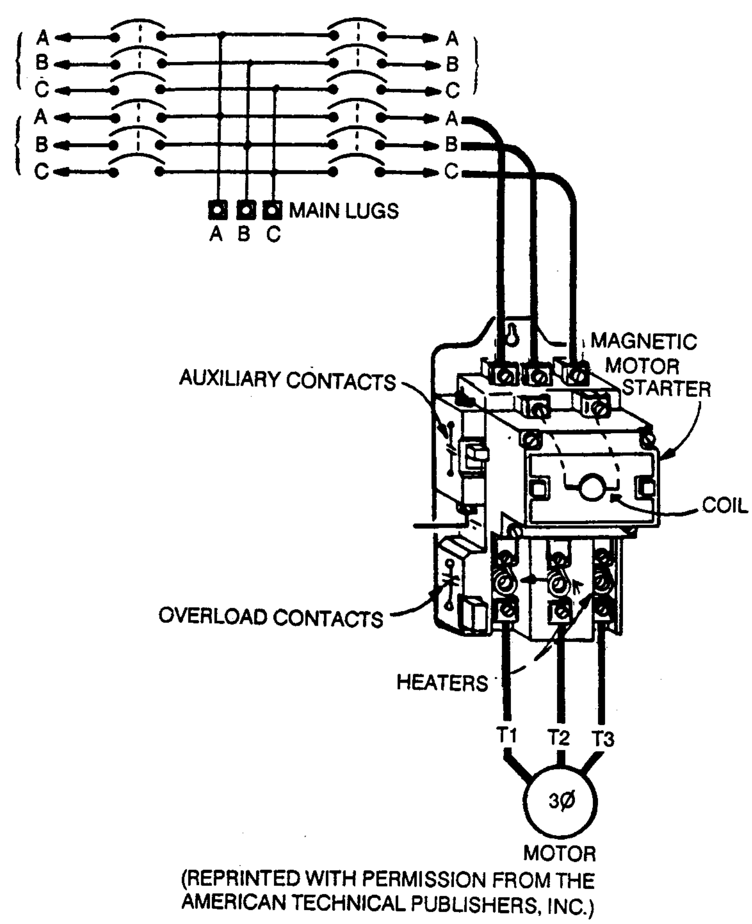

FIGURE 16-9. Magnetic Motor Starter Power Source.

Inside the magnetic motor starter, directly under the coil, are three large main contact sets. These contacts are in series with the power panel A, B, and C phase terminals and the Tl, T2, and T3 motor terminals. As long as these contacts are closed, current from the power distribution panel can operate the motor. This is one circuit.

The other circuit controls the three large contact sets explained above. The coil in Figure 16-9 actually moves the contacts. Figure 16-10 shows the control circuit that the coil is actually in. M represents the coil in Figure 16-9.

The M coil is supplied single-phase power from the magnetic motor starters A and B phase terminals (also known as L1 and L2 terminals). Figure 16-10 shows two M coils: one in its true physical position in the magnetic motor starter and the other in the line diagram to explain its function electrically. There is actually only one M coil. The same applies to the NC overload contacts.

When the START button is pressed, a complete circuit from A phase through the M coil, through the NC overload contacts, to the B phase is completed in the control circuit. The M coil energizes and moves a bar, known as an armature, that is in physical contact with the three large power contacts in the motor's three-phase power circuit. Figure 16-11 illustrates this action.

The main power circuit contacts for the motor are held open by spring tension (Figure 16-11 view A). When the coil becomes energized, the magnetic attraction between the armature and the magnet overcomes spring tension, and the main contacts for the motor close (Figure 16-11 view B). The motor now operates.

When the current to the motor is too great, the overload heaters get hot. The heaters are in series with the motor terminals and the main contacts for the motor. The heaters directly control what happens to the NC overload contacts in the control

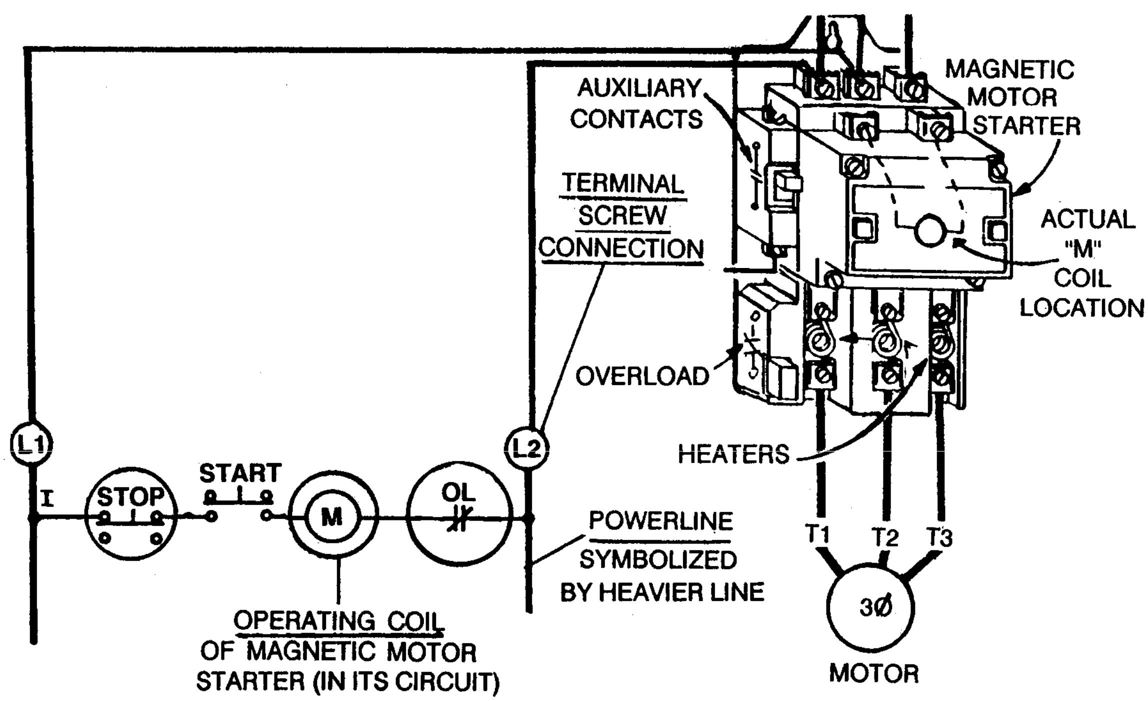

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FIGURE 16-10. The Control Circuit.

circuit. When the heaters get hot enough, the overload contacts open, and the M coil de-energizes. The loss of the magnetic field allows spring pressure to open the three main contacts in series with the motor, and the motor stops operating. By de-energizing the one coil (M), all three sets of main contacts open. Detrimental single phasing is avoided.

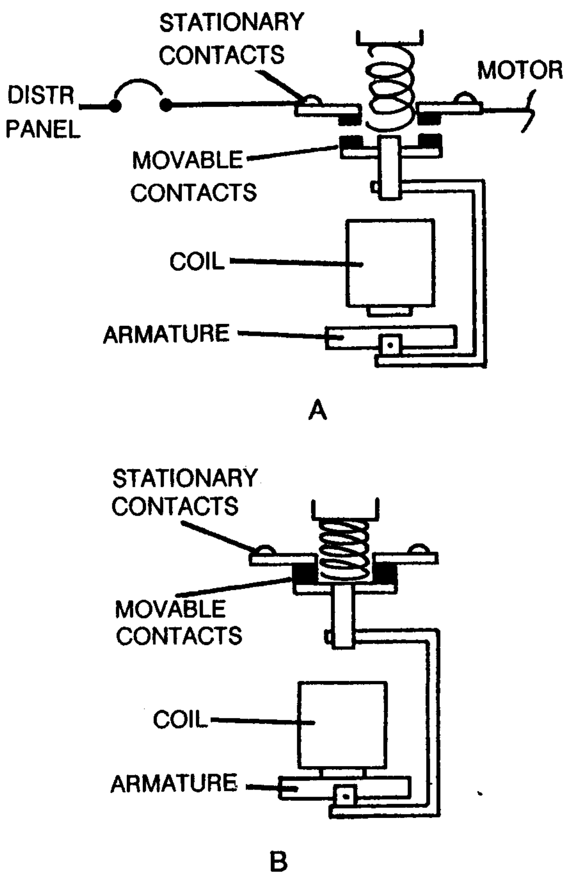

FIGURE 16-11. Coil and Main Contact Action.

A minor disadvantage of the thermal overload device is its need to cool off before being reset. Figure 16-12 shows a magnetic motor starter and the overload heater and NC overload contact section separately.

Thermal Heater and NC Overload Operation

The common thermal overload uses heater coils in the main power line in series with the main contractors and the motor stator windings. The current going to the motor must go through the overload heaters first. These heater coils surround a eutectic alloy solder pot (Figure 16-13). Eutectic meansit has a very low melting point. Characteristically, a eutectic solder goes from solid to liquid and back again without developing a mushy condition.

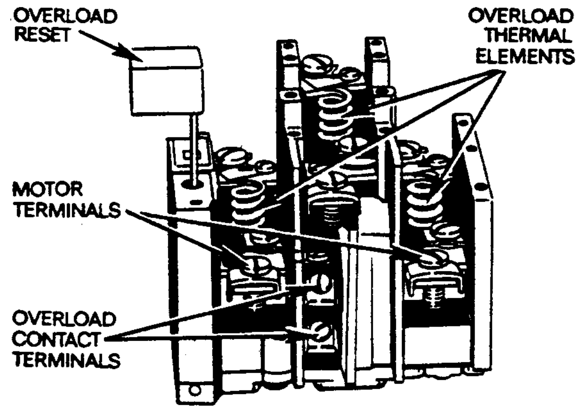

FIGURE 16-12. Magnetic Motor Starter With Thermal Protection.

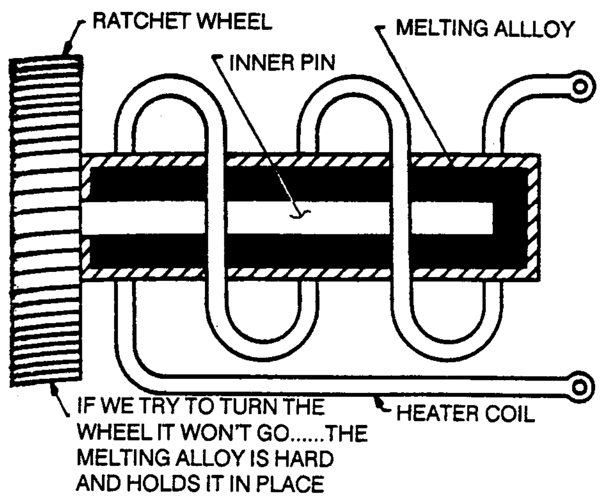

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FIGURE 16-13. Heater and Eutectic Alloy.

The solidified solder holds a ratchet wheel and pin assembly firmly in place (Figure 16-14). The ratchet wheel is under tension and holds a set of contacts closed. These contacts have the ability to interrupt the magnetic coil circuit that opens and closes the main contacts. When the magnetic coil is de-energized, the main contacts open. The main contacts no longer supply power to the motor, and the motor stops (Figure 16-15).

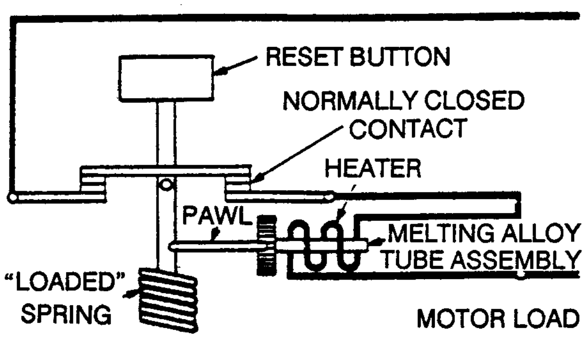

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FIGURE 16-14. Ratchet Wheel Heater Assembly.

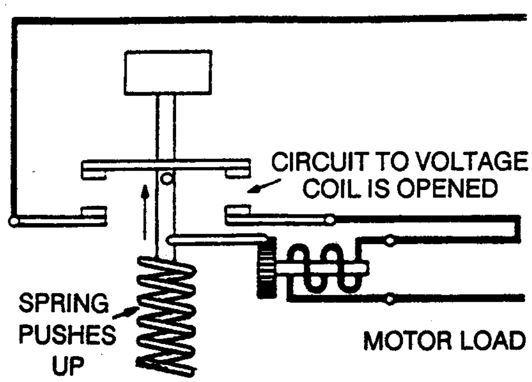

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FIGURE 16-15. Coil Control Circuit Opened.

The thermal overloads effectively monitor motor current by developing a comparative heat in the heater coils. The more current that flows though the heaters, the faster the heaters become hot. When the motor is first started, the heat from the momentary high inrush current is dissipated rapidly by the heater coils. The operation of the motor is not interrupted. If, however, the high current should last but another moment longer, the contacts would open, and the motor would stop. If a small overcurrent condition exists, the heaters will still get hot enough to melt the eutectic alloy, but it will take longer. Once enough heat is generated in the heaters and the eutectic alloy melts, the ratchet wheel and pin assembly move under spring pressure. As a result, the contacts in the control circuit of the magnetic motor starter open. This de-energizes the coil in the magnetic motor starter and opens the main contacts, disconnecting the motor from the line. Notice in Figure 16-16 that the overload contacts are not in the motor power supply line. They are in the control circuit that operates the main contactors. The main contractors and the overload heaters are in the motor's main three-phase supply line.

The protection afforded by the overload device is determined by the heater coil selection. By using different heater coils, a variety of overcurrent protection can be selected. This must be based on the full-load current rating of the motor. The temperature surrounding the motor and the magnetic motor starter must also be considered. Heat and current have the same destructive nature toward electrical equipment. Electrical components in engine compartments are exposed to greater heat than those in the ward room. Likewise, the controller, which houses the magnetic motor starter, must be in the same area as the motor it protects. Only in this manner will the heater be affected by the same ambient temperature as the motor windings.

Proper motor protection is required in the motor control centers in the engine room. The MCC is air conditioned, and the motors in the engine compartment are not. If adequate motor protection selection is not provided, additional investigation is necessary.

Every motor starter manufacturer has specific overload guidelines supplied with the equipment. Magnetic motor starters are provided with heater selection charts because magnetic motor starters do not come with overload heaters. Each heater must be identified for the specific motor application, full-load current, and ambient temperatures. The manufacturer guides are self-explanatory. Additional information is available in the Code of Federal Regulations, Title 46, Subpart 111.70, and the National Electrical Code (NEC), Article 430.

A less common protective device is the magnetic overload relay (Figure 16-17). This device uses a current coil that creates a magnetic field in proportion to the current carried in it. Once the magnetic field is strong enough, the contacts are opened, and the circuit is de-energized. The main benefit to this type of overload device is its ability to be reset immediately.

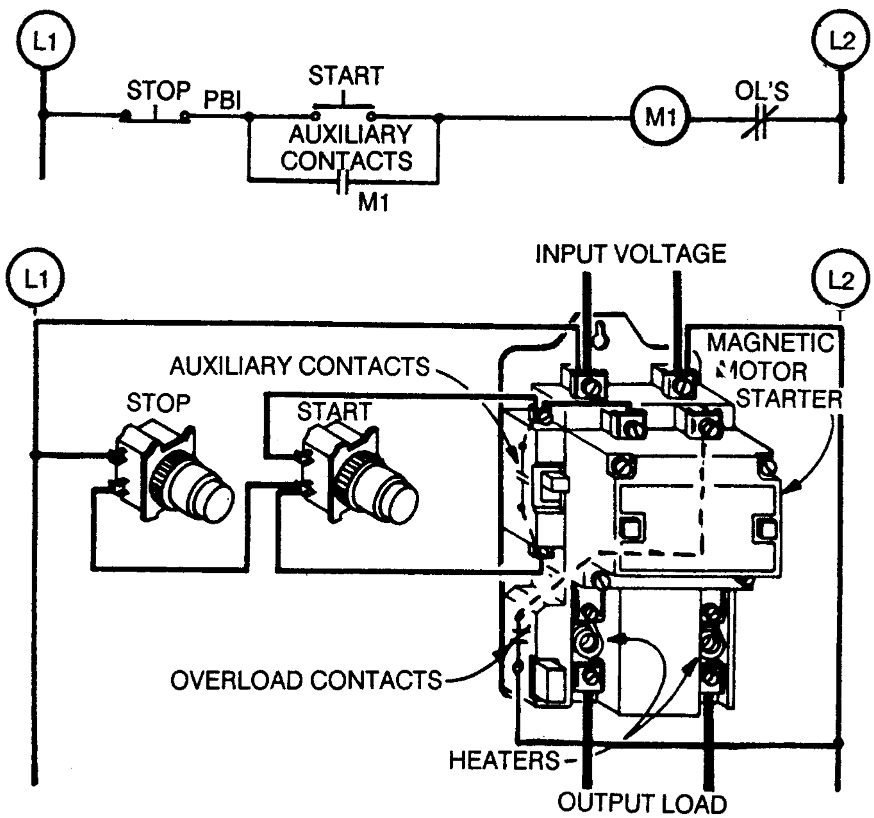

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FIGURE 16-16. Two Magnetic Motor Starter Control Circuits.

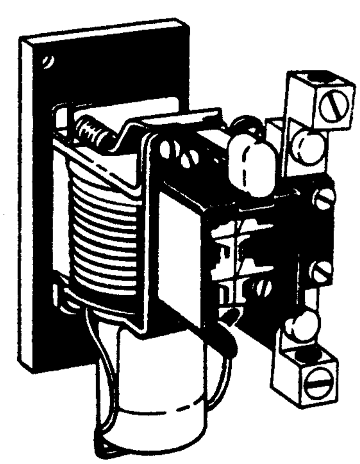


FIGURE 16-17. Magnetic Overload Relay.

MOTOR NAMEPLATE DATA

Motors are designed and developed for specific applications. Identifying their proper usage may be difficult. To ensure the correct component for the correct application, all government regulatory societies require a minimum of specific information to be printed on the motor's nameplate. Additional information may be obtained in IEEE Standard 45, Section 24, and NEC Article 430. This data includes–

- Manufacturer's name.
- Motor frequency. This may be represented as Hz for hertz or as CPS for cycles per second. This is always an indication of AC application.
- Phases (either three phase or single phase). This is also an indication of AC application.
- Voltage. The motor is designed to operate at this voltage or within a specified voltage

range. Two voltages separated by a slash, such as 450/225, indicate a two-voltage system. Either voltage may be used by connecting the electrical stator leads as directed in the manufacturer's manual or on the data plate.

- Full-load current (FLC). This is the current required to operate the motor at its rated load and speed. This is not the current draw when the motor is started. If two current values are given, this indicates the current when supplied with one of the two possible voltage connections. When the higher voltage is used, less current is necessary to operate the motor.

- Full-load speed. This is the speed in revolutions per minute the rotor will turn under full load.

- C rise. This Celsius value plus the motor's rated ambient temperature add together to determine the maximum temperature range the motor can obtain under full-rated load (40C equals 104F).

- Time rating. This is the time the motor can operate continuously without stopping. Usually 5, 15, 30, or 60 minutes or continuous ratings are specified.

- Rated horsepower.

- Code letter. This indicates the highest current the motor will draw when the rotor is physically prevented from moving initially. The current is rated in kVA per horsepower. This is a measurement of locked rotor amperage. Table 16-3 lists code letters from the National Electrical Code.

- Design. This provides starting kVA, running kVA, and running KW characteristics. This is a product of the internal resistance of the rotor. Generally, designs B, C, and D are used:

  - Design A is of limited usage. This motor has extremely high starting kVA, as much as 50 percent higher than the B, C, or D design motors.

  - Design B is a standard rotor design. This type of rotor has a low internal resistance. It has normal starting torque, low starting current, and low slip at full load.

  - Design C has a higher internal rotor resistance. This improves the rotor power factor at the start, providing more starting torque. Fully loaded, the extra resistance creates a greater slip.

  - Design D has more resistance. The starting torque is maximum.

  - Serial number. The serial number or identification number is extremely useful when dealing with the manufacturer. The serial number and appropriate information is maintained on file with the company.

  - Type. This is the manufacturer's specific application information. This will also identify the housing characteristics (waterproof, drip-proof, and so forth).

  - Service factor. This is an allowable overload above the full-load current. It is expressed as a decimal. Multiplying the full-load current by the service factor establishes the maximum allowable current acceptable above full-load current for a short period of time.

  - Frame. Many of the dimensions found on a blueprint are incorporated in the frame identification. Some of these specifications may include the rotor shaft length, diameter, and machining the motor housing and bolting placements; and so forth.

When a motor is ordered, all the data plate information must accompany the supply document. There is no substitute for the correct electrical component. Universal equipment does not exist in a marine distribution system unless the specifications can be matched exactly.

TABLE 16-3. Starting Kilovolt-Amps per Horsepower.

CODE LETTERS	STARTING kVA/HP	COMMONLY USED ON:
A	0 - 3.14	
B	3.15 - 3.54	
C	3.55 - 3.99	
D	4.0 - 4.49	
E	4.5 - 4.99	
F	5.0 - 5.59	15 HP and up
G	5.6 - 6.29	10 HP
H	6.3 - 7.09	7.5 and 5.0 HP
J	7.1 - 7.99	3 HP
K	8.0 - 8.99	2.0 and 1.5 HP
L	9.0 - 9.99	1 HP
M	10.0 - 11.19	Less than 1 HP
N	11.2 - 12.49	
P	12.5 - 13.99	
R	14.0 - 15.99	
S	16.0 - 17.99	
T	18.0 - 19.99	
U	20.0 - 22.39	
V	22.4 and up	

Table 16-4 provides a sample of some three-phase mot or starting characteristics for design B, C, or D. Design A motors may have starting kVA values that are as much as 50 percent higher. Many 3,600 RPM motors are design A.

TABLE 16-4. Motor Starting Characteristics.

HP	RPM	Running KW	Running kVA	Starting kVA
1	3,600	1.05	1.3	13
	1,800	1.06	1.4	12
	1,200	1.02	1.5	12
2	3,600	1.9	2.2	19
	1,800	1.9	2.3	13
	1,200	2.0	2.7	18
3	3,600	2.9	3.2	25
	1,800	2.8	3.4	24
	1,200	2.8	3.7	24
7.5	3,600	6.7	7.5	48
	1,800	6.9	7.9	46
10	3,600	8.8	9.8	62
	1,800	8.8	10.1	60
15	1,800	13.0	14.7	84
	1,200	12.9	15.2	82
20	1,800	17.2	19.4	112
	900	17.4	21.6	110

MOTOR EFFICIENCY

Efficiency is the ratio of output to input. Only part of the power going into a motor is actually delivered to the load in the form of mechanical power. Some power is lost in the resistance in the stator windings and in the stator core. Other losses are transmitted across the air gap to the rotor. Resistance in the rotor uses up power. Finally, the power needed to overcome windage and friction losses reduces the mechanical output even further.

The copper losses are proportional to the current squared ($P = I^2R$). This is the only variable loss. Rotational and core losses do not change as the motor becomes loaded.

CHAPTER 17

SINGLE-PHASE MOTORS

INTRODUCTION

Single-phase AC motors are the most common motors built. Every home, workshop, and vessel has them. Since there is such a wide variety of these motors, it is impossible to describe all of them. This chapter will describe the most common types found on Army watercraft. Figure 17-1 shows the basic schematic diagrams for the single-phase motors.

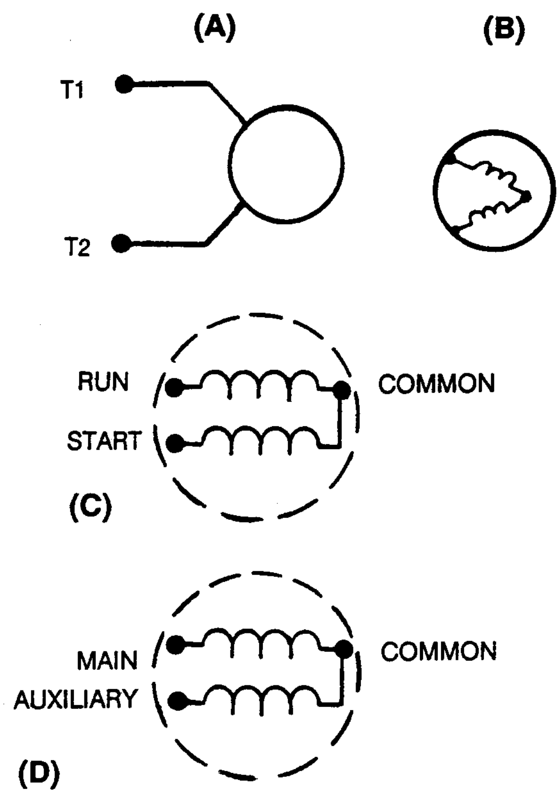


FIGURE 17-1. Single-Phase Motor Symbols.

The basic diagram (view A) shows a circle with two leads labeled T1 and T2. Just as in the three-phase motor diagram, the motor shows the power supply lines as being identified with the T. For most shore facility applications, this is the case. In many cases, the single-phase motors on board a ship will be wired into the lighting distribution panels. The lighting distribution panels are the source for single-phase power supply. The power distribution panels are the source of the three-phase power supply. For this reason, the single-phase motors are commonly connected to L1 and L2, as shown in Figure 17-2.

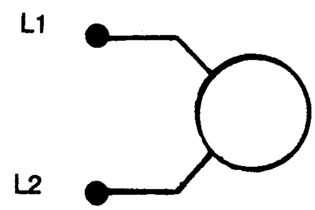


FIGURE 17-2. Single-Phase Motor Labeled L1 and L2.

Figure 17-1 shows four single-phase motor diagrams. Diagram A shows the motor as it will be seen on blueprints and general layouts. It is concerned only with the overall operation of the electrical distribution system. Diagrams B and C show a more involved internal wiring system indicating two inductors and three terminals. These diagrams are necessary to understand the exact nature and function of the single-phase motor. Refrigeration and manufacturer's wiring schematics also use diagrams B and C to ensure a positive troubleshooting application.

Figure 17-3 shows a very basic one-line diagram of the single-phase motor. Refer back to this diagram as the operational requirements of the single-phase motor are discussed.

The single-phase induction motor is much the same in construction as the three-phase motor. Some single-phase induction motors are also called squirrel cage motors because of the rotor's similarity to a circular animal exercise wheel. As discussed in Chapter 16, the squirrel cage comprises the bars and shorting-rings that make up the rotor windings. The squirrel cage is also considered the secondary windings of the motor (Figure 17-4).

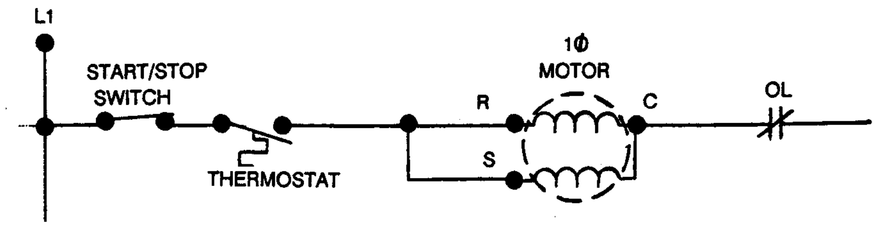


Figure 17-3. Line Diagram of the Single-Phase Motor.

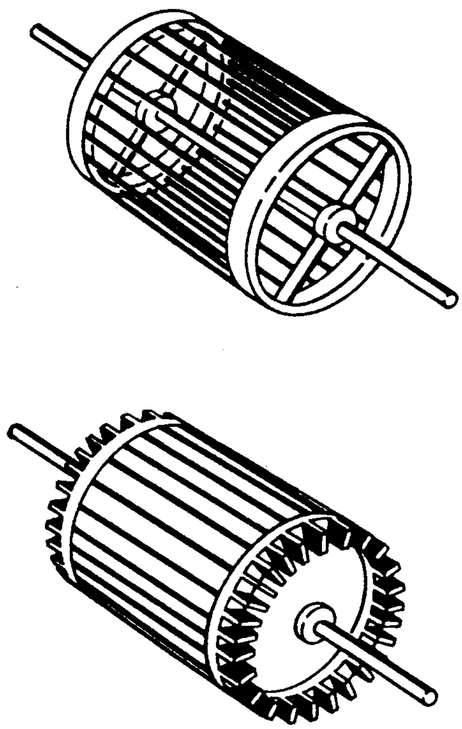


FIGURE 17-4. Squirrel Cage Induction Motor Rotor.

INDUCTION MOTORS

Despite the fact that the three-phase motor has more phases than the single-phase motor, the single-phase motor is a much more complex machine. Several additional components are necessary to operate the single-phase motor.

Single-phase motors have only two power source supply lines connected. The single-phase motor can operate off either the A-B, B-C, C-A, A-N, B-N, or C-N power source phases. The two-wire power supply can provide only a single-phase alternating source (Figure 17-5). The individual single-phase current arriving in the stator winding of the single-phase motor does not have the same "revolving" effect that the three individual phases of the three-phase power supply provides. The magnetic field developed by the single-phase current is created in the stator windings and then is gone. An entire cycle must be completed before current is again available at the single-phase motor stat or. This prevents the development of the revolving field so easily obtained with the three-phase power supply. The problem with the single-phase motor is its inability to develop a revolving field of its own accord. Without a revolving field, torque cannot be developed, and the rotor will never turn. With only one stator winding, the single-phase motor can only produce an oscillating magnetic field.

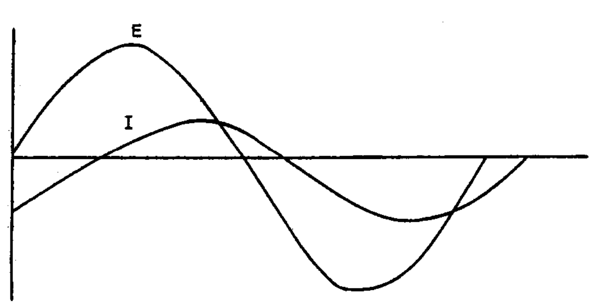


FIGURE 17-5. Single-Phase Voltage and Current Sine Waves.

Figure 17-6 shows a main winding separated into two coils. Each winding is wound in a different direction. The importance of the two different coil winding directions is to emphasize the application of the left-hand rule for coils as expressed in previous chapters. By winding the wire in a different direction, the polarity of the coil face closest to the rotor can be changed. By using one wire wrapped in two different directions, the polarity of every other coil can be changed.

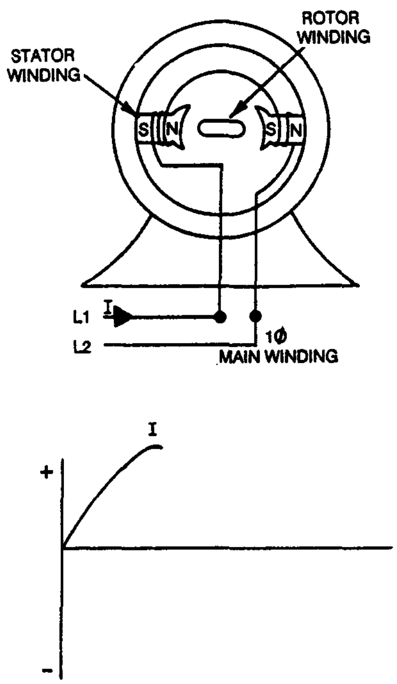


FIGURE 17-6. Current Flow Through Four Main Windings.

When current flows in the main winding, the magnetic field is established throughout the windings (Figure 17-6). Soon the current flow stops and changes direction (Figure 17-7). With this change in current direction comes a change in all the coil polarities.

The magnetic field of the rotor is developed through induction in the same manner as described for the three-phase induction motor rotor. The rotor bars and the shorting rings have an induced EMF created in them, and a current flow develops. This current flow establishes a magnetic field of an opposite polarity of the stator coil directly across from it. Unfortunately, there are no overlapping 120-degree individual stator windings in this single-phase motor.

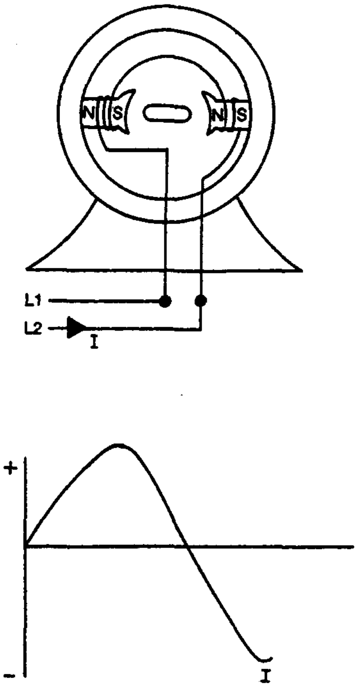


FIGURE 17-7. Current Flow Changes Direction and so Does the Coil Polarity.

Whenever current changes direction and a new magnetic field is established in the stator, the induced rotor magnetic field changes to the opposite polarity of the stator coil directly across from it. All the rotor can do is oscillate. Without some force to twist or turn the rotor, no torque can be developed.

A person examining this motor will hear a distinct hum. This is called an AC hum. It is often heard coming from transformers or single-phase motors that are not turning. If the soldier physically turned the rotor shaft (not recommended) in either direction, the rotor would start to move. The speed would continue to increase until it reached its normal operating speed.

> **NOTE:** Although certain motors, such as fans, can be found to be started physically by turning the rotor shaft, this action is not recommended. Whenever a motor does not start of its own accord, it is because something is wrong. If the motor has an electrical malfunction, it is not wise to touch the electrical components when current is applied.

As long as the rotor's magnetic field is slightly displaced from the magnetic field in the stator, a torque can be developed. Slip will keep the rotor's field slightly behind the stator's field. The difference in speed (relative motion) is necessary to maintain the torque. Relative motion is necessary to induce the EMF into the rotor to maintain the rotor's magnetic field. If the soldier disconnects power and allows the rotor to stop, he again must provide the initial movement to start the rotor. This is not an acceptable condition for a motor.

Without the use of a three-phase alternating current, an artificial phase displacement must be established. If the stator could only develop another current, slightly out of phase from the original current, a revolving field could be assimilated. This is the problem encountered by single-phase induction motors. It is also the area of greatest component failure and maintenance requirements, In fact, the specific names for induction motors represent the means in which the revolving field is developed from a single-phase power source.

There are a multitude of single-phase motor combinations. This text will discuss only five basic designs:

- Split-phase (resistance-start).
- Capacitor-start.
- Permanent-capacitor.
- Two-capacitor.
- Shaded-pole.

Single-Phase Motor Starting

In addition to the run or main winding, all induction single-phase motors are equipped with an auxiliary or start winding in the stator. The auxiliary or start winding overlaps the main or run winding. This provides the revolving field necessary to turn the rotor. The terms are used in sets. The frost group is the run and start set. The second group is the main and auxiliary winding set. Each group has a common terminal connection.

Run and Start Winding Set. The term "run winding" is used to designate a winding that receives current all the time the motor is in operation. It is the outermost winding, located next to the motor housing. The term "run" is used only when the other winding is a start winding.

A start winding is in parallel with the run winding. The start winding receives current only during the initial starting period. Then it becomes disconnected from the power source. The start winding is the set of coils located nearest to the rotor (Figure 17-8).

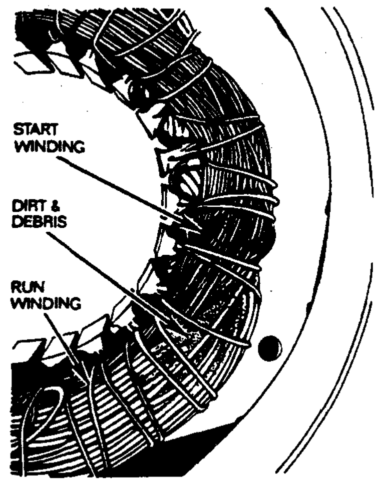


FIGURE 17-8. Two Overlapping Stator Windings in the Single-Phase Motor.

Main and Auxiliary Winding Set. The term "main winding" is used to designate a winding that receives current all the time the motor is operating. The main winding is located next to the motor housing. The term "main" is used only when the other winding is an auxiliary winding.

An auxiliary winding receives current all the time the motor is operating. It is always in parallel with the main winding. The auxiliary coils are located closest to the rotor. By creating a winding with better insulating properties and a motor housing with better heat dissipation qualities, the auxiliary winding can remain in the circuit as long as the main winding. This then increases the motor's running load capabilities.

Common Connection. The auxiliary or start winding is connected to the main or run winding through a connection called the common. The auxiliary or start winding is in parallel with the main or run winding (Figure 17-9). Both the windings in the motor use the same single-phase power source. The common connection between the set of windings is necessary to complete the parallel circuit.

SPLIT-PHASE (RESISTANCE-START) MOTORS

Figure 17-10 is a basic one-line diagram of the split-phase motor. It shows the run and start winding of the stator as well as the centrifugal switch (CS).

The run and start stator windings are connected in parallel. If you apply current to both windings and establish a magnetic field simultaneously, the rotor could do nothing more than oscillate. Unless two or more slightly out of phase currents arrive in different windings, torque cannot be achieved. Every time current changed directions, the magnetic polarities of the stator coils would switch as well. The induced rotor EMF and its resulting magnetic field would also switch. No torque can be produced. Something must be done so that a given magnetic field in one winding can happen at a slightly different time than in the other winding, thus producing a pulling or pushing effect on the established magnetic polarity in the rotor. The would create motion.

Figure 17-11 illustrates the run winding (view A) and the start winding (view B) as separate coils of wire. In view C, the two coils are connected at a common terminal. This is how the two windings are placed in the circuit in parallel.

Figure 17-12 shows how the start and run windings are in parallel with the same voltage source available to each.

Current entering a node must divide between the two windings (Figure 17-13). Magnetism is a property of current. Forcing current to arrive at one winding before it arrives at the other winding would create the phase difference necessary to create a torque.

The split-phase motor takes advantage of an increased resistance in the start winding. This is done by merely making the start winding wire a smaller diameter. Contrary to popular beliefs, the higher resistance in the start winding lets the current develop a magnetic field in the start winding before the run winding.

More current goes into the run winding because there is less resistance in the wire. The greater current in the run winding generates a greater CEMF than can be developed in the start winding. This forces the run current to lag voltage by about 50 degrees.

The smaller current entering the start winding generates less CEMF. Power supply EMF quickly overcomes the start winding CEMF. Start winding current lags voltage by about 20 degrees. This puts the magnetic field in the start winding ahead of the run winding by about 30 degrees (Figure 17-14).

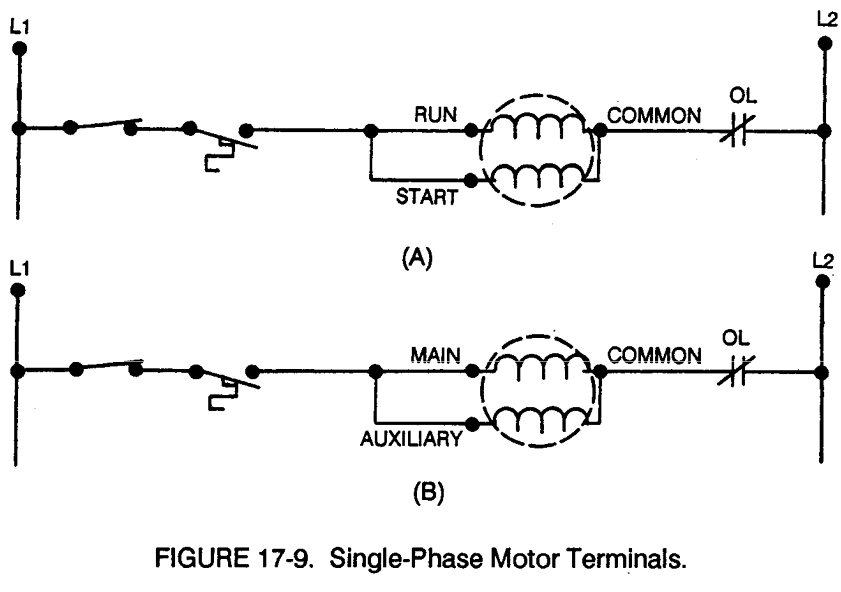


FIGURE 17-9. Single-Phase Motor Terminals.

