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Introduction

Welcome to the first course in the STEP series, **S**iemens **T**echnical **E**ducation **P**rogram designed to prepare our distributors to sell Siemens Industry, Inc. products more effectively. This course covers **Basics of Electricity** and is designed to prepare you for courses on Siemens Industry, Inc. products.

Upon completion of Basics of Electricity you will be able to:

- Explain the difference between conductors and insulators
- Use Ohm's law to calculate current, voltage, and resistance
- Calculate equivalent resistance for series, parallel, or series-parallel circuits
- Calculate voltage drop across a resistor
- Calculate power given other basic values
- Identify factors that determine the strength and polarity of a current-carrying coil's magnetic field
- Determine peak, instantaneous, and effective values of an AC sine wave
- Identify factors that effect inductive reactance and capacitive reactance in an AC circuit
- Calculate total impedance of an AC circuit
- Explain the difference between real power and apparent power in an AC circuit
- Calculate primary and secondary voltages of single-phase and three-phase transformers
- Calculate the required apparent power for a transformer

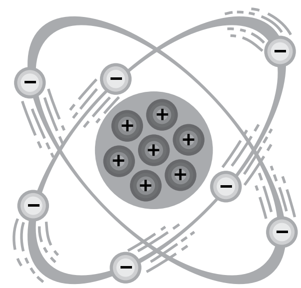
This knowledge will help you better understand customer applications. In addition, you will be better able to describe products to customers and determine important differences between products.

After you have completed this course, if you wish to determine how well you have retained the information covered, you can complete a final exam online as described later in this course. If you pass the exam, you will be given the opportunity to print a certificate of completion from your computer.

Conductors and Insulators

Elements of an Atom

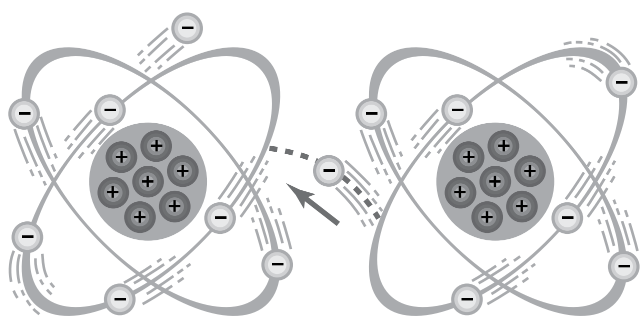
All matter is made up **atoms**. Atoms have a nucleus with electrons in motion around it. The nucleus is composed of protons and neutrons (not shown). **Electrons** have a negative charge (-). **Protons** have a positive charge (+). **Neutrons** are neutral. In the normal state of an atom, the number of electrons is equal to the number of protons and the negative charge of the electrons is balanced by the positive charge of the protons.



Free Electrons

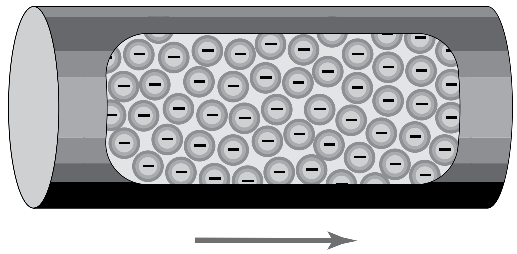
Electrons move about the nucleus at different distances. The closer to the nucleus, the more tightly bound the electrons are to the atom. Electrons in the outer band can be easily force out of the atom by the application of some external force such as a magnetic field, friction, or chemical action.

Electrons forced from atoms are sometimes called **free electrons**. A free electron leaves a void which can be filled by an electron forced out of another atom.



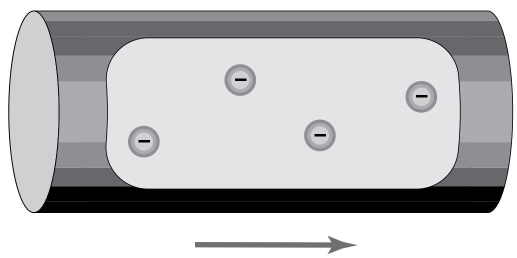
Conductors

An **electric current** is produced when free electrons move from atom to atom in a material. Materials that permit many electrons to move freely are called **conductors**. Copper, silver, gold, aluminum, zinc, brass, and iron are considered good conductors. Of these materials, copper and aluminum are the ones most commonly used as conductors.



Insulators

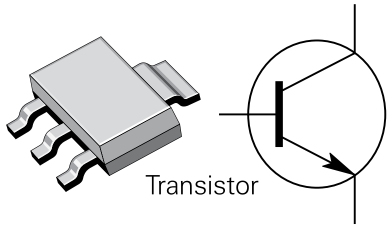
Materials that allow few free electrons are called **insulators**. Materials such as plastic, rubber, glass, mica, and ceramic are good insulators.

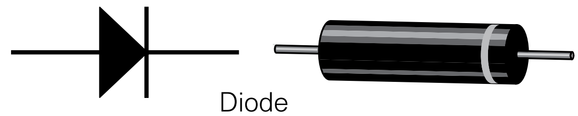


An electric cable is one example of how conductors and insulators are used. Electrons flow along a copper or aluminum conductor to provide energy to an electric device such as a radio, lamp, or a motor. An insulator around the outside of the copper conductor is provided to keep electrons in the conductor.

Semiconductors

Semiconductor materials, such as silicon, can be used to manufacture devices that have characteristics of both conductors and insulators. Many semiconductor devices act like a conductor when an external force is applied in one direction and like an insulator when the external force is applied in the opposite direction. This principle is the basis for transistors, diodes, and other solid-state electronic devices.


Transistor


Diode

Review 1

1. List the three basic particles of an atom and state the charge of each (positive, negative, or neutral).

Element	Charge
________	________
________	________
________	________

2. Materials that permit many electrons to move freely are called ________.

3. Which of the following materials are good conductors?

a. copper	e. aluminum
b. plastic	f. glass
c. silver	g. iron
d. rubber	h. mica

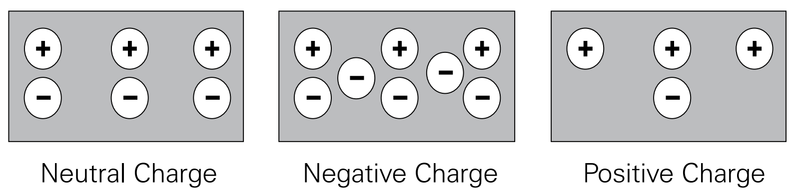
4. Materials that allow few free electrons are called ________.

Current, Voltage, and Resistance

All materials are composed of one or more elements. An element is a material made up of one type of atom. Elements are often identified by the number of protons and electrons in one atom of the element. A hydrogen atom, for example, has only one electron and one proton. An aluminum atom has 13 electrons and 13 protons. An atom with an equal number of electrons and protons is electrically neutral.

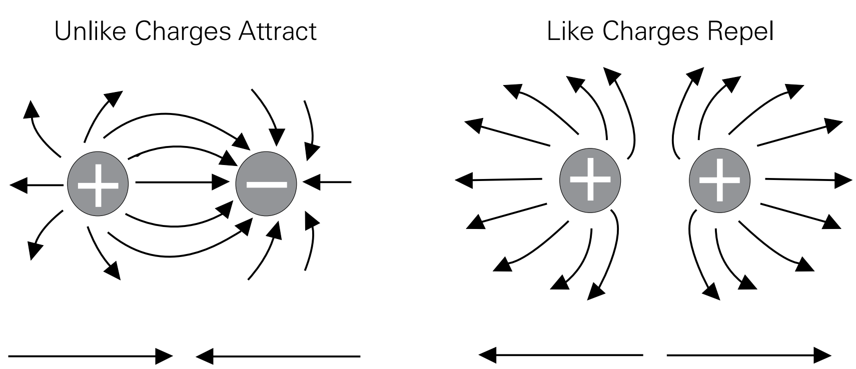
Electrical Charges

Electrons in the outer band of an atom can be easily displaced by the application of external force. When an electron is forced out of an atom, the atom it leaves behind has more protons than electrons. This atom now has a **positive charge.** Atoms or molecules of a material can also have an excess of electrons, giving the material a **negative charge**. A positive or negative charge is caused by an absence or excess of electrons. The number of protons remains constant.



Attraction and Repulsion of Electric Charges

The old saying, “opposites attract,” is true when dealing with electric charges. Charged bodies have an invisible electric field around them. These invisible lines of force cause attraction or repulsion. When two like-charged bodies are brought together, their electric fields repel one body from the other. When two unlike-charged bodies are brought together, their electric fields attract one body to the other.



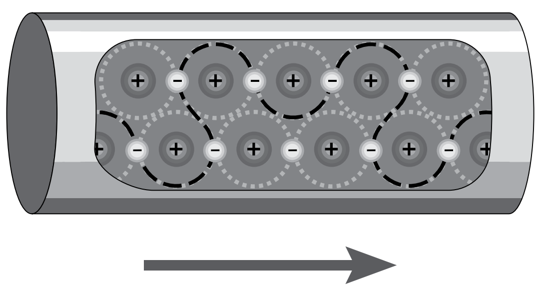
The interaction of electrical charges is dependent upon both the both the amount of each charge and the distance between charges. The greater the amount of each charge the more charged objects attract or repel one another. However this interaction is inversely proportional to the square of the distance between charges.

Current

The flow of free electrons in a material from one atom to the next atom in the same direction is referred to as **current** and is designated by the symbol **I**. The amount of current flowing is determined by the number of electrons that pass through a cross-section of a conductor in one second.

Keep in mind that atoms are very small. It takes about 10^{24} atoms to fill one cubic centimeter of a copper conductor. This means that trying to represent even a small value of current as electrons would result in an extremely large number.

For this reason, current is measured in **amperes,** often shortened to **amps**. The letter **A** is the symbol for amps. A current of one amp means that in one second about 6.24×10^{18} electrons move through a cross-section of conductor. These numbers are given for information only and you do not need to be concerned with them. It is important, however, to understand the concept of current flow.

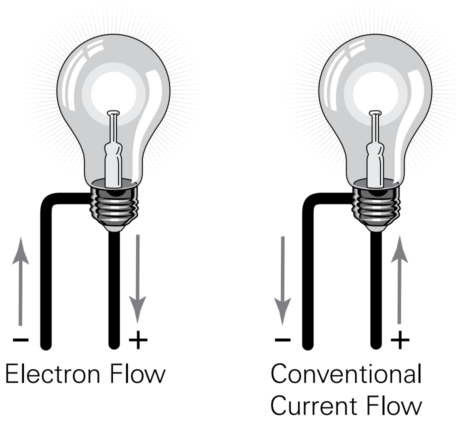


Because in practice it is common to find wide variations in the magnitude of electrical quantities, electrical units often have metric unit prefixes that represent powers of ten. The following chart shows how three of these prefixes are used to represent large and small values of current.

Unit	Symbol	Equivalent Measure
kiloampere	kA	1 kA = 1000 A
milliampere	mA	1 mA = 0.001 A
microampere	µA	1 µA = 0.000001 A

Direction of Current Flow

Some sources distinguish between electron flow and current flow. The conventional current flow approach ignores the flow of electrons and states that current flows from positive to negative. To avoid confusion, this book uses the **electron flow** concept which states that electrons flow from negative to positive.

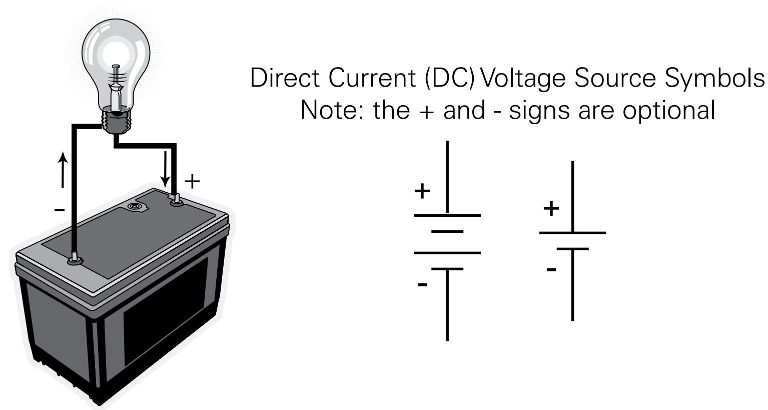


Voltage

The force required to make electricity flow through a conductor is called a **difference in potential**, **electromotive force (emf)**, or **voltage**. Voltage is designated by the letter **E** or the letter V. The unit of measurement for voltage is the **volt** which is also designated by the letter **V**.

A voltage can be generated in various ways. A battery uses an electrochemical process. A car's alternator and a power plant generator utilize a magnetic induction process. All voltage sources share the characteristic of an excess of electrons at one terminal and a shortage at the other terminal. This results in a difference of potential between the two terminals.

For a **direct current (DC)** voltage source, the polarity of the terminals does not change, so the resulting current constantly flows in the same direction.



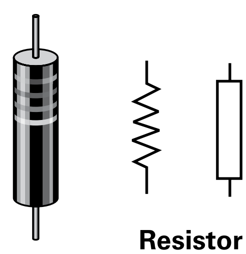
The following chart shows how selected metric unit prefixes are used to represent large and small values of voltage.

