Overview of Electrical Theory

Course No: E04-053
Credit: 4 PDH

Elie Tawil, P.E., LEED AP

CED engineering.com
PDH FOR THE PROFESSIONAL

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.com

This course was adapted from the Naval Education and Training Professional Development and Technology Center, Publication No. NAVEDTRA 14026A, "Chapter 1: Basic Electrical Theory and Mathematics", which is in the public domain.

2.0.0 ELECTRICAL TERMS and SYMBOLS

2.1.0 General Information

In order to discuss the theory of electricity, it is necessary to first define some electrical terms.

2.1.1 Voltage

Voltage is described as the pushing force behind electricity. Voltage may also be referred to as Difference of Potential, Electromotive Force (EMF), or Electrical Pressure. Think of electricity as water running through a hose. The pressure (voltage) is what causes the water (current) to flow out of the end of the hose. The unit of measurement for voltage is the volt, and the letter for voltage is "V" except when used in formulas to calculate voltage. In this case the letter "E" is used to denote Electromotive Force. Voltage is calculated by multiplying current and resistance; this formula is known as Ohm's Law. As an example E = I x R. Refer to *Figure 1-13*.

2.1.2 Current

Current is the actual movement of electrons through the conductor. In relationship to the water hose, current is the water running through the hose. In order for current to flow, there must be a complete path. If there are opens in the circuit, then no current will flow. The unit of measurement for current flow is the ampere (amp), and the letter for amperage is "A" except when used in formulas to calculate current. In this case the letter "I" is used to denote current. Ohm's Law is also used to calculate current. Current is calculated by dividing voltage by resistance. As an example I = E ÷ R. Refer to *Figure 1-13.*

2.1.3 Resistance

Resistance is defined as the opposition to current flow. Some materials offer more resistance than others. An example of this is rubber. Rubber has more resistance in comparison to copper because of the difference in their molecular construction. Materials with little resistance are known as conductors because current can flow through them easily.

Materials with high resistance are used as insulators because current cannot flow through them as easily. Examples of low resistance materials are copper and aluminum. A few examples of high resistance materials are rubber, porcelain, fiberglass and dry wood.

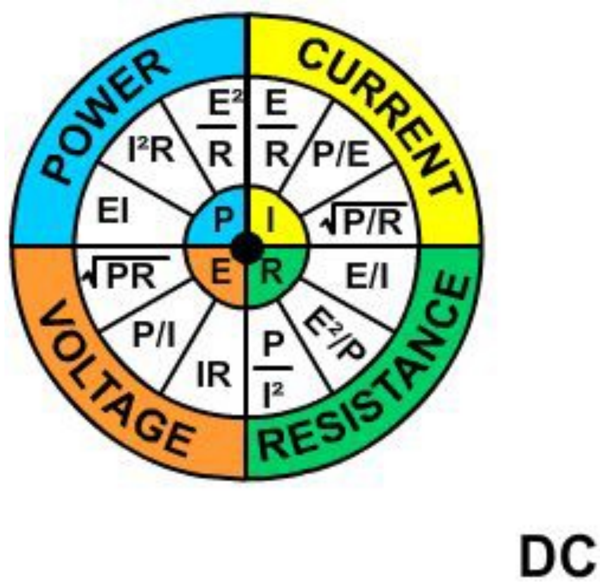


Figure 1-13 – Ohms Law wheel.

The unit of measurement for resistance is the ohm, and the symbol for resistance is "Ω". When used in formulas to calculate resistance the symbol "R" is used to denote Resistance. Ohm's Law is also used to calculate resistance. Resistance is calculated by dividing voltage by current. As an example R = E ÷ I. Refer to *Figure 1-13*.

2.1.4 Power

Power is the rate at which work is done, or the usable electricity produced or consumed. The unit of measurement is the watt, and the letter designator is "P". Electrical appliances are measured in watts. Wattage is calculated by multiplying volts and amperes; this formula is known as the power law. As an example P = E x I. Refer to *Figure 1-13*.

2.2.0 Types of Electricity

2.2.1 Direct Current

Current flowing in only one direction is referred to as Direct Current. The letters "DC" represent direct-current. A battery produces direct-current. The voltage source behind this direct-current has the same polarity all the time. The current flow is from negative to positive. Refer to *Figure 1-14*.

2.2.2 Alternating Current

Most of the time you will be working with Alternating Current. The letters "AC" represent alternating current. It is called AC because it alternates (changes) directions. An AC cycle is made up of one positive and one negative alternation. AC flows one way for half a cycle then the other way for half a cycle. In the United States, we use 60 cycles per second (60 Hertz (Hz). Since there is one positive and one negative alternation per cycle, 60 Hz AC changes directions 120 times per second. Refer to *Figure 1-15*.

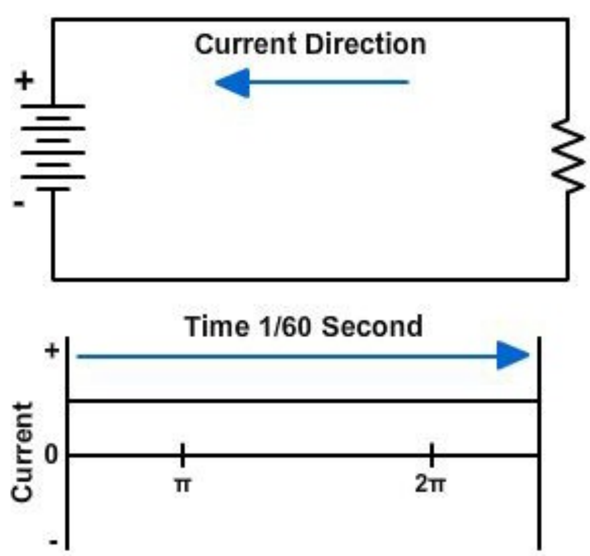


Figure 1-14 – DC circuit and waveform.

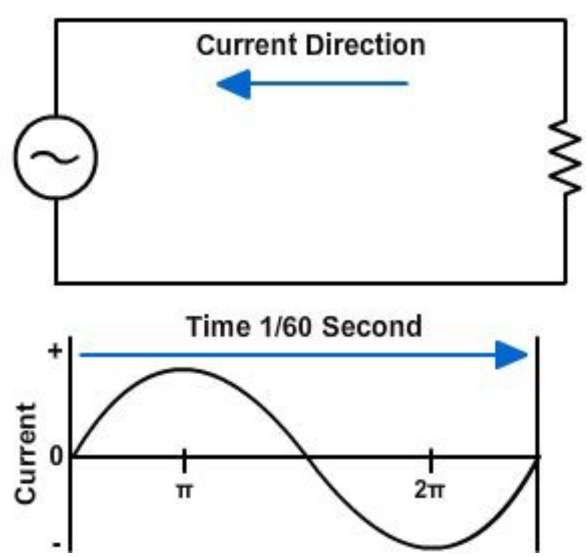


Figure 1-15 – AC circuit and waveform.

2.2.3 Electrical Components

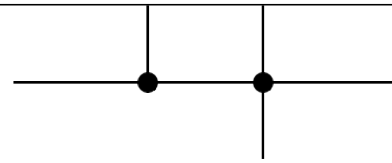
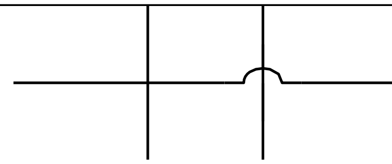
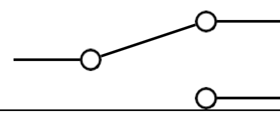
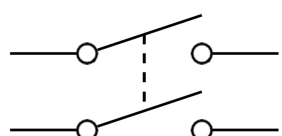
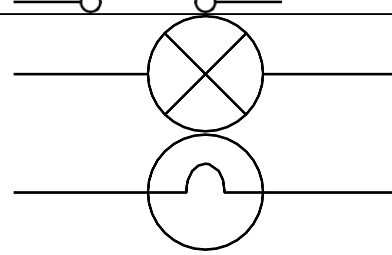
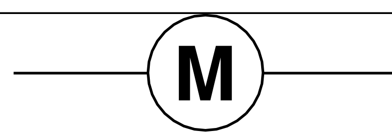
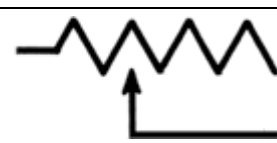
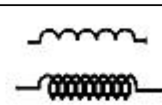
As a Construction Electrician you will be required to interpret a variety of electrical drawings, schematics and wiring diagrams in the accomplishment of your day-to-day duties.

These products will be used to provide you with essential information required to install, maintain and troubleshoot electrical circuits as well as show the manner in which electrical devices within the circuit are connected. Since it would be impossible to make pictorial drawings of each electrical component shown within any of these products, the components are represented by use of symbols. See *Table 1-7*.

It should be noted that a symbol is a simplified picture of the device represented. Without these symbols, electrical drawings, schematics and wiring diagrams would cover many pages. It would also require many hours of drafting time as well as hours of piecing drawings together to come up with a useful product.

A list of some of the most commonly used electrical symbols, terms for electrical components along with a brief description of what the component does are provided as follows:

Table 1-7 – Commonly used electrical symbols.

NAME	DESCRIPTION	SYMBOL
Wire or Conductor	Path for current flow	
Wires Connected	Two or more electrical paths of current flow that are connected so that the same voltage is present in both wires.	
Wires Not Connected:	Conductors of current flow insulated from each other. They may cross each other but are not electrically connected. Current cannot flow from one conductor to the other.	
Switch (single pole, single throw)	Switch is used to change the direction or completely stop current flow by opening or closing a circuit. A single pole, single throw (SPST) has one pivot point and one set of contacts.	
Switch (single pole, double throw):	Used to control two different circuits when they both can't be energized at the same time.	
Switch (single pole, double throw):	Used to control two circuits at the same time. When one circuit is energized, so is the other one.	
Lamp	An electrical device that converts electrical energy into light.	
Motor:	Converts electrical energy into mechanical energy.	
Rheostat:	A variable resistor used to limit current flow. Resistance can be between 0-100% of the resistor rating.	
Coil:	A length of wire looped with very limited space between the loops.	

3.0.0 ELECTRICAL THEORY

A basic understanding of electrical theory is important in order to understand your job as a construction electrician. Scientists, such as Faraday, Ohm, Lenz, and Kirchhoff have found that electricity seems to behave in a constant and predictable manner in a given condition. These scientists observed and described the predictable characteristics of electricity and electric current in the form of certain rules. These rules are often referred to as "laws". Although we cannot see the electrons in motion, through experiments and observation we know how they behave. By learning the laws applying to the behavior of electricity and by understanding the methods of producing, controlling, and using it, electricity may be "learned" without ever actually seeing it.

3.1.0 General Background Information

3.1.1 Atomic Structure

The smallest building blocks of matter are called atoms. All atoms are made of three basic parts: the proton, the neutron, and the electron (See *Figure 1-16*). Different numbers and arrangements of protons, neutrons, and electrons give atoms different properties which make up any one of the more than 100 fundamental substances known as elements.

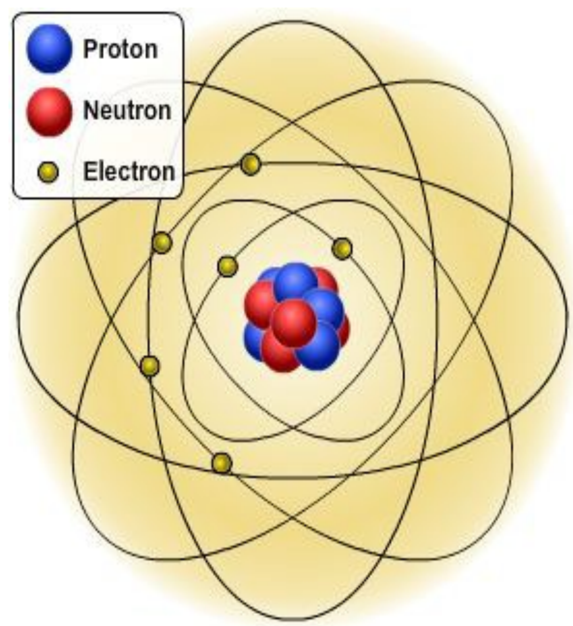


Figure 1-16 – Atom structure.

3.1.1.1 Nucleus

The nucleus is positively charged. It is the center part of an atom and contains protons and neutrons. It accounts for 99.9% of an atoms weight. Refer to *Figure 1-16* for nucleus position.

