Basics of Electricity

A quickSTEP Online Course

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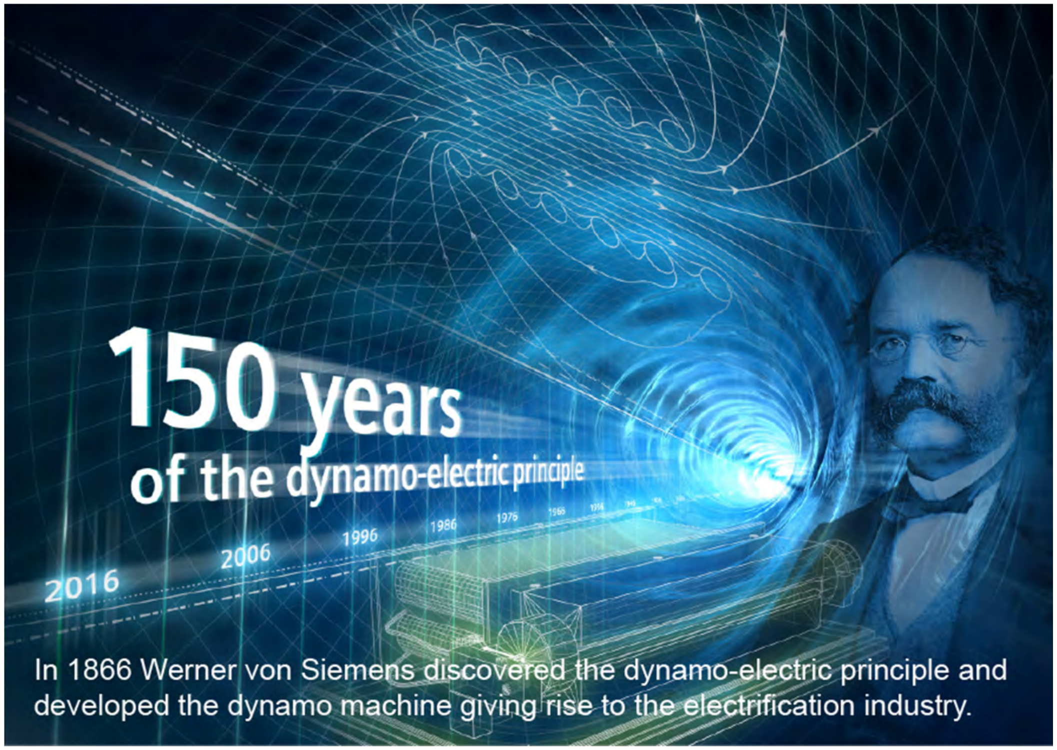
Course Topics



Welcome to Basics of Electricity. This course covers the following topics:

Introduction
Chapter 1 – Direct Current
- Direct Current Basics
- DC Circuits
- Magnetism

Chapter 2 – Alternating Current
- Alternating Current Basics
- Inductance and Capacitance
- AC Circuits
- Transformers

Final Exam

If you do not have a basic understanding of electricity, complete this course before starting other quickSTEP online courses.

Course Objectives

Upon completion of this course 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
- Define inductive reactance, capacitive reactance, and impedance
- Calculate total impedance of a simple AC circuit
- Explain the difference between real power and apparent power in an AC circuit
- Determine how a transformer turns ratio affects secondary voltage and current

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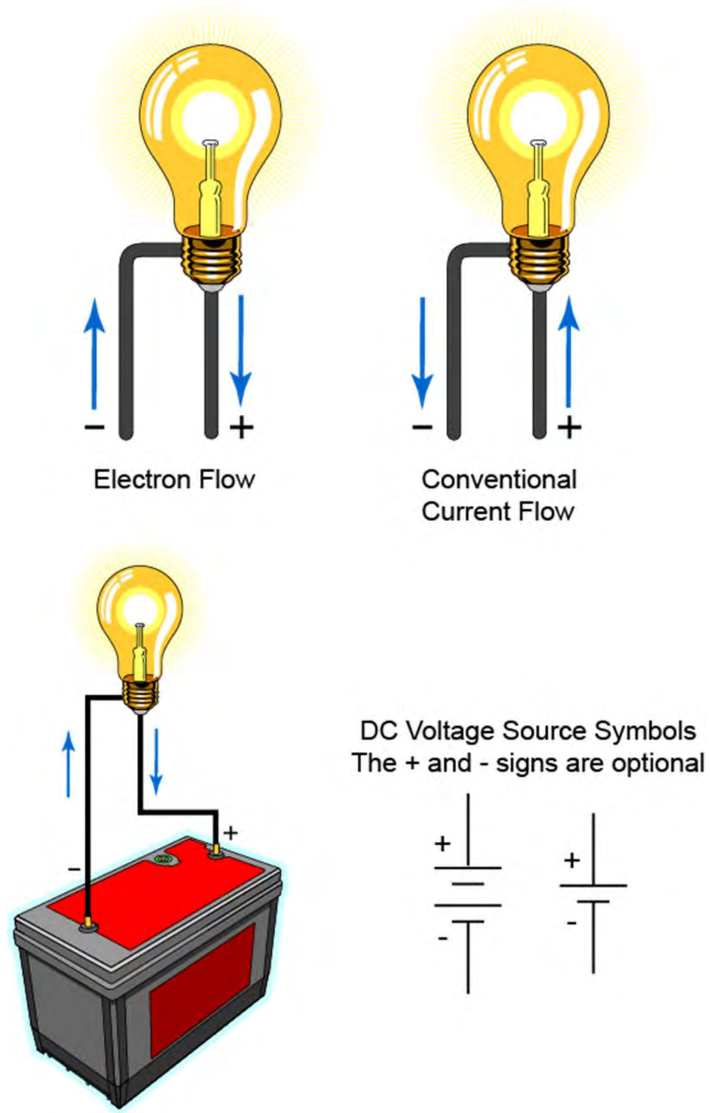
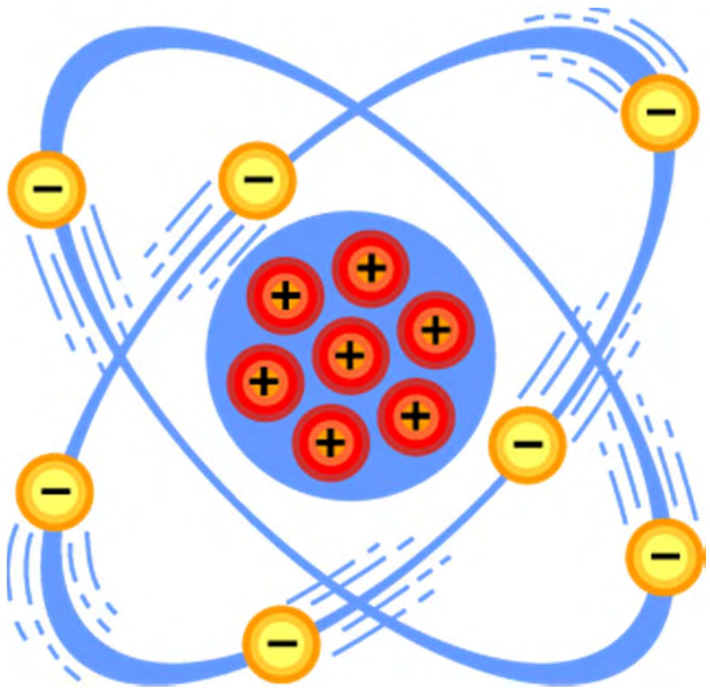
Chapter 1 – Direct Current



This chapter covers the following topics:

- **Direct Current Basics**
- DC Circuits
- Magnetism

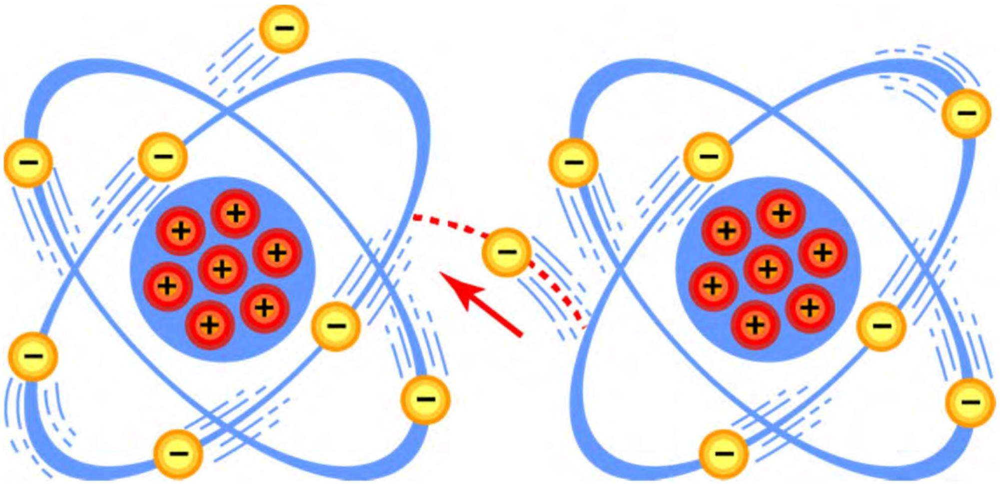
Atoms



All matter is composed atoms. Atoms have a nucleus with electrons moving around it. The nucleus is composed of protons and neutrons (not shown).

In their neutral state, atoms have an equal number of electrons and protons. Electrons have a negative charge. Protons have a positive charge . Neutrons are neutral. The negative charge of the electrons is balanced by the positive charge of the protons. Electrons are bound in their orbit by their attraction to protons.

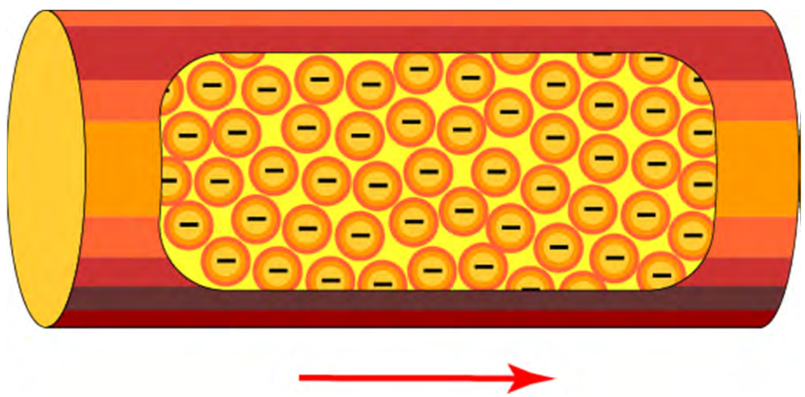
Free Electrons



Electrons in the outer band can become free of their orbit by the application of some external force such as movement through a magnetic field, friction, or chemical action. These are referred to as free electrons.

A free electron leaves a void which can be filled by an electron forced out of orbit from another atom. As free electrons move from one atom to the next an electron flow is produced. This is the basis of electricity.

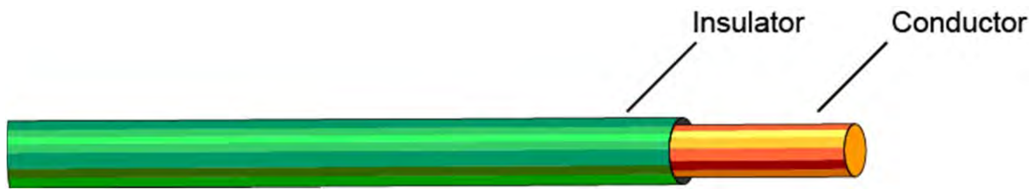
Conductors



An electric current is produced when free electrons move from one atom to the next. Materials that permit many electrons to move freely are called conductors.

Copper, gold, silver, and aluminum are examples of materials that are good conductors. Copper is widely used as a conductor because it is one of the best conductors and is relatively inexpensive.

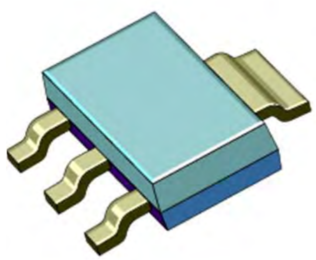
Insulators



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

An electrical cable is one example of how conductors and insulators are used together. Electrons flow along a copper conductor in a circuit and the insulator around the outside of the copper conductor keeps electrons in the conductor.

Semiconductors



Transistor

Diode

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 an external force is applied in the opposite direction.

This principle is basic to the operation of transistors, diodes, and other solid-state electronic devices.

Electric Charges

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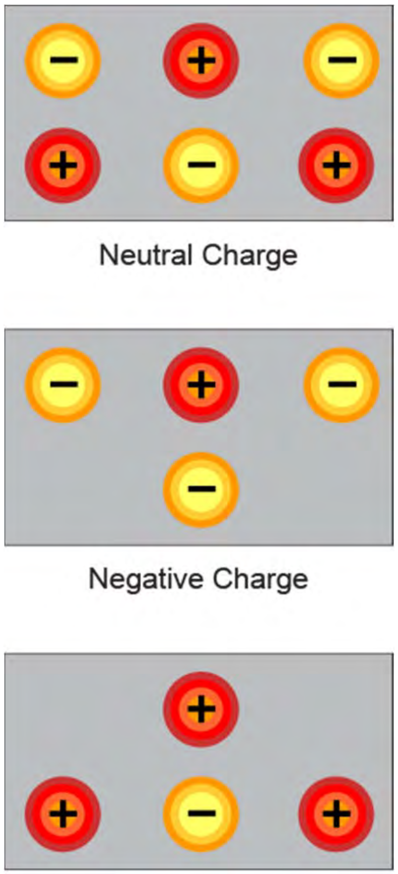


Neutral Charge

Negative Charge

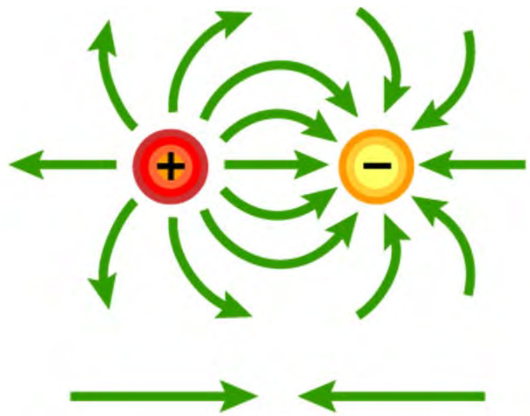
Positive Charge

Elements are defined by the number of electrons in orbit around the nucleus of an atom and by the number of protons in the nucleus. 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 said to be electrically neutral.