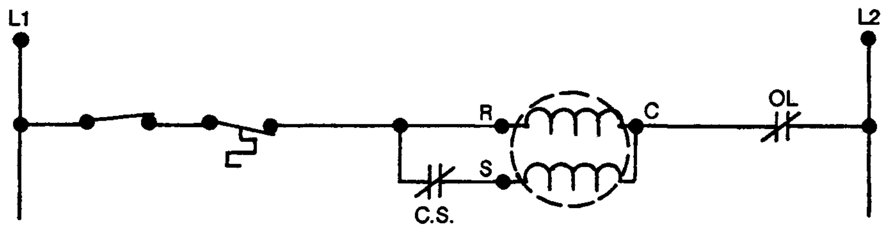


FIGURE 17-10. Simple Line Diagram Of the Single-Phase Motor.

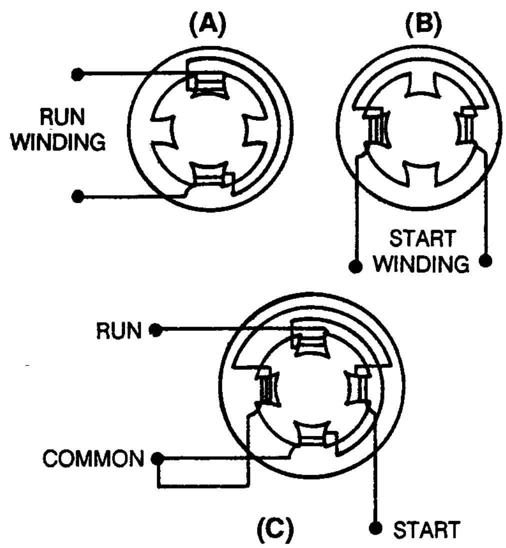


FIGURE 17-11. Run and Start Windings.

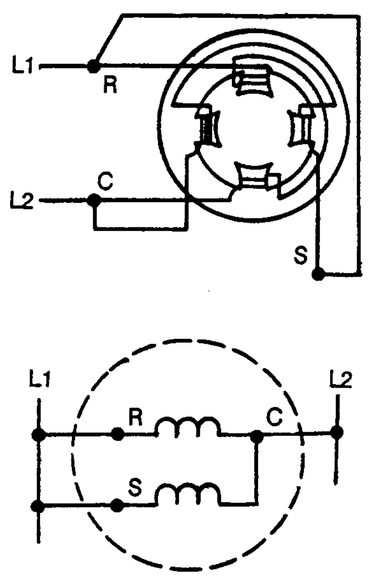


FIGURE 17-12. Run and Start Windings Joined at the Common Terminal.

In Figure 17-15, the start winding current precedes the current arriving in the run winding. The magnetic field develops in the start winding first. A moment later, the start winding current starts to diminish, and its magnetic field decreases. As this happens, the current and the magnetic field in the run winding is increasing.

The induced rotor EMF, resulting current flow, and magnetic polarity remain the same. The magnetic polarities of the rotor winding were first developed under the start winding. Now the increasing magnetic pull of the run winding, which is displaced physically, attracts the rotor. This is the phase displacement necessary for torque. The direction of rotation will always be from the start winding to the adjacent run winding of the same polarity.

At about 75 percent of the rotor rated speed, the centrifugal switch disconnects the start winding from the power supply. Once motion is established, the motor will continue to run efficiently on the run winding alone (Figure 17-16).

Centrifugal Switch

Many single-phase motors are not designed to operate continuously on both windings. At about 75 percent of the rated rotor speed, the centrifugal switch opens its contacts. It only takes a few moments for the motor to obtain this speed. An audible click can be heard when the centrifugal switch opens or closes.

The centrifugal switch operates on the same principle as the diesel governor flyballs. Weights attached to the outside periphery of the switch rotate with the rotor shaft (Figures 17-17 and 17-18). As the rotor shaft speed increases, centrifugal force moves the weights outward. This action physically opens a set of contacts in series with the start winding.

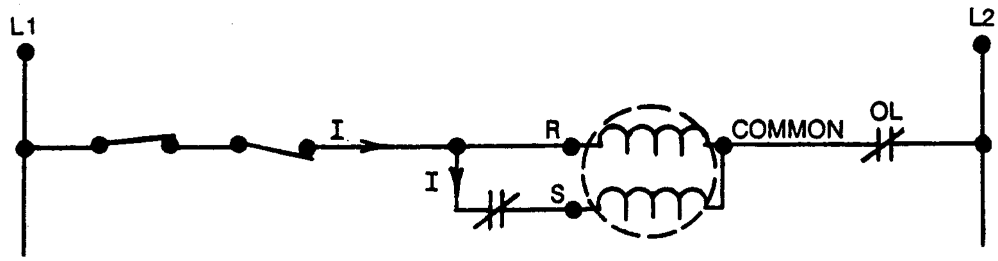


FIGURE 17-13. Current Divides According to Resistance.

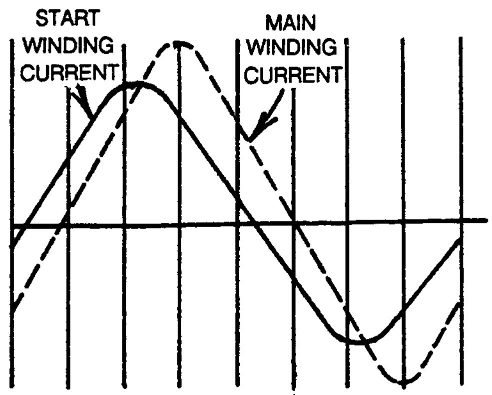


FIGURE 17-14. Start Winding Current Leads Run Winding Current.

Once the start winding is disconnected from the circuit, the momentum of the rotor and the oscillating stator field will continue rotor rotation. If, however, the motor is again stopped, the start winding is reconnected through the normally closed and spring-loaded centrifugal switch. The motor can only develop starting torque with both start and run windings in the circuit.

Reversal of Direction of Rotation

The rotor will always turn from the start winding to the adjacent run winding of the same polarity. Therefore, the relationship between the start and run windings must be changed. To change the relationship and the direction of rotation, the polarity of only

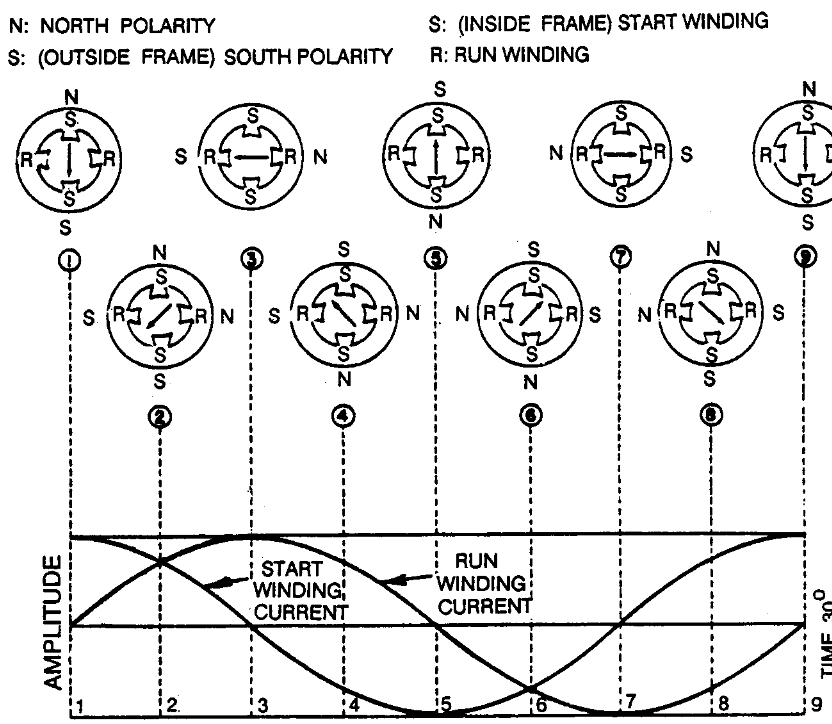


FIGURE 17-15. Start and Run Winding Magnetic Field.

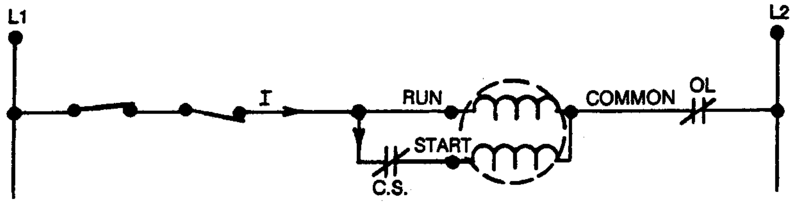


FIGURE 17-16. Centrifugal Switch Opens.

one of the fields must be reversed. In this manner, only one field polarity will change, and the rotor will still move toward the run winding of the same polarity as the start winding. The current entering the run winding or the current entering the start winding must be reversed, but not both. Figure 17-19 shows a schematic of the reversal of the start winding.

If the main power supply lines, L1 and L2, are switched, then the polarity of all the windings will be reversed. This, however, will not change the direction of rotation because the polarity of both the start winding and the run winding reverses. The relationship between the start winding and the run winding has not changed. The rotor will still turn in the direction from the start winding to the run winding of the same polarity (Figure 17-20).

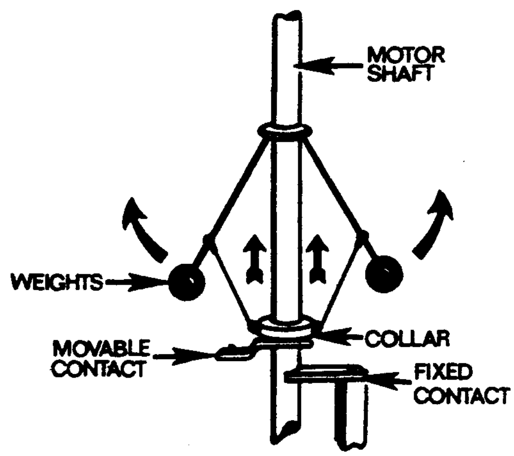


FIGURE 17-17. Centrifugal Switch Operation.

Split-Phase Motor Applications

Split-phase motors are generally limited to the 1/3 horsepower size. They are simple to manufacture and inexpensive. The starting torque is very low and can be used for starting small loads only.

CAPACITOR-START MOTORS

Capacitor-start motors are the most widely used single-phase motors in the marine engineering field. They are found on small refrigeration units and portable pumps. They come in a variety of sizes up to 7.5 horsepower. The characteristic hump on the motor frame houses the capacitor (Figure 17-21).

The capacitor-start motor is derived from the basic design of the split-phase motor. The split-phase motor had a current displacement, between the start and run winding, of 30 degrees with wire resistance alone. To increase this angle and increase motor torque, a capacitor can be added. The product of capacitance can be used to increase the current angles, or in other words, to increase the time between current arrival in the start and current

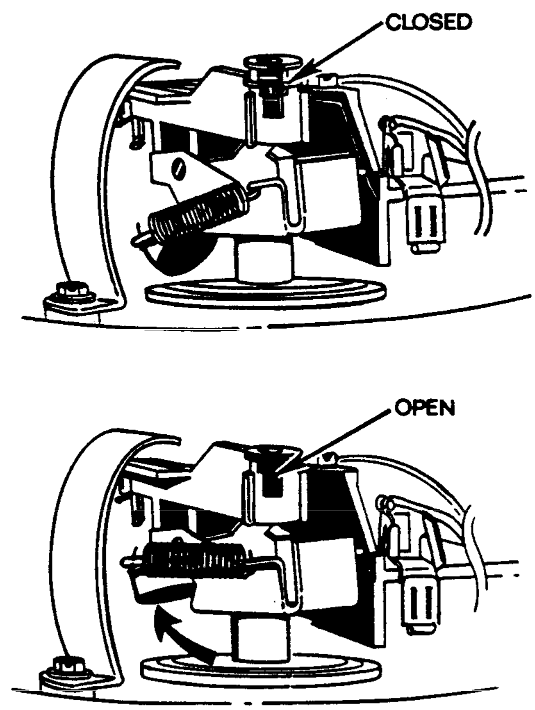


FIGURE 17-18. The Centrifugal Switch.

arrival in the run windings. In capacitance, current leads voltage.

The capacitor, unlike a resistor, does not consume power but stores it so it can be returned to the circuit. The combining of the inductive run (current lagging) winding and the capacitive start (current leading) winding would create a greater current displacement. This would increase the torque.

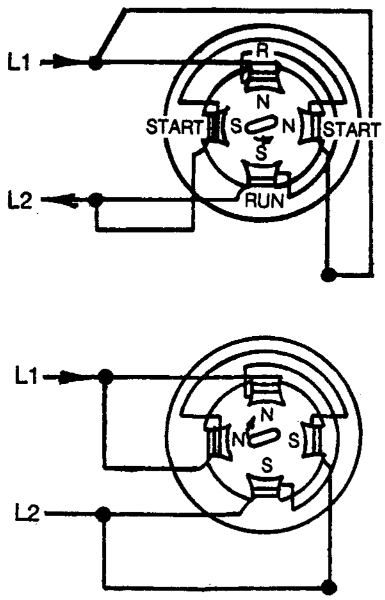


FIGURE 17-19. Reversing the Direction of Current Through the Start Winding.

Capacitor Application

The capacitor is placed in series with the start winding. Figure 17-22 shows a line diagram of its position. Optimum torque can be delivered if the current entering the run and the start winding is displaced by 90 degrees. With this in mind, and knowing an inductive run winding current can lag voltage by 50 degrees, an appropriated capacitor can be selected. A capacitor that can effectively produce a current lead of 40 degrees would give the optimum 90-degree displacement angle (Figure 17-23).

Once the motor has attained 75 percent of its rated speed, the start capacitor and start winding can be eliminated by the centrifugal switch. It is not necessary for this motor to operate on both windings continuously.

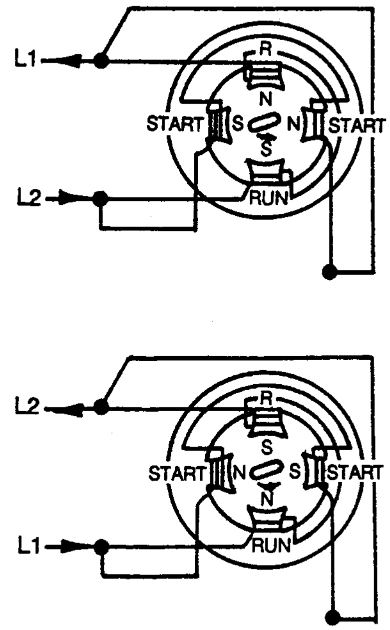


FIGURE 17-20. No Change in the Relationship Between the Start and Run Winding.

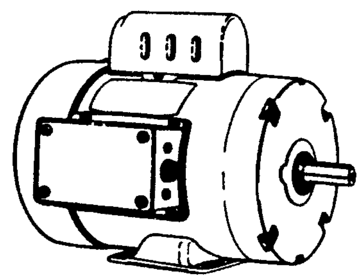


FIGURE 17-21. Capacitor Housing.

PERMANENT-CAPACITOR MOTORS

The capacitor of the capacitor-start motor improves the power factor of the electrical system only on starting. Letting a capacitor remain in the circuit will improve the electrical power factor that was modified initially by the use of a motor. The permanent capacitor is placed in series with one of the windings. The two windings are now called the main and auxiliary (sometimes called the phase) windings. They are constructed exactly alike. Both are left in the circuit during the operation of the motor. A centrifugal switch is no longer needed. Another switch will let the capacitor be connected to either the main or auxiliary winding. The advantage of this is the comparative ease in which the capacitor can be connected to the main or auxiliary winding to reverse direction of rotation. The capacitance forces the current to lead the voltage in the winding it is connected to. This means that the magnetic field is developed in the capacitor winding first.

Certain disadvantages become apparent. The permanent-capacitor motor is very voltage-dependent. How much current delivered to the winding depends on the capacity of the capacitor and the system voltage. Any fluctuation in line voltage affects the speed of the motor. The motor speed may be reduced as low as 50 percent by small fluctuations. Speed changes from no load to full load are extreme. No other induction motor undergoes such severe speed fluctuations.

TWO-CAPACITOR MOTORS

When additional torque is required to start and keep a motor operating, additional capacitors can be added. An excellent example is the refrigeration compressor. A lot of torque is required to start the motor when the compressor it turns may be under refrigerant gas pressure. Also, the compressor may become more heavily loaded during operation, as the refrigeration system requires it. In this case, the high starting torque of the start capacitor motor and an increased phase angle while the motor is running are needed to handle additional torque requirements.

Figure 17-24 shows the two-capacitor motor. It is commonly referred to as the capacitor-start/

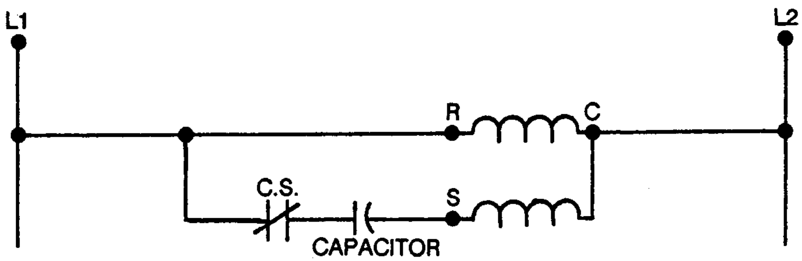


FIGURE 17-22. Capacitor-Start Motor.

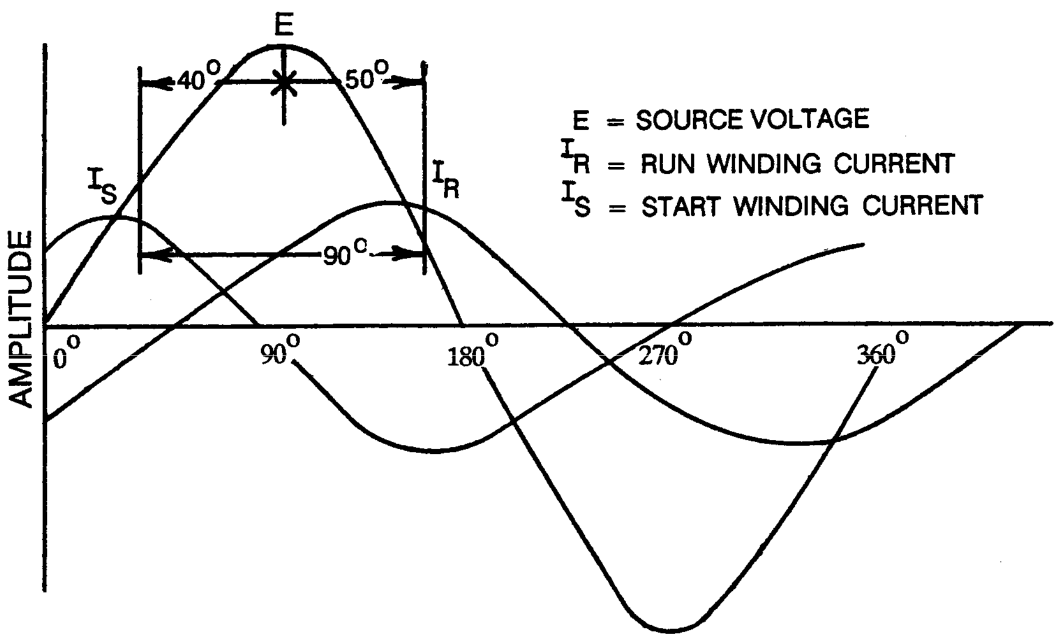


FIGURE 17-23. Capacitor Starting Current and Run Winding Current.

capacitor-run motor. Notice that the start capacitor is in series with the auxiliary winding. The centrifugal switch is used to control the start capacitor in the same manner as it did in the capacitor-start motor. This capacitor is used only to develop enough torque to start the motor turning.

The run capacitor is connected in parallel with the start capacitor. In this manner, both capacitor capacitances add together to increase the total phase angle displacement when the motor is started. Also, the run capacitor is connected in series with the auxiliary winding. With the run capacitor connected in series with the auxiliary winding, the motor always has the auxiliary winding operating, and increased torque is available.

At about 75 percent of the rated motor speed, the centrifugal switch opens and removes the start capacitor from the auxiliary winding. The run capacitor is now the only capacitor in the motor circuit.

CAPACITORS

The capacitor is the heart of most single-phase revolving field motors. If the single-phase motor fails to operate, always check the source voltage first. Then check the fuses or circuit breakers. If these areas are operable, check the capacitor. Visually inspect the capacitor for cracks, leakage, or bumps. If any of these conditions exist, discard the capacitor immediately.

CAUTION

Always discharge a capacitor before testing, removing, or servicing the single-phase motor. This is done by providing a conductive path between the two terminals.

WARNING

Never connect a capacitor to a voltage source greater than the rated voltage of the capacitator. Capacitors will explode violently due to excessive voltage.

Capacitor Operation

A capacitor is not a conductor. Current does not pass through the device as it would a resistor or motor winding (Figure 17-25). Instead, the capacitor must depend on its internal capacity to shift electrons.

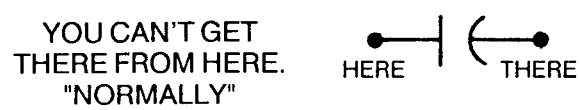


FIGURE 17-25. The Capacitor Symbol Does Not Show A Completed Circuit Between the Terminals.

The power supply voltage establishes a magnetic polarity at each plate. Remember, even AC generators establish a freed polarity (or difference in potential) throughout the distribution system. However, the polarity changes 120 times a second. The capacitor plates change polarity from negative potential and positive potential rapidly, depending on the frequency of the generated voltage (Figure 17-26).

Between the two capacitor plates is an insulator called a dielectric. The dielectric can store energy in an electrostatic field, known commonly as static

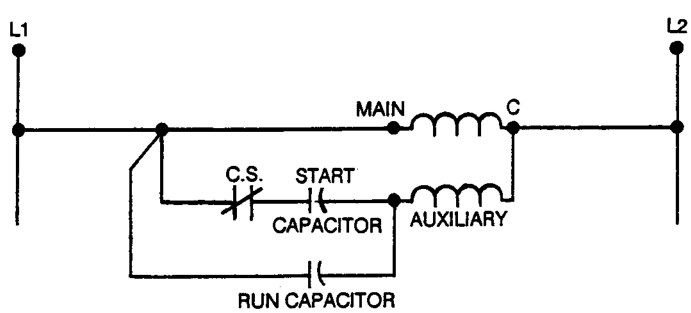


FIGURE 17-24. The Two-Capacitor Motor.

electricity. This is done in the following manner: The electrons in the dielectric of the capacitor are tightly bound in their orbits around the nucleus of their atom. A positive polarity is established in one capacitor plate by virtue of the connection to the positive ion terminal of the generator. A negative polarity is established in the other plate of the capacitor by virtue of the negatively charged electrons from the other generator terminal.

The positive polarity at the capacitor plate pulls the negative electrons in the dielectric. The negative polarity at the other plate pushes the dielectric electrons away. The distorted electron orbit has energy much like that found in a stretched out spring. When the spring is no longer forcibly held in the extended position, it pulls itself back together (Figure 17-27).

The greater the circuit voltage, the greater the difference in potential at the capacitor plates. The stronger the magnetic effects at the capacitor plates, the greater the effect on the electrons in the dielectric.

When the voltage in the AC system is reduced, before changing its direction, the magnetic field decays, and the dielectric electrons are pulled back into their original orbits by their nucleus. This movement of dielectric electrons offsets all the other electrons throughout the capacitor circuit (Figure 17-28). This generates the electron flow (current) that is required to produce the desired magnetic effects in motors. Current flows through the circuit in the opposite direction as would have been originally intended by the generator. Because of this action, current now arrives before the voltage of the next comparable voltage direction.

Capacitor Inspection

The internal condition of a capacitor maybe checked with an ohmmeter (Figure 17-29). Always consult the manufacturer's manuals or appropriate technical manuals for specific information on the capacitor being inspected. Remove the capacitor from the motor and disconnect it. Always short the

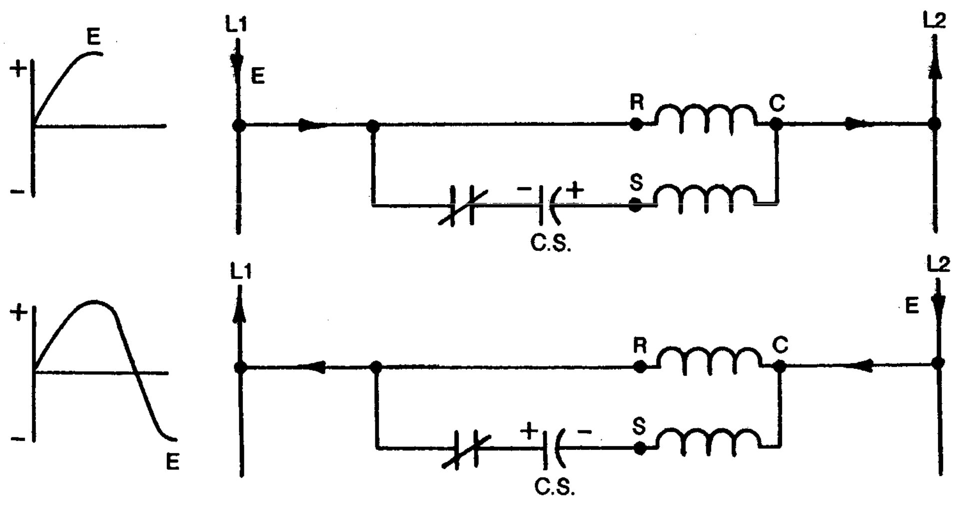


FIGURE 17-26. Polarity from AC at the Capacitor.

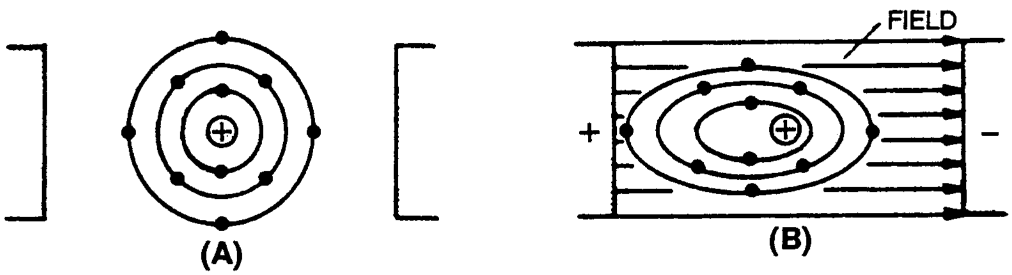


FIGURE 17-27. Electron Orbits With and Without the Presence of an External Electric Field

capacitor terminals before making a test. If a spark occurs when you short the capacitor terminals, this is a good indication that the capacitor is serviceable and maintaining its charge.

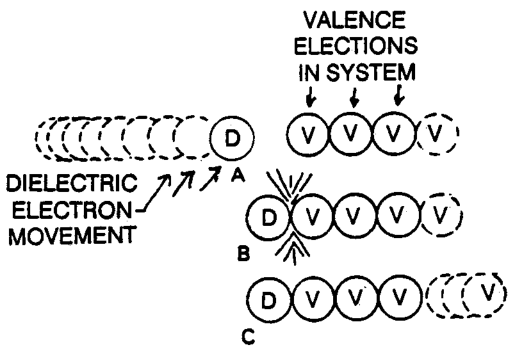


FIGURE 17-28. Displacement of the Circuit Valence Electrons.

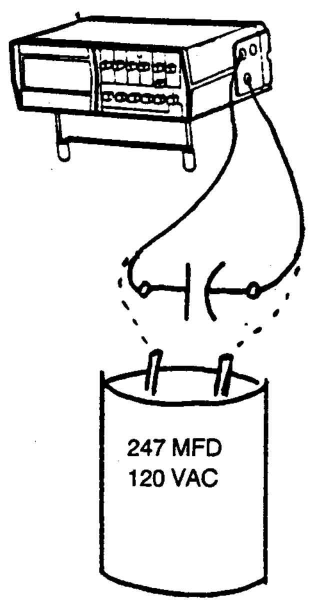


FIGURE 17-29. Testing the Capacitor.

CAUTION

The capacitor starting tool should have an insulated handle. The actual shorting bar should be high-resistance (15k to 20k ohms).

Consult the meter manual to determine the correct range for testing capacitors with the ohmmeter. This is usually a range that provides the highest internal battery voltage from the ohmmeter.

Connect the meter leads to the terminals. Notice the meter display. A good capacitor will indicate charging by an increase in the display's numerical value. This indicates that the capacitor is accepting the difference in potential from the ohmmeter's battery. Once the display stops charging, remove the meter leads and discharge the capacitor (short the terminals).

Reconnect the ohmmeter again, but this time remove one of the meter leads just before the meter display would have indicated the capacitor has stopped charging. Remember the display reading. Wait 30 seconds and reconnect the ohmmeter leads to the same capacitor terminals. The meter's display should start off with the value displayed before removing one ohmmeter lead. If the meter returns to zero, this indicates that the capacitor is unable to hold its charge and must be replaced.

NOTE: Digital meters require some familiarity before this test can be done with a degree of confidence. It may take a moment for the digital meter to display the correct reading upon reconnection. Practice with known good capacitors.

Shorted and Open Capacitors

Capacitors that are shorted or open will not display a charge on the ohmmeter. These meters will show either continuity or infinity.

A shorted capacitor means that the plates of the capacitor have made contact with each other and pass current readily. This will be indicated by a very low and steady resistance reading on the ohmmeter. A shorted capacitor must be replaced.

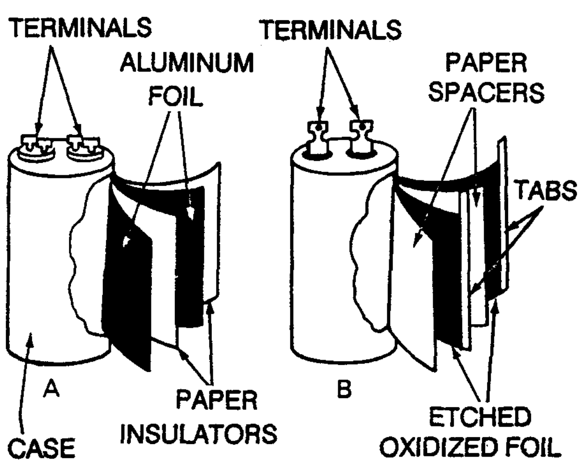
An open capacitor means that the distance between the plates of the capacitor is too far apart. The magnetic fields are not close enough to properly distort the electrons and their nucleus in the dielectric. The ohmmeter will not show a charging condition. For example, when the terminals of the capacitor have become disconnected from the capacitor plates, there will bean indication of infinite or maximum meter resistance. The capacitor must be replaced.

Types of AC Motor Capacitors

There are two capacitors commonly found on single-phase motors: the start capacitor, which has a plastic housing, and the run capacitor, which has a metal housing.

The start or electrolytic capacitors are encased in plastic and have as much as 20 times the capacitance of the run capacitor. One of the plates consists of an electrolyte of thick chemical paste. The other plate is made of aluminum. The dielectric is an aluminum oxide film formed on the aluminum plate surface. These capacitors cannot be operated continuously.

Run or paper capacitors are generally used for the motor-running circuit in the single-phase motor. These capacitors are encased in metal and made durable for continuous operation. The internal construction is made of two or more layers of paper rolled between two layers of aluminum foil (Figure 17-30).



Construction of capacitors varies according to their use.
A - Paper capacitor used with rinning motors.
B - Electrolytic capacitor used for starting ac motors
(Sprague Electric Co.)

FIGURE 17-30. Capacitor Construction.

AC Capacitors

The start winding of a single-phase motor can be damaged if the run capacitor is shorted to ground. This type of damage can be easily avoided if care is taken when installing replacement capacitors.

Manufacturers mark the capacitor terminal connected to the outermost foil. General Electric uses a red dot. Cornell Dubilier indents a "dash." Sprague points an arrow to the problem terminal. When the outer foil fails and comes in contact with the capacitor housing, a short to ground completes a circuit which bypasses the normal circuit protection. When this happens, the start winding can be destroyed. To prevent this casualty from developing, connect the marked terminal to the "R" or power supply line. Never connect the marked terminal to the "S" (start) terminal.

DC Capacitors

The discussion on capacitors has been directed toward the AC capacitor. Our field technology, however, spans decades of marine engineering. For this reason, a few cautions are in order for installing DC capacitors.

The DC capacitor is designed differently from the AC capacitor. The DC capacitor must be placed in the DC circuit in one position only. Always connect the positive terminal of the capacitor to the positive conductor in the DC circuit. Connect the negative terminal in a like manner to the negative conductor. Always observe the polarity of the capacitor. The terminals will be marked positive(+) and negative (-). If the capacitor terminals are incorrectly connected in the circuit, the capacitor will be ruined.

WARNING

Never connect the DC capacitor in an AC circuit. If this is done, the DC capacitor can explode.

Capacitor Rating

Capacitors are rated by the amount of current that results from the changing frequency of the generated voltage. Every time voltage changes polarity, current is displaced through the capacitor circuit. This action is a measurement of farads (F). A capacitor has a capacity (to displace electrons) of 1 farad when a current of 1 ampere (6.242 x 10 to the

18th electrons per second) is produced by a rate of change of 1 volt per second.

The farad is an extremely large value for our motor applications. Most common motor capacitor ratings will be found in the microfarad range.

The capacitance of a capacitor is determined by its construction. The area of the capacitor plates as well as the dielectric material and thickness determine the capacity. Always select a capacitor by the capacitance desired (farad rating) and the voltage rating of the system.

Capacitor Characteristics

When two capacitors are connected in series, the magnetic effects that distort the electron's orbit are further apart. Remember that distance determines the influence that can be exerted by a magnetic field. The capacitor is not a conductor so that only the outermost capacitor plates have a magnetic polarity when they are connected in series (Figure 17-31).

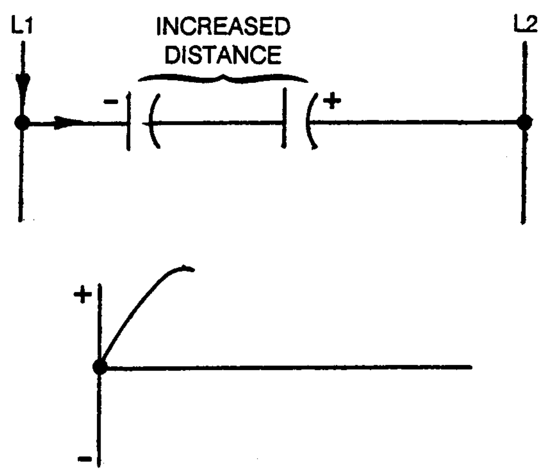


FIGURE 17-31. Capacitors Connected in Series.

The total capacitance of capacitors connected in series can be derived by using the product-over-sum method (as used for determining resistance in a parallel circuit). Notice that the total capacitance is now less than the smallest capacitor.

Capacitors connected in parallel are like adding extra storage batteries in parallel (Figure 17-32). The voltage does not change, but the current, or ability to move electrons, increases. To determine the total capacitance of the circuit, add all the capacitors in parallel.

Voltage is constant in a parallel circuit. This provides an equal positive potential at every capacitor plate connected by a node. A negative potential is also available at the other plates of the other capacitors. In this manner, the magnetic effects available from a difference in potential (voltage) can be most effectively used to displace electrons in the dielectric.

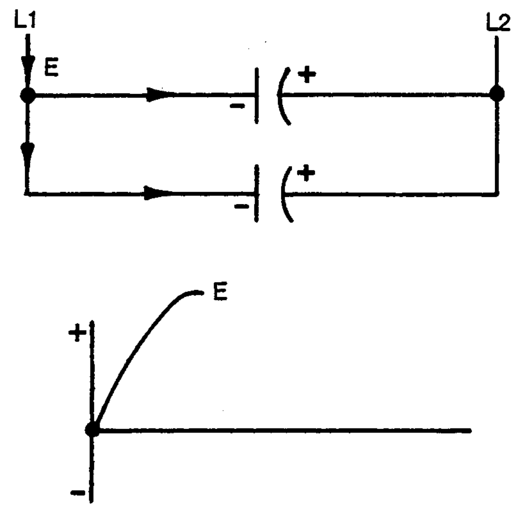


FIGURE 17-32. Capacitors in Parallel.

SHADED-POLE MOTORS

The shaded-pole motor does not use two windings to develop the torque necessary to turn the rotor. Instead, the stator pole piece is divided into two sections. One section has a copper ring encircling the tip (Figure 17-33).

Alternating current enters the stator winding field coil surrounding the stator pole. A magnetic field is readily developed in the stator pole portion without the copper ring.

This expanding magnetic field develops an EMF and resulting magnetic field in the squirrel cage rotor of the opposite polarity of the stator field that induced it. In other words, the stator pole might have been a north polarity, but by virtue of the property of induction, the polarity in the squirrel cage rotor winding directly beneath the stator north polarity would become a rotor pole of south polarity.

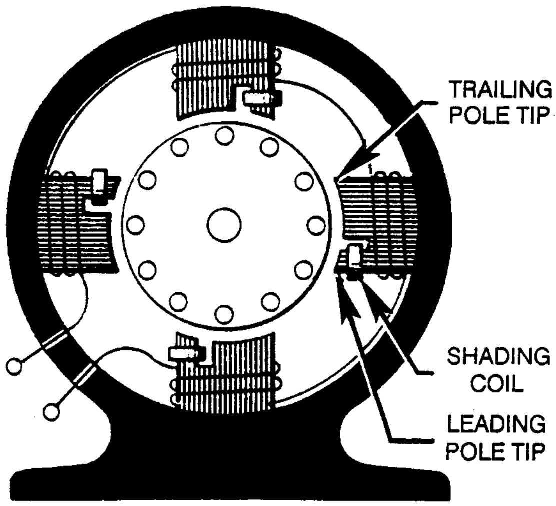


FIGURE 17-33. Shaded-Pole Motor Pole Piece.

While this is happening, the copper ring has impeded the developing magnetic field in the shaded-pole section of the stator pole piece. First, the growing magnetic field expands across the copper ring. The copper ring is short-circuited, like the winding in an induction motor rotor, and an EMF is induced in the ring. An EMF is induced into the copper ring (shaded pole) by the impeded, yet expanding magnetic field. Since the copper ring is short-circuited a current ensues. With this shaded pole current, a magnetic field is established. All of this takes time and inhibits the magnetic field from developing, or decaying, during the same time as the remaining field winding.