3.1.1.1.1 Proton

The proton is positively charged. The atomic number of an atom is equal to the number of protons in the atom. Atoms have the same number of protons and electrons, making atoms electrically neutral.

3.1.1.1.2 Neutron

The neutron has no electrical charge making it neutral. Lighter elements have about the same number of protons and neutrons. Heavier elements have more neutrons than protons. Since they have no electrical charge, they do not make the material more positive or negative.

3.1.1.2 Electrons

Electrons are at various distances from the nucleus and are arranged in energy levels called shells or rings. Electrons occupy almost the entire volume of an atom, but electrons themselves account for only a small fraction of an atom's mass.

Largely, the number of electrons in its outermost ring (commonly known as the valence ring) determines the chemical behavior of an atom.

When atoms combine and form molecules, electrons in the outermost shell are either transferred from one atom to another or shared between atoms in a process known as covalent bonding.

Uniform movement of electrons in a specific direction is known as current flow and can be utilized to perform work. Electron flow is fundamental to electrical theory.

3.1.1.2.1 Electrical Charge

Electrons are negatively charged particles. Ordinarily, an atom has an equal number of electrons and protons. Each electron carries one unit of negative charge and each proton carries one unit of positive charge. As a result, the atom is electrically neutral.

If an atom gains electrons, it becomes negatively charged. If it loses electrons, it becomes positively charged. Electrically charged atoms are called ions.

3.1.1.2.1 Valence Ring

The outermost ring determines whether a material is going to be a conductor or an insulator. Conductors allow current to flow through them with little or no resistance. Conductors are used to move electricity from place to place. Insulators do not allow electricity to readily flow through them and have a very high resistance. Insulators are used to contain electricity. Examples of both conductive and insulating materials are as follows:

Conductors	Insulators
Silver	Dry Air
Copper	Glass
Aluminum	Mica
Zinc	Rubber
Brass	Asbestos
Iron	Bakelite

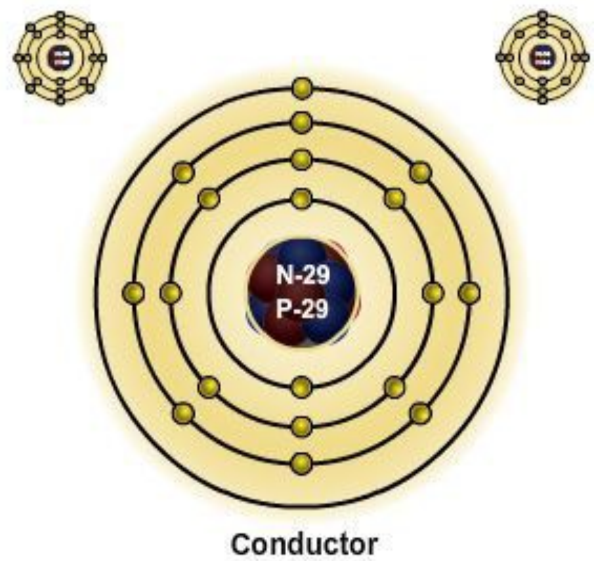


Figure 1-17 – Valence rings.

Atoms may contain anywhere from one to eight electrons in their valance ring. Materials with 1 or 2 electrons in their valance ring allow room for other electrons to pass through easily. These materials make good conductors. Materials with more electrons in the valance ring (7 or 8) make good insulators. Materials having 4 or 5 electrons in the valance ring make for good semiconductors. A semiconductor is a material that is neither a good conductor nor a good insulator. See *Figure 1-17*.

Some of the electrons of certain metallic atoms are so loosely bound to the nucleus that they are comparatively free to move from atom to atom. Thus, a very small force or amount of energy will cause such electrons to be removed from the atom and become free electrons. These free electrons constitute the flow of an electric current in electrical conductors. The best conductors are silver, copper, and aluminum, in that order.

However, copper is used more extensively because it is less expensive. In contrast to good conductors, some substances such as rubber, glass, and dry wood have very few free electrons. In these materials, large amounts of energy must be expended in order to break the electrons loose from the influence of the nucleus. Substances containing very few free electrons are called Poor Conductors, Non Conductors, or Insulators. Actually, there is no sharp dividing line between conductors and insulators, since electron flow is known to exist to some extent in all matter. You as a Construction Electrician will simply use the best conductors as wires to carry current and the poorest conductors as insulators to prevent the current from being diverted from the wires.

3.1.2 Effects of Current Flow

Current flow has four effects that are used in various ways: magnetism, heat, chemical action, and physical shock.

3.1.2.1 Magnetism

Whenever current flows in a conductor, it produces a magnetic field around that conductor. Most manufactured magnets are created using this principle. This principle is also incorporated into devices called electromagnets. Electromagnets serve many useful purposes, such as relays, circuit breakers and electric motors.

3.1.2.2 Heat

Remember that current flow is the movement of free electrons. In essence, atomic structures are being rearranged. Electrons are being pulled off one atom and attached to another in a kind of domino effect. This action causes friction, which develops the heat effect that is a characteristic of current. Have you ever unplugged an appliance and felt the warmth of the cord? If so, you have felt one of the effects of current.

3.1.2.3 Chemical Action

Current produces a chemical action when it flows through a liquid. For example, when an electric current is passed through water, the water molecules will begin to separate into hydrogen and oxygen gas. This effect of current makes possible such things as the electroplating process, the operation of batteries and may other useful processes.

3.1.2.4 Physical Shock

As a Construction Electrician you must always stay alert to your work and your surroundings. This will help prevent current from affecting you with a physical shock. Under certain circumstances, as little as 0.1 amperes could stop your heart. A common 60-watt light bulb uses five times that much current.

3.1.3 Relationship of Voltage, Current, and Resistance

All electrical circuits are a combination of three electrical properties: voltage, current and resistance. Voltage is defined as the force that causes free electrons to move in a conductor. Current can be defined as a uniform movement of electrons in a specified direction and resistance simply stated is the opposition to current flow. No matter what the property each will have a direct bearing on the other and behave according to predictable principles.

3.1.3.1 Voltage to Current

Voltage has a major effect on current. As voltage rises, current rises. Think of voltage like water pressure, the higher the water pressure the more water comes out and the further it will jump. Electricity works the same way. Higher voltage pushes more current. The higher the voltage the farther current will jump. Since it is easy to change voltage, it is the most common means of regulating current flow.

3.1.3.2 Resistance to Voltage

Increasing resistance will cause voltage to drop. This is hard to do because to add resistors the circuit has to be physically changed.

3.1.3.3 Resistance to Current

Anything that uses electrical power offers resistance. Resistance is opposition to current flow. Think of resistance as blockage in the water pipe. As resistance rises, current flow drops. There are four main factors that affect resistance:

- Temperature: As heat rises, resistance increases. In a cool conductor, it is easier for the electrons to flow in one direction. When the conductor heats up, the electrons are more agitated and this causes increased resistance. The cooler a conductor the less resistance. The hotter the conductor the more resistance.
- Length: The longer the conductor the more resistance it will have. The shorter the conductor the less resistance it will have.
- Material: As stated earlier, the type of material will affect its ability to conduct electricity. The relative resistance of conductors with the same length and cross-sectional area are given in the following list with silver as a standard of 1 and the remaining metals arranged in order of ascending resistance.
- Cross sectional Area: Just as a larger water pipe can carry more water, a larger conductor can carry more current. The larger the conductor, the less resistance to current flow. The smaller the conductor, the more resistance to current flow.

Although all conductors are designed to have low resistance, they still have some resistance depending on the four factors stated above.

3.1.4 Ohm's Law

Ohm's Law states that current is directly proportional to the voltage and inversely proportional to the resistance. This means that if voltage is increased, current will increase at the same rate. If voltage is decreased, current will decrease. Ohm's Law applies to resistance as well. CURRENT IS INVERSELY PROPORTIONAL TO RESISTANCE. In other words, if applied voltage remains the same, and resistance is increased, the current will decrease. If the resistance is decreased, the current will increase. Higher resistance allowed less current to go through. This means that if the resistance is increased, the current is decreased. If the resistance is decreased, the current is increased.

This can be represented by a formula as follows:

- $V = I \times R$
- $I = V/R$
- $R = V/I$

Where:

V = Voltage in volts (V)

I = Current in amperes (A)

R = Resistance in ohms (Ω)

Test your Knowledge

1. What type of charged particles are associated with electrons?

   A. Neutral
   B. Positive
   C. Negative
   D. Canceling

2. Which of the following statements is true?

   A. The shorter the conductor the more resistance it will have
   B. The longer the conductor the less resistance it will have
   C. The more bends in a conductor the more resistance it will have
   D. The shorter the conductor the less resistance it will have

4.0.0 PRINCIPLES of DC

As a Construction Electrician, you will encounter DC while working on DC motors and most electronic equipment found in fire alarm, intrusion detection and traffic signal systems. While alternating current (AC) is better for transmitting electricity, DC is used extensively to provide a constant direct power source. This section will introduce you to the general uses, generating sources and characteristics of DC.

4.1.0 Identifying Principles of DC

Direct-current is used to power most electronic components found in fire alarm, traffic signal, and security alarm systems. It is also used in control circuits for motors and battery backup systems for high voltage substations and emergency lighting systems. Two sources of DC are batteries and DC generators.

4.1.1 Sources of DC

4.1.1.1 Battery

The most common source of DC is the battery. Batteries convert chemical energy to electrical energy. As an electrician, batteries are used as an emergency power source for substations and emergency lights. There are two basic types of batteries: primary and secondary cell. Both types of batteries require a chemical reaction to create electricity.

4.1.1.2 Symbol

The symbol for a single cell battery is shown on the bottom of *Figure 1-18*. The longer vertical line on the far left represents the positive terminal and the shorter vertical line on the right represents the negative terminal.

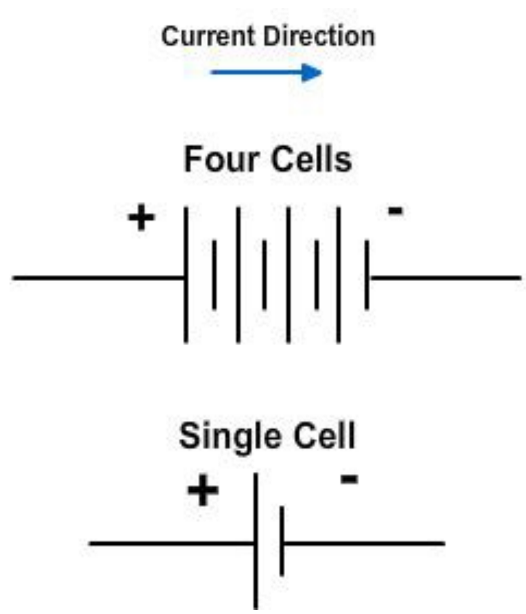


Figure 1-18 – Schematic diagram of batteries.

By adding additional long and short vertical lines a multi-celled battery can be represented. The battery symbol on the top of *Figure 1-18* is representative of a four cell battery.

4.1.1.3 Chemical Action

A battery consists of three main components: a positive electrode, a negative electrode, and an electrolyte. General-purpose batteries use strips of zinc and copper for the electrodes and sulfuric acid and water for the electrolyte. When the electrodes are connected by a conductor through a load a chemical reaction occurs that causes one electrode to lose electrons giving it a positive charge and the other electrode to gain electrons giving it a negative charge as shown in *Figure 1-19.*

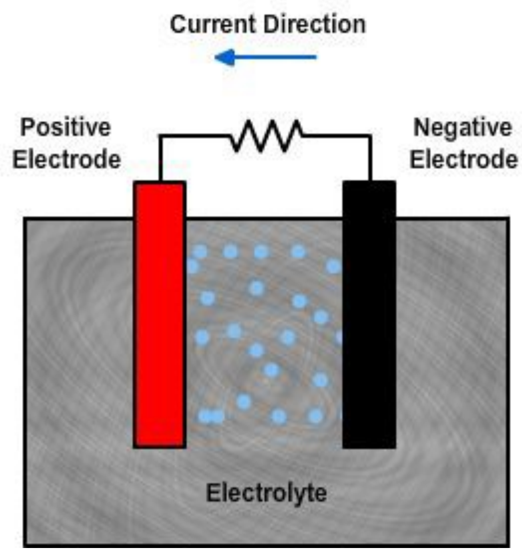


Figure 1-19 – Current flow in a battery

4.1.1.4 Primary Cell

Flashlight batteries are common examples of a primary cell. The primary cell is usually a dry cell, so called because it uses a paste for the electrolyte. The primary cell is a “one time” use battery, and is properly disposed of when the stored electrical charge is fully depleted.