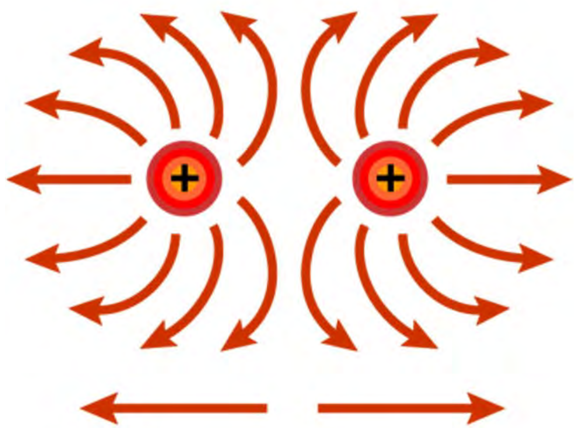
Electrons in the outer band of an atom are easily displaced by the application of some external force. Electrons which are forced out of their orbits can result in a lack of electrons where they leave and an excess of electrons where they come to rest.

A material with more protons than electrons has a net positive charge, and a material with more electrons than protons has a net negative charge. A positive or negative charge is caused by an absence or excess of electrons, because the number of protons in an atom remains constant.

Attraction and Repulsion of Electric Charges



Unlike Charges Attract Each Other



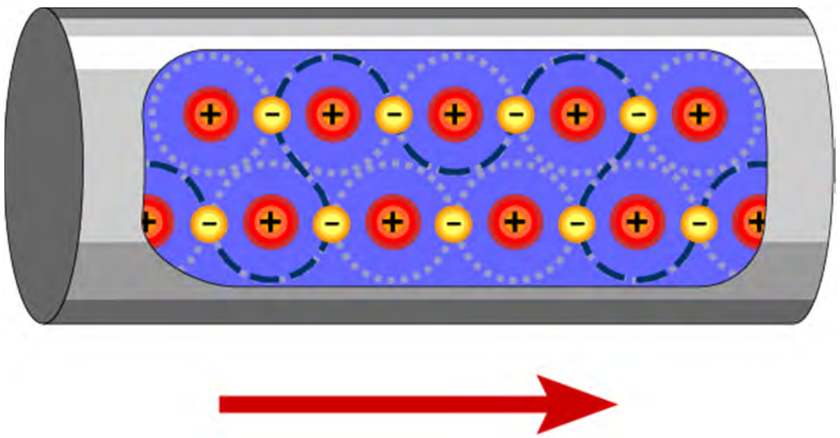
Like Charges Repel Each Other

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

During the 18th century a French scientist, Charles A. Coulomb, studied fields of force that surround charged bodies. Coulomb discovered that charged bodies attract or repel each other with a force that is directly proportional to the product of the charges and inversely proportional to the square of the distance between them.

Today we call this Coulomb’s Law of Charges. Simply put, the force of attraction or repulsion depends on the strength of the charges and the distance between them.

Current



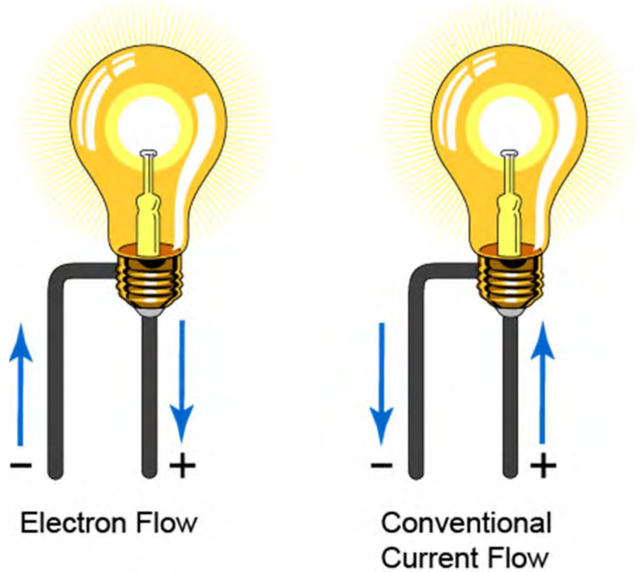
Commonly Used Units		
Unit	**Short Form**	**Decimal Value**
1 kiloampere	1 kA	1000 A
1 ampere	1 A	1 A
1 milliampere	1 mA	0.001 A
1 microampere	1 µA	0.000001 A

Electricity is the flow of electrons in a conductor from one atom to the next atom in the same general direction. This flow of electrons is referred to as current and is designated by the symbol “I”.

Current is measured in amperes, which is often shortened to “amps”. The letter “A” is the symbol for amps. Because the amount of voltage present can vary significantly, metric unit prefixes are sometimes used. For example, a current of 0.001 amps is equal to 1 milliamp or 1 mA for short.

Current that constantly flows in the same direction is called direct current (DC). Current that periodically changes direction is called alternating current (AC).

Direction of Current Flow

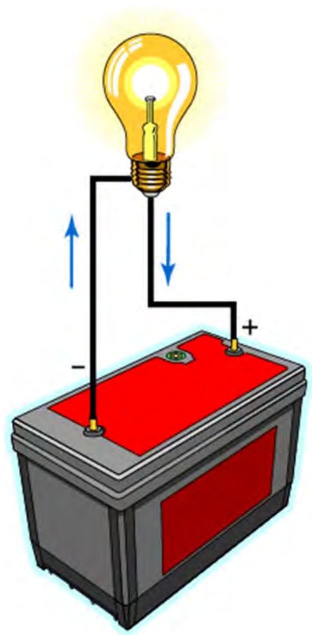


Some authorities distinguish between electron flow and current flow.

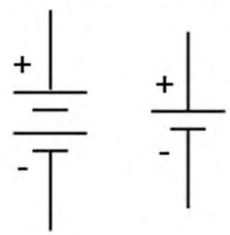
Conventional current flow theory ignores the flow of electrons and states that current flows from positive to negative.

Electric circuits can be correctly analyzed using either conventional current flow or electron flow; however, to avoid confusion, this course uses the electron flow concept which states that electrons flow from negative to positive.

Voltage



DC Voltage Source Symbols
The + and - signs are optional



Commonly Used Units		
Unit	**Short Form**	**Decimal Value**
1 kilovolt	1 kV	1000 V
1 volt	1 V	1 V
1 millivolt	1 mV	0.001 V
1 microvolt	1 µV	0.000001 V

The force that causes current to 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 volts which is also designated by the letter “V.” Because the amount of voltage present can vary significantly, metric unit prefixes are sometimes used. For example, a voltage of 1000 volts is equal to 1 kilovolt or 1kV for short.

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 DC voltage source, the polarity of the terminals does not change, so the resulting current constantly flows in the same direction.

The terminals of an AC voltage source periodically change polarity, causing the current flow direction to change with each switch in polarity.

Resistance

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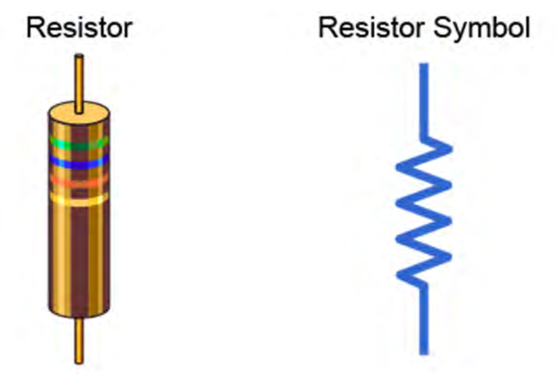


Commonly Used Units		
Unit	**Short Form**	**Decimal Value**
1 Megaohm	1 MΩ	1,000,000 Ω
1 kiloohm	1 kΩ	1000 Ω
1 ohm	1 Ω	1 Ω

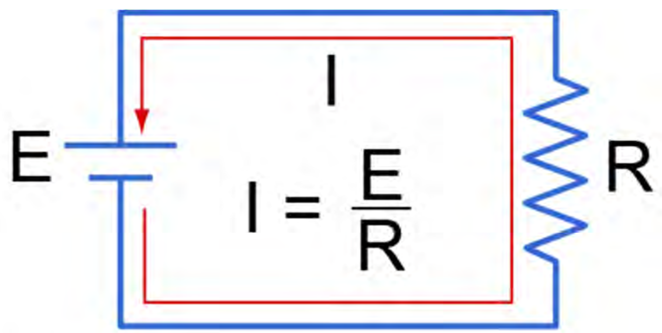
A third factor that plays a role in an electrical circuit is resistance. Resistance is the property of a circuit, component, or material that opposes current flow. All material resists the flow of electrical current to some extent.

The amount of resistance depends upon the composition, length, cross-section, and temperature of the resistive material. For any specific material at a constant temperature, the resistance of a conductor increases with an increase of length or a decrease in cross-section.

Resistance is designated by the symbol "R." The unit of measurement for resistance is the ohm, symbolized by the Greek letter omega (Ω). Because 1 ohm is a small unit and circuit resistances are often large values, metric unit prefixes are often used. For example, 1 million ohms is equal to 1 Megaohm or 1 M Ω for short.

While all circuit components have resistance, a resistor is a component manufactured to provide a designated resistance that is often shown in color coded bands around the resistor.

Ohm’s Law

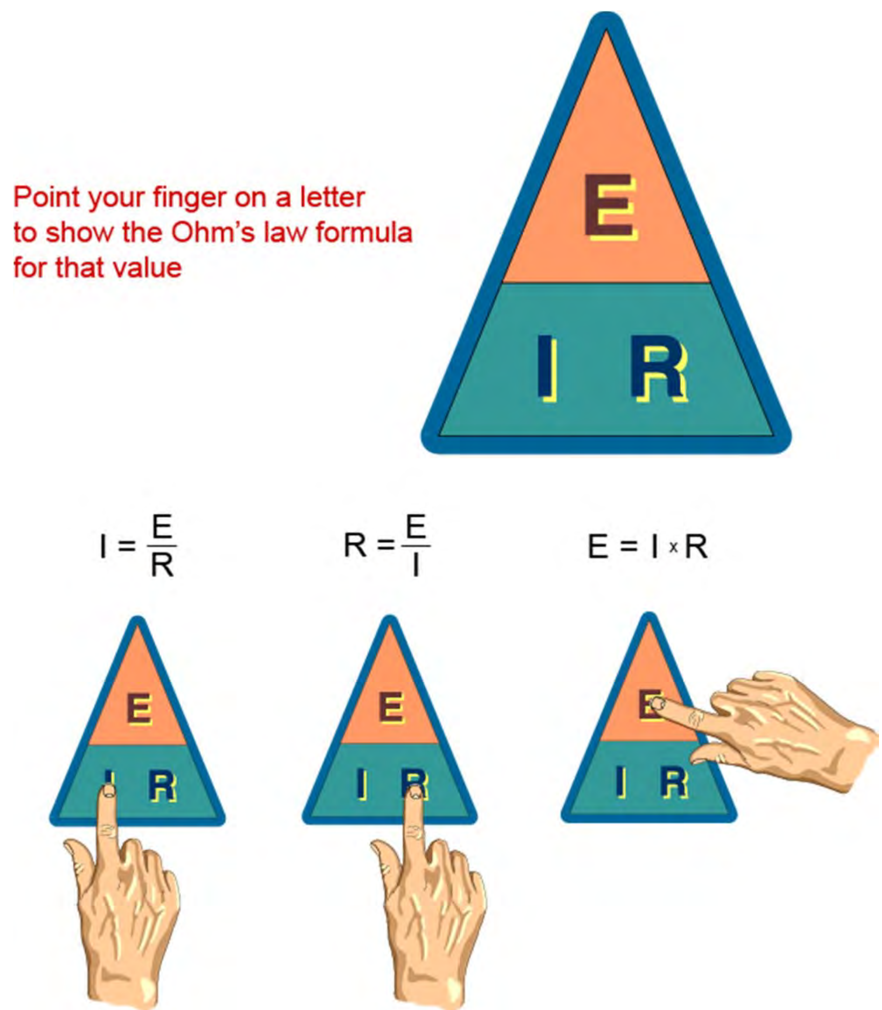


Current (I) is measured in amperes (amps)
Voltage (E) is measured in volts
Resistance (R) is measured in ohms

A simple electric circuit 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 defines the relationship between current, voltage, and resistance and shows that current varies directly with voltage and inversely with resistance.

Ohm’s Law Triangle

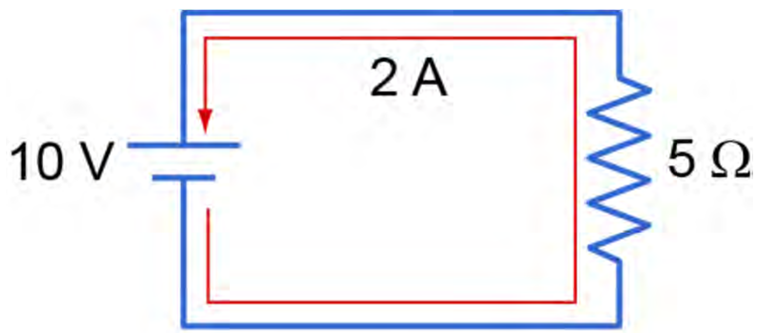


Ohm’s law can be expressed in three ways. There is an easy way to remember which form of Ohm’s law to use.

