Department of Energy
Fundamentals Handbook

ELECTRICAL SCIENCE
Module 1
Basic Electrical Theory

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TERMINAL OBJECTIVE

1.0 Given a simple electrical circuit, **APPLY** basic electrical theory fundamental principles to describe circuit operation.

ENABLING OBJECTIVES

1.1 **DESCRIBE** the following terms:
- a. Electrostatic force
- b. Electrostatic field
- c. Potential difference
- d. Electromotive force (EMF)
- e. Ion charge

1.2 **DEFINE** the following terms:
- a. Conductor
- b. Insulator
- c. Resistor
- d. Electron current flow
- e. Conventional current flow
- f. Direct current (DC)
- g. Alternating current (AC)
- h. Ideal source
- i. Real source

1.3 **DESCRIBE** the following electrical parameters, including the unit of measurement and the relationship to other parameters.
- a. Voltage
- b. Current
- c. Resistance
- d. Conductance
- e. Power
- f. Inductance
- g. Capacitance

1.4 Given any two of the three component values of Ohm's Law, **DETERMINE** the unknown component value.

ENABLING OBJECTIVES (Cont.)

1.5 **DESCRIBE** how the following methods produce a voltage:
   a. Electrochemistry
   b. Static electricity
   c. Magnetic Induction
   d. Piezoelectric effect
   e. Thermoelectricity
   f. Photoelectric effect
   g. Thermionic emission

1.6 **DEFINE** the following terms:
   a. Magnetic flux
   b. Magnetic flux density
   c. Weber
   d. Permeability
   e. Magnetomotive force (mmf)
   f. Ampere turns
   g. Field intensity
   h. Reluctance

1.7 **DESCRIBE** the following materials as they relate to permeability, including an example and an approximate relative permeability.
   a. Ferromagnetic materials
   b. Paramagnetic materials
   c. Diamagnetic materials

1.8 **EXPLAIN** the physical qualities of a simple magnetic circuit, including relationships of qualities and units of measurements.

1.9 Given the physical qualities of a simple magnetic circuit, **CALCULATE** the unknown values.

1.10 **DESCRIBE** the shape and components of a BH magnetization curve.

1.11 **EXPLAIN** the cause of hysteresis losses.

1.12 Given Faraday's Law of induced voltage:
   a. **DESCRIBE** how varying parameters affect induced voltage.
   b. **CALCULATE** voltage induced in a conductor moving through a magnetic field.

1.13 **STATE** Lenz's Law of induction.

ENABLING OBJECTIVES (Cont.)

1.14 Given a standard electrical symbol, **IDENTIFY** the component that the symbol represents. The symbols will be for the following components:

a. Resistor
b. Capacitor
c. Inductor
d. Relay
e. Contacts
f. Breaker
g. Switch
h. Transistor
i. Rheostat
j. Diode
k. Ground connections
l. Vacuum tube
m. Fuse
n. Junction
o. AC voltage source
p. Voltmeter
q. Ammeter
r. Wattmeter
s. Relay operated contacts
t. Potential transformer
u. Current transformer
v. Wye (Y) connection
w. Delta (Δ) connection
x. Light bulb
y. Battery

ATOM AND ITS FORCES

What is electricity? Electricity is defined as "the flow of electrons through simple materials and devices" or "that force which moves electrons." Scientists think electricity is produced by very tiny particles called electrons and protons. These particles are too small to be seen, but exist as subatomic particles in the atom. To understand how they exist, you must first understand the structure of the atom.

EO 1.1 DESCRIBE the following terms:

a. Electrostatic force
b. Electrostatic field
c. Potential difference
d. Electromotive force (EMF)
e. Ion charge

The Atom

Elements are the basic building blocks of all matter. The atom is the smallest particle to which an element can be reduced while still keeping the properties of that element. An atom consists of a positively charged nucleus surrounded by negatively charged electrons, so that the atom as a whole is electrically neutral. The nucleus is composed of two kinds of subatomic particles, protons and neutrons, as shown in Figure 1. The proton carries a single unit positive charge equal in magnitude to the electron charge. The neutron is slighty heavier than the proton and is electrically neutral, as the name implies. These two particles exist in various combinations, depending upon the element involved. The electron is the fundamental negative charge (-) of electricity and revolves around the nucleus, or center, of the atom in concentric orbits, or shells.