4.1.1.5 Secondary Cell

Secondary cells are also known as rechargeable batteries, storage batteries or accumulators. They are different from primary cells in that they can be recharged and reused.

This is accomplished by applying current to the battery in the opposite direction of normal current flow. The chemical reaction is reversed to restore the active material, which is depleted during normal operation. Secondary cells are often found in emergency lights, exit lights and vehicle batteries to name a few. Depending on its use, the secondary cell could be a dry cell as described earlier, or the higher maintenance wet cell. Wet cells use a liquid for the electrolyte and need regular maintenance.

4.1.2 DC Generator

Another method of obtaining DC is through use of a DC generator. A generator converts mechanical energy to electrical energy with the help of magnetism. In order to create electricity with a generator you need three things: a conductor, a magnetic field and relative motion (the conductor is moving relative to the magnetic field.) When a conductor is moved through a magnetic field an electrical energy in the form of voltage and current is produced.

4.1.2.1 Conductor

When the conductor is moved through the magnetic field, the electrons inside the conductor are excited and move in a specific direction providing current flow. The conductor is often a coil of wire instead of the simplified conductor shown in *Figure 1- 20*.

4.1.2.2 Magnetic Field

The magnetic field must be present in order to produce the current flow in the conductor. Either a permanent magnet or an electromagnet can produce the magnetic field. The stronger the magnetic field the stronger the current flow.

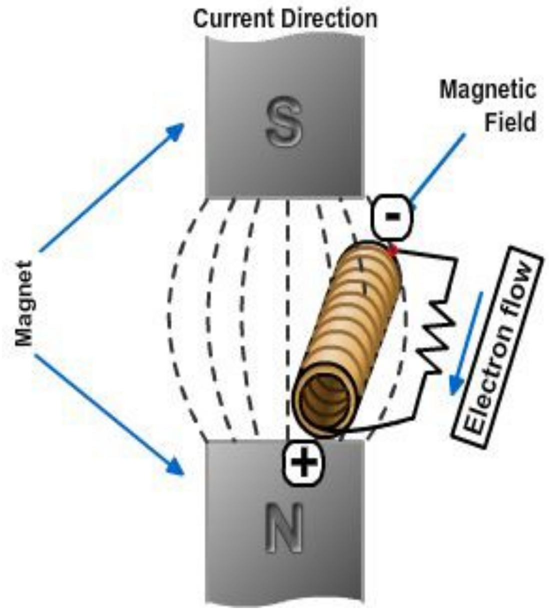


Figure 1-20 – Converting mechanical energy to electrical energy.

4.1.2.3 Relative Motion

In order to produce electricity, you must have relative motion.

The idea is that you must cut magnetic lines of force with the conductor. The conductor must be moved perpendicular to the magnetic lines of force. If the conductor were moved parallel to the magnetic field, the effect would be retarded.

4.1.3 Split Rings

A DC generator uses split rings. A simplified diagram of a DC generator is illustrated in *Figure 1-21*.

A loop of wire represents the conductor, which rotates through the magnetic field. The ends of the loop terminate in two copper half-rings, called split rings, which are insulated from each other. Fixed brushes make contact with the copper split rings to conduct electricity to the external circuit. The loop is rotated in a clockwise direction.

As the brushes are stationary, they deliver direct-current because either conductor in contact with a particular brush has the same direction of motion across the field.

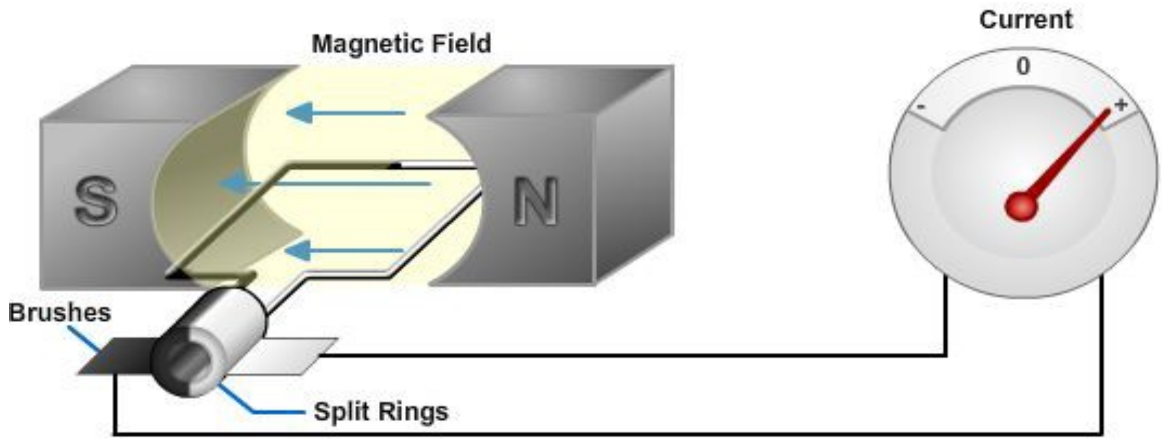


Figure 1-21 – DC generator.

With two brushes riding on the split rings to carry the current on an external circuit, you have an elementary DC generator producing electrical current. An AC generator is almost identical. The difference is a DC generator uses split rings to give direct-current while the slip rings of an AC circuit give you alternating current. AC generation will be covered extensively in the next block of instruction.

4.2.0 Characteristics of DC

DC is generally easier to understand than AC because there are fewer variables. Most DC circuits are purely resistive. Electrical properties of a DC circuit are easily determined using Ohm's Law.

4.2.1 Flows in One Direction

In a DC circuit, it is important for you to understand that direct-current flows only in one direction. Direct-current always flows from negative to positive. Direction of current flow is referred to as polarity. When wiring any DC circuit, you must ensure that you wire the polarity correctly; in other words, make sure the current is flowing in the direction required. If you disregard polarity, you could damage the power source, the circuit, or cause injury to yourself. To wire a DC circuit correctly refer to the manufacturer's instructions and strictly observe the position of the positive and negative terminals.

4.2.2 Relationship of Voltage, Current, and Resistance (Ohm's Law)

As previously stated, Ohm's Law of Electricity applies to DC circuits as well. Ohm's Law states that for any circuit the electric current is directly proportional to the voltage and inversely proportional to the resistance**.**

Another way of remembering the relationship of these electrical properties is that the current is DIRECTLY proportional to the applied voltage and INVERSELY proportional to the resistance – simply stated this means that if the voltage is increased, the current is increased. If the voltage is decreased, the current is decreased, if applied voltage remains the same, and resistance is increased, the current will decrease. If the resistance is decreased, the current will increase.

Test your Knowledge

3. Which of the following is NOT part of a standard battery?

   A. Positive electrode
   B. Gap Suppressor
   C. Negative electrode
   D. Electrolyte

5.0.0 PRINCIPLES of AC

5.1.0 Principle Definitions

5.1.1 AC vs. DC

5.1.1.1 Direct Current

Direct current is a constant output that does not vary with respect to time. In other words, as time passes after you turn the power on the output stays at the same level. *Figure 1-22* shows the relationship between volts (vertical axis) and time (horizontal axis). Note that for DC, assuming that the switch is turned on at the zero-time mark, the value of 120 volts stays constant as time passes. A good example of a DC power source is the common automobile battery.

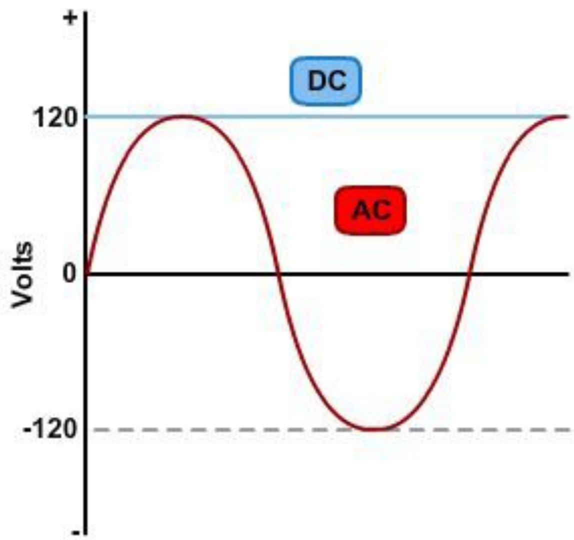


Figure 1-22 – DC vs. AC waveforms.

5.1.1.2 Alternating Current

AC power sources do not have a fixed polarity.

As the polarity of the power source changes, the direction of the current it produces also changes. Looking at *Figure 1-22* again, and assuming that the switch is turned on at the zero mark for the AC source, note that the voltage does not reach the 120 volts level until some time has passed. Once it reaches this level, it starts descending again to zero. After this point, the voltage drops below zero until it reaches the *negative* 120 volts level. Then it goes back to the zero level to continue alternating between the positive 120 volts value and the negative 120 volts value.

5.1.2 Generation of AC

5.1.2.1 Conditions Needed

As was the case with DC generation (using a DC generator), a conductor, a magnetic field, and relative motion must also exist to generate AC.

Figure 1-23 is similar to the DC generator. The wire loop rotating within the magnetic field generates the power as it breaks through the magnetic lines of force.

The rings collect this power and it is displayed in the measuring device connected to them. The difference between the DC generator and this AC generator is that the rings are not split for the AC generator, they are continuous. This causes one side of the loop to be in constant contact with one brush only.

When, for example, the black side of the wire loop moves from its vertical position to the horizontal position, it causes the needle in the measuring device to move from zero to a maximum value. As the wire loop continues to rotate from the horizontal position to the vertical inverted position, the needle in the measuring device moves back to zero.

The next rotation again causes the needle to move to a maximum value but in the opposite direction. Imagine the wire loop rotating at several revolutions per minute—the needle in the measuring device would be pointing right and left alternately. In a practical generator the wire loop, or windings, rotate at thousands of revolutions per minute. A measuring device with a needle like the one depicted in *Figure 1-23* would not be able to move that fast and it would only vibrate at the zero mark.

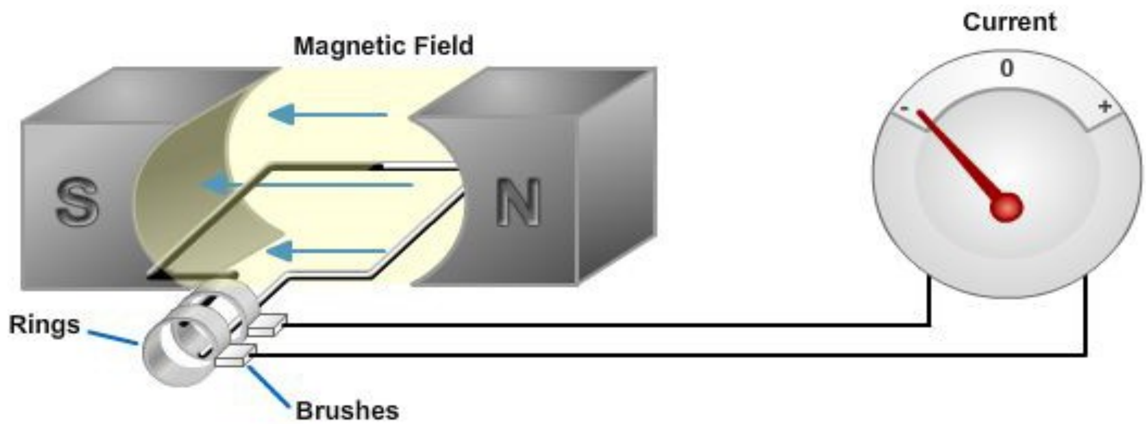


Figure 1-23 – AC generator.

Measuring devices for AC are designed specifically for that purpose and are constructed so that the pointing needle will point to the maximum value without alternating. Modern equipment use digital displays that eliminate the mechanical needle movement. One of these instruments is called an *oscilloscope*.

It is used to display the voltage, current or both at the same time in the form of waves, sinusoidal waves through a Cathode Ray Tube (CRT). Although this instrument is not one of the common instruments you will use, what it displays is very useful in the analysis of AC generation.

5.1.2.2 Sine Wave

The direction in which a conductor cuts through a magnetic field, or the direction in which a magnetic field cuts across a conductor, determines the polarity of the voltage that is induced. An easy method of showing how the polarity change is to use a graph that represents the generation of voltage over a period of time. *Figure 1-24* represents the voltage induced as the conductor makes a complete rotation through the magnetic field. A sine wave is shown to coincide with the rotation of the conductor.