First, draw a triangle with the letters for current, voltage and resistance positioned as shown in the accompanying illustration.

Then, when you need to use the ohms law formula, point your finger on the value you want to calculate. The remaining letters make up the formula.

Ohm’s Law Example



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

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

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

The accompanying illustration shows that if you know any two Ohm’s law values, you can easily find the third value using the appropriate Ohm’s law formula.

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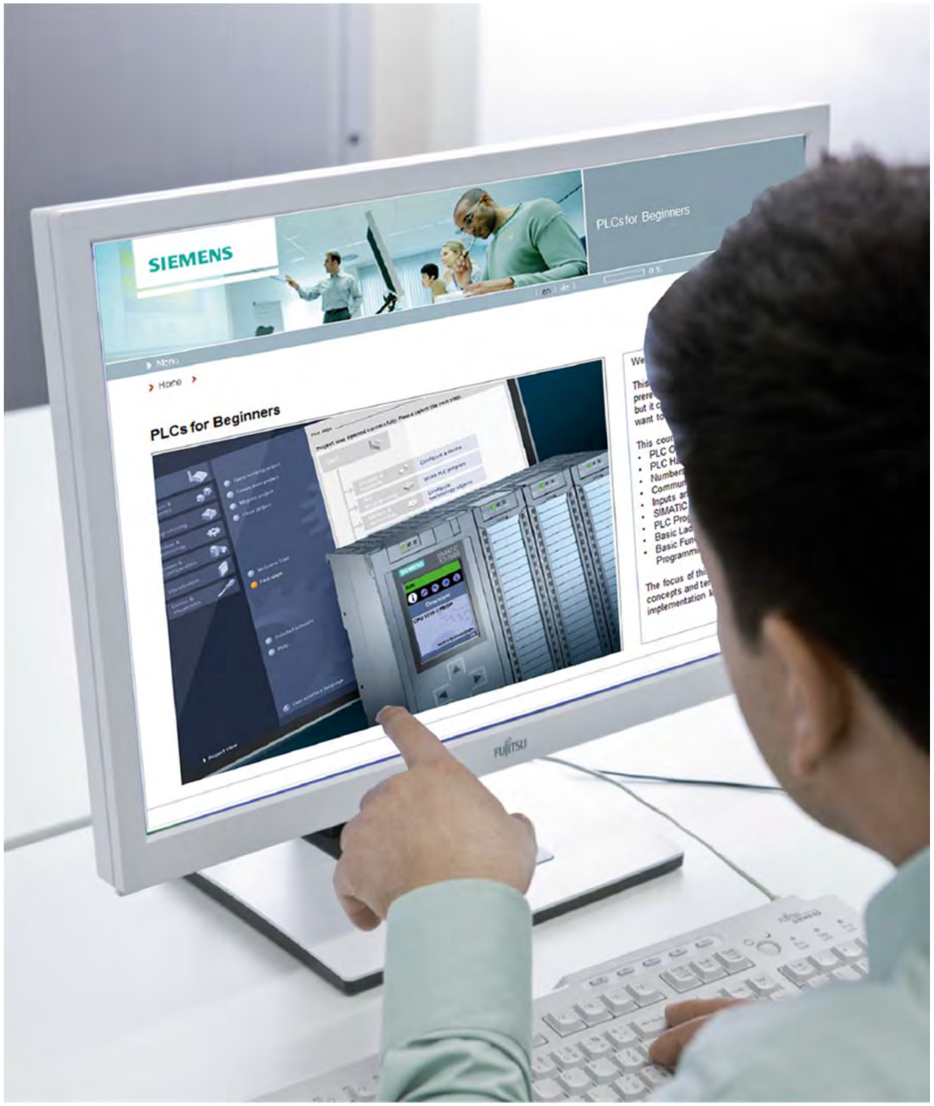

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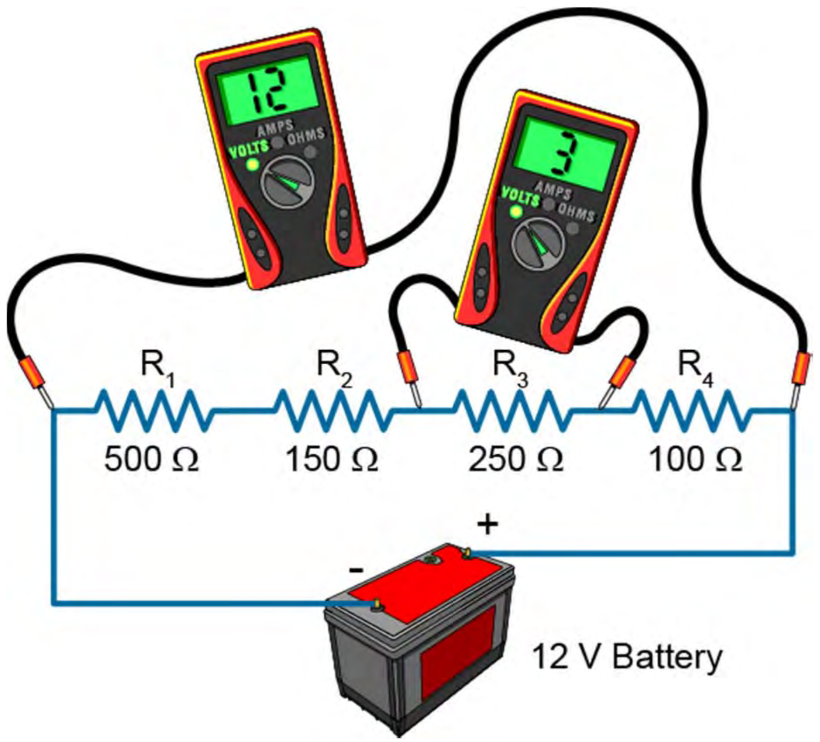
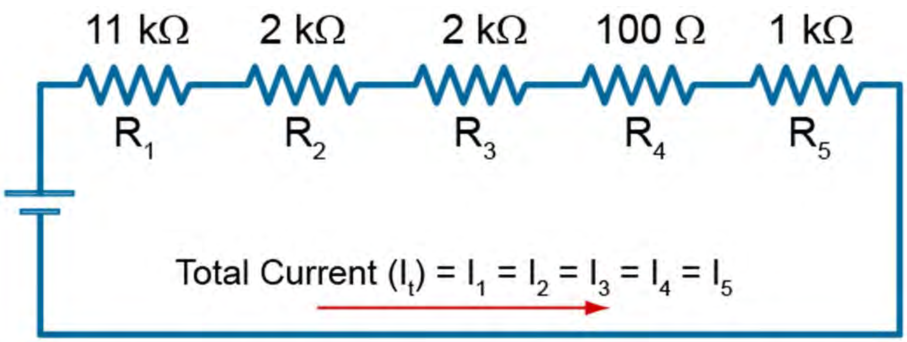


This chapter covers the following **topics:**

- Direct Current Basics
- **DC Circuits**
- Magnetism

Series Circuit Resistance



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

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

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

Commonly Used Units		
Unit	**Short Form**	**Decimal Value**
1 Megaohm	1 MΩ	1,000,000 Ω
1 kiloohm	1 kΩ	1000 Ω
1 ohm	1 Ω	1 Ω

A series circuit is formed when any number of resistors are connected end-to-end so that there is only one path for current to flow. The resistors can be actual resistors or other devices that have resistance.

The accompanying illustration shows five resistors connected end-to-end. There is one path of current flow from the negative terminal of the voltage source through all five resistors and returning to the positive terminal.

The total resistance in a series circuit is 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.

Series Circuit Voltage and Current

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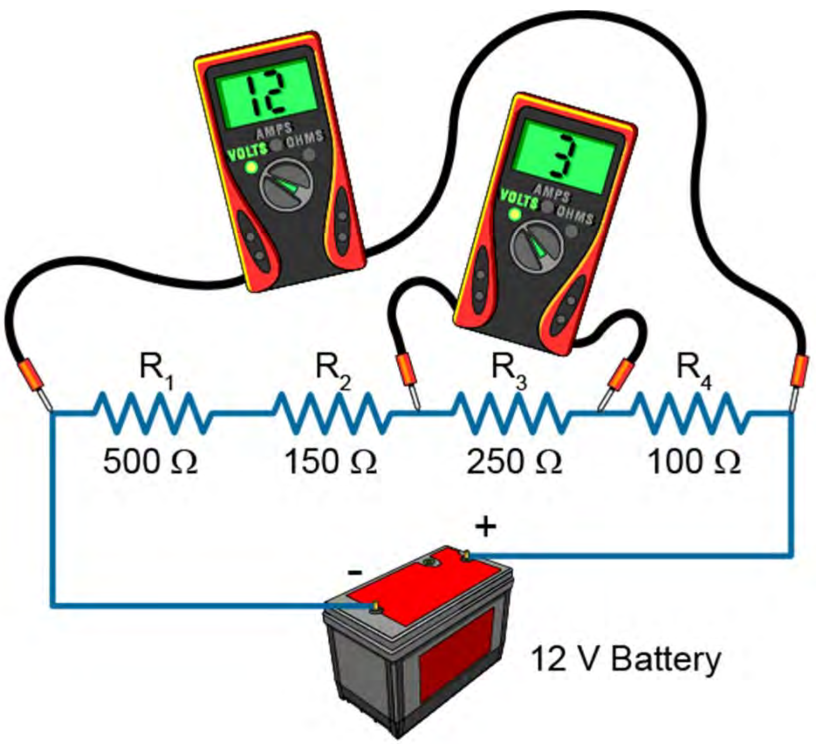


$$R_t = 500\ \Omega + 150\ \Omega + 250\ \Omega + 100\ \Omega = 1000\ \Omega = 1\ k\Omega$$

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

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

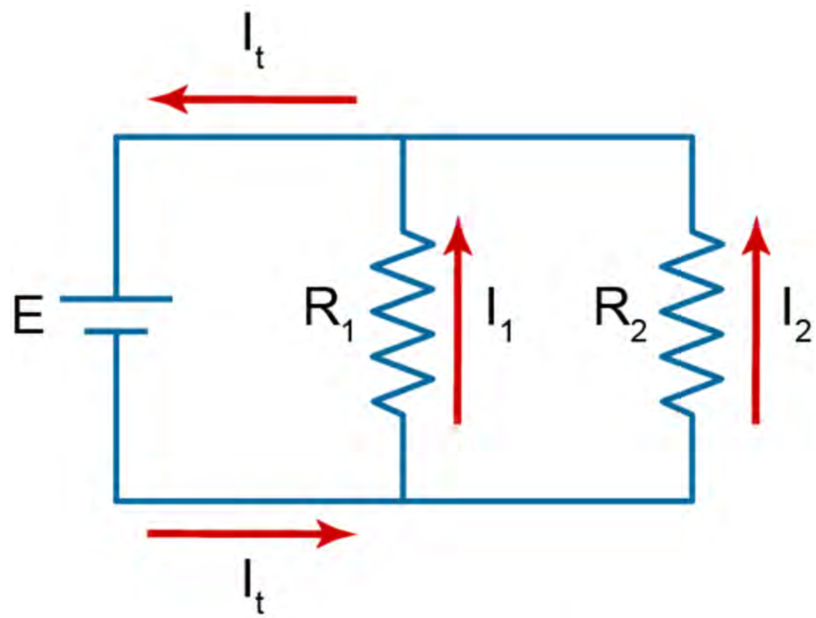
$$E_t = E_1 + E_2 + E_3 + E_4 = 6\ V + 1.8\ V + 3\ V + 1.2\ V = 12\ V$$

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

Parallel Circuits



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

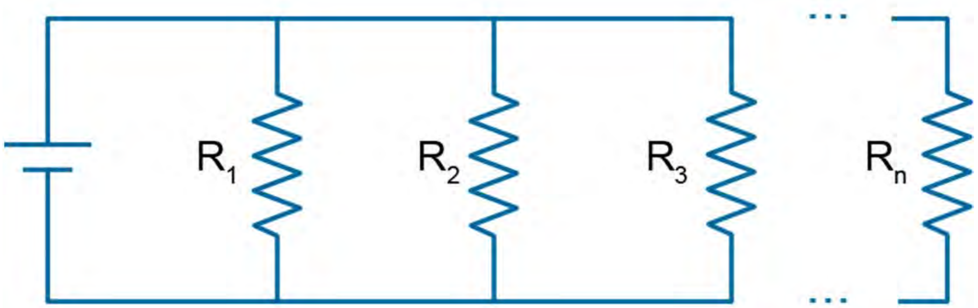
$$I_t = I_1 + I_2$$

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

The accompanying 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 R1 returning to the positive terminal. The second path is from the negative terminal of the battery through R2 returning to the positive terminal of the battery.

The current through any resistor can be determined by dividing the circuit voltage by the resistance of that resistor. The total current is the sum of the branch currents.