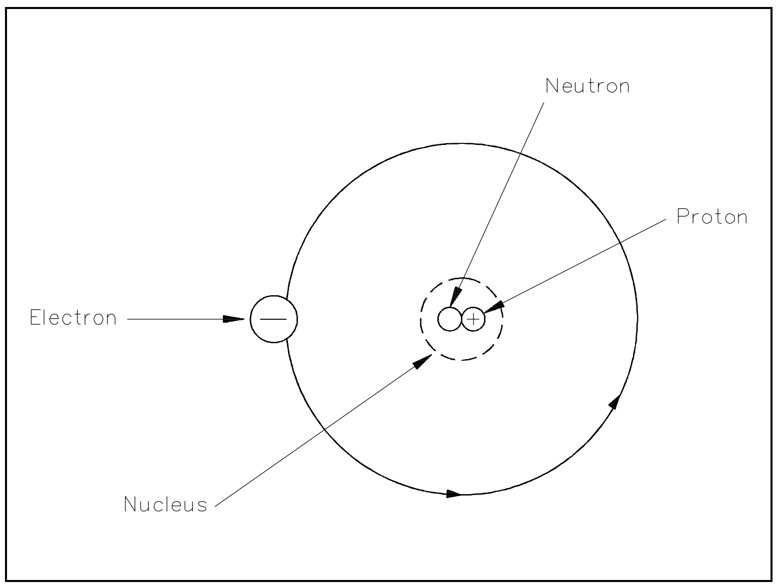

Figure 1 The Atom

The proton is the fundamental positive charge (+) of electricity and is located in the nucleus. The number of protons in the nucleus of any atom specifies the atomic number of that atom or of that element. For example, the carbon atom contains six protons in its nucleus; therefore, the atomic number for carbon is six, as shown in Figure 2.

In its natural state, an atom of any element contains an equal number of electrons and protons. The negative charge (-) of each electron is equal in magnitude to the positive charge (+) of each proton; therefore, the two opposite charges cancel, and the atom is said to be electrically neutral, or in balance.

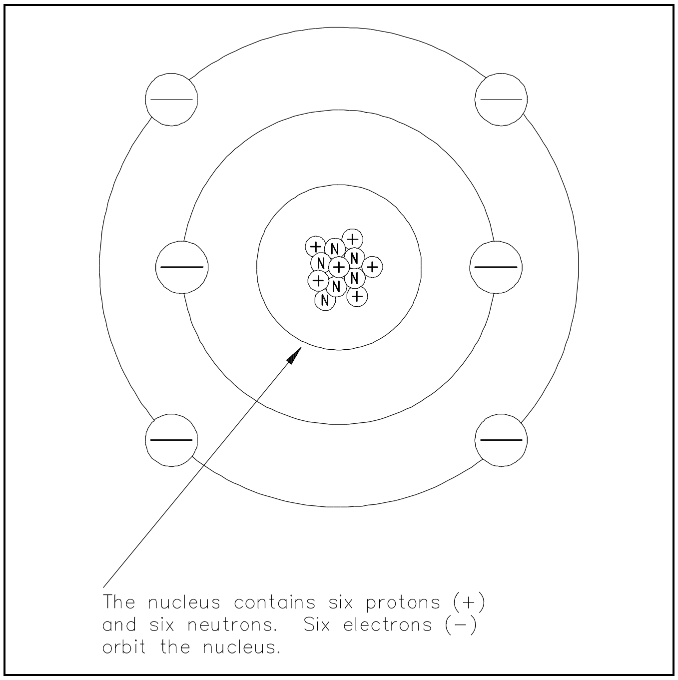

Figure 2 The Carbon Atom

Electrostatic Force

One of the mysteries of the atom is that the electron and the nucleus attract each other. This attraction is called *electrostatic force*, the force that holds the electron in orbit. This force may be illustrated with lines as shown in Figure 3.

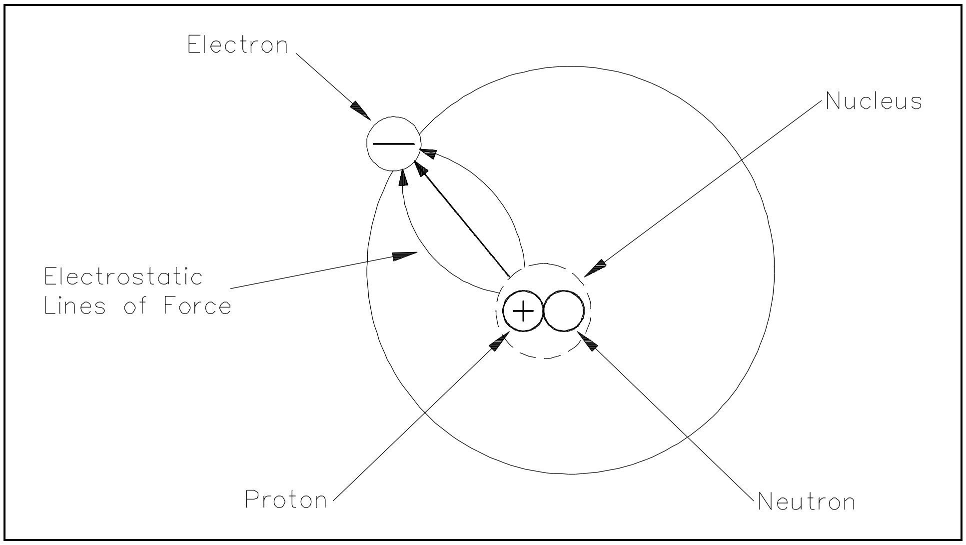

Figure 3 Electrostatic Force

Without this electrostatic force, the electron, which is traveling at high speed, could not stay in its orbit. Bodies that attract each other in this way are called charged bodies. As mentioned previously, the electron has a negative charge, and the nucleus (due to the proton) has a positive charge.