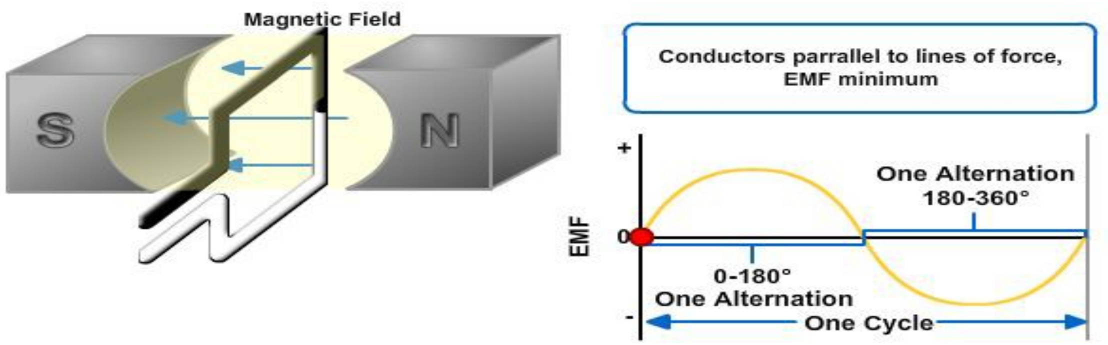


Figure 1-24 – Generating a sine wave.

5.1.2.2.1 Maximum/Peak Value

The amount of voltage or current at the maximum positive or negative point on a sine wave is called the peak value, as shown in *Figure 1-25*. Peak value occurs twice in each cycle: once positive and once negative. The amount represented between the positive peak and the negative peak is called the peak-to-peak value, which is simply twice the peak value.

5.1.2.2.2 Instantaneous Value

Instantaneous value is simply the value of the sine wave at any given point in time. Note that in *Figure 1-25*. the instantaneous value label points at three different locations of the sine wave.

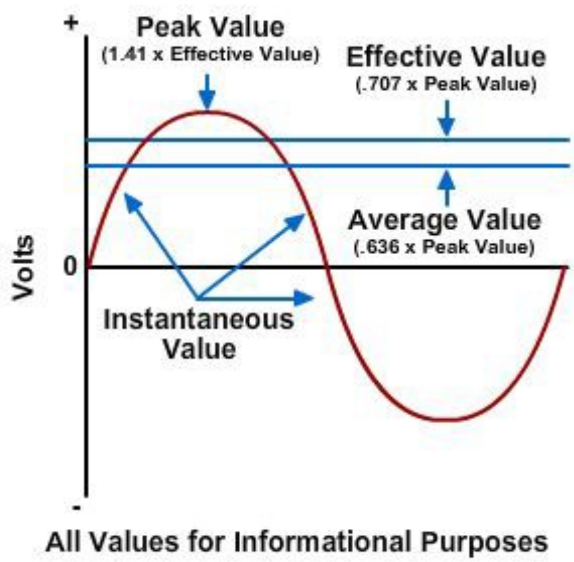


Figure 1-25 – Sine wave: One cycle.

This is only to indicate that this value can be any point in the curve and not a fixed amount like the other values

5.1.2.2.3 Average Value

The average value in AC is the average of all the instantaneous values during one alternation. Except for the fact that the average value is a mathematical viewpoint, it is of no great significance since it is merely a numerical average of all the sine values for all the angles. Average value is computed to be equal to 0.636 x peak value. It is always this constant.

5.1.2.2.4 Effective Value

Effective values for AC are often called RMS values. RMS stands for root-mean-square, which refers to the mathematical formula used to determine effective values. The formula itself is not important here. The important thing to understand is that RMS values are used to rate operating voltages on almost all AC equipment. In electrical work, you will deal mostly with effective values of voltage. Do not confuse this value, as new electricians often do, with the "average value" because the "effective value" is the actual rating of the useful power available to do work.

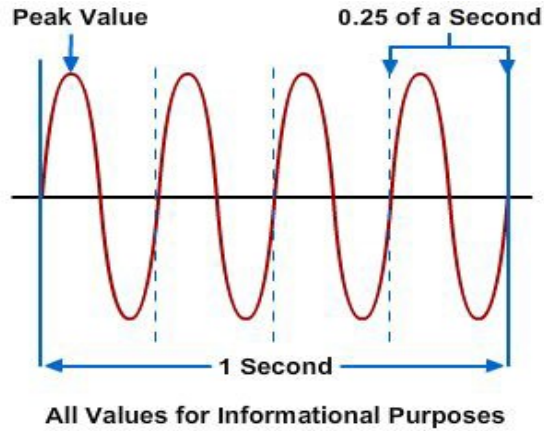


Figure 1-26 – Frequency.

5.1.2.3 Cycle and Frequency

As it has been mentioned already, a complete revolution of the rotating part, called a rotor or armature, produces a positive alternation and a negative alternation, which completes a cycle.

Each cycle has two maximum or peak values: one for the positive half-cycle and the other for the negative half-cycle. The number of times that this cycle is repeated over time is known as frequency. When discussing electrical frequency, the unit of time used to measure is the second. In other words, frequency is measured in cycles per second.

5.1.2.3.1 Hertz

The unit of measure for frequency is the Hertz (Hz). *Figure 1-26* shows a continuous sine wave that generates a complete cycle in 0.25 seconds. In one second, four complete cycles are generated. Therefore, the frequency is 4 cycles per second, or 4 Hz. In United States, power is generated with a frequency of 60 Hz to be used in all household appliances. Some other countries generate power at a frequency of 50 Hz, and equipment used in aircrafts use 400 Hz power.

5.1.2.3.2 Frequency Formula

You can determine the frequency of the power output from a generator by using the following formula: **F = P/2 x N/60 = PN/120**

Where **P** is the number of poles and **N** is the speed in Revolution per Minute (RPM). For example, a two-pole, 3600-rpm generator has a frequency of **2/120x3600=60Hz**. A four-pole, 1800-rpm generator has the same frequency.

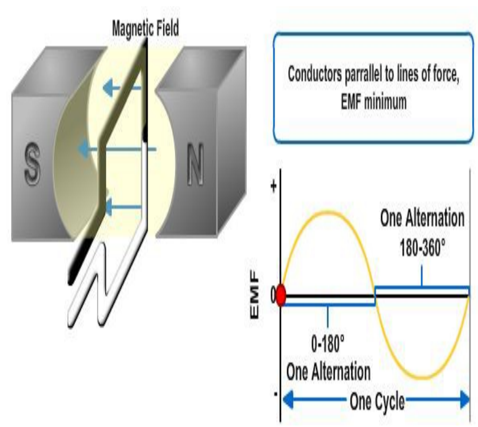


Figure 1-27 – Single phase generator.

5.1.2.4 AC Generators

A generator converts mechanical energy to electrical energy.

All generators can be classified as either AC or DC, and consist of a rotating section (rotor) and a stationary section (stator). AC generators are the most common means of producing either single- phase or poly-phase power. The design of the generator will determine which power is generated and from where the output is taken. One example of how a generator operates is as follows: a mechanical force is applied to the shaft of the rotating section to cause relative motion within the magnetic lines of force. The shaft turns and electrical energy in the form of voltage and current is delivered to the external circuit load via conductors.

Generators use the principle of electromagnetic induction to produce voltage and current. This principle states that if a conductor lies within a magnetic field, and either the field or the conductor moves, a voltage is induced in the conductor. When a voltage is induced, electrons move providing current flow.

5.1.2.4.1 Single Phase

A simple single-phase generator consists of one conductor and one magnetic field, as shown in *Figure 1-27*. As the conductor cuts the magnetic field, a voltage of varying amount and direction is generated. In a practical generator, the conductor is wound to form a coil or winding. The magnetic field is produced from other windings, or electromagnets. If you connect an oscilloscope to the output of a single-phase generator you will see a continuous sine wave like the ones discussed previously.

5.1.2.4.2 Three Phase

Three-phase electricity is widely used to power heavy equipment, i.e., motors and air conditioning systems. The majority of generators used in power plants produce three-phase electricity. These generators have three separate coils distributed uniformly around a stationary section called the “stator”. If you divide 360° (a complete circle) by three, you get 120°. This is the separation between coils as shown in the simplified generator represented in *Figure 1-28*.

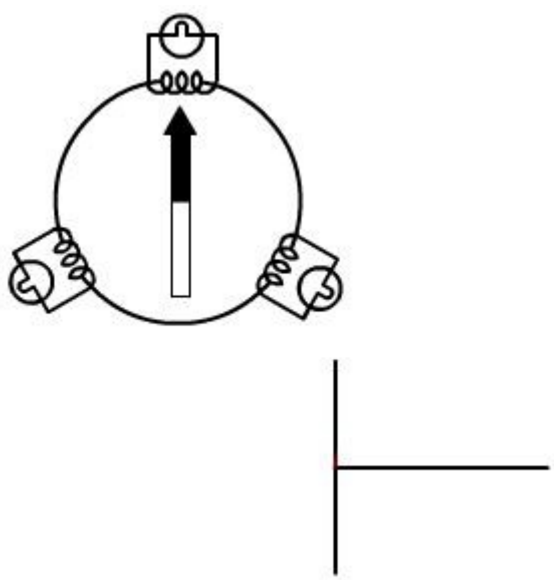


Figure 1-28 – Rotating magnetic field

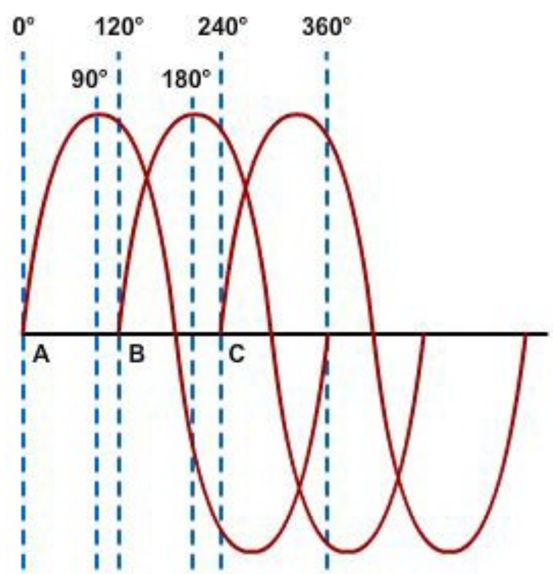


Figure 1-29 – Three phase at 120°

The black and white arrow in the center of the generator in *Figure 1-27* represents a rotating magnetic field. *Figure 1-28* shows the magnetic field rotating clockwise from its vertical position and the corresponding outputs. Keep in mind that for simplicity and to avoid confusion this figure represents the generation of power from the winding only. However, other windings would also be producing power as the rotating magnetic field passes by them. Because the windings are physically separated by 120°, the sine waves produced by each winding will be also separated by 120° as shown in *Figure 1- 29*.

Looking at *Figure 1-29*, you can see that the A phase starts at 0°; the B phase starts at 120°; and the C phase starts at 240°. The other marks (90°, 180°, 360°) are shown as references with respect to the A phase.

5.1.3 Characteristics of AC Circuits

5.1.3.1 Resistance

Every material offers some resistance or opposition to the flow of current. Good conductors, such as copper, silver, and aluminum offer very little resistance. Poor conductors, or insulators, such as glass, wood and paper, offer a high resistance to current flow. The determining factors for the resistance of a conductor include the size and type of conductor material. In addition, the devices and equipment that make up an electrical circuit will offer resistance and will be referred to as the "load" in upcoming areas of study.

In a purely resistive AC circuit, meaning that the load has only resistors, the relationship between current and voltage is not affected, as it will be with inductors and capacitors. To illustrate this, refer to *Figure 1-30*. The two sine waves represent the voltage and current through a purely resistive circuit. Note that both waves cross the zero mark at the same time and reach their peak values at the same time. When this occurs, the voltage and current in the circuit are said to be in-phase and the AC circuit will conform to the same laws as an equivalent DC circuit. This means that you can apply Ohm's Law to find the missing variables in a circuit.

Up to this point you can see that the electrical properties for both AC and DC circuits are the same. What you are about to learn is that there are some unique characteristics that only apply to AC circuits. These characteristics are inductance and capacitance.