Unit	Symbol	Equivalent Measure
kilovolt	kV	1 kV = 1000 V
millivolt	mV	1 mV = 0.001 V
microvolt	µV	1 µV = 0.000001 V

Resistance

A third factor that plays a role in an electrical circuit is **resistance**. All material impedes the flow of electrical current to some extent. The amount of resistance depends upon the composition, length, cross-section and temperature of the resistive material. As a rule of thumb, the resistance of a conductor increases with an increase of length or a decrease of cross-section. Resistance is designated by the symbol **R**. The unit of measurement for resistance is the **ohm** (Ω).

Resistors are devices manufactured to have a specific resistance and are used in a circuit to limit current flow and to reduce the voltage applied to other components. A resistor is usually shown symbolically on an electrical drawing in one of two ways, a zigzag line or an unfilled rectangle.



Resistor **Resistor Symbols**

In addition to resistors, all other circuit components and the conductors that connect components to form a circuit also have resistance.

The basic unit for resistance is 1 ohm; however, resistance is often expressed in multiples of the larger units shown in the following table.

Unit	Symbol	Equivalent Measure
megohm	MΩ	1 MΩ = 1,000,000 Ω
kilohm	kΩ	1 kΩ = 1000 Ω

Review 2

1. A material that has an excess of electrons has a ________ charge.

2. A material that has a deficiency of electrons has a ________ charge.

3. Like charges ________ and unlike charges ________.

4. ________ is the force that, when applied to a conductor, causes current flow.

5. Electrons move from ________ to ________.

6. Identify the basic unit of measure for each of the items shown below.

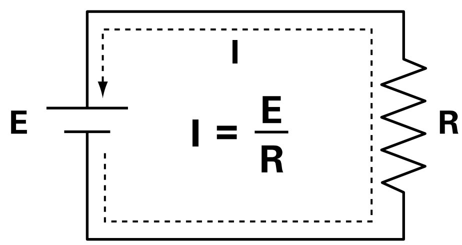
   a. Resistance ________
   b. Current ________
   c. Voltage ________

Ohm's Law

Electric Circuit

A simple **electric circui**t consists of a voltage source, some type of load, and conductors to allow electrons to flow between the voltage source and the load.

Ohm's law shows that current varies directly with voltage and inversely with resistance.



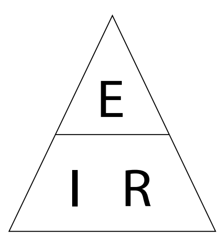
Current (I) is measured in amperes (amps)
Voltage (E) is measured in volts
Resistance (R) is measured in ohms

There are three ways to express Ohm's law.

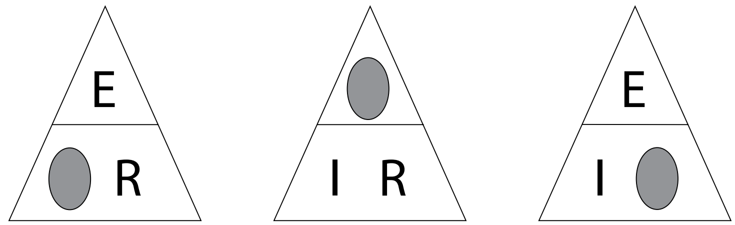
$I = \frac{E}{R} \quad E = I \times R \quad R = \frac{E}{I}$

Ohm's Law Triangle

There is an easy way to remember which formula to use. By arranging current, voltage and resistance in a triangle, you can quickly determine the correct formula.



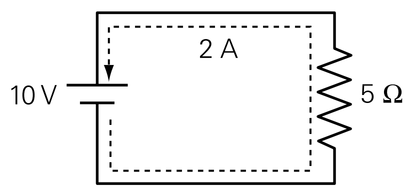
To use the triangle, cover the value you want to calculate. The remaining letters make up the formula.



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

Ohm's Law Example

As the following simple example shows, if any two values are known, you can determine the other value using Ohm's law.



$$I = \frac{E}{R} = \frac{10\ V}{5\ \Omega} = 2\ A$$

$$R = \frac{E}{I} = \frac{10\ V}{2\ A} = 5\ \Omega$$

$$E = I \times R = 2\ A \times 5\ \Omega = 10\ V$$

Using a similar circuit, but with a current of 200 mA and a resistance of 10 Ω. To solve for voltage, cover the E in the triangle and use the resulting equation.

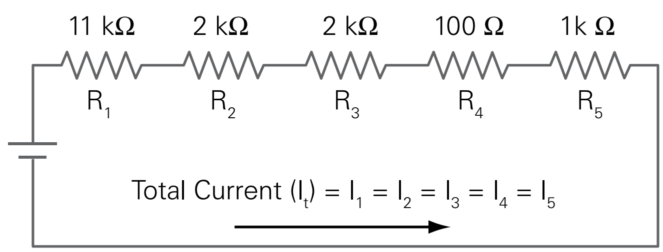
$$E = I \times R \longrightarrow E = 0.2\ A \times 10\ \Omega = 2\ V$$

Remember to use the correct decimal equivalent when dealing with numbers that are preceded with milli (m), micro (μ), kilo (k) or mega (M). In this example, current was converted to 0.2 A, because 200 mA is 200 x 10^{-3} A, which is equal to 0.2 A.

DC Circuits

Series Circuits

A **series circuit** is formed when any number of devices are connected end-to-end so that there is only one path for current to flow. The following illustration shows five resistors connected in series. There is one path for current flow from the negative terminal of the voltage source through all five resistors and returning to the positive terminal.



$$\text{Total Resistance} = R_t = R_1 + R_2 + R_3 + R_4 + R_5$$

$$R_t = 11{,}000\ \Omega + 2000\ \Omega + 2000\ \Omega + 100\ \Omega + 1000\ \Omega$$

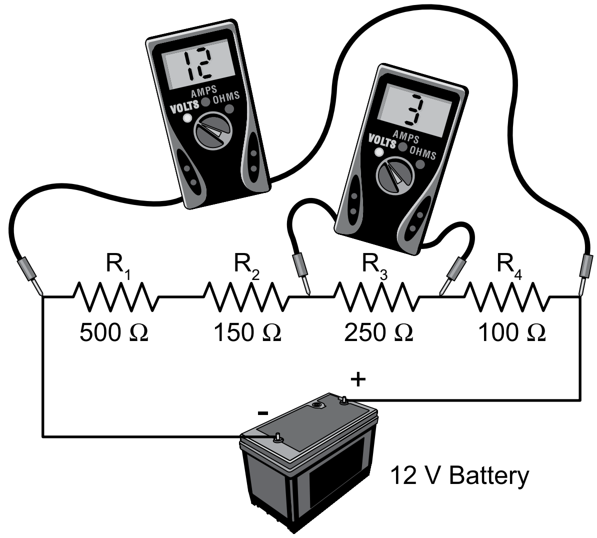
$$R_t = 16{,}100\ \Omega = 16.1\mathbf{k}\ \Omega$$

The total resistance (R_t) in a series circuit can be determined by adding all the resistor values. Although the unit for resistance is the ohm, different metric unit prefixes, such as kilo (k) or mega (M) are often used. Therefore, it is important to convert all resistance values to the same units before adding.

Current in a series circuit can be determined using Ohm's law. First, total the resistance and then divide the source voltage by the total resistance. This current flows through each resistor in the circuit.

The voltage measured across each resistor can also be calculated using Ohm's law. The voltage across a resistor is often referred to as a voltage drop. The sum of the voltage drops across each resistor is equal to the source voltage.

The following illustration shows two voltmeters, one measuring total voltage and one measuring the voltage across R3.



$$R_t = 500\ \Omega + 150\ \Omega + 250\ \Omega + 100\ \Omega = 1000\ \Omega = 1\text{k}\ \Omega$$

$$I = \frac{12\ V}{1000\ \Omega} = 0.012\ A = 12\ mA$$

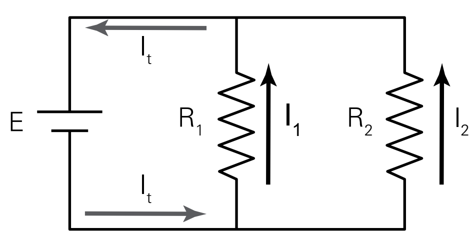
$$E_3 \text{ (The voltage accross } R_3\text{)} = I \times R_3 = 0.012\ A \times 250\ \Omega = 3\ V$$

$$E_t = E_1 + E_2 + E_3 + E_4 = 6\ V + 1.8\ V + 3\ V + 1.2\ V = 12\ V$$

Parallel Circuits

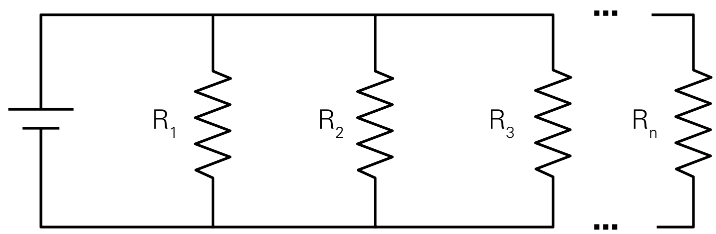
A **parallel circuit** is formed when two or more devices are placed in a circuit side-by-side so that current can flow through more than one path.

The following illustration shows the simplest parallel circuit, two parallel resistors. There are two paths of current flow. One path is from the negative terminal of the battery through R_1 returning to the positive terminal. The second path is from the negative terminal of the battery through R_2 returning to the positive terminal of the battery. The current through either resistor can be determined by dividing the circuit voltage by the resistance of that resistor.



$$I_1 = \frac{E}{R_1} \qquad I_2 = \frac{E}{R_2} \qquad I_t = I_1 + I_2$$

The total resistance for a parallel circuit with any number of resistors can be calculated using the formula shown in the following illustration.

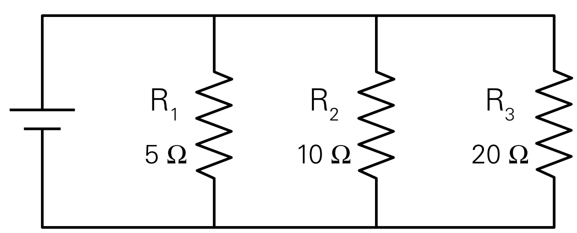


$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \cdots + \frac{1}{R_n}$$

$$R_t = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \cdots + \frac{1}{R_n}}$$

In the unique example where all resistors have the same resistance, the total resistance is equal to the resistance of one resistor divided by the number of resistors.

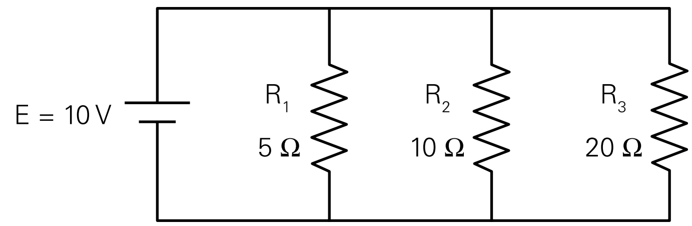
The following example shows a total resistance calculation for a circuit with three parallel resistors.



$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{5\,\Omega} + \frac{1}{10\,\Omega} + \frac{1}{20\,\Omega} = \frac{4}{20\,\Omega} + \frac{2}{20\,\Omega} + \frac{1}{20\,\Omega} = \frac{7}{20\,\Omega}$$

$$R_t = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \frac{1}{\frac{7}{20\,\Omega}} = \frac{20\,\Omega}{7} = 2.86\,\Omega$$

Current in each of the branches of a parallel circuit can be calculated by dividing the circuit voltage, which is the same for all branches, by the resistance of the branch. The total circuit current can be calculated by adding the current for all branches or by dividing the circuit voltage by the total resistance.

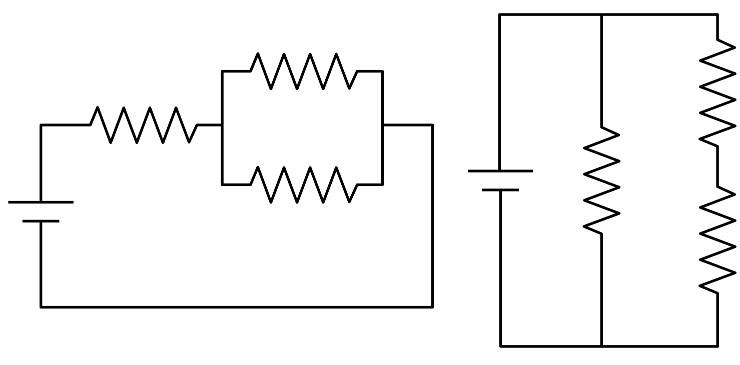


$$I_t = I_1 + I_2 + I_3 = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3} = \frac{10\text{ V}}{5\ \Omega} + \frac{10\text{ V}}{10\ \Omega} + \frac{10\text{ V}}{20\ \Omega} = 2\text{ A} + 1\text{ A} + 0.5\text{ A} = 3.5\text{ A}$$

$$I_t = \frac{E}{R_t} = \frac{10\text{ V}}{2.86\ \Omega} = 3.5\text{ A}$$

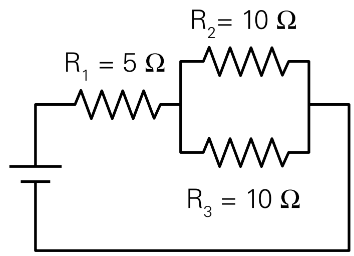
Series-Parallel Circuits

Series-parallel circuits are also known as compound circuits. At least three components are required to form a series-parallel circuit. The following illustration shows the two simplest series-parallel circuits. The circuit on the left has two parallel resistors in series with another resistor. The circuit on the right has two series resistors in parallel with another resistor.



