NUCLEAR OPERATIONS TRAINING

ELECTRICAL SCIENCES

ES-1

ELECTRICAL THEORY

REVISION 8

Recommended ______________________________ Date ________________

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Senior Instructor, Development

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OBJECTIVES

TERMINAL OBJECTIVE: The student shall be able to relate the basic concepts of electrical theory to the practical operation of motors and generators.

ENABLING OBJECTIVES: The student shall be able to:

		AO	**RO**	**SRO**	**SE**
ES-1-01	**DESCRIBE** the physical characteristics of the atom.	X	X	X	X
ES-1-02	**DEFINE** the following terms: 1. Conductor 2. Semiconductor 3. Insulator.	X	X	X	X
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ES-1-04	**DEFINE** electromotive force (emf).	X	X	X	X
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LESSON TEXT

INTRODUCTION

The use of electricity in the world is so widespread that most people take it for granted without understanding what it is or where it comes from. The V. C. Summer Nuclear Station is one of the largest electrical generating stations in the South Carolina Electric & Gas Company system and therefore generates a large portion of the electricity supplied to customers. The station also utilizes electricity in various forms to assist in generation of its electrical output.

The word “electric“ is actually a Greek derived word meaning AMBER. Amber is a translucent (semitransparent), yellowish mineral, which is composed of fossilized resin. The ancient Greeks used the words “electric force“ in referring to the mysterious forces of attraction and repulsion exhibited by amber when it was rubbed with a cloth. They did not understand the fundamental nature of this force. They could not answer the seemingly simple question, “What is electricity?" For our purposes, electricity is the flow of electrons in response to a difference in potential (voltage).

From time to time, various scientists have found that electricity behaves in a constant and predictable manner in given situations, when subjected to given conditions. These scientists, such as Faraday, Ohm, Lenz, and Kirchoff, to name only a few, 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“. Electricity is an easily used form of energy and one of the most widely used power sources in modern time. By learning the rules, or laws, applying to the behavior of electricity, and by understanding the methods of producing, controlling, and using it, electricity may be safely and efficiently utilized.

This chapter will address some fundamental concepts of electricity, how electricity is produced, how electricity is used, and how electricity is supplied to customers of an electric utility.

GENERAL DESCRIPTION

Review of the Atom

In the study of chemistry, it soon becomes apparent that the molecule is far from being the ultimate particle into which matter may be subdivided. The salt molecule may be decomposed into radically different substances - sodium and chlorine. These particles that make up molecules can be isolated and studied separately. They are called ATOMS.

The atom is the smallest particle that makes up that type of material called an ELEMENT. The element retains its characteristics when subdivided into atoms. More than 100 elements have been identified. They can be arranged into a table of increasing weight, and can be grouped into families of material having similar properties. This arrangement is called the PERIODIC TABLE OF THE ELEMENTS.

Most of the weight of the atom is in the protons and neutrons of the nucleus. Whirling around the nucleus are one or more smaller particles of negative electric charge. These are the **electrons**. Normally, there is one proton for each electron in the entire atom so that the net positive charge of the nucleus is balanced by the net negative charge of the electrons whirling around the nucleus. Thus, the atom is electrically **neutral**.

The number of protons, which is usually the same as the number of electrons, determines the kind of element in question. Figure ES1.1 shows a simplified picture of several atoms of different materials based on the conception of planetary electrons describing orbits about the nucleus. For example, hydrogen has a nucleus consisting of

1 proton, around which rotates 1 electron. The helium atom has a nucleus containing 2 protons and 2 neutrons with 2 electrons encircling the nucleus. Near the other extreme of the list of elements is curium (not shown in the figure), an element discovered in the 1940's, which has 96 protons and 96 electrons in each atom. The Period Table of the Elements is an orderly arrangement of the elements in ascending atomic number (number of electrons) and also in atomic weight (number of protons and neutrons in the nucleus). The various kinds of atoms have distinct masses or weights with respect to each other. The element most closely approaching unity (meaning 1) is hydrogen whose atomic weight is 1.008 as compared with oxygen whose atomic weight is 16. Helium has an atomic weight of approximately 4, lithium 7, fluorine 19, and neon 20, as shown in Figure ES1.1.

When an electric force is applied to a conducting medium, such as copper wire, electrons in the outer orbits of the copper atoms are forced out of orbit and impelled along the wire. The direction of electron movement is determined by the direction of the impelling force. The protons do not move, mainly because they are extremely heavy. The proton of the lightest element, hydrogen, is approximately 1,850 times heavier than its electron. Thus, it is the relatively light electron that is moved by electromotive force.

When an orbital electron is removed from an atom, it is called a free electron. 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. It is these free electrons that constitute the flow of an electric current in electrical conductors.

If the internal energy of an atom is raised above its normal state, the atom is said to be excited. Excitation may be produced by causing the atoms to collide with particles that are impelled by an electric force. In this way, energy is transferred from the electric source to the atom. The excess energy absorbed by an atom may become sufficient to cause loosely bound outer electrons to leave the atom against the force that acts to hold them within. An atom that has thus lost or gained one or more electrons is said to be ionized. If the atom loses electrons, it becomes positively charged and is referred to as a positive ion. Conversely, if the atom gains electrons, it becomes negatively charged and is referred to as a negative ion. An ion may then be defined as a small particle of matter having a positive or negative charge.

Conductors, Semiconductors, and Insulators

Electrical energy is transferred through conductors by the movement of free electrons that migrate from atom to atom inside the conductor. A good conductor is said to have a low opposition or low resistance to the current (electron) flow.

In contrast to good conductors, some substances, such as rubber or glass, have very tightly bound electrons. In these materials, large amounts of energy are necessary to break the electrons free from the atom. These substances are called poor conductors, nonconductors, or insulators. Actually, there is no sharp dividing line between conductors and insulators, since electron motion is known to exist to some extent in all matter. Simply put, the best conductors are used as wires to carry electrical current and the poorest conductors are used as insulators to prevent the current from being diverted from the wires.

Listed below are some of the best conductors and best insulators arranged in accordance with their respective abilities to conduct or resist the flow of electrons:

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

A semiconductor is a material that is neither a good conductor nor a good insulator. These materials may, under certain conditions, act as either conductors or as insulators, often depending on the voltage applied to them.

Difference In Potential

The force that causes free electrons to move in a conductor as an electric current may be referred to as follows:

- Electromotive force (emf)
- Voltage
- Difference in potential

When a difference in potential exists between two charged bodies that are connected by a wire, electrons will flow through the wire. The flow is from the negatively charged body to the positively charged body until the potential difference no longer exists.

An analogy of this action is shown in the two water tanks connected by a pipe and valve in Figure ES1.2. At first the valve is closed and all the water is in tank A. Thus, the water pressure across the valve is at 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.

Current flow through an electric circuit is directly proportional to the difference in potential across the circuit, just as the flow of water through the pipe in Figure ES1.2 is directly proportional to the difference in water level in the two tanks.

A fundamental law of current electricity is that “The current is directly proportional to the applied voltage“; that is, if the voltage is doubled, the current (electron flow) is doubled. If the voltage is halved, the current is halved.

Methods of Producing A Voltage

There are six commonly used methods of producing electromotive force (emf). Some of these methods are much more widely used than others. The following is a list of the six most common methods of producing electromotive force:

- **FRICTION** - voltage produced by rubbing two materials together (static electricity).
- **PRESSURE** - (Piezoelectricity) - voltage produced by squeezing crystals of certain substances (pressure/strain instrumentation).
- **HEAT** (Thermoelectricity) - voltage produced by heating the joint (junction) where two unlike metals are joined (thermocouple instruments).
- **LIGHT** (Photoelectricity) - voltage produced by light striking photosensitive (light sensitive) substances (radiation instruments).
- **CHEMICAL ACTION** - voltage produced by chemical reaction (battery cells).
- **MAGNETISM** - voltage produced in a wire when the wire moves through a magnetic field, or a magnetic field moves through the wire in such a manner as to cut the magnetic lines (north/south pole) of the field (generators).

Voltage Produced By Friction (Figure ES1.3)

This is the least used of the six methods of producing voltages. Its main application is in Van de Graf generators, used by some laboratories to produce high voltages. As a rule, friction electricity (often referred to as static electricity) is a nuisance. Most individuals are familiar with static electricity and have probably received unpleasant shocks from friction electricity upon sliding across dry seat covers or walking across dry carpets, and then coming in contact with some other object. Static electric charges can be high enough to damage sensitive electric components such as integrated circuit (IC) chips. Static buildup inside transformers (due to friction with the pumped oil) can lead to repeated discharges and eventual equipment failure.