By the time the magnetic field finally becomes established in the shaded-pole section of the pole piece, the current flow through the field coil encompassing the entire pole piece has stopped. The shaded-pole section has developed a strong north pole. The unshaded portion weakens rapidly because of the elimination of current in the field coil.

The shaded-pole section retains its magnetic field longer because it takes longer for the field to collapse. The magnetic field developed in the copper ring collapses first. This relative motion of the collapsing field helps induce and sustain an EMF. The resulting current flow and magnetic field are momentarily maintained in the pole piece surrounded by the copper ring.

The property of induction states that induction opposes a change in current. This reluctance to stop current flow maintains the magnetic field longer.

The south polarity developed in the rotor winding directly under the unshaded portion of the pole piece is now attracted to the stronger magnetic field of the shaded-pole section. This is how torque is developed.

Figure 17-34 shows the magnetic field developed in the unshaded portion of the stator pole, the field developed in the shaded stator pole section, and finally the field developed in the copper ring. All these things happen very rapidly, but at different periods in time.

Shaded-pole motors are low cost but are not capable of developing enough torque to turn large equipment. Shaded-pole motors usually range from 1/500 to 1/4 horsepower.

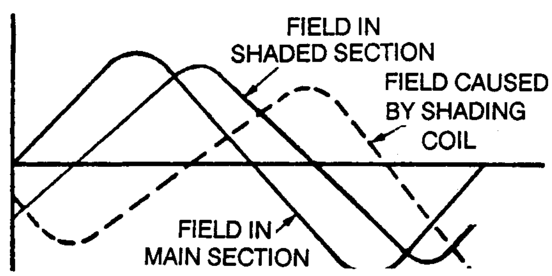


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FIGURE 17-34. The Three Current Sine Waves In the Shaded-Pole Motor.

CHAPTER 18

DIRECT CURRENT GENERATORS

INTRODUCTION

Chapters 18 and 19 provide a comprehensive compilation of nearly 40 years of DC machines and procedures. The DC principles presented here are still valid and provide the means for building the groundwork necessary to understand the DC marine electrical system.

Moreover, the vessels in prepositional fleets, those in storage, and the tugboats and floating cranes currently on station in the marine field require the use of this information. Army marine personnel, active and reserve, need to understand the principles behind the operation of their equipment.

BASIC DC GENERATORS

Fundamentally, all electric generators operate on the same principle, regardless of whether they produce AC or DC. Internally, all generators produce AC. If DC is required, a device to rectify, or change, the AC to DC is needed. The DC generators use a device called a commutator just for such a purpose (Figure 18-1). The AC induced into the armature windings is directed to a set of copper segments that, with the aid of the brushes, keeps current moving in a single direction. The commutator and brush assembly is a crude but effective way to rectify the AC to DC (Figure 18-2).

FIELD POLES

A copper conductor is wound around a metal core called a pole piece or pole shoe. Together, the coil of wire and the pole piece is called the field pole and is bolted directly to the inside of the generator housing or frame. Field poles are always found in pairs. Half of the total number of field poles become electromagnets with the north polarity toward the center of the generator. The other half of the total number of field poles are electromagnets with their south polarity toward the center of the generator. Figure 18-3 shows a four-pole generator.

Shims are often placed between the pole pieces and the frame. These precisely measured shims are used to maintain the air gap between the field poles and the armature windings. The distance between the field poles and the armature must be properly maintained to allow the magnetic field to induce an EMF into the armature windings effectively. If the air gap is too great, an acceptable armature output voltage is impossible.

Direct current is supplied to the field poles to establish a fried magnetic field. This field never changes polarity under normal operating conditions. Other coils of wire are turned by a prime mover in the magnetic field produced by the field poles. These coils of wire are called the armature windings (Figure 18-2).

ARMATURE WINDINGS

Armature windings are heavy copper wires wrapped to form coils around a laminated core. The coils of wire are completely insulated from other coils and the laminated core. The coils of wire are also insulated their entire length to prevent turn-to-turn shorts or accidental grounds. Each armature coil is connected to two copper commutator segments. Figure 18-4 shows the armature coils as A, B, C, and so on. Note that each armature coil joins another armature coil at a commutator segment (1, 2, 3, and so on). The brushes are shown inside the commutator segments to show their relative position only (refer to Figure 18-4). The diagram would otherwise become too cluttered if the brushes were shown superimposed over the armature windings.

This entire assembly is called the armature. Only the armature Windings are located within the magnetic field of the field poles. The brushes and the commutator segments are located outside of the magnetic field pole influence.

When a prime mover turns the armature, an EMF is induced in the armature windings. When an electrical circuit is connected to the armature windings, a current flow is developed. The current developed in the armature windings goes to the commutator. From the commutator segments, the current is channeled to brushes and out to the distribution system.

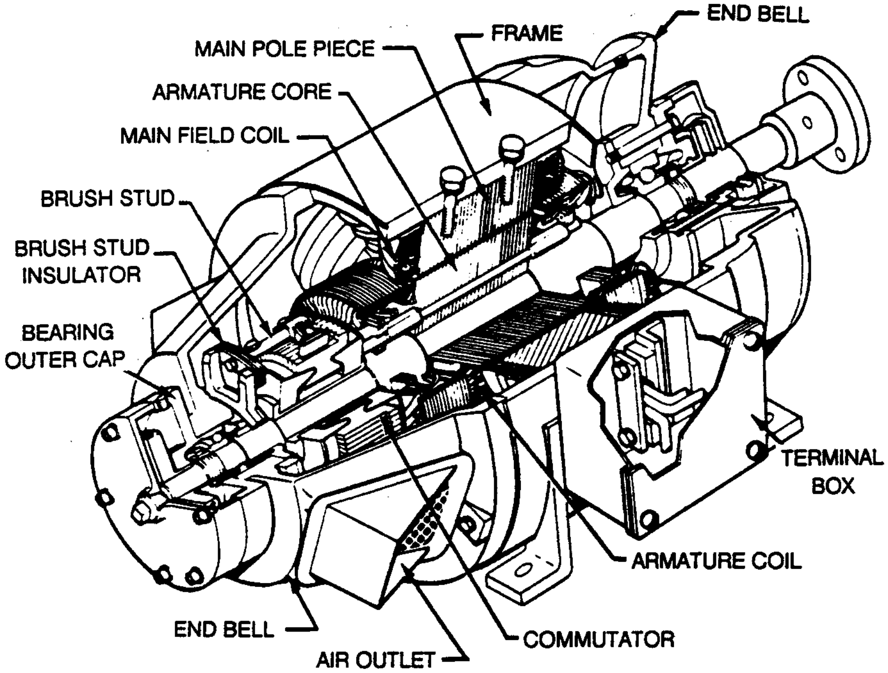

FIGURE 18-1. The DC Machine Construction.

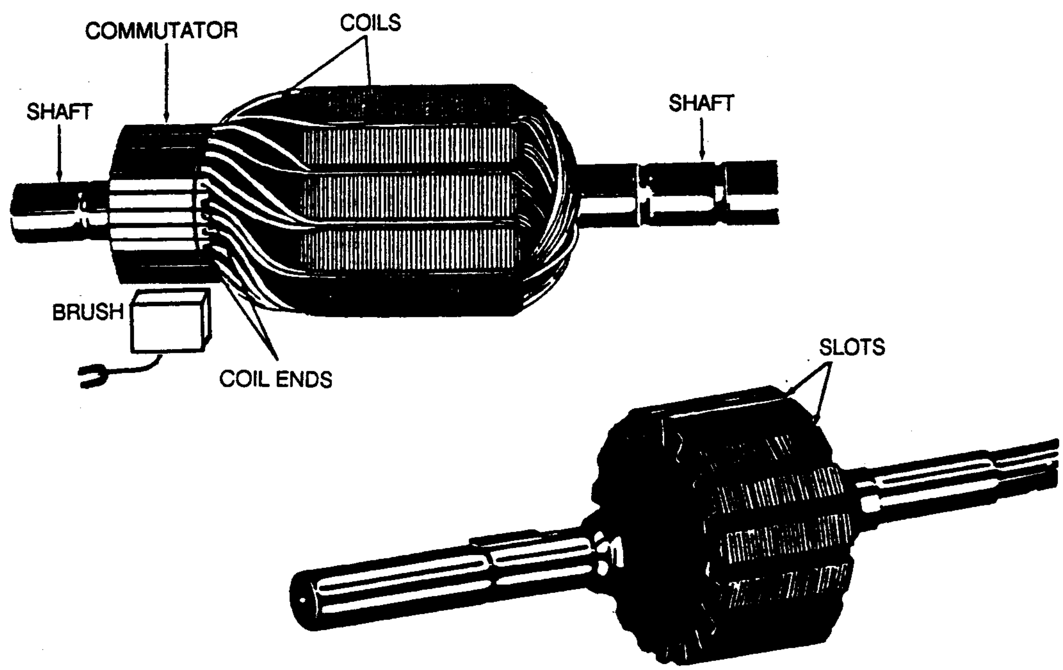

FIGURE 18-2. The DC Armature, Commutator, and Brush Assembly.

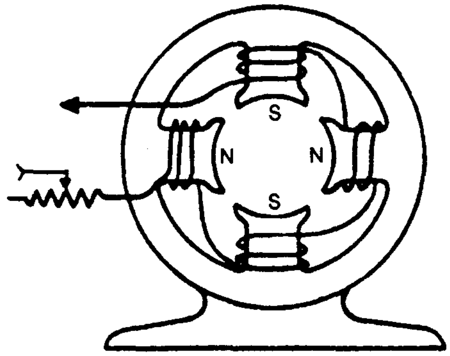

FIGURE 18-3. Four-Pole Machine (Without Armature).

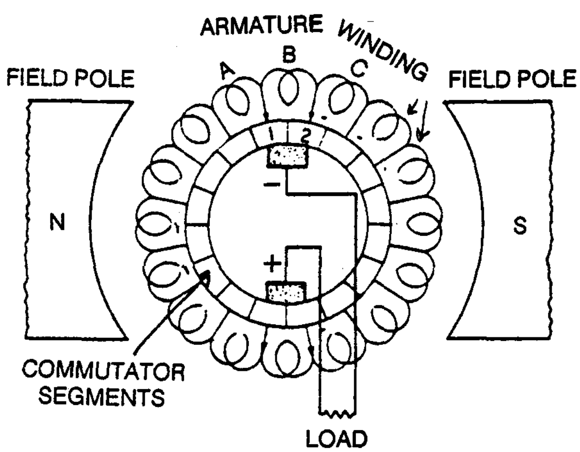

FIGURE 18-4. Armature and Commutator in a Two-Pole DC Machine.

COMMUTATOR

The commutator is fundamentally a reversing switch synchronized with the action of the armature. Figure 18-5 shows how a commutator performs its work. The simple commutator shown here consists of a cylinder of conducting metal split into two halves called segments. One segment is connected to branch (a) of the armature coil, the other to branch (b). These segments are separated from each other by a space that provides insulation so that the current generated in one branch does not short-circuit directly into the other. Two stationary conductors called brushes make contact with the rotating commutator segments and conduct the generated current from the commutator to the point of application, called the load. Figure 18-5 omits the field pole electromagnet to simplify the illustration. However, it is assumed that the magnet is still in position.

At the instant shown in view A of Figure 18-5, the current in branch (a), which is moving upward through the magnetic field, is flowing toward the commutator. The current in branch (b), which is moving downward through the field, is flowing away from the commutator. When this occurs, the polarity is negative on commutator segment (a) and positive on segment (b). The negative brush is in contact with segment (a), and the positive brush is in contact with segment (b).

As the loop continues to turn, it arrives at the position shown in view B of Figure 18-5. In this position, the branches of the armature coil no longer cut the magnetic field. The current in both conductors drops to zero because a difference in potential no longer exists. In other words, both segments (a) and (b) are at zero potential, and no current flows through the generator or out through the external load. During this period, the two brushes bridge the gap between the segments. As a result, the armature coil is short-circuited on itself. However, since no current is flowing, this condition is harmless.

As the loop continues to turn (view C of Figure 18-5), branch (a) starts to move downward through the magnetic field, and branch (b) starts to move upward. As a result, the polarity of commutator segment (a) changes to positive, and segment (b) changes to negative. However, the continued rotation has also brought segment (a) into contact with the positive brush and segment (b) with the negative brush. As a result, the positive brush develops a positive potential from branch (a), and the negative brush develops a negative potential from branch (b). In other words, at the exact moment when current flow in the conductor loop is reversing, the commutator is counteracting the reversal in the brushes. Current flow is always maintained in the same direction throughout the circuit.

The commutator is the basis of all DC machines (generators and motors). In practice, many armature coils are used. Individual commutator segments are insulated by mica, and a commutator segment is provided for each armature coil lead. There is no difference in the basic principles of the generator or the motor. For this reason, the term “machine” is often used to identify both components when dealing in generalities.

The DC generator may supply electrical ship service loads or just charge batteries. The generator is designed to incorporate its own field poles as part of the electrical load circuit. In this manner, the generator can provide for its own field current in the development of its magnetic field.

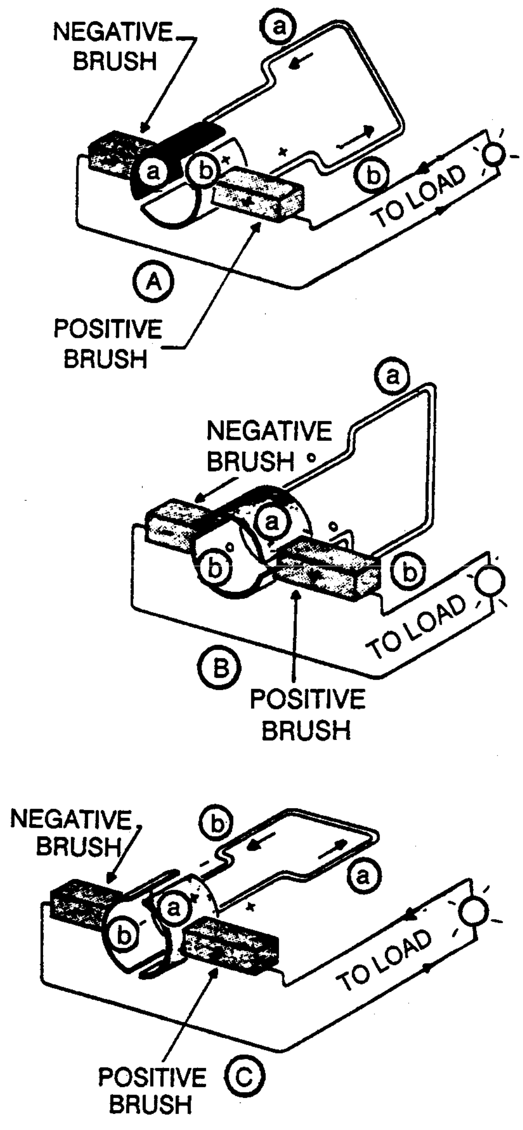

FIGURE 18-5. Commutation.

ARMATURE REACTION

Magnetic lines of force exist between two magnets. These magnets represent the field poles. Circular magnetic lines of force exist around any current-carrying conductor. These current-carrying conductors are representative of the armature coils.

Separately, each of these magnetic fields has its own neutral plane. The neutral plane is the area outside the influence of the magnetic fields. The magnetic field of the field. poles alone show the neutral plane perpendicular to the lines of flux (Figure 18-6 view A). Current flow in the armature conductors (view B) without the field pole flux present produces a neutral plane parallel to the lines of flux. In each instance, the neutral plane is located in the same place and outside of the magnetic fields.

Under normal operating conditions, when both magnetic fields exist, these magnetic lines of force combine and become distorted from their original positions. The neutral plane is shifted in the direction of generator rotation. As long as there is motion and a magnetic field, current will be induced into the armature windings. It is this current that produces the circular lines of force in the armature conductors. As current demands change, so does the current flow in the armature. The varying armature coil magnetic fields result in various distortions of the neutral lane.

The brushes are designed to short-circuit an armature coil when it is located outside the influence of the field poles' magnetic field (in the neutral plane). In this manner, the commutator will not be damaged by excessive sparking because the armature coils are not undergoing induction. When brushes short-circuit two segments that have their armature coils undergoing induction, excessive sparking results, and there is a proportional reduction in EMF (voltage). In Figure 18-6 view C, AB illustrates the original (mechanical) neutral plane. If the brushes were left in this position and the neutral plane shifted, several armature windings would be short-circuited while they were having an EMF induced into them. There would be a great deal of arcing and sparking. Provided the distribution current demands remained constant, the brushes could be moved to the A'B' position where the neutral plane has shifted. This would reduce the amount of sparking at the commutator and sliding brush connections.

However, constantly changing current is the rule, rather than the exception for DC machines.

The effects of armature reaction are observed in both the DC generator and motor. To reduce the effects of armature reaction, DC machines use high flux density in the pole tips, compensating windings, and commutating poles.

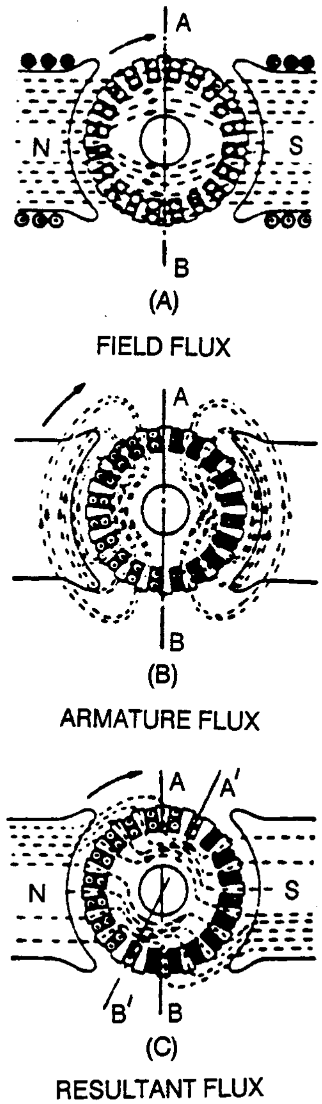

FIGURE 18-6. Flux Distribution in a DC Generator.

Pole Tip Reduced Cross-Sectional Area

The cross-sectional area of the pole tip is reduced by building the field poles with laminations having only one tip (Figure 18-7). These laminations are alternately reversed when the pole core is stacked so that a space is left between alternate laminations at the pole tips. The reduced cross section of iron at the pole tips increases the flux density so that they become saturated. The cross magnetizing and demagnetizing forces of the armature will not affect the flux distribution in the pole face to as great an extent as they would at reduced flux densities.

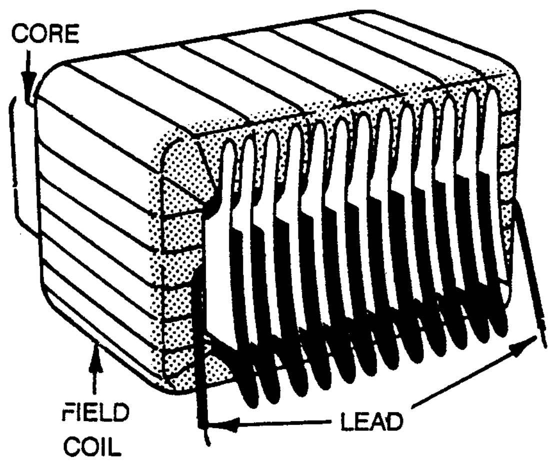

FIGURE 18-7. Reduced Pole Tip Area.

Compensating Windings

The compensating winding consists of conductors imbedded in the pole faces parallel to the armature conductors (Figure 18-8). The winding is connected in series with the armature and is arranged so that the magnetizing forces are equal in magnitude and opposite in direction to those of the armature's magnetizing force. The magnetomotive force of the compensating winding therefore neutralizes the armature magnetomotive force, and armature reaction is practically eliminated. Because of the relatively high cost, compensating windings are ordinarily used only on high-speed and high-voltage DC machines of large capacity.

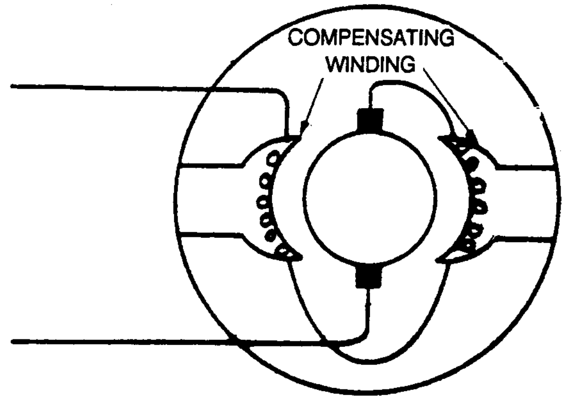

FIGURE 18-8. Compensating Windings.

Commutating Poles

Commutating poles, or interpoles, provide the required amount of neutralizing flux without shifting the brushes from their original position. Figure 18-9 shows the commutating or interposes located midway between the main field poles. The smaller interposes establish a flux in the proper direction and of sufficient magnitude to produce satisfactory commutation. They do not contribute to the generated EMF of the armature as a whole because the voltages generated by their fields cancel each other between brushes of opposite polarity.

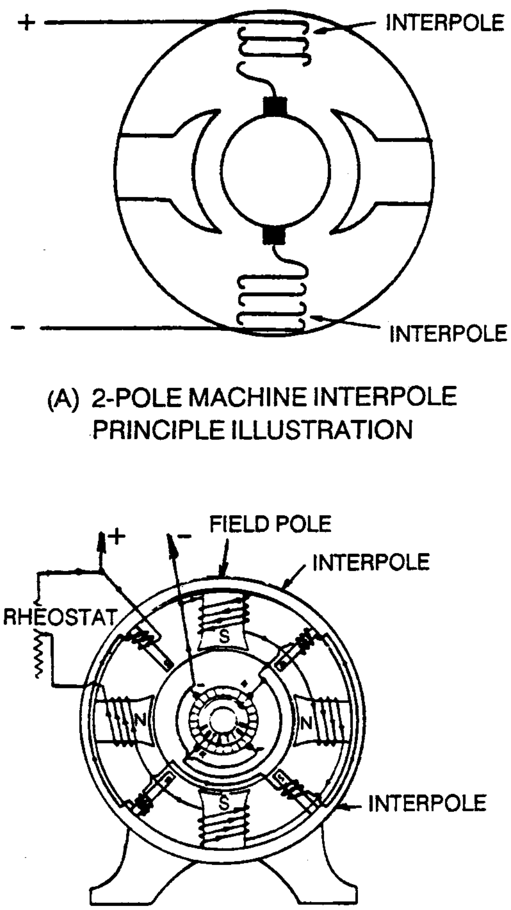

FIGURE 18-9. Interpole Principle.

The commutating poles are also connected in series with the armature (Figure 18-9 view A). As current increases in the armature, with a resulting increase in armature reaction, the current through the commutating poles also increases. Because these two fields counteract each other, the variable armature reaction is counteracted proportionally. Small DC machines may have only one of these poles.

COMMUTATION

Commutation is the process of reversing the current in the individual armature coils and conducting current to the external circuit during the brief interval of time required for each commutator segment to pass current under a brush. In Figure 18-10, commutation occurs simultaneously in the two coils that are undergoing momentary short circuit by the brush coil B by the negative brush and coil J by the positive brush. As mentioned previously, the brushes are placed on the commutator in a position that short-circuits the coils that are moving through the electrical neutral plane. There is no voltage generated in the coils at that time, and no sparking occurs between commutator and brush.

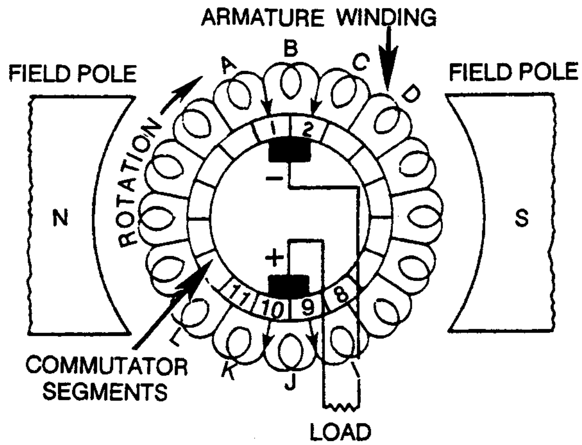

FIGURE 18-10. Commutation in a DC Generator.

There are two paths for current through the armature winding. One current flow moves in the opposite direction of the armature rotation, starting at segment 9 and moving to segment 2 through coils I to C. The other current flow moves in the direction the armature rotates, from segment 10 to segment 1 through coils K to A. In this example, the armature maintains two parallel paths for current flow. Current in the coils will reverse directions between the right side and the left side of the armature.

If the load current is 100 amperes, each path will contain 50 amperes. Thus, each coil on the left side of the armature carries 50 amperes in a given direction, and each coil on the right side of the armature carries 50 amperes in the opposite direction. The reversal of the current in a given coil occurs during the time that particular coil is being short-circuited by a brush. For example, as coil A approaches the negative brush, it is carrying the full value of 50 amperes which flows through commutator segment 1 and the left half of the negative brush where it joins 50 amperes from coil C.

At the instant shown, the negative brush spans half of segment 1 and half of segment 2. Coil B is on short circuit and is moving parallel to the field so that its generated voltage is zero, and no current flows through it. As rotation continues in a clockwise direction, the negative brush spans more of segment 1 and less of segment 2. When segment 2 leaves the brush, no current flows from segment 2 to the brush, and commutation is complete.

As coil A continues into the position of coil B, the induced EMF becomes negligible, and the current in A decreases to zero. Thus, the current in the coils approaching the brush is reduced to zero during the brief interval of time it takes for coil A to move to the position of coil B. During this time, the flux collapses around the coil and induces an EMF of self-induction which opposes the decrease of current. Thus, if the EMF of self-induction is not neutralized, the current will not decrease in coil A, and the current in the coil lead to segment 1 will not be zero when segment 1 leaves the brush. This delay causes a spark to form between the toe of the brush and the trailing edge of the segment. As the segment breaks contact with the brush, this action burns and pits the commutator.

The reversal of current in a coil takes place very rapidly. For example, in an ordinary four-pole generator, each coil passes through the process of commutation several thousand times per minute. It is important that commutation be done with as little sparking as possible.

The IEEE Recommended Practice for Electric Installations on Shipboard defines successful commutation in the following manner: “Successful commutation is attained if neither the brushes nor the commutator is burned or injured in an acceptance test; or in normal service to the extent that abnormal maintenance is required. The presence of some visible sparking is not necessarily evidence of unsuccessful commutation.”

A commutator with a brown film is an indication of successful commutation. This film should be allowed to remain. To help finely adjust commutation, a small incremental brush adjustment is provided on the brush rigging. When dealing with a generator, the brush rigging may be moved to show the highest voltage reading with limited sparking. This is not a normal maintenance adjustment. Extreme care must be exercised. This adjustment should be done only by a qualified individual.

MULTIPOLAR MACHINES

Generators may have more than one pair of field poles used in combination. This construction is especially advisable on large generators because it permits the production of a given voltage at a much lower speed. For example, to produce a given voltage, a two-pole machine must be driven twice as fast as a four-pole machine and three times as fast as a six-pole machine, assuming equal pole strength in all cases.

TYPES OF DIRECT CURRENT GENERATORS

DC generators are classified according to their field excitation methods. There are four common types of DC generators:

- Series wound.
- Shunt wound.
- Compound wound.
- Permanent magnet (magneto) and externally excited generators used for special applications.

Series Wound Generator

Figure 18-11 shows the elements of a series wound generator, semipictorially in view A and schematically in view B. The field winding of any generator supplies the magnetic field necessary to induce a voltage in the armature. In most generators, this field winding is supplied with electrical energy by the generator itself. If the generator is connected as shown in Figure 18-11, it is called series wound. One commutator brush is connected to the external load through a switch, the other through a field winding.

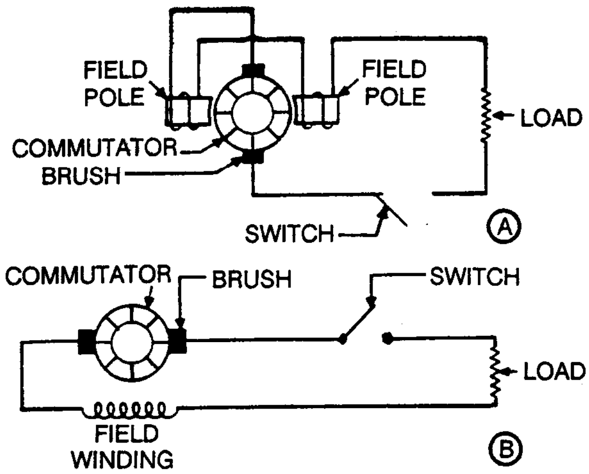

FIGURE 18-11. Series Wound Generator.

Suppose that the generator is being turned by the prime mover. As long as the switch is open, no current can flow through the field winding, and no generator voltage can be built up. When the switch is closed, there is a complete circuit through the load, and any current produced by the generator armature flows through the field windings and sets up the magnetic field necessary for the generator to produce power. In a case of this kind, the heavier the load (the smaller the resistance in the distribution system), the greater the current flow through the field winding. The more current there is in the field winding, the stronger the magnetic field becomes (up to the point of saturation) and the higher the terminal volt age becomes. If the load is made still heavier after the point of saturation is reached, there is a decided drop in voltage due to internal resistance of the armature and the fields.

The opposite is also the case when the distribution system exhibits a high resistance, and current flow from the armature is low. The current from the armature moves through the series field winding producing a negligible magnetic field. The small magnetic field is not sufficient to induce a satisfactory EMF into the armature windings, and terminal voltage also reduces. The terminal voltage of a series generator is greater at full load than at no load. This is the distinguishing characteristic of the series wound generator.

Building Up Series Field Strength. At first glance, it would seem that a self-excited generator could never get started producing current because there must be a magnetic field before any voltage is induced in its coils. With no field, there would be no output from the armature, and with no output, there would be no field. However, an initial field is supplied by residual magnetism. In a theoretically perfect iron core of the field pole, the magnetism would disappear as soon as the field was de-energized. But the fact is that even the best soft iron core retains some of the magnetism induced in previous electrical operations. This weak magnetic field permits a very small voltage (EMF) to be built up across the commutator brushes without the aid of a separately energized field winding. As soon as the voltage begins to build up, a very small current flows through the field winding and slightly increases the strength of the magnetic field. This process goes on until the generator has built up to its full rated voltage for the given load. In practical operation, in order to increase the speed of buildup, a direct short circuit is often substituted for the resistance of the load. This makes the beginning current much higher than it would normally be, and the generator field winding builds up its full magnetic strength almost at once.

Restoring Residual Field. Occasionally, generators will be found that will not build up an initial EMF because of some previous error that resulted in neutralizing or reversing the residual magnetic field. This could happen, for instance, if the direction of rotation had been accidentally reversed during the previous run. In this case, a battery may be connected to the field winding to create the necessary small magnetic field that will initiate the buildup. As soon as the buildup begins, the battery may be disconnected.

Applying the Series Generator. Series wound generators are of little use for general power work. They are principally used as boosters in long lines and for test work in laboratories. They are rarely found on shipboard. They have been discussed here only because their operation is important in understanding the principles of the widely used compound wound generators.

Shunt Wound Generator

Figure 18-12 shows the principle of the shunt wound generator, semipictorially in view A and schematically in view B. In this type of generator, the field coil is connected directly across the commutator brushes. The armature and shunt field are connected in parallel.

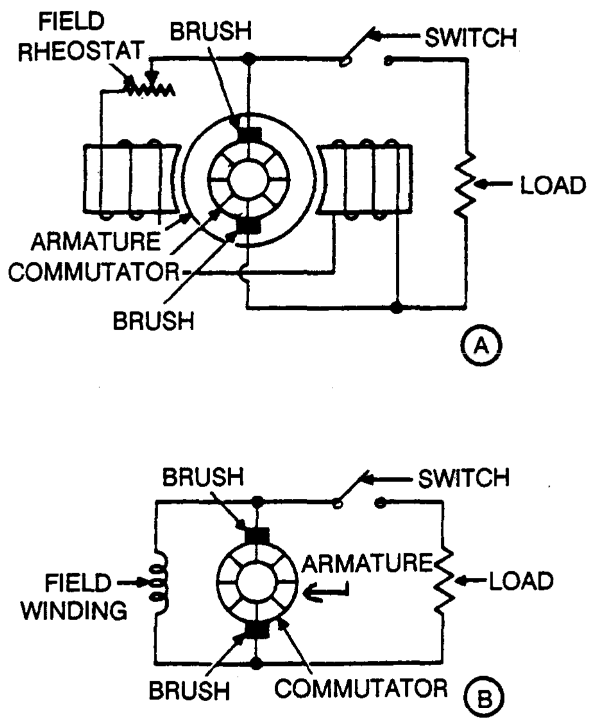

FIGURE 18-12. Shunt Wound Generator.

In practical machines, the shunt winding is usually provided with a series-connected variable resistance or field rheostat as shown in view A. This permits the strength of the field to be varied to compensate for changes in load.

Inherent Regulation of the Shunt Generator. Internal changes, both electrical and mechanical, that occur in a generator automatically with load change give the generator certain typical characteristics by which it may be identified. These internal changes are referred to as the inherent regulation of the generator.

At no load, when the generator is disconnected from the distribution system, the armature current equals the field current. This is because the shunt field is the only electrical load in the generator's circuit. In Figure 18-12 view B, the armature current flows through the shunt field winding. The winding is actually in series with the armature winding at this time. The shunt field winding has a relatively high resistance, and armature current is kept low. The voltage dropped in the armature is kept low as well because of the small current in the armature and field circuit. Voltage drop in the armature equals the current through the armature multiplied by the internal resistance of the armature ($E = IR$). With low armature resistance and low field current, there is little armature voltage (IR) drop, and the generated voltage equals the terminal voltage.

With a load applied, the armature IR drop increases but is relatively small compared with the generated voltage. The terminal voltage decreases only slightly provided the speed is maintained at the rated RPM.

Loading is added to generators by increasing the number of parallel paths across the generator terminals. This action reduces the total load circuit resistance. When electrical loads are connected to the generator, the shunt field stops operating like a series load to the armature. Now that all the loads are connected in parallel with the armature, the voltage across each load will remain relatively constant. If the voltage can remain relatively constant in a generator's field, then there is sufficient force to maintain a constant current flow through the field windings. As long as the field is constant, then the armature-induced EMF can be constant.

Since the terminal voltage is approximately constant with the shunt field generator, armature current increases directly with the load. Since the shunt field acts as a separate parallel branch circuit, it receives only a slightly reduced voltage, and its field current does not change to any great extent. Thus, with low armature resistance and a relatively strong field, there is only a small variation in terminal voltage between no load and full load.

External Voltage Characteristics. Curve A of Figure 18-13 shows a graph of the variation in terminal voltage with load on a shunt generator. This curve shows that the terminal voltage of a shunt generator falls slightly with increase in load from no-load to full-load condition. It also shows that with heavy overload the terminal voltage falls more rapidly. The shunt field current is reduced, and the magnetizing effect of the field falls to a low value. The dotted curve A indicates the way terminal voltage falls beyond the breakdown point. In large generators, the breakdown point occurs at several times the rated load current. Generators are not designed to be operated at these large values of current.

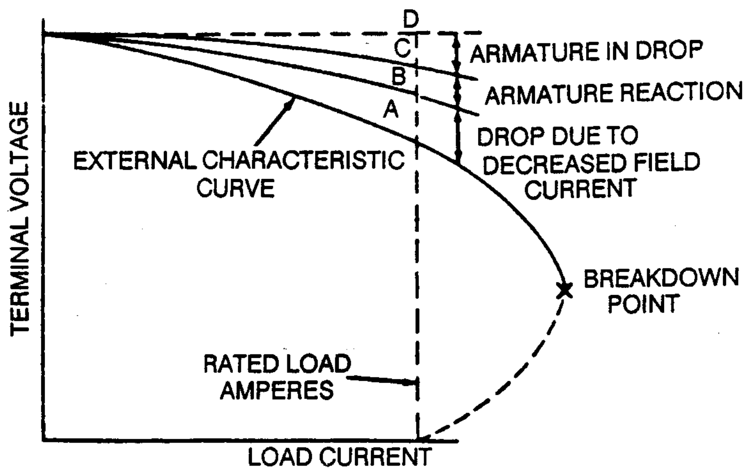

FIGURE 18-13. Shunt Generator External Characteristics.

Buildup of Shunt Field Strength. Since the shunt field winding is connected directly across the commutator brushes, it is unnecessary to short-circuit the field externally to make the generator build up to the required voltage. Otherwise, it is built up in the same manner as the series wound generator. The initial residual magnetic field induces an EMF into the armature when the armature is turned by the prime mover. The initial armature output is returned to the residual magnetic field strength until a sufficient EMF can be induced and a suitable current can be applied to the loads.

Applications. With reasonable loading, the shunt generator may be perfectly stable. However, it can be used in practical work only where it can be known in advance that the load will not be increased to the point where the voltage drop becomes intolerable. Shunt generators are therefore ordinarily used only where the load is completely predictable, and the generator can be selected to carry that load without serious voltage drop. Shunt wound generators are not widely used on shipboard because shipboard power circuits make widely varying demands on the power supply system. They are covered here because an understanding of them is needed to understand compound wound generators.

Compound Wound Generators

The compound wound generator uses both the series and shunt fields. The series field coils are made of a relatively small number of turns of large diameter copper conductor, either circular or rectangular in cross-section area, 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 magnetic field that influences the total magnetic field of the generator. Figure 18-14 schematically shows a compound wound generator of the type known as a long shunt, semipictorially in view A and schematically in view B.

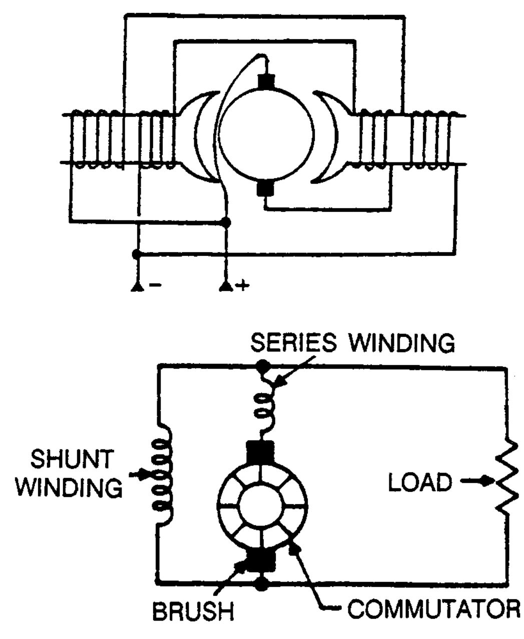

FIGURE 18-14. Compound Wound Generator.

The shunt winding tends to have a drop in terminal voltage with an increase in load, and the series winding tends to have a terminal voltage increase with a load. Compound windings combine the virtues and cancel out the faults of the series and shunt generators. Within reasonable limits, the compound generator will deliver a constant voltage varying from practically no load to its full-rated capacity. Beyond its rated capacity, voltage will drop seriously. Most generators are so designed that they may be overloaded as much as 25 percent for short periods without serious effects. However, no generator should be expected to run at any great amount over its rated capacity.

Flashing the Field of Compound Generators. Flashing the field of an Army marine compound generator requires special consideration. The brushes must be lifted or insulated from the commutator before battery voltage is applied to the field windings. If this is not done, a short circuit condition will result. Since the armature has very little resistance, maximum current will flow from the battery through the armature. If the voltage source is sufficient, the generator would develop a torque and turn.