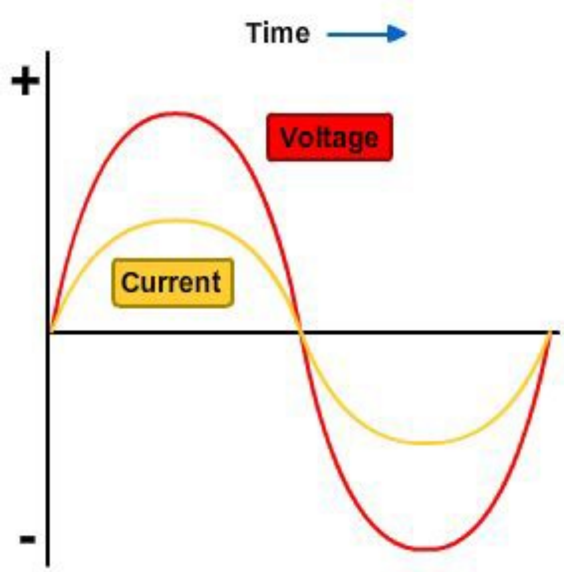


Figure 1-30 – Voltage/Current relationship in a purely resistive circuit.

5.1.3.2 Inductance/Inductive Reactance

Current through an AC circuit, as you already know, reverses direction in every cycle.

When using AC at 60 Hz, for example, means that current will flow in one direction for 1/120th of a second (half a cycle) and then reverse direction for the next 1/120th of a second (complete the cycle). This reversal continues for every cycle in the sine wave and for as long as current is flowing through a circuit.

Current flow through a conductor produces a magnetic field. *Figure 1-31* illustrates how current flowing through a conductor (dashed line) produces a magnetic field around that conductor (arrows circling the conductor). When the conductor is formed into a coil, sometimes called an inductor or winding, the magnetic field effect is increased.

To produce a voltage, you need to have a conductor, a magnetic field, and relative motion. When AC flows through a coil, or inductor, it produces a magnetic field that constantly changes polarity as current changes direction. This constant change of polarity in the magnetic field produces the same effect that relative motion of the conductor through a fixed magnetic field would have. Therefore, the three conditions to produce a voltage exist: a conductor (the coil), a magnetic field, and relative motion (constant change of polarity). The voltage generated through a coil is small compared to the current that helped generate it. However, this small voltage opposes normal current flow much like a resistor opposes current flow.

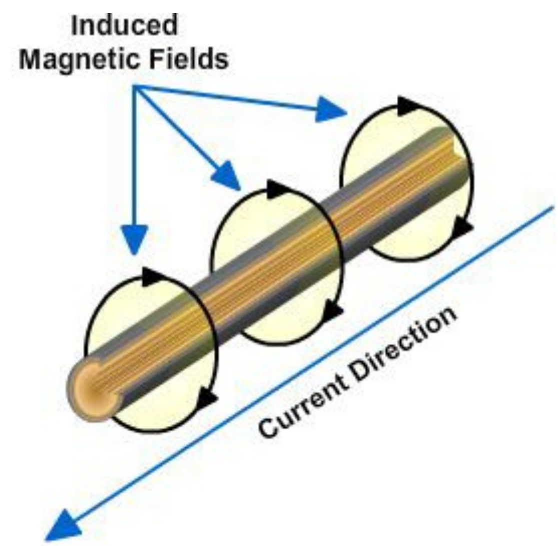


Figure 1-31 – Magnetic field produced by current flow.

Opposition to changes in current flow is the effect that a coil has in an AC circuit.

This physical property is called Inductance, and its symbol is "**L**". The unit for inductance is the henry, and its symbol is "**H**". Inductive reactance is the measure of the opposition to current flow that is created by inductance. Since inductive reactance, like resistance, limits current flow, it is measured in ohms. To convert the inductance of a coil given in henries to inductive reactance in ohms, the following formula is used:

$$\mathbf{X_L = 2\pi f L}$$

X_L = Inductive reactance (in ohms) 2π = Constant

f = frequency (in Hz)

L = Inductance (in henries)

However, it is important to remember that inductive reactance will be associated with AC circuits that contain inductors like motor windings, transformer windings, and other coiled conductors.

Figure 1-32 shows a circuit that contains two coils, or inductors, and a resistor. Note the graphic symbol used to depict an inductor. Engineers, circuit designers and technicians use circuits like this one to calculate the combined effects of resistance and inductive reactance. Inductors L1 and L2 simulate the effects of transformer windings or motor windings.

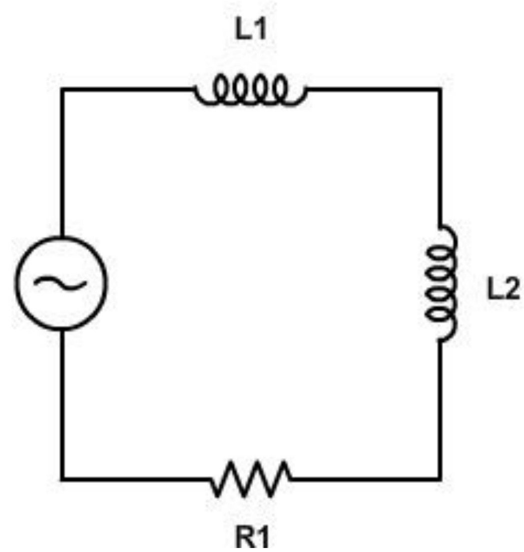


Figure 1-32 – AC circuit with inductors.

Resistor R1 simulates the total wire resistance in the circuit. This is also helpful when calculating the total current required from the generator.

As discussed before, in a purely resistive circuit the relationship between voltage and current in an AC circuit is not affected. However, in a purely inductive circuit, one that theoretically would have zero resistance and all inductance voltage and current are affected by a shift of 90º between the two sine waves, as shown in *Figure 1-33*. Note in the figure that the voltage sine wave starts at zero, whereas the current sine wave does not begin until the voltage sine wave has reached its peak, or 90º. This is because the inductance in the circuit opposes current flow momentarily, until the current overtakes it 90º later.

When the voltage builds up before the current as shown in *Figure 1-33*, it is said that the voltage leads the current. In other words, current lags the voltage.

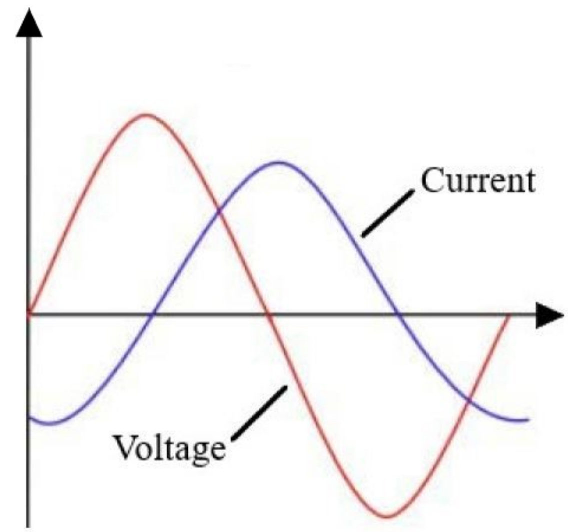


Figure 1-33 – Voltage/current relationship in a purely inductive circuit.

In a purely inductive circuit, voltage and current are out-of-phase by 90º. By now you know that all materials have some resistance. Therefore, a purely inductive circuit is practically impossible. With resistance present in the circuit, the phase angle decreases. Just like resistors and inductors offer some opposition to current flow in an AC circuit and affect the phase relationship between voltage and current, capacitors also affect an AC circuit.

5.1.3.3 Capacitance/Capacitive Reactance

Capacitors have the ability to store a charge and oppose changes in voltage. Capacitor has four stages: charging, charged, discharging, and discharged.

Figure 1-34 shows a capacitor being charged with a DC source and discharging through a lamp. This is the example that was used in that previous unit. However, what happens when the capacitor is connected into the circuit without the switch? *Figure 1-35* will be used to answer this question and to transition into the effects of a capacitor in an AC circuit. The arrows indicate the current flow from the negative side of the battery, through the capacitor and through the lamp.

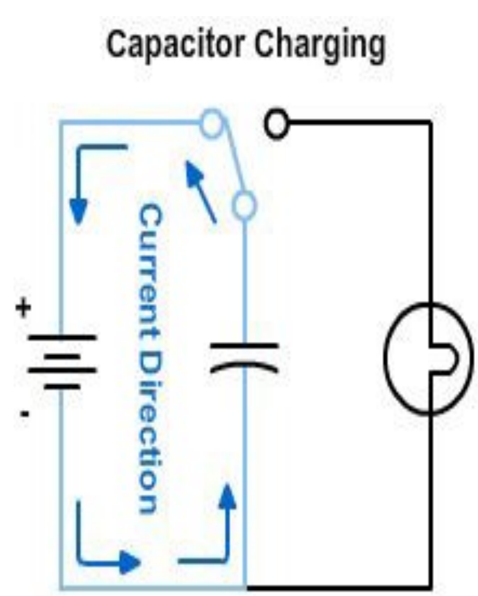


Figure 1-34 – Capacitor in a DC circuit.

The current going into the capacitor only occurs momentarily while the capacitor is charging. Once it has charged current flow through the capacitor stops. The graph below the circuit in *Figure 1-35* shows what happens to the voltage while the capacitor is charging. Notice that it does not reach the 12 V level until after the capacitor has been charged. This period of time is usually a fraction of a second that has no noticeable effect on a DC circuit and is therefore not even considered in basic circuit calculations. Capacitors, with their ability to oppose changes in voltage, have a unique effect in AC circuits. This effect is known as Capacitance, and its symbol is "**C**". Capacitance is measured in units called farads and its symbol is "**F**". Capacitive reactance is the measure of the opposition to current flow caused by capacitance, or the placement of capacitors in a circuit, and is measured in ohms. To convert the capacitance in a circuit given in farads to capacitive reactance given in ohms, the following formula is used:

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

X_C = Capacitive reactance (in ohms)

2π = Constant

f = frequency (in Hz)

C = Capacitance (in farads)

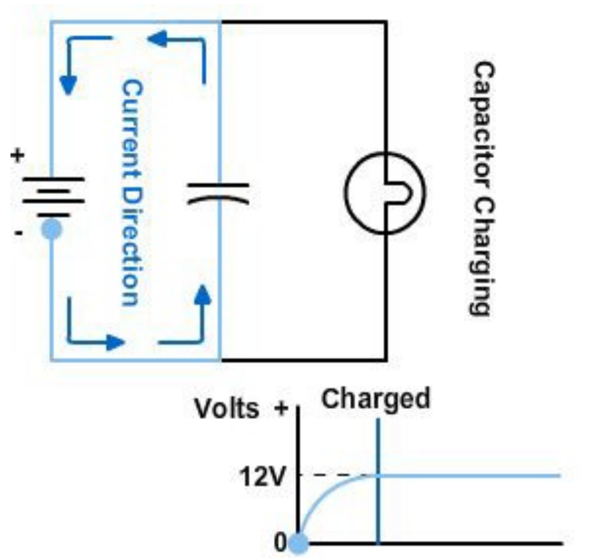


Figure 1-35 – AC circuit with capacitors.

Figure 1-36 shows a circuit with two capacitors and a resistor that could be used to simulate, for example, the capacitance between two wires lying side by side over a long distance. This is usually the job of engineers and circuit designers. However, you as a construction electrician will work with capacitors in motor circuits, power conditioning circuits, and other applications. Understanding the basic purpose of a capacitor in an AC circuit will help you when troubleshooting more complicated circuits. Capacitance and capacitive reactance are related in the same way that inductance and inductive reactance are related. Capacitive reactance, like inductive reactance, is measured in ohms. The effects of capacitance, like the effects of inductance, cause current and voltage to be out of phase. However, the effects of capacitance are not the same as the effects of inductance. Since capacitors oppose changes in voltage, the current in a purely capacitive circuit will be ahead of the voltage. When the voltage starts to build up from zero, the current is already at its peak value, or 90º ahead of the voltage.

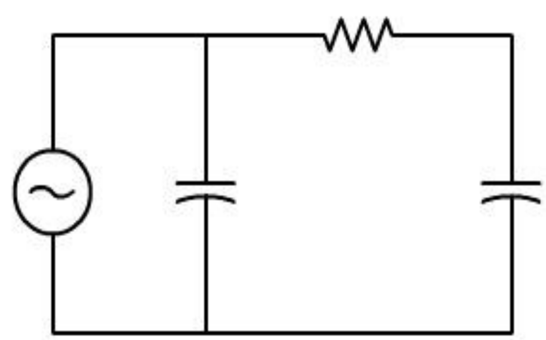


Figure 1-36 – Voltage/current relationship in a purely capacitive circuit.