Voltage Produced By Pressure (Figure ES1.4)

This action is referred to as piezoelectricity. It is produced by compressing or decompressing crystals of certain substances. For instance, when a crystal of quartz is compressed, as in Figure ES1.4, electrons tend to move through the crystal as shown. This tendency creates an electric difference or potential between the two opposite faces of the crystal. If an external wire is connected while the pressure and voltage potential are present, electrons will flow. If the pressure is held constant, the electron flow will continue. When the force is removed, the crystal is decompressed, and immediately causes an electric force in the opposite direction. Thus, the crystal is able to convert mechanical force, either pressure or tension, to electrical force.

The power capacity of a crystal is extremely small. However, they are useful because of their extreme sensitivity to changes of mechanical force. Due to these characteristics crystals are most widely used in pressure and strain measuring instruments.

Voltage Produced by Heat (Figure ES1.5)

When a length of metal, such as copper, is heated at one end, electrons tend to move away from the hot end towards 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. These characteristics are illustrated in Figure ES1.5. 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 at the hot junction, and from the copper through the current meter to the iron at the cold junction. This device is generally referred to as a thermocouple.

Thermocouples have somewhat greater power capacities than crystals, but their capacity is still very small as compared to some other sources. The thermoelectric voltage in a thermocouple depends mainly on the difference in temperature between the hot and cold junctions. Consequently, they are widely used to measure temperature, and as heat-sensing devices in automatic temperature control equipment. Thermocouples generally can be subjected to much greater temperatures than ordinary thermometers, such as the mercury or alcohol types. Thermocouples are used at V. C. Summer to measure the temperature of the water as it exits the core. The ability of the thermocouple to accurately measure temperatures over a wide range makes it the best choice in this application.

Voltage Produced By Light (Figure ES1.6)

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 enough energy to energize the outermost atoms (photoelectric effect).

Some substances (mostly metals) are far more sensitive to light than others. That is, more electrons will be dislodged and emitted from the surface of a highly sensitive metal, with a given amount of light, than will be emitted from a less sensitive substance. Upon losing electrons, the photosensitive (light sensitive) metal becomes positively charged; and an electric force is created.

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 on the photoelectric principle is referred to as a ***photoelectric voltage***. There are many sizes and types of photoelectric cells in use, each of which serves the special purpose for which it was designed. Nearly all, however, have some of the basic features of the photoelectric cells shown in Figure ES1.6.

A photocell's power capacity is very small. However, it reacts to light-sensitive variations in an extremely short time. This characteristic makes the photocell very useful in detecting or accurately controlling a great number of processes or operations. For instance, the photoelectric cell, or some form of the photoelectric principle, is used in television cameras, automatic manufacturing process controls, door openers, radiacs, and so forth. Outside lighting around the plant is turned on by photoelectric cells. The photoelectric effect is also used in the scintillation detectors of the Radiation Monitoring System, and in “optical isolators“ between safety and non-safety related circuits.

Voltage Produced By Chemical Action (Figure ES1.7)

Up to this point, it has been shown that electrons may be removed from their parent atoms and set in motion by energy derived from a source of friction, pressure, heat, or light. In general, these forms of energy do not alter the molecules of the substances being acted upon. That is, molecules are not usually added, taken away, or split-up when subjected to these four forms of energy. Only electrons are involved.

When the molecules of a substance are altered, the action is referred to as chemical. For instance, if the molecules of a substance combines with atoms of another substance, or gives up atoms of its own, the action is chemical in nature. Such atoms always change the chemical name and characteristics of the substance affected. For instance, when atoms of oxygen from the air come in contact with bare iron, they merge with the molecules of iron. This iron is **oxidized**. It has changed chemically from iron to iron oxide, or **rust**. Its molecules have been altered by chemical action.

In some cases, when atoms are added to or taken away from the molecules of a substance, the chemical change will cause the substance to take on an electric charge. The process of producing a voltage by chemical action is used in batteries.

Several types of batteries are used at the station. Portable devices, such as walkie-talkies and flashlights, typically use dry cells (D-Cells, for example). A dry cell produces a voltage due to the chemical changes occurring in it. When a load is connected to it, the chemical action taking place consumes one of the electrodes of the battery; and, therefore, the battery must eventually be replaced.

The type of battery used for station vital power is the wet cell or secondary cell. In this type of battery, the chemical action in the cell can be reversed by applying an external electric current to the cell. The battery then can store electric energy, deliver an electric current when needed, and be recharged again. The station vital batteries, shown in Figures ES1.7, consist of many cells with two types of lead plates submerged in an electrolyte of sulfuric acid and water. The electrolyte reacts chemically with the lead plates producing a voltage and electric current flow. The electrical energy stored in the batteries is available to provide emergency lighting and vital instrumentation power during a blackout situation.

Voltage Produced by Magnetism (Figure ES1.8)

Magnets or magnetic devices are used for thousands of different jobs. One of the most useful and widely employed applications of magnets is in the production of electric power from mechanical sources. The mechanical power may be provided by a number of difference sources, such as gasoline or diesel engines, and water or steam turbines. The conversion of these source energies to electricity is accomplished by generators employing the principle of electromagnetic induction. These generators, of many types and sizes, are discussed in the Detailed Description later.

To begin with, there are three fundamental conditions which must exist before a voltage can be produced by magnetism. They are as follows:

- There must be a conductor (wire), 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 the conductor. The conductor must be moved and cut across the magnetic lines of force, or the field must be moved so that the lines of force are cut by the conductor.

In accordance with these conditions, when a conductor or conductors move across a magnetic field and cut the lines of force, electrons within the conductor are impelled in one direction or another. Thus, an electric force, or voltage, is created.

In Figure ES1.8, note the presence of the three conditions needed for creating an induced voltage:

- A magnetic field exists in the bar magnet.
- There is a conductor (copper wire).
- There is a relative motion. The magnet is moved back and forth across the conductor.

When the conductor is stopped (B), relative motion is eliminated (one of the three required conditions); and there is no longer an induced voltage.

Consequently, there is no longer any difference in potential between the two ends of the wire. Note in Figure ES1.9 that the reversal of motion has caused a reversal of direction in the current flow (electron flow). The reversal in current flow is evidenced by the opposite meter deflection in the figure.

This principle of reversed current flow is the foundation for alternating current flow (AC), whereby current will go in a positive direction, then reverse direction and go in a negative direction.

Electromagnetism (Figure ES1.10)

Whenever electric current is passed through a conductor, it creates a magnetic field around the conductor. The lines of force in this field always encircle the conductor which carries the current, forming concentric circles around the conductor. The strength of the magnetic field depends on the amount of current flow, with a large current producing many lines of force and a small current producing only a few lines of force. If we take our conductor and wind it into a coil, the magnetic fields interact and produce a field similar to a simple bar magnet with a north and south pole. Placing a material of high permeability such as iron inside the coil concentrates the magnetic field and makes it stronger. This is known as an electromagnet. Electromagnets are used in the station in the diesel and main generators. The tendency of the iron core to move into the center of the coil when current is applied is used in solenoid-operated valves and in various relays and breaker operating coils.

Inductance (Figure ES1.11)

When the circuit current increases or decreases, the magnetic field strength increases and decreases in the same direction. As the field strength increases, the lines of force increase in number and expand outward from the center of the conductor. Similarly, when the field strength decreases, the lines of force contract toward the center of the conductor. It is actually this expansion and contraction of the magnetic field as the current varies which causes an EMF of self-induction, and the effect is known as **inductance.** The EMF or self-induction is caused by the changing magnetic field acting on the conductor. The induced EMF is always in a direction that is opposite to the effect (current flow) that caused it. Inductance, then, opposes the current flow that caused it. Inductance is the characteristic of an electric conductor which opposes a change in current flow. The **inductance** is expressed by the symbol L **.**

Factors Which Affect Inductance (Figures ES1.12 and ES1.13)

Every complete electric circuit has some inductance since even the simplest circuit forms a complete loop or single-turn cell. An induced EMF is generated even in a straight piece of wire by the action of the magnetic field expanding outward from the center of the wire or collapsing inward to the wire center. The greater the number of adjacent turns of wire cut by the expanding field, the greater the induced EMF generated (Figure ES1.12) - so that a coil of wire having many turns has a high inductance.

Any factors which tend to affect the strength of the magnetic field also affect the inductance of a circuit. For example, an iron core inserted in a coil increases the inductance (Figure ES1.13) because it provides a better path for magnetic lines of force than air. Therefore, more lines of force are present that can expand or contract when there is a change in current. A copper core piece has exactly the opposite effect. Since copper opposes lines of force more than air, inserting a copper core piece results in less field change when the current changes, thereby reducing the inductance.

The principles of electromagnetism and self-induction are very important to understanding the operation of transformers, generators, and motors.