Flashing the field with a battery creates another problem with old equipment. Identifying the generator cable field polarity markings may be impossible. If battery voltage is applied in an improper manner, then the generator will develop a voltage that prevents paralleling. This is readily observable at the switchboard. The field polarity will be reversed when the generator is started, and the voltmeter needle deflects in a way to indicate less than zero voltage. This is the only way the generator voltmeter can illustrate the reverse current flow from the generator terminals. To stop the generator and flash the fields in the opposite manner, apply the opposite polarity combination from the battery to the field terminals.

In extreme cases, flashing the field of Army marine DC generators may be done in this manner:

- Secure the generator, and disconnect it from the bus.
- Insulate all the brushes from the commutator segments. Place 3 x 5 cards between the brushes and the commutator.
- Do not start the generator to be flashed.
- Start another, properly operating generator.
- Place the properly operating generator on line.
- Temporarily close the switchboard circuit breaker of the generator to be flashed, connecting it to the switchboard bus.
- Open the circuit breaker, disconnecting the flashed generator from the switchboard bus.
- Remove the 3 x 5 cards.
- Operate the flashed generator normally, and observe the voltmeter needle deflection.

Avery short time is required when flashing the generators field. Modern electrical texts recommend a 30-second flashing period, maximum. However, these texts are not unit specific. Always consult the applicable technical manual.

Short and Long Shunt. In the short shunt generator shown in Figure 18-14, the shunt field is connected directly across the commutator and does not receive its current through the series field. The long shunt generator (Figure 18-15) has a shunt field connected to one commutator and what might be called the far end of the series field winding. Long shunt machines are usually used on shipboard.

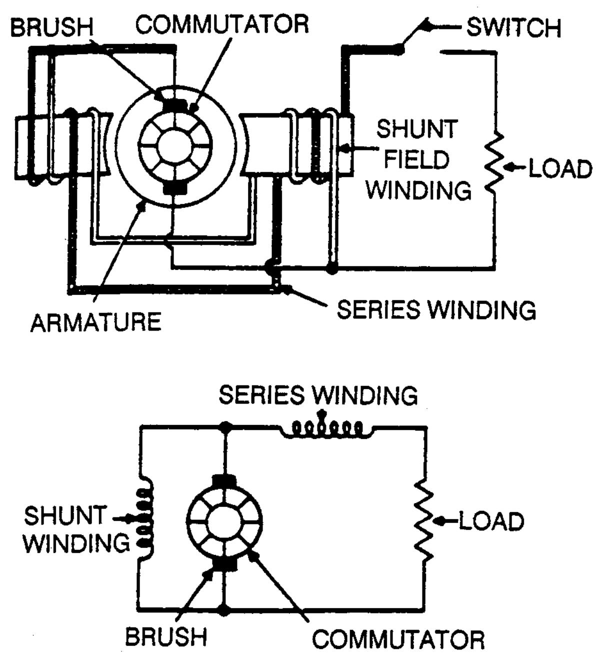

FIGURE 18-15. Compound Wound Generator, Long Shunt Type.

Series and Shunt Field Comparison. The armature develops the current required by the distribution system. If the distribution system has a very high electrical load (very little resistance), then the induced current will be very high in the armature. The series field is in series with the armature. This means that whatever current is developed in the armature must go through the series windings first before it is supplied to the electrical distribution system. For this reason, the series field is of a very large diameter, low-resistance conductor.

The shunt field, in parallel to the armature, is a very fine winding. Only a small portion of the armature current goes through the shunt winding. To make up for the small current and a subsequent small magnetic field, the shunt field has a multitude of turns. The increased turns improve the total strength of the shunt magnetic field. The shunt field winding is extremely small in diameter, but long in length.

When it becomes necessary to identify these two windings, an ohmmeter can be used. The large diameter series winding should have a very low resistance. The small diameter shunt winding should have a much higher resistance. Figure 18-16 shows how these windings are marked in the line diagram.

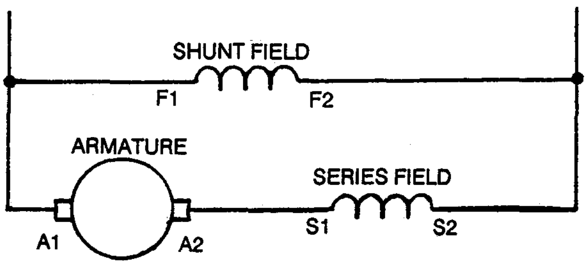

FIGURE 18-16. Field Winding Terminal Markings.

Stabilized Shunt. Many of the DC ship service generators found on Army watercraft are identified as stab shunt. The stabilized shunt generator is a form of compound generator. The independent significance of the stabilized shunt indicates that there are just enough series winding turns to prevent unwanted voltage fluctuations within the rated capacity of the shunt generator.

Over-, Flat-, and Under-Compounding. Compound generators may be so constructed that either the shunt or the series field characteristics are dominant or equal. If the series field characteristics prevail over the shunt field characteristics, the generator is called over-compounded. If the two fields are equal in strength, the machine is called flat-compounded. If the shunt field characteristics are dominant over the series field characteristics, the machine is called under-compounded. For most work, flat-compounded generators are desirable. They may be used over a wide range of loading without serious fluctuations in voltage output. Over-compounded generators are sometimes used in industry to compensate for long line losses but are unnecessary on shipboard. Under-compounded generators are sometimes used where a decrease of voltage with added load is desirable.

The following are descriptions of under-, flat-, and over-compounding:

- Under-compounding - very few series winding turns. Full-load voltage is less than no-load voltage. Shunt field characteristics are prominent. See Figure 18-17.

- Flat-compounding - no-load voltage and full-load voltage are the same.

- Over-compounding - many series winding turns. Full-load voltage is greater than no-load voltage. Series field characteristics are prominent.

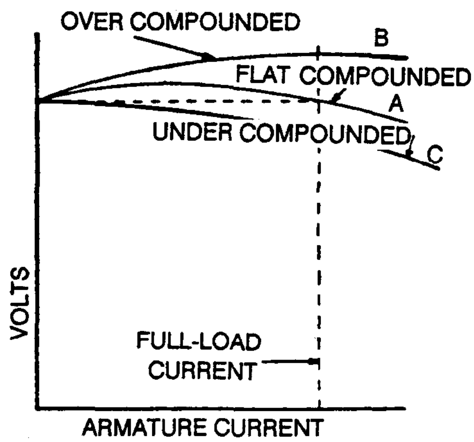

FIGURE 18-17. Compound Generator External Characteristics.

Diverter. A variable resistor is connected in shunt (parallel) with the series field to adjust the degree of compounding. This device is called a diverter and actually controls the full-load voltage characteristics of the generator.

Figure 18-18 shows the diverter rheostat in shunt with the series field. View A shows the series field operating at maximum current because the shunt rheostat is adjusted for full resistance. This means that minimum current goes through the rheostat, and maximum current goes through the series field. View A illustrates a compound generator adjusted for an over-compounded condition. In this situation, the generator is designed for a greater voltage at full load than at no load. The maximum resistance position compensates for extreme changes in current demands. A drop in voltage, under extremely high current demands, is prevented.

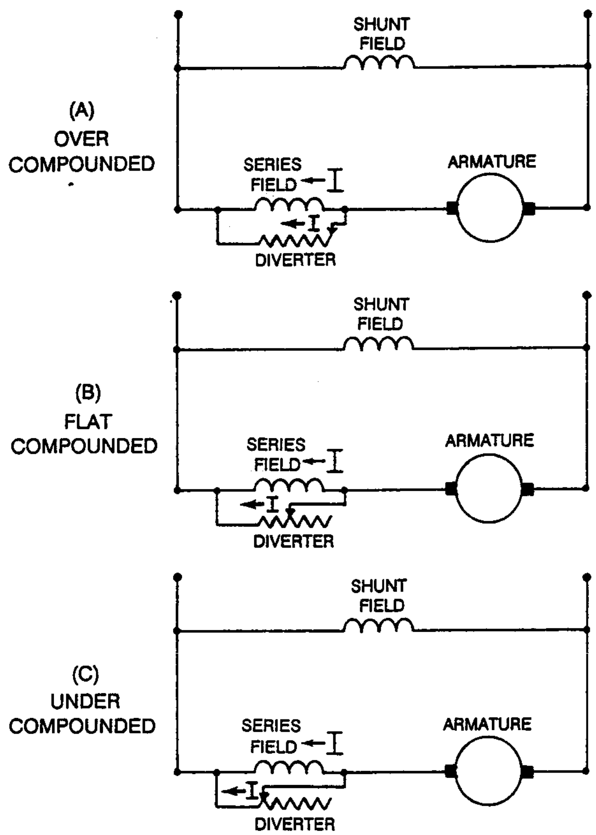

FIGURE 18-18. Compounding Adjustment With the Diverter.

View C illustrates the diverter adjusted for the under-compounded condition. The rheostat is adjusted for minimum resistance. Most of the current bypasses the series field, and the generator operates with the characteristics of a shunt generator.

The preceding two examples are the extreme conditions. It is the intent of the operator to adjust the diverter for the most stable voltage condition under the immediate electrical load demands of the distribution system. Adjusting the diverter between these two extremes provides the voltage regulation characteristics necessary for operating the generator at or near full-load conditions (view B).

Applications. The compound wound generator is commonly used for shipboard DC power. It is versatile and will stand a wide variety of loads. This is particularly important on cargo ships as the loading from a single winch, for example, may vary from half the capacity of the generator when the winch is hoisting to what might be considered less than zero when the winch is lowering a load.

DIRECT CURRENT GENERATOR CONTROL

Speed Control of Generator Output

Since for a given load the output of a DC generator is approximately proportional to the speed at which it is driven (assuming constant field strength), it is possible to control the output by varying the speed. However, most diesel generators are designed to be run at a certain constant speed most suitable for their construction. Therefore, speed control of generator output is seldom satisfactory except in specialized applications, such as propulsion generators.

Field Strength Control of Generator Output

For a given load, the voltage output of any generator is proportional to the field strength of its field poles. The most practical way to regulate generator voltage is to control the field strength. This may be done by placing resistances in series with the shunt field winding, by placing resistances across the series field winding, or by tapping a winding so that any part or all of it may be included in the circuit as desired.

The most practical method of varying field strength is by inserting a variable resistor or rheostat in series with the shunt winding of a compound generator or in the only winding of the simple shunt generators. Figure 18-19 view A shows the circuit of a simple shunt generator. View B shows the circuit of a compound generator. Since the shunt generator, when lightly loaded, tends to deliver a higher voltage than it does as the load increases, it is ordinarily started with a large value of resistance in series with the shunt winding. This keeps the voltage down to a normal value. As loading is increased, the operator cuts more and more of the resistance out of the circuit. At maximum load, the remaining shunt field resistance is very low. This method of control is also used with the compound wound generator, as shown in view B. It is used not so much to compensate for wide voltage variations with loading, but ordinarily to bring the voltage of the compound generator up to a value suitable to connect it across the switchboard bus when it is to be paralleled with another generator.

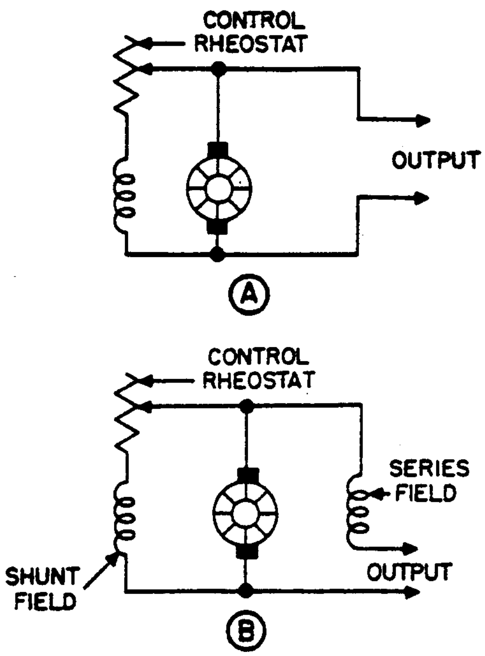

FIGURE 18-19. Series Resistance Control of Shunt and Compound Wound DC Generators.

NO-LOAD VOLTAGE CONTROL

When a generator is started, the voltage is adjusted by a rheostat in series with the shunt field. When the resistance is increased in the rheostat, current in the shunt field is reduced. With a reduction in shunt field current, a decrease in EMF results. The generator now produces less voltage. If the shunt field resistance is reduced, the generated voltage increases. Figure 18-20 shows the rheo-stat in series with the shunt field. The shunt field adjusts the no-load voltage of the generator. All Army marine generators have this control. As the electrical distribution system requires the generator to produce more and more current, the generated voltage drops lower and lower. This voltage drop must be manually compensated for by adjusting the shunt field rheostat.

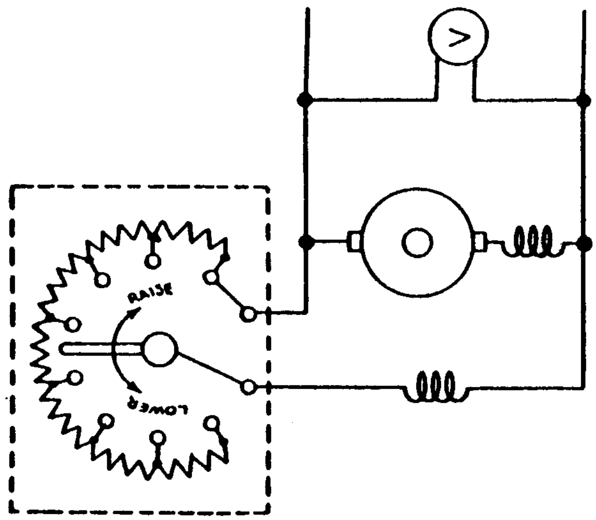

FIGURE 18-20. Hand-Operated Shunt Field Rheostat.

CRITICAL FIELD RESISTANCE

There are many reasons why a generator will fail to buildup the required voltage. Although it is not the object of this manual to be a troubleshooting text, it is prudent to mention a common field-related problem encountered in this area.

When resistance is placed in series with the shunt field, the voltage produced by the generator is decreased. When a certain resistance value is reached, it becomes impossible to generate enough voltage to operate electrical components. This is known as the critical field resistance. A bad rheostat or broken field connection increases shunt field resistance. Corrosion and deterioration on our prepositional fleets will also become a problem. Oxidation on electrical connections, terminals, and rheostat windings will increase the resistance in the shunt field. Always inspect the shunt field controlling circuit when the correct voltage value cannot be reached.

OPERATION OF GENERATORS IN PARALLEL

Whenever the current load is more than can be carried by a single generator, the problem may be solved by operating two or more generators as a single unit. This is called paralleling generators.

Figure 18-21 illustrates the simple circuit required for operating compound generators in parallel. It is necessary to watch the voltage and amperage much more closely when generators are operating in parallel to prevent troubles that might occur if one generator were to take more than its share of the load. Paralleled generators need to divide the current equally between them. If they do not, the dominant generator will pick up more and more current from the other generator. Eventually, and without any protective devices, the dominant generator will try to motorize the unloaded generator. Because of the like internal resistances of the generators (the maximum power transfer theory), current flow will become excessive, and damage will occur. The reverse current relay is designed to prevent one generator from trying to motorize the other generator.

Suppose that generator 1 in Figure 18-21 is already online and is delivering to the bus its normal electromotive force of 120 volts and its full-rated current of 100 amperes. If the load is increased, it will be necessary to start generator 2 to prevent generator 1 from becoming disconnected from the distribution system by its own circuit breaker. Figure 18-21 shows generator 1 as connected in the circuit and delivering power to the line. If the load is to be increased, it will be necessary to bring generator 2 up to speed so that its voltage will be correct before connecting it into the line with generator 1. For this reason, switch 2 is not closed until generator 2 has been brought up to speed. When constant speed has been reached and generator 2 is at operating temperature, generator 2 must have its shunt field rheostat adjusted so that its voltage is about 1 to 5 volts higher than generator 1.

If the voltage of generator 2 were adjusted to the same voltage as generator 1 and then they both were connected to the bus, generator 2 voltage would decrease. The reduction in generator 2 voltage would result because of the addition of an electrical load. Generator 1 would have an increase in terminal

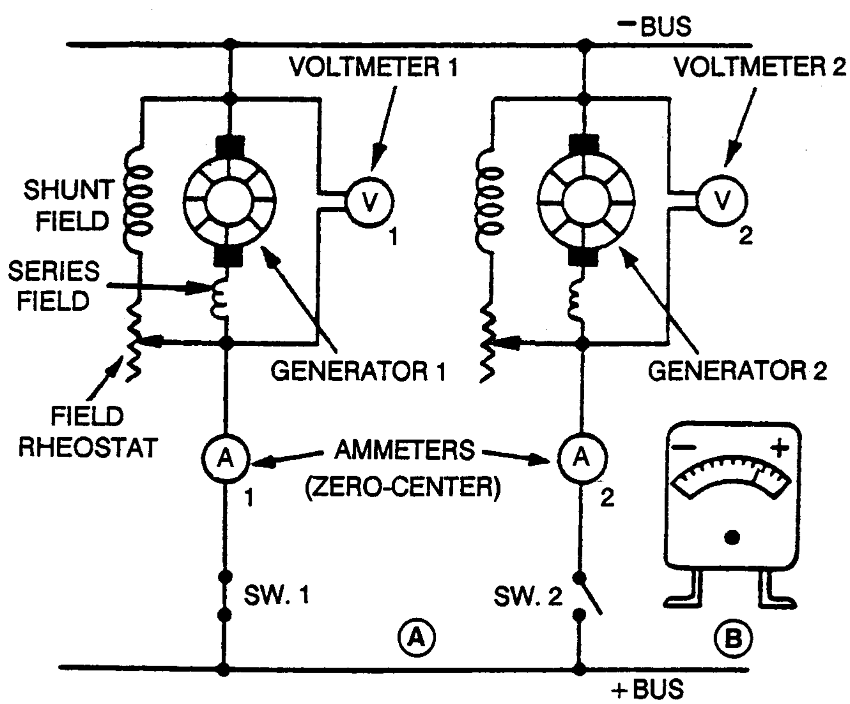

FIGURE 18-21. Parallel Generator Circuit.

voltage because of the reduction in its electrical load. Generator 1 would start to take more and more of the electrical load from generator 2. Generator 2 could eventually become a load itself, and generator 1 may even try to drive it as a motor. Basically DC generator paralleling is quite simple.

To place one generator on line –

- Start generator 1 first. Bring it up to operating speed and warm it up, according to its technical manual.
- Close generator 1 disconnect switch.
- Adjust the voltage rheostat of generator 1 to 120 volts.
- Close the circuit breaker, and place generator 1 on the bus. Check and adjust the voltage if necessary.
- Close the distribution circuit breakers, and increase the load on the generator. Watch the voltage and amperage meters. Adjust voltage as required.

To parallel generators –

- Start generator 2. Bring it up to operating speed and warm it up, according to its technical manual.
- Close generator 2 disconnect switch.
- Adjust the voltage rheostat on generator 2 for 121 volts to 125 volts (1 to 5 volts higher than the generator on line).
- Close the circuit breaker for generator 2, connecting it to the bus.
- Monitor both generator ammeter gauges. Adjust the amperage equally for each generator by turning the voltage control rheostats slowly.

The generators are paralleled. To secure a generator, follow the sequence below.

- Slowly increase the voltage on the generator you want to remain on line, and slowly decrease the voltage on the generator that is to be secured with the voltage control rheostat. Watch the ammeter gauges as the load is transferred to the generator to remain on line. Ensure the voltage stays at 120 volts.
- When the amperage reaches about 5 amperes on the generator to be secured, open that generator's circuit breaker, disconnecting it from the bus.
- Recheck and adjust the voltage on the power-generating generator. Ensure that you have not exceeded the current rating of that generator.
- Open the off-line generator disconnect switch.
- Secure the generator prime mover as required.

NOTE: Just as when dealing with any other component, always check the manufacturer's manual or technical references for specific information. The above procedure has been provided in lieu of the information lost to antiquity.

NOTE: Maintenance and repair procedures of the DC motor and generator can be found in TM 5-764, Electric Motor and Generator Repair, dated September 1964.

CHAPTER 19

DIRECT CURRENT MOTORS

INTRODUCTION

Although more expensive and difficult to maintain than AC motors, DC motors have been extensively used on shipboard because they had a great advantage where precise speed control and varying loads are concerned. Direct current is better suited to handle the various cargo-handling winches and capstans. Speed and torque requirements are precise and dependable.

In all important aspects, DC motors are identical to DC generators. Their construction and operating principles, as discussed in Chapter 18, are interchangeable. Many manufacturers make DC machines for use either as a DC motor or DC generator. The main differentiating factor between the motor and the generator is what the marine engineer must electrically control. The engineer must control what comes out of the generator and what goes into the motor. As with generators, the major classes of DC motors are –

- Shunt wound.
- Series wound.
- Compound wound.
- Separately excited.

These types of motors differ only in the connection of the field circuits (Figure 19-1). The armatures, commutators, and so forth are nearly identical with each other and with those of the generators. All four major classes of motors are widely used. This is in contrast to the generators, in which the compound wound type is used for nearly all general power applications.

PRINCIPLE OF DC MOTOR ROTATION

The operation of a DC motor depends on the attraction and repulsion principles of magnetism. When current is supplied to the field poles of a motor, the field poles turn into electromagnets. If a two-pole machine is used, north and south polarities are established toward the center of the machine.

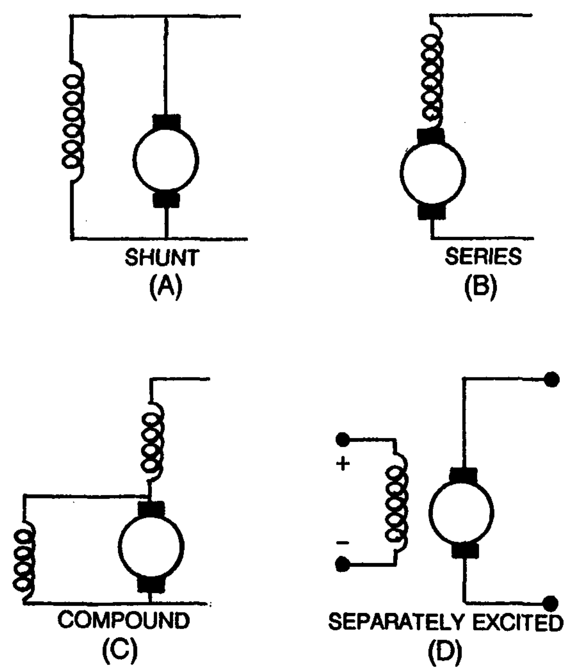

FIGURE 19-1. Schematic Diagrams of DC Motors.

Figure 19-2 view A shows how the two field poles are wound to produce the opposite magnetic effect. The magnetic lines of force, between these two unlike magnetic poles, establish a direction of movement from the north polarity to the south polarity. By themselves, these lines of force from the field poles cannot do anything to force the motor's armature to rotate.

If current is supplied from the generator through the motor's brushes and commutator to the armature windings, a magnetic field results around the armature windings (view B). DC motor torque depends on the principle that a current-carrying armature conductor has a magnetic force encircling it. These lines of force are determined by the left-hand rule for conductors. You can determine these lines of force when you know which direction the current flows through the conductor. If you visualize yourself grasping the insulated conductor in your left hand with your thumb extended in the direction of current flow, negative (-) to positive (+), your fingers will point in the direction of the magnetic lines of force. Figure 19-3 illustrates this point.

The current entering the motor armature windings and the magnetic lines of force that result around the armature windings interact with the magnetic lines of force from the field poles. Torque is produced in proportion to the current in the armature windings. The greater the armature current, the greater the motor torque. Additionally, the direction of current flow through the armature and the polarity of the field poles determine the direction that the armature will revolve.

Figure 19-4 shows the lines of force established around the armature coils. The cross signifies the current from the generator's negative terminal moving away from us into the motor armature. The dot represents the current moving toward us (and toward the positive generator terminal) in the motor armature. The left-hand rule establishes the lines of force around these armature conductors.

The two field poles show their magnetic lines of force establishing a direction from north to south (left to right). The armature conductor magnetic lines of force are circular and are determined by the current direction. The following outline describes the combining of the current-carrying

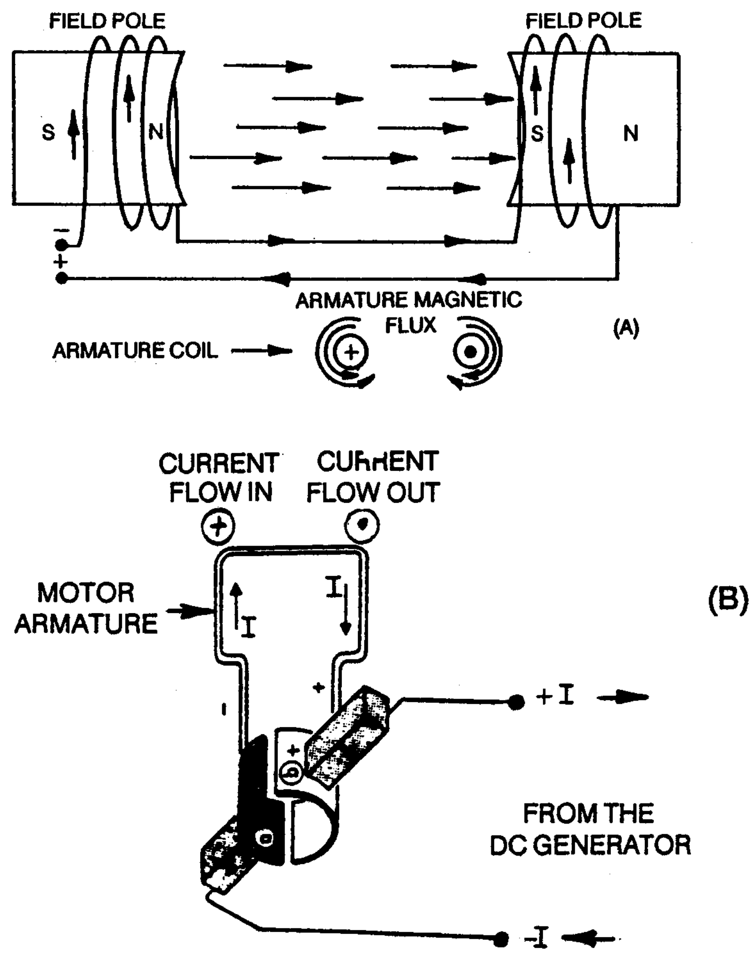

FIGURE 19-2. Lines of Force in the Magnetic Field.

armature magnetic lines of force with the field pole magnetic lines of force:

- The circular lines of force in the cross conductor and the magnetic lines of force from the field poles effectively cancel out each other directly above the cross conductor.

- The circular lines of force below the cross conductor work with or add to each other's magnetic lines of force. In this way, the additive force below the cross conductor forces the conductor up through the canceled lines of force directly above it.

- The circular lines of force developed from the dot conductor effectively cancel the magnetic lines of force from the field poles directly below the dot conductor.

- The circular lines of force directly above the dot conductor add to the magnetic lines of force from the field poles. In this manner, the dot portion of the armature is moved down.

Since both the cross and the dot conductors are connected together and rotate at the center, the armature starts to turn. This turning force developed from the magnetic lines of force is known

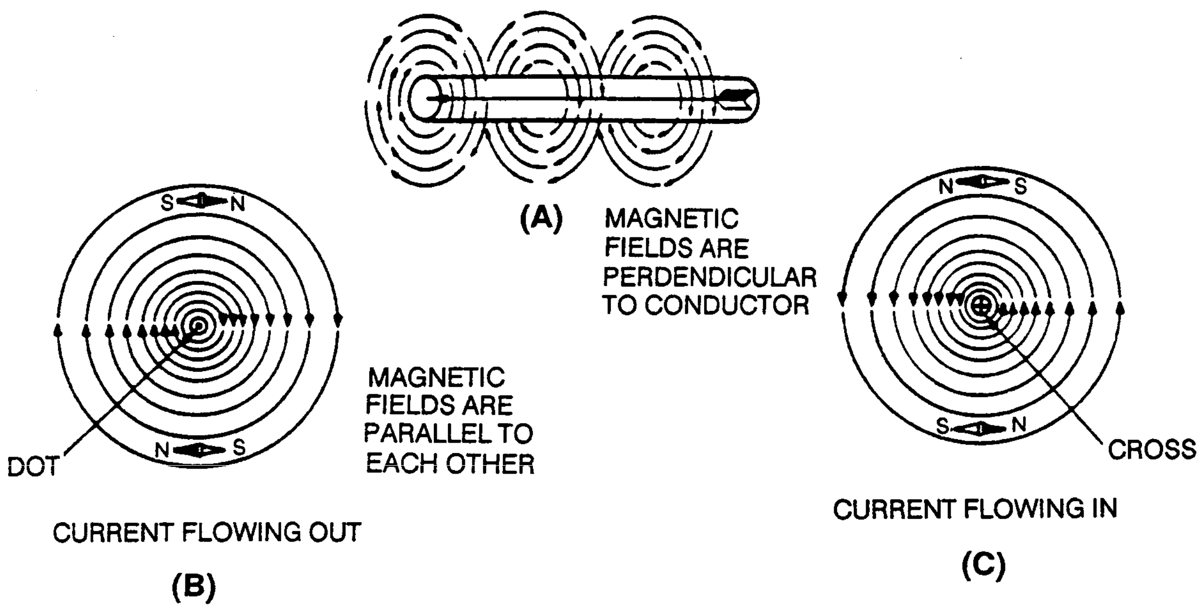

FIGURE 19-3. Magnetic Lines of Force Surrounding a Current-Carrying Conductor.

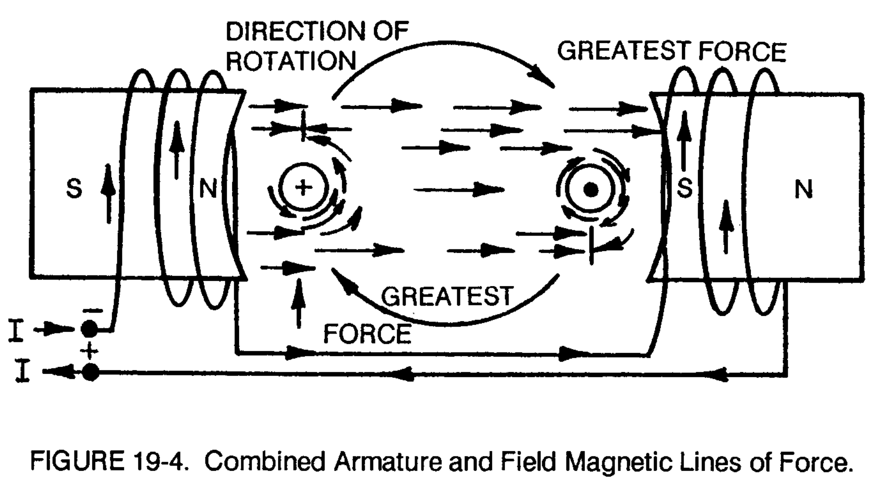

FIGURE 19-4. Combined Armature and Field Magnetic Lines of Force.

as torque. The amount of torque developed depends primarily on the current through the armature.

COUNTER EMF

Any time a conductor is moved in a magnetic field, an EMF is produced. When this occurs in a motor as a by-product of motor torque, the EMF is called counter EMF. This is because the EMF produced in the motor opposes the EMF of the generator. To distinguish between the two EMFs, the term "counter EMF" is applied to every component that is not a prime distribution system power-generating device. The ship service generator, battery systems, and the emergency generator are EMF-designated devices.

Counter EMF is directly proportional to the speed of the armature and the field strength. That is, the counter EMF is increased or decreased if the speed is increased or decreased, respectively. The same is true if the field strength is increased or decreased.

Counter EMF is a form of resistance. Any resistance opposes and reduces the current. The greater the CEMF, the less current delivered to the motor armature. When the motor is first started, during that infinitesimal moment when the armature has not yet begun to turn, armature CEMF is at zero. Maximum current is available from the generator to the motor armature because the only resistance is in the motor wire.

CEMF is produced in the motor armature as it begins to turn. The faster the armature turns, the more CEMF is generated. This counter EMF reduces the current from the ship service generator. Table 19-1 is a comparison of the armature speed, CEMF, motor armature current, and resulting motor torque for normal motor operations.

The CEMF restricts the current flow. When current in the motor armature is reduced so is the motor's torque. Since CEMF is proportional to the speed of a motor and current is indirectly proportional to CEMF, a motor automatically adjusts its speed to corresponding changes in load. When the motor's RPM decreases because of an increase in load, the CEMF is reduced, and current increases. The increased current produces greater torque, and the motor increases its RPM.

TABLE 19-1. Normal DC Motor Operation Comparisons.

	START UP	NORMAL OPERATION	INCREASING LOAD
Motor Armature Speed (RPM)	Zero	Highest	Decreasing
CEMF	Zero	Highest	Decreasing
Armature Motor Current	Highest	Lowest	Increasing
Motor Torque	Highest	Lowest	Increasing

All our DC motors conform to Table 19-1. They will deviate only in the specific characteristics of that motor's individual design. For example, all torque is increased when the armature moves slowly. In the series motor, however, its design produces an unusually high value of motor torque. This becomes the characteristic of the series motor.

A motor is not designed to operate at the excessive current levels exhibited when it is first started. If the motor were unable to increase in speed because it was too heavily loaded, sufficient CEMF would be unavailable to reduce the generator's current. This excessive current would shortly burn out the motor. A motor must be allowed to come up to its rated speed rapidly.

ARMATURE REACTION

There are individual magnetic lines of force from the field poles and the armature. Magnetic fields tend to combine. Additionally, the magnetic lines of force are distorted (or concentrated) by an iron core. Figure 19-5 shows the field flux (view A) and the armature flux (view B) individually. View C shows the distortion caused by the interaction of the two fields and the armature core movement. This distortion is known as armature reaction.

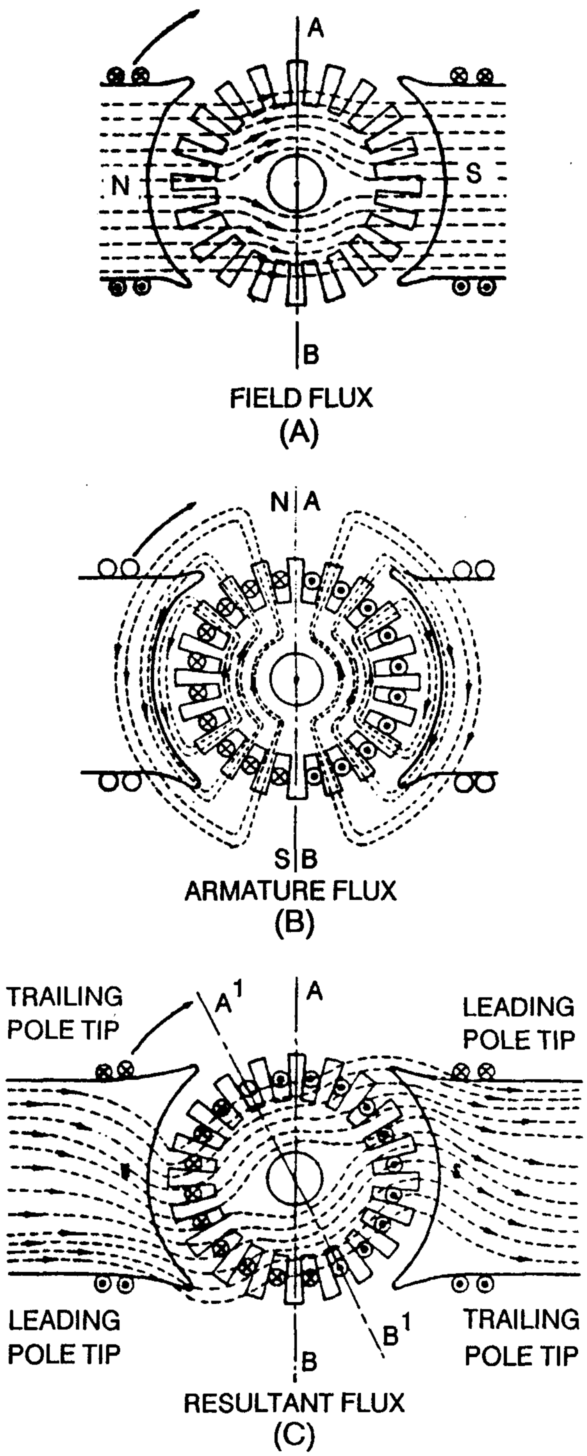

FIGURE 19-5. Armature Reaction in a Motor.

The armature current in a generator flows in the same direction as the generated EMF, but the armature current in a motor is forced to flow in the opposite direction to that of the CEMF. In a motor, the main field flux is always distorted in the opposite direction to armature rotation (view C); whereas in a generator, the main field flux is always distorted in the same direction as armature rotation. The resultant field in the motor (view C) is strengthened at the leading pole tips and weakened at the trailing pole tips. This action causes the neutral plane to shift to A'B'.

The armature reaction is overcome in a motor by the same methods used in the generator; that is, by the use of laminated pole tips with slotted ends, interposes, and compensating windings. In each case, the effect produced is the same as the results produced in the generator, but it is in the opposite direction.

To further ensure successful commutation, small slots on the brush rigging permit a slight brush position adjustment. By placing a tachometer on the motor shaft, an indication of motor efficiency may be obtained. Adjust the brush position for the fastest armature rotation in the absence of sparking.

SHUNT WOUND MOTOR

The shunt wound motor is used where uniform speed, regardless of load, is wanted. It has reasonably good starting torque but is not suited for starting very heavy loads. It is therefore used where the starting load is not too heavy, as in blowers, or where the mechanical load is not applied until the motor has come up to speed. It is essentially a constant speed machine.

The shunt motor is electrically identical with the shunt generator diagramed in Figure 19-6. It is considered a constant speed machine because speed does not ordinarily change more than 10 to 15 percent within the load limits.

The field pole circuit of a shunt motor is connected across the line and is thus in parallel with the motor armature. Both the motor armature and the shunt field are in parallel with the switchboard bus. If the supply voltage is constant, the current through the field pole coils and consequently the magnetic field will remain constant. The resistance in the field pole coils will change little. Hence, the current in the field poles will remain virtually constant. On the other hand, the resistance in the armature will change as the CEMF increases and decreases. This means that the current in the armature will vary inversely with the CEMF.

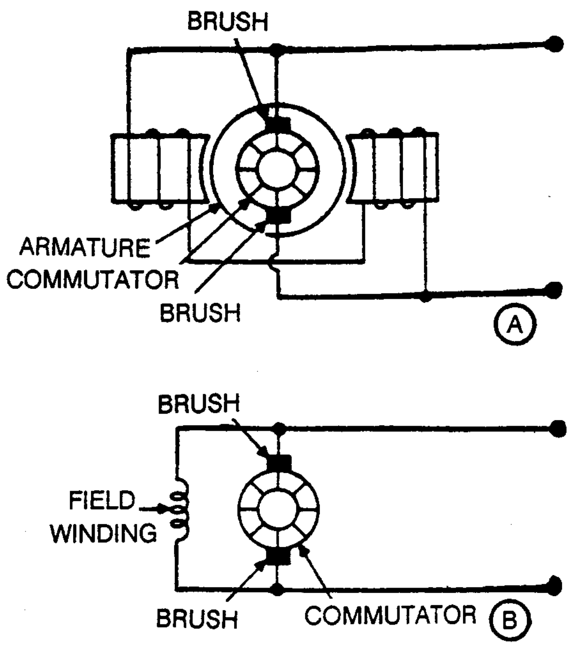

FIGURE 19-6. Shunt Motor Diagram.