Parallel Circuit Resistance



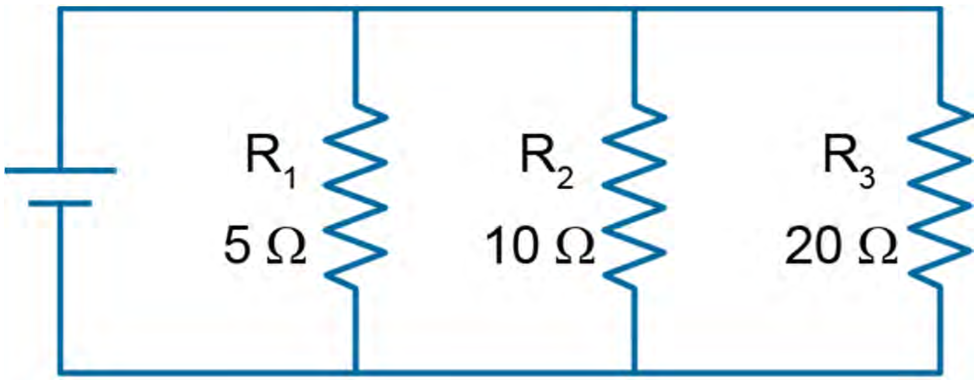
$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \cdots + \frac{1}{R_n}$$

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

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

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.

Parallel Circuit Resistance Example

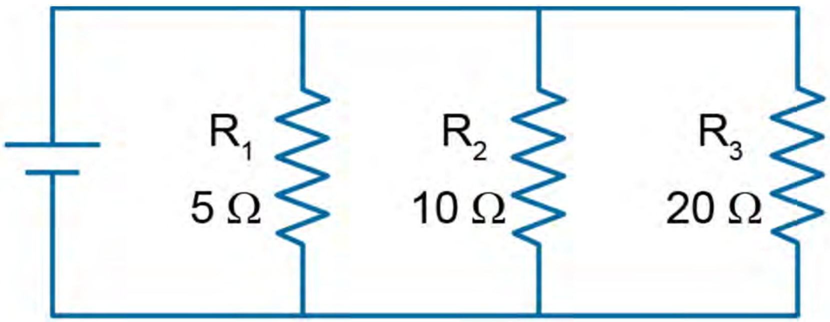


The accompanying illustration shows a circuit with three parallel resistors. See if you can complete the total resistance calculation. Then go to the next page of this course to see the solution.

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

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

Parallel Circuit Resistance Solution

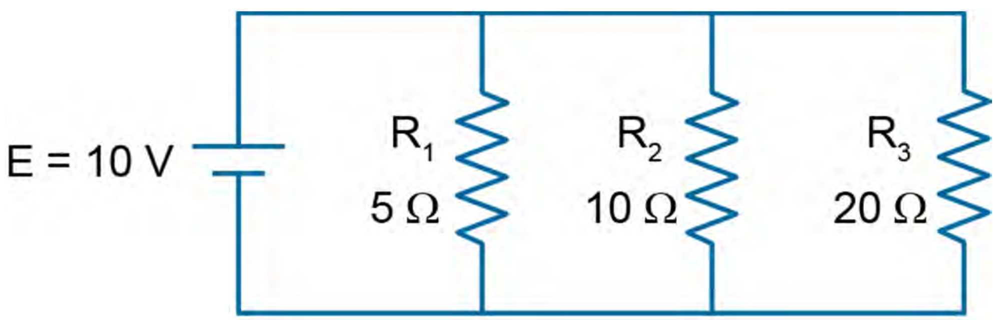


Note the total resistance calculation for this circuit.

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

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

Parallel Circuit Current Example



$$I_t = I_1 + I_2 + I_3 = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3} =$$

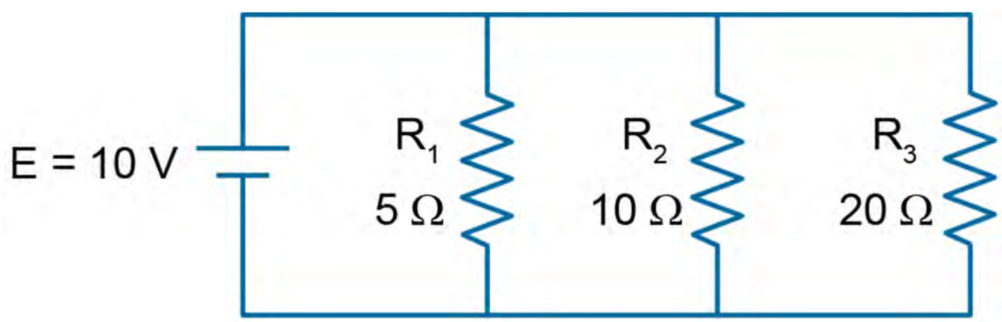
$$I_t = \frac{E}{R_t} =$$

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.

See if you can complete the calculations for each branch current and for the total current. Then go to the next page of this course to see the solution.

Parallel Circuit Current Example

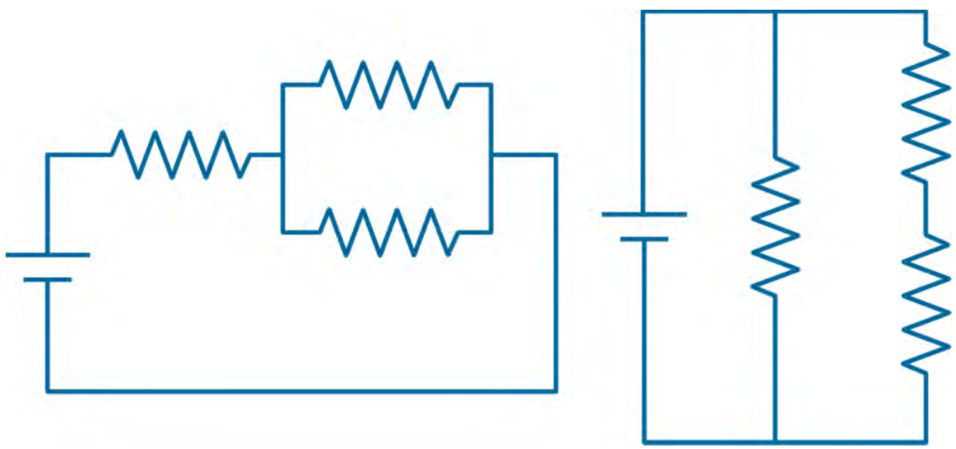


Note the current calculations for this circuit.

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

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

Series-Parallel Circuits



Series-parallel circuits are also known as compound circuits. At least three resistors are required to form a series-parallel circuit. The accompanying 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.

Series-Parallel Circuit Resistance Calculations

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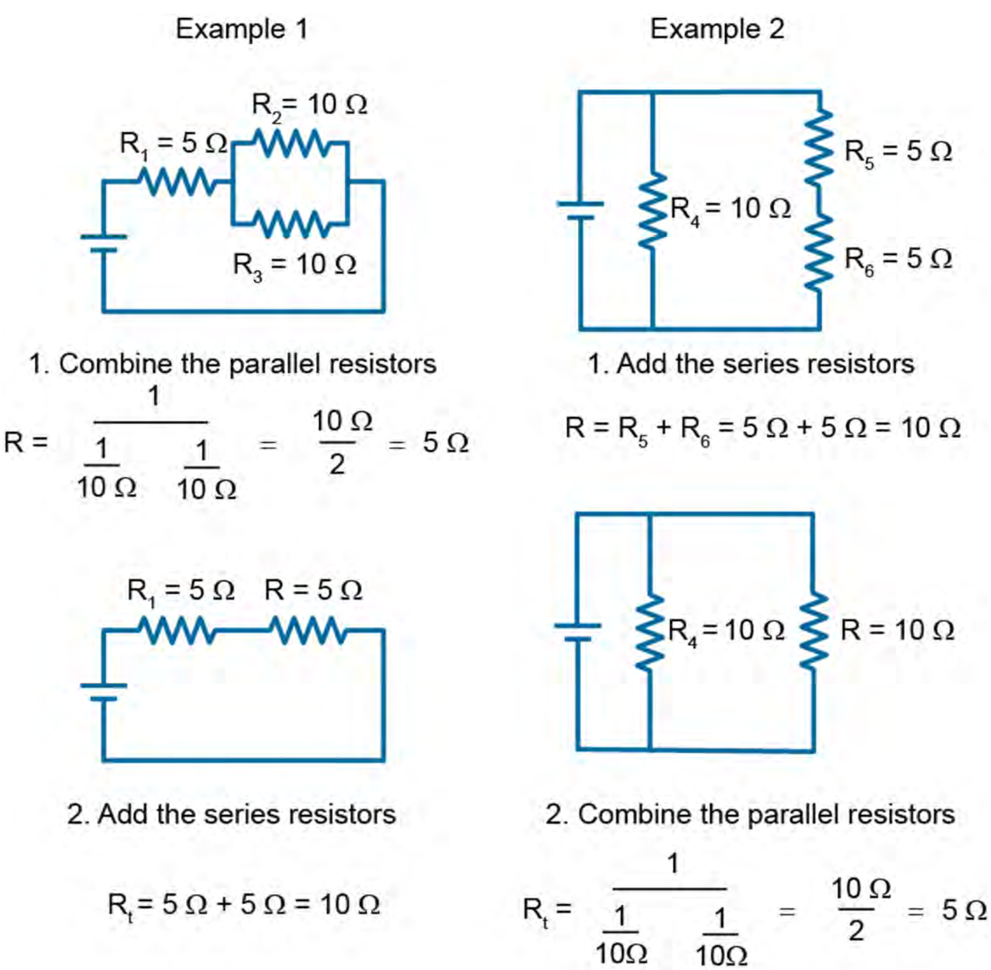

The accompanying illustration shows how total resistance can be determined for two series-parallel circuits in two easy steps for each circuit.

More complex circuits require more steps, but each step is relatively simple. In addition, by using Ohm’s law, you can also solve for current and voltage throughout each circuit, if the source voltage is known.

Series-Parallel Circuit Current Calculations

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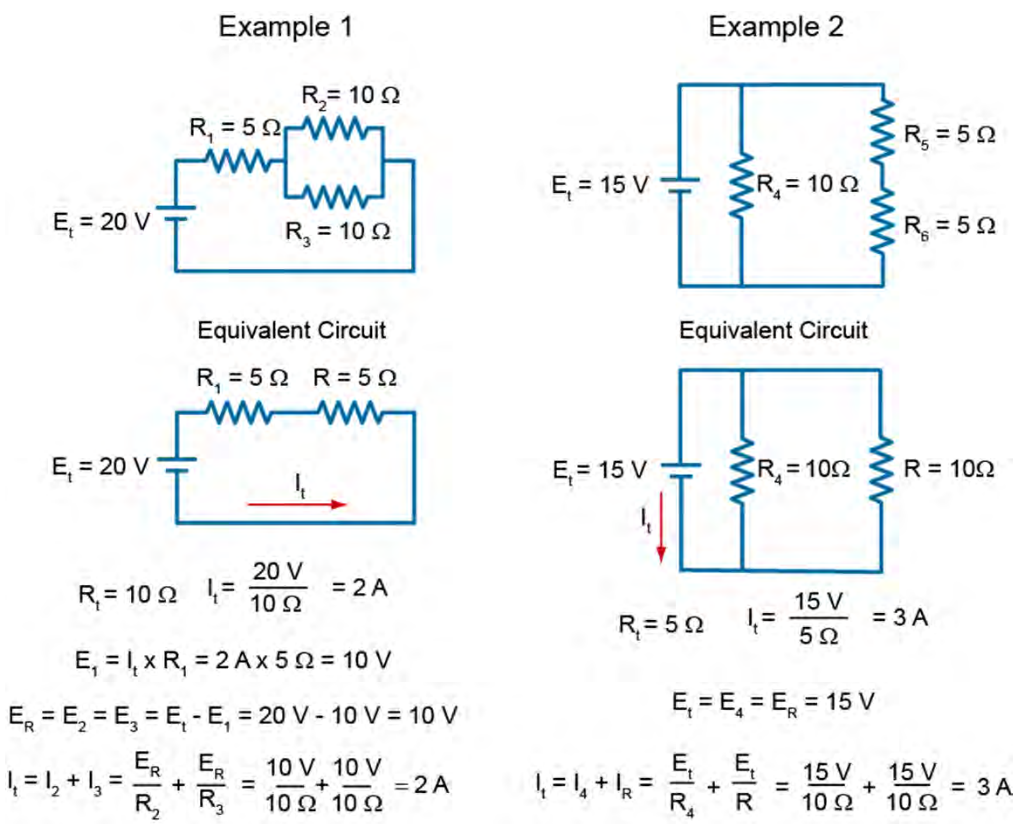


Using the same two series-parallel circuits as in the previous example, but with source voltages included, the accompanying illustration shows how Ohm's law can be used to calculate current values.

Power in a DC Circuit

Direct Current Power Formulas

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

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

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

Ohm's Law

$$E = I \times R = IR$$

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

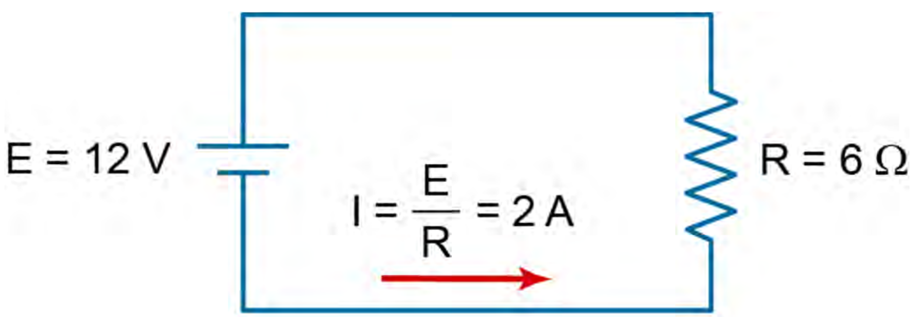
Whenever a force of any kind causes motion, work is accomplished. If a force is exerted without causing motion, then no work is done.

In an electrical circuit, voltage applied to a conductor causes electrons to flow. Voltage is the force and electron flow is the motion. The rate at which work is done is called power and is represented by the symbol "P."

Power is measured in watts, 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.