Electric Current

The drift, or flow, of electrons through a conductor is called electric current or electron flow. The direction of electron movement is from a region of negative potential to one of positive potential. Various terms may be used to describe current flow. The terms current, current flow, electron flow, electron current, etc., may be used to describe the same phenomenon; however, you would realize that regardless of the term used, the movement of electrons will be from a negative potential to a positive potential.

Electric current is generally classified into two general types - direct current and alternating current. Direct current flows in one direction whereas an alternating current periodically reverses direction. These two types of current are discussed further in the Detailed Description.

In order to determine the amount (number) of electrons flowing in a given conductor, it is necessary to adopt a unit of measurement of current flow. The term **ampere** is used to define the unit of measurement of the rate at which current flows (electron flow).

The symbol for current flow is I**.** Current flow is measured in amperes. The abbreviation for ampere is **amp**. One ampere may be defined as the flow of $6.28\ x\ 10^{18}$ electrons per second through a fixed section of a conductor.

Resistance

Every material offers some resistance, or opposition, to the flow of electric current through it. 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 size and type of material of the wires in an electric circuit are chosen so as to keep the electrical resistance as low as possible. In this way, current can flow easily through the conductors, just as water flows through the pipe between the tanks in Figure ES1.2. If the water pressure remains constant, the flow of water in the pipe will depend on how far the valve is opened. The smaller the opening, the greater the opposition to the flow, and the smaller the rate of flow in gallons per second will be.

In the electric circuit, the larger the diameter of the wires, the lower will be their electrical resistance (opposition) to the flow of current through them. In the water analogy, pipe friction opposes the flow water between the tanks. This friction is similar to electrical resistance. The resistance of the pipe to the flow of water through it depends upon:

- The length of the pipe,
- The diameter of the pipe, and
- The nature of the inside walls (rough or smooth).

Similarly, the electrical resistance of the conductors depend upon:

- The length of the wires,
- The diameter of the wires, and
- The material of the wires (copper, aluminum, etc.).

Temperature also affects the resistance of electrical conductors to some extent. In most conductors (copper, aluminum, iron, etc.), the resistance increases with temperature. This effect is used for measuring the temperature of various processes with a device called a Resistance Temperature Detector (RTD). The RTD is exposed to the process stream (for example; Reactor Coolant flow) and connected to a circuit providing a current flow through the RTD. As the temperature increases, the RTDs resistance increases. This resistance change causes the current in the circuit to decrease. The current change is converted to a remote temperature readout.

The resistance in an electrical circuit is expressed by the symbol R. Manufactured circuit parts containing definite amounts of resistance are called **resistors**. Resistance (R) is measured in **ohms**. One ohm is the resistance of a circuit element, or circuit, that permits a steady current of 1 ampere (1 coulomb per second) to flow when a steady emf of 1 volt is applied to the circuit.

DETAILED DESCRIPTION

DC Circuits

Ohm's Law

Current, voltage, and resistance have been discussed as three separate items, and we have described the physical basis for each. One of the most important experimental laws of physics is that of the German physicist, George Ohm, which provides a relationship between these quantities. This relationship, called Ohm's Law, is the basic law of electricity and forms the foundation of all applications of electricity, from simple DC circuits to sophisticated electronic systems. Ohm found that when a source is applied to a conductor, the current which flows is directly proportional to the magnitude of the source and inversely proportional to the resistance:

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

$where:$

I = current (amperes)
V = potential difference (volts)
R = resistance (ohms)

It is important to note that the current flow through resistors, due to the motion of electrons, is always from a point of low voltage to a point of higher voltage (the opposite, of course, is true for the direction of current flow through a **source** of EMF). If there is no voltage difference, no current can flow.

Ohm's Law applies to **every** element in an electrical circuit. It will be shown how it is used in subsequent sections.

Kirchoff's Laws

In dealing with electrical circuits, we are usually interested in determining currents and voltage drops. In a simple circuit, this can be accomplished by a straight-forward application of Ohm's Law. The analysis of more complicated circuits is greatly aided by two laws known as **Kirchoff's Laws**.

Kirchoff's Current Law states that at any point in a circuit, the total current which enters that point must be the same as the total current which leaves it. Notice that all this law really says is that electrons cannot **pile-up** anywhere. Therefore, if there is a point in an electrical circuit where the current divides, it does so in accordance with Kirchoff's Current Law. Refer to Figure ES1.14(A). The equation for this law is:

$$I = I_1 + I_2$$

There is a great deal of similarity between current flow and the flow of a fluid in a pipe. In the case of fluid flow, it is almost intuitive that the amount of fluid flowing into a junction must equal the amount leaving; i.e., fluid does not pile up. The same applies to electrons.

Example:

In the circuit in Figure ES1.14(B), write an expression or expressions which relate the currents I_1, I_2, I_3, and I_A.

The current leaving the battery and flowing through resistor R_1 is the total current arriving at B. This must be equal to the current leaving point B by flowing through resistors R_2 and R_3. Putting this in the form of an equation results in:

$$I_1 = I_2 + I_3$$

Note also that I_A = I_2 + I_3 = I_1. This is as would be expected: the current entering the battery equals the current leaving the battery.

Of course, this law, as applied to a simple series circuit, means that the current must be the same everywhere.

Kirchoff's Voltage Law states that the **algebraic** sum of all potential differences or voltage drops in a **closed** loop is equal to zero. A closed loop means any completely closed path which may consist of resistors, batteries, or other components. To see why this is so, remember that the potential difference, or voltage drop, between two points is just the work done in moving a charge between those two points.

Refer to Figure ES1.15(A) for this discussion. If we begin at point A and go completely around the loop back to point A again, the net work done on a charge must be zero. If this were not true, it would be possible to gain work simply by going around and around the loop. This leads to an extremely important result for **parallel** circuits. A parallel circuit, shown in Figure ES1.15(B), is one in which the current divides, flows through electrically parallel paths, and then recombines.

The resistors R_1 and R_2 are in parallel. The current I divides into I_1 and I_2 and then recombines to I again. The voltage drop across R_1 and R_2 must be the **same**, i.e.,

$$I_1R_1 = I_2R_2$$

This result applies to **all** circuit elements which are in parallel. If this result were not true, then net work could be obtained simply by moving a charge around a loop formed by the two resistors.

Example:

In Figure ES1.15C, compute the current through the 50Ω resistor and the 12.5Ω resistor, given that the current through the 10Ω resistor is one amp.

The voltage drop across the 10Ω resistor is 10 volts $\left(10V = 1\,amp \times 10\,ohms\right)$. The voltage drop across the two resistors in parallel must also be 10 volts, since the two voltage drops must equal the source voltage of 20 volts.

$$Therefore: \quad \frac{10V}{50\Omega} = 0.2A$$

The current through the 12.5 Ω resistor is:

$$\frac{10V}{12.5\Omega} = 0.8A$$

Note that the sum of the currents is $1A$, in accordance with Kirchoff's current law.

Kirchoff's Voltage Law applies to **every** circuit. In more complicated circuits, it is necessary to write a number of simultaneous equations and solve them. **Each** equation results from the voltage law.

Series and Parallel Resistive Circuits

It has been seen that circuits may contain more than one resistor, and that these resistors may be connected either in series or in parallel. When resistors are connected in series, all of them can be replaced by a single resistor whose value is the sum of all the individual resistors. To see why this is so, Kirchoff's Voltage Law is applied to the series circuit shown in Figure ES1.16(A) which contains three resistors R_1, R_2 and R_3.

In a series circuit, the current must be the same everywhere, and the sum of the voltage drops across the resistors must equal the voltage rise across the battery:

$$V = IR_1 + IR_2 + IR_3$$

Since the current is the same everywhere, it can be factored out of the equation.

$$V = I(R_1 + R_2 + R_3)$$

Thus, the circuit appears to have a resistance equal to the sum of the individual resistors.

$$R = R_1 + R_2 + R_3$$

and this is the **equivalent** resistance of the series circuit. This equation has been derived using three resistors, but the same result would be obtained regardless of how many resistors were used, provided they are in series.

Example:

Find the equivalent resistance of the circuit shown in Figure ES1.16(B).

Since the resistors are in series, the equivalent resistance is the sum,

$$\begin{aligned} R &= 10 + 5 + 3 + 13 + 7 \\ R &= 38\Omega \end{aligned}$$

If we replace the five resistors with one 38Ω resistor, the same current would flow.

When resistors are connected in parallel, the equivalent resistance is slightly more complicated. We can find it by using Kirchoff's Current Law.