The First Law of Electrostatics

The negative charge of the electron is equal, but opposite to, the positive charge of the proton. These charges are referred to as electrostatic charges. In nature, unlike charges (like electrons and protons) attract each other, and like charges repel each other. These facts are known as the *First Law of Electrostatics* and are sometimes referred to as the law of electrical charges. This law should be remembered because it is one of the vital concepts in electricity.

Some atoms can lose electrons and others can gain electrons; thus, it is possible to transfer electrons from one object to another. When this occurs, the equal distribution of negative and positive charges no longer exists. One object will contain an excess of electrons and become negatively charged, and the other will become deficient in electrons and become positively charged. These objects, which can contain billions of atoms, will then follow the same law of electrostatics as the electron and proton example shown above. The electrons that can move around within an object are said to be free electrons and will be discussed in more detail in a later section. The greater the number of these free electrons an object contains, the greater its negative electric charge. Thus, the electric charge can be used as a measure of electrons.

Electrostatic Field

A special force is acting between the charged objects discussed above. Forces of this type are the result of an *electrostatic field* that exists around each charged particle or object. This electrostatic field, and the force it creates, can be illustrated with lines called "lines of force" as shown in Figure 4.

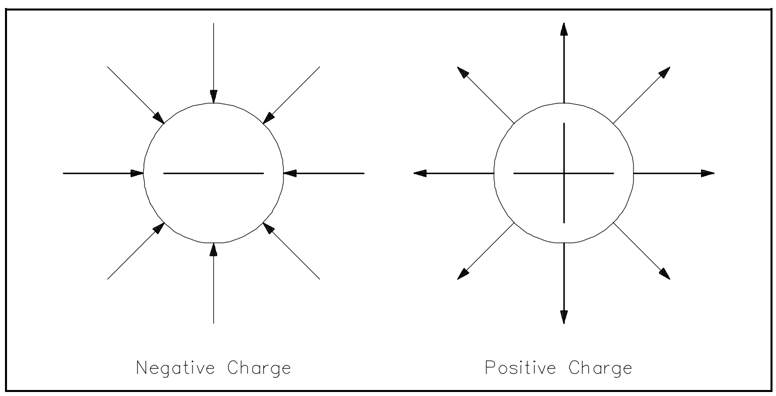

Figure 4 Electrostatic Field

Charged objects repel or attract each other because of the way these fields act together. This force is present with every charged object. When two objects of opposite charge are brought near one another, the electrostatic field is concentrated in the area between them, as shown in Figure 5. The direction of the small arrows shows the direction of the force as it would act upon an electron if it were released into the electric field.

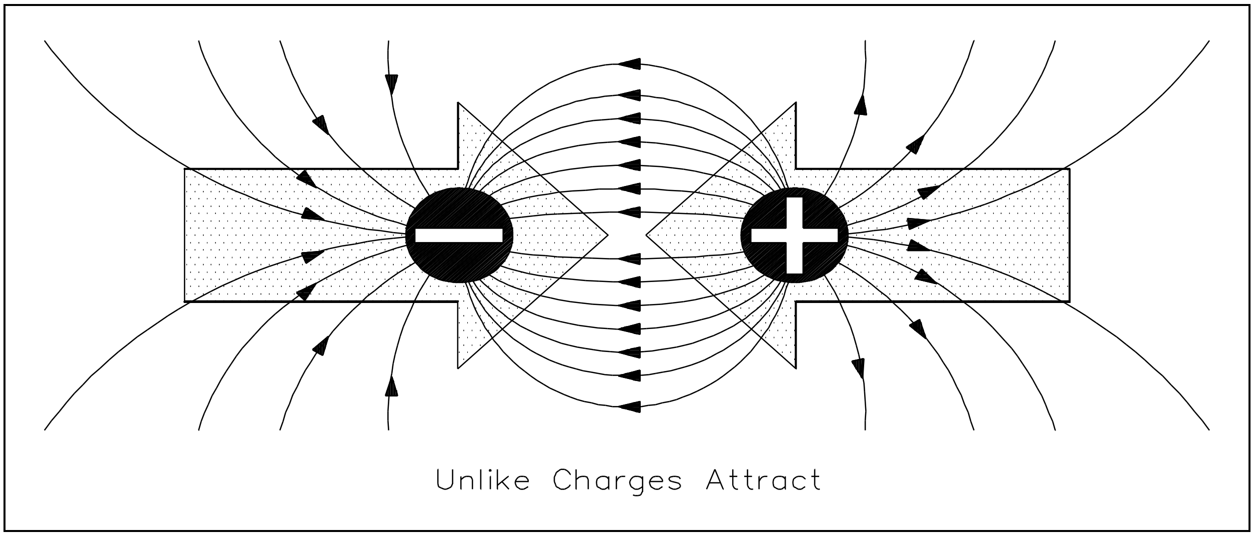

Figure 5 Electrostatic Field Between Two Charges of Opposite Polarity

When two objects of like charge are brought near one another, the lines of force repel each other, as shown in Figure 6.