When there is no load on a shunt motor, the only torque necessary is that which is required to overcome friction and windage. (Windage is a mechanical loss due to the friction between the moving armature and the surrounding air.) The rotation of the armature coils through the field pole flux develops a CEMF. The CEMF limits the armature current to the relatively small value required to maintain the necessary torque to run the motor at no load.

When an external load is applied to the shunt motor, it tends to slow down slightly. The slight decrease in speed causes a corresponding decrease in CEMF. If the armature resistance is low, the resulting increase in armature current and torque will be relatively large. Therefore, the torque is increased until it matches the resisting torque of the load. The speed of the motor will then remain constant at the new value as long as the load is constant. Conversely, if the load on the shunt motor is reduced, the motor tends to speed up slightly. The increased speed causes a corresponding increase in CEMF and a relatively large decrease in armature current and torque.

The amount of current flowing through the armature of a shunt motor depends on the load on the motor. The larger the load, the larger the current. Conversely, the smaller the load, the smaller the current. The change in speed causes a change in CEMF and armature current in each case.

No Field Condition

In order for a DC motor to turn, there must be the magnetic lines of force from the armature and the magnetic lines of force from the field poles. As shunt motors age and corrosion becomes a problem, a runaway condition may present itself. When the shunt field is opened and current is available only to the armature, the motor speed will increase dangerously.

It would seem that without the shunt field the motor would stop. However, the large metal pole shoes of the DC machine support a fairly substantial residual magnetic field. This residual magnetism is just enough to ensure that the magnetic principles that sustain the armature movement are present.

The residual magnetic field is not, however, substantial enough to develop a suitable CEMF in the armature. Without the proper proportion of CEMF, current flow to the armature increases. The more current to the armature, the greater the torque and the faster the damaged shunt motor rotates. A no field release is employed by shunt motors to prevent such a casualty. When the shunt field is de-energized, the no field release disconnects the motor from the circuit.

Speed Control

The magnetic field from the shunt motor field poles is necessary to maintain an adequate CEMF in the motor armature. As long as the CEMF is maintained, the current to the armature is restricted, and the motor operates at its rated speed.

Above Normal Speed Control. DC motors with shunt fields (both shunt and compound motors) can control the speed above a certain operating (or base) point. This is called speed control above normal speed. Figure 19-7 shows a shunt motor with full field resistance. A rheostat in series with the shunt field will determine the amount of resistance in the shunt field. The greater the resistance in the shunt field, the less current will enter the shunt field. The reduced current in the shunt field means that the magnetic field has been reduced. With a reduction in magnetic field, there is a reduction in armature CEMF. When the CEMF is reduced, the motor armature receives more current. The more current in the armature, the greater the torque developed. Therefore, motor speed increases.

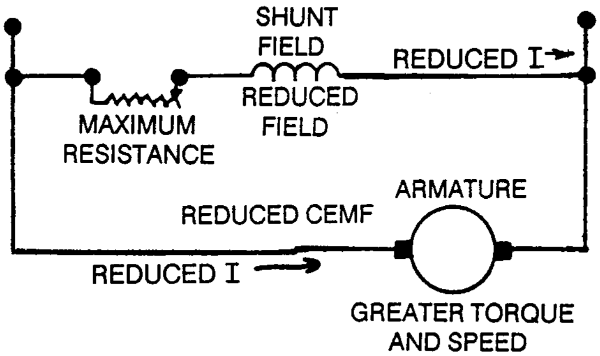

FIGURE 19-7. Shunt Motor With Full Field Resistance.

Below Normal Speed Control. To reduce the speed of the shunt or any DC motor, it is necessary to reduce the current to the armature. A rheostat in series with the armature will increase the resistance in the armature circuit or decrease the resistance in the armature circuit. As armature resistance is increased, current to the armature is decreased. The decrease in armature current decreases the torque and armature speed. Control of the armature circuit in this manner does not substantially affect the CEMF created from the rotating armature conductors within the field poles' strong magnetic field.

Use of Shunt Motors

The speed of a shunt motor remains nearly constant for a given field current. The constant speed characteristic makes the use of shunt motors desirable for driving machine tools or any other device that requires a constant speed driving source.

SERIES WOUND MOTOR

Where there is a wide variation in load or where the motor must start under a heavy load, series motors have desirable features not found in shunt motors. The series wound motor is used where high starting torque and varying speed is desired. The armature and the series field are connected in series. With high armature and field currents, it has a very high starting torque and is well suited for starting heavy loads such as the diesel engines.

Figure 19-8 illustrates the series motor. Notice that the series field is in series with the armature windings. When the motor is first started, with the negligible effects of the CEMF, current flow through the armature is high. Since the armature and the series field are in series, the current in the armature is the same current through the series winding. TM large current develops a very strong magnetic field and results in an extremely high torque. Conversely, if the motor is operating at rated speed, the CEMF will be very high, and the current in the series field winding and armature is reduced proportionally. This means that the series motor can develop a very high torque and respond to increases in loading (reductions in armature RPM) rapidly.

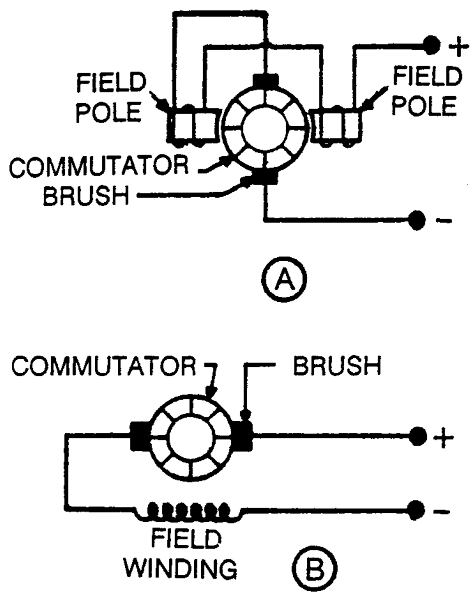

FIGURE 19-8. Series Wound Motor.

Series Motor Speed

The series motor will continue to increase in speed as long as there is more torque developed than is necessary to turn the load. This additional torque is called acceleration torque.

When a series motor is heavily loaded, it slows and produces more torque. As the load is removed, the motor increases in speed. If the load is suddenly removed from the series motor, the accelerating torque is just enough to continue to increase the motor's speed. The continuously increasing speed can destroy the motor.

No-Load Operation

With the load removed and armature speed increasing, CEMF should also increase. However, CEMF is a by-product of a conductor moving in a magnetic field. The series motor field varies with armature current, and CEMF decreases as the field decreases.

There is sufficient CEMF to reduce current to the armature, but in doing so, CEMF also limits the current to the series field pole windings. The series field still passes enough current to overcome windage and friction and develop an accelerating torque. However, at a reduced current flow, there is not enough of a magnetic field established to generate a proportional CEMF at these reduced current levels. Even though CEMF increases as speed increases, the overall reduction of current through the series field winding makes it impossible for a magnetic field to produce the CEMF necessary to eliminate the acceleration torque. Due to internal losses, the CEMF will always be overcome by the EMF in a branch circuit. After all, the EMF from the power supply was essential to the creation of the CEMF. The difference between the shunt field and the series field is that the shunt field current is not changed by the armature current.

When the load is removed from the series motor, enough current and accelerating torque is available to exceed the feeble CEMF. Armature RPM increases endlessly.

To prevent the series motor from overspeeding and destroying itself, many series motors are provided with a small shunt field to maintain adequate CEMF if the load is accidentally removed from the motor.

COMPOUND MOTORS

Compound motors, like compound generators, have both a shunt and a series field. In most cases, the series winding is connected so that its magnetic field aids that of the shunt winding magnetic field (Figure 19-9 view A). The current entering both the series field and the shunt field is moving in the same direction. Both fields produce the same magnetic field and aid each other. Motors of this type are called cumulative compound motors. In the cumulative motor, the speed decreases (when a load is applied more rapidly than it does in a shunt motor, but less rapidly than in a series motor. The cumulative compound motor is used where reasonably uniform speed combined with good starting torque is needed.

The differential compound motor is used only for low power work. Figure 19-9 view B shows the opposing magnetic fields of the differential compound motor. Notice that the series winding's magnetic field is connected to oppose the shunt winding's magnetic field. The differential compound motor maintains even better constant speed, within its load limit, than the shunt motor. But it has very poor starting torque and is unable to handle serious overloads.

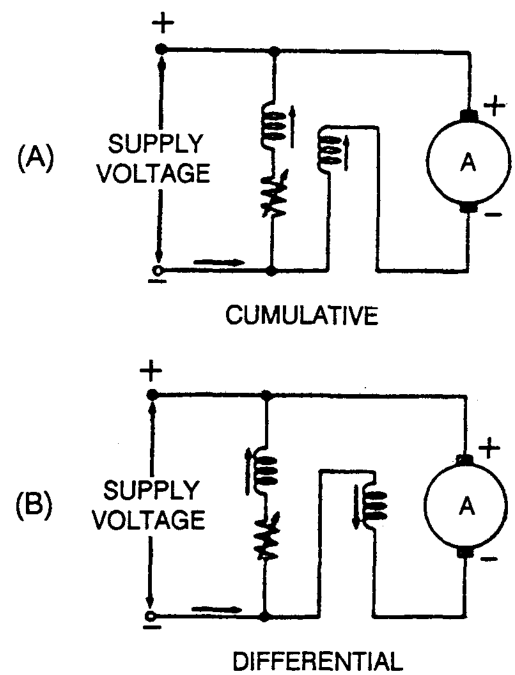

FIGURE 19-9. Types of Compound Motors.

SEPARATELY EXCITED MOTOR

Figure 19-10 shows the separately excited DC motor. This circuit diagram shows an individual armature circuit and an individual field circuit. A DC power source that is not armature-connected supplies power to the field poles. Notice the variable resistors for speed control. The armature rheostat controls speeds below the normal base speed, and the rheostat in the separately excited field controls speeds above the rated base speed. Separately excited motors are not commonly found in the Army marine field.

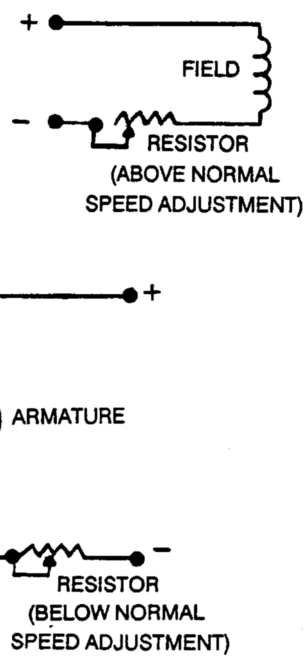

FIGURE 19-10. Separately Excited DC Motor.

DC MOTOR ROTATION REVERSAL

The direction in which the DC motor armature will rotate depends on two conditions:

- The direction of the magnetic lines of force from the field poles.
- The direction of the current through the armature windings and the resulting armature lines of force.

The section on the principle of DC motor rotation at the beginning of this chapter discussed how the lines of force from the field poles and the current-carrying armature conductors interacted to produce torque. To change the direction of armature rotation, it is necessary only to change the two fields' relationship. In practice, it is unimportant what magnetic field is changed as long as their relationship is changed.

Figure 19-11 view A shows an armature turning in a clockwise direction. By changing the direction of current through the armature alone (Figure 19-11 view B), the magnetic lines of force from the armature react differently to the field pole lines of force. The armature now moves in the counterclockwise direction. Any interposes or compensating windings must also maintain the same current direction as the armature windings to effectively eliminate the armature reaction caused by armature current. However, the shunt and/or series fields must not be changed.

The motor rotation can also be changed by reversing the current through the field poles alone. If the motor is a compound motor, then both the series and shunt fields must have their current flow reversed. The current flow in the armature must be maintained in the original direction.

The motor direction cannot be changed by reversing the polarity of the incoming power lines. Figure 19-11 view C shows the armature rotating in a clockwise direction. When the incoming power line polarities are reversed, the motor still rotates in the same direction. Although the field pole polarity and the armature conductor current flows have reversed, the relationship between the fields in view A and view C have not changed. As long as the relationship between the field pole magnetic lines of force and the armature magnetic lines of force remain unchanged, the direction of rotation will not change.

MOTOR BRAKING

Electromechanical Braking

Hoists are equipped with ordinary friction brakes so that cargo loads can be stopped exactly when and where desired. Friction brakes, like those found on the automobile, are an asbestos and metallic material that is pressed against a metal drum connected to the motor armature or winch drum. The friction between the brake pads and the drum bring the motor armature speed rapidly under control. Since the point where braking is to take place is usually remote from the operator, the brakes are usually mechanically applied and electrically released. When electrical power is not applied to the brake system, springs hold the friction brake and drum securely. Energizing a solenoid provides a magnetic field that overcomes the spring pressure, and the brake is released. This arrangement follows a fail-safe principle employed on winches and capstans. If a power failure should occur with a load hoisted, the load could otherwise drop, damaging the cargo and endangering anyone working nearby. Instead, the power failure would de-energize the solenoid, and the spring pressure would again be applied to the brake drum. A friction brake is very effective at moderate and slow speeds.

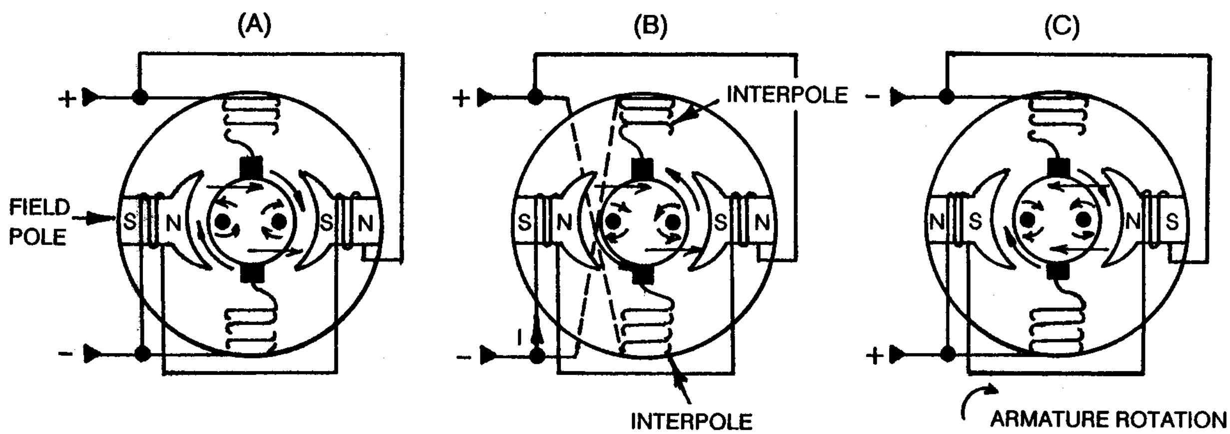

FIGURE 19-11. Reversing DC Motors.

Dynamic Braking

Depending on the motor application, either friction braking alone or in conjunction with dynamic braking can be used. There are only minor differences between generators and motors. A voltage applied to a generator will produce torque. Similarly, when a motor is mechanically turned, it will produce an EMF. Dynamic braking takes advantage of the similarities (Figure 19-12).

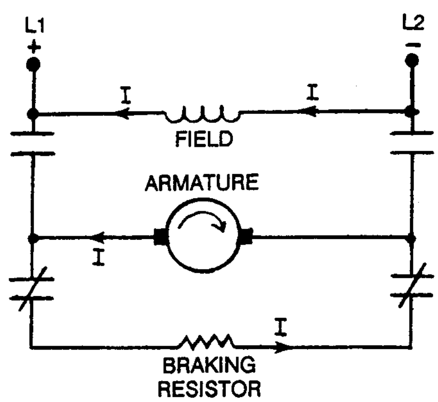

FIGURE 19-12. Dynamic Braking Circuit.

Any motor will stop eventually when power is disconnected. To decrease the armature speed rapidly, the motor is reconnected as a generator. The field poles maintain their excitation from the normal line voltage.

When the STOP button is pressed, the friction brake is applied. At high armature speeds, the friction brake is inefficient and would bum out after a few applications. To prevent this, only the armature of the motor is disconnected from the line voltage. The armature conductors are rapidly turning in the magnetic field of the field poles. Through external switches, a complete path has been provided through the armature and brush assemblies and connected to a braking resistor. As the armature conductors cut the lines of force from the magnetic field poles, the armature produces an EMF. Since there is a completed electrical circuit, a current flow exists in the armature. The magnetic lines of force from the armature current interact with the lines of force from the field poles in a way that opposes the rotation of the armature. The faster the armature moves, the greater the generated EMF and resulting opposing armature magnetic field. The greater the armature speed, therefore, the greater the slowing ability of the motor. As armature speed reduces, so does the generated EMF. A motor cannot be stopped with dynamic braking; it can only be slowed. Dynamic braking is exceptionally well suited for rapidly slowing fast-moving armatures. Together, dynamic braking and the friction brake provide an effective way to manage motor armature and winch speeds.

For additional information on the inspection, testing, troubleshooting, and overhaul of DC machines, refer to TM 5-764, *Electric Motor and, Generator Repair,* dated September 1964.

> **NOTE:** The current developed in the armature during dynamic braking is applied to a resistor bank (braking resistor), and the power is consumed as heat.

CHAPTER 20

THE ELECTRICAL CIRCUIT

INTRODUCTION

The basic items found in the ship's distribution have been presented. Power-consumers, such as motors and resistors, and those nonpower-consuming devices, such as circuit breakers and switches, have been examined. Generators, through the distribution system, provide power to the loads and switches that control or protect those loads. How these loads are controlled and protected between the last lighting or power panel will now be discussed.

WIRING SCHEMATICS

Diagrams are used to accurately portray the electrical system. Over the years, many techniques have been used to simplify the diagram for the reader. These attempts often produced more questions than they answered. Symbols were not standardized, and pictorial schematics showed the electrical system in various degrees of accuracy. Often the illustrator took for granted that his codes could be understood. In effect, there were no industry standards. Although each diagram might be electrically accurate, it was not developed for uniform individual interpretation. Today, as electrical systems become more complex, the electrical community has adopted specific standards to allow a more universal comprehension of the electrical circuits they describe. Up-to-date industry standards have been presented throughout this text. However, you will still find many variations due to physical constraints, cost, and the broad time span encompassing our fleet.

BASIC DIAGRAM

Chapter 15 used a one-line diagram of the ship's distribution system in describing the power supply and its distribution to individual loads. The one-line diagram identified the main feeder and branch circuits. Major loads and controls were also identified. This provided abroad overall view of the main electrical system. This information, although useful in certain applications, falls short of telling the complete story.

The circuit extending from the last overcurrent protective device in the lighting or control panel is called a branch circuit. The branch circuit can then be further divided into two more circuits within a motor controlling enclosure (motor controller). These circuits are called the power and control circuits.

Power Circuit

The power circuit usually consists of heavier cables used to carry the higher currents necessary to operate large components. Power circuits can be three-phase, single-phase, or direct current. In the majority of cases, the power circuit will always carry the highest current or voltage from the branch circuit.

Control Circuit

The control circuit is derived directly from the power circuit. The control circuit provides power to the timers, relays, and switches necessary to control the operating contacts of the main component in the power circuit. The control circuit "controls" the normally open contacts in the power circuit that turn on or turn off the main component.

The control circuit is almost always a single-phase derivative from a three-phase power circuit. The control circuit will almost always consist of cables intended to carry less ampacity or low voltages than the power circuit.

The control circuit provides the logic behind the operation of the main component in the power circuit. The heavy vertical lines, L1 and L2, are connected to the distribution system in an immediate and convenient manner. The control circuit consists of an electrical load, the pilot light, and a control device (the float switch). Whenever the float switch rises and completes a circuit between L1 and L2, the pilot light will light.

The pilot light in Figure 20-1 could just as easily be replaced with a relay. If the relay physically operated three normally closed contacts and these contacts were placed in the power supply lines of a three-phase motor, then the motor operation would indirectly be controlled by the float switch (Figure 20-2).

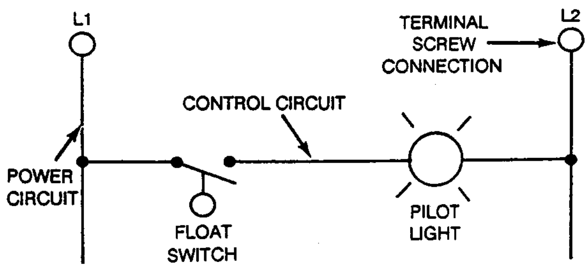

Figure 20-1. Basic Control Circuit.

As long as the float switch was in the open position (down), the E relay would not be energized. The contacts the E relay controlled would be closed, and the pump motor would run. When the float rose sufficiently to complete the control circuit, the E relay would become energized. When the relay was energized, all its contacts would change position. This means that the three E contacts would open the power circuit to the pump motor, and the motor would stop. This three-phase circuit is controlled with a simple single-phase circuit. The coil code letter E is used to make a point E simply shows possession. All E contacts are controlled by the E coil. An E coil does not control an X contact or any other contact not labeled E.

LINE DIAGRAM

The line diagram, or ladder diagram, is constructed to show the basic operation of the electrical control circuit and explain the process, in a logical order, of the electrical sequence of events. This diagram does not show the actual wiring present in the system and may even eliminate actual connections not necessary for the understanding of the circuit's operation.

The line diagram shows specifically–

- The power source supply lines provided by the power circuit, represented in heavier black lines generally running vertically.
- The control circuit, containing the controlling devices and the loads, represented by thin lines, generally running horizontally.
- The relationship of the control devices to the loads they control.

Figure 20-3 shows another line diagram. The operating coil and the pilot light represent the electrical loads in this control circuit. The stop, start, auxiliary contacts, and overload contacts represent the controlling devices.

L1 and L2 are the power-supplying lines from the ship's distribution system branch circuit. L1 and L2 provide the difference in potential (voltage)

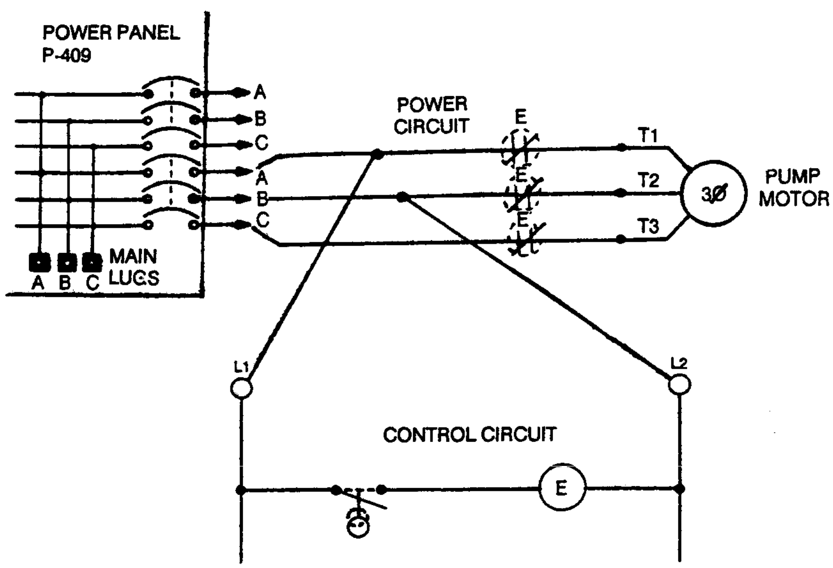

FIGURE 20-2. Control and Power Circuit.

necessary to operate the control circuit components. The actual connection of L1 and L2 to the electrical system is often left out. It is, however, readily visible when the actual circuit is inspected. Some of the more common connection points for L1 and L2 are the magnetic motor starter terminals, disconnect switch, or a small step-down transformer within the control circuit enclosure.

Figure 20-4 shows the line diagram from the LCU 2000 emergency generator control circuit. The line diagram is designed like a ladder. The heavy vertical lines represent the power supply. The vertical TB1 line represents the terminal that supplies positive potential from the DC batteries, and the GRD vertical line represents the node of the negative battery potential. The power circuit in this case receives its power from the batteries, BT1 and BT2.

The light horizontal (and some vertical) lines represent the control circuit. The line diagram is designed mainly to show the operation of the control circuit and not the power circuit. In this case, the largest load is the starter motor, incorporated in the line diagram. There is no reason to make a distinction between a "power" circuit and a "control" circuit because there is no voltage charge.

Each of the circuits contain only one electrical load. This is because the electrical system is based on parallel connections. Most loads have the same voltage requirement as the other electrical loads in the same circuit. In parallel-connected circuits, the volt age is a constant across each branch circuit. Any loads in series must equal the applied voltage available in each branch of the line diagram (ETbranch = Elbranch + E2branch).

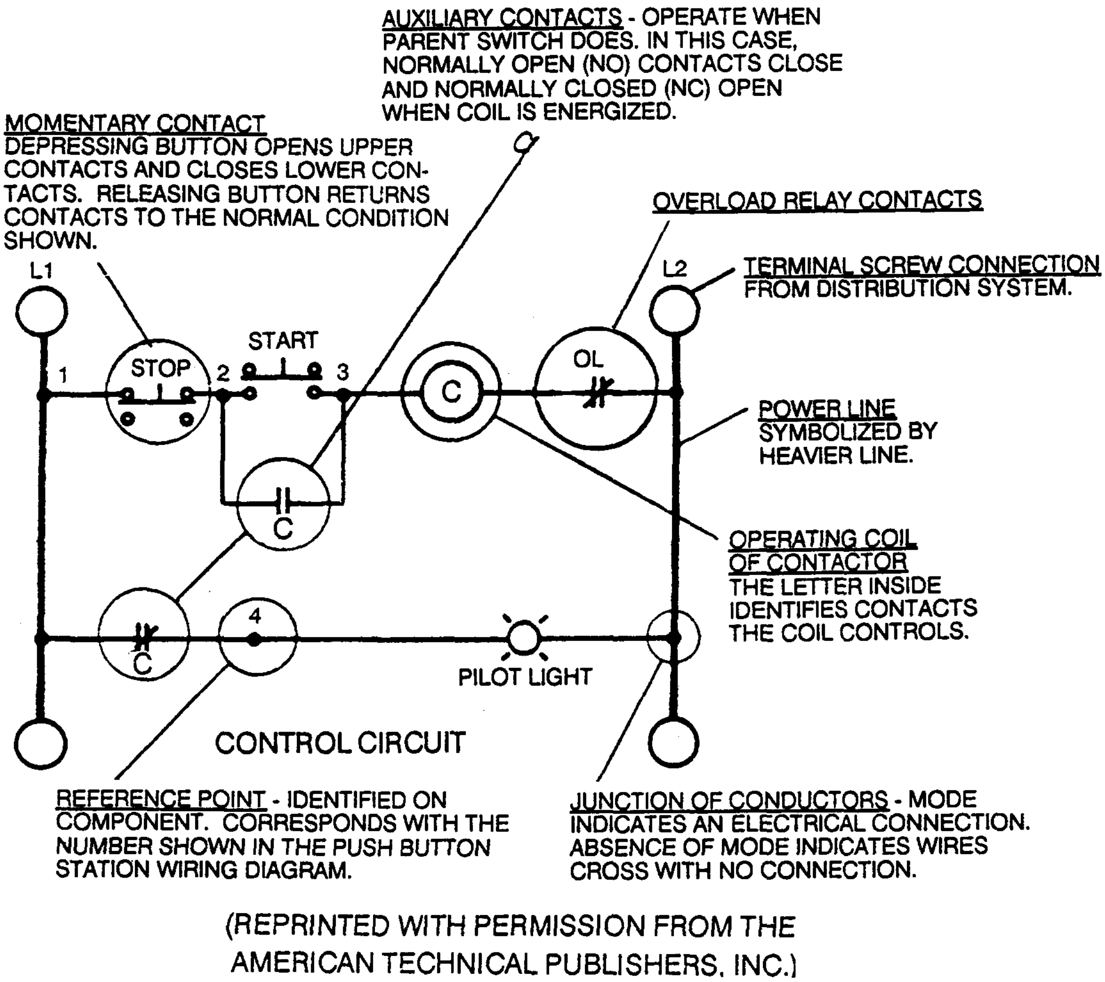

FIGURE 20-3. The Line Diagram of a Control Circuit.

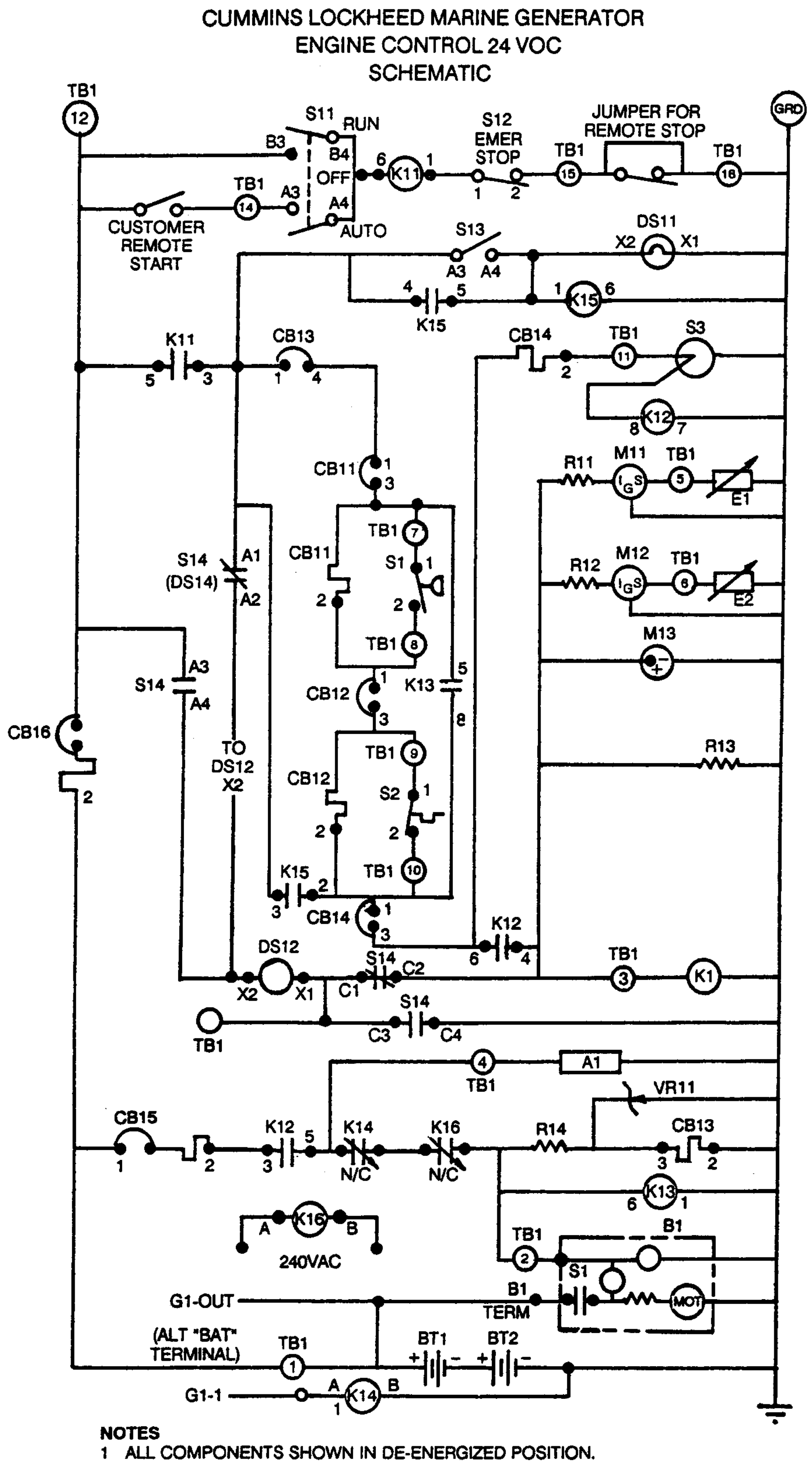

FIGURE 20-4. Emergency Marine Generator Engine Control 24 VDC Schematic.

The simple design of the line diagram is a graphic representation of operation, not the physical placement or the actual electrical connections. The line diagram needs to be consulted anytime a load is not energizing. By identifying the component that is not functioning, you can then determine the control devices, switches, and protective devices that might have prevented a completed circuit to the component.

Figure 20-4 identifies the starting motor and control circuit. Check the legend in Table 20-1 for the appropriate symbol or alphabetic/numerical code.

The vertical power lines are supplied from the batteries, BT1 and BT2. This identifies the source of power for the starter motor. Next, the starter motor, Bl, is identified.

NOTE: In the case of a starting motor and solenoid, there will always be two unusual parallel loads. This nature of the operation will be explained as required.

One circuit is completed directly from the batteries to the starter motor (Figure 20-5). The direct battery connection is a dashed line. A secondcircuit, a dotted line, provides additional control of the starter motor.

As Figure 20-6 shows, when all contacts are closed in the dotted and dashed circuits, a difference in potential exists across the starter motor armature and the solenoids. This causes the starter to operate.

TABLE 20-1. Cummins Marine Emergency Generator Engine Control 24 VDC Legend.

A-1	Governor	K-13	24-volt DC relay
A-2	Resistor	K-14	24-volt AC relay
A-4	Actuator	K-15	24-volt DC relay
A-5	Resistor	K-16	240-volt AC relay
B-1	Starter	M-11	Gauge, oil pressure
BT1,2	12-volt battery	M-12	Gauge, coolant temperature
		M-13	Meter, hour
CB-10	Circuit breaker		
CB-11	Circuit Breaker, .4 amp	R-11	Resistor
CB-12	Circuit breaker, .4 amp	R-12	Resistor
CB-13	Circuit breaker, .5 amp		
CB-14	Circuit Breaker, .4 amp	S-1	Switch, oil pressure
CB-15	Circuit Breaker, 20 amp	S-2	Switch, water temperature
CR1	Rectifier	S-3	Switch, overspeed
		S-11	Selector Switch, 3 position
E-1	Sender, oil pressure	S-12	Switch, rotary
E-2	Sender, water temperature	S-13	Switch, push button
		S-14	Switch, push button (engine fault button)
G-1	Alternator		
		TB-1	16-point terminal block
K-1	Fuel solenoid		
K-11	24-volt DC relay	W-1	Jumper wire for remote starting
K-12	24-volt DC relay		

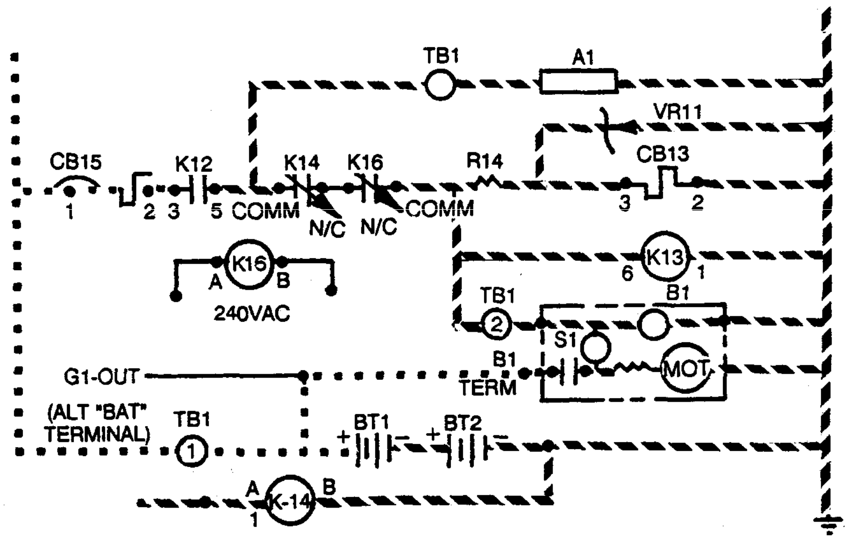

FIGURE 20-5. The Two Controlling Circuits of the Starter Motor.

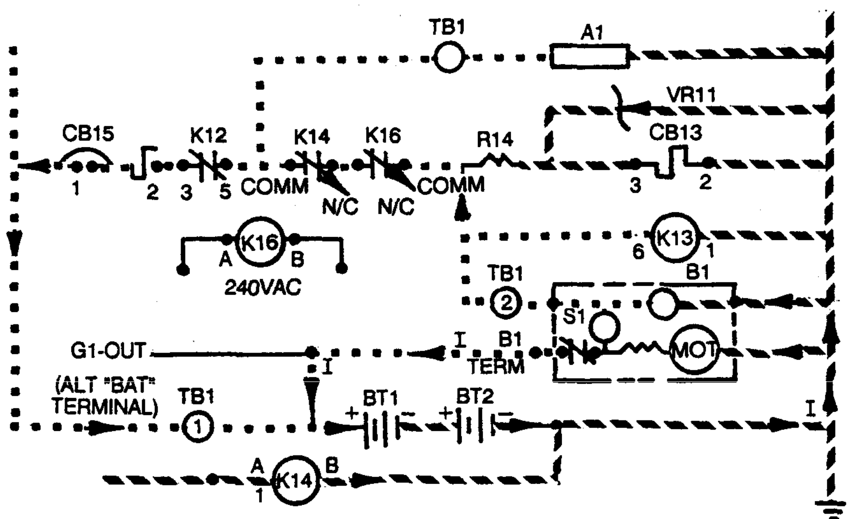

FIGURE 20-6. Complete Starter Motor Circuit.

Wiring Diagram

Now that some components and control devices have been identified on the line diagram, the wiring diagram must be consulted to locate the actual terminal connections and component locations. Figure 20-7 shows the actual equipment instrument panel. The equipment shows a complex system of wires and components, some of which you are seeking. The wiring diagram will simplify this search.

The wiring diagram shows the actual component location and the physical run of the wires. It also shows some component parts. Figure 20-8 shows the electrical interior of the starter motor and solenoid.

Figure 20-9 shows the wiring diagram. The right side door (rear inside) view is presented in the same perspective as you would see if you were looking directly into the open panel. You see the inside of the open panel door, the back wall of the cabinet (inside view), and the bottom of the cabinet (inside view) in the wiring diagram in the same way as it is presented on the equipment with the door open for your inspection. The wiring diagram provides a detailed presentation of actual component and device, as well as terminal connections for the equipment. Ensure the equipment is not modified from the wiring diagram.

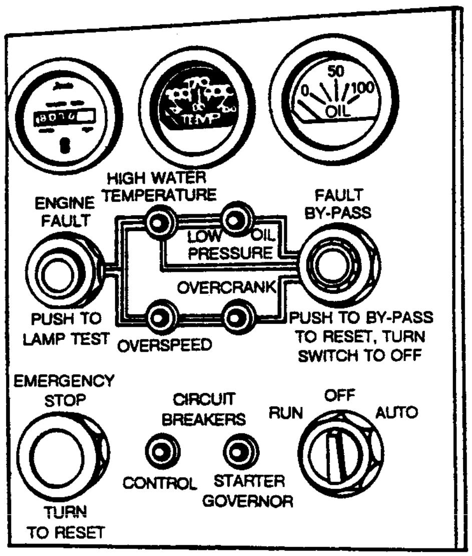

FIGURE 20-7. Emergency Electrical Control Panel.