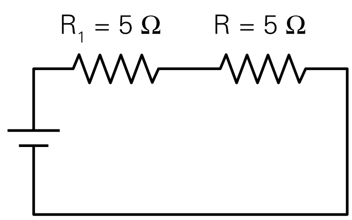
Series-parallel circuits are usually more complex than the circuits shown here, but by using the circuit formulas discussed earlier in this course, you can easily determine circuit characteristics.

The following illustration shows how total resistance can be determined for two series-parallel circuits in two easy steps for each circuit. More complex circuits require more steps, but each step is relatively simple. In addition, if the source voltage is known, by using Ohm's law you can also solve for current and voltage throughout each circuit, .



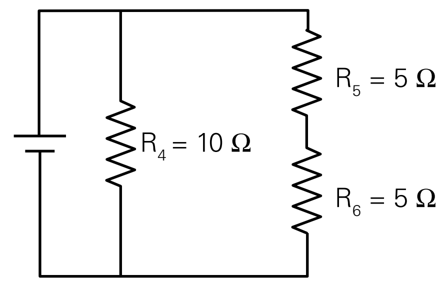
1. Combine the parallel resistors

$$R = \frac{1}{\frac{1}{10\ \Omega} + \frac{1}{10\ \Omega}} = \frac{10\ \Omega}{2} = 5\ \Omega$$



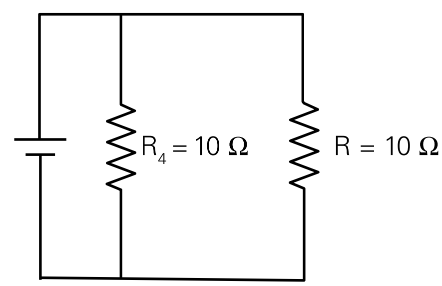
2. Add the series resistors

$R_t = 5\ \Omega + 5\ \Omega = 10\ \Omega$



1. Add the series resistors

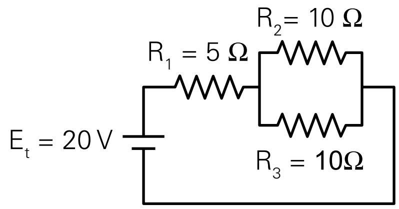
$R = R_5 + R_6 = 5\ \Omega + 5\ \Omega = 10\ \Omega$

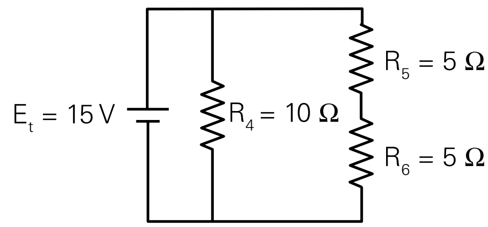


2. Combine the parallel resistors

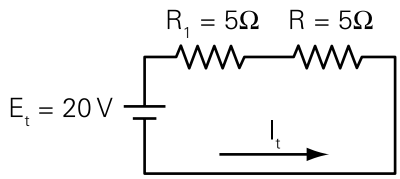
$$R_t = \frac{1}{\frac{1}{10\ \Omega} + \frac{1}{10\ \Omega}} = \frac{10\ \Omega}{2} = 5\ \Omega$$

Using the same two series-parallel circuits as in the previous example, but with source voltages included, the following illustration shows how Ohm's law can be used to calculate other circuit values.

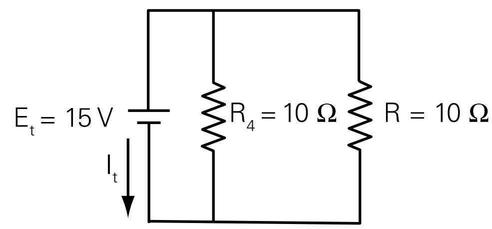




Equivalent Circuit



Equivalent Circuit



$$R_t = 10\ \Omega \quad I_t = \frac{20\ V}{10\ \Omega} = 2\ A$$

$$E_1 = I_t \times R_1 = 2\ A \times 5\ \Omega = 10\ V$$

$$E_R = E_2 = E_3 = E_t - E_1 = 20\ V - 10\ V = 10\ V$$

$$I_t = I_2 + I_3 = \frac{E_R}{R_2} + \frac{E_R}{R_3} = \frac{10\ V}{10\ \Omega} + \frac{10\ V}{10\ \Omega} = 2\ A$$

$$R_t = 5\ \Omega \quad I_t = \frac{15\ V}{5\ \Omega} = 3\ A$$

$$E_t = E_4 = E_R = 15\ V$$

$$I_t = I_4 + I_R = \frac{E_t}{R_4} + \frac{E_t}{R} = \frac{15\ V}{10\ \Omega} + \frac{15\ V}{10\ \Omega} = 3\ A$$

Power in a DC Circuit

Whenever a force of any kind causes motion, work is accomplished. If a force is exerted without causing motion, then no work is done.

In an electrical circuit, voltage applied to a conductor causes electrons to flow. Voltage is the force and electron flow is the motion. **Power** is the rate at which work is done and is represented by the symbol **P**. The unit of measure for power is the **watt**, represented by the symbol **W**. In a direct current circuit, one watt is the rate at which work is done when 1 volt causes a current of 1 amp. You will learn later that there are other types of power that apply to alternating current circuits.

From the basic formula power = current times voltage, other formulas for power can be derived using Ohm's law.

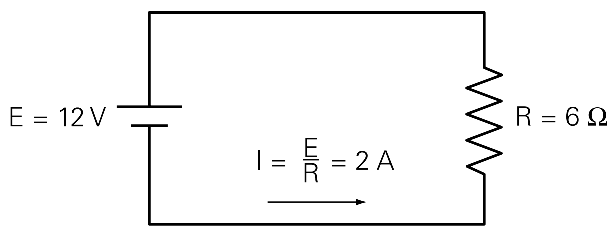
<u>Direct Current Power Formulas</u> <u>Ohm's Law</u>

$$P = I \times E = IE$$

$$P = IE = I(IR) = I^2R \qquad E = I \times R = IR$$

$$P = IE = \left(\frac{E}{R}\right)E = \frac{E^2}{R} \qquad I = \frac{E}{R}$$

The following example shows how power can be calculated using any of the power formulas.



$$P = IE = (2\text{ A})(12\text{ V}) = 24\text{ W}$$

$$P = I^2R = (2\text{ A})^2(6\ \Omega) = 24\text{ W}$$

$$P = \frac{E^2}{R} = \frac{(12\text{ V})^2}{6\ \Omega} = 24\text{ W}$$

Review 3

1. The total current in a circuit that has a voltage of 12 V and a resistance of 24 Ω is ________ A.

2. The total resistance of a series circuit with resistors of the following values: R_1 = 10 Ω, R_2 = 15 Ω, and R_3 = 20 Ω is _______ Ω.

3. The voltage for a series circuit that has a current of 0.5 A and a resistance of 60 Ω is ________ V.

4. The total resistance of a parallel circuit that has four 20 Ω resistors is ________ Ω.

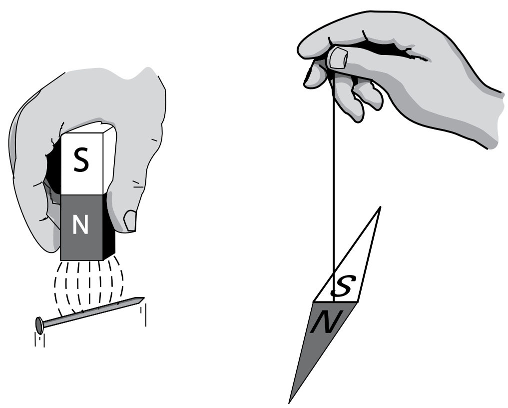
5. In a parallel circuit with two resistors of equal value and a total current flow of 12 A, the current through each resistor is ________ A.

6. For a DC circuit with a voltage of 24 V and a current of 5 A, the power is ________ W.

Magnetism

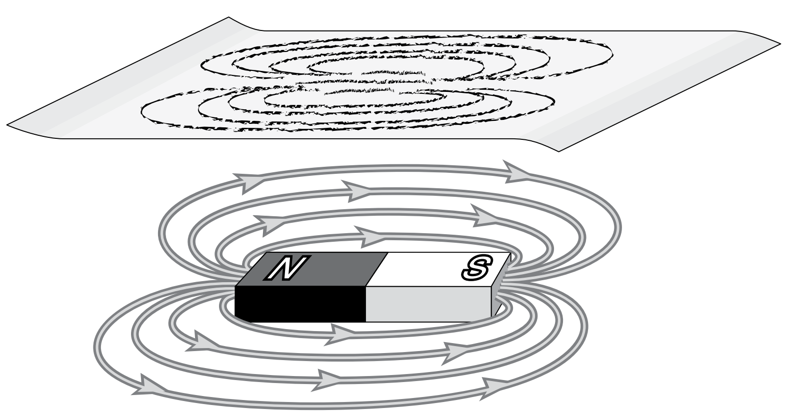
The principles of **magnetism** are an integral part of electricity. In fact, magnetism can be used to produce electric current and vice versa.

When we think of a permanent magnet, we often envision a horse-shoe or bar magnet or a compass needle, but permanent magnets come in many shapes. However, all magnets have two characteristics. They attract iron and, if free to move (like the compass needle), a magnet assumes a north-south orientation.



Magnetic Lines of Flux

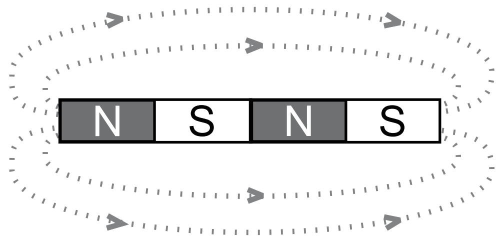
Every magnet has two **poles**, one north pole and one south pole. Invisible **magnetic lines of flux** leave the north pole and enter the south pole. While the lines of flux are invisible, the effects of magnetic fields can be made visible. When a sheet of paper is placed on a magnet and iron filings loosely scattered over it, the filings arrange themselves along the invisible lines of flux.



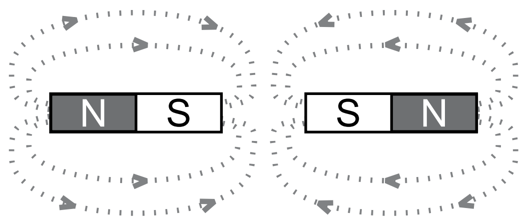
The density of these lines of flux is greatest inside the magnet and where the lines of flux enter and leave the magnet. The greater the density of the lines of flux, the stronger the magnetic field.

Interaction Between Magnets

When two magnets are brought together, the magnetic flux around the magnets causes some form of interaction. When two unlike poles are brought together the magnets attract each other. When two like poles brought together the magnets repel each other.



Unlike Poles Attract

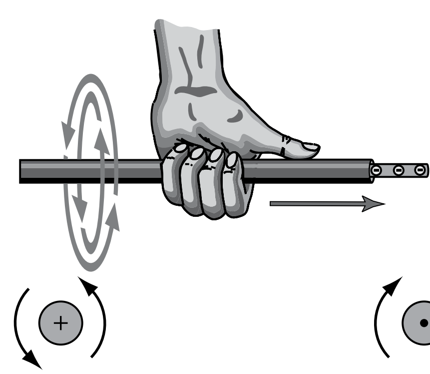


Like Poles Repel

Electromagnetism

An electromagnetic field is a magnetic field generated by current flow in a conductor. Every electric current generates a magnetic field and a relationship exists between the direction of current flow and the direction of the magnetic field.

The **left-hand rule for conductors** demonstrates this relationship. If a current-carrying conductor is grasped with the left hand with the thumb pointing in the direction of electron flow, the fingers point in the direction of the magnetic lines of flux.



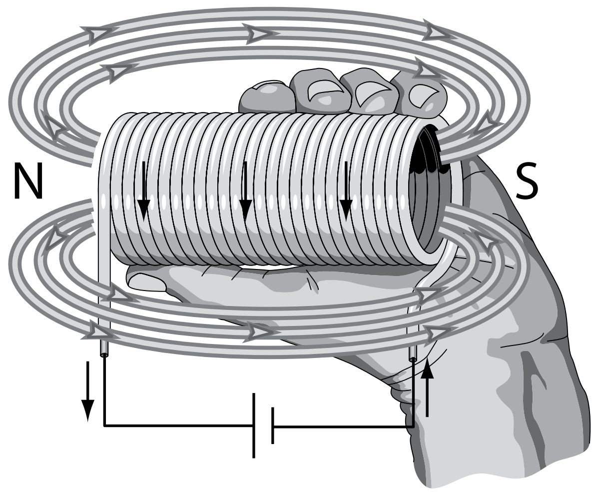
Electron Flow Away From You
Causes Counterclockwise Magnetic Flux

Electron Flow Towards You
Causes Clockwise Magnetic Flux

Current-Carrying Coil

A coil of wire carrying a current, acts like a magnet. Individual loops of wire act as small magnets. The individual fields add together to form one magnet. The strength of the field can be increased by adding more turns to the coil, increasing the amount of current, or winding the coil around a material such as iron that conducts magnetic flux more easily than air.