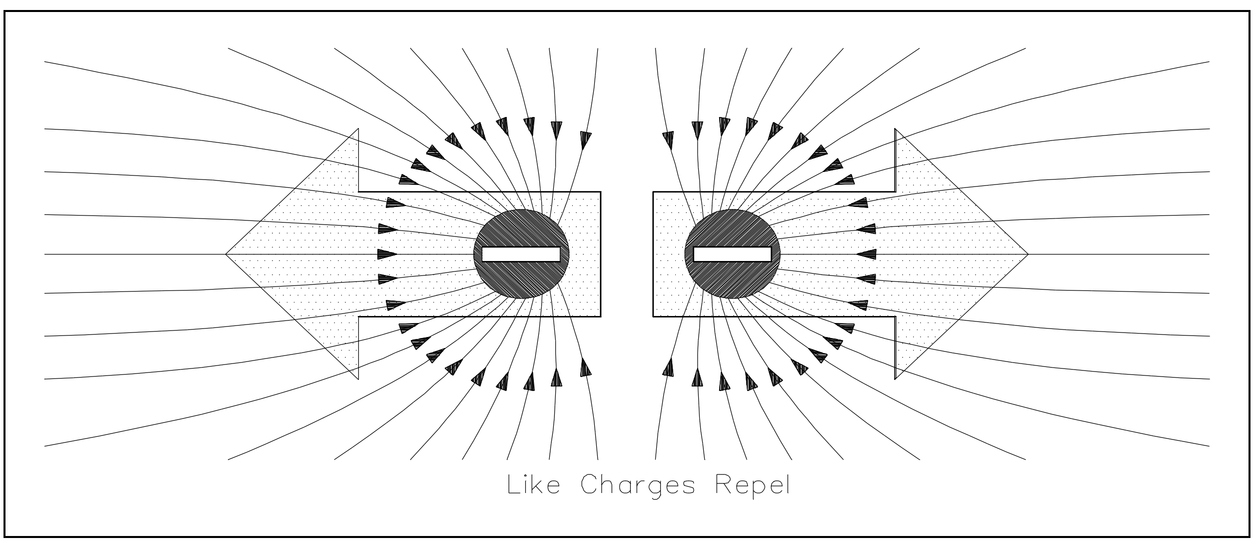

Figure 6 Electrostatic Field Between Two Charges of Like Polarity

The strength of the attraction or of the repulsion force depends upon two factors: (1) the amount of charge on each object, and (2) the distance between the objects. The greater the charge on the objects, the greater the electrostatic field. The greater the distance between the objects, the weaker the electrostatic field between them, and vice versa. This leads us to the law of electrostatic attraction, commonly referred to as Coulomb's Law of electrostatic charges, which states that the force of electrostatic attraction, or repulsion, is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them as shown in Equation 1-1.

$$F = K\frac{q_1 - q_2}{d^2} \qquad (1\text{-}1)$$

where

F = force of electrostatic attraction or prepulsion (Newtons)
K = constant of proportionality (Coulomb ^{2}/N-m^2)
q_1 = charge of first particle (Coulombs)
q_2 = charge of second particle (Coulombs)
d = distance between two particles (Meters)

If q_1 and q_2 are both either positively or negatively charged, the force is repulsive. If q_1 and q_2 are opposite polarity or charge, the force is attractive.

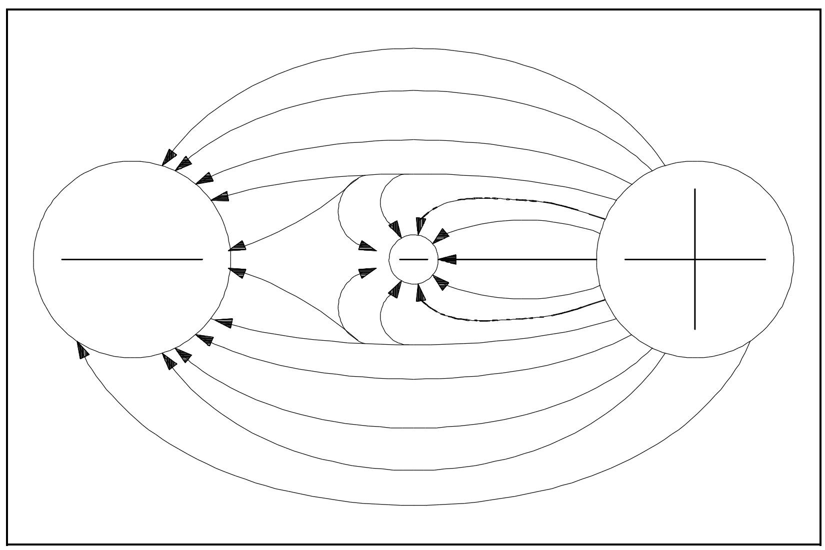

Figure 7 Potential Difference Between Two Charged Objects

Potential Difference

Potential difference is the term used to describe how large the electrostatic force is between two charged objects. If a charged body is placed between two objects with a potential difference, the charged body will try to move in one direction, depending upon the polarity of the object. If an electron is placed between a negatively-charged body and a positively-charged body, the action due to the potential difference is to push the electron toward the positively-charged object. The electron, being negatively charged, will be repelled from the negatively-charged object and attracted by the positively-charged object, as shown in Figure 7.