As shown on the left, from the formula power (P) = current (I) times voltage (E), the other formulas for power can be derived using Ohm's law.

DC Circuit Power Example



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

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

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

The accompanying illustration shows how power can be calculated using any of the power formulas.

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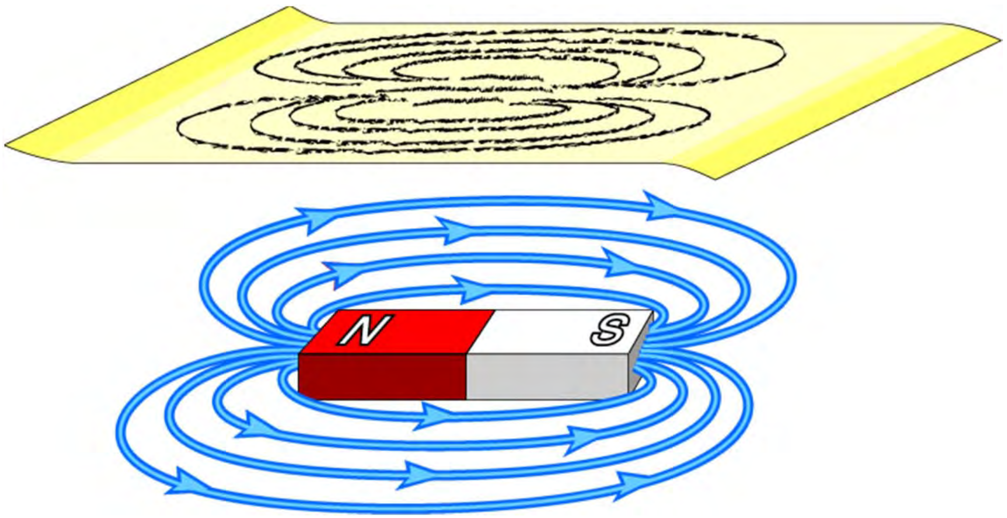
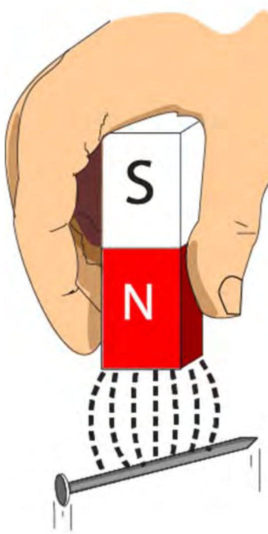
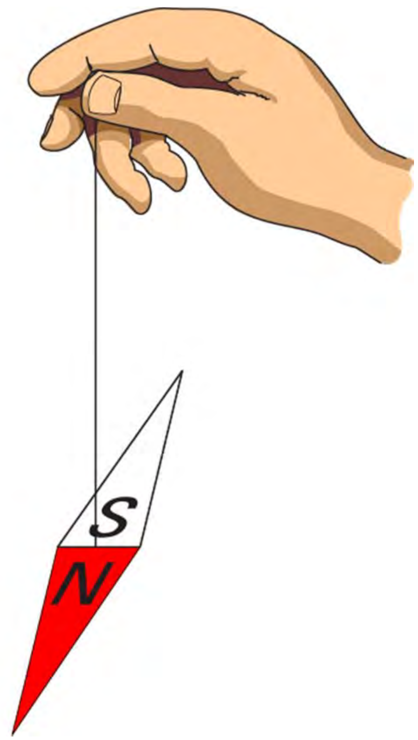


This chapter covers the following **topics:**

- Direct Current Basics
- DC Circuits
- **Magnetism**

Permanent Magnets



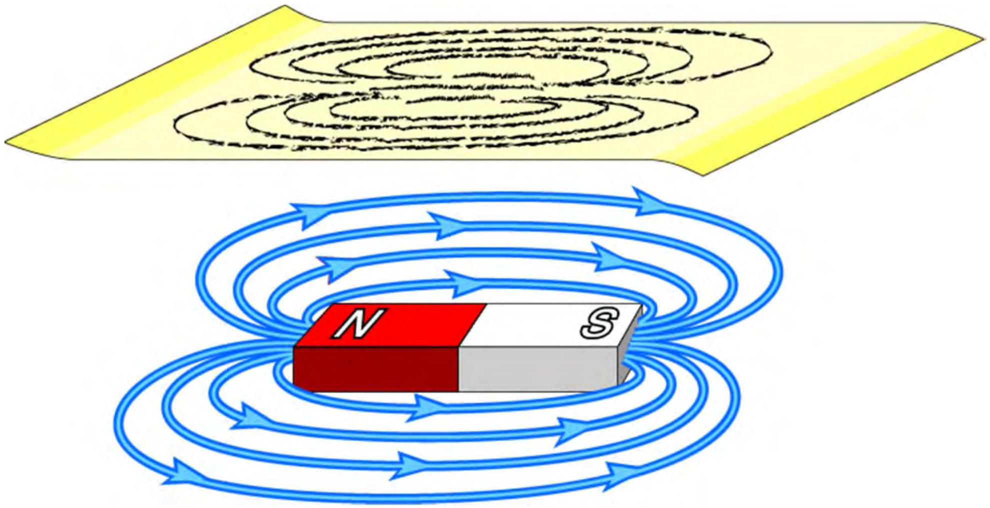


Magnetism and electricity are related concepts. Magnetism can be used to produce electric current and electric current produces a magnetic field.

When we think of a permanent magnet, we often envision a horseshoe 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 will assume a north-south orientation.

Magnetic Lines of Flux

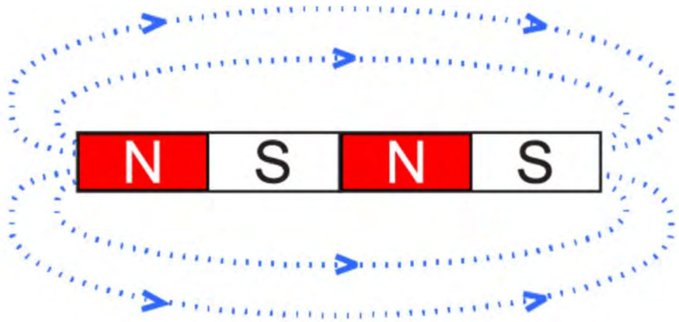


Every magnet has two poles, a north pole and a south pole. Invisible magnetic lines of flux leave the north pole and enter the south pole.

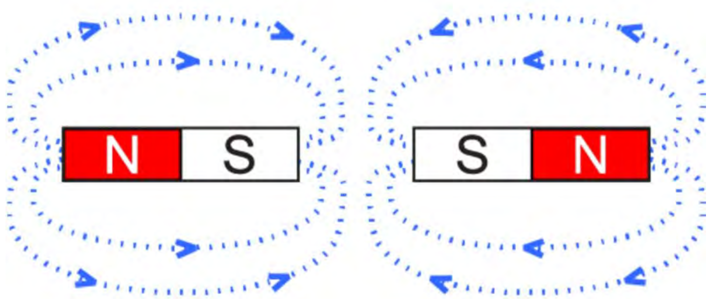
Although the lines of flux are invisible, the effects of magnetic fields can be made visible. When a sheet of paper is placed on a magnet and iron filings loosely scattered over it, the filings arrange themselves along the invisible lines of flux.

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



Unlike Poles Attract



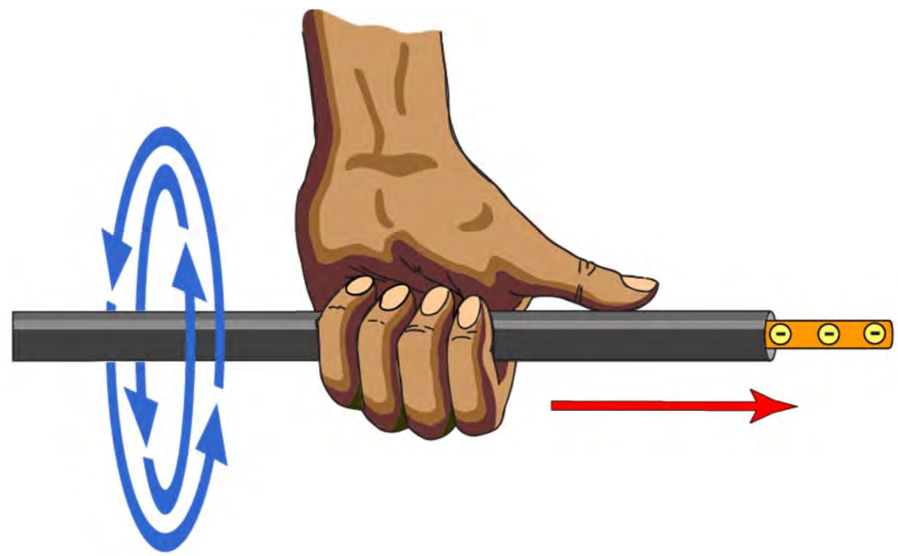
Like Poles Repel

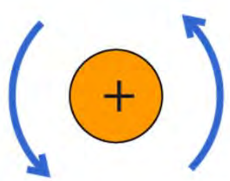
When two magnets are brought together, the magnetic field around the magnets causes some form of interaction.

When two unlike poles are brought together, the magnets attract each other.

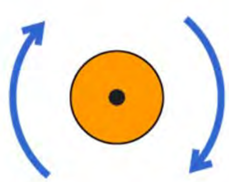
When two like poles are brought together, the magnets repel each other.

Electromagnetism





Electron Flow Away From You
Causes Counterclockwise Magnetic Flux

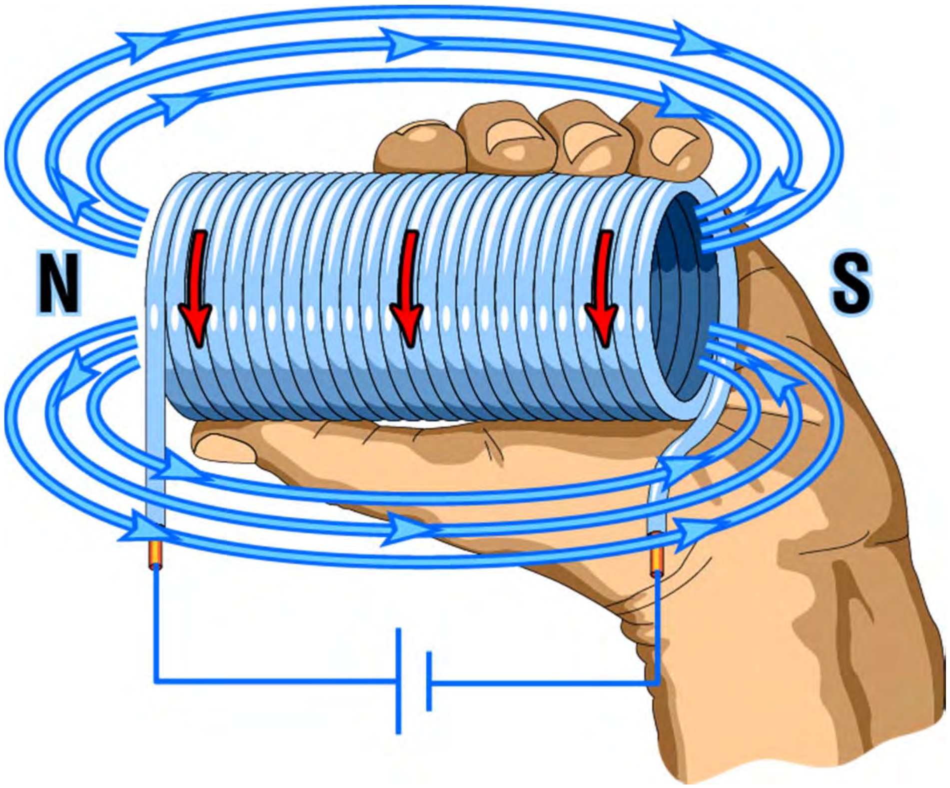


Electron Flow Towards You
Causes Clockwise Magnetic Flux

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.