The **left-hand rule for coils** states that, if the fingers of the left hand are wrapped around the coil in the direction of electron flow, the thumb points to the north pole of the electromagnet.



An electromagnet is usually wound around a core of soft iron or some other material that easily conducts magnetic lines of force.

A large variety of electrical devices such as motors, circuit breakers, contactors, relays and motor starters use electromagnetic principles.

Review 4

1. The two characteristics of all magnets are: they attract and hold ________, and, if free to move, they assume roughly a ________ position.

2. Lines of flux always leave the ________ pole and enter the _________ pole.

3. The left-hand rule for conductors states that, when the left hand is placed around a current-carrying conductor with the thumb pointing in the direction of ________ flow, the fingers point in the direction of ________.

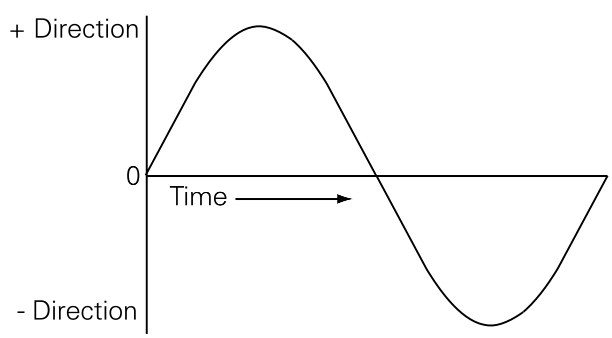
Alternating Current

The supply of current for electrical devices may come from a direct current (DC) source or an **alternating current (AC)** source. In a direct current circuit, electrons flow continuously in one direction from the source of power through a conductor to a load and back to the source of power. Voltage polarity for a direct current source remains constant. DC power sources include batteries and DC generators.

By contrast, an AC generator makes electrons flow first in one direction then in another. In fact, an AC generator reverses its terminal polarities many times a second, causing current to change direction with each reversal.

AC Sine Wave

Alternating voltage and current vary continuously. The graphic representation for AC is a sine wave. A sine wave can represent current or voltage. There are two axes. The vertical axis represents the direction and magnitude of current or voltage. The horizontal axis represents time.

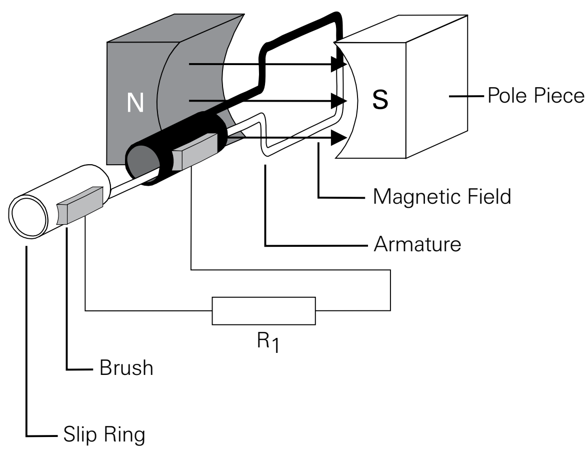


When the waveform is above the time axis, current is flowing in one direction. This is referred to as the positive direction. When the waveform is below the time axis, current is flowing in the opposite direction. This is referred to as the negative direction. A sine wave moves through a complete rotation of 360 degrees, which is referred to as one cycle. Alternating current goes through many of these cycles each second.

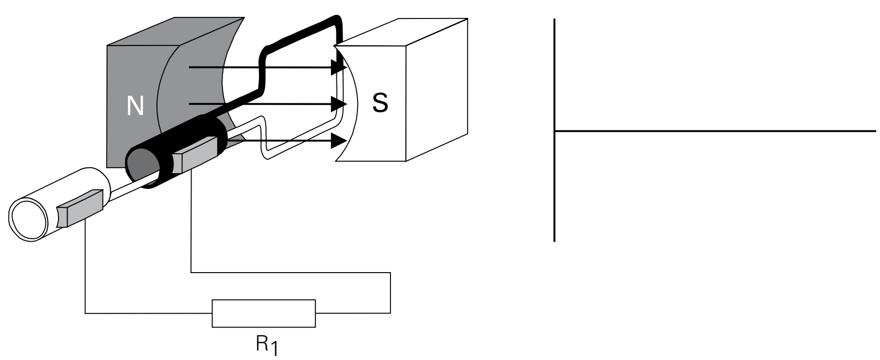
Basic AC Generator

A basic **generator** consists of a magnetic field, an armature, slip rings, brushes and a resistive load. In a commercial generator, the magnetic field is created by an electromagnet, but, for this simple generator, permanent magnets are used.

An **armature** is any number of conductive wires wound in loops which rotates through the magnetic field. For simplicity, one loop is shown. When a conductor is moved through a magnetic field, a voltage is induced in the conductor. As the armature rotates through the magnetic field, a voltage is generated in the armature which causes current to flow. Slip rings are attached to the armature and rotate with it. Carbon brushes ride against the slip rings to conduct current from the armature to a resistive load.

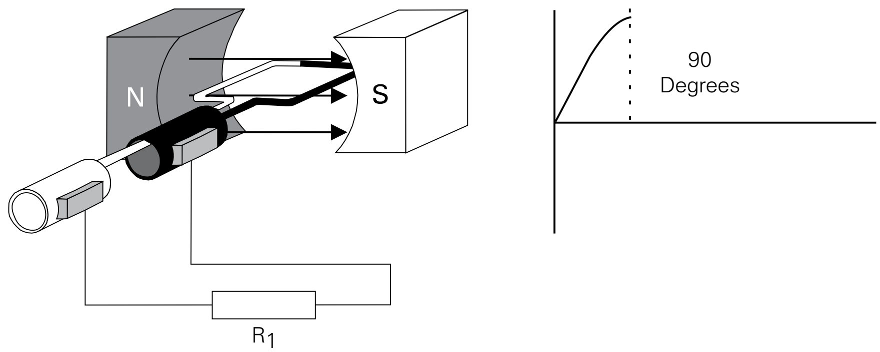


An armature rotates through the magnetic field. At an initial position of zero degrees, the armature conductors are moving parallel to the magnetic field and not cutting through any magnetic lines of flux. No voltage is induced.



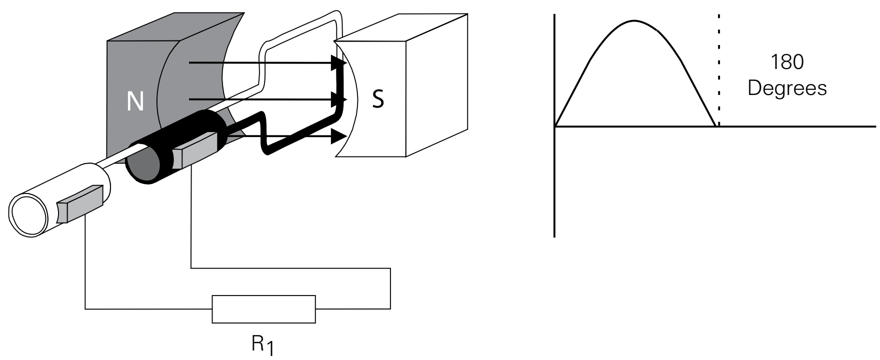
Generator Operation from Zero to 90 Degrees

As the armature rotates from zero to 90 degrees, the conductors cut through more and more lines of flux, building up to a maximum induced voltage in the positive direction.



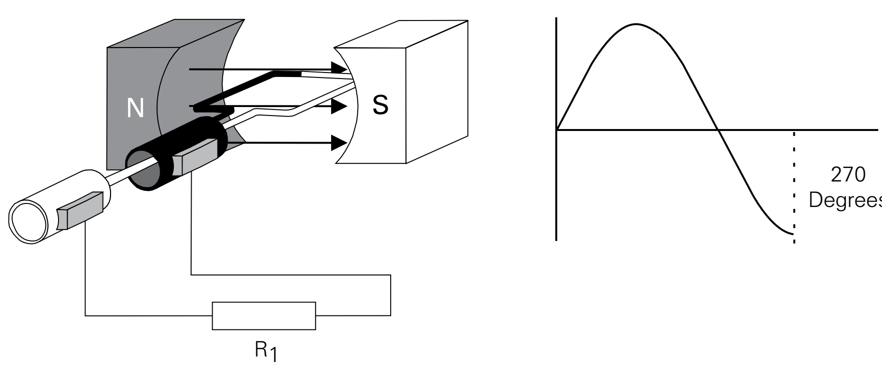
Generator Operation from 90 to 180 Degrees

The armature continues to rotate from 90 to 180 degrees, cutting fewer lines of flux. The induced voltage decreases from a maximum positive value to zero.



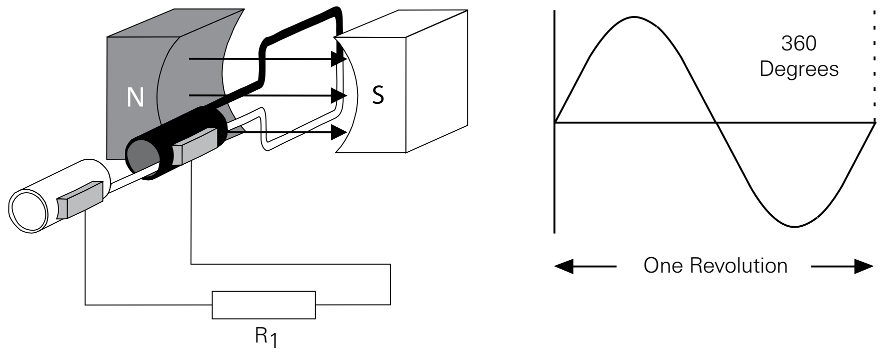
Generator Operation from 180 to 270 Degrees

As the armature continues to rotate from 180 degrees to 270 degrees, the conductors cut more lines of flux, but in the opposite direction, and voltage is induced in the negative direction, building up to a maximum at 270 degrees.



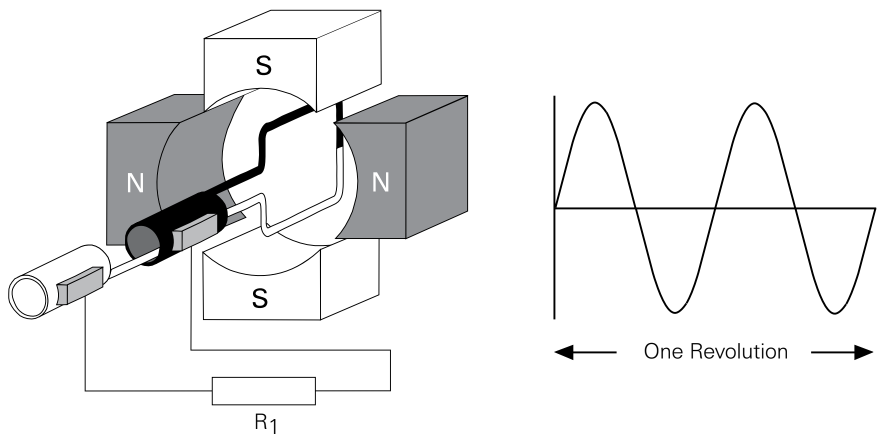
Generator Operation from 270 to 360 Degrees

As the armature continues to rotate from 270 to 360 degrees, induced voltage decreases from a maximum negative value to zero. This completes one cycle. The armature continues to rotate at a constant speed causing the cycle to repeat as long as the armature rotates.



Four-Pole AC Generator

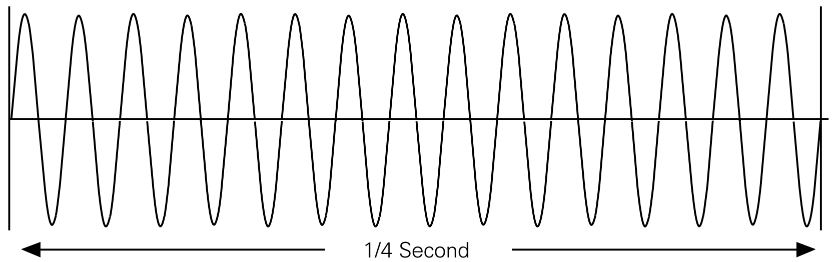
An AC generator produces one cycle per revolution for each pair of poles. An increase in the number of poles, causes an increase in the number of cycles completed in a revolution. A two-pole generator completes one cycle per revolution and a four-pole generator completes two cycles per revolution.



Frequency

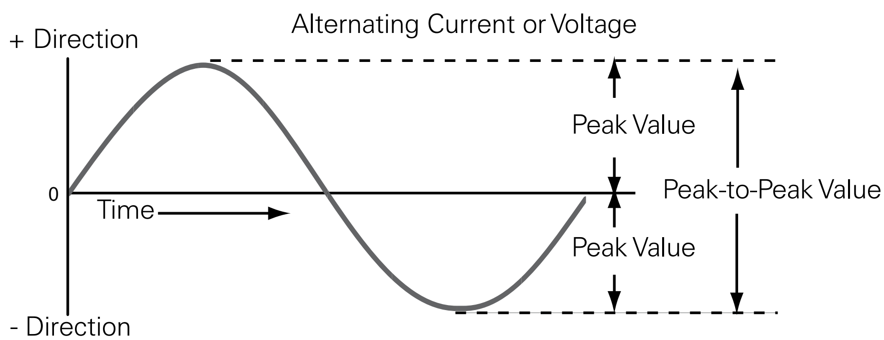
The number of cycles per second of voltage induced in the armature is the **frequency** of the generator. If a two-pole generator armature rotates at a speed of 60 revolutions per second, the generated voltage have a frequency of 60 cycles per second. The recognized unit for frequency is **hertz**, abbreviated **Hz**. 1 Hz is equal to 1 cycle per second.