Due to the force of its electrostatic field, these electrical charges have the ability to do work by moving another charged particle by attraction and/or repulsion. This ability to do work is called "potential"; therefore, if one charge is different from another, there is a potential difference between them. The sum of the potential differences of all charged particles in the electrostatic field is referred to as *electromotive force* (EMF).

The basic unit of measure of potential difference is the "volt." The symbol for potential difference is "V," indicating the ability to do the work of forcing electrons to move. Because the volt unit is used, potential difference is also called "voltage." The unit volt will be covered in greater detail in the next chapter.

Free Electrons

Electrons are in rapid motion around the nucleus. While the electrostatic force is trying to pull the nucleus and the electron together, the electron is in motion and trying to pull away. These two effects balance, keeping the electron in orbit. The electrons in an atom exist in different energy levels. The energy level of an electron is proportional to its distance from the nucleus. Higher energy level electrons exist in orbits, or shells, that are farther away from the nucleus. These shells nest inside one another and surround the nucleus. The nucleus is the center of all the shells. The shells are lettered beginning with the shell nearest the nucleus: K, L, M, N, O, P, and Q. Each shell has a maximum number of electrons it can hold. For example, the K shell will hold a maximum of two electrons and the L shell will hold a maximum of eight electrons. As shown in Figure 8, each shell has a specific number of electrons that it will hold for a particular atom.

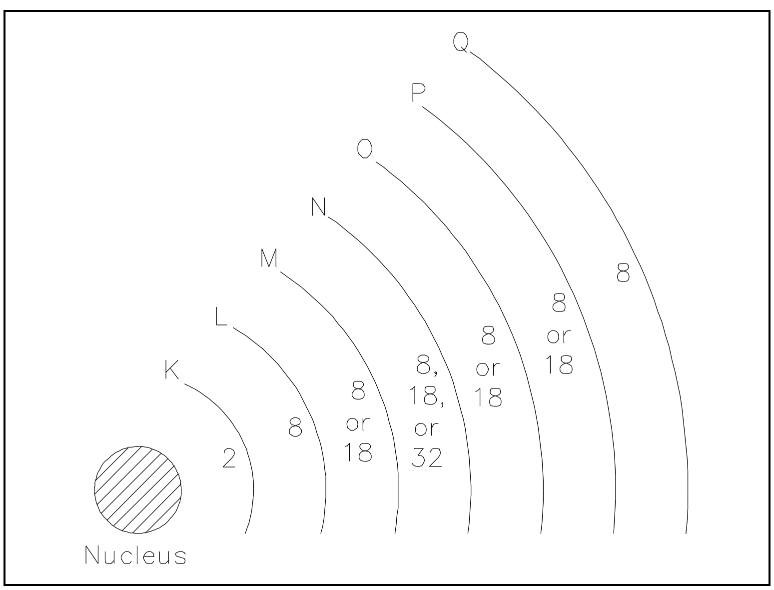

Figure 8 Energy Shells and Electron Quota

There are two simple rules concerning electron shells that make it possible to predict the electron distribution of any element:

1. The maximum number of electrons that can fit in the outermost shell of any atom is eight.

2. The maximum number of electrons that can fit in the next-to-outermost shell of any atom is 18.

An important point to remember is that when the outer shell of an atom contains eight electrons, the atom becomes very stable, or very resistant to changes in its structure. This also means that atoms with one or two electrons in their outer shell can lose electrons much more easily than atoms with full outer shells. The electrons in the outermost shell are called *valence electrons*. When external energy, such as heat, light, or electrical energy, is applied to certain materials, the electrons gain energy, become excited, and may move to a higher energy level. If enough energy is applied to the atom, some of the valence electrons will leave the atom. These electrons are called *free electrons*. It is the movement of free electrons that provides electric current in a metal conductor. An atom that has lost or gained one or more electrons is said to be *ionized* or to have an *ion change*. If the atom loses one or more electrons, it becomes positively charged and is referred to as a *positive ion*. If an atom gains one or more electrons, it becomes negatively charged and is referred to as a *negative ion*.

Summary

The important information contained in this chapter is summarized below.

Forces Around Atoms Summary

- Electrostatic Force - force that holds an electron in orbit around a nucleus
- Electrostatic Field - force acting between charged objects that causes them to repel or attract
- Potential Difference - measures how large the electrostatic force is between two charged objects. According to Coulomb's Law, charged bodies attract or repel each other with a force that is directly proportional to the product of their charges and is inversely proportional to the square of the distance between them.
- Electromotive Force (EMF) - sum of the potential differences of all charged particles in an electrostatic field
- Ion Charge - dependent on the loss or gain of free electrons (if an atom gains an electron - negative ion charge; if an atom loses an electron - positive ion charge)

ELECTRICAL TERMINOLOGY

Knowledge of key electrical terminology is necessary to fully understand principles in electrical science.

EO 1.2 DEFINE the following terms:

a. Conductor
b. Insulator
c. Resistor
d. Electron current flow
e. Conventional current flow
f. Direct current (DC)
g. Alternating current (AC)
h. Ideal source
i. Real source

Conductors

Conductors are materials with electrons that are loosely bound to their atoms, or materials that permit free motion of a large number of electrons. Atoms with only one valence electron, such as copper, silver, and gold, are examples of good conductors. Most metals are good conductors.