Electromagnets



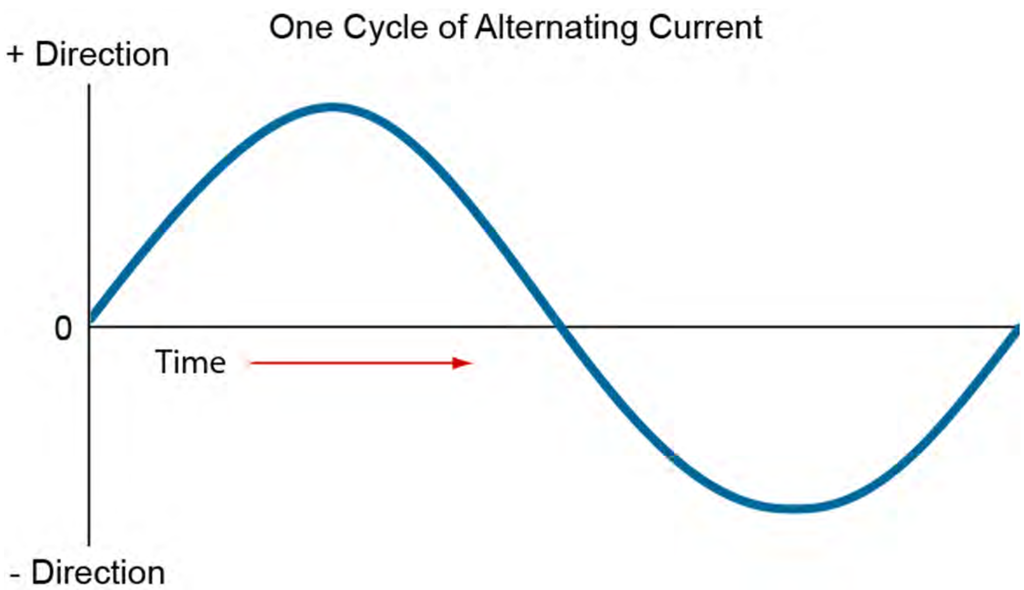
A coil of wire carrying a current, acts like a magnet. Individual loops of wire act as small magnets. The individual fields add together to form one magnet. The strength of the field can be increased by adding more turns to the coil, increasing the amount of current, or winding the coil around a material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

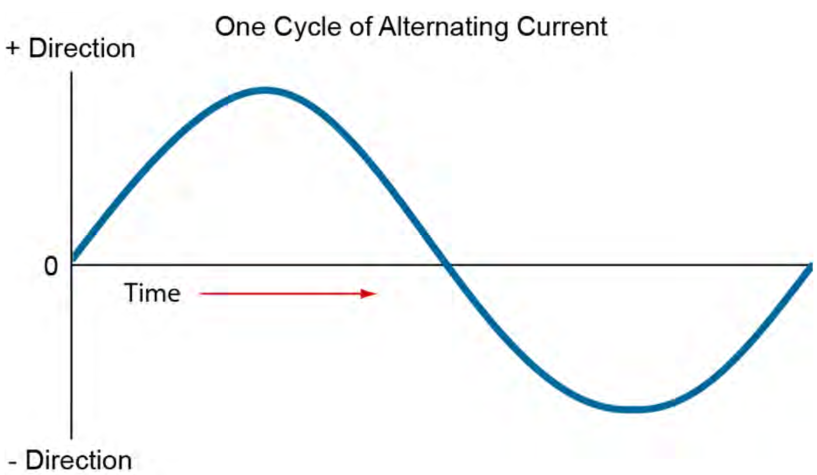
Chapter 2 – Alternating Current



This chapter covers the following topics:

- **Alternating Current Basics**
- Inductance and Capacitance
- AC Circuits
- Transformers

Alternating Current



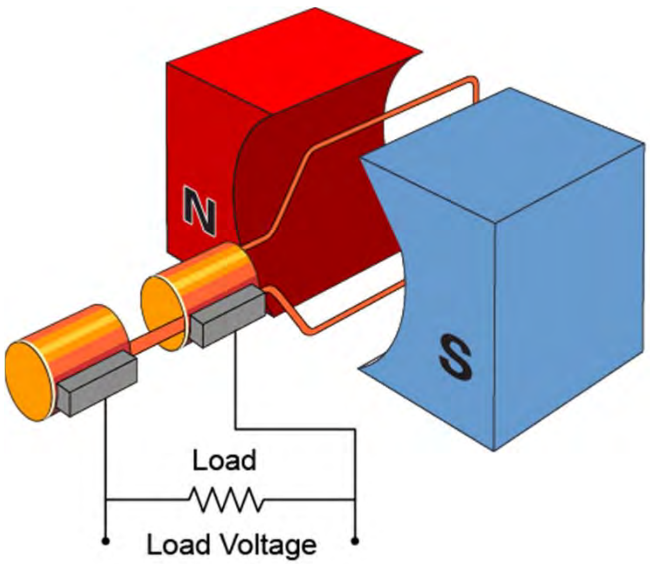
Current may come from a direct current (DC) source or an alternating current (AC) source. In a direct current circuit, electrons flow continuously in one direction from the source of power through a conductor to a load and back to the source of power. Voltage polarity for a DC source remains constant.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

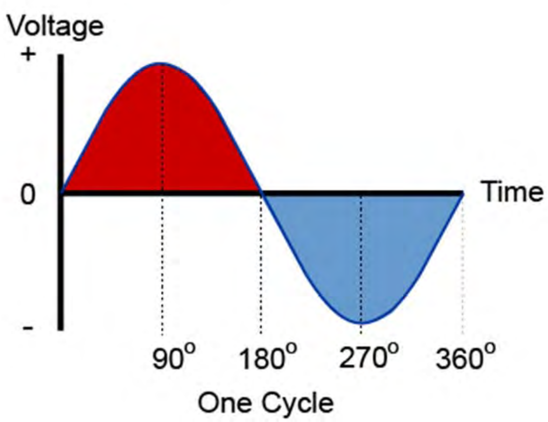
By contrast, an AC generator makes electrons flow first in one direction and then in another. In fact, an AC generator reverses its terminal polarities many times a second, causing current to change direction with each reversal.

Alternating voltage and current vary continuously in a pattern referred to as a sine wave. A sine wave can represent current or voltage. The accompanying illustration shows one cycle of a sign wave on a graph with 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 complete cycle of a sine wave has 360 degrees. Alternating current and voltage go through many of these cycles each second.

Basic AC Generator



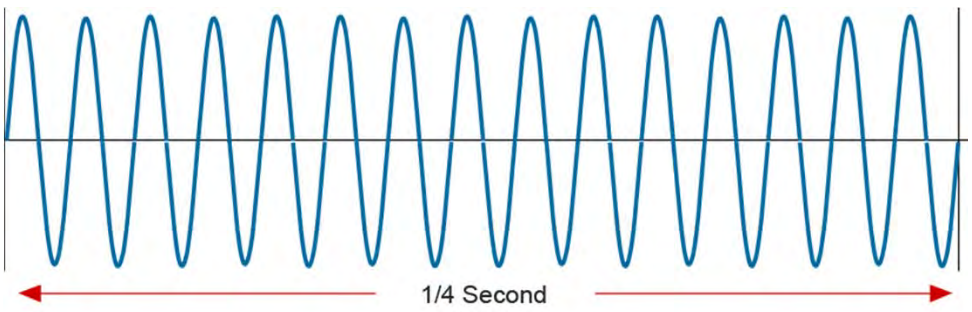


A basic generator consists of a magnetic field, an armature, slip rings, and brushes which connect to the load. In a commercial generator, the magnetic field is usually created by an electromagnet, but, this simple generator has permanent magnets. An armature is any number of conductive wires wound in loops which rotates through the magnetic field. For simplicity, this simple generator has only one loop.

As the armature rotates through the magnetic field, a voltage is generated in the armature, causing 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 the load, which in this case is a resistor.

If the movement of the AC generator is tracked through a complete rotation of 360 degrees, during the first quarter of a revolution, voltage increases until it reaches a maximum positive value at 90 degrees. Voltage decreases during the next quarter cycle to zero at 180 degrees. During the third quarter cycle, voltage increases in a negative direction and reaches a peak at 270 degrees. During the last quarter cycle, voltage returns to zero. This is one complete revolution. This process continues as long as the generator is in operation.

Frequency

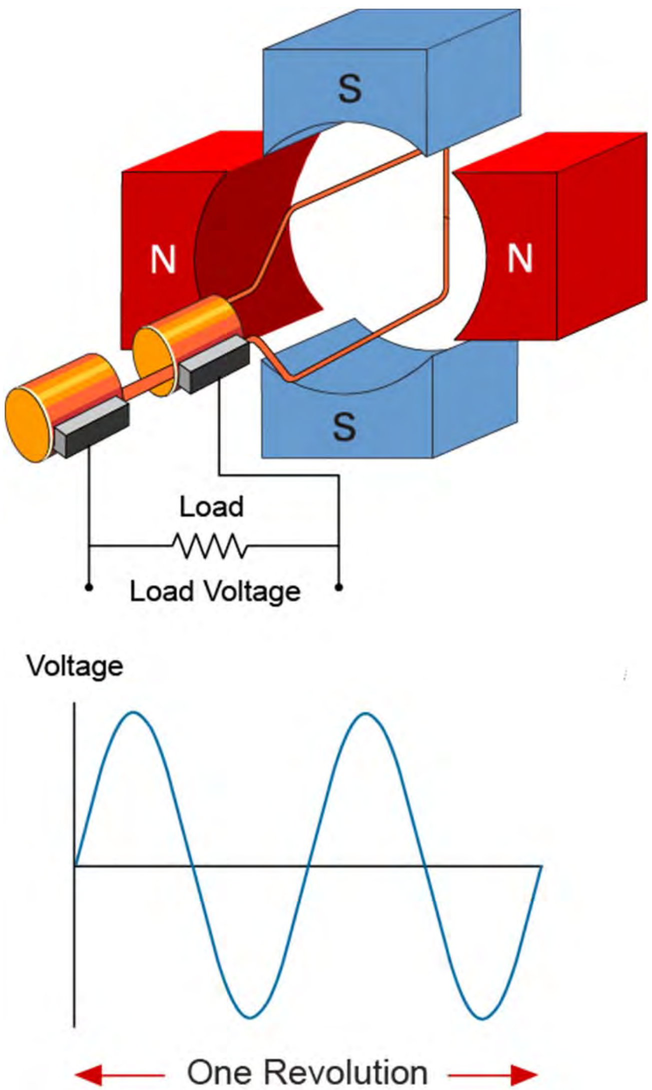


60 Hertz Alternating Current Waveform

The number of cycles per second of voltage and current induced in the armature is the frequency of the generator. If the armature rotates at a speed of 60 revolutions per second, the generated voltage will be 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 accompanying illustration shows 15 cycles in 1/4 second which is equivalent to 60 Hz.

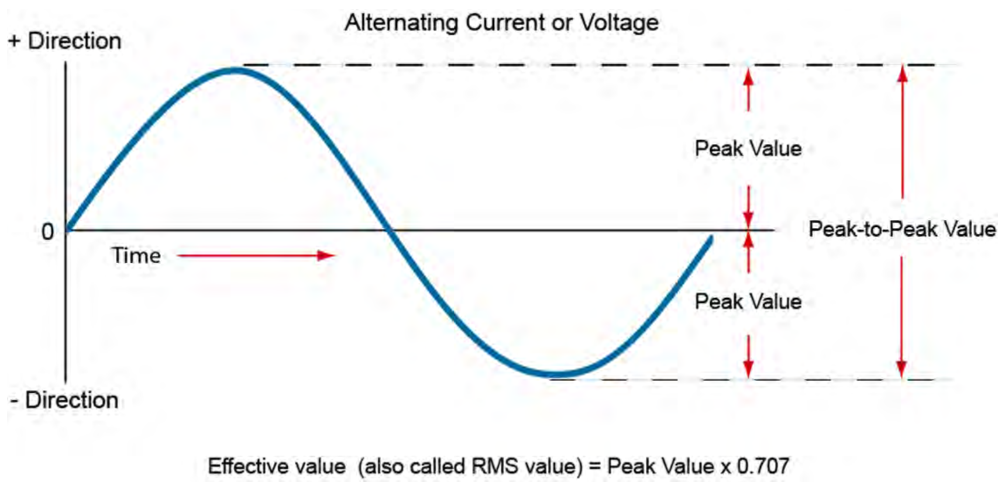
Four-Pole AC Generator



The frequency is the same as the number of rotations per second if the magnetic field is produced by only two magnetic 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, like the one shown on the left, completes two cycles per revolution. In other words, an AC generator produces one cycle per revolution for each pair of poles.

Amplitude



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.

The peak value of a sine wave is the maximum value for each half of the sine wave.

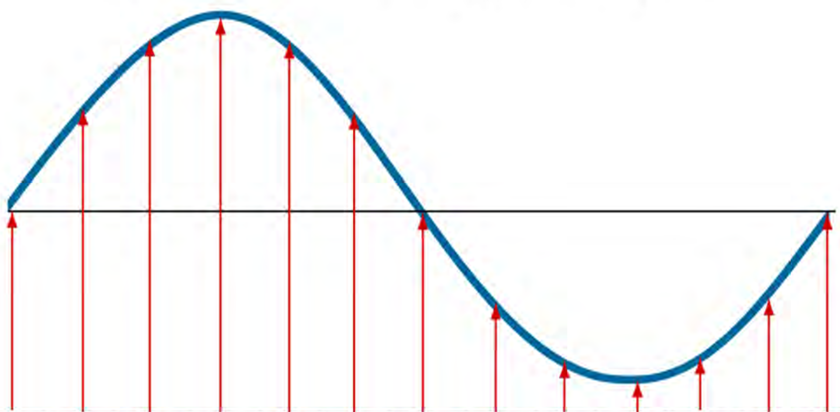
The peak-to-peak value is the range from the positive peak to the negative peak. This is twice the peak value.

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 determine the effective value of a waveform.

Instantaneous Value

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 V)(0.5) = 85 V

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 accompanying illustration, the instantaneous voltage (e) and current (i) at any point on the sine wave is 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. Also note that the angle is often symbolized by a Greek letter such as Theta (θ).