In Figure ES1.17(A) two resistors, R_1 and R_2, are in parallel; and the current through each is I_1 and I_2, respectively. If the current law is applied to point A,

$$I_1 + I_2 = I$$

Since the resistors are in parallel, the voltage drop across each must be equal:

$$V = I_1 R_1 = I_2 R_2$$

Thus, $I_1 = V / R_1$ and $I_2 = V / R_2$ and if these values of current are substituted into the current law equation, we obtain,

$$\frac{V}{R_1} + \frac{V}{R_2} = I$$

or

$$V\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = I$$

The equivalent resistance of the parallel circuit is R, where:

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

Note that for the two resistor case, algebra yields

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

Again, we have derived this result for two resistors in parallel, but it can be extended to any number. The reciprocal of the equivalent resistance is equal to the <u>sum</u> of the reciprocals of the individual resistances.

Example:

Find the equivalent resistance of the circuit in Figure ES1.17(B)

Since the resistors are in parallel,

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

$$\frac{1}{R} = \frac{1}{200} + \frac{1}{200} + \frac{1}{100} + \frac{1}{50}$$

$$\frac{1}{R} = 0.04$$

$$R = 25\Omega$$

Thus, the combination of these four resistors in parallel has a resistance equal to a single 25Ω resistor.

Note that, for resistors in **series**, the equivalent resistance is always **greater** than any of the individual resistors, while for resistors in **parallel**, the equivalent resistance is always **less** than any of the individual resistors.

Power

Suppose that we have an electrical circuit as shown in Figure ES1.18. The circuit contains a battery, a switch, and a resistor; but the resistor is immersed in a container of water (it is, of course, electrically insulated from the water). A thermometer is also immersed in the water.

When the switch is closed, it is observed that the temperature of the water begins to rise. Heat is obviously being transferred from the resistor to the water; that is, the resistor is a source of heat. It must rise as a result of the passing of a current through the resistor, and this process is called **resistance heating**.

The **rate** at which heat is transferred to the water, or the **power** generated by the resistor, can be computed by considering the product of the voltage drop across the resistor, V , and the current through the resistor, I . Voltage has units of joules/coul and current has units of coul/sec. Thus,

$$VI = \left(\frac{joules}{coul}\right)\left(\frac{coul}{s}\right)$$

$$= \frac{joule}{s}$$

But (joule/s) is just the unit of power, the **watt**. Therefore,

$$P = VI$$

This gives the power in terms of the voltage across a resistor and the current through it, but Ohm's Law can be used to write it in terms of the value of the resistance.

$$V = IR$$

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

Thus, power is also equal to the product of the resistance and the **square** of the current.

In electrical circuits, power is **only** consumed in resistors. Power is **produced** by sources of EMF, and is just the product of the voltage across the source and the current through it. Of course, the power produced by the source must equal the power consumed by resistance.

Example:

Find the power consumption in the circuit in Figure ES1.19:

First, find the total current in the circuit. The equivalent resistance of the parallel portion of the circuit is:

$$\frac{1}{R} = \frac{1}{40} + \frac{1}{280} = 0.0286$$

$$R = 35\Omega$$

or

$$R = \frac{(40)(280\Omega)}{40+280} = 35\Omega$$

The total resistance is then:

$$R_T = 15\Omega + 35\Omega = 50\Omega$$

and the total current is,

$$I = \frac{20V}{50\Omega} = 0.4A$$

The power consumed by the resistance is:

$$P = I^2 R$$

$$= (0.4A)^2 (50\Omega)$$

$$P = 8 watts$$

This is also the power produced by the source:

$$P = (20V)(0.4A)$$

$$P = 8\ watts$$

This is the same result that we would obtain if we added the power consumed by each resistor. To do this, we need to find the current through each resistor. This is left as a practical exercise.

Figure ES1.46 provides a summary of the relationships between voltage, current, resistance, and power for DC circuits.

Inductors

Recall, when a conductor is carrying an electric current, a magnetic field surrounds the conductor. So long as the current is constant, this magnetic field is stationary; and its magnitude is directly proportional to the magnitude of the current. If, however, the magnitude of the current changes, so does the magnitude of the field. But it has already been shown that if a conductor moves through a magnetic field, cutting lines of force, an EMF will be induced. It makes no difference if the source of the field is the current through the conductor itself; there is still relative motion between a conductor and a field if the current changes. The EMF induced in the conductor is called the **self-EMF**, or sometimes the **counter EMF** (CEMF).

It is important to remember that the EMF exists **only** during the time that the current, and hence the magnetic field, is changing (Figure ES1.11).

The magnitude and the polarity of the self-induced EMF is given by **Lenz's Law.** The magnitude of the EMF is proportional to **the time rate of change** of current:

$$E = -L\frac{\Delta I}{\Delta t}$$

The constant of proportionality is the **self-inductance**, L, of the conductor. There are three very important points concerning Lenz's Law. First, as already stated, there is no EMF induced unless the current is changing; that is, $\Delta I / \Delta t$ is not zero. For a constant current, of course, $\Delta I / \Delta t$ is zero. Second, the presence of the minus sign indicates that the direction of the induced EMF is such that it **opposes** the change in current. To see how this operates, consider the circuit shown in Figure ES1.20 (B&C).

When the switch S is closed, a steady current, I, flows and a steady magnetic field surrounds the conductor. When the switch is opened, the current through the conductor decreases. The EMF induced in the conductor is in such a direction as to **try** to maintain the current.

The conductor is now acting as a source of EMF (imagine it to be a battery). If the polarity of the source is as shown, current will try to flow in the same direction it had prior to opening the switch.

Finally, the self-inductance, L, of the conductor depends very much on the geometry of the conductor. Inductance is a measure of the ability of a conductor to induce an EMF, and this ability is fundamentally related to the manner in which the magnetic lines of force **cut** the conductor as they are changing. If a conductor is arranged in the form of a loop as in Figure ES1.20(C), then the changing magnetic lines of force can interact with more of the conductor. Thus, a conductor constructed in this manner can provide a large induced EMF. Circuit elements which are specifically designed for this purpose are called **inductors,** and the standard circuit symbol is shown on Figure ES1.20.

The unit of inductance is the **henry** (h). An inductor has an inductance of 1 henry if it induces an EMF of 1 volt when the current changes at a rate of 1 ampere per second.

In circuit analysis, it is convenient to consider “ideal“ elements. For example, a conductor which is designed to have a large inductance also has resistance, but the resistance can be generally ignored. Thus, we speak of “pure“ inductors. The same argument applies to resistors, wherein its inductance can be ignored. Since a pure inductor has no resistance, **it consumes no power.** The only function of an inductor is to **store** energy in the form of the magnetic field. When the current decreases (for example), the collapsing field induces an EMF; that is, the stored energy is returned to the circuit. In circuits which contain resistance **and** inductance, voltages and currents cannot change instantaneously, since the inductor opposes any such changes.

In fact, these circuits exhibit **exponential** changes. The time required for voltage or current to increase by a factor of $\left(1-1/e\right)$ (63.2%) or decrease by a factor of $1/e$ (36.8%) is called the **time constant**, T. For inductive circuits, the **time constant** is:

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

Where,

T = time constant (seconds)
L = inductance (henrys)
R = resistance (ohms)

RL Circuits

To see the effect of inductance, consider the circuit shown in Figure ES1.21.

When the switch S is closed (in position 1), a voltage V equal to the battery voltage immediately appears across the series combination of R and L. The current through R and L, however, does not instantly increase because the inductor opposes any **change** of current. The current grows exponentially reaching a final value:

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

The voltage drop across the resistor, V_r, must increase in direct proportion to the increase in current. Note that at the instant the switch is closed, e_r is zero since no current flows through R. Thus, the entire battery voltage V must appear across L. At **all** times, the sum of V_r and V_L must equal the battery voltage V, in accordance with Kirchoff's Voltage Law.

This behavior following the closing of the switch is called a **transient**. As a **rule of thumb,** the transient is complete after 5 time constants.

When the switch S is moved to position 2 (Figure ES1.22), the battery is removed from the circuit and so the current decreases. The voltage across the series combination of R and L immediately reduces to zero, but the current decreases exponentially due to the opposition provided by the inductor. The voltage drop across the resistor decays as the current decays. Note that initially the voltage is equal to the battery voltage V. The voltage drop across the inductor is initially 0 (prior to moving the switch) since a steady current was flowing. When the switch is moved, a voltage is induced across the inductor such that the sum of the inductor voltage drop and the resistor voltage drop is zero. Note that the current decreases to 36.8% $(1/e)$ of its initial value after one time constant.

The presence of an inductor can lead to very large voltages immediately following a transient. In the circuit shown in Figure ES1.23, a current of 10 amperes flows through the inductor, causing a large **stationary** magnetic field to surround the coil. (Remember that a pure inductor has no resistance.) When the switch is opened, current is cut off to the inductor and the collapsing field induces a voltage. The induced voltage is such that it tries to maintain a current of 10 amperes, but this 10 amperes must flow through 201 Ω of resistance. The EMF required is:

$$EMF = (102\Omega)(10A)$$

$$= 2010\ volts$$

Since the switch is open, the circuit looks just like a series RL circuit without a battery. The time constant is:

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

$$= \frac{2h}{201\Omega}$$

$$= 0.01 \text{ second}$$

Thus, the current decays to 36.8% of its original value (3.68 amperes) in 0.01 seconds.