Insulators

Insulators, or nonconductors, are materials with electrons that are tightly bound to their atoms and require large amounts of energy to free them from the influence of the nucleus. The atoms of good insulators have their valence shells filled with eight electrons, which means they are more than half filled. Any energy applied to such an atom will be distributed among a relatively large number of electrons. Examples of insulators are rubber, plastics, glass, and dry wood.

Resistors

Resistors are made of materials that conduct electricity, but offer opposition to current flow. These types of materials are also called *semiconductors* because they are neither good conductors nor good insulators. Semiconductors have more than one or two electrons in their valence shells, but less than seven or eight. Examples of semiconductors are carbon, silicon, germanium, tin, and lead. Each has four valence electrons.

Voltage

The basic unit of measure for potential difference is the *volt* (symbol V), and, because the volt unit is used, potential difference is called *voltage*. An object's electrical charge is determined by the number of electrons that the object has gained or lost. Because such a large number of electrons move, a unit called the "coulomb" is used to indicate the charge. One coulomb is equal to 6.28×10^{18} (billion, billion) electrons. For example, if an object gains one coulomb of negative charge, it has gained 6,280,000,000,000,000,000 extra electrons. A volt is defined as a difference of potential causing one coulomb of current to do one joule of work. A volt is also defined as that amount of force required to force one ampere of current through one ohm of resistance. The latter is the definition with which we will be most concerned in this module.

Current

The density of the atoms in copper wire is such that the valence orbits of the individual atoms overlap, causing the electrons to move easily from one atom to the next. Free electrons can drift from one orbit to another in a random direction. When a potential difference is applied, the direction of their movement is controlled. The strength of the potential difference applied at each end of the wire determines how many electrons change from a random motion to a more directional path through the wire. The movement or flow of these electrons is called *electron current flow* or just *current*.

To produce current, the electrons must be moved by a potential difference. The symbol for current is (I). The basic measurement for current is the ampere (A). One ampere of current is defined as the movement of one coulomb of charge past any given point of a conductor during one second of time.

If a copper wire is placed between two charged objects that have a potential difference, all of the negatively-charged free electrons will feel a force pushing them from the negative charge to the positive charge. This force opposite to the conventional direction of the electrostatic lines of force is shown in Figure 9.

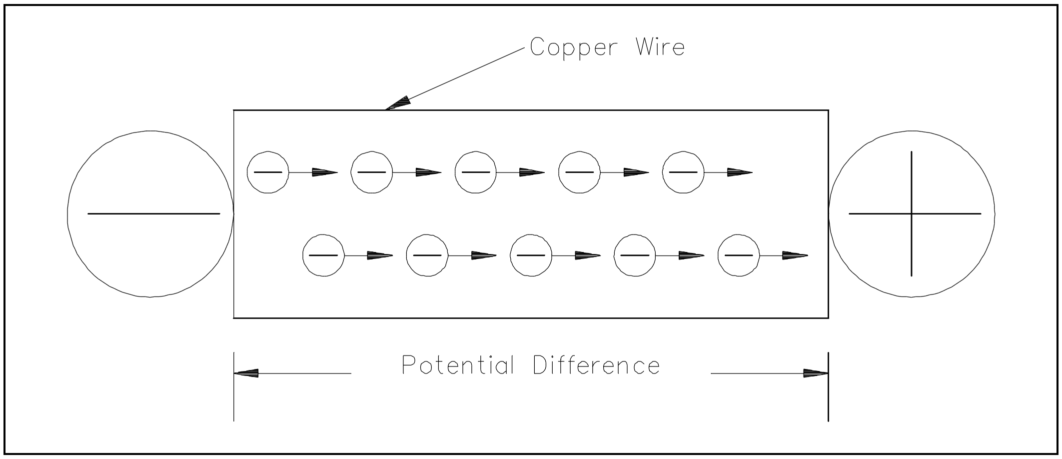

Figure 9 Electron Flow Through a Copper Wire with a Potential Difference

The direction of electron flow, shown in Figure 10, is from the negative (-) side of the battery, through the wire, and back to the positive (+) side of the battery. The direction of electron flow is from a point of negative potential to a point of positive potential. The solid arrow shown in Figure 10 indicates the direction of electron flow. As electrons vacate their atoms during electron current flow, positively charged atoms (holes) result. The flow of electrons in one direction causes a flow of positive charges. The direction of the positive charges is in the opposite direction of the electron flow. This flow of positive charges is known as *conventional current* and is shown in Figure 10 as a dashed arrow. All of the electrical effects of electron flow from negative to positive, or from a higher potential to a lower potential, are the same as those that would be created by a flow of positive charges in the opposite direction. Therefore, it is important to realize that both conventions are in use and that they are essentially equivalent; that is, all effects predicted are the same. In this text, we will be using electron flow in our discussions.