Power companies generate and distribute electricity at very low frequencies. The standard power line frequency in the United States and many other countries is 60 Hz. 50 Hz is also a common power line frequency used throughout the world. The following illustration shows 15 cycles in 1/4 second which is equivalent to 60 Hz.



Amplitude

As previously discussed, voltage and current in an AC circuit rise and fall over time in a pattern referred to as a sine wave. In addition to frequency, which is the rate of variation, an AC sine wave also has **amplitude**, which is the range of variation. Amplitude can be specified in three ways: peak value, peak-to-peak value, and effective value.



Effective value (also called RMS value) = Peak Value x 0.707

The **peak value** of a sine wave is the maximum value for each half of the sine wave. The **peak-to-peak value** is the range from the positive peak to the negative peak. This is twice the peak value. The **effective value** of AC is defined in terms of an equivalent heating effect when compared to DC. Instruments designed to measure AC voltage and current usually display the effective value. The effective value of an AC voltage or current is approximately equal to 0.707 times the peak value.

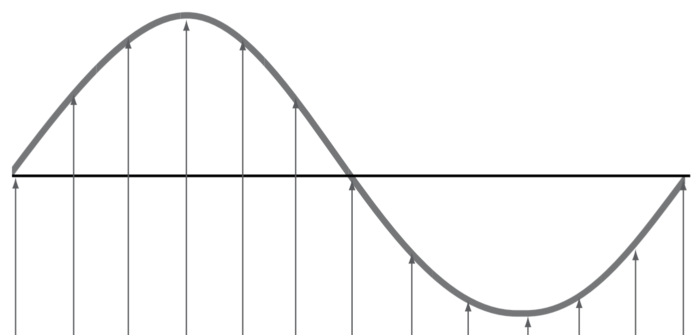
The effective value is also referred to as the **RMS value**. This name is derived from the root-mean-square mathematical process used to calculate the effective value of a waveform.

Instantaneous Value

The **instantaneous value** is the value at any one point on the sine wave. The voltage waveform produced as the armature of a basic two-pole AC generator rotates through 360 degrees is called a sine wave because the instantaneous voltage or current is related to the sine trigonometric function.

As shown in the following illustration, the i**nstantaneous voltage (e)** and **current (i)** at any point on the sine wave are equal to the peak value times the sine of the angle. The sine values shown in the illustration are obtained from trigonometric tables. Keep in mind that each point has an instantaneous value, but this illustration only shows the sine of the angle at 30 degree intervals. The sine of an angle is represented symbolically as sin θ, where the Greek letter theta (θ) represents the angle.

Instantaneous Value of Alternating Current or Voltage



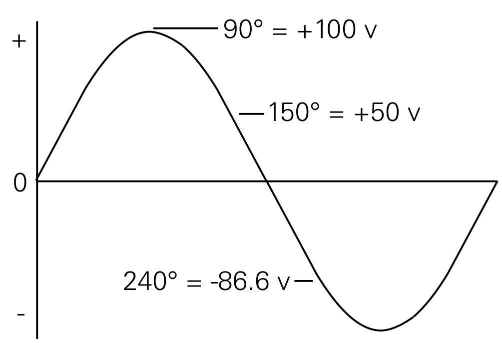
Angle	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	360°
Sin θ	0.000	0.500	0.866	1.000	0.866	0.500	0.000	-0.500	-0.866	-1.000	-0.866	-0.500	0.000

Instaneous current (i) = I_{peak} x sin θ

Instantaneous voltage (e) = E_{peak} x sin θ

Example: if E_{peak} = 170 v, at 150 degrees e = (170)(0.5) = 85 v

The following example illustrates instantaneous values at 90, 150, and 240 degrees for a peak voltage of 100 volts. By substituting the sine at the instantaneous angle value, the instantaneous voltage can be calculated.



Review 5

1. A __________ is the graphic representation of AC voltage or current values over time.

2. An AC generator produces ____________ cycle(s) per revolution for each pair of poles.

3. The instantaneous voltage at 240 degrees for a sine wave with a peak voltage of 150 V is ________ V.

4. The effective voltage for a sine wave with a peak voltage of 150 V is ________ V.

Inductance and Capacitance

Inductance

The circuits studied to this point have been resistive. Resistance and voltage are not the only circuit properties that effect current flow, however. **Inductance** is the property of an electric circuit that opposes any change in electric current. Resistance opposes current flow, inductance opposes changes in current flow. Inductance is designated by the letter **L**. The unit of measurement for inductance is the **henry (h)**; however, because the henry is a relatively large unit, inductance is often rated in millihenries or microhenries.

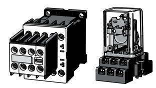
Unit	Symbol	Equivalent Measure
millihenry	mh	1 mh = 0.001 h
microhenry	µh	1 µh = 0.000001 h

Current flow produces a magnetic field in a conductor. The amount of current determines the strength of the magnetic field. As current flow increases, field strength increases, and as current flow decreases, field strength decreases.

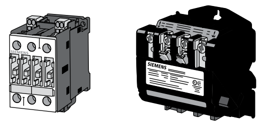
Any change in current causes a corresponding change in the magnetic field surrounding the conductor. Current is constant for a regulated DC source, except when the circuit is turned on and off, or when there is a load change. However, alternating current is constantly changing, and inductance is continually opposing the change. A change in the magnetic field surrounding the conductor induces a voltage in the conductor. This self-induced voltage opposes the change in current. This is known as **counter emf**.

All conductors and many electrical devices have a significant amount of inductance, but **inductors** are coils of wire wound for a specific inductance. For some applications, inductors are wound around a metal core to further concentrate the inductance. The inductance of a coil is determined by the number of turns in the coil, the coil diameter and length, and the core material. As shown in the following illustration, an inductor is usually indicated symbolically on an electrical drawing as a curled line.

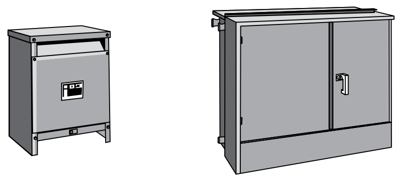
All electrical products have inductance, but the products shown below are examples of products that are primariliy inductive.



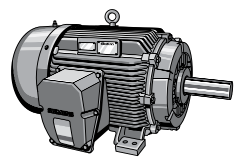
Control Relays



Contactors

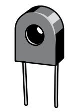


Transformers



Electric Motor

Inductors are components manufactured to have a specific inductance.



Inductor

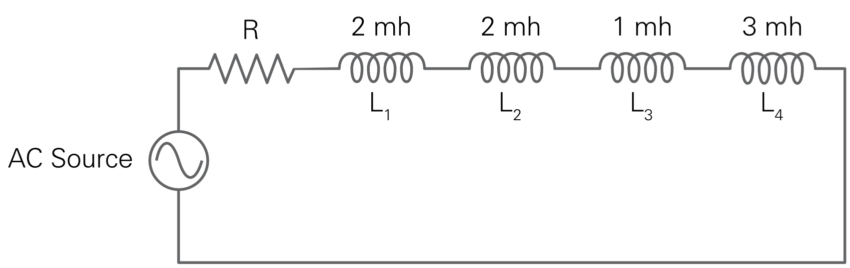
Schematic Symbols

Inductor Iron Core Inductor

$$L = (\text{Permeability of Core}) \times \frac{(\text{Number of Turns})^2 \times (\text{Cross Sectional Area})}{\text{Length}}$$

Inductors in Series

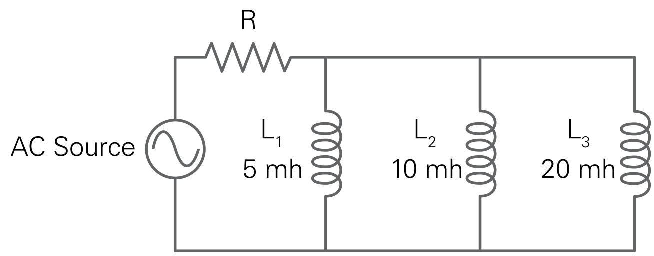
In the following circuit, an AC source supplies electrical power to four inductors. Total inductance of series inductors is equal to the sum of the inductances.



$$L_t = L_1 + L_2 + L_3 + L_4 = 2\text{ mh} + 2\text{ mh} + 1\text{ mh} + 3\text{ mh} = 8\text{ mh}$$

Inductors in Parallel

The total inductance of inductors in parallel is calculated using a formula similar to the formula for resistance of parallel resistors. The following illustration shows the calculation for a circuit with three parallel inductors.

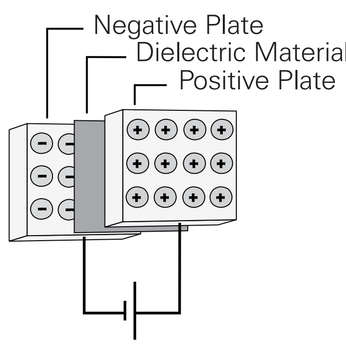


$$\frac{1}{L_t}=\frac{1}{L_1}+\frac{1}{L_2}+\frac{1}{L_3}=\frac{1}{5\text{ mh}}+\frac{1}{10\text{ mh}}+\frac{1}{20\text{ mh}}=\frac{4}{20\text{ mh}}+\frac{2}{20\text{ mh}}+\frac{1}{20\text{ mh}}=\frac{7}{20\text{ mh}}$$

$$L_t=\frac{1}{\frac{1}{L_1}+\frac{1}{L_2}+\frac{1}{L_3}}=\frac{1}{\frac{7}{20\text{ mh}}}=\frac{20\text{ mh}}{7}=2.86\text{ mh}$$

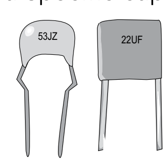
Capacitance and Capacitors

Capacitance is a measure of a circuit's ability to store an electrical charge. A device manufactured to have a specific amount of capacitance is called a capacitor. A capacitor is made up of a pair of conductive plates separated by a thin layer of insulating material. Another name for the insulating material is dielectric material. A capacitor is usually indicated symbolically on an electrical drawing by a combination of a straight line with a curved line or two straight lines.

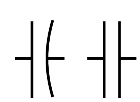


Direct current cannot flow through a capacitor unless it is defective

Capacitors are components manufactured to have a specific capacitance.



Schematic Symbols



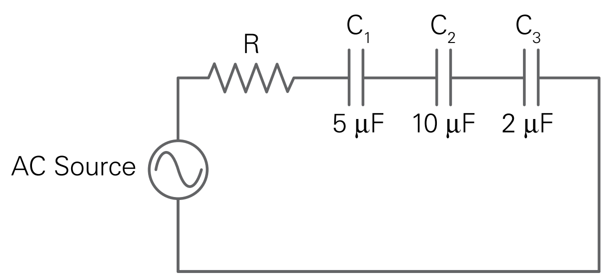
When a voltage is applied to the plates of a capacitor, electrons are forced onto one plate and pulled from the other. This charges the capacitor. Direct current cannot flow through the dielectric material because it is an insulator; however, the electric field created when the capacitor is charged is felt through the dielectric. Capacitors are rated for the amount of charge they can hold.

The capacitance of a capacitor depends on the area of the plates, the distance between the plates, and type of dielectric material used. The symbol for capacitance is **C** and the unit of measurement is the **farad (F)**. However, because the farad is a large unit, capacitors are often rated in microfarads (μF) or picofarads (pF).

Unit	Symbol	Equivalent Measure
microfarad	μF	1 μF = 0.000001 F
picofarad	pF	1 pF = 0.000000000001 F

Capacitors in Series

Connecting capacitors in series decreases total capacitance. The formula for series capacitors is similar to the formula for parallel resistors. In the following example, an AC source supplies electrical power to three capacitors.

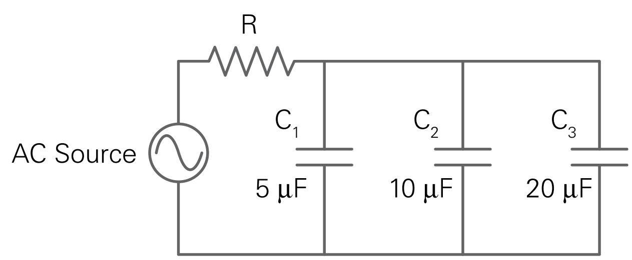


$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_3} + \frac{1}{C_2} = \frac{1}{5\,\mu F} + \frac{1}{10\,\mu F} + \frac{1}{2\,\mu F} = \frac{2}{10\,\mu F} + \frac{1}{10\,\mu F} + \frac{5}{10\,\mu F} = \frac{8}{10\,\mu F}$$

$$C_t = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}} = \frac{1}{\frac{8}{10\,\mu F}} = \frac{10\,\mu F}{8} = 1.25\,\mu F$$

Capacitors in Parallel

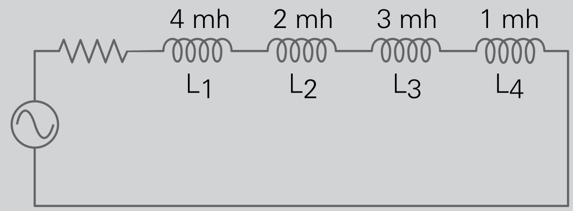
Adding capacitors in parallel increases circuit capacitance. In the following circuit, an AC source supplies electrical power to three capacitors. Total capacitance is determined by adding the values of the capacitors.