When this occurs, it is said that the current leads the voltage or that the voltage lags the current. In a purely capacitive circuit, voltage and current are out-of-phase by 90º.

You may have noticed that the effects of capacitance in a circuit are opposite to the effects of inductance. In fact, capacitance is often added to AC circuits to counter the effects of inductance. For example, when the inductance in a circuit would limit current flow more than a desirable amount, capacitance can be added to that circuit to bring current flow up to the level that is needed. If a circuit has 10 ohms of inductive reactance (X_L), then 10 ohms of capacitive reactance (X_C) would cancel the inductance out of the circuit. Think of X_L as positive numbers and X_C as negative numbers, they are opposite. A purely capacitive circuit is practically nonexistent because of the added resistance of the wiring and other components of a circuit. Because of this resistance, the phase angle between voltage and current will be less than 90º, depending on the amount of resistance vs. capacitance. Resistance, inductive reactance and capacitive reactance are all measured in ohms. Now that you know how resistance, inductance and capacitance affect voltage and current in an AC circuit individually, it's time to study their combined effect—impedance.

5.1.3.4 Impedance

Impedance is defined as the total opposition to the flow of AC in a circuit. It is the combined effect of the total inductive reactance, capacitive reactance and resistance in an AC circuit. The symbol for impedance is the letter **Z**, and the unit of measurement for impedance is ohms.

The total effects of impedance in a circuit can be better understood with the basic diagram shown in *Figure 1-37*. The three properties that make up impedance are shown in relation to the horizontal axis.

Note how X_L is 90º above and X_C is 90º below this axis. Here you can really see how X_L is in the opposite direction of X_C, hence having the opposite effect. R is shown in line with the horizontal axis, meaning that it has 0º. *Figure 1-37* depicts a circuit that has 10 ohms of inductive reactance and 10 ohms of resistance. The resulting impedance is shown as the line between zero and the point where the other two values intercept. The angle labeled "θ" is the resulting angle of phase that the voltage and current will have due to the combined effects.

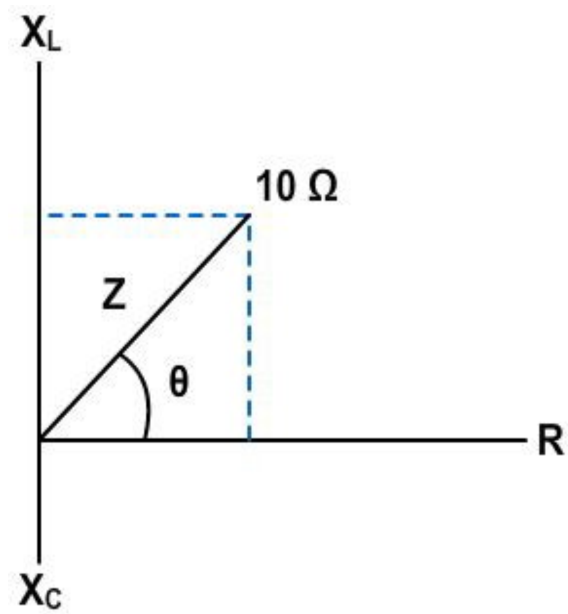


Figure 1-37 – Impedance (Z).

5.1.3.5 AC Power

To determine the power in an AC circuit, you must take into consideration not only the amount of current, voltage, and resistance, but the amount of inductance and capacitance as well. Because inductance and capacitance can cause AC voltage and current to be out of phase, there are three different kinds of power in AC circuits: apparent power, true power, and reactive power. Refer to *Figure 1-38*.

5.1.3.5.1 Apparent Power

Apparent power is the power used to do work plus the power stored during part of a cycle by inductance and capacitance and then returned to the power source. Apparent power is the voltage times the current in any circuit. (In a purely resistive circuit, apparent power and true power are the same). Refer to equations below for apparent power.

$S = I^2 \times Z$; $S = E^2/Z$; $S = I \times E$

S = Apparent Power

I = Current

E = Voltage

Z = Impedance

Measured in units of Volt-Amps (VA)

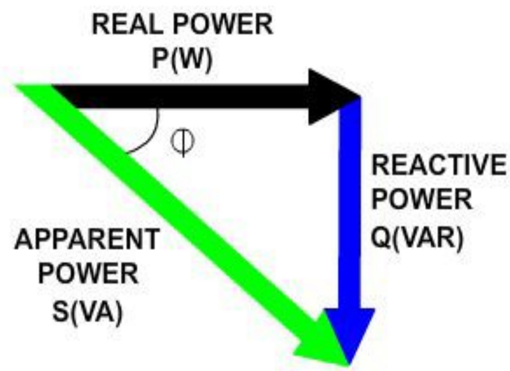


Figure 1-38 – Relationship of AC power.

5.1.3.5.2 True Power

True power in an AC circuit is the power actually used to do work. The power used in a purely resistive circuit is true power. True power can be determined by multiplying the voltage at any instant by the current at the same instant. If the voltage and current are in phase, their product, true power, will always be positive, since two positive numbers or two negative numbers multiplied together will always yield a positive result. When the voltage and the current are out-of-phase, at some points in time the instantaneous value of voltage may be positive while the value for current may be negative. Power, therefore, will be negative. What does this mean? This means that positive power is used by the load to do work, while negative power is reflected back to the source and being counterproductive. Refer to equations below for true power.

$P = I^2 \times R$ $P = E^2/R$

P = True Power

I = Current

R = Resistance

E = Voltage

Measured in units of Watts

5.1.3.5.3 Power Factor

The power factor for an AC circuit is the ratio of the true power to the apparent power in that circuit. The difference between true power and apparent power is directly caused by the phase separation of the voltage and the current in an AC circuit.

5.1.3.5.4 Reactive Power

Reactive power is the type of power found in a purely inductive circuit or a purely capacitive circuit. Unlike true power, reactive power does no useful work.

As defined earlier, positive power is power that goes from a power source to a load. In a purely inductive circuit, positive power goes from the power source to the inductance. Negative power, as defined earlier, is power reflected back to the power source. In an inductive circuit, the negative power periods are those during which the power absorbed by the inductance returns to the power source as the magnetic field collapses. In a purely inductive circuit, then, power just goes back and forth between the power source and the inductance. Since no power is used to do work, there is no power that can be identified as true power. The power in a purely inductive circuit is only reactive power.

The power in a purely capacitive circuit is also reactive power. When power is positive, the capacitor is charging, so it is storing up power. When the power is negative, the capacitor is discharging, (it is returning power to the source). The effect is the same for a purely capacitive circuit as the purely inductive circuit in the respect that the amount of power supplied by the power source to the capacitor is equal to the amount of power that is returned to the power source. The power in a capacitive circuit does not do any work, so it is reactive power rather than true power. Refer to equations below for reactive power.

$$Q = I^2 \times X \qquad Q = E^2/X$$

Q = Reactive Power

I = Current

E = Voltage

X = Reactance

Measured in units of Volt-Amps-Reactive (VAR)

5.1.3.6 Harmonics of an AC Circuit

A harmonic is defined as a sinusoidal component added to a sine wave, having a frequency that is a multiple of the fundamental frequency. When generated, an AC waveform is sinusoidal.

However, when various loads are connected into the circuit, other waveforms that may not be sinusoidal are produced as a result. Non-sinusoidal waveforms are important for an electrical technician to understand. Modern digital electronics systems, such as computers, data communications radar, pulse systems and circuits requiring ramp waveforms, have an effect on the fundamental sine wave in an AC circuit. They can cause a sinusoidal wave to become non-sinusoidal. A pure AC sine wave is comprised of one single frequency. Non-sinusoidal signal waveforms can be mathematically shown to be composed of a fundamental frequency sine wave plus a number of multiples of that frequency. These multiples are called harmonics. If the sine wave is not sinusoidal, it indicates the presence of harmonics. These harmonics can be either “odd” or “even”. Odd harmonics are those that represent frequencies of 3-times, 5-times, 7-times, and so on, of the fundamental sine wave. Even harmonics are those that represent frequencies of 2- times, 4-times, 6-times, and so on, of the fundamental sine wave. Sinusoidal waveforms can be distorted because of the presence of “odd” harmonics, “even” harmonics, or a mixture of both.

Figure 1-39 is an example of the effects of having harmonics in a circuit. In this example, the third harmonic is added to the fundamental sine wave. Notice that while the fundamental wave completes one cycle, the other wave completes three cycles in the same time period, this is why is called the third harmonic.

Harmonics have a number of effects on a variety of equipment. Harmonics can cause control and monitoring equipment to register improperly. The harmonic components of voltage can affect motor and generator efficiency, and can affect the torque developed.

Harmonics applied to transformers may result in increased levels of audible noise. However, the main effect of harmonics on transformers is excess heat. Harmonics can also shorten the life of capacitors by deteriorating the dielectric over time. Power electronic equipment may also be affected by harmonic distortion. Remember that harmonics are only associated with AC circuits and not with DC circuits.

6.0.0 ELECTRICAL CIRCUITS

6.1.0 Circuit Requirements and Configurations

6.1.1 Circuit Requirements

A closed loop of wire (conductor) is not necessarily a circuit. In any electric circuit where electrons move around a closed loop, current, voltage and resistance must be present. The physical pathway for current flow is actually the circuit. Its resistance controls the amount of current flow around the circuit. Therefore, at a minimum, a simple circuit must contain three things: a voltage source, some type of load, and a conducting pathway for current to flow. As an example, a lamp connected by conductors across a dry cell form a simple electric circuit as shown in *Figure 1-39.*

In any AC or DC electrical circuit, you know that current flows from negative (-) to positive (+). *Figure 1-39* illustrates current flow in a simple DC circuit. Notice that as long as the circuit's pathway is unbroken, it is a closed circuit and current will flow. However, if the path is broken at any point, it is an open circuit and current will stop.

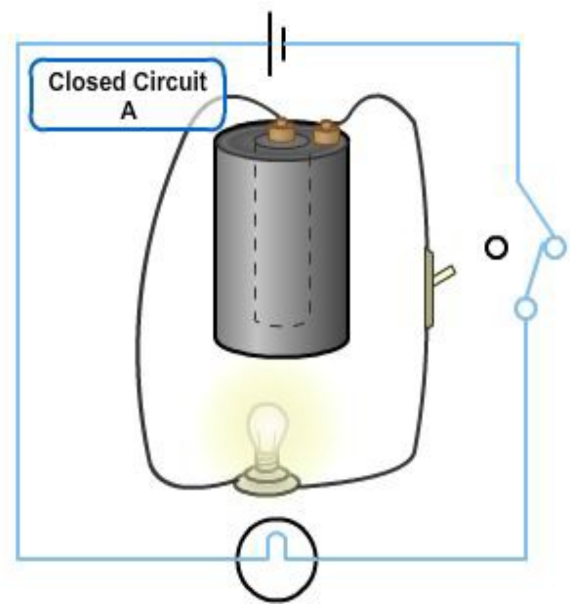


Figure 1-39 – Simple circuit.

6.1.1.1 Voltage Source

As previously stated every electrical circuit must have a voltage source. The most common source of voltage is either through generators (AC/DC) or batteries.

6.1.1.1.1 Generator

An AC generator provides much larger power and voltage ratings than DC generators. By producing alternating current, the voltage can be stepped up or stepped down efficiently by the use of transformers.

6.1.1.1.2 Battery

A battery is a good example of a direct-current power supply. Power and voltage control is limited with this type of power source. Voltage control with DC power is complicated.

6.1.1.2 Conductor

Every electrical circuit must have conductors to connect the other components of the circuit. The conductors create a complete electrical path for current to flow.

6.1.1.3 Resistive Load

A resistive load is required to drop the voltage and/or restrict current flow. A lamp is one example of a resistive load.

6.1.1.4 Complete Path(s) for Current Flow

For current to flow, there must always be a complete electrical path. A complete path allows the current to return to its place of origin, whether it be a battery or a generator.

6.1.2 Configuration Identification

6.1.2.1 Series Circuit

A series circuit is defined as two or more units of resistance connected end to end to form only one path for current flow and an AC or a DC voltage source. The series circuit in *Figure 1-40* contains two resistors and one voltage source. Each resistor is labeled with an "**R**", the symbol for resistance. In addition, each "**R**" is followed by a numeral to identify (called a subscript) the specific resistor (R_1, R_2, etc.).