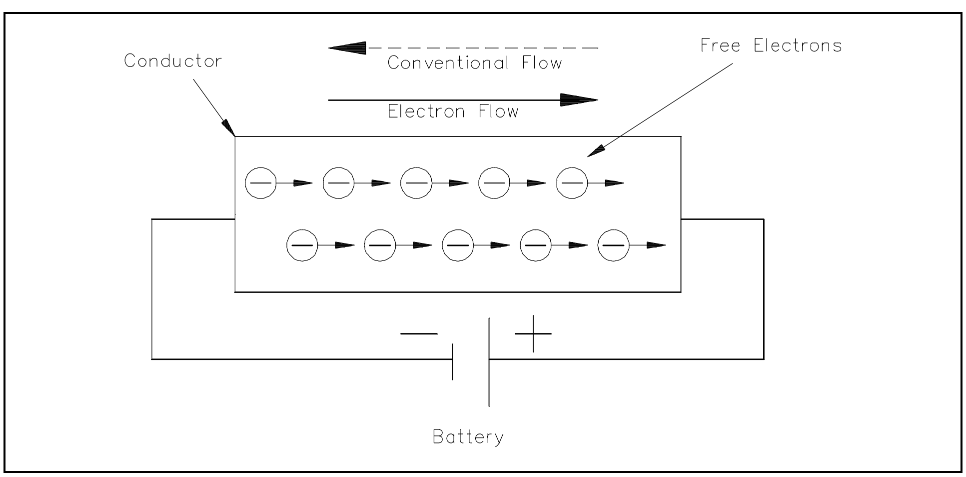

Figure 10 Potential Difference Across a Conductor Causes a Current to Flow

Generally, electric current flow can be classified as one of two general types: *Direct Current* (DC) or *Alternating Current* (AC). A direct current flows continuously in the same direction. An alternating current periodically reverses direction. We will be studying DC and AC current in more detail later in this text. An example of DC current is that current obtained from a battery. An example of AC current is common household current.

Real and Ideal Sources

An *ideal source* is a theoretical concept of an electric current or voltage supply (such as a battery) that has no losses and is a perfect voltage or current supply. Ideal sources are used for analytical purposes only since they cannot occur in nature.

A *real source* is a real life current or voltage supply that has some losses associated with it.

Summary

The important information contained in this chapter is summarized below.

Terminology Summary

- Conductor - material with electrons loosely bound to its atoms or that permits free motion of large number of electrons
- Insulator - material with electrons tightly bound to its atoms; requires large amounts of energy to free electrons from its nuclei
- Resistor - material that conducts electricity, but opposes current flow
- Electron Current Flow - current flow from negative to positive potentials
- Conventional Current Flow - current flow from positive to negative potentials
- Direct Current - current flow continuously in the same direction
- Alternating Current - current flow periodically reverses direction
- Ideal Source - theoretical current or voltage supply with no losses
- Real Source - actual current or voltage supply with losses

UNITS OF ELECTRICAL MEASUREMENT

Using Ohm's Law and the System Internationale (SI) Metric System, electrical measuring units can be derived.

EO 1.3 DESCRIBE the following electrical parameters, including the unit of measurement and the relationship to other parameters.

a. Voltage
b. Current
c. Resistance
d. Conductance
e. Power
f. Inductance
g. Capacitance

EO 1.4 Given any two of the three component values of Ohm's Law, DETERMINE the unknown component value.

System Internationale (SI) Metric System

Electrical units of measurement are based on the International (metric) System, also known as the SI System. Units of electrical measurement include the following:

- Ampere
- Volt
- Ohm
- Siemens
- Watt
- Henry
- Farad

Appendix A provides more information concerning the metric system, metric prefixes, and powers of 10 that are used in electrical measuring units.

Voltage

Voltage, electromotive force (emf), or potential difference, is described as the pressure or force that causes electrons to move in a conductor. In electrical formulas and equations, you will see voltage symbolized with a capital E, while on laboratory equipment or schematic diagrams, the voltage is often represented with a capital V.

Current

Electron *current*, or amperage, is described as the movement of free electrons through a conductor. In electrical formulas, current is symbolized with a capital I, while in the laboratory or on schematic diagrams, it is common to use a capital A to indicate amps or amperage (amps).

Resistance

Now that we have discussed the concepts of voltage and current, we are ready to discuss a third key concept called resistance. *Resistance* is defined as the opposition to current flow. The amount of opposition to current flow produced by a material depends upon the amount of available free electrons it contains and the types of obstacles the electrons encounter as they attempt to move through the material. Resistance is measured in ohms and is represented by the symbol (R) in equations. One ohm is defined as that amount of resistance that will limit the current in a conductor to one ampere when the potential difference (voltage) applied to the conductor is one volt. The shorthand notation for ohm is the Greek letter capital omega (Ω). If a voltage is applied to a conductor, current flows. The amount of current flow depends upon the resistance of the conductor. The lower the resistance, the higher the current flow for a given amount of voltage. The higher the resistance, the lower the current flow.

Ohm's Law

In 1827, George Simon Ohm discovered that there was a definite relationship between voltage, current, and resistance in an electrical circuit. Ohm's Law defines this relationship and can be stated in three ways.