In DC circuits, an inductor is only important when current is interrupted by a switch. In AC circuits, however, the current continually changes and so an inductor plays a major role in the behavior of the circuit.

Capacitors

It has been shown that inductance is a measure of the ability of a conductor to induce an EMF. Conductors also have the ability to store electric charge, and this is measured by **capacitance**. The circuit in Figure ES1.24(A) consists of two separated conductors, in the form of plates, a battery and a switch.

When the switch is closed, electrons are repelled from the negative terminal of the battery and accumulate on Plate A. Similarly, an equal number of electrons are attracted from Plate B to the positive terminal of the battery. Plate A is thus negatively charged (due to the accumulation of electrons) and Plate B is positively charged (due to the deficiency of electrons). After a short period of time, there is no further movement of electrons; and the capacitor is said to be fully charged. If the switch is now opened, the charge will remain on the plates indefinitely (ignoring leakage). The capacitor, therefore, stores electric charge; and the capacitance, C, is measured in **farads.** If the total charge on either plate (they are equal in magnitude, but differ in sign) is denoted by Q and the **charging voltage** (battery voltage) is V, then:

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

i.e., a one farad capacitor can hold a charge of one coulomb established by a one-volt battery.

Note that for a DC circuit, a capacitor is really an open circuit. Aside from the initial motion of electrons, **no** current can flow. Just as the inductance of an inductor is determined by the geometry of the inductor, so is the capacitance of a capacitor. For example, if the surface area of the plates is increased, more charge can be stored. To see this, it is only necessary to understand what limits the movement of electrons.

As electrons move on to the plate, the buildup of negative charge repels additional electrons which are moving toward the plate from the battery. Eventually, a balance is established between the repulsive force of the electrons on the plate and the force which repels electrons from the negative terminal of the battery. This occurs in a very short time. Since more charge can be stored before this balance occurs, the capacitance increases as the area of the plates increases.

The capacitance can also be increased by decreasing the distance between the plates. Since one of the plates is positively charged, this tends to neutralize the repulsive effects of the negative charge on the other plate, allowing more electrons to be stored. Thus, capacitance is directly proportional to plate area and inversely proportional to plate spacing:

$$C = K\frac{A}{d}$$

The constant of proportionality, K, is called the **dielectric constant**, and depends on the material which is between the capacitor plates. Thus, as in the case of inductance, capacitance is determined by material properties and geometry.

As a practical matter, the unit of capacitance, the farad, is very large. The more common unit is the **microfarad**, μf, where

$$1\ \mu f = 10^{-6} f$$

or the **pico farad**, $\mu\mu f$, where:

$$1\ \mu\mu f = 10^{-12} f$$

The relationship between charge, voltage, and capacitance is given by:

$$Q = CV$$

Since the capacitance is a constant, the only variables are the charge Q and voltage V, and the time rate of change of these quantities is:

$$\frac{\Delta Q}{\Delta t} = C\frac{\Delta V}{\Delta t}$$

The quantity $\Delta Q / \Delta t$ is the rate at which charge accumulates on the plate, and since this charge travels through the wire attached to the plate, $\Delta Q / \Delta t$, is just the current, i.

$$i = \frac{\Delta Q}{\Delta t}$$

Similarly, ΔV/Δt is the change in voltage across the capacitor. The effect of a capacitor in a DC circuit can be illustrated by the circuit in Figure ES1.24(B). When the switch S is open, the voltage drop across the capacitor and the current are both zero. When the switch is closed, current begins to flow; and charge is stored on the capacitor plates. If there is no resistance in the circuit to retard the flow of current, the capacitor becomes charged extremely rapidly. Once the capacitor is fully charged, the current ceases. The charge stored on the capacitor is:

$$\begin{aligned} Q &= CV \\ &= \left(1\,x\,10^{-6}\,f\right)\left(10V\right) \\ Q &= 10^{-5} coulombs \end{aligned}$$

If the switch is again opened, the charge would remain on the plates of the capacitor; and the voltage across the capacitor would still be 10 volts.

As in the case of inductive and resistive circuits, capacitive and resistive circuits exhibit the characteristic **exponential growth** of current and voltage. The time constant for RC circuits is:

$$T = RC$$

where,

T = time constant (seconds)
R = resistance (ohms)
C = capacitance (farads)

This effect can be illustrated in Figure ES1.25.

When the switch S, in Figure ES1.25(A), is closed (position 1), the battery voltage V immediately appears across the series combination of R and C. Charge immediately flows to the capacitor, but the flow rate (current) decreases [Figure ES1.25B] as the charge on the capacitor builds up. Thus, the current is a maximum at the instant the switch is closed.

Eventually, the capacitor becomes completely charged and the current ceases. The voltage drop across the resistor, V_r, decreases (Figure ES1.25C) as the current decreases. Similarly, the voltage drop across the capacitor, V_C, increases (Figure ES1.25D) as the charge builds up.

At **all** times, the sum of V_r and V_C must equal the battery voltage, V. In accordance with the exponential nature of RC circuits, the voltage drop across the capacitor increases to 63.8% of its final value in one time constant, T.

When the switch is moved to position 2, a path is provided for the capacitor to discharge. The voltage across the series combination of R and C immediately drops to zero (Figure ES1.26A). Since the voltage across the capacitor is V, the voltage across the resistor must be $-V$; and so, initially, the current becomes -V/R (Figure

ES1.26B). As the capacitor discharges, the current exponentially decays to zero. The voltage drops across the resistor and capacitor always add to zero following the movement of the switch.

The **only** function of a capacitor is the storage and release of energy. In the case of the inductor, energy is stored in the magnetic field. For a capacitor, energy is stored in the electric field between the capacitor plates. A capacitor consumes **no** power. All the energy stored during the charging period of the capacitor is released when the capacitor discharges. This storage and release of energy with no consumption of power (for both the inductor and capacitor) has a great effect in the behavior of AC circuits.

AC Circuits

The behavior of the resistor, inductor, and capacitor in a DC circuit has already been studied. The response of the circuit was determined from Kirchhoff's Voltage and Current Laws. These laws, as well as Ohm's Law, also apply to AC circuits, **provided** that they are used with respect to the **instantaneous** values of voltage and current. This leads to some interesting results when these circuits' elements are used in AC circuits.

Figure ES1.27 a simple AC circuit containing only a resistor.

Ohm's Law as applied to this circuit is:

$$v = iR$$

where the voltage and current are **instantaneous** values. But the instantaneous values are:

$$i = I_{\max} \sin\omega t = 1.414 I_{eff} \sin\omega t$$

and:

$$\upsilon = V_{\max} \sin\omega t = 1.414 V f_{eff} \sin\omega t$$

where:

$$\omega = 2\pi / T = angular\ frequency\ (eq. 2\pi\ \ x\ 60hz$$

Therefore:

$$V_{eff} = I_{eff} R$$

and:

$$V_{\max} = I_{\max} R$$

Note that there is no term in this equation which contains frequency. Thus, we obtain the very important result that the current through a resistor, and the voltage drop across the resistor are **always** in phase: the voltage and current cycles begin and end at the same time, and their peaks occur at the same time. The voltage and current relationship for a resistor is just the same in an AC circuit as it is in a DC circuit.

We now turn to the case of the inductor. It has been shown that the voltage drop across an inductor is related to the **rate of change** of current through the inductor by

$$V = \frac{L\Delta i}{\Delta t}$$

This relationship emphasizes the fact that in order for a voltage drop to be developed, the current must be changing. For a pure inductor (one having no resistance), the voltage drop in a DC circuit is zero. In an AC circuit, however, the current is changing according to:

$$i = I_{\max} \sin \omega t$$

as shown in Figure ES1.28.

In order to calculate the voltage drop, $\Delta i / \Delta t$ must be evaluated. But $\Delta i / \Delta t$ is just the **slope** of the curve of $i\ vs.\ t$. The curves of current i and the rate of change of current $\Delta i / \Delta t$ are shown in Figure ES1.29.

Since the rate of change of current is proportional to the voltage drop, what is really being plotted is the current through the inductor and the voltage drop across it. Note that they are **not** in phase. In fact, the voltage drop reaches its peak 90° before the current reaches its peak; i.e., the voltage **leads** the current by 90°. This will **always** be the case for an inductor. (Remember that for a resistor, the voltage and current are always in phase.)