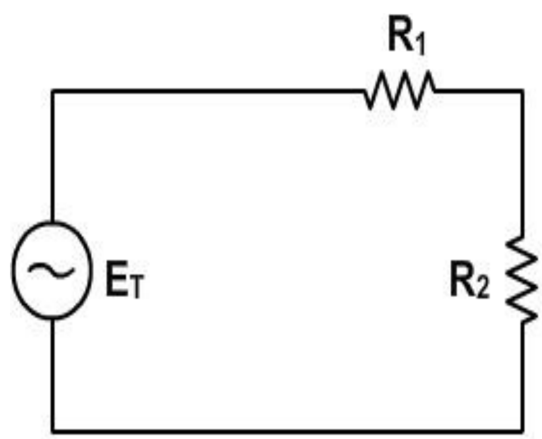


Figure 1-40 – Series AC circuit.

Subscripts are numbers or letters written below and to the right of the original circuit function letter, as in R_1 or R_2. Total circuit values are normally identified with a subscript "**t**". Total voltage, total current and total resistance is identified as E_t, I_t, and R_t.

6.1.2.2 Parallel Circuit

A parallel circuit is defined as having more than one current path connected to a common voltage source. Parallel circuits must contain two or more resistors, which are not connected in series. An example of a basic parallel circuit is shown in *Figure 1-41*. Starting at the voltage source (E_t) and tracing counterclockwise around the circuit, two complete and separate paths can be identified in which current can flow. One path is traced from the source through resistance R_1 and back to the source: the other, from the source through resistance R_2 and back to the source.

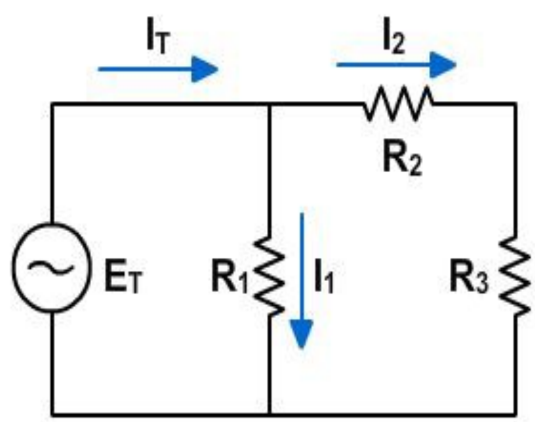


Figure 1-41 – Parallel circuit.

6.1.2.2.1 Multiple Paths for Current Flow

A parallel circuit must contain at least (can have more) two paths for current flow. All of these paths must return to the same voltage source.

6.1.2.2.2 Number of Paths = Number of Resistors

Each path for current flow must contain only one resistor for the circuit to be considered a parallel circuit. The circuit is considered a true parallel circuit when the number of current paths equals the number of resistors.

6.1.2.3 Series Parallel Circuit

A series parallel electrical circuit is defined as a circuit that contains more than one path of current flow and at least two resistors in series in one of the paths. Keep in mind; each path must contain at least one resistor and one path with at least two, so there will always be more resistors than paths for current flow. *Figure 1-42* shows an example of a series parallel circuit. Remember that current in an AC circuit changes direction continuously. To study the paths of current flowing in the circuit of *Figure 1-41*, an instant in time is taken when the current is flowing in one direction. Total current in the circuit is indicated by I_t. This current leaves the generator from the top towards point A. From point A, I_t has two paths: down through R_1 and to the right towards R_2 and R_3, the series branch. These currents are labeled I_1 and I_2. Mathematically stated, $I_t = I_1 + I_2$. It should be noted that the values of I_1 and I_2 depend on the resistance of each path.

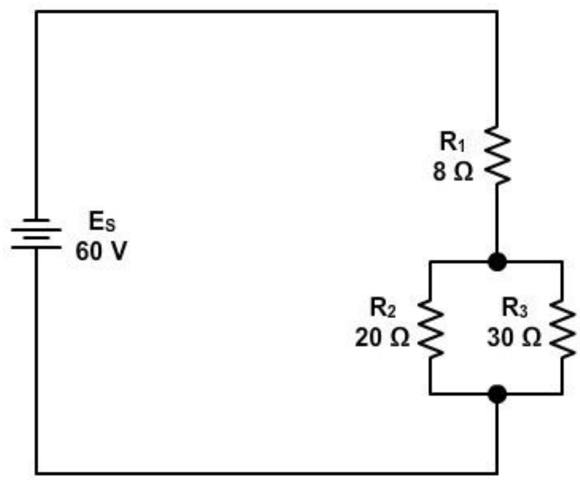


Figure 1-42 – Series parallel circuit.

Towards the bottom of *Figure 1-42*, currents I_1 and I_2 will join at point B to become I_t again, returning to the bottom of the generator. When current reverses polarity during the second half of the sine wave, current will leave the generator from the bottom towards point B, split again, and then rejoin at point A to return to the top of the generator.

7.0.0 ELECTRICAL CIRCUIT COMPUTATIONS

7.1.0 Series Circuit Computations

When performing calculations to determine electrical property values in circuits containing two or more components, it becomes necessary to use subscripts to identify specific components. By knowing any two of the three electrical property quantities, i.e., voltage and current, the third (resistance) may be determined mathematically using Ohm's Law. However, you can also apply Kirchhoff's Voltage and Current Laws in some instances.

7.1.1 Kirchhoff's Voltage Law (E)

The voltage drop across a resistor in a simple circuit is the total voltage across the circuit and is equal to the applied voltage. The total voltage drop across a series circuit is also equal to the applied voltage. In any series circuit, the SUM of the voltage drops must equal the total voltage. The formula, which expresses this relation, is:

$$E_t = E_1 + E_2 + E_3 + \ldots E_N$$

It must be emphasized that the potential difference across a resistor remains constant as it is a measure of the amount of energy required to move a unit charge from one point to another. As long as the source produces electric energy as rapidly as it is consumed in a resistance, the potential difference across the resistance will remain at a constant voltage. The applied voltage and the proportional relationship of each resistance in the circuit determine the value of this voltage. The voltage drops that occur in a series circuit are in direct proportions to the resistance across which they appear. This is a result of having the same current flow through each resistor. Thus, the larger the resistor the larger will be the voltage drop across it. The current in a series circuit, in completing its electrical path, must flow through each resistive load inserted into the circuit.

7.1.2 Kirchhoff's Current Law (I)

As stated previously, a series circuit is defined as two or more units of resistance connected end to end to form only one path for current flow. Current will only have one path to follow. Current flow in the series circuit is the same throughout the circuit, so the value of current flowing through any resistor (I_1, I_2, I_3, etc.) is equal to the value of total current (I_t).

The formula, which expresses this relation, is:

$$I_t = I_1 = I_2 = I_3 = \ldots I_N$$

7.1.3 Resistance Law (R)

Since the current flow will only take one path through the series circuit, it will have to travel through all of the resistors in the circuit. Therefore, the individual resistors will work to limit current flow. The total resistance of the circuit will be equal to the sum of the individual resistances. This statement can be expressed in equation form as:

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

It should be noted here that although these laws mention only resistance, the meaning of the word should be understood to mean a load in the circuit that may not be purely resistive. Previously you learned how inductive and capacitive loads could be measured in ohms (X_L and X_C).

7.1.4 Power Law (P)

Each resistor, or load, in a series circuit consumes power to do work and some of it is dissipated in the form of heat. Since this power must come from the source, the total power must be equal in amount to the power consumed by the circuit resistance. In a series circuit, the total power is equal to the SUM of the powers dissipated by the individual resistors. In equation form:

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

7.2.0 Parallel Circuit Computations

7.2.1 Kirchhoff's Voltage Law (E)

You have seen that the source voltage in a series circuit divides proportionately across each resistor in the circuit. In a parallel circuit, the same voltage is present across all the resistors of a parallel circuit. This voltage is equal to the applied voltage (E_t). This statement can be expressed in equation form as:

$$E_t = E_1 = E_2 = E_3 = \ldots E_N$$

Note that Kirchhoff's voltage law for parallel circuits is similar to Kirchhoff's current law for a series circuit.

7.2.2 Kirchhoff's Current Law (I)

The current in a circuit is inversely proportional to the circuit resistance. This fact establishes the relationship upon which the following discussion is developed. A single current flows in a series circuit. The total resistance of the circuit determines its value. However, the source current in a parallel circuit is distributed among the available paths or branches in relation to the value of the resistors in each branch. The characteristics of current in a parallel circuit can be expressed in terms of the following equation:

$$I_t = I_1 + I_2 + I_3 + \ldots I_N$$

Note again that Kirchhoff's current law for parallel circuits is similar to Kirchhoff's voltage law for series circuits. Make sure you know the differences so you will not confuse the laws for series circuits and parallel circuits.

7.2.3 Resistance Law (R)

The total resistance of a parallel circuit will always be less than the smallest resistor in the circuit. This stems directly from Ohm's Law where resistance is directly proportional to voltage and inversely proportional to current. In relation to current this means that, when voltage is constant, as current increases resistance must be decreasing in the (parallel) circuit. Scientists like Ohm and Kirchhoff developed the formula to express total resistance in a parallel circuit as follows:

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

In words this equation states that the total resistance in a parallel circuit is equal to the inverse value of the addition of the inversed values of individual resistors (loads) in the circuit. If, for example, you have three resistors of 30 ohms each connected in parallel, the total resistance of the circuit would be expressed as follows:

$$Rt = \frac{1}{1/30 + 1/30 + 1/30}$$

Working with the bottom operation of the equation first, you would need to find a common denominator for 30. Since all resistors have the same value, the common denominator would be this same value of 30:

$$1/30 + 1/30 + 1/30 = 3/30 = 1/10 \text{ (simplified)}$$

The top operation of the equation, the one by itself, is only indicating that when the bottom operation is executed the final value is inverted. For this example, the 1/10 will become 10/1, which is equal to simply 10, or in this case 10 ohms of resistance. Note that although there are three 30-ohm resistors in the circuit, the total resistance is only 10 ohms. From this formula, and knowing that in a parallel circuit where all the resistors have the same value, the common denominator will always be the value of the resistors. Therefore, this formula for parallel circuits with resistors of the same value can be simplified to:

$$R_t = R/N$$

Where R_t represents total resistance; R represents the value of the resistors; and N represents the number of resistors in the circuit.

$$Rt = \frac{1}{1/R1 + 1/R2} = \frac{1}{\frac{R1 + R2}{(R1)(R2)}}$$

Therefore,

$$Rt = \frac{(R1)(R2)}{R1 + R2}$$

7.2.4 Power Law (P)

Power computations in a parallel circuit are essentially the same as those used for the series circuit. The total power dissipated is equal to the sum of the powers dissipated by the individual resistors. Like the series circuit, the total power consumed by the parallel circuit is expressed by the formula:

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

7.3.0 Series Parallel Combination

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 combination circuit problems, the network shown in *Figure 1-43* 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 R_2 and R_3.

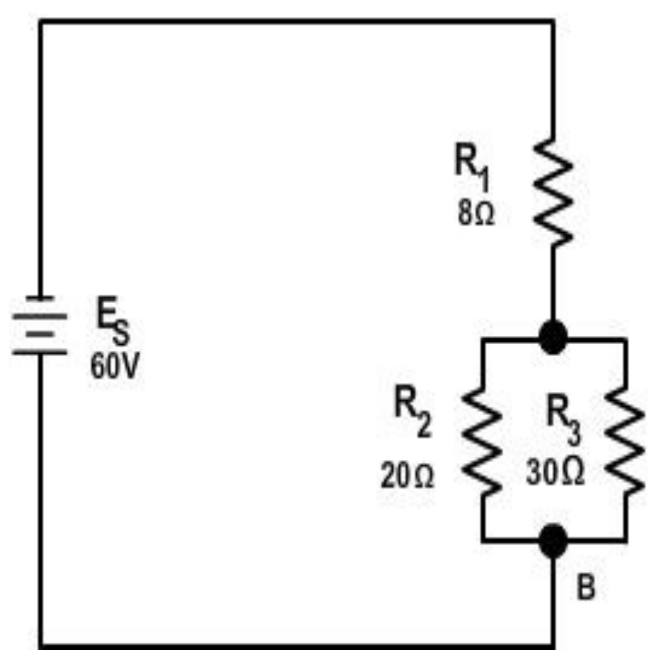


Figure 1-43 – Example combination circuit.