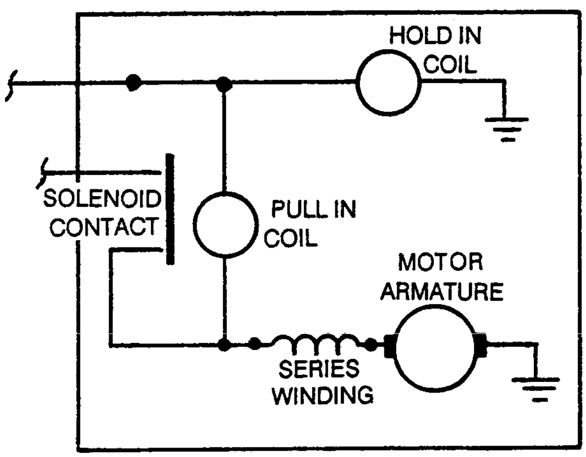

FIGURE 20-8. Starter Motor B1 Wire Diagram.

These views are separated by dashes which indicate the actual structure of the surrounding panel. The engine harness on the outside of the dashes means that these components are not located within the control panel. These components are located elsewhere on the equipment. The items are relatively large and readily identifiable. The starter motor and batteries are identified here.

From the line diagram (Figure 20-5), we determined the need to find the CB-15 circuit breaker; the K-12, K-14, and K-16 contacts; TB-1-1, TB-1-2, and B-1; and the GRD. These are all the components in the starter motor control circuit. Look for the identification markings on the wiring diagram. These are dotted lines. Notice how they are spread throughout the compartment. All the terminals are marked in the same manner that they were marked on the line diagram.

The BT1 and BT2 batteries and the B-1 starting motor from the line diagram are also identified with dased lines. Now testing and replacement can begin. The larger batteries and starter motor are easily located outside the control panel. The small controlling devices are located within the control panel exactly as they appear on the wiring diagram.

Additional Diagram Aids

Following a line diagram, such as Figure 20-4, can be very involved. When it becomes necessary to understand the entire sequence of events in the operation of a particular component, failing to interpret any of the controlling devices will circumvent any well-intentioned investigation. The line diagram can be made easier to follow when the horizontal lines are numbered. Many manufacturers have already numbered their diagrams to aid the engineer in troubleshooting. If the manufacturer has not done this already, it is advantageous to do this yourself.

CAUTION

Do not write over existing prints or permanently mark the schematics in controllers or other electrical components. Instead, use a grease pencil or make a copy from a technical manual. Maintain existing diagrams in their original conditions and ensure they are always legible. Note any modifications to a system in the logbook and procure updated diagrams.

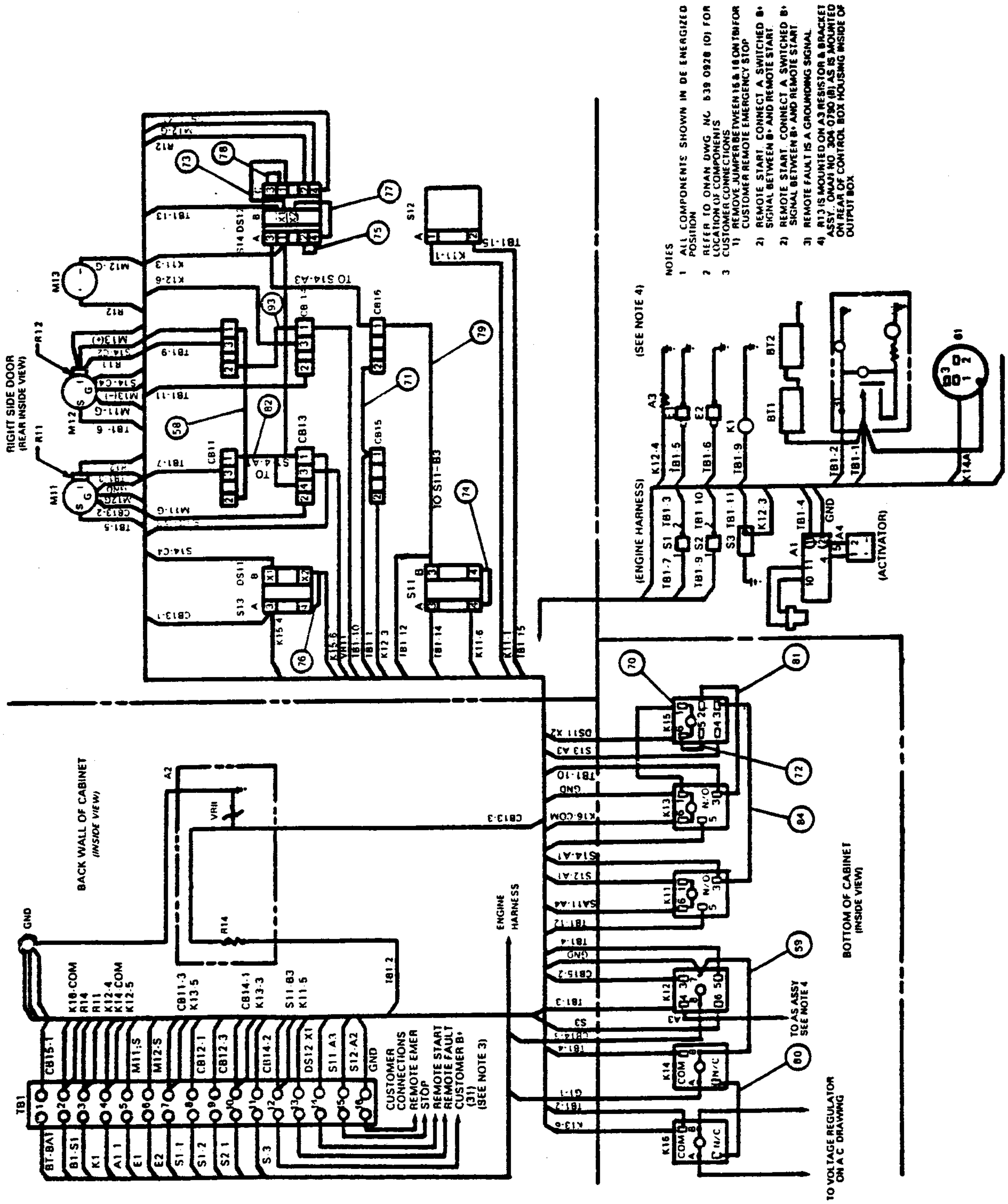

FIGURE 20-9. Wiring Diagram.

Figure 20-10 is a properly numbered line diagram. The important horizontal lines are identified with a number, in numerical sequence from top to bottom. The line numbers are always located on the left side of the line diagram. Use a straight edge to ensure accuracy.

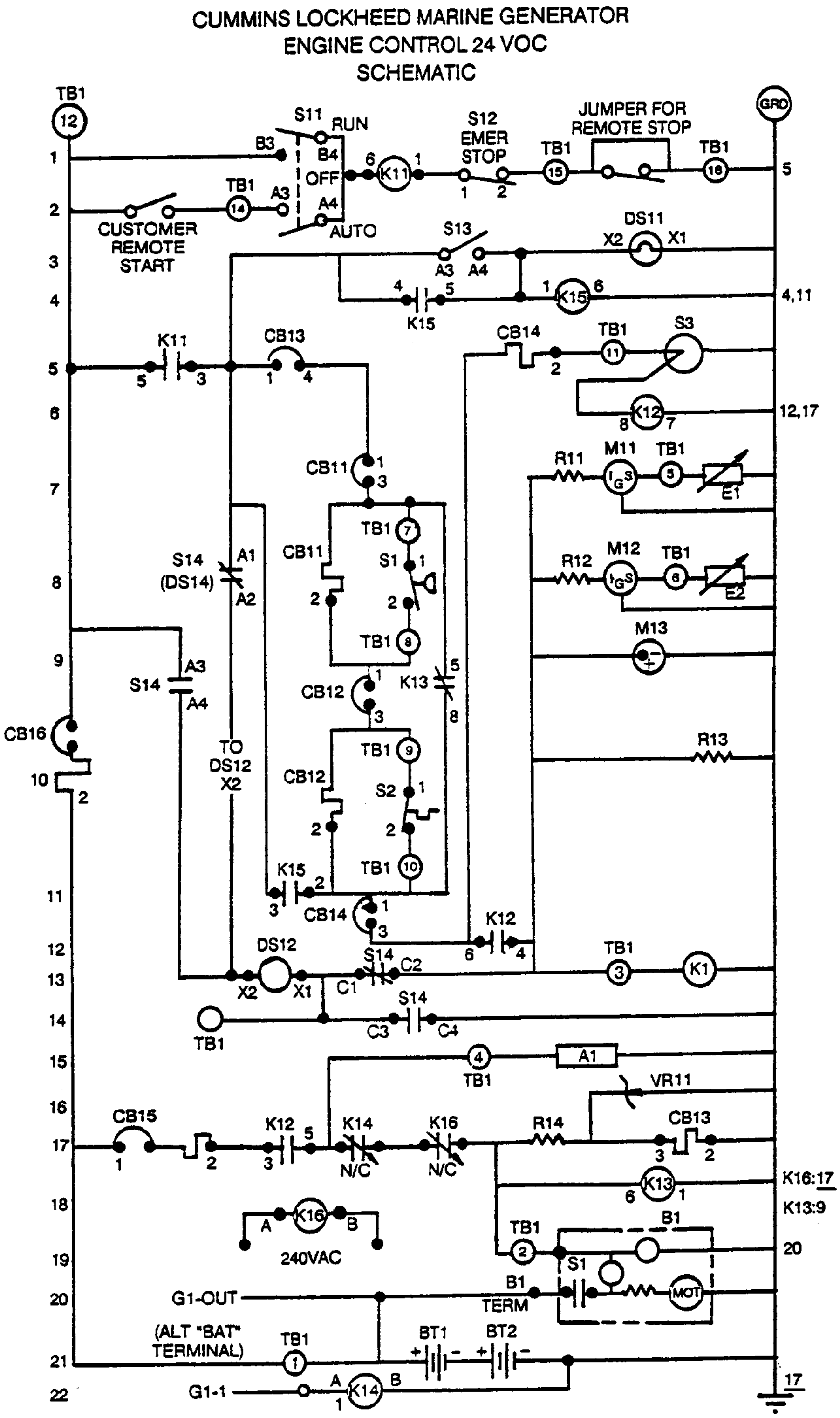

FIGURE 20-10. Numbering the Line Diagram.

The right side of the line diagram has a number on only those lines where a contactor, relay, or solenoid actually operates contacts. The K-11 relay, for example, is located on line 1. The number to the right side of the line diagram indicates two things:

- There is a component on this line that controls another part of the circuit (the K-11 relay itself).
- The location of the items being controlled.

The number 5, to the right of line 1, indicates that a set of normally open (NO) contacts exists on line 5. If the number to the right of the line diagram was underlined, such as the 17 at the bottom right of the diagram, then this would indicate that you are looking for a contact that is normally closed (NC).

A diagram always illustrates contacts, switches, and devices in their de-energized position. They are pictured in the position they are in when the device is unaffected by an outside force.

The force that changes the position of contacts can come from any number of places. For example, the force can be the electromagnetic force from a relay coil becoming energized and physically moving an armature and changing the position of its contacts. The force can also be exerted from a finger, such as the S-11 RUN / AUTO switch.

A normally open (NO) contact means that the contact's magnetic coil, for instance, has not yet been energized. Therefore, when the coil becomes energized, the normally open contact closes, and a normally closed contact would open.

BASIC CIRCUIT LOGIC

Electrical components are confined by the series and parallel rules learned earlier. These rules are essential in the understanding of the electrical diagram. To place the series and parallel rules into perspective, it is necessary to reexamine the line diagram. Every resistor, motor, coil, or indicating lamp is designed to operate at a specific voltage value. If all these loads require 24 volts DC and they are connected in parallel, then the voltage supply can properly provide 24 volts to each device. If as few as two 24-volt components were connected in series, the 24-volt power supply could not provide enough voltage to operate them properly. For this reason, loads are generally restricted to one load per line. Each component is provided with access to a positive potential and a negative potential. In alternating current, this is still true. AC provides alternating differences in potential 120 times a second at 60 hertz.

Control Device Locations

Components that consume power are always considered electrical loads. Control devices are those items that interrupt a circuit for specific reasons. Control devices should not consume power. A push button, contact, and pressure switch are components that do not consume power because there is no resistance to the flow of current when they are closed. When these devices are open, the circuit is broken, and current cannot flow. It is in the engineer's favor to locate all controlling devices in the same branch circuit as the component he is investigating. It is easier to troubleshoot a system when these components and their relationship to the load become identified. Control devices are generally located between L1 and the load. The location is subject to the constraints of room and cost and thus may be placed elsewhere in the circuit out of necessity.

Overload Placement

When overload protective devices are used in control circuits as a means of protecting motors from overload conditions, they will be located between the control circuit load and L2. Figure 20-11 shows the magnetic motor starter coil and an overload. The overload de-energizes the control circuit when it opens. The is not to protect the control circuit, but rather the motor located in the power circuit not shown.

When the overload device is used to protect the control circuit, such as a fuse or circuit breaker, then it will be located in the power supply line before the control circuit wiring (Figure 20-12).

STARTER MOTOR OPERATION OF THE LCU 2000 EMERGENCY GENERATOR

To provide an insight into the function of a control circuit and the application of electrical schematics, the emergency diesel generator starting system for the 2000 series LCU will be addressed. This is a 24-volt DC system. All the rules of electricity apply to this DC control circuit in the same way as their relationship applies to the AC control circuit. In the application of line diagrams and control circuits, there is basically no difference in determining the logical function of a circuit. If this was an AC line diagram, the first thing the engineer must do is to establish an imaginary direction for current to flow. In other words, he will "magically" stop time with the AC in a perpetual state of single direction current flow. In AC control circuits (without semi-conductors), it does not matter if he chooses his direction of current flow from L2 to L1 or from L1 to L2. The only thing that matters is consistency. Only in this manner can a logical sequence of events be discovered.

The lime diagram will be used to follow the progress of the starting system sequence of events. The following discussion will be restricted to the starter motor as closely as possible to eliminate confusion. Keep in mind that the difference in potential is available to many other circuits within this system through the same nodes. Any time a positive node and a negative node have their different potentials joined through a load, the load can become energized, and that device should function.

The interpretation of the line diagram starts with the concept of a node. The node is an exceptionally important concept. The schematic symbol represents the node as a solid dot indicating a connection of two or more wires (Figure 20-13).

Kirchhoff's Current Law states that the algebraic sum of the currents entering and leaving a node is zero. In other words, the sum of the currents entering a node must equal the sum of the currents leaving anode

I in= I out

As purposeless as it may sound at first, Kirchhoff's description of the node holds a very important meaning to the understanding of the sequence of events in the electrical system. The following definition of a node takes a few liberties. A node is an electrically conductive point in the diagram that does not consume power. The size of this point is restricted only by opened circuit devices, such as open contacts and open switches, or the existence of a power-consuming component, such as a motor, resistor, light bulb, or solenoid.

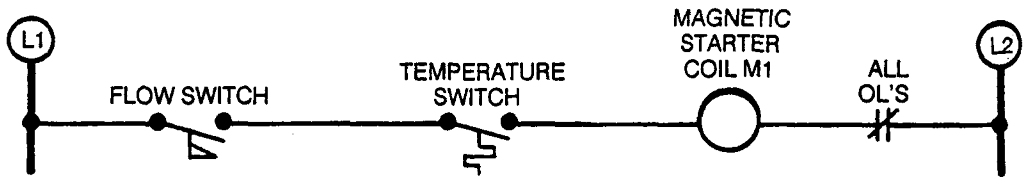

FIGURE 20-11. Line Diagram Overload.

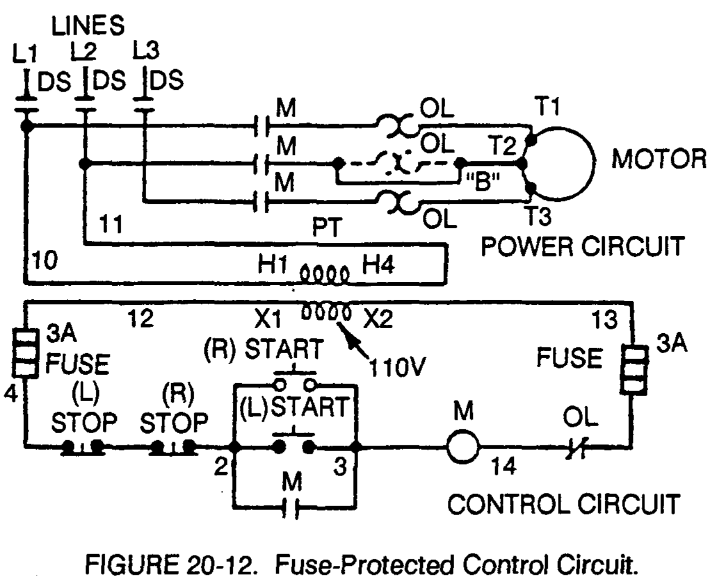

FIGURE 20-12. Fuse-Protected Control Circuit.

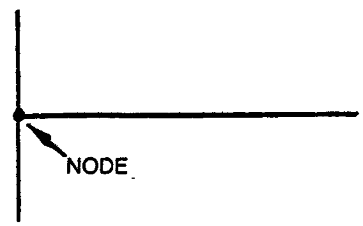

Figure 20-13. Wires Connected at a Node.

There are two nodes we are always concerned with on the line diagram: the node of positive potential and the node of negative potential. Whenever a load is connected between these two nodes, current flows through the device, and it becomes energized. In Figure 20-14, the current entering the node at L2 must equal the current leaving the node to the three other electrical power-consuming devices (loads Rl, R2, and R3).

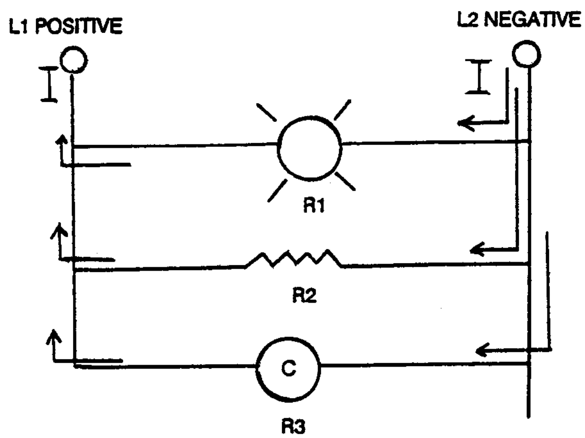

FIGURE 20-14. Current in Equals Current Out.

Figure 20-15 is a normal parallel circuit. All three loads, Rl, R2, and R3, have their polarities marked. The positive node combines all the connecting wires between the positive terminal, Ll, and the electrical load terminals of the same polarity. These are dotted lines. Another node combines all the negative areas between the L2 terminal and the electrical loads of the same polarity. These are dashed lines.

Any electrical load connected between both nodes at any place will energize. An additional light bulb, for example, can have one bulb terminal connected anywhere on the dotted line and the other bulb terminal connected anywhere on the dashed line and the light bulb will light. In Figure 20-16, both light bulbs A and B will operate. In a parallel circuit, the node represents the same point as the connection made to the generator or battery terminal directly.

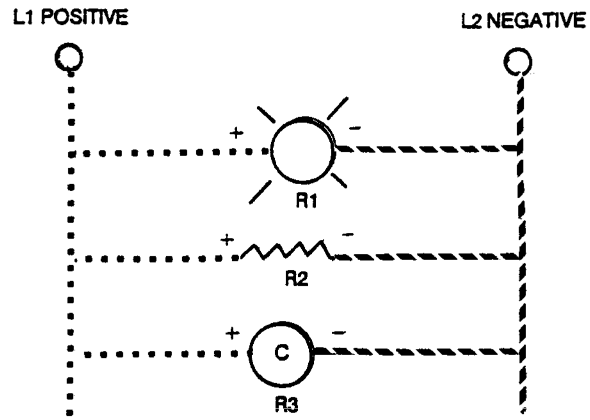

FIGURE 20-15. Parallel Circuit.

The dotted line node is the positive potential of the circuit; the dashed line node is the negative potential of the circuit. Anytime an electrical load is connected between a difference in potential, current will flow, and the component will be energized.

Starting Motor Circuit

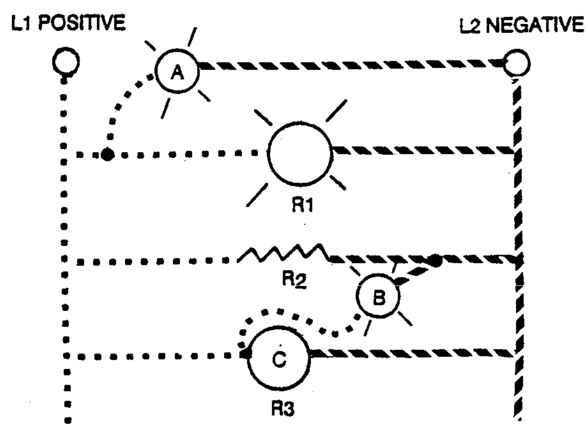

FIGURE 20-16. Two Loads Added to the Parallel Circuit.

This section presents the basic starting motor circuit. The use of the emergency generator starter and charging circuit for the 2000 series LCU contains many additional variables. The automatic emergency starting functions, electronic governor, fuel module, and alternator circuit are also incorporated in the following diagram. So the circuit can be analyzed by the lime and wiring diagrams, the starter motor will be started by the most direct method possible keeping with the actual sequence of events in the process. Solid-state DC circuitry and electronic governor control will not be addressed at this time. For additional information and all possible production updates, consult the applicable technical manual.

Developing the Node

Any device that does not consume power, such as a closed set of contacts, a circuit breaker, or stop push button (closed), becomes part of that node. Figure 20-17 shows the engine control line diagram nodes. The dotted lines indicate the positive node, and the dashed lines indicate the negative node. Anywhere a voltmeter is connected between the dotted and dashed lines, a reading from the power source should be observed. This reading indicates a difference in potential. In this case, about 24 volts DC should be noted from the batteries.

An open defines (establishes) a difference in potential in the branch circuit of Figure 20-18. This takes precedence over any other item. If there is an open to either side of a load, then current does not move, and the difference in potential is established by the open. The node will extend through the load to one of the open terminals. The same potential (in this case, negative) will exist on each side of the load. If there is no difference in potential, then there is no voltage to be measured.

Second in priority is a power-consuming device that current actively moves through as shown in Figure 20-19. The voltage consumed, pushing current through the load, defines the difference in potential.

Only when there is a completed circuit to the load does the difference in potential separate on each side of the load. If there is an open to both sides of a load, then the outer open terminals connected directly to the power circuit define the furthest reaches of the node. In Figure 20-20, neither node extends to or through the load.

Another power supply or capacitor may define a difference in potential in the branch. Care must be used when analyzing voltage readings.

If a difference in potential is not separated (defined) by any of the above mentioned components or devices, then the circuit is short-circuited.

A difference in potential is an imbalance of nature's atom. The negative electrons are at one node, and the positive ions are at the other node. When an adequate path is completed between the two nodes, the electrons move (current flows) to the positive terminal, energizing any electrical load they pass en route.

When a normally open switch closes, the node is extended as shown in Figure 20-21. Pressing and closing the RUN / AUTO switch S-11 extends the positive node to a load.

When a positive and negative node (the two differences in potential) are actually permitted to reach the load, the load becomes energized by the electrons. The electrical load, in this case relay K-11, becomes energized. K-11 controls its normally open contact online 5. The normally open contact labeled K-11 on line 5 now closes (Figure 20-22).

The dotted positive node has been extended to several circuits: the engine fault bypass (S-11), the engine fault indicator (DS-12), and the circuit to starter relay K-12.

The positive node is temporarily extended to the overspeed trip (S-3) and the starter relay K-12 and through the CB-11 and CB-12 circuit breakers. This is temporary because these thermal circuit breaker elements have a relatively high resistance to them. Unless the oil pressure builds sufficiently to close the oil pressure switch (S-1) and shunt the current around the thermal elements, the circuit breakers will open. This provides a limited period of time for the generator to operate before the pressure (S-1) and temperature (S-2) switches activate and control the relay K-12.

Figure 20-23 shows the relay K-12 energizing. K-12 has two NO contacts. NO K-12 contact closes

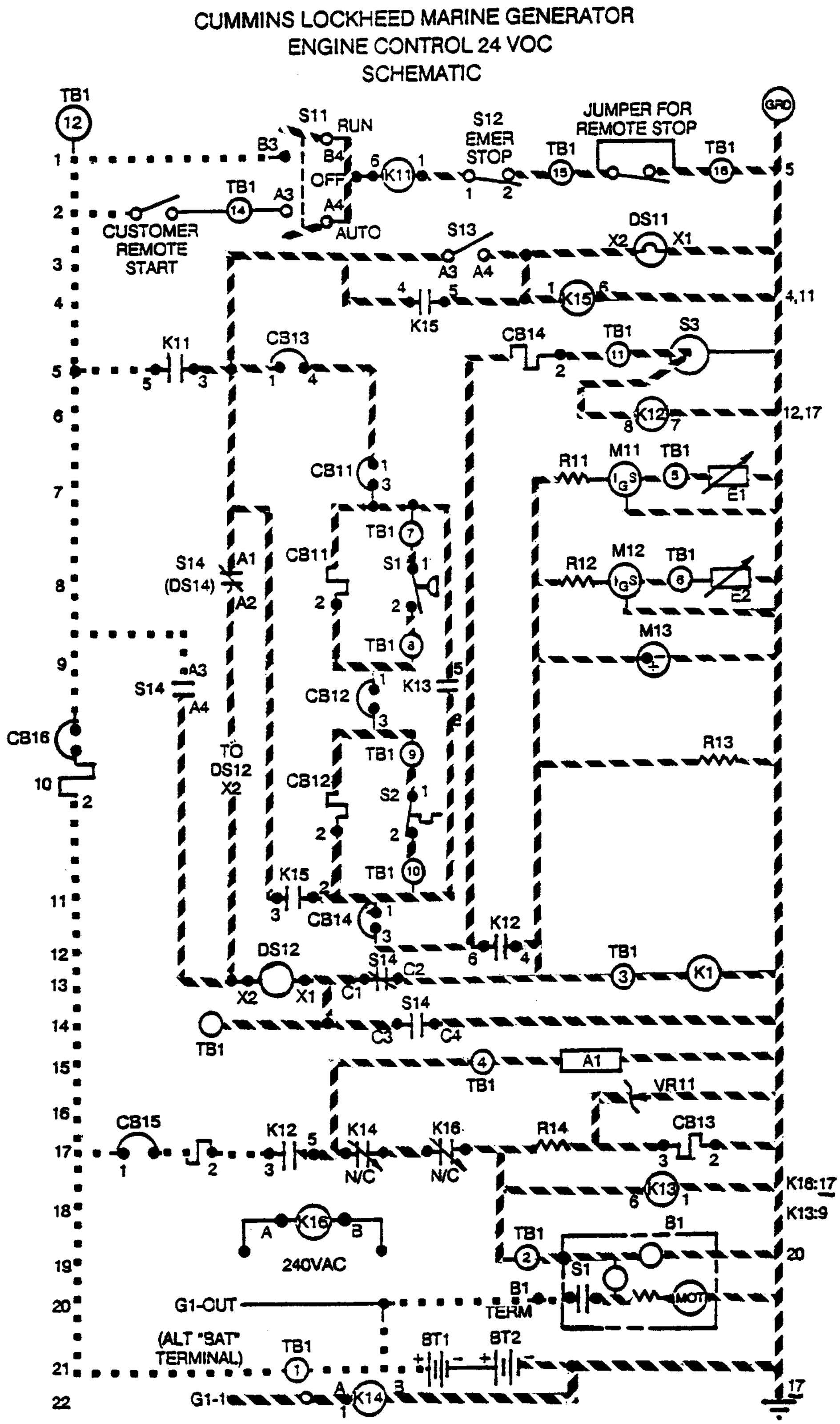

FIGURE 20-17. Initial Areas of Difference in Potentials Expressed as Nodes.

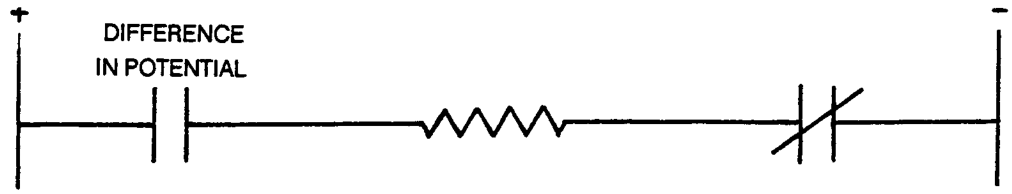

FIGURE 20-18. Primary Difference in Potential Defined by an Open.

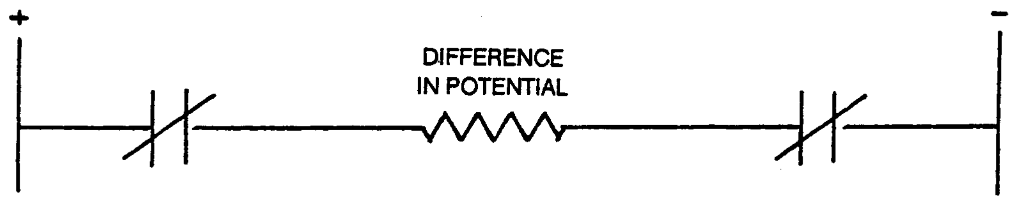

FIGURE 20-19. Secondary Difference in Potential Defined by a Power Consuming Service.

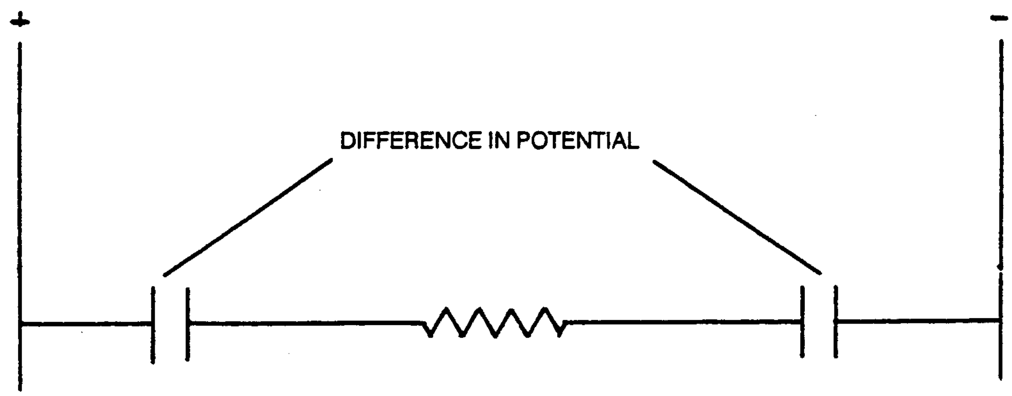

FIGURE 20-20. Difference in Potential Defined by More Than One Open.

Figure 20-23 shows the relay K-12 energizing. K-12 has two NO contacts. NO K-12 contact closes on line 12 and extends the positive potential to the following circuits:

- M-11, the electronic oil pressure gauge.
- M-12, the electronic water temperature gauge.
- M-13, the hour-meter gauge.
- K-1, the fuel solenoid. This provides fuel to the diesel engine for starting.

The K-12 relay also has contacts it influences online 17. The NO K-12 contacts close and complete the following circuits:

- A-1, the electric governor control.
- VR-11 and CB-13, for current monitoring.
- K-13, a 24-volt relay.

NOTE: K-13 energizes with the starting system long enough to bypass current around the thermal elements of CB-11 and CB-12. After the diesel starts, the oil pressure switch closes, and K-13 contacts are no longer needed. Moments later, relay K-13 de-energizes.

- B-1, the starter motor solenoids.

When the difference in potential is extended to the starting motor solenoids, the starter motor contacts close, and the starter motor revolves (Figure 20-24).

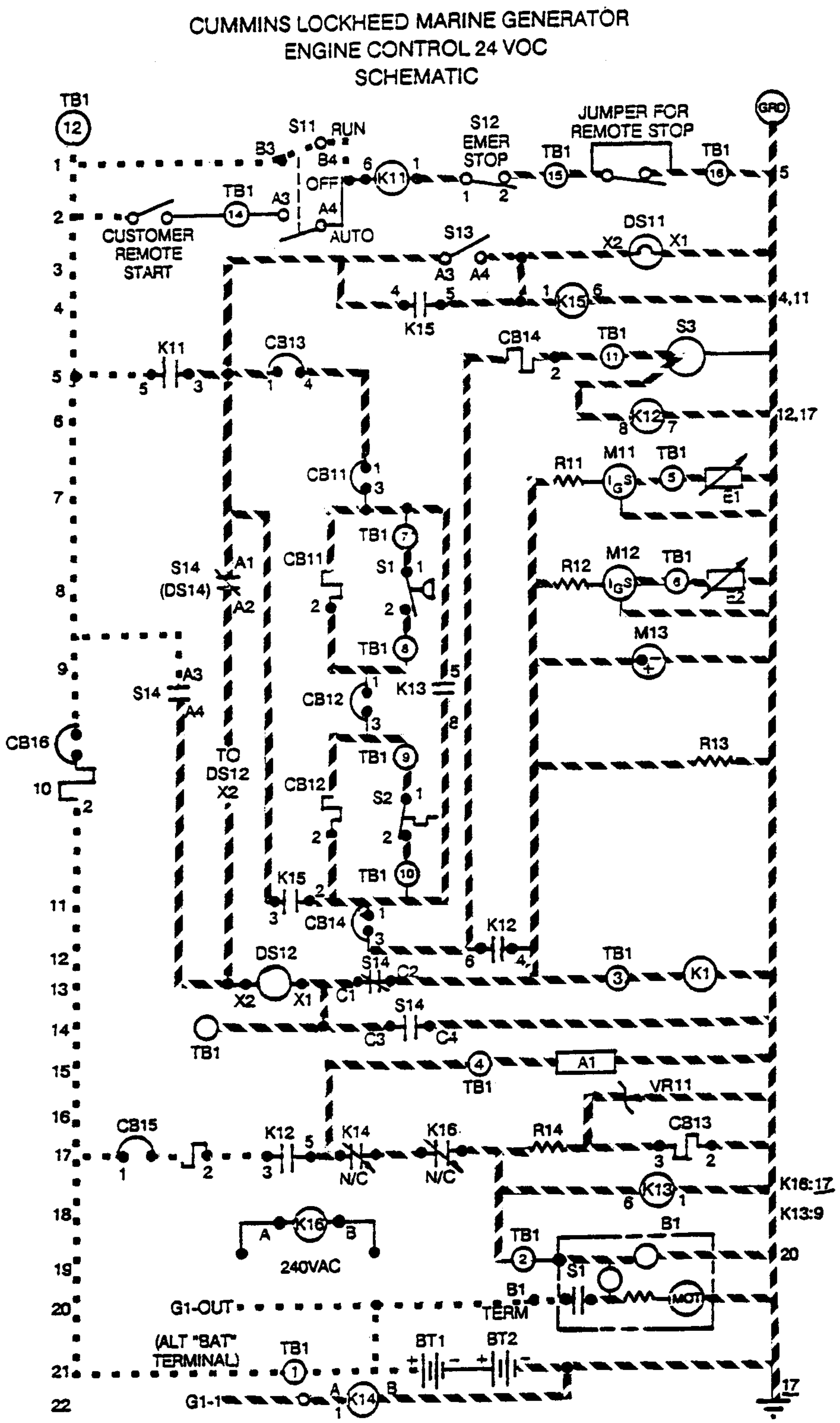

FIGURE 20-21. RUN/AUTO \Switch Closed and the Positive Node Extended.

CUMMINS LOCKHEED MARINE GENERATOR
ENGINE CONTROL 24 VOC
SCHEMATIC

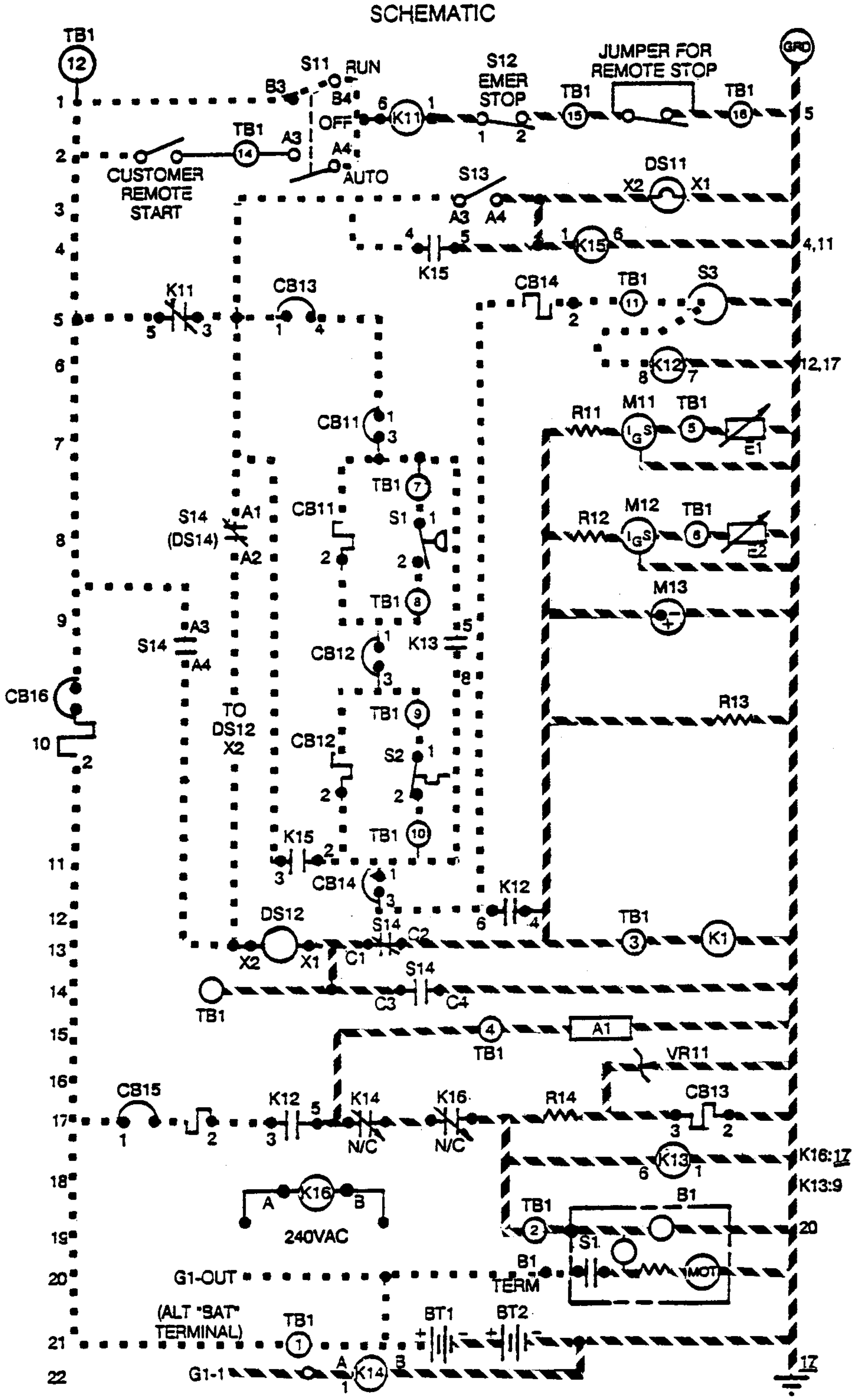

FIGURE 20-22. Contacts K-11 Closed, Extending the Positive Potential.