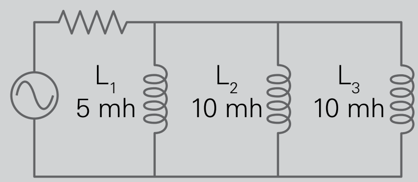
$$C_t = C_1 + C_2 + C_3 = 5\,\mu F + 10\,\mu F + 20\,\mu F = 35\,\mu F$$

Review 6

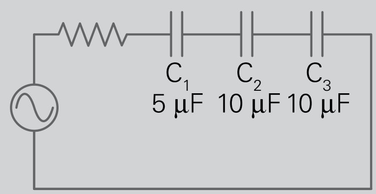
1. The total inductance for this circuit is ________ mh.



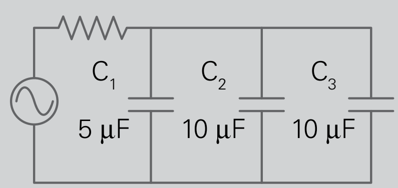
2. The total inductance for this circuit is ________ mh.



3. The total capacitance for this circuit is ________ μF.



4. The total capacitance for this circuit is ________ μF.



Reactance and Impedance

In a purely resistive AC circuit, resistance is the only opposition to current flow. In an AC circuit with only inductance, capacitance, or both inductance and capacitance, but no resistance, opposition to current flow is called **reactance**, designated by the symbol **X**. Total opposition to current flow in an AC circuit that contains both reactance and resistance is called **impedance**, designated by the symbol **Z**. Just like resistance, reactance and impedance are expressed in ohms.

Inductive Reactance

Inductance only affects current flow when the current is changing. Inductance produces a self-induced voltage (counter emf) that opposes changes in current. In an AC circuit, current is changing constantly. Therefore inductance causes a continual opposition to current flow that is called **inductive reactance** and is designated by the symbol $\mathbf{X_L}$.

Inductive reactance is proportional to both the inductance and the frequency applied. The formula for inductive reactance is shown below.

$X_L = 2\pi fL = 2 \times 3.14 \times \text{frequency} \times \text{inductance}$

For a 60 Hz circuit containing a 10 mh inductor, the inductive reactance is:

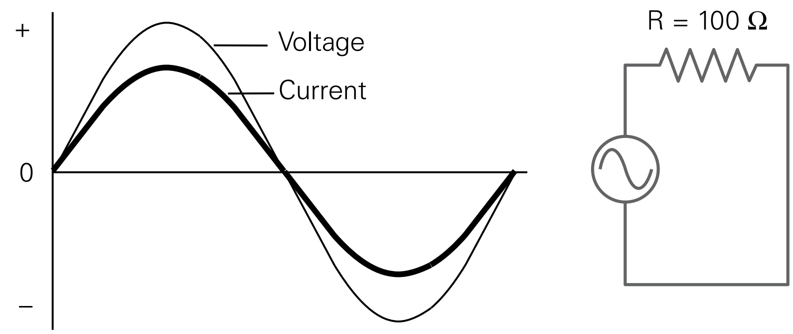
$X_L = 2\pi fL = 2 \times 3.14 \times 60\ \text{Hz} \times 0.010\ \text{h} = 3.768\ \Omega$

For this example, the resistance is zero, so the impedance is equal to the reactance. If the voltage is known, Ohm's law can be used to calculate the current. If, for example, the voltage is 10 V, the current is calculated as follows:

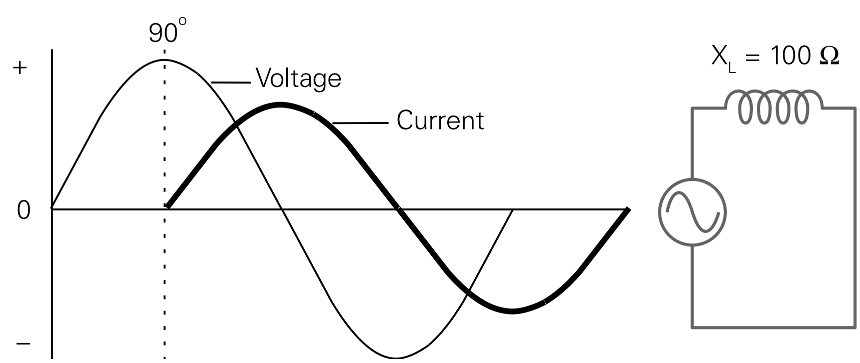
$$I = \frac{E}{Z} = \frac{10\ \text{V}}{3.768\ \Omega} = 2.65\text{A}$$

Current and Voltage Phases

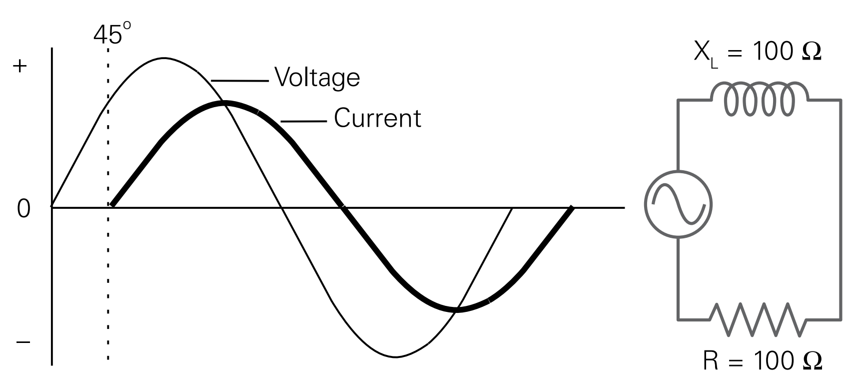
In a purely resistive AC circuit, current and voltage are said to be **in phase** current because they rise and fall at the same time as shown in the following example.



In a purely inductive AC circuit, current and voltage are said to be **out of phase** because voltage leads current by 90 degrees as shown in the following example. Another way of saying that voltage leads current by 90 degrees is to say that current lags voltage by 90 degrees.



In an AC circuit with both resistance and inductance, current lags voltage by more than 0 degrees and less than 90 degrees. The exact amount of lag depends on the relative amounts of resistance and inductive reactance. The more resistive a circuit is, the closer it is to being in phase. The more reactive a circuit is, the more current and voltage are out of phase. In the following example, resistance and inductive reactance are equal and current lags voltage by 45 degrees.



Calculating Impedance in an Inductive Circuit

When calculating impedance for a circuit with resistance and inductive reactance, the following formula is used.

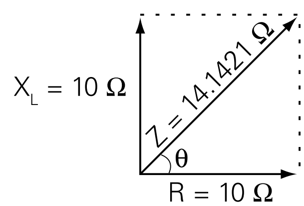
$$Z = \sqrt{R^2 + X_L^2}$$

Fore example, if resistance and inductive reactance are each 10 Ω, impedance is calculated as follows.

$$Z = \sqrt{10^2 + 10^2} = \sqrt{200} = 14.1421\ \Omega$$

Vectors

A common way to represent AC circuit values is with a vector diagram. A vector is a quantity that has magnitude and direction. For example, the following vector diagram illustrates the relationship between resistance and inductive reactance for a circuit containing 10 ohms of each. The angle between the vectors is the phase angle represented by the symbol θ. When inductive reactance is equal to resistance the resultant angle is 45 degrees. This angle represents how much current lags voltage for this circuit.



Capacitive Reactance

Circuits with capacitance also have reactance. **Capacitive reactance** is designated by the symbol $\mathbf{X_C}$. The larger the capacitor, the smaller the capacitive reactance. Current flow in a capacitive AC circuit is also dependent on frequency. The following formula is used to calculate capacitive reactance.

$$X_C = \frac{1}{2\pi fC}$$

The capacitive reactance for a 60 Hz circuit with a 10 μF capacitor is calculated as follows.

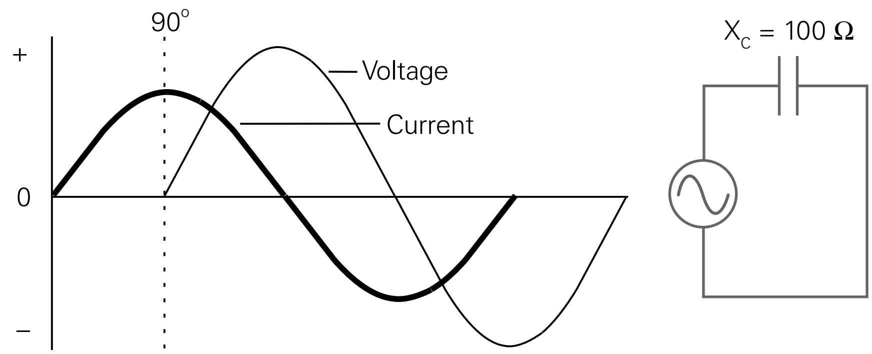
$$X_C = \frac{1}{2\pi fC} = \frac{1}{2 \times 3.14 \times 60\text{ Hz} \times 0.000010\text{ F}} = 265.39\ \Omega$$

For this example, the resistance is zero so the impedance is equal to the reactance. If the voltage is known, Ohm's law can be used to calculate the current. For example, if the voltage is 10 V, the current is calculated as follows.

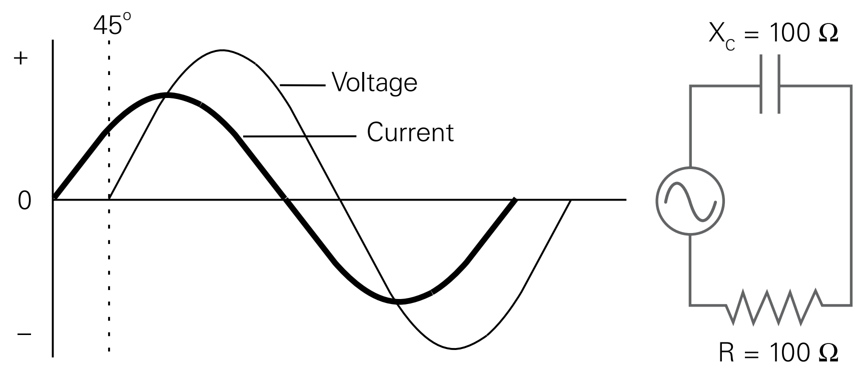
$$I = \frac{E}{Z} = \frac{10\text{ V}}{265.39\ \Omega} = 0.0376\text{ A}$$

Current and Voltage Phases

The phase relationship between current and voltage in a capacitive circuit is opposite to the phase relationship in an inductive circuit. In a purely capacitive circuit, current leads voltage by 90 degrees.



In a circuit with both resistance and capacitive reactance, AC current leads voltage by more than 0 degrees and less than 90 degrees. The exact amount of lead depends on the relative amounts of resistance and capacitive reactance. The more resistive a circuit is, the closer it is to being in phase. The more reactive a circuit is, the more out of phase it is. In the following example, resistance and capacitive reactance are equal and current leads voltage by 45 degrees.



Calculating Impedance in a Capacitive Circuit

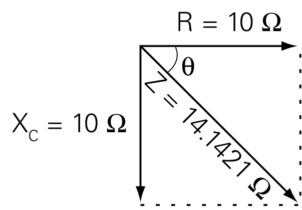
The following formula is used to calculate impedance in a circuit with resistance and capacitive reactance.

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

For example, if resistance and capacitive reactance are each 10 ohms, impedance is calculated as follows.

$$Z = \sqrt{10^2 + 10^2} = \sqrt{200} = 14.1421\ \Omega$$

The following vector illustrates the relationship between resistance and capacitive reactance for a circuit containing 10 ohms of each. The angle between the vectors is the phase angle represented by the symbol θ. When capacitive reactance is equal to resistance, the resultant angle is 45 degrees. This angle represents how much current leads voltage for this circuit.



Review 7

1. ________ is the opposition to current flow in an AC circuit caused by inductance and capacitance.

2. ________ is the total opposition to current flow in an AC circuit with resistance, capacitance, and/or inductance.

3. For a 50 Hz circuit with a 10 mh inductor, the inductive reactance is ________ Ω.

4. In a purely inductive circuit, ________.

   a. current and voltage are in phase
   b. current leads voltage by 90 degrees
   c. current lags voltage by 90 degrees

5. In a purely capacitive circuit, ________.

   a. current and voltage are in phase
   b. current leads voltage by 90 degrees
   c. current lags voltage by 90 degrees

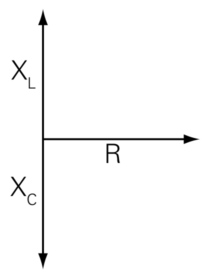
6. For a 50 Hz circuit with a 10 μF capacitor, the capacitive reactance is ________ Ω.

7. A circuit with 5 Ω of resistance and 10 Ω of inductive reactance has an impedance of ________ Ω.

8. A circuit with 5 Ω of resistance and 4 Ω of capacitive reactance has an impedance of ________ Ω.

Series and Parallel R-L-C Circuits

Circuits often contain resistance, inductance, and capacitance. In an inductive AC circuit, current lags voltage by 90 degrees. In a capacitive AC circuit, current leads voltage by 90 degrees. Therefore, when represented in vector form, inductive and capacitive reactance are 180 degrees apart. The net reactance is determined by taking the difference between the two quantities.