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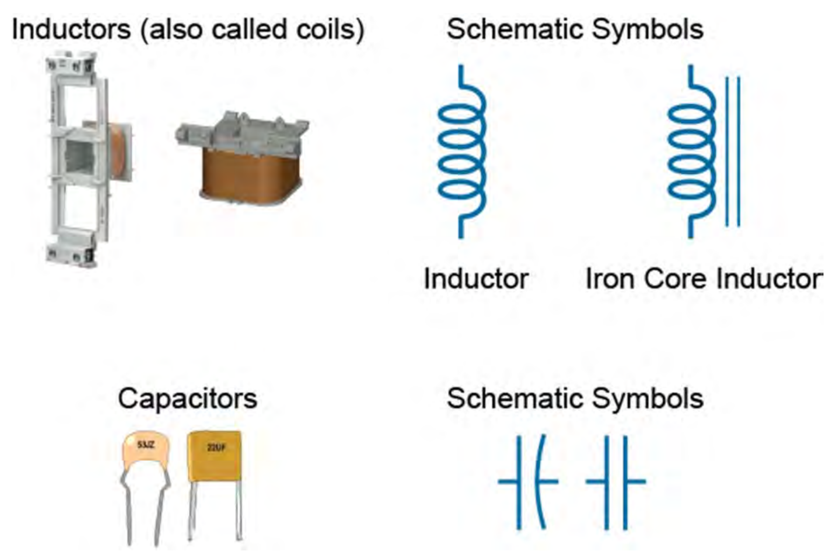
Chapter 2 – Alternating Current

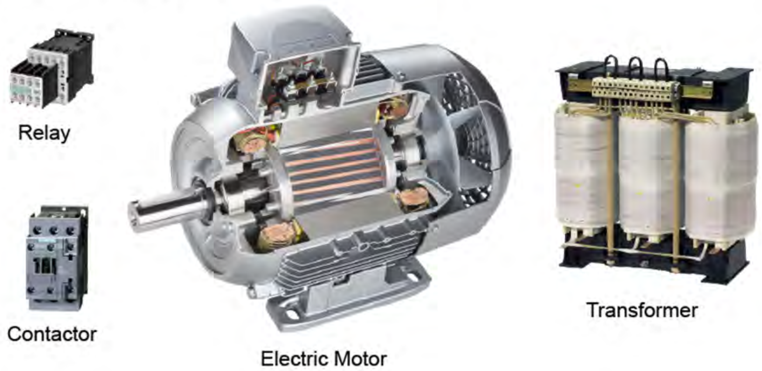


This chapter covers the following topics:

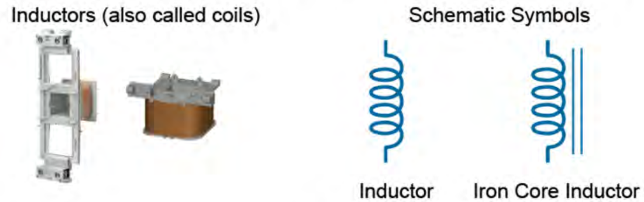
- Alternating Current Basics
- **Inductance and Capacitance**
- AC Circuits
- Transformers

Inductance and Inductors

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



Inductors are components manufactured to have a specific inductance.



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

Commonly Used Units		
Unit	**Short Form**	**Decimal Value**
1 henry	1 h	1 h
1 millihenry	1 mh	0.001 h
1 microhenry	1 µh	0.000001 h

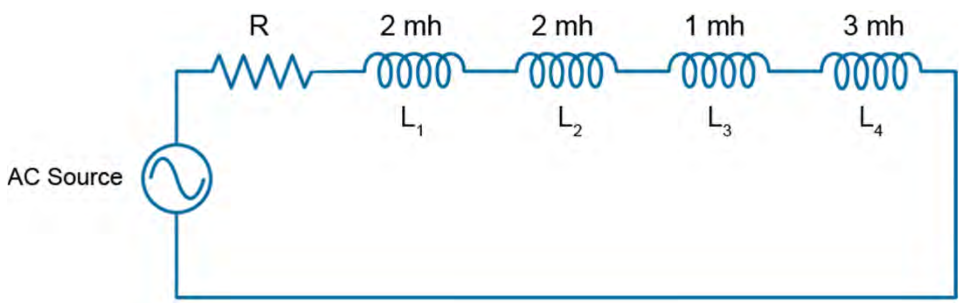
The circuits shown to this point have been resistive. Resistance and voltage are not the only circuit properties that effect current flow, however. Resistance opposes current flow. Inductance opposes changes in current flow. Inductance is designated by the letter “L”. The unit of measurement for inductance is the henry (h).

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 is referred to as counter emf because it opposes the change in current.

All circuits have inductance, but an inductor is a coil 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.

Inductors in Series



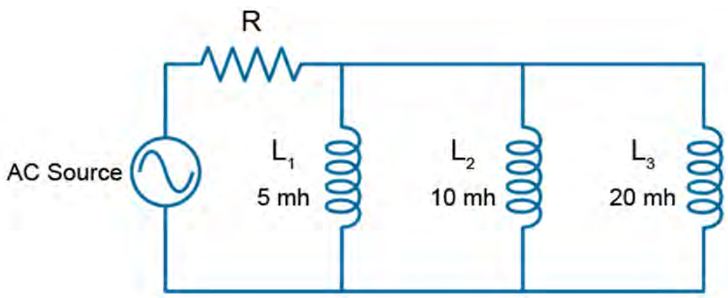
$$L_t = L_1 + L_2 + L_3 + L_4 = 2\text{ mh} + 2\text{ mh} + 1\text{ mh} + 3\text{ mh} = 8\text{ mh}$$

Commonly Used Units		
Unit	**Short Form**	**Decimal Value**
1 henry	1 h	1 h
1 millihenry	1 mh	0.001 h
1 microhenry	1 µh	0.000001 h

The accompanying circuit diagram shows an AC source that supplies electrical power through a resistor to four inductors connected in series. The total inductance of series inductors is equal to the sum of the inductances.

Because the henry is a large unit of inductance, inductance is often expressed using metric unit prefixes. For example, 0.001 h is equal to 1 millihenry or 1 mh for short.

Inductors in Parallel



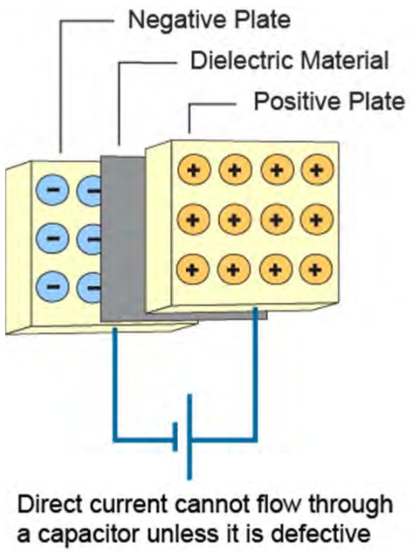
$$\frac{1}{L_t} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} = \frac{1}{5\text{ mh}} + \frac{1}{10\text{ mh}} + \frac{1}{20\text{ mh}} = \frac{4}{20\text{ mh}} + \frac{2}{20\text{ mh}} + \frac{1}{20\text{ mh}} = \frac{7}{20\text{ mh}}$$

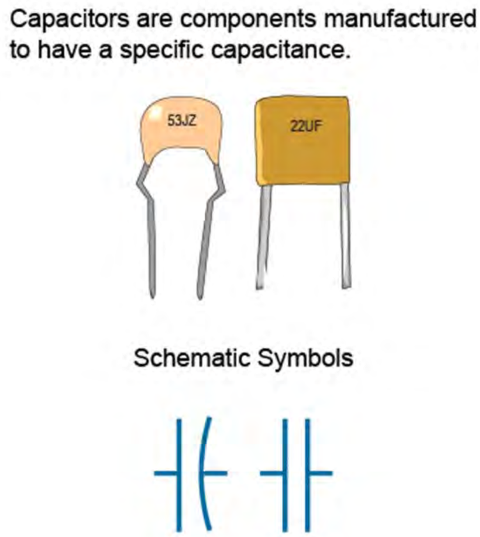
$$L_t = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}} = \frac{1}{\frac{7}{20\text{ mh}}} = \frac{20\text{ mh}}{7} = 2.86\text{ mh}$$

The accompanying circuit diagram shows an AC source that supplies electrical power through a resistor to three parallel inductors. Connecting inductors in series decreases the total inductance.

The total inductance of parallel inductors is calculated using a formula similar to the formula for the resistance of parallel resistors.

Capacitance and Capacitors





Commonly Used Units		
Unit	**Short Form**	**Decimal Value**
1 farad	1 F	1 F
1 microfarad	1 µF	0.000001 F
1 picofarad	1 pF	0.000000000001 F

Capacitance is a measure of a circuit's ability to store an electrical charge. All circuits have some amount of capacitance, but a capacitor is a device manufactured to have a specific amount of capacitance.

A capacitor is made up of a pair of conductive plates separated by a thin layer of insulating material called a dielectric.

When a voltage is applied to the plates, electrons are forced onto one plate. That plate has an excess of electrons while the other plate has a deficiency of electrons. The plate with an excess of electrons is negatively charged. The plate with a deficiency of electrons is positively charged.

Direct current cannot flow through the dielectric because it is an insulator; however, the electric field created when the capacitor is charged is felt through the dielectric.

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

Capacitors in Series

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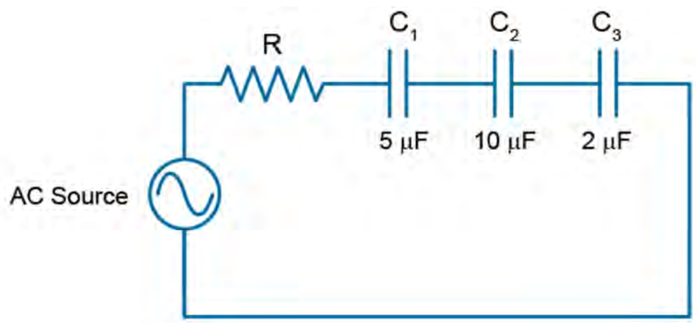


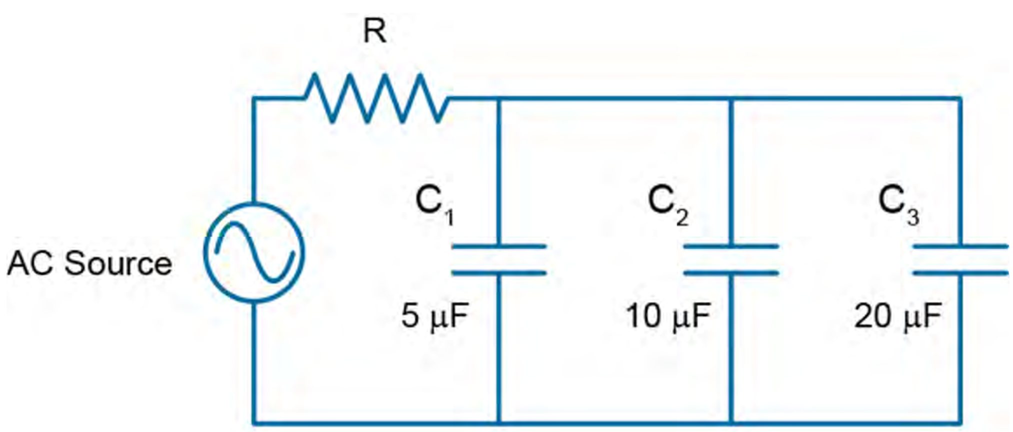
$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_3} + \frac{1}{C_2} = \frac{1}{5\ \mu F} + \frac{1}{10\ \mu F} + \frac{1}{2\ \mu F} = \frac{2}{10\ \mu F} + \frac{1}{10\ \mu F} + \frac{5}{10\ \mu F} = \frac{8}{10\ \mu F}$$

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

The accompanying circuit diagram shows an AC source that supplies electrical power through a resistor to three series capacitors. Connecting capacitors in series decreases the total capacitance.

The total capacitance of series capacitors is calculated using a formula similar to the formula for the resistance of parallel resistors.

Capacitors in Parallel



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

The accompanying circuit diagram shows an AC source that supplies electrical power through a resistor to three parallel capacitor. Connecting capacitors in parallel increases the total capacitance.

The total capacitance of parallel capacitors is equal to the sum of the capacitances.

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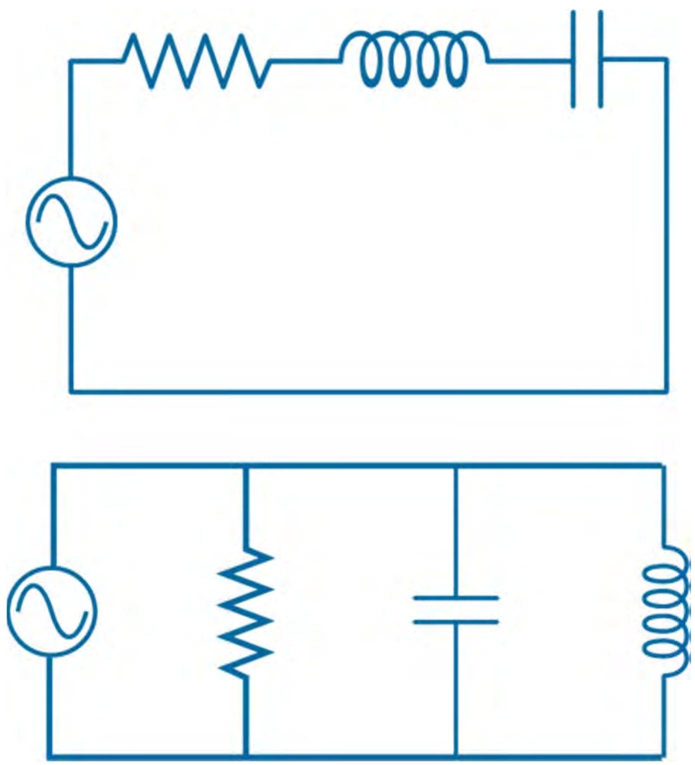
Chapter 2 – Alternating Current



This chapter covers the following topics:

- Alternating Current Basics
- Inductance and Capacitance
- **AC Circuits**
- Transformers

Inductive Reactance

Inductive Reactance $(X_L) = 2\pi fL$

f = Frequency, L = Inductance
2π is approximately equal to 6.28

If f = 60 Hz and L = 100 mh

$X_L = 6.28 \times 60 \times 0.1 = 37.7\ \Omega$

The same inductor has a inductive reactance of 628 Ω at 1 kHz.