In an AC circuit, the inductor limits current, since it is always producing a counter EMF. The measure of opposition to current flow is provided by the **inductive reactance**, X_L. It is analogous to resistance in DC circuits, and is also measured in ohms. It is used like resistance in a form of Ohm's law.

$$I_{eff} X_L = V_{eff}$$

Unlike resistance, however, inductive reactance depends on **frequency**. The reason for this is that the more rapidly the current changes (the higher the frequency), the greater is the counter EMF which opposes current flow; and inductive reactance X_L is directly proportional to the produce of the inductance L and the angular frequency ω (or $2\pi f$).

$$X_L = \omega L = 2\pi f L = \frac{2\pi}{T} L$$

The higher the frequency, the greater the inductive reactance. For a 0.1061 henry inductor at 60 hertz:

$$X_2 = (2)(\pi)(60)(0.1061) = 40\ ohms$$

The presence of an inductor leads to a very interesting and important result. In Figure ES1.30, a series circuit containing a voltage source, a resistor, and an inductor is shown. Since it is a series circuit, the current must be the same everywhere. We wish to find the terminal voltage (effective value) of the source. The effective value of the current is 1A, and the effective value of the voltage drop across the resistor is:

$$\begin{aligned} V_{eff} &= I_{eff} R \\ &= (1A)(30\Omega) \\ V_R &= 30 volts \end{aligned}$$

The effective value of the voltage drop across the inductor is:

$$\begin{aligned} V_{eff} &= I_{eff} X_L \\ &= (1A)(40\Omega) \\ V_L &= 40 volts \end{aligned}$$

The voltage of the source can be determined from Kirchoff's Voltage Law, **but, it is not 70 volts**. Voltage drops are vectors V_r and V_L, and they must be added vectorially (Figure ES1.30B).

The voltage drop across the inductor leads the voltage drop across the resistor by 90°, because the current through each is the same. Therefore, the sum of the voltage drops is the vector sum, and this is 50 volts. This is the source voltage, as demanded by **Kirchoff's Voltage Law**. Because the voltage drops are not in phase, the resultant cannot be determined simply by adding their magnitudes. They must be added in vector fashion. Note that the source voltage leads the voltage drop across the resistor.

The analysis of the behavior of a capacitor in an AC circuit begins with the fundamental relation between charge and voltage:

$$Q = CV$$

By definition, the rate of change of **charge** is just current, and so

$$i = \frac{\Delta Q}{\Delta t} = C\frac{\Delta V}{\Delta t}$$

If the voltage drop across the capacitor is plotted versus time, then the slope of the curve, $\Delta V / \Delta t$, will be proportional to current, i. Refer to Figure ES1.31(A).

In this case, the current reaches its peak 90° before the voltage does; i.e., it **leads** the voltage. This is directly opposite to the case of the inductor. In terms of vectors, the current vector is displaced by 90°. Refer to Figure ES1.31(B).

A capacitor retards current flow because, as the charge builds up, it repels additional charge. Thus, the ability of a capacitor to provide opposition to current flow is measured by the **capacitive reactance,** X_c. It is measured in ohms and is used like resistance and inductive reactance in a form of Ohm's law.

$$V_{eff} = I_{eff} X_c$$

The capacitive reactance depends on frequency. Unlike the inductor, however, the capacitive reactance **decreases** with frequency:

$$X_c = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

For a 66.3 microfarad capacitor at 60 hertz:

$$X_c = 1/(2)(\pi)(60)(66.3x10^{-6}) = 40ohms$$

As the capacitor charges and discharges at a more rapid rate, more current flows. Thus, reactance decreases as the frequency increases. Consider a series circuit; containing a voltage source, a resistor, and a capacitor and shown in Figure ES1.32(A).

In order to find the terminal voltage of the voltage source, the voltage drops across the resistor and capacitor must be added vectorially. In this case, the voltage drop across the capacitor **lags** the voltage drop across the resistor by 90° (Figure ES1.32B).

The **resultant**, or source voltage, is 50 volts, but lags the voltage drop across the resistor.

It has been shown that Kirchoff's Voltage Law applies to AC circuits **provided** that the voltage drops are added in the proper way. The same is true in applying **Kirchoff's Current Law**. In the circuit in Figure ES1.32(A), a resistor, capacitor, and inductor are in parallel with a voltage source. Since these elements are in parallel, the voltage drop across each must be exactly the same (and also equal to the voltage source).

The currents through each element are indicated. Kirchoff's Current Law states that the sum of the three currents must equal the total current i_T. The total current is **not** 16A. Since these currents are not in phase with each other, they must be added in vector fashion. Refer to Figure ES1.33(B).

The resultant of these three vectors is 10.2A, and this is the total current, i_T. Note that the total current **leads** the current through the resistor by 11.4°.

It is this feature that makes the analysis of AC circuits sometimes confusing. The fact that currents and voltages must be added with due regard for phase differences is all-important.

Effective AC Voltage

In AC circuits the voltage and current are constantly changing. In dealing with AC circuits, some constant value needs to be established to calculate voltage and current. This value is called the **Effective** current or voltage. This value is defined as the value of an AC voltage or current that produces the same heating effect as that same value of DC voltage or current. For example, consider a wall receptacle in the home, where the receptacle is rated at 110-120 volts. In reality, this voltage at the receptacle is constantly varying with a maximum value of approximately 160 volts. Taking all of the changes into account, the resulting **Effective** voltage is 110 volts.

Power in a 3-Phase System

In DC circuits, the power consumed is the sum of all the I^2R heating in the resistors. It is also equal to the power produced by the source, that is, the product of the terminal voltage and current through the source. In AC circuits containing resistors, capacitors and inductors, the **only** mechanism for power consumption is the ${I_{eff}}^2R$ heating in the resistors. Inductors and capacitors consume **no** power: the only function of inductors and capacitors is the storage and release of energy. However, because of the phase shifts which are introduced by these elements, the power consumed by the resistors is not in general equal to the product of source terminal voltage and current through the source. It is very important to understand that whenever the word **power** is used, it **always** refers to the power consumed by resistors, (true power) and always has units of watts (or kilowatts or megawatts). The product of source terminal voltage and current is called **apparent power**, and has units of volt-amperes (VA). The ratio of true power to apparent power is called **power factor**. Recall the circuit that was analyzed in the last section. (Refer again to Figure ES1.33).

The true power is the power consumed by the resistor, and this is:

$$P_T = I^2R = (10A)^2(10\Omega)$$

$$P_T = 1000 watts = 1 kilowatt (kw)$$

The apparent power is the product of source terminal voltage and source current, and is

$$P_A = (10.2A)(100\ V) = 1020VA$$

The ratio is the power factor

$$pf = \frac{1000}{1020} = 0.9804 = \cos(11.4^\circ)$$

It is of interest to compute the phase angle between the source terminal voltage and the source current. The source current leads the resistor current by 11.4°. Since the source voltage is in phase with the resistor current, the source current must also lead the source voltage by 11.4°.

The **cosine** of this angle is 0.9804. Thus, the cosine of the phase angle between source voltage and current is the power factor.

These relationships are more easily visualized on a **power triangle** (Figure ES1.34). If the true power is one leg of a right triangle, the apparent power will be the hypotenuse, and the cosine of the angle between them will be the power factor.

The other leg of the triangle is **reactive power**, and has units of **volt-amperes reactive** (VARS). In the above example, the apparent power **leads** the true power by the phase angle θ. It is also possible, depending on the circuit, for the apparent power to <u>lag</u> the true power. This is the case, for example, when there is a large amount of inductance in the circuit.

The power factor may be changed from leading to lagging (or vice versa) by adjusting the amount of capacitance and inductance in the circuit. In the above example, the reactive power is 202 VARS.

Advantages Of AC Over DC

Most power lines carry alternating current. Very little direct current is used for electric lighting and power. (The exception being very high voltage DC transmission lines at approx. 500,000V.) Early experimenters with electricity had to fabricate nearly all of the laboratory equipment used in their experiments. The only convenient source of electrical energy available to these early scientists was the simple wet-cell battery. Because batteries were the only source of power available, most of the early electrical devices were designed to operate on Direct Current (DC). The earliest electrical generators were DC. When the use of electricity became widespread, alternating current (AC) systems were adopted. There are many good reasons for this choice of AC over DC for electric power transmission. Alternating current voltage can be increased or decreased easily and without appreciable power loss through the use of a transformer, while direct current voltages cannot be changed without considerable power loss. This is a very important factor in the transmission of electric power, since various voltages are required by different users. At the power station, the voltage is “stepped up“ by transformers to very high voltages and sent over the transmission line; then at the other end of the line, other transformers “step down“ the voltage to values which can be used for lighting and power.

Various kinds of electrical equipment require different voltages for proper operation, and these voltages can easily be obtained by using a transformer and an AC power line. To obtain such voltages from a DC power line requires a complicated and inefficient circuit.