An AC circuit is:

- Resistive if X_L and X_C are equal
- Inductive if X_L is greater than X_C
- Capacitive if X_C is greater than X_L

The following formula is used to calculate total impedance for a circuit containing resistance, capacitance, and inductance.

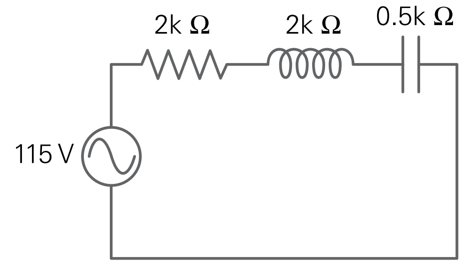
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

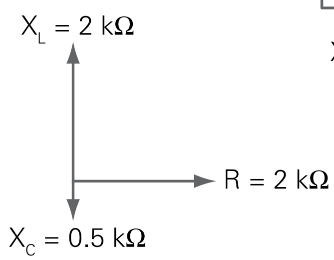
In the case where inductive reactance is greater than capacitive reactance, subtracting X_C from X_L results in a positive number. The positive phase angle is an indicator that the net circuit reactance is inductive and current lags voltage.

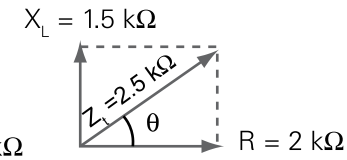
In the case where capacitive reactance is greater than inductive reactance, subtracting X_C from X_L results in a negative number. The negative phase angle is an indicator that the net circuit reactance is capacitive and current leads voltage.

Series R-L-C Circuit

The following example shows a total impedance calculation for a series R-L-C Circuit. Once total impedance has been calculated, current is calculated using Ohm's law.







$$Z_t = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z_t = \sqrt{2000^2 + 1500^2}$$

$$Z_t = \sqrt{6{,}250{,}000}$$

$$Z_t = 2500\ \Omega = 2.5\ \text{k}\Omega$$

Z_t = Total Impedance

$$I = \frac{E}{Z_t} = \frac{115\ \text{V}}{2500\ \Omega} = 0.046\ \text{A} = 46\ \text{mA}$$

Keep in mind that because both inductive reactance and capacitive reactance are dependant upon frequency, if the frequency of the source changes, the reactances change. For example, if the frequency increases, the inductive reactance increases, but the capacitive reactance decreases.

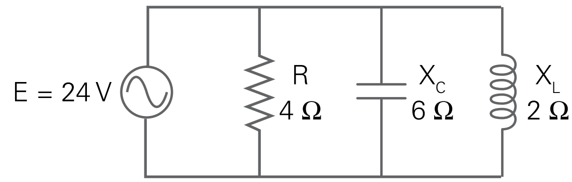
For the special case where the inductive reactance and capacitive reactance are equal, the inductive and capacitive reactances cancel and the net impedance is resistance. In this case, the current is equal to the voltage divided by the resistance. This is referred to as a **series resonant circuit**.

Parallel R-L-C Circuit

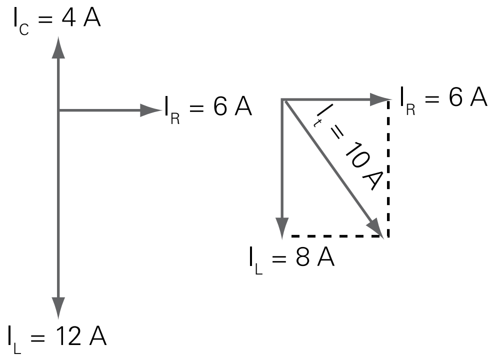
Many circuits contain values of resistance, inductance, and capacitance in parallel. One method for determining the total impedance for a parallel circuit is to begin by calculating the total current.

In a capacitive AC circuit, current leads voltage by 90 degrees. In an inductive AC circuit, current lags voltage by 90 degrees. When represented in vector form, capacitive current and inductive current and are plotted 180 degrees apart. The net reactive current is determined by taking the difference between the reactive currents.

The total current for the circuit can be calculated as shown in the following example. Once the total current is known, the total impedance is calculated using Ohm's law.



$I_R = \frac{E}{R} = \frac{24\text{ V}}{4\ \Omega} = 6\text{ A}$ $\quad I_C = \frac{E}{X_C} = \frac{24\text{ V}}{6\ \Omega} = 4\text{ A}$ $\quad I_L = \frac{E}{X_L} = \frac{24\text{ V}}{2\ \Omega} = 12\text{ A}$



I_t = Total Current

$$I_t = \sqrt{I_R^2 + (I_c - I_L)^2}$$

$$I_t = \sqrt{6^2 + 8^2}$$

$$I_t = \sqrt{100}$$

$$I_t = 10\text{ A}$$

Z_t = Total Impedance

$$Z_t = \frac{E}{I_t} = \frac{24\text{ V}}{10\text{ A}}$$

$$Z_t = 2.4\ \Omega$$

Because inductive reactance and capacitive reactance are dependant upon frequency, if the frequency of the source changes, the reactances and corresponding currents also change. For example, if the frequency increases, the inductive reactance increases, and the current through the inductor decreases, but the capacitive reactance decreases and the current through the capacitor increases.

For the special case where the inductive and capacitive reactances are equal, the inductive and capacitive currents cancel and the net current is the resistive current. In this case, the inductor and capacitor form a **parallel resonant circuit**.

Power and Power Factor in an AC Circuit

Power consumed by a resistor is dissipated in heat and not returned to the source. This is called **true power** because it is the rate at which energy is used.

Current in an AC circuit rises to peak values and diminishes to zero many times a second. The energy stored in the magnetic field of an inductor, or plates of a capacitor, is returned to the source when current changes direction.

Although reactive components do not consume energy, they do increase the amount of energy that must be generated to do the same amount of work. The rate at which this non-working energy must be generated is called **reactive power**. If voltage and current are 90 degrees out of phase, as would be the case in a purely capacitive or purely inductive circuit, the average value of true power is equal to zero. In this case, there are high positive and negative peak values of power, but when added together the result is zero.

Power in an AC circuit is the vector sum of true power and reactive power. This is called **apparent power**. True power is equal to apparent power in a purely resistive circuit because voltage and current are in phase. Voltage and current are also in phase in a circuit containing equal values of inductive reactance and capacitive reactance. In most circuits, however, apparent power is composed of both true power and reactive power.

Power Formulas

The formula for apparent power is shown below. The unit of measure for apparent power is the **volt-ampere (VA)**.

$P = EI$

True power is calculated from another trigonometric function, the cosine of the phase angle (cos θ). The formula for true power is shown below. The unit of measure for true power is the **watt (W)**.

$P = EI \cos \theta$

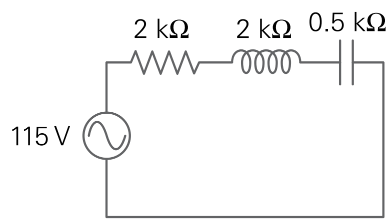
In a purely resistive circuit, current and voltage are in phase and there is a zero degree angle displacement between current and voltage. The cosine of zero is one. Multiplying a value by one does not change the value. Therefore, in a purely resistive circuit, the cosine of the angle is ignored.

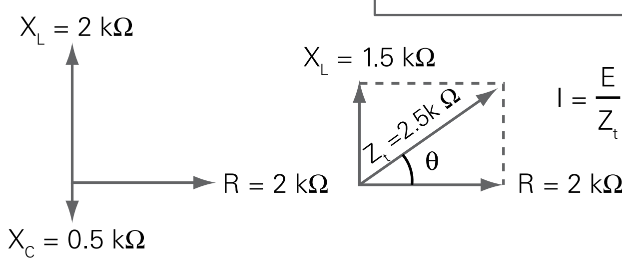
In a purely reactive circuit, either inductive or capacitive, current and voltage are 90 degrees out of phase. The cosine of 90 degrees is zero. Multiplying a value times zero results in a zero product. Therefore, no energy is consumed in a purely reactive circuit.

Although reactive components do not consume energy, they do increase the amount of energy that must be generated to do the same amount of work. The rate at which this non-working energy must be generated is called reactive power. The unit for reactive power the **var** (or **VAr**), which stands for volt-ampere reactive.

Power Calculation Example

The following example shows true power and apparent power calculations for the circuit shown.





$$I = \frac{E}{Z_t} = \frac{115\ V}{2500\ \Omega} = 0.046\ A = 46\ mA$$

True Power = I^2R = $(0.046\ A)^2 \times 2\ k\Omega = 4.232\ W$

Apparent Power = IE = $0.046\ A \times 115\ V = 5.29\ VA$

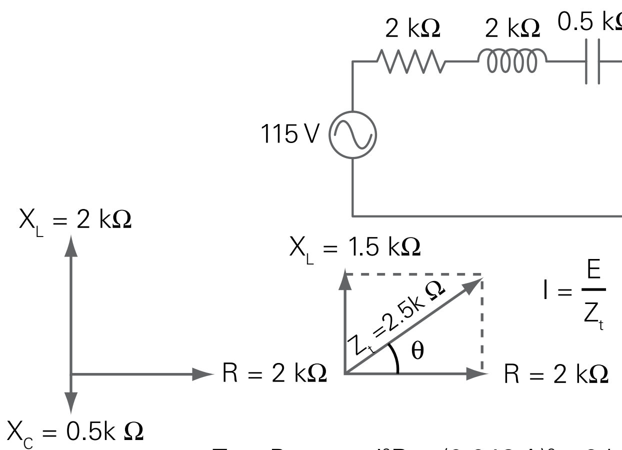
Power Factor

Power factor is the ratio of true power to apparent power in an AC circuit. As previously indicated, this ratio is also the cosine of the phase angle.

In a purely resistive circuit, current and voltage are in phase. This means that there is no angle of displacement between current and voltage. The cosine of a zero degree angle is one. Therefore, the power factor is one. This means that all energy delivered by the source is consumed by the circuit and dissipated in the form of heat.

In a purely reactive circuit, voltage and current are 90 degrees apart. The cosine of a 90 degree angle is zero. Therefore, the power factor is zero. This means that all the energy the circuit receives from the source is returned to the source.

For the circuit in the following example, the power factor is 0.8. This means the circuit uses 80 percent of the energy supplied by the source and returns 20 percent to the source.



$$I = \frac{E}{Z_t} = \frac{115\text{ V}}{2500\ \Omega} = 0.046\text{ A} = 46\text{ mA}$$

$$\text{True Power} = I^2R = (0.046\text{ A})^2 \times 2\text{ k}\Omega = 4.232\text{ W}$$

$$\text{Apparent Power} = IE = 0.046\text{ A} \times 115\text{ V} = 5.29\text{ VA}$$

$$\text{Power Factor (PF)} = \frac{\text{True Power}}{\text{Apparent Power}} = \cos\theta \quad \text{(cosine of angle } \theta\text{)}$$

$$\text{PF} = \frac{4.232\text{ W}}{5.29\text{ VA}} = 0.8$$

$$\text{True Power} = \text{Apparent Power} \times \text{PF} = \text{Apparent Power} \times \cos\theta = \text{IE}\cos\theta$$

Another way of expressing true power is as the apparent power times the power factor. This is also equal to I times E times the cosine of the phase angle.

Review 8

1. An AC circuit is ________ if inductive reactance and capacitive reactance are equal.

2. A series AC circuit is ________ if there is more inductive reactance than capacitive reactance.

3. A series AC circuit is ________ if there is more capacitive reactance than inductive reactance.

4. In a 120 V, 60 Hz series circuit with resistance of 1000 Ω, 10 mh of inductance, and 4 μF of capacitance, impedance is ________ Ω and current is ________ A.

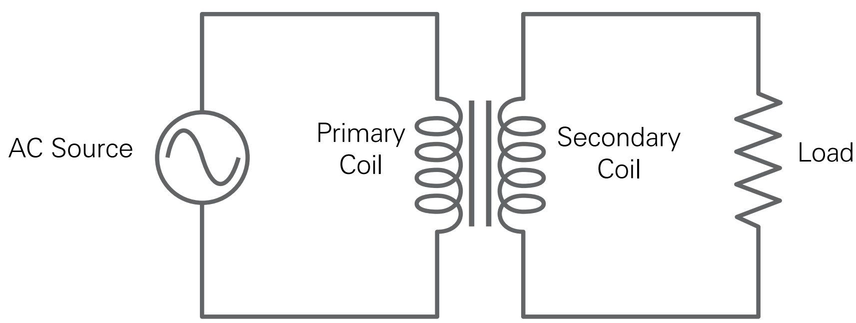
5. For a circuit with a 120 V AC source and a current of 10 A, the apparent power is __________ VA.

6. For a circuit with an apparent power of 3000 VA and a power factor of 0.8, the true power is ________ W.

Transformers

Transformers are electromagnetic devices that transfer electrical energy from one circuit to another by **mutual induction**. A single-phase transformer has two coils, a **primary** and a **secondary**. Mutual induction is the transfer of electrical energy from the primary to the secondary through magnetic fields . For example, in the following a single-phase transformer circuit. The AC generator provides electrical power to the primary coil. The magnetic field produced by the primary induces a voltage into the secondary coil, which supplies power to a load.