1. Applied voltage equals circuit current times the circuit resistance. Equation (1-2) is a mathematical respresentation of this concept.

$$E = I \times R \quad \text{or} \quad E = IR \tag{1-2}$$

2. Current is equal to the applied voltage divided by the circuit resistance. Equation (1-3) is a mathematical representation of this concept.

$$I = \frac{E}{R} \tag{1-3}$$

3. Resistance of a circuit is equal to the applied voltage divided by the circuit current. Equation (1-4) is a mathematical representation of this concept.

$$R \ (\text{or } \Omega) = \frac{E}{I} \tag{1-4}$$

where

I = current (A)

E = voltage (V)

R = resistance (Ω)

If any two of the component values are known, the third can be calculated.

Example 1: Given that I = 2 A, E = 12 V, find the circuit resistance.

Solution:

Since applied voltage and circuit current are known, use Ohm's Law to solve for resistance.

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

$$R = \frac{12 \ V}{2 \ A} = 6 \ \Omega$$

Example 2: Given E = 260 V and R = 240 Ω, what current will flow through a circuit?

Solution:

Since applied voltage and resistance are known, use Ohm's Law to solve for current.

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

$$I = \frac{260 \ V}{240 \ \Omega} = 1.08\overline{3} \ A$$

Example 3: Find the applied voltage, when given circuit resistance of 100 Ω and circuit current of 0.5 amps.

Solution:

Since circuit resistance and circuit current are known, use Ohm's Law to solve for applied voltage.

$E = IR$

$E = (0.5\ A)(100\ \Omega) = 50\ V$

Conductance

The word "reciprocal" is sometimes used to mean "the opposite of." The opposite, or reciprocal, of resistance is called *conductance*. As described above, resistance is the opposition to current flow. Since resistance and conductance are opposites, conductance can be defined as the ability to conduct current. For example, if a wire has a high conductance, it will have low resistance, and vice-versa. Conductance is found by taking the reciprocal of the resistance. The unit used to specify conductance is called "mho," which is ohm spelled backwards. The symbol for "mho" is the Greek letter omega inverted (℧). The symbol for conductance when used in a formula is G. Equation (1-5) is the mathematical representation of conductance obtained by relating the definition of conductance (1/R) to Ohm's Law, Equation (1-4).

$$G = \frac{1}{\text{RESISTANCE}} = \frac{I}{E} \tag{1-5}$$

Example: If a resistor (R) has five ohms, what will its conductance (G) be in mhos?

Solution:

$$G \text{ (or } \mho) = \frac{1}{R} = \frac{1}{5} = 0.2\ \mho$$

Power

Electricity is generally used to do some sort of work, such as turning a motor or generating heat. Specifically, *power* is the rate at which work is done, or the rate at which heat is generated. The unit commonly used to specify electric power is the watt. In equations, you will find power abbreviated with the capital letter P, and watts, the units of measure for power, are abbreviated with the capital letter W. Power is also described as the current (I) in a circuit times the voltage (E) across the circuit. Equation (1-6) is a mathematical representation of this concept.

$$P = I \times E \quad \text{or} \quad P = IE \tag{1-6}$$

Using Ohm's Law for the value of voltage (E),

$$E = I \times R$$

and using substitution laws,

$$P = I \times (I \times R)$$

power can be described as the current (I) in a circuit squared times the resistance (R) of the circuit. Equation (1-7) is the mathematical representation of this concept.

$$P = I^2R \tag{1-7}$$

Inductance

Inductance is defined as the ability of a coil to store energy, induce a voltage in itself, and oppose changes in current flowing through it. The symbol used to indicate inductance in electrical formulas and equations is a capital L. The units of measurement are called henries. The unit henry is abbreviated by using the capital letter H. One henry is the amount of inductance (L) that permits one volt to be induced (V_L) when the current through the coil changes at a rate of one ampere per second. Equation (1-8) is the mathematical representation of the rate of change in current through a coil per unit time.

$$\left(\frac{\Delta I}{\Delta t}\right) \tag{1-8}$$

Equation (1-9) is the mathematical representation for the voltage V_L induced in a coil with inductance L. The negative sign indicates that voltage induced opposes the change in current through the coil per unit time ($\Delta I/\Delta t$).

$$V_L = -L\left(\frac{\Delta I}{\Delta t}\right) \tag{1-9}$$

Inductance will be studied in further detail later in this text.

Capacitance

Capacitance is defined as the ability to store an electric charge and is symbolized by the capital letter C. Capacitance (C), measured in farads, is equal to the amount of charge (Q) that can be stored in a device or capacitor divided by the voltage (E) applied across the device or capacitor plates when the charge was stored. Equation (1-10) is the mathematical representation for capacitance.

$$C = \frac{Q}{E} \tag{1-10}$$

Summary

The important information contained in this chapter is summarized below.

Electrical Units Summary

Parameter	Measuring Unit	Relationship
Voltage	volt (V or E)	$E = I \times R$
Current	amp (I)	$I = \frac{E}{R}$
Resistance	ohm (R or Ω)	$R = \frac{E}{I}$
Conductance	mho (G or ℧)	$G = \frac{I}{R} = \frac{I}{E}$
Power	watt (W)	$P = I \times E$ or $P = I^2R$
Inductance	henry (L or H)	$V_L = -L \left(\frac{\Delta I}{\Delta t}\right)$
Capacitance	farad (C)	$C = \frac{Q}{E}$ (Q = charge)