$X_L = 6.28 \times 1000 \times 0.1 = 628\ \Omega$

(Note: 100 mh = 0.1 h)

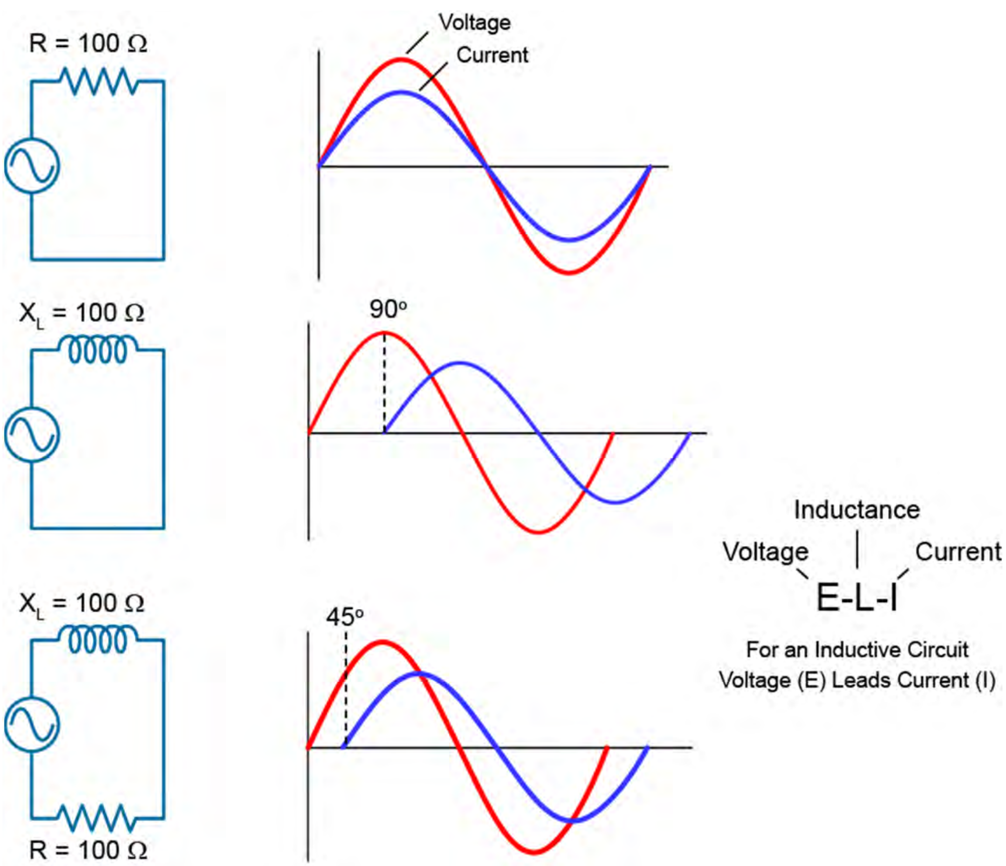
In a purely resistive AC circuit, resistance is the only opposition to current flow. In an AC circuit with only inductance, capacitance, or both inductance and capacitance, but no resistance, opposition to current flow is called reactance, designated by the symbol "X."

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.

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. Inductance in an AC circuit, therefore, causes a continual opposition. This opposition to current flow is called inductive reactance. As the accompanying formula for Inductive reactance (X_L) shows, it is proportional to both inductance (L) and frequency (f).

Current and Voltage Phases



In a purely resistive circuit, current and voltage rise and fall at the same time. They are said to be "in phase." For the circuit in the top illustration, there is no inductance. Therefore, resistance and impedance are the same.

In a purely inductive circuit, voltage leads current by 90 degrees. Current and voltage are said to be "out of phase." For the circuit in the middle illustration, impedance and inductive reactance are the same.

All circuits have some resistance, however, and in an AC circuit with both resistance and inductive reactance, voltage leads the current by more than 0 degrees and less than 90 degrees. For the circuit in the bottom illustration, resistance and inductive reactance are equal and voltage leads current by 45 degrees.

Another way to say this is that current lags the voltage in a circuit with resistance and inductance. 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 out of phase it is.

Capacitive Reactance

$$\text{Capacitive Reactance } (X_c) = \frac{1}{2\pi fC}$$

f = Frequency, C = Capacitance
2π is approximately equal to 6.28

If f = 60 Hz and C = 100 μF

$$X_c = \frac{1}{6.28 \times 60 \times 0.0001} = \frac{1}{0.0377} = 26.5\ \Omega$$

The same capacitor has a capacitive reactance of 1.59 Ω at 1 kHz

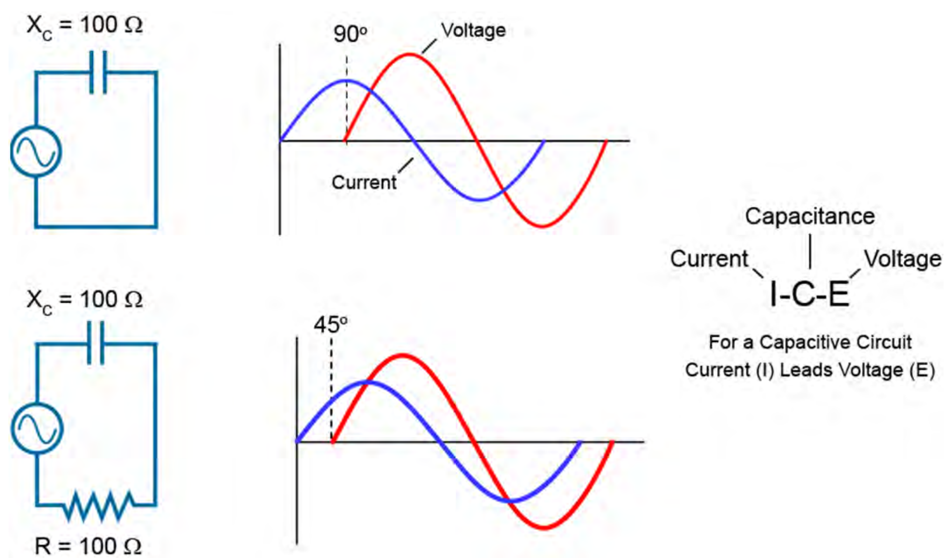
$$X_c = \frac{1}{6.28 \times 1000 \times 0.0001} = \frac{1}{0.628} = 1.59\ \Omega$$

(Note: 100 μF = 0.0001 F)

Capacitors also oppose current flow in an AC circuit. This opposition is called capacitive reactance.

Capacitive reactance is inversely proportional to frequency and capacitance. Therefore, the larger the capacitor or the higher the frequency, the smaller the capacitive reactance. .

Current and Voltage Phases

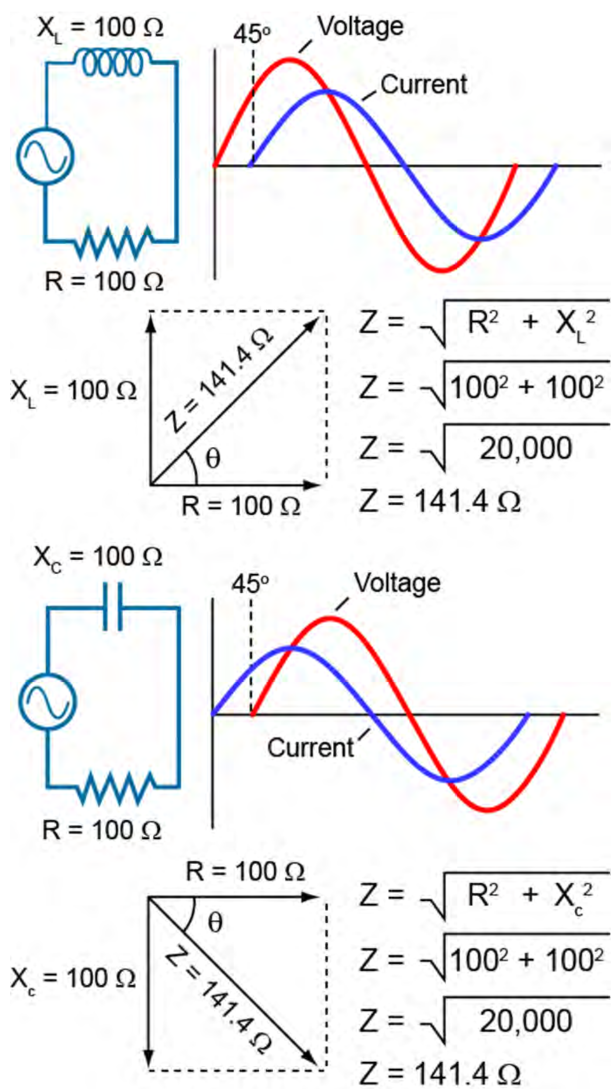


For capacitive circuits, the phase relationship between current and voltage is opposite to the phase relationship for an inductive circuit. In a purely capacitive circuit, current leads voltage by 90 degrees.

In an AC circuit with both resistance and capacitive reactance, 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 bottom illustration, resistance and capacitive reactance are equal and current leads voltage by 45 degrees.

Calculating Impedance



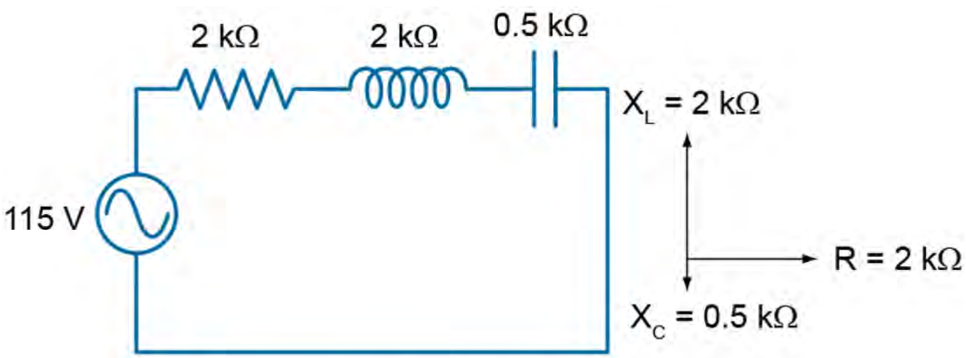
Impedance (Z) is the total opposition to current flow in an AC circuit. Impedance is often represented as a vector. A vector is a quantity that has magnitude and direction.

An impedance vector diagram shows reactance and resistance vectors at right angels to each other with the impedance vector plotted at some angle in between the reactance and resistance vectors. Resistance is plotted at 0 degrees, inductive reactance at 90 degrees, and capacitive reactance at -90 degrees.

The accompanying illustration shows two circuits with equal values of resistance and reactance. The upper circuit has inductive reactance and resistance, and the lower circuit has capacitive reactance and resistance. The magnitude of the impedance vectors is determined by taking the square root of the sum of the squares of reactance and resistance.

Although the magnitude of the impedance vector (141.4 ohms) is the same for both circuits, the angles of the impedance vectors are different. For the upper circuit, the impedance vector has an angle of +45 degrees, but for the lower circuit, the angle is -45 degrees. Note the relationship between the impedance vector angle and the phase relationship between voltage and current for each circuit.

Series R-L-C Circuit



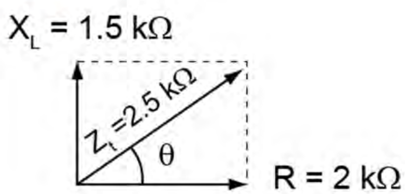
$$Z_t = \sqrt{R^2 + (X_L - X_C)^2}$$

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

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

$$Z_t = 2500\ \Omega = 2.5\ k\Omega$$

Z_t = Total Impedance



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

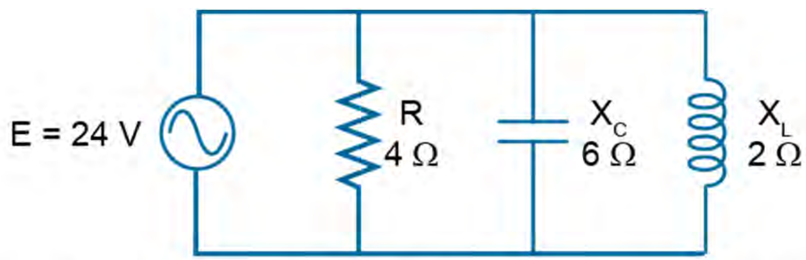
Many circuits contain values of resistance, inductance, and capacitance in series. In an inductive AC circuit, current lags voltage by 90 degrees. In a capacitive AC circuit, current leads voltage by 90 degrees. When represented in vector form, inductive reactance and capacitive reactance are plotted 180 degrees apart. As a result, the net reactance is determined by taking the difference between the two reactances.

The total impedance of the circuit can be calculated using the formula shown in the accompanying illustration. Once the total impedance is known, the current can be determined using Ohm's law.

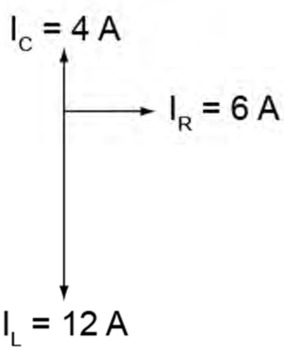
Keep in mind that because both inductive reactance and capacitive reactance are dependent upon frequency, if the frequency of the source voltage changes, the net reactance changes. For example, if frequency increases, inductive reactance increases and capacitive reactance decreases.

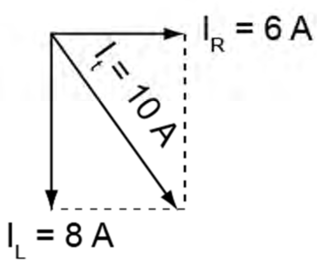
For the special case where the inductive reactance and capacitive reactance are equal, the circuit impedance is the total resistance. This type of circuit is called a series resonant circuit.

Parallel R-L-C Circuit



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





I_t = Total Current

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

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

$$I_t = \sqrt{100}$$

$$I_t = 10\ A$$

Z_t = Total Impedance

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

$$Z_t = 2.4\ \Omega$$