Since the power transmitted equals the voltage multiplied by the current $(P = VI)$, and the size of the wire limits the maximum current which can be used, the voltage must be increased if more power is to be transmitted over the same size wires. Also, excessive current flow causes overheating of the wires, resulting in large power loss, so that the maximum current is kept as low as possible. The voltage, however, is limited only by the insulation of the transmission line. Since the insulation can be easily strengthened, the voltage can be increased considerably, permitting the transfer of large amounts of power with smaller wires and much less power loss.

When current flows through a wire to reach the electrical device using power, there is a power loss in the wire proportional to the square of the current $(P = I^2R)$. Any reduction in the amount of current flow required to transmit power results in a reduction in the amount of power lost in the transmission line. By using high voltage, lower current is required to transmit a given amount of power. Transformers are needed to raise the voltage for power transmission and lower it for use by the consumer; and since transformers can only be used with AC, nearly all electric power lines are AC rather than DC.

SUMMARY

Because of the widespread use and application of electricity in the plant, it is essential to understand electricity's fundamentals. V. C. Summer Station produces a significant part of the regional electric requirements. Within the station, every principle of electrical theory can be found in a practical application. These applications range from simple solenoid valves to the diesel and main generators.

Electron Flow

Electromotive force (EMF), can be produced by batteries, generators, and other devices. Sometimes this EMF is called **electrical pressure**, because it is similar to water pressure that causes water to flow in a pipe, or air pressure that causes air to flow in a ventilation duct. EMF is the force that causes electrons (current) to flow in a wire and it is measured in **volts**.

Resistance

When electricity flows through a circuit, the elements of the circuit resist the flow of current. This resistance produces heat. More heat is produced as the resistance (or friction) gets higher.

Circuits

In most electrical circuits, the pathways for the flow of current look complex. However, no matter how complex a circuit may be, it can be classified into one of three types:

- **SERIES CIRCUIT -** A circuit with all the loads connected end to end.
- **PARALLEL CIRCUIT -** A circuit that provides two or more paths for current to travel.

- **SERIES PARALLEL CIRCUIT -** One or more series elements and one or more parallel elements.

Electrical Power

Power in an electrical system, with voltage and current in phase, is the product of the voltage and the current. The formula for power is:

$$\begin{aligned} Power &= volts\ x\ amps \\ &= V\ x\ I \end{aligned}$$

The unit of measure for electric power is watts.

Alternating Current

Is a current that changes its flow back and forth at a constant rate. It can be compared to the pendulum on a clock that moves back and forth.

Frequency

Is the number of cycles (back and forth) made in a certain amount of time. Most electric companies supply current at 60 cycles per second (60 Hertz).

Electricity with Magnetism

Magnetism can produce electricity by moving a conductor through a magnetic field. The conductor cuts through the magnetic lines of force. The motion between a conductor and a magnetic field can be produced in two ways:

- **MECHANICALLY -** Physically moving a conductor through a magnetic field.
- **ELECTRICALLY -** Reversing the flow of current in a coil to induce a voltage and current in an adjacent coil.

Power Factor

Whenever volts and amps are not in phase, the apparent power or volt-amperes must be multiplied by the same factor (power factor) to account for this displacement in order to get the true power in watts. Therefore:

$$Watts\ (true\ power) = (Volts \times Amps) \times Power\ Factor$$
$$P = (V \times I) \times Pf$$

Power Distribution

The production and distribution of electricity are enormous tasks that require a variety of electrical equipment. The three main parts of a power system are the:

- **GENERATION SYSTEM -** Natural sources of energy are converted to electrical energy.
- **TRANSMISSION SYSTEM -** The network of transmission lines placed overhead and underground and linked to substations.
- **DISTRIBUTION SYSTEM -** Transmission lines that carry electricity to the customer.

REFERENCES

1. Basis Electricity, Bureau of Naval Personnel, Rate Training Manual, NAVPERS 10086-B

2. Electricity for Operators, General Physics Corporation

3. Physics, Ohanian (1985)

4. SER 11-90, Main Transformers Damage and Fires Caused By Static Electrification

SELF-ASSESSMENT QUESTIONS

1. A negatively charged particle that orbits the atom’s nucleus is a (n) (proton/electron/neutron).

2. Like charges (repel/attract).

3. The electron is (lighter/heavier) than the proton.

4. Unlike charges (attract/repel) each other.

5. If a substance has more electrons than protons, it has a (negative/positive) charge.

6. If a substance has more protons than electrons, it has a (negative/positive) charge.

7. State the law of attraction and replusion.

8. Atoms have three kinds of particles, which are electrons, protons, and neutrons. (True or False)

9. Large quantities of electrons are measured in (coulombs, gallons, pounds).

10. Amperes measure rate of flow of (volts, electrons, resistance).

11. Volts measure (current, resistance, EMF).

12. Ohms measure (electrical pressure, coulombs per second, resistance).

13. A material having electrical resistance and used to control current or produce heat is a (n) (conductor, insulator, resistor).

14. Explain the difference between an open electrical circuit and a closed electrical circuit.

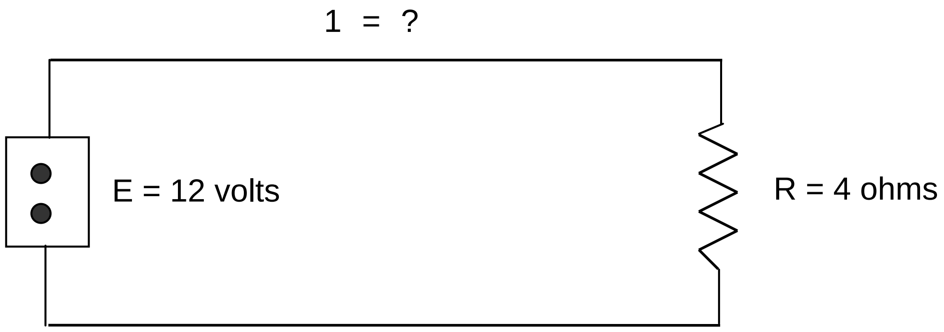
15. Resistors are used to control current or to produce heat. (True or False)

16. Resistors can be fixed or variable. (True or False)

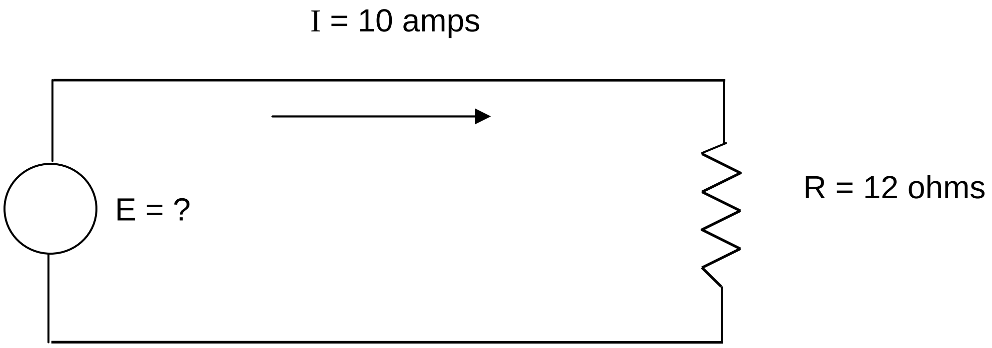
17. Longer wires have less resistance than shorter wires with the same diameter. (True of False)

18. What is the formula for Ohm’s Law?

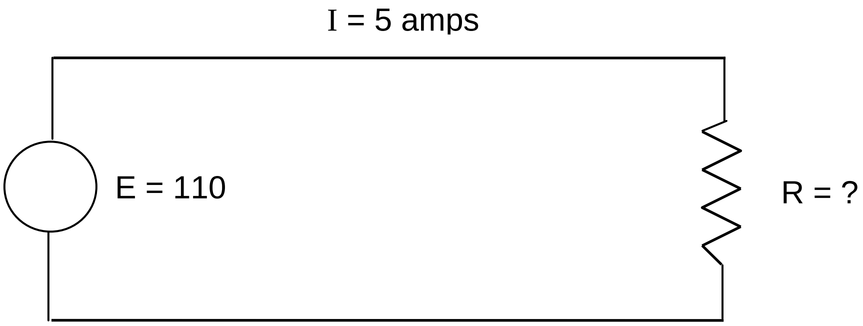
19. Using Ohm’s Law, calculate the current in this circuit.



20. Using Ohm's Law, calculated the voltage in this circuit.



21. Using Ohm's Law, calculate the resistance in this circuit.



22. What is a series circuit?

23. What is a parallel circuit?

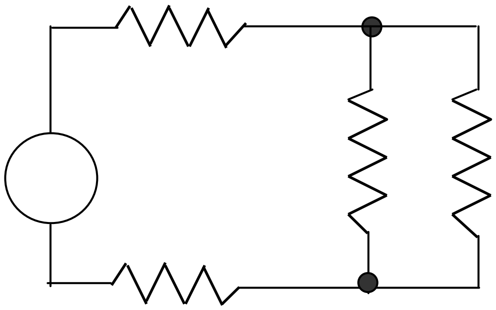
Shown below are three circuits.