Single-phase, Iron Core Transformer



Transformers are used to step a voltage up to a higher level, or down to a lower level. To understand the need to stepping up or down voltages, consider how electrical power is generated and distributed.

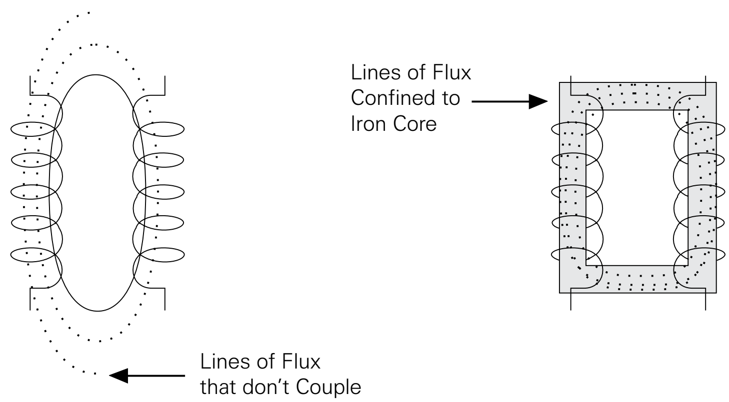
Generators used by power companies typically generate voltages of 30 kV or less. While this is a relatively high voltage compared to the voltages used by power customers, it is more efficient for utilities to transmit this power at still higher voltages, up to as high at 765 kV.

The electrical power is received at substation transformers many miles away where it is stepped down and distributed locally. When it arrives at the customer's location, it is further stepped down to the level needed for the type of customer.

Even within a customer's facility, voltage may need to be stepped down further to meet requirements of some equipment.

This process of stepping up or down the voltage throughout a power distribution system is accomplished using transformers. The size and ratings of the transformers vary, but the basic operation of these devices is the same.

Mutual inductance between two coils depends on their flux linkage. Maximum coupling occurs when all the lines of flux from the primary coil cut through the secondary winding. The amount of coupling which takes place is referred to as **coefficient of coupling**. To maximize coefficient of coupling, both coils are often wound on an iron core which is used to provide a path for the lines of flux. The following discussion of step-up and step-down transformers applies to transformers with an iron core.



There is a direct relationship between voltage, impedance, current, and the number of primary and secondary coil turns in a transformer. This relationship can be used to find either primary or secondary voltage, current, and the number of turns in each coil. The following "rules-of-thumb" apply to transformers:

- If the primary coil has fewer turns than the secondary coil, the transformer is a **step-up transformer**.
- If the primary coil has more turns than the secondary coil, the transformer is a **step-down transformer**.

When the number of turns on the primary and secondary coils of a transformer are equal, input voltage, impedance, and current are equal to output voltage, impedance, and current.

Transformer Formulas

There are a number of useful formulas for calculating, voltage, current, and the number of turns between the primary and secondary of a transformer. These formulas can be used with either step-up or step-down transformers. The following legend applies to the transformer formulas:

E_S = secondary voltage
E_P = primary voltage
I_S = secondary current
I_P = primary current
N_S = turns in the secondary coil
N_P = turns in the primary coil

To find voltage:

$$E_S = \frac{E_P \times I_P}{I_S} \qquad E_P = \frac{E_S \times I_S}{I_P}$$

For example, if a transformer has a primary voltage of 240 V, a primary current of 5 A, and a secondary current of 10 A, the secondary voltage can be calculated as shown below.

$$E_S = \frac{E_P \times I_P}{I_S} = \frac{240\text{ V} \times 5\text{ A}}{10\text{ A}} = \frac{1200}{10} = 120\text{ V}$$

To find current:

$$I_S = \frac{E_P \times I_P}{E_S} \qquad I_P = \frac{E_S \times I_S}{E_P}$$

To find the number of coil turns:

$$N_S = \frac{E_S \times N_P}{E_P} \qquad N_P = \frac{E_P \times N_S}{E_S}$$

Transformer Ratings

Transformers are rated for the amount of apparent power they can provide. Because values of apparent power are often large, the transformer apparent power rating is frequently given in **kVA (kilovolt-amperes)**. The kVA rating determines the current and voltage a transformer can deliver to its load without overheating.

For a single-phase transformer, the apparent power rating is calculated by multiplying secondary voltage by the maximum load current. This means that if a transformer needs to provide a secondary voltage of 240 V at a maximum load current of 75 A, the kVA rating of the transformer must be at least 18 kVA.

240 V x 75 A = 18,000 VA = 18 kVA

Transformer Losses

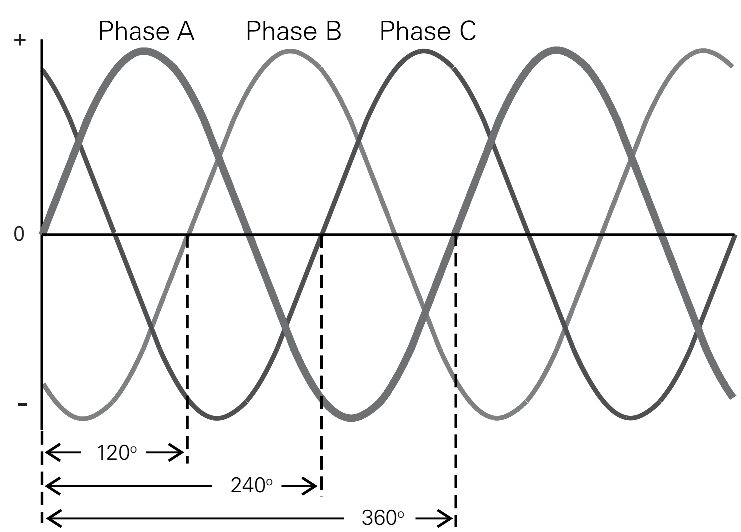
Most of the electrical energy provided to the primary of a transformer is transferred to the secondary. Some energy, however, is lost in heat in the wiring or the core. Some losses in the core can be reduced by building the core of a number of flat sections called laminations.

Three-Phase AC

Up till now, we have been talking only about **single-phase AC power**. Single-phase power is used in homes, offices, and many other types of facilities.

However, power companies generate and distribute **three-phase power**. Three-phase power is used in commercial and industrial applications that have higher power requirements than a typical residence.

Three-phase power, as shown in the following illustration, is a continuous series of three overlapping AC cycles. Each wave represents a phase and is offset by 120 electrical degrees from each of the two other phases.



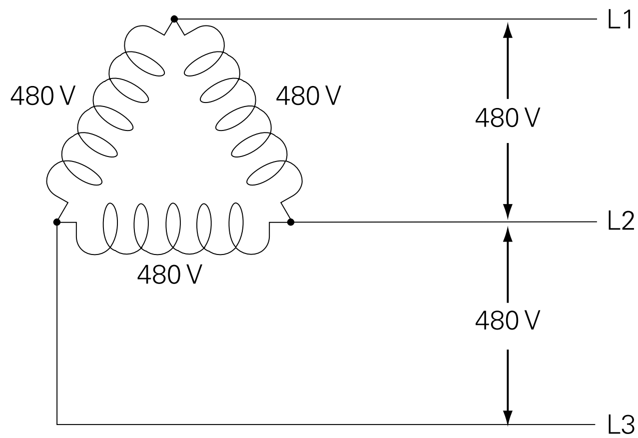
Three-Phase Transformers

Three-phase transformers are used when three-phase power is required for larger loads such as industrial motors. There are two basic three-phase transformer connections, **delta** and **wye**.

Delta Connections

Delta transformers are schematically drawn in a triangle. The voltages across each winding of the delta triangle represents one phase of a three phase system. The voltage is always the same between any two wires. A single phase (such as L1 to L2) can be used to supply single phase loads. All three phases are used to supply three phase loads.

The secondary of a delta transformer is illustrated below. For simplicity, the primary is not shown in this example. The voltages shown on the illustration are examples. Just as with a single-phase transformer, the secondary voltage depends on both the primary voltage and the turns ratio.

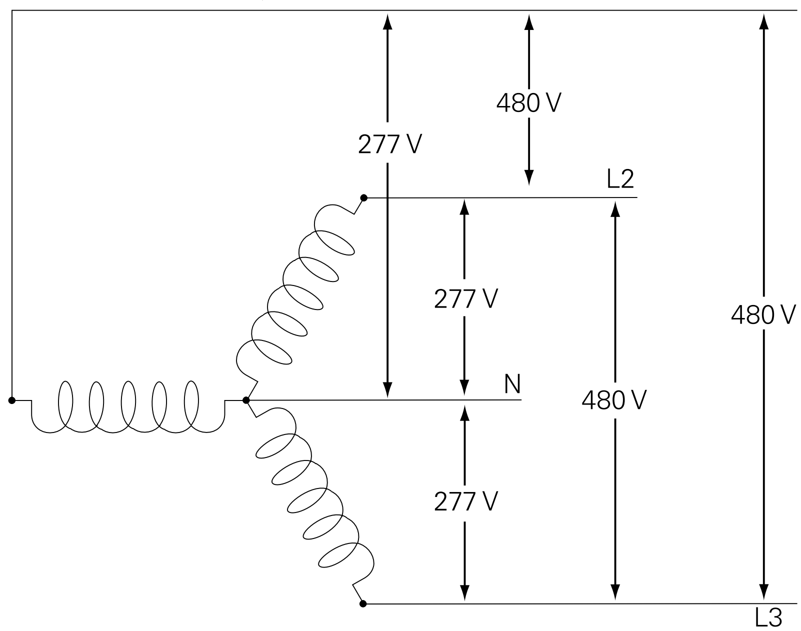


When current is the same in all three coils, it is said to be **balanced**. In each phase, current has two paths to follow. For example, current flowing from L1 to the connection point at the top of the delta can flow down through one coil to L2, and down through another coil to L3. When current is balanced, the current in each line is equal to the square root of 3 times the current in each coil.

Wye Connections

The wye connection is also known as a star connection. Three coils are connected to form a "Y" shape. The wye transformer secondary has four leads, three phase leads and one neutral lead. The voltage across any phase (line-to-neutral) will always be less than the line-to-line voltage. The line-to-line voltage is the square root of 3 times the line-to-neutral voltage. The following example shows a wye transformer secondary with a line-to-neutral voltage is 277 volts and a line-to-line voltage of 480 volts.

$$V_{\text{Line-to-Line}} = \sqrt{3} \times 277\ V = 1.732 \times 277\ V = 480\ V$$



Review 9

1. If the primary of a transformer has more turns than the secondary, it is a _________ transformer.

2. If the primary of a transformer has fewer turns than the secondary, it is a _________ transformer.

3. The secondary voltage of an iron-core transformer with 240 V on the primary, 40 A on the primary, and 20 A on the secondary is ________ V.

4. A single-phase transformer with a 480 V and a maximum load current of 20 A must have an apparent power rating of at least ________ kVA.

5. A wye-connected, three-phase transformer secondary, with 208 V line-to-line will have ________ V line-to-neutral.

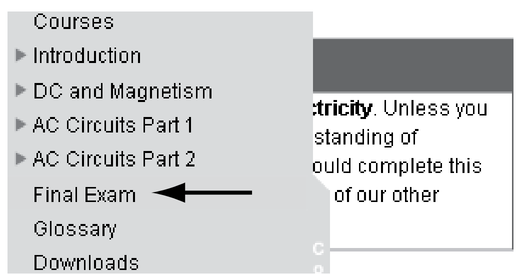
Review Answers

Review 1	1) electron (-), proton (+), neutron (neutral); 2) conductors; 3) a, c, e, g; 4) insulators.
Review 2	1) negative; 2) positive; 3) repel, attract; f) Voltage; 6) negative, positive; 7) a. ohm, b. ampere, c. volt.
Review 3	1) 0.5; 2) 45; 3) 30; 4) 5; 5) 6; 6) 120.
Review 4	1) iron, north-south; 2) north, south; 3) electron, lines of flux.
Review 5	1) sine wave; 2) one; 3) -129.9; 4) 106.05.
Review 6	1) 10; 2) 2.5; 3) 2.5; 4) 25.
Review 7	1) Reactance; 2) Impedance; 3) 3.14; 4) c; 5) b; 6) 318.5; 7) 11.18; 8) 6.4.
Review 8	1) resistive; 2) inductive; 3) capacitive; 4) 1198, 0.1; 5) 1200; 6) 2400.
Review 9	1) step-down; 2) step-up; 3) 480; 4) 9.6; 5) 120.

Final Exam

You can test your knowledge by taking the final exam for this course online at **http://www.usa.siemens.com/step**. This web page provides links to a variety of our quickSTEP online courses. To complete the final exam for this course, click on the **Basics of Electricity** link.

Next, move your mouse over to the left so that the navigation bar pops out and select the **Final Exam** link. The final exam page will appear. Before taking the final exam, it is recommended that you delete the temporary files on your computer. For most versions of **Internet Explorer**, you can do this by selecting **Internet Options** from the **Tools** menu and then clicking on the **Delete Files** button. If you do not perform this step, you may see a score of 0% after you submit your exam for grading.



After you complete the final exam, click on the **Grade the Exam** button at the bottom of the page. Your score on the exam will be displayed along with the questions that you missed.

If you score 70% or better on the exam, you will be given two options for displaying and printing a certificate of completion. The **Print Certificate** option allows you to display and print the certificate without saving your score in our database and the **Save Score** option allows you to save your score and display and print your certificate.