CUMMINS LOCKHEED MARINE GENERATOR
ENGINE CONTROL 24 VOC
SCHEMATIC

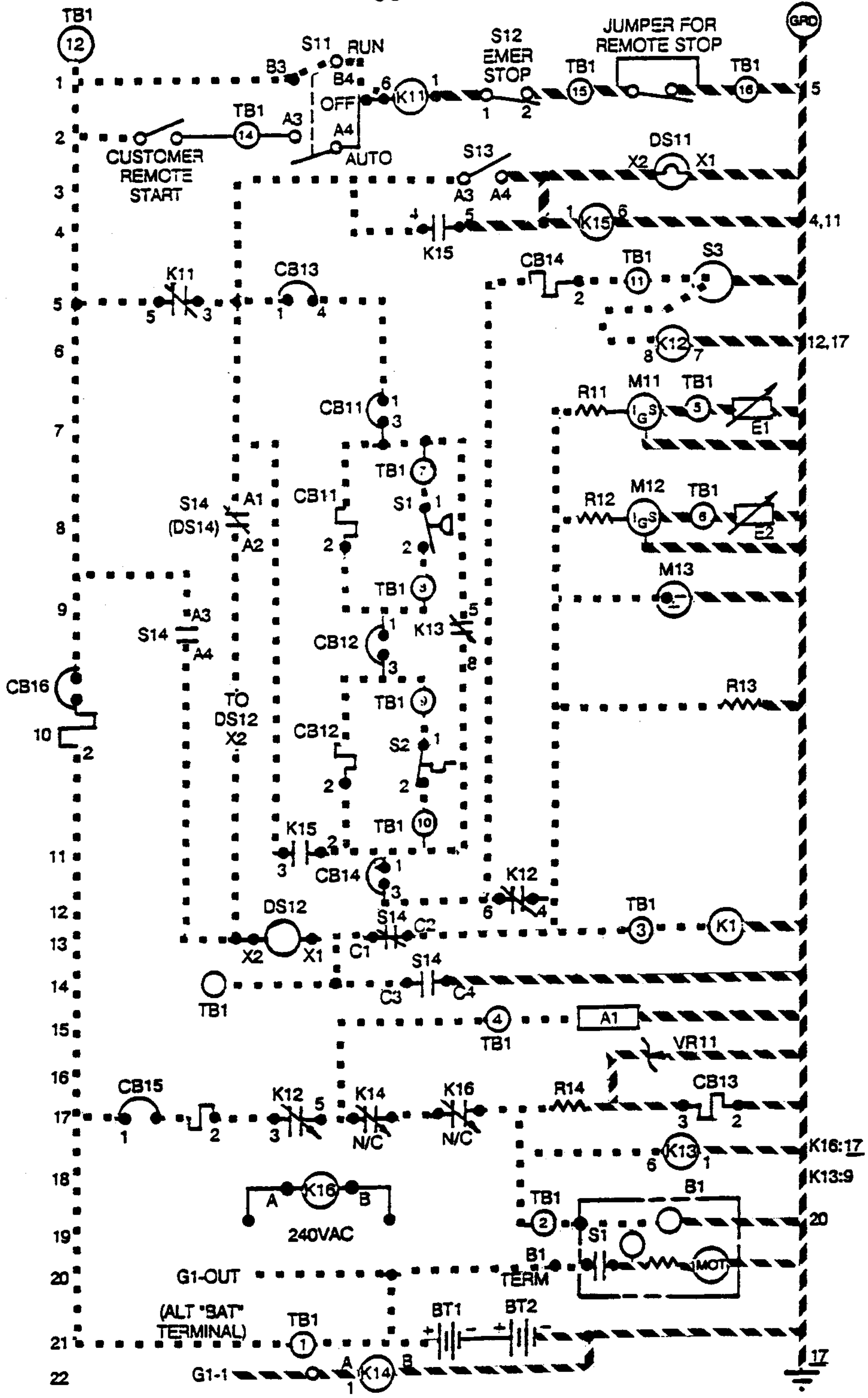

FIGURE 20-23. Relay K-12 Energizes.

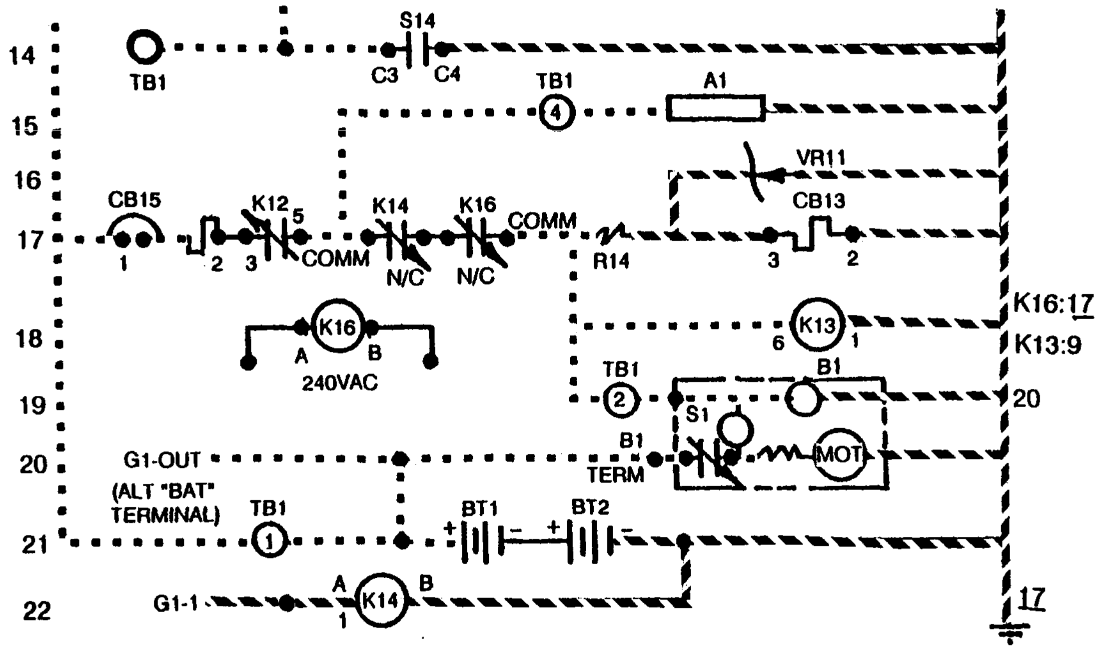

FIGURE 20-24. Potentials Extend to the Starter Motor.

STARTER MOTOR SOLENOID

The starter solenoid has two different coils. Both of these coils are needed to shift the starter pinion (Figure 20-25) into mesh with the flywheel and to close the solenoid contacts.

Pull-In Coil

The pull-in coil is pictured as the coil in the starter B-1 with the vertical terminals in Figure 20-8. The pull-in coil is made of heavy copper conductors. This is necessary because the current that is going to go through the armature and series winding will also go through the pull-in coil. The armature, series winding, and pull-in coil are all heavy-gauge copper conductors of low resistance. The current draw by a slow-moving series motor is enormous.

The high current going through the pull-in coil, acting in conjunction with the hold-in coil (shown in Figure 20-8 with horizontal terminals), pulls the shifting fork and moves the pinion into position with the flywheel. If this extremely high current were to pass through the pull-in coil for more than a moment, the pull-in coil would overheat and burn up. As the shifting fork is pulling the pinion into position with the flywheel teeth, contacts S-1 in the starter motor (Figures 20-24 and 20-26) close and eliminate the pull-in coil from the circuit. Notice how both sides of the pull-in coil have the same positive polarity (and therefore no difference in polarity) in Figure 20-24.

The starter motor series field and armature are now directly connected to the battery voltage, and the starter armature rotates. Even though the pull-in coil is eliminated from the starting circuit, the S-1 contacts remain closed. This is because of the hold-in coil.

Hold-In Coil

The hold-in coil is a thin-diameter conductor. There are many turns of this conductor. A much higher resistance exists than existed in the pull-in coil. Together the pull-in and the hold-in coil were necessary to shift the pinion into position. Once the iron core of the solenoid was positioned completely within the solenoid field, less magnetic force was necessary to retain it in position. The hold-in coil maintains the S-1 contacts closed until the diesel starts, and the circuit is de-energized.

Once the diesel starts, the alternator produces power and energizes coil K-14 (on line 22), or the voltage regulator energizes coil K-16 (on line 18) and proves the generator is actively producing power (Figure 20-27). Contacts K-14 and K-16 on line 17 open and disconnect the starter motor from the circuit. Relay K-13 is also de-energized, and now the oil pressure switch (S-1) and the water temperature switch (S-2) monitor the safe operation of the generator prime mover by controlling the circuits to the governor control (A-1) and the fuel solenoid (K-1) with the now closed contacts from the K-12 relay.

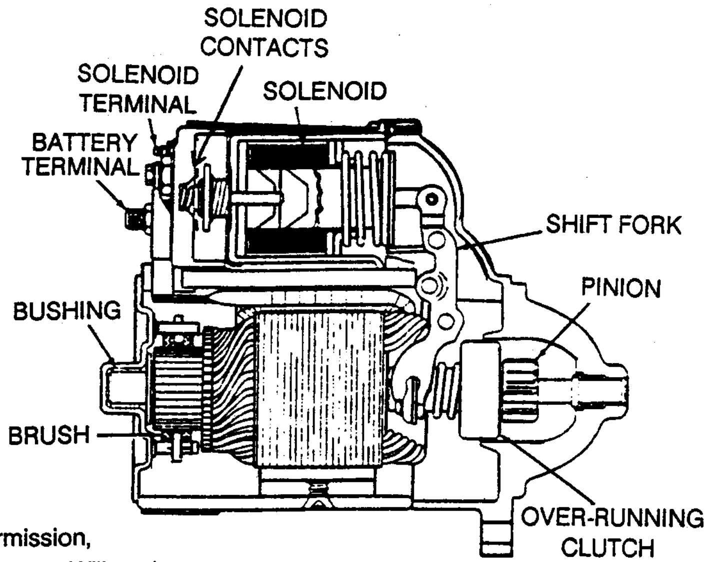

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FIGURE 20-25. Starter Motor Cutaway With Overrunning Clutch.

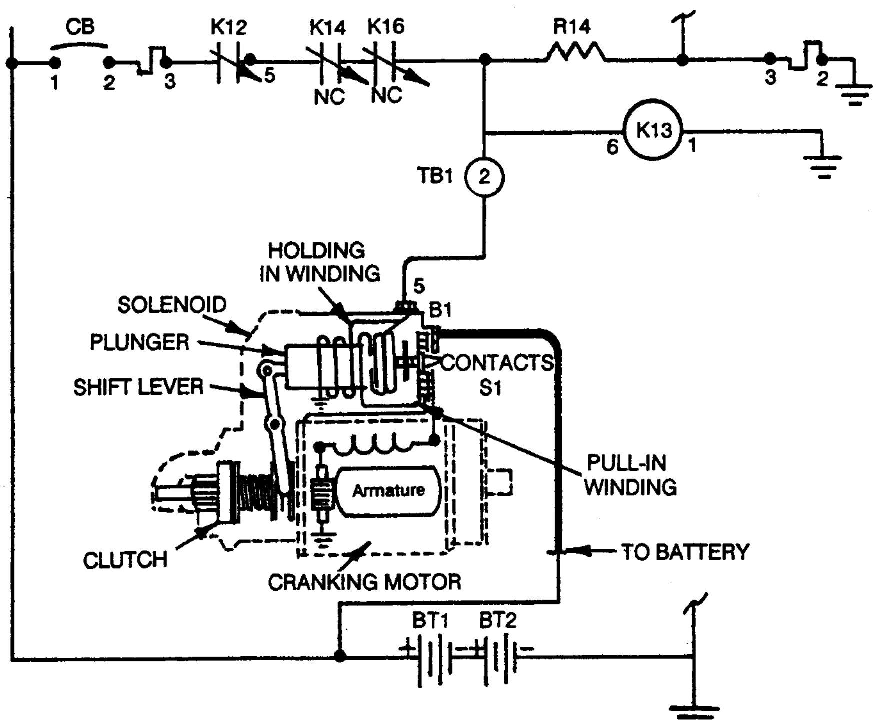

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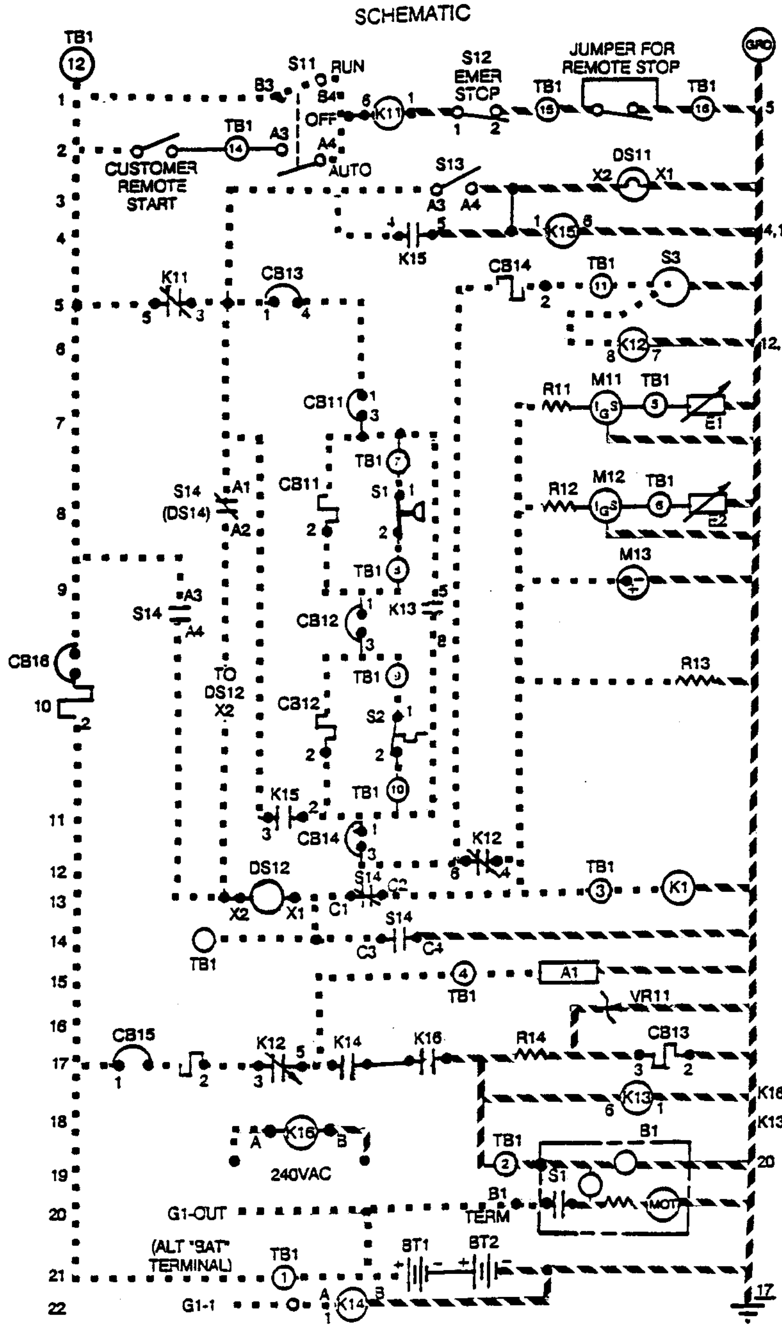
FIGURE 20-26. Pictorial Starter Motor Circuit.

CUMMINS LOCKHEED MARINE GENERATOR
ENGINE CONTROL 24 VOC
SCHEMATIC



NOTES
1 ALL COMPONENTS SHOWN IN DE-ENERGIZED POSITION.
2 REFER TO ONAN DWG. NO. 539-0928 (D) FOR LOCATION OF COMPONENTS.
3 CUSTOMER CONNECTIONS
   1) REMOVE JUMPER BETWEEN 15 & 16 ON TB1 FOR CUSTOMER REMOTE EMERGENCY STOP.
   2) REMOTE START CONNECT A SWITCHED B+ SIGNAL BETWEEN B+ AND REMOTE START.
   3) REMOTE FAULT IS A GROUNDING SIGNAL
4 R15 IS MOUNTED ON A A3 RESISTOR & BRACKET ASSY ONAN NO. 304-0790(B). A3 IS MOUNTED ON REAR OF CONTROL BOX HOUSING INSIDE OF OUTPUT BOX.

FIGURE 20-27. Starting Motor Disconnected from the Circuit.

APPENDIX

ELECTRICAL SYMBOLS

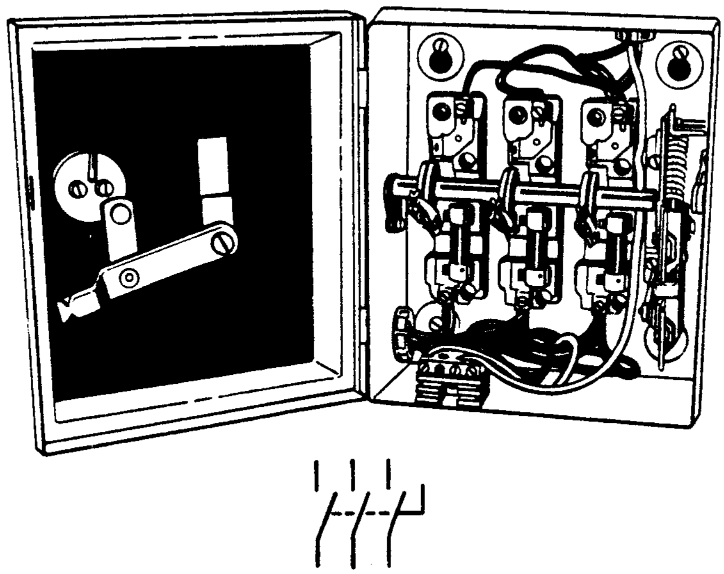


FIGURE A-1. Disconnect.

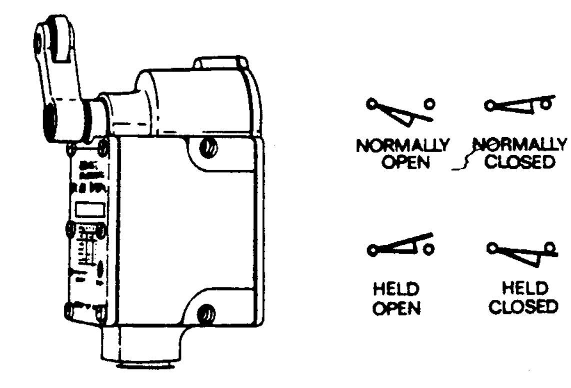


FIGURE A-2. Limit Switches.

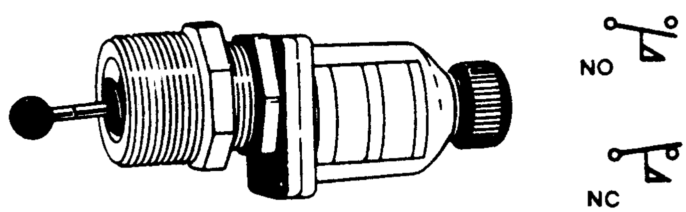


FIGURE A-3. Flow Switch (Air, Water, and So Forth).

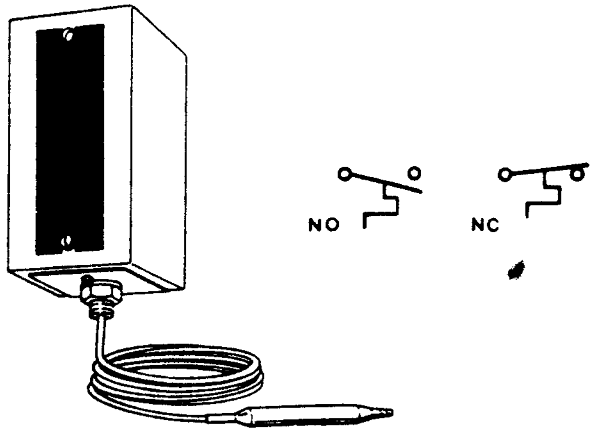


FIGURE A-4. Temperature-Actuated Switch.

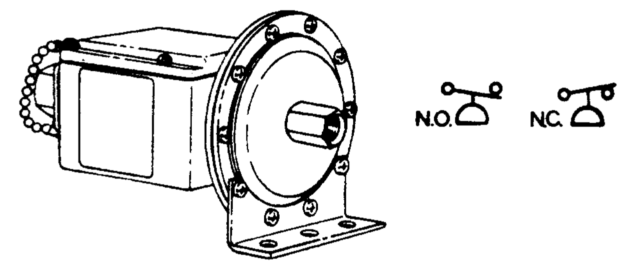
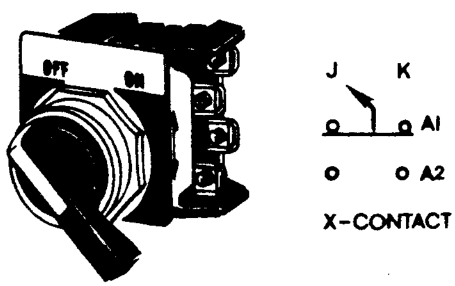


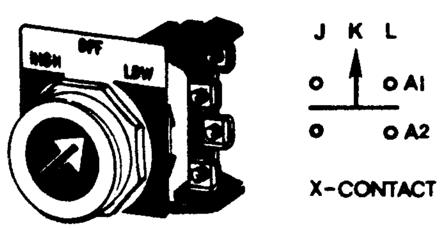
FIGURE A-5. Pressure and Vacuum Switches.



	J	K
AI	X	
A2		X

X-CONTACT CLOSED

FIGURE A-6. Selector Switch, 2-Position.



	J	K	L
AI	X		
A2			X

X-CONTACT CLOSED

FIGURE A-7. Selector Switch, 3-Position.

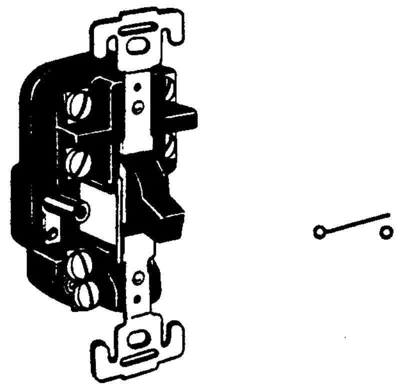


FIGURE A-8. Toggle Switch.

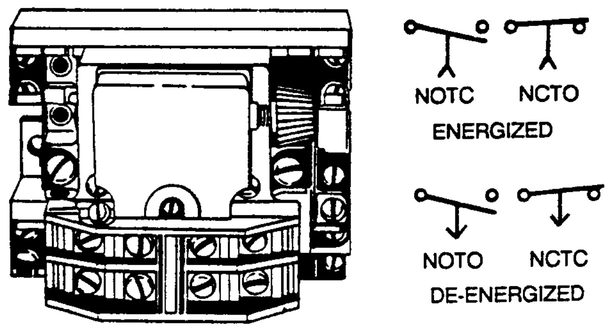


FIGURE A-9. Pneumatic Timer.

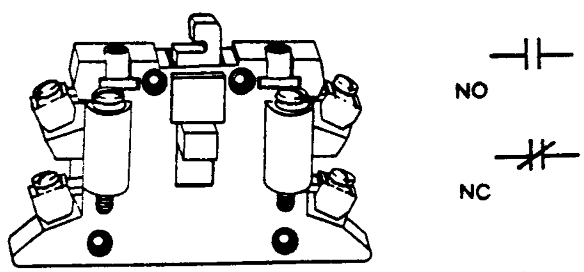


FIGURE A-10. Auxiliary Contacts.

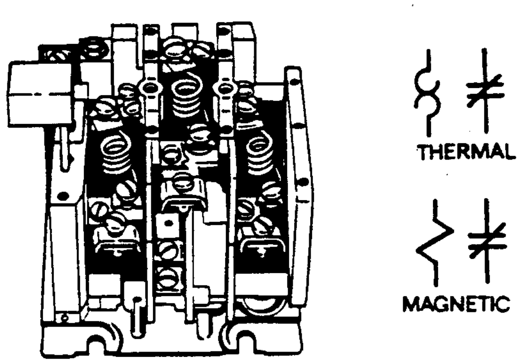


FIGURE A-11. Overload Relays.

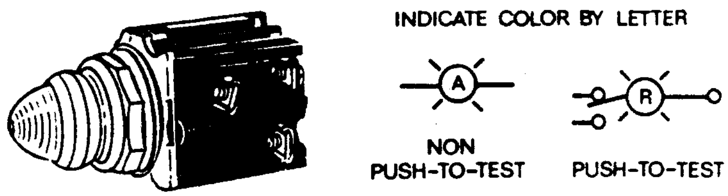


FIGURE A-12. Pilot Lights.

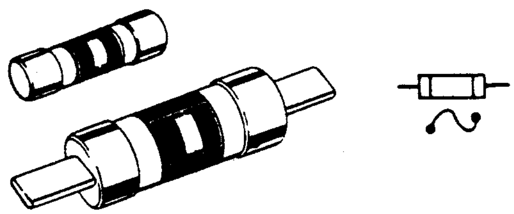


FIGURE A-13. Fuse Power or Control.

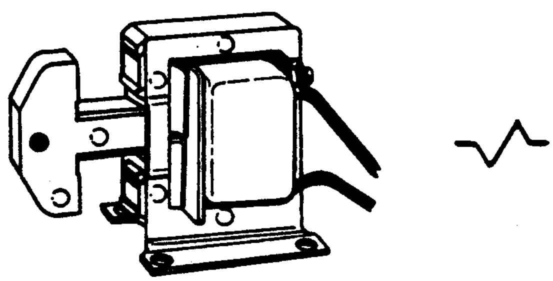


FIGURE A-14. Solenoid.

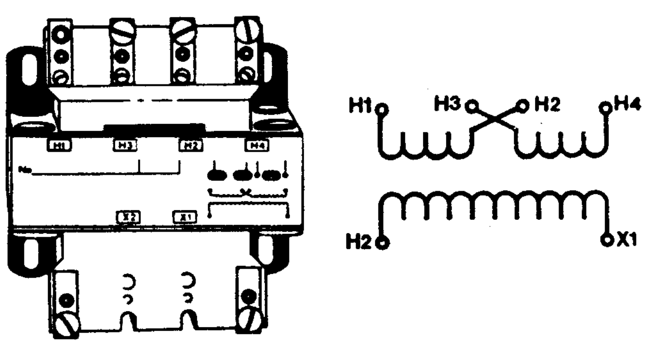


FIGURE A-15. Control Transformer.

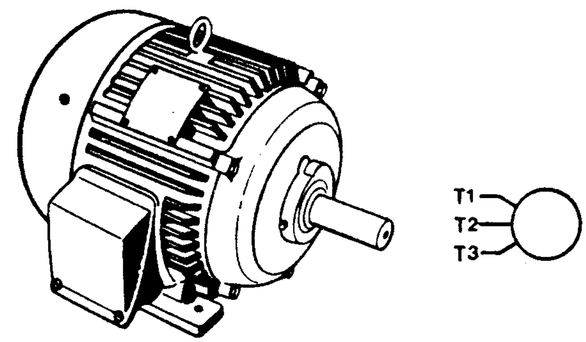


FIGURE A-16. Three-Phase Motor.

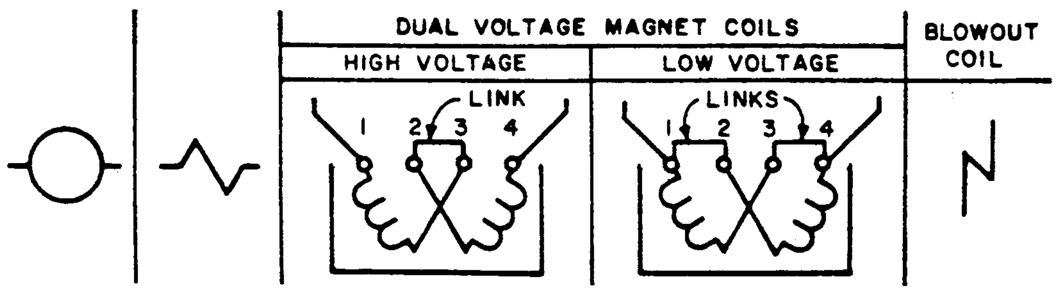


FIGURE A-17. Coil.

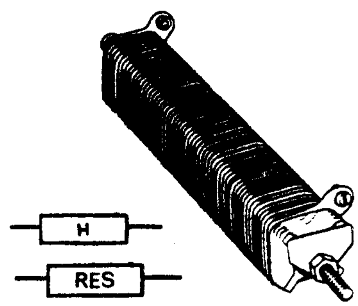


FIGURE A-18. Fixed Resistor; Heating Element.

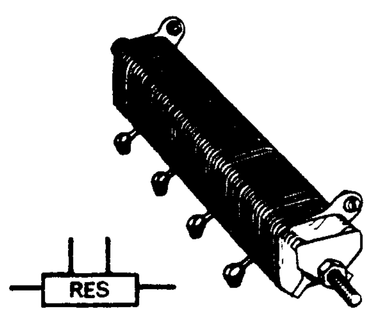


FIGURE A-19. Tapped Resistor.

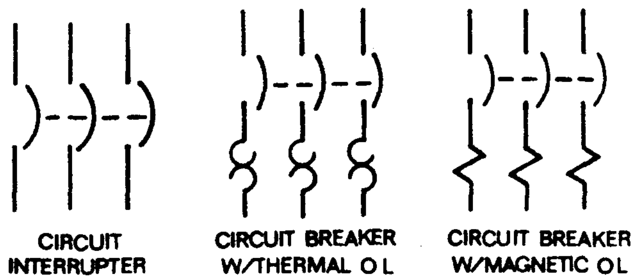


FIGURE A-20. Circuit Interrupter and Circuit Breakers.

FIGURE A-21. Foot Switches.

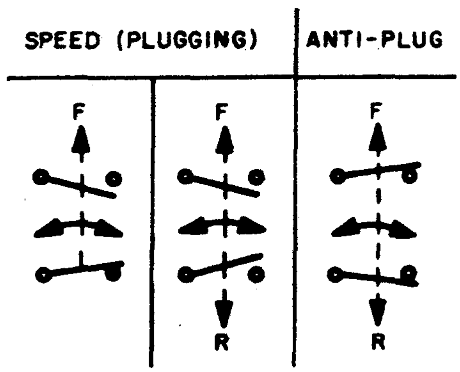


FIGURE A-22. Speed (Plugging); Anti-Plug.

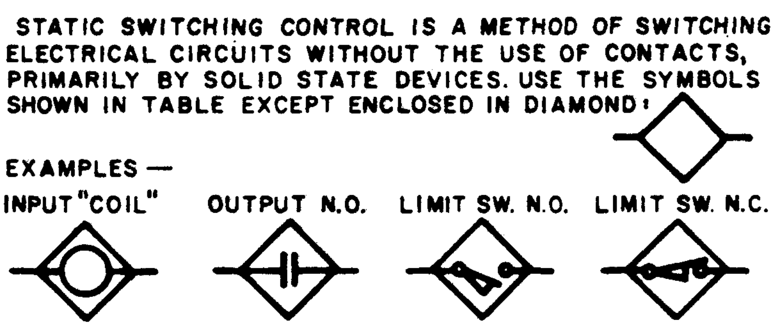


FIGURE A-23. Symbols for Static Switching Control Devices.

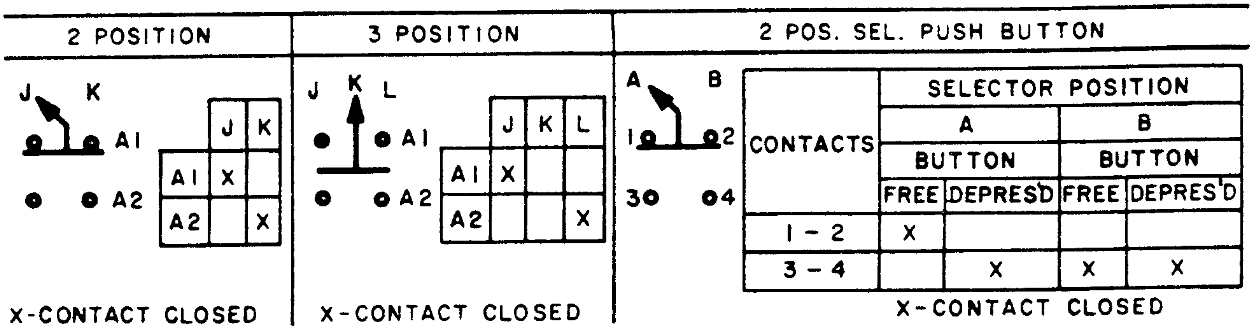


FIGURE A-24. Selector.

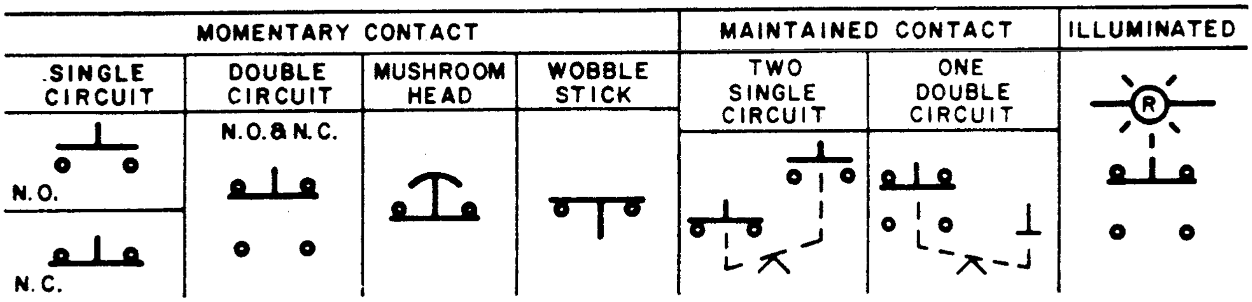


FIGURE A-25. Push Buttons.

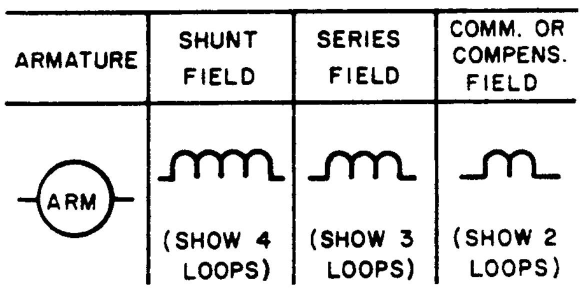


FIGURE A-26. DC Motors.

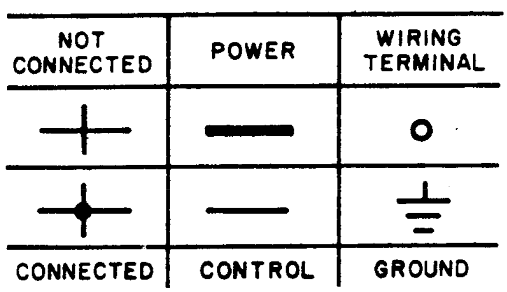


FIGURE A-27. Wiring.

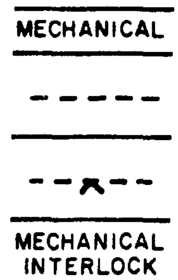


FIGURE A-28. Connections.

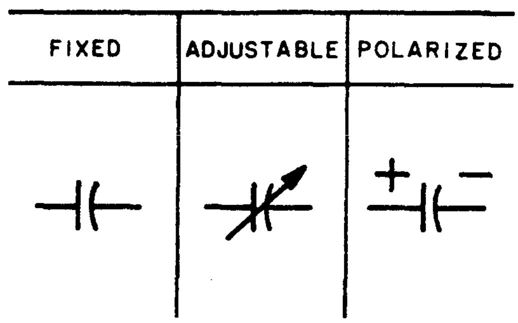


FIGURE A-29. Capacitors.

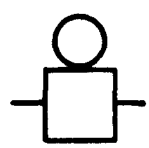


FIGURE A-30. Bell.

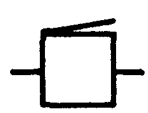


FIGURE A-31. Buzzer.

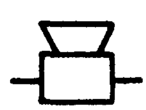


FIGURE A-32. Horn.

FIGURE A-33. Half-Wave Rectifier.

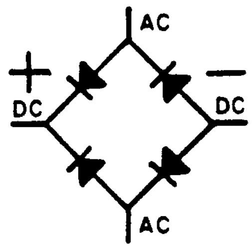


FIGURE A-34. Full-Wave Rectifier.

FIGURE A-35. Battery.

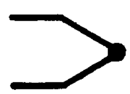


FIGURE A-36. Thermocouple.

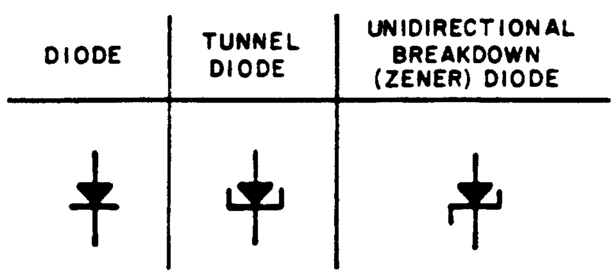


FIGURE A-37. Semiconductors.