24. The parallel circuit is marked ______________________.

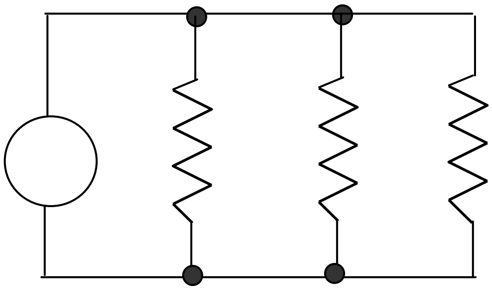
25. The series circuit is marked ______________________.

26. The series-parallel circuit is marked ______________________.

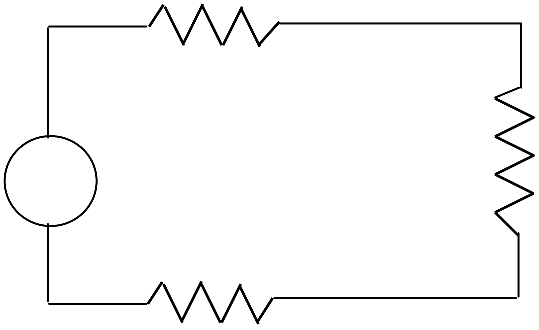
A.



B.



C.



True or False:

27. If another parallel resistance is added in parallel to a parallel resistor circuit, the total circuit resistance decreases.

28. The current in a parallel circuit has two or more paths to follow.

29. If voltage increases in a series circuit, the resistance also increases.

30. Select the correct statement. Power factor is:

A. A measure of the rate at which power is used in a circuit.
B. The ratio of true power to apparent power.
C. The combined opposition to current flow in a circuit.

Select the correct definitions for the following words (31-35).

31. Magnet

32. Magnetism

33. Lines of force

34. Electromagnet

35. Transformer

A. A current-carrying conductor wrapped around a core with high permeability for the purpose of developing a strong magnetic field.

B. A material that has the property of magnetism.

C. A device used to raise or lower AC voltage. It consists of a primary and secondary coil linked by lines of magnetic force.

D. The property of material that enables it to attract pieces of iron.

E. The paths of magnetism that flow from the north pole of a magnet to the south pole of a magnet.

36. List three reasons why most electricity is generated as alternating current.

Select the words that correctly fill in the statements (37-40).

- A. Leading current
- B. Lagging current
- C. Impedance
- D. In-phase current

37. Inductance causes a (n) ______________________.

38. The combined opposition to current flow caused by inductance, capacitance, and resistance is called ______________________.

39. Capacitance causes a (n)__________________.

40. Resistance causes a (n)_________________________.

41. What is impedance?

42. What is a capacitor?

43. Capacitors store electric charges. (True or False)

44. Impedance is caused only by resistors. (True or False)

45. Impedance is measured in ohms. (True or False)

Select the words that correctly fill in statements (46 and 47).

- A. Electrical energy
- B. Mechanical energy

46. A generator converts______________________ into ___________________.

47. A motor converts_________________________ into___________________.

48. Generators use magnetism to produce electricity. (True or False)

49. The two basic parts of a generator are the armature and the motor. (True or False)

50. The two basic parts of a motor are the rotor and the stator. (True or False)

51. AC generators produce DC currents. (True or False)

52. During a locked rotor event on a large centrifugal pump starting amps will change. Which of the following best describes how and why the affected RCP amps change?

    - A. Increase due to the increase in pump friction
    - B. Increase due to the increase in stator counter electromotive force (CEMF)
    - C. Decrease due to the decrease in pump speed
    - D. Decrease due to the increase in rotor counter electromotive force (CEMF)

53. A locked rotor during centrifugal pump startup can be differentiated from a sheared rotor primarily by

A. Loop flow indications
B. Pump ammeter indications
C. Loop differential temperatures
D. Time to reactor trip

54. Which of the following best describes the initial centrifugal pump ammeter response to a locked rotor event during pump startup?

A. Increases
B. Decreases
C. Remains the same
D. Fluctuates

55. Which of the following is <u>not</u> a possible consequence of overheating motor and generator electrical insulation?

A. Discoloration of parts
B. Blown fuses
C. Bearing Damage
D. Electrical grounds

56. Which of the following consequences result from motor and generator electrical insulation overheating?

A. Decreased electrical current demand
B. Decreased equipment life
C. Increased plant efficiency
D. Decreased power interruptions

57. Excessive A.C. motor currents can be caused by

- A. Overvoltage
- B. Undervoltage
- C. Low slip ratio
- D. Low ambient temperatures

58. Excessive A.C. motor currents <u>cannot</u> be caused by which of the following simultaneous conditions?

- A. Overvoltage while overloading
- B. Overvoltage while underloading
- C. Undervoltage while overloading
- D. Undervoltage while underloading

59. Which of the following is <u>not</u> a cause of excessive A.C. motor current?

- A. Undervoltage
- B. Overload
- C. Mechanical binding
- D. Low ambient temperatures

60. If the true power supplied by an A.C. generator in an isolated system is held constant while voltage is decreased, the current supplied by generator will

- A. Fluctuate
- B. Decrease
- C. Increase
- D. Remain the same

61. Excessive A.C. generator currents can be caused by

A. Overvoltage
B. Undervoltage
C. Overload
D. All of the above

62. An increase in the stator temperature of a centrifugal pump motor can be caused by the motor current

A. Increasing
B. Decreasing
C. Remaining constant
D. Fluctuating

63. Starting current in a squirrel cage motor is typically _____times full-load rated current.

A. 2 to 3
B. 3 to 4
C. 5 to 6
D. 8 to 9

64. The starting current in an A.C. motor is significantly higher than the full-load running current because

A. Little current is induced onto the rotor because of the slow rotor speed
B. Higher torque is required during a starting event, thus requiring high currents
C. Little counter electromotive force is induced onto the stator to limit stator current during start
D. A.C. motors are started under load and the starting current reflects this

65. Which of the following best describes the motor current indications that would be observed during the start of a large A.C. motor at full load?

A. Amps slowly increase to the full-load value
B. Amps increase immediately to the full-load value
C. Amps increase immediately to three times the full-load value and then decrease to the normal full-load value
D. Amps increase immediately to six times the full-load value and then decrease to the normal full-load value

66. High induced rotor currents due to maximum slip and accompanied by motor currents 5 to 6 times normal best describes the response of a large AC motor during which of the following events?

A. Motor start
B. Motor at breakdown torque
C. Motor in thermal overload
D. Motor with commutator flashover

67. Which of the following best describes the ammeter response during the normal start of a large A.C. motor-driven centrifugal pump? (Assume discharge valve is closed.) The ammeter indication will

A. Stay on scale because motor start is the basis for range selection, and then return to a no-load value
B. Go off-scale high and then return to a no-load value as the pump comes up to speed
C. Rise to the full-load value and then return to a no-load value as the pump comes up to speed
D. Go offscale high and then return to the full-load value because the pump is operating at shutoff head

68. The number of starts for an electrical motor in a given period of time should be limited because

A. Overheating of the windings can occur
B. Excessive electromotive force is generated during motor startup
C. Running current is much higher than starting current
D. Motors are normally started under full-load conditions

69. Which of the following is <u>not</u> a reason for limiting the number of motor starts in a given time period?

A. Overheating of windings may occur
B. Running current is much higher than starting current
C. Starting current is much higher than running current
D. The possibility of insulation failure during motor startup is reduced

70. Reactive power is the portion of the apparent power that is

A. Effectively returned to the source and is measured in KVAs
B. Actually dissipated in the load and is measured in watts
C. Effectively returned to the source and is measured in KVARs
D. Obtained by multiplying applied voltage and line current and is measured in watts-reactive

71. True power is that portion of apparent power that is

A. Effectively returned to the source and is measured in KVAs
B. Actually dissipated in the load and is measured in watts
C. Effectively returned to the source and is measured in KVARs
D. Obtained by multiplying applied voltage and line current and is measured in watts-reactive

72. Voltage (volts) can best be defined in terms of

A. An electrical potential difference
B. The rate of doing electrical work
C. Coulombs of charge
D. Cycles per second

73. Current (amps) can best be defined in terms

A. Electrical work
B. Electrical potential difference
C. Coulombs per second
D. Cycles per second

74. Frequency (Hz) can be best defined in terms of

A. Electrical work
B. Electrical potential difference
C. Coulombs of charge
D. Cycles per second