Given: $R_2 = 20\Omega$

$R_3 = 30\Omega$

Solution: $R_{eq1} = \frac{R_2 \times R_3}{R_2 + R_3}$

$R_{eq1} = \frac{20\Omega \times 30\Omega}{20\Omega + 30\Omega}$

$R_{eq1} = \frac{600\Omega}{50\Omega}$

$R_{eq1} = 12\Omega$

Now that the equivalent resistance for R2 and R3 has been calculated, the circuit can be redrawn as a series circuit as shown in *Figure 1-44.*

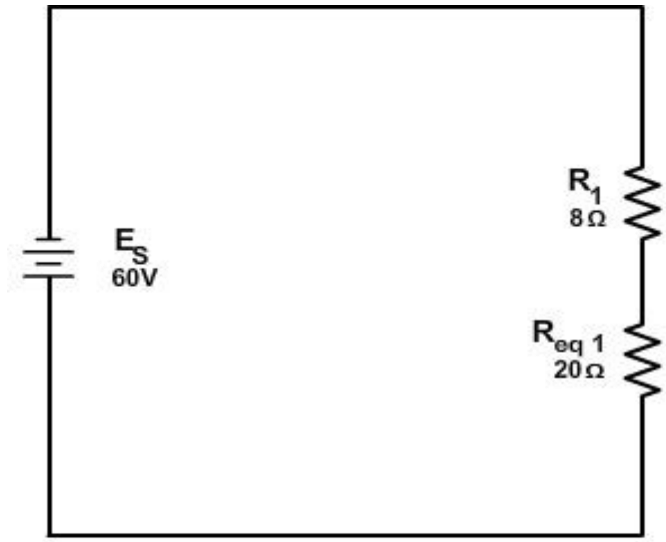


Figure 1-44 – Example combination circuit.

Given: $R_1 = 8\Omega$

$R_{eq1} = 12\Omega$

Solution: $R_{eq} = R_1 + R_{eq1}$

$R_{eq} = 8\Omega + 12\Omega$

$R_{eq} = 20\Omega$ or $R_T = 20\Omega$

The original circuit can be redrawn with a single resistor that represents the equivalent resistance of the entire circuit as shown in *Figure 1-45*.

To find total current in the circuit:

Given: $E_S = 60V$

$R_T = 20\Omega$

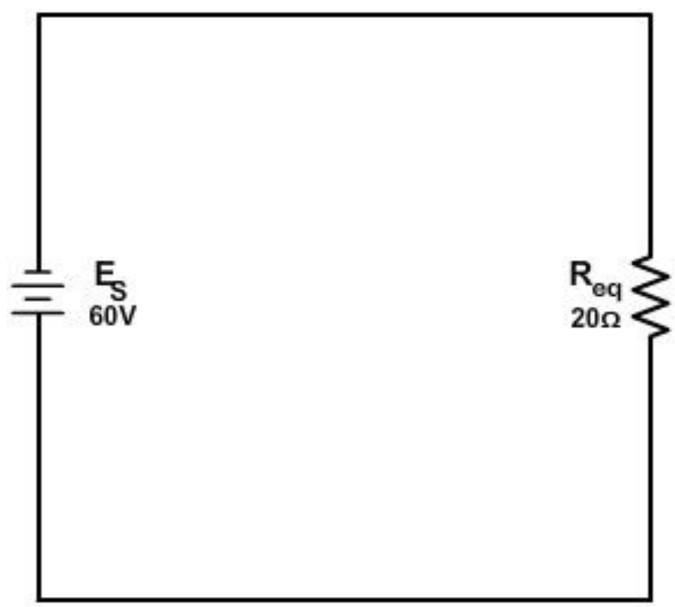


Figure 1-45 – Example combination circuit.

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

$I_T = \frac{60V}{20\Omega}$

$I_T = 3A$

To find total power in the circuit:

Given: $E_S = 60V$

$I_T = 3A$

Solution: $P_T = E_S \times I_T$

$P_T = 60V \times 3A$

$P_T = 180W$

To find the voltage dropped across R_1, R_2, and R_3, refer to *Figure 1-45*. R_{eq1} represents the parallel network of R_2 and R_3. Since the voltage across each branch of a parallel circuit is equal, the voltage across R_{eq1} (E_{eq1}) will be equal to the voltage across R_2 (E_{R2}) and also equal to the voltage across R_3 (E_{R3}).

Given: $I_T = 3A$

$R_1 = 8\Omega$

$R_{eq1} = 12\Omega$

Solution: $E_{R1} = I_1 \times R_1$

$E_{R1} = 3A \times 8\Omega$

$E_{R1} = 24V$

$E_{R2} = E_{R3} = E_{eq1}$

$E_{eq1} = I_T \times R_{eq1}$

$E_{eq1} = 3A \times 12\Omega$

$E_{eq1} = 36V$

$E_{R2} = 36V$

$E_{R3} = 36V$

To find power used by R_1:

Given: $E_{R1} = 24V$

$I_T = 3A$

Solution: $P_{R1} = E_{R1} \times I_T$

$P_{R1} = 24V \times 3A$

$P_{R1} = 72W$

To find the current through R_2 and R_3, refer to the original circuit, *Figure 1-43*. You know E_{R2} and E_{R3} from previous calculation.

Given: $E_{R2} = 36V$

$E_{R3} = 36V$

$R_2 = 20\Omega$

$R_3 = 20\Omega$

Solution: $I_{R2} = \frac{E_{R2}}{R_2}$

$I_{R2} = \frac{36V}{20\Omega}$

$I_{R2} = 1.8A$

$I_{R3} = \frac{E_{R3}}{R_3}$

$I_{R3} = \frac{36V}{30\Omega}$

$I_{R3} = 1.2A$

To find power used by R_2 and R_3, using values from previous calculations:

Given: $E_{R2} = 36V$

$E_{R3} = 36V$

$I_{R2} = 1.8A$

$I_{R3} = 1.2A$

Solution: $P_{R2} = E_{R2} \times I_{R2}$

$P_{R2} = 36V \times 1.8A$

$P_{R2} = 64.8W$

$P_{R3} = E_{R3} \times I_{R3}$

$P_{R3} = 36V \times 1.2A$

$P_{R3} = 43.2W$

8.0.0 CONSTRUCTING an ELECTRICAL CIRCUIT

8.1.0 Construction of a Series Circuit

When you construct a series circuit, you need to follow a wiring diagram or schematic drawing of some kind. It could be provided by an electrical engineer or a manufacturer. The important point to remember is to start at one point and systematically follow the drawing until you have all components built into your circuit.

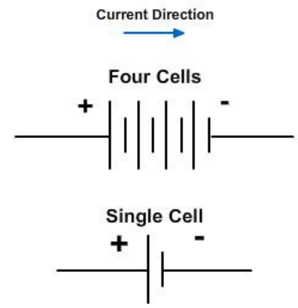


Figure 1-46 – Voltage source.

8.1.1 Voltage Source

A voltage source, which can be a battery or a generator, is required to provide the electrical pressure to generate current flow. This voltage source will supply the power necessary to do work. Refer to *Figure 1-46*.

8.1.2 Overcurrent Protection

A fuse or circuit breaker is required to protect the conductors and the load. The overcurrent protection device, whether it is a fuse or a circuit breaker, must be sized according to the current flow (load) required by the equipment being connected. Overcurrent protection is connected in series with the circuit. The power supply provides power to the “input” side of the breaker or fuse and equipment is connected to the “load” side. Refer to *Figure 1-47*.

Figure 1-47 – Fuse.

8.1.3 Switch

Most electrical circuits require some means of turning on or shutting off power to them. You accomplish this daily by turning on and off lights, air conditioners, or even the ignition on your car. Switches allow you start or stop the flow of power to electrical equipment by physically opening or closing the circuit. Switches are connected in series within the circuit and must be installed on the ungrounded conductor. A switch must also be rated according to the current flow and voltage generated by the power supply. Refer to *Figure 1-48*.

Figure 1-48 – Switch.

8.1.4 Resistive Load

The load limits current flow. It is electrical equipment, such as a light bulb or hair-dryer motor that actually accomplishes the useful work. Equipment can be as simple as a clothes iron or as complicated as a computer. In a series circuit, the resistors (load) are connected end-to-end. Refer to *Figure 1-49*.

Figure 1-49 – Resistive Load.

8.1.5 Conductors

Current requires an electrical path to keep flowing. Without a complete path, current will not flow. The conductors provide the physical connection between the power source, overcurrent protection, switch, and the load and provide a return path back through the components so that current can flow back to its place of origin. Like the overcurrent protection devices and switch, conductors must also be rated according to the current flow and voltage generated by the power supply. Refer to *Figure 1-50*.

Figure 1-50 – Conductor.

8.2.0 Construction of a Parallel Circuit

Constructing a parallel circuit is very similar to constructing a series circuit. You need a power source, conductors, and at least two resistors or loads not connected in series in at least two paths for the current to flow. All paths must return to the same voltage source. The difference is that you connect the resistors in parallel, or side-by-side, instead of end-to-end as in the series circuit. Ensure power is off before constructing any circuit.

8.2.1 Voltage Source

As with the series circuit, a parallel circuit requires a voltage source to provide the electrical pressure needed to generate current flow. Connections are the same as in the series circuit.

8.2.2 Overcurrent Protection

Like all electrical circuits, parallel circuits require some sort of overcurrent protection. Overcurrent protection connections are the same for parallel circuits as for series circuits. The overcurrent protection is connected immediately after the power supply and in line (in series) with the circuit. It is important to note that even though you are constructing a parallel circuit, the circuit breaker or fuse must be placed in series. If it is placed in parallel, then current will have another path to flow, bypassing the protective device.

8.2.3 Switch

As stated earlier, electrical circuits require a switch to provide a means of opening or closing the circuit. Switch connections for parallel circuits are the same as for series circuits. Switches are connected in series within the circuit and must be installed on the ungrounded conductor.

8.2.4 Junction(s)

Junctions in a parallel circuit are used where three or more conductors meet each other. At a junction, the current splits into the individual branch conductors that feed their respective resistive loads.

8.2.5 Resistive Load

As stated before, the load is what will be limiting current flow in the electrical circuit. In a parallel circuit, the number of resistors equals the number of current paths. The minimum number of resistive loads needed for a parallel circuit is two. The resistive loads are connected in parallel.

8.2.6 Conductors

Conductors are required in parallel circuits just as they are in series circuits. These conductors provide the means for current to flow through the circuit to electrical equipment and return to the power source.

8.3.0 Construction of Series Parallel Combination Circuit

Constructing a series -parallel circuit is very similar to constructing a series and parallel circuits. You still require a power source, conductors containing more than one path of current flow and at least two resistors in series in one of those paths. Keep in mind, each path must contain at least one resistor and one path with at least two, so there will always be more resistors than paths for current flow. All paths must return to the same voltage source. Resistors are connected in parallel, or side-by-side, and end- to-end as in the series circuit. Ensure power is off before constructing any circuit.
Review series and parallel circuit construction.

Summary

Your knowledge and use of electrical theory is essential for the safe conduct and completion of your job as a Construction Electrician. As a Construction Electrician, you need the knowledge of the concepts and principles when dealing with alternating and direct current. During your career as a Construction Electrician, you will apply this and other electrical and electronic theory in your everyday conduct.

Additional Resources and References

This chapter is intended to present thorough resources for task training. The following reference works are suggested for further study. This is optional material for continued education rather than for task training.

Unified Facilities Criteria (UFC) 3-560-01 (Electrical Safety, Operation and Maintenance)

OSHA Regulations (Standards – 29 CFR)

American National Standards Institute (ANSI Z89.2-1971)

Tools and Their Uses. NAVEDTRA 14256. June 1992.

Hazard Communication, Code of Federal Regulations, 29 CFR 1910.1200, 1991.

Naval Construction Force Manual, NAVFAC P-315, Naval Facilities Engineering Command, Washington, D.C., 1985.

Safety and Health Requirements Manual, EM-385-1-1, Department of the Army,

U.S. Army Corps of Engineers, Washington, DC, 1992.

Use of Wire Rope Slings and Rigging Hardware in the Naval Construction Force, COMSECOND/COMTHIRDNCBINST 11200.11, Department of the Navy, Naval Construction Battalions, U.S. Pacific Fleet, Pearl Harbor, Hawaii, Naval Construction Battalions, U.S. Atlantic Fleet, Naval Amphibious Base, Little Creek, Norfolk, VA, 1988.

Wire and Fiber Rope and Rigging, Naval Ship's Technical Manual, NAVSEA S9086-UU-STM-000/CH-613, Chapter 613, Commander, Naval Sea System Command, Washington, DC, 1978.

Cranes and Attachments 1, SCBT 540.1, Naval Construction Training Center, Gulfport, MS, 1988.

NAVEDTRA 14167 Naval Safety Supervisor

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