GLOSSARY

Section I. ACRONYMS AND ABBREVIATIONS

ABS .... American Bureau of Shipping
ABT .... automatic bus transfer
AC .... alternating current
adj .... adjustment
alt .... alternate
amp .... ampere
ANSI .... American National Standard Institute, Inc.
assm .... assembly
auto .... automatic
avg .... average
AWG .... American wire gauge

bat .... battery
BDU .... battle dress uniform

CEMF .... counter electromotive force
COMA .... circular mil area
comm .... communication
cond .... condition
CPR ....Cardiopulmonary resuscitation
CS .... centrifugal switch

DC .... direct current
distr .... distribution
DPDT .... double-pole, double-throw
DPST .... double-pole, single-throw

EFC .... electronic fuel control
elf .... efficiency
EMF .... electromotive force
exc .... exciter

FLC ....full-load current

H .... henry
HP ....horsepower
Hz .... hertz

IEEE .... Institute of Electric and Electronics Engineers

kHz .... kilohertz
kV .... kilovolt
kVa .... apparent power (thousands of volts x amps)
KW .... kilowatt (true power)
kWh .... kilowatt hour

LCD .... liquid crystal display
LCM .... landing craft, mechanized
LCU .... landing craft, utility
LED .... light-emitting diode
LSV .... logistics support vessel
ltg .... lighting

mA .... milliampere
max .... maximum
MCC .... motor control center
mfr .... manufacturer
mho .... unit of conductance
MOS .... military occupational specialty
MPU .... magnetic pickup
mV .... millivolt

NC .... normally closed
NEC .... National Electrical Code
NEMA. .... National Electrical Manufacturers Association
NICAD .... nickel-cadmium

NO . . . . normally opened

OBA . . . . oxygen breathing apparatus

PF . . . . power factor
PMG . . . . permanent magnet generator
press . . . . pressure
psia . . . . pounds per square inch atmospheric
psig . . . . pounds per square inch gauge
PVC . . . . polyvinyl chloride

RF . . . . radio frequency
rheo. . . . . rheostat
rm . . . . room

RMS. . . . . root mean square
RPM . . . . revolutions per minute

SPST . . . . single-pole, single-throw
SW . . . . switch

temp . . . . temperature

uA . . . . microampere
uV . . . . microvolt

VA . . . . volt-ampere (apparent power)
VAC . . . . volts alternating current
VAR . . . . volt-amperes reactive
VDC . . . . volts direct current

Section II. TERMS

accuracy - limitation that a measurement may vary from its true value; usually represented as a percentage of full scale, such as +1%.

across-the-line starter - starting a motor when connected directly to the supply lines.

active power - true electrical power; power that is actually doing work.

air-core transformer - a transformer composed of two or more coils that are wound around a nonmetallic core.

air gap - the air space between two magnetically or electrically related components for example, the space between the armature and poles in a motor.

alternating current - an electrical current that constantly changes amplitude and changes in polarity at regular intervals.

alternator - device mounted on a diesel engine to charge starting batteries; sometimes used as a term for alternating current generators.

ambient temperature - average temperature of the air surrounding an electrical device; usually expressed in degrees Celsius (C).

ammeter - an instrument for measuring the amount of electron flow in amperes.

ampere - the basic unit of electrical current.

amplification - production of an output larger than the corresponding input.

amplifier - an electrical device producing an output signal larger than its input signal.

analog device - device that measures continuous information (voltage, current). The analog has an infinite number of possible values; its limitation is the accuracy of the measuring device. It uses a meter with a needle and scale.

analog signal - a signal having a continuous and smooth signal over a given range.

AND logic - control circuits where all inputs must have a signal for the circuit to operate. For example, with two NO inputs in a series, both must be closed to energize the circuit.

anode - a positive electrode of an electromagnetic device, such as a primary or secondary electric cell, toward which the negative ions are drawn.

apparent power - that power apparently available for use in an AC circuit containing a reactive element. It is the product of effective voltage times effective current expressed in volt-amperes. It must be multiplied by the power factor to obtain true power available.

arc chute - cover around contacts to prevent arcs from reaching surrounding parts.

arc hood - separate cover over a relay. The function is the same as an arc chute.

armature - a winding that has an EMF induced (or produced) into it.

armature reaction - reaction of the magnetic field coils to the magnetic field produced by current in the armature windings of a DC generator.

attraction - the force that tends to make two objects approach each other. Attraction exists between two unlike magnetic poles (north and south) or between two unlike static charges (plus and minus).

automatic controller - a motor control device that uses automatic pilot devices to turn the circuit on and off.

autotransformer - a transformer with a single coil. The entire length of the coil acts as a primary winding; only part of the winding functions as a secondary winding. It is used primarily as a device to reduce inrush current for motor starting.

average value of AC - The average of all instantaneous values of one-half cycle of alternating current.

AWG (American wire gauge) - a standard for wire size used by industry, replaced by the circular mil by the military.

back voltage - a term sometimes used to refer to counter EMF.

battery - a device for converting chemical energy into electrical energy.

battery capacity - the amount of energy available from a battery. Battery capacity is expressed in ampere-hours.

blowout coil - a coil in a relay used to stretch the arc (blow it out) when opening.

branch - an individual current path in a parallel circuit.

brush - a sliding contact, normally made of carbon, and riding on a commutator or slip ring to provide a mechanical contact between the rotating and stationary portions of an electrical device.

capacitance - the property of an electrical circuit that opposes changes in voltage.

capacitive reactance - the opposition offered to the flow of alternating current by capacitance, expressed in ohms. The symbol for capacitive reactance is X_C.

capacitor - an electrical device capable of storing electrical energy in an electrostatic field.

capacitor start motor - an alternating current split-phase motor using a capacitor to achieve a phase shift between the start and run windings. It uses a centrifugal switch to disconnect the start winding when the motor achieves between 75 and 90 percent running speed.

cathode - the general name for any negative electrode.

cell - a single unit that transforms chemical energy into electrical energy. Batteries are made up of cells.

charge - represents electrical energy. A material having an excess of electrons is said to have a negative charge. A material having an absence of electrons is said to have a positive charge.

charge cycle - the period of time that a capacitor in an electrical circuit is storing a charge.

choke - a coil used in a direct current circuit to smooth out ripples or a pulsating waveform.

circuit - the complete path of an electric current.

circular mil - an area equal to that of a circle with a diameter of 0.001 inch. It is used for measuring the cross-sectional area of wires.

coil - an inductive device created by looping turns of wire around a core.

combination circuit - a series-parallel circuit.

commutator - a segmented bar section on an armature providing a place for the brushes to make contact with the armature windings.

compensating windings - windings embedded in the face of the pole pieces of a DC machine to oppose armature reaction and control arcing at the brushes.

compound generator - a generator using both series and shunt windings on each pole piece.

compound motor - direct current motor with both series and shunt windings.

conductance - the ability of a material to conduct or carry an electric current. It is the reciprocal of resistance of the material and is expressed in mhos or siemens.

conductivity - ease with which a substance transmits electricity.

conductor - a material with a large number of free electrons; a material that permits electric current to flow.

control point - the level at which a system will be maintained (such as temperature and pressure).

control voltage - voltage level used in a control circuit to actuate coils and other devices.

controller - a device for starting a motor in either direction of rotation or adjusting the speed of rotation.

copper loss (I^2R loss) - the power lost due to the resistance of the conductors. In transformers, the power is lost because of current flow (I) through the resistance (R) of the windings.

core - any material that affords a path for magnetic flux lines in a coil.

coulomb - a measure of the quantity of electricity. One coulomb equals 6.242 x 1,018 electrons.

Coulomb's Law - also called the law of electric charges or the law of electrostatic attraction. Coulomb's Law states charged bodies attract or repel each other with a force that is directly proportional to the product of their individual charges and inversely proportional to the square of the distance between them.

counter EMF (counter electromotive force) - an electromotive force (voltage) induced in a coil that opposes applied voltage; voltage induced in the coils of a load.

coupling, coefficient of - an expression of the extent to which two inductors are coupled by magnetic lines of force. This is expressed as a decimal or percentage of maximum possible coupling and represented by the letter K.

cross-sectional area - the area of a slice of an object. When applied to electrical conductors, it is usually expressed in circular mils.

current - the drift of electrons pasta reference point; the passage of electrons through a conductor. It is measured in amperes.

current, inrush - current flowing into a circuit immediately upon energizing the circuit. It is normally used in conjunction with inductive loads.

cycle - one complete positive and one complete negative alternation of a current or voltage.

damper windings - windings embedded in the pole pieces of generators used to oppose changes in frequency or speed of the rotor. They allow generators to remain in parallel operation.

dead short - a short circuit having minimum resistance.

delta connection - three-phase circuit where the windings are connected in the form of a closed ring or end to end. It is often used to connect windings in three-phase transformers and motors.

delta-delta connection - a transformer connection where both the input and output windings are delta-connected.

delta-wye connected - a transformer connection where the input is delta-connected and the output is wye-connetted.

dielectric - an insulator; the insulating material between the plates of a capacitor.

dielectric constant - the ratio of capacitance of a capacitor with a dielectric between the electrodes to the capacitance of a capacitor with air between the electrodes.

dielectric field - the space between and around charged bodies in which their influence is felt; also called electric field of force or electrostatic field.

dielectric hysteresis loss - power loss of a capacitor due to the changes in orientation of electron orbits in the dielectric caused by rapid reversal in polarity of line voltage. The higher the frequency, the greater the loss.

dielectric leakage - power loss of a capacitor due to leakage of current through the dielectric. It also relates to leakage resistance. The higher the leakage resistance, the lower the dielectric leakage.

digital - a class of devices in which outputs vary in discreet or distinct steps, such as pulses; test equipment that displays readingds in the form of LCD or LED readouts.

direct current - an electric current that flows in one direction.

displacement current - the current that appears to flow through a capacitor.

domain theory - a theory of magnetism based upon the electron-spin principle. Spinning electrons have a magnetic field. If more electrons spin in one direction than another, the atom is magnetized.

doping - the process in which a crystalline structure is altered by replacing existing atoms with those atoms from other elements. For example, germanium and silicon are base elements used in electronics. To give these base elements a more positive or negative quality, bismith or boron atoms can be added, respectively.

dot notation - a system used by drafters to indicate relative instantaneous polarity in AC motor and transformer windings.

drum switch - a type of motor controller using switches in the form of fingers actuated by a cam to control various contractors in a control circuit. It is usually used in reversing or braking controllers.

dry cell - an electric cell in which the electrolyte is not a liquid. In most dry cells, the electrolyte is in paste form.

dynamic braking - braking a motor by using the motor as a generator and dissipating the generated voltage through resistors. Dynamic braking uses motor reaction to slow the motor.

eddy current - induced circulating currents in a conducting material that are caused by a varying magnetic field.

eddy current loss - losses caused by random current flowing in the core of a transformer. Power is lost in the form of heat.

effective value - same as root mean square.

efficiency - the ratio of output power to the input power; generally expressed as a percentage.

electric current - electric energy stored on or in an object. It is the negative charge caused by an excess of electrons or the positive charge caused by a deficiency of electrons. Its symbol is Q, q.

electrochemical - the action of converting chemical energy into electrical energy.

electrode - the terminal at which electricity passes from one medium into another, such as in an electrical cell where the current leaves or returns to the electrolyte.

electrolyte - a solution of a substance that is capable of conducting electricity; may be either a liquid or a paste.

electromagnet - an electrically excited magnet capable of exerting mechanical force or performing mechanical work.

electromagnetic - describes the relationship between electricity and magnetism, having both magnetic and electrical properties.

electromagnetic induction - the production of a voltage in a coil due to a change in the number of magnetic lines of force (flux linkages) passing through the coil.

electromagnetism - the generation of a magnetic field around a current-carrying conductor.

electron - the elementary negative charge that revolves around the nucleus of an atom.

electron shell - a group of electrons that have a common energy level that forms part of the outer structure (shell) of an atom.

electrostatic - pertaining to electricity at rest, such as charges on an object (static electricity).

electrostatic field - the field of influence between two charged bodies.

element - a substance in chemistry that cannot be divided into simpler substances by any means normally available.

EMF (electromotive force) - the force that causes electricity to flow between two points with different electrical charges; or when there is a difference in potential between the two points, the unit of measurement in volts.

energy - the ability or capacity to do work.

equivalent resistance - a resistance that represents the total ohmic values of a circuit component or group of circuit components. It is usually drawn as a single resistor when simplifying complex circuits.

excitation - creating a magnetic field; passing current through a conductor to create an electromagnetic field.

excitation current - the current that produces the magnetic field in a generator; the current that flows in the primary winding of a transformer, which produces a magnetic flux field. It is also called magnetizing current.

farad - the basic unit of capacitance. A capacitor has a capacitance of 1 farad when a voltage change of 1 volt per second across it produces a current of 1 ampere.

ferromagnetic material - a highly magnetic material, such as iron, cobalt, nickel, or alloys.

field - the winding in rotating machines that accounts for the magnetic properties necessary to induce an EMF.

field intensity - the amount of magnetizing force available to produce flux lines in the core of a magnet.

field of force - describes the total force exerted by an action-at-a-distance phenomenon, such as gravity upon matter, electric charges acting upon electric charges, and magnetic forces acting on other magnets or magnetic materials.

filter - device used to smooth a signal; electrical device used to suppress undesired noise.

fixed resistor - a resistor having a definite resistance value that cannot be adjusted.

flashing the field - passing current through the windings of a field oil to establish residual magnetism.

flat compounded generator - a compound generator wound so that the series and shunt fields produce an almost constant voltage output for current values from no load to full load.

flux - in electrical or electromagnetic devices, a general term used to designate collectively all the electric or magnetic lines of force in a region.

flux density - the number of magnetic lines of force passing through a given area.

frequency (f) - the number of complete cycles per second existing in any form of wave motion, such as the number of cycles per second of an alternating current.

gaseous - one of the four states of matter; having no fixed shape or volume. For example, steam is a gas.

generator - a rotating machine that uses magnetic induction to produce an EMF, converting mechanical energy into electrical energy.

generator action - inducing a voltage into a wire that is cutting across magnetic lines of force.

graph - a pictorial presentation of the relationship between two or more variable quantities, such as between applied voltage and current it produces in a circuit.

ground - an electrical or mechanical connection, either intentional or accidental, connected from a conductor to earth. The conductor may or may not carry current.

ground potential - zero potential with respect to the ground or earth.

heat sink - a piece of metal used to mount components and draw heat away from them. It is usually made of finned aluminum.

henry (H) - the electromagnetic unit of inductance or mutual inductance. The inductance of a circuit is 1 henry when a current variation of 1 ampere per second induces 1 volt. It is the basic unit of inductance. In radio, smaller units are used, such the millihenry (mH), which is one-thousandth of a henry (H), and the microhenry (uH), which is one-millionth of a henry.

hertz (Hz) - a unit of frequency equal to one cycle per second.

high side - in a transformer, designates the high voltage coil.

horsepower - the English unit of power, equal to work done at a rate of 550 foot-pounds per second, equal to 746 watts of electrical power.

horseshoe magnet - a permanent magnet bent into the shape of a horseshoe or having a U-shape to bring the two poles near each other.

hydrometer - an instrument used to measure specific gravity. In batteries, hydrometers are used to indicate the state of charges by the specific gravity of the electrolyte.

hysteresis - the time lag of the magnetic flux in a magnetic material behind the magnetizing force producing it; caused by the molecular friction of the molecules trying to align themselves with the magnetic force applied to the material.

hysteresis loss - the power loss in an iron-core transformer or other alternating-current device as a result of magnetic hysteresis.

impedance - the total opposition offered to the flow of an alternating current. It may consist of any combination of resistance, inductive reactance, and capacitive reactance. The symbol for impedance is Z.

inching - applying reduced power to a motor to move a motor or its load slowly to a desired position.

induced charge - an electrostatic charge produced on an object by the electric field that surrounds a nearby object.

induced current - current that flows in a conductor because of a changing magnetic field.

induced electromotive force - the electromotive force induced in a conductor due to the relative motion between a conductor and a magnetic field.

induced voltage - see induced electromotive force.

inductance - the property of a circuit that tends to oppose a change in the existing current flow. The symbol for inductance is L.

induction - the act or process of producing voltage by the relative motion of a magnetic field across a conductor.

inductive coupling - coupling of two coils by means of magnetic lines of force. In transformers, it is coupling applied through magnetic lines of force between the primary and secondary windings.

inductive reactance - the opposition to the flow of an alternating current caused by the inductance of a circuit, expressed in ohms. It is identified by the letter X.

in phase - applied to the condition that exists when two waves of the same frequency pass through their maximum and minimum values of like polarity at the same instant.

infinite - extending indefinitely, endless; boundless having no limits; an incalculable number.

instantaneous value - the magnitude at any particular instant when a value is continually varying with respect to time.

insulation - a material used to prevent the leakage of electricity from a conductor and to provide mechanical spacing or support to protect against accidental contact; a material in which current flow is negligible, used to surround or separate a conductor to prevent loss of current.

insulator - material of such low conductivity that the flow of current through it can usually be neglected; device having high-electrical resistance, used for supporting or separating conductors so as to prevent undesired flow of current from the conductors to other objects.

integrated circuit - a solid state circuit made up of transistors, resistors, and similar components. All components are packaged into a single device called a chip or one piece of semiconductor material.

interlock - mechanical connection between electrical devices. It may be used to open and close contacts together or prevent components from energizing together.

interpole - a separate winding and pole piece, connected in series and 180 degrees out of phase with the armature of a DC machine. It is used to oppose armature reaction.

inversely - inverted or reversed in position or relationship.

inverter - circuit that changes direct current into alternating current.

ion - an electrically charged atom or group of atoms. Negative ions have an excess of electrons, positive ions have a deficiency of electrons.

ionize - to make an atom or molecule of an element lose an electron, as by X-ray bombardment, and thus be converted into a positive ion. The freed electron may attach itself to a neutral atom or molecule to form a negative ion.

isolation - separation; the value of insulation resistance, measured between the input and output, input to case, or output to case.

jogging - rapid application of full power to a motor to move it or its load into position desired.

junction - the connection between two or more conductors; the contact between two dissimilar metals or materials, as is in the thermocouple.

kilo - a prefix meaning one thousand.

kinetic energy - energy that a body possesses by virtue of its motion.

Kirchhoff's Laws - the talebearing sum of the currents flowing toward any point in an electrical network is zero; the algebraic sum of the products of the current and resistance in each of the conductors at any closed path in a network equals the algebraic sum of the electromotive forces in the path.

lag - the amount one wave is behind another in time, expressed in electrical degrees.

laminated core - a core built up from thin sheds of metal insulated from each other and used in transformers.

law of magnetism - like poles repel; unlike poles attract.

lead - the opposite of lag; also a wire or connection.

lead-acid battery - a cell in an ordinary storage battery, in which electrodes are grids of lead containing an active material consisting of certain lead oxides that change composition during charging and discharging. The electrodes are plates that are immersed in an electrolyte of diluted sulfuric acid.

leakage flux - magnetic lines of flux produced by the primary winding that do not link the turns of the secondary winding.

leakage resistance - the electrical resistance that opposes the flow of current through the dielectric of a capacitor. The higher the leakage resistance, the slower the capacitor will discharge or leak across the dielectric.

left-hand rule for generators - a rule or procedure used to determine the direction of current flow in a generator.

Lenz's Law - the current induced in a circuit due to its motion in a magnetic field or to a change in its magnetic flux in such a direction as to exert a mechanical force opposing the motion or to oppose the change in flux.

light-emitting diode (LED) - a diode that emits light when energized in a forward bias; may be used as a control device or in a digital display.

line diagram - industry standard method of representing control circuits. It is also called a ladder diagram.

lines of force - a lime in an electric or magnetic field that shows the direction of the force.

liquid - one of the four states of matter that has a definite volume but no definite form. For example, water is a liquid.

liquid crystal display (LCD) - a semiconductor device used for displaying digital readouts.

load - a device through which an electric current flows and that changes electrical energy into another form; power consumed by a device or circuit in performing its function.

local action - a continuation of current flow within an electrical cell when there is no external load. It is caused by impurities in the electrode.

locked rotor current - the current level in the motor the instant power is applied, before the motor starts to turn and build CEMF. It is the maximum current level in a motor in good condition.

locked rotor torque - the torque developed by the motor as it is first energized; the greatest amount of torque a motor produces.

logic - a method of using the symbols AND, OR, NAND, NOR, and NOT to represent the function of a circuit.

low side - the low voltage side of a transformer.

magnetic contactor - a switching device actuated by a magnetic coil. It is usually used in AC circuits.

magnetic field - region in which the magnetic forces created by a permanent magnet or by a current-carrying conductor or coil can be detected.

magnetic lines of force - imaginary lines used for convenience to designate the direction in which magnetic forces are acting as a result of magnetomotive force.

magnetic motor starter - a magnetic contactor with an overload section added. It is used to start AC motors.

magnetic poles - the section of a magnet where the flux lines are concentrate also where they enter and leave the magnet.

magnetism - the property possessed by certain materials by which these materials can exert mechanical force on neighboring masses of magnetic materials and can cause currents to be induced in conducting bodies moving rotative to the magnetized bodies.

magnetomotive force - the force that produces magnetic lines of force in a magnetic circuit.

matter - any physical entity that possesses mass.

mechanical energy - in moving objects, the force of motion they possess.

mega - a prefix meaning one millon.

memory - characteristic of a motor control circuit that makes it continue to follow the last input; the part of a programmable controller where data and instructions are stored.

mho - unit of conductance; the reciprocal of the ohm.

micro - a prefix meaning one-millionth.

microfarad - one-millionth of a farad. It is the most commonly used unit of measurement of capacitors for motor starting.

microprocessor - a central computer unit that processes input information.

milli - a prefix meaning one-thousandth.

motor controller - device used in a motor circuit to control starting, stopping, direction, breaking, overloads, and inrush current.

motor efficiency - ratio of input power to output power.

motor reaction - magnetic reaction developed in a generator as the armature windings are energized. As the armature builds current and a magnetic field, it reacts with the energized field windings, opposing the generator's direction of rotation.

mutual flux - The total flux in the core of a transformer that is common to both the primary and the secondary windings. The flux links both windings.

mutual inductance - a circuit property existing when the relative position of two inductors causes the magnetic lines of force from one to link with the turns of another. The symbol for mutual inductance is M.

NAND logic - circuit where there are two or more NC inputs in parallel.

NEC (National Electrical Code) - regulatory guidance for electrical devices and shore installations.

negative alternation - the negative half of an AC waveform.

negative electrode - a terminal or electrode having more electrons than normal. Electrons flow out of the negative terminal of a voltage source.

negative temperature coefficient - the temperature coefficient expressing the amount of reduction in the value of a quantity, such as resistance for each degree of increase in temperature.

NEMA (National Electrical Manufacturers Association) - organization that standardizes electrical devices.

network - a combination of electrical components. In a parallel circuit, it is composed of two or more branches.

neutral - in a normal condition, hence neither negative or positive. A neutral object has a normal number of electrons.

neutron - one of the principle parts of the atom. It has no electrical charge and is found in the nucleus of the atom.

newton - metric unit of measure of force. The symbol is N. It is the force that causes a kilogram of mass to accelerate at 1 meter per second. It equals about ¼ pound.

node - used to indicate an electrical connection of two of more conductors. An electrical node can be considered to extend throughout the circuit where all connections, components, switches, and conductors maintain the same source potential.

no-load condition - the condition that exists when an electrical source or the secondary of a transformer is operated without an electrical load.

no-load test - test of a motor or generator with no electrical load on the device.

NOR logic - two or more NC contacts in series, such as multiple stop buttons.

normally closed (NC) contacts - a set of contacts that are closed in the resting position (no outside force applied).

normally open (NO) contacts - a set of contacts that are open in the resting position (no outside force applied).

NOT logic - a single NC contact in a circuit.

ohm - the unit of electrical resistance. It is that value of electrical resistance through which a constant potential difference of 1 volt across the resistance will maintain a current flow of 1 ampere through the resistance.

Ohm's Law - the current in an electrical circuit is directly proportional to the electromotive force in the circuit. The most common form of the law is $E = IR$, where E is the electromotive force or voltage across the circuit, I is the current flowing in the circuit, and R is the resistance in the circuit.

open circuit - the condition of an electrical circuit caused by the breaking of continuity of one or more of the conductors of the circuit, usually an undesired condition; a circuit that does not provide a complete path of current flow.

OR logic - two or more NO inputs in parallel; either input will energize the load.

out of phase - two or more phases of alternating current that are changing in direction and amplitude at different times.

over compounding - in a compound wound machine, placing more emphasis on the series winding and the series characteristics.

overload relay - a device for protecting electrical circuits and loads from excess current levels. They may be magnetic, thermal, or bimetallic type.

parallel circuit - two or more electrical devices connected to the same pair of terminals so separate currents flow through each. Electrons have more than one path to travel from the negative to the positive terminal.

peak to peak - the measure of absolute magnitude of an AC waveform, measured from the greatest positive alternation to the greatest negative alternation.

peak value - the highest value, either positive or negative, in an alternating current system.

period time - the time required to complete one cycle of a waveform.

permanent capacitor motor - a single-phase motor using a capacitor to create a phase shift in one set of windings.

permanent magnet - a magnet that retains its magnetic properties indefinitely.

permeability - the measure of the ability of a material to act as a path for magnetic lines of force.

phase - the angular relationship between two alternating currents or voltages when the voltage or current is plotted as a function of time. When the two are in phase, the angle is zero and both reach their peak simultaneously. When out of phase, one will lead or lag the other. At the instant when one is at its peak; the other will not beat peak value and (depending on the phase angle) may differ in polarity as well as magnitude.

phase angle - the number of electrical degrees of lead or lag between the voltage and current waveforms in an AC circuit.

phase difference - the time in electrical degrees by which one wave leads or lags another.

phase sequence - the order in which the different phases rise to peak voltage. It may be ABC or CBA.

phase shift - creating a lag or lead in time between the current wave and the voltage wave in an alternating current system. Voltage is the constant.

phase voltage - voltage across a coil in a transformer or generator.

photoelectric voltage - a voltage produced by light.

piezoelectric voltage - the effect of producing a voltage by placing stress, either by compression, expansion, or twisting, on a crystal and, conversely, producing a stress on a crystal by applying a voltage to it.

plate - one of the electrodes in a storage battery.

polarity - the condtion in an electrical circuit by which the direction of the current flow can be determined, usually applied to batteries and other direct current voltage sources; two opposite charges, one positive and one negative, a quality of having two opposite poles, one north and one south.

polarization - the effect of hydrogen surrounding the anode of a cell that increases the internal resistance of the cell; the magnetic orientation of molecules in a magnetizable material in a magnetic field, whereby tiny internal magnets tend to lime up in the field.

polyphase - a multiple phase alternating current system. The term has been mostly replaced with the term "three-phase."

positive alternation - the positive half of an AC waveform.

potential energy - energy due to the position of one body with respect to another body or to the relative parts of the same body.

potentiometer - a three-terminal resistor with one or more sliding contacts, which functions as an adjustable voltage divider.

pounds of force - English unit of measure for power.

power - the rate of doing work or the rate of expending energy. The unit of electrical power is the watt.

power factor - the ratio of the actual power of an alternating or pulsating current, as measured by a wattmeter, to the apparent power, as indicated by ammeter and voltmeter readings. The power factor of an inductor, capacitor, or insulator is an expression of their losses.

primary cell - an electrochemical cell in which the chemical action eats away one of the electrodes, usually the negative electrode.

primary windings - the winding of a transformer connected to the power source.

prime mover - the driving force for a generator. It may be a diesel engine, a gas or steam turbine, or even an electric motor.

program - the sequence of instructions used to tell a computer how to operate.

prony brake - a device for loading a motor and measuring torque.

proton - one of the particles making up an atom and having a positive electrical charge. It may be found in the nucleus.

pulsating current - direct current that has been rectified from an alternating current. It has a waveform but does not generally drop below the zero plane.

radio frequency (RF) - any frequency of electrical energy capable of propagation into space.

ratio - the value obtained by dividing one number by another, indicating their relative proportions.

RC constant - time constant of a resistor-capacitor circuit; equal in seconds to the resistance value in ohms multiplied by the capacitance value in farads.

reactance - the opposition offered to the flow of an alternating current by the inductance, capacitance, or both in any circuit.

reactive load - a load developing reactive power, such as an inductive or capacitive load.

reciprocal - the value obtained by dividing the number 1 by any quantity.

rectification - the process of mechanically or electronically converting an alternating current into direct current.

rectifier - a device that changes alternating current into direct current.

reduced inrush starting - using motor starting circuits to limit inrush current.

reference point - a point in a circuit to which all other points in the circuit are compared.

regenerative braking - an inherent ability in a motor to generate a small current and develop motor reaction as the load slows when de-energized.

relay - an electromechanical device using a coil to actuate contacts to control current to a load. Normally, it is the term for magnetic devices in large direct current systems.

relay, solid-state - a solid-state switching device using a control signal to switch current on and off to a load.

reluctance - a measure of the opposition that a material offers to magnetic lines of force.

repulsion - the mechanical force tending to separate bales having like electrical charges or like magnetic polarity.

residual magnetism - magnetism remaining in a substance after removal of the magnetizing force.

resistance - the property of a conductor that determines the amount of current that will flow as the result of the application of a given electromotive force. All conductors possess some resistance, but when a device is made especially for the purpose of limiting current flow, it is called a resistor. A resistance of 1 ohm will allow current of 1 ampere to flow through it when a potential of 1 volt is applied. It is the opposition that a device or material offers to the flow of current. The effect of resistance is to raise the temperature of the material or device carrying the current. Resistance also refers to a circuit element designed to offer predetermined resistance to current flow.

resistive load - a load that converts electrical energy into heat or light; a load characterized by having virtually no inrush current.

resistor - the electrical component that offers resistance to current flow. It may be a coil of fine wire or a composition rod.

resonance - the condition existing in a circuit when values of inductance, capacitance, and the applied frequency are such that the inductive reactance and capacitive reactance cancel each other.

retentivity - the ability of a material to retain its magnetism.

reverse current relay - device in a DC switchboard that senses current being delivered to a generator and removes the generator from the circuit. This prevents the generator from being driven like a motor.

reverse polarity protection - devices used to protect generators from being driven like a motor.

reverse power relay - device in an AC switchboard that senses current being delivered to a generator and removes the generator from the circuit. This prevents the generator from being driven like a motor.

rheostat - a resistor whose value can be varied; a variable resistor that is used for the purpose of adjusting the current in a circuit.

ripple - a series of peaks in current or voltage value when alternating current has been rectified to direct current.

RLC circuit - an electrical circuit that has the properties of resistance, inductance, and capacitance.

root mean square (RMS) - the equivalent heating value of an alternating current or voltage, as compared to a direct current or voltage. It is 0.707 times the peak value of the same sine wave.

rotating armature generator - an alternating current generator having the output voltage generated in the rotating windinds (rotor).

rotating field generator - an alternating current generator using the rotating windings (rotor) as the field and having the output voltage developed in the stationary windings (stator).

rotational losses - power lost in rotating equipment due to windage and friction.

rotor - rotating windings or the rotating portion of AC machines.

salient pole - the pole pieces bolted to the shaft in AC generators.

saturation - the condition or point where a magnetic or electrical device can take no more magnetic flux.

saturation curve - a magnetization curve showing the relationship between current and magnetic flux.

schematic circuit diagram - a diagram using symbols to indicate devices in a circuit. Schematics show function, not location.

SCR (silicon-controlled rectifier) - a three-lead semiconductor used as a switching device. Normally an open circuit, when a signal is delivered to the gate, the device rapidly allows current to flow. It is an extremely rapid operation.

secondary - the output coil of a transformer.

secondary cell - a cell that can be recharged bypassing a current through the cell in a direction opposite to the discharge current.

self-excited - a generator that uses residual magnetism to develop its magnetic field and output voltage.

self-induction - the production of a counter electromotive force in a conductor when its own magnetic field collapses or expands with a change in current in the conductor.

separately excited - a generator that needs an outside power source to energize its field windings.

series aiding - when power sources are connected so the positive terminal of one source is connected to the negative terminal of another source. The voltage developed is the sum of the two voltages.

series circuit - an arrangement where electrical devices are connected so that the total current must flow through all the devices. Electrons have one path to travel from the negative to the positive terminal.

series field - a winding in a rotating machine that is connected in series with the armature of the machine.

series motor - a rotating machine with the field winding in series with the armature. It develops a high starting torque and may be either AC or DC.

series opposing - power sources that are connected positive terminal to positive terminal.

series-parallel circuit - a circuit that consists of both series and parallel networks.

shaded pole motor - a single-phase squirrel cage motor using slotted stator poles with copper bands to create a phase shift. The copper band creates an auxiliary winding and a slight delay in the magnetic field.

shading coil - a coil with a slotted pole piece wrapped with a copper band. The copper band causes a delay in the magnetic field. It may be used to create a rotating magnetic field or to keep AC contractors from chattering.

shelf life - the period of time that a cell or battery may be stored and still be useful.

shell-type transformer - a transformer using a coil constructed to surround the coil as well as pass through the center of the coil.

shielding - a metallic covering used to prevent magnetic or electromagnetic fields from affecting an object.

short circuit - a low-resistance connection between two points of different potential in a circuit, usually accidental and usually resulting in excessive current flow that may cause damage.

shunt - a parallel connection a device used with an ammeter to direct most of the current around the meter movement.

shunt field - afield coil in a DC machine connected in parallel with the armature.

shunt wound - a DC machine having the field coils in parallel with the armature windings.

shuttle power - power stored in the inductive or capacitive load and returned to the circuit.

siemens - the new and preferred term for conductance, replacing the mho.

sine wave - the curve traced by the projection on a uniform time scale of the end of a rotating arm or vector. It is also known as a sinusoidal wave.

single phase - an alternating current system using a single voltage and current sine wave.

slip - the difference in speed between synchronous speed and rotor speed.

slip rings - rings of copper on the rotor of an AC machine to provide a path of current from brushes to the rotor windings.

solder pot - the device in a thermal overload that holds the device in a normal operating condition. Heat generated by excess current causes the solder to melt, releasing springs that open the overload contacts.

solid - one of the four states of matter, which has a definite volume and shape. For example, ice is a solid.

solid-state - another term for electronic devices.

source of voltage - the device that furnishes the electrical energy used by a load.

specific gravity - the ratio between the density of a substance and that of pure water at a given temperature.

split-phase (resistance-start) motor - an induction motor using greater resistance in one winding to create the phase shift necessary for the motor to start.

squirrel cage rotor - a rotor using bars that are shorted at the ends. Current is induced into the rotor.

stall torque - the point at which the torque demanded of a motor exceeds the motor's torque output.

static electricity - stationary electricity that is in the form of a charge. It is the accumulated charge on an object.

stator - the stationary windings in an AC machine.

stator field - the magnetic field setup in the stator windings.

stroboscopic effect - used to measure speed of a rotating shaft. When a strobe light flashes on the shaft, the shaft will appear to stop if the flash speed and rotating speed are the same.

switch **-** a device to connect, disconnect, or change the connections in an electrical circuit.

synchronous - in step or in phase as applied to currents, voltages, or two different rotating machines.

synchronous speed - the rate of travel of a stator field of a three-phase machine; determined by the frequency and number of poles.

synchroscope - a device used to determine phased differences between two AC generators. It allows aligning phases of generators for parallel operation.

tapped resistor - a wire-wound fixed resistor having one or more additional terminals along its length, generally for voltage divider applications.

taps - terminals added to freed resistors to allow connections at various points along the resistor with varied values.

temperature coefficient - the amount of change of resistance in a material per unit change in temperature.

terminal - an electrical connection.

tesla - measure of flux density.

thermistor - a temperature-controlled variable resistor.

thermocouple - a junction of two dissimilar metals that produces a voltage when heated.

thermostat - a device in a control circuit used to start and stop air conditioning, refrigeration, or heating systems based on temperature.

theta - the Greek letter (θ)used to represent phase angle.

three-phase - alternating current devices using three sine waves, 120 electrical degrees out of phase.

time constant - the time required to charge a capacitor to 63.2 percent of maximum voltage or discharge to 36.8 percent of its final voltage. It is the time required for the current in an inductor to increase to 63.2 percent of maximum current or decrease to 36.8 percent of its final current.

timer - a control device that turns on or turns off a control circuit based a preset time delay.

tolerance - the maximum error or variation from the standard permissible in a measuring instrument; a maximum electrical or mechanical variation from specifications that can be tolerated without impairing the operation of the device.

torque - the force that produces a twisting or rotating action.

total resistance (Rt) - the equivalent resistance of an entire circuit. For a series circuit Rt = R1 + R2 + R3 + . . . Rn. For parallel circuits:

$$\frac{1}{Rt} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} + \ldots \frac{1}{Rn}$$

transducer - a device that converts physical parameters, such as pressure and temperature, into an electrical signal.

transformer - a device composed of two or more coils, linked by magnetic lines of force, used to transfer energy from one circuit to another.

transformer efficiency - the ratio of output power to input power, generally expressed as a percentage:

$$\text{Efficiency} = \frac{P\ out}{Pin} \times 100$$

transformer, isolation - a transformer with the same number of turns in the primary and secondary windings. This construction will deliver the same voltage in the secondary winding as in the primary windings. Isolation transformers are used to protect circuits or portions of the distribution system.

transformer, step-down - a transformer so constructed that the number of turns in the secondary winding is less than the number of turns in the primary winding. This construction will provide less voltage in the secondary circuit than in the primary circuit.

transformer, step-up - a transformer so constructed that the number of turns in the secondary winding is more than the number in the primary winding. This construction will provide more voltage in the secondary winding than in the primary winding.

transient - a temporary current or voltage that occurs randomly in the AC sine wave.

true power - the power dissipated in the resistance of the circuit or the power actually used by the circuit.

turn - one complete loop of a conductor about a core.

turns ratio - the ratio of number of turns in the primary winding to the number of turns in the secondary winding of a transformer.

two-capacitor motor - an induction motor using two capacitors to develop the starting phase shift. One is the start capacitor, which is taken out of the circuit by a centrifugal switch. The other capacitor is the run capacitor, which remains in the system at all times.

undercompounded - a compound wound DC machine with the emphasis on the shunt winding.

unidirectional - in one direction only.

unity power factor - when all the generated power in a system is being used to drive loads. The voltage and current waves are in phase. Unity is expressed as a power factor of 1 (100 percent efficiency).

universal time constant - a chart used to find the time constant of a circuit if the impressed voltage and the values of R and C or R and L are known.

valence - the measure of the extent to which an atom is able to combine directly with other atoms. It is believed to depend on the number and arrangement of the electrons in the outermost shell of the atom.

valence shell - the electrons that form the outermost shell of an atom.

variable resistor - a wire-wound or composition resistor, the value of which may be changed.

vector - a line used to represent both direction and magnitude; the angular difference in the direction the conductors which are moving in relation to the magnetic lines of flux.

volt - the unit of electromotive force or electrical pressure; 1 volt is the pressure required to send 1 ampere of current through a resistance of 1 ohm.

voltage - signifies electrical pressure. Voltage is a force that causes current to flow through an electrical conductor. The voltage of a circuit is the greatest effective difference of potential between any two conductors in the circuit.

voltage divider - a series circuit in which desired portions of the source voltage may be tapped off for use in equipment.

voltage drop - the difference in voltage between two points. It is the result of the loss of electrical pressure as a current flows through a resistance.

watt - the practical unit of electrical power. It is the amount of power used when 1 ampere of DC flows through a resistance of 1 ohm.

wattage rating - a rating expressing the maximum power that a device can safely handle.

watt-hour - a practical unit of electrical energy equal to one watt of power for one hour.

wattmeter - a device used to measure electrical power.

waveform - the shape of the wave obtained when instantaneous values of an AC quantity are plotted against time in a rectangular coordinate.

wavelength - the distance, usually expressed in meters, traveled by a wave during the time interval of one complete cycle. It equals the velocity of light divided by the frequency.

Weber's theory - a theory of magnetism that assumes that all magnetic material is composed of many tiny magnets. A piece of magnetic material that is magnetized has all of the tiny magnets aligned so that the north pole of each magnet points in one direction.

windage - rotational losses in a generator that are due to the friction as the armature or rotor passes through the surrounding air.

wire - a solid or stranded group of solid cylindrical conductors having a low resistance to current flow, with any associated insulation.

wiring diagram - a diagram intended to show as closely as possible the placement and actual connections of electrical devices.

work - the product of force and motion.

working voltage - the maximum voltage that a capacitor may operate at without the risk of damage.

wye or star connection - an electrical connection in three-phase machines where all terminals having the same instantaneous polarity are joined at the neutral junction. It is shown as coils connected to form a symbol resembling the letter Y.

wye-delta - a transformer connection where the primary windings are connected wye and the secondary windings are connected delta.

wye-wye - a transformer connection where both primary and secondary windings are connected in a wye pattern.

yoke - the framework or housing in a DC motor that the field windings are attached to.

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☆ U.S. GOVERNMENT PRINTING OFFICE 1995 - 388-421/41184

PIN: 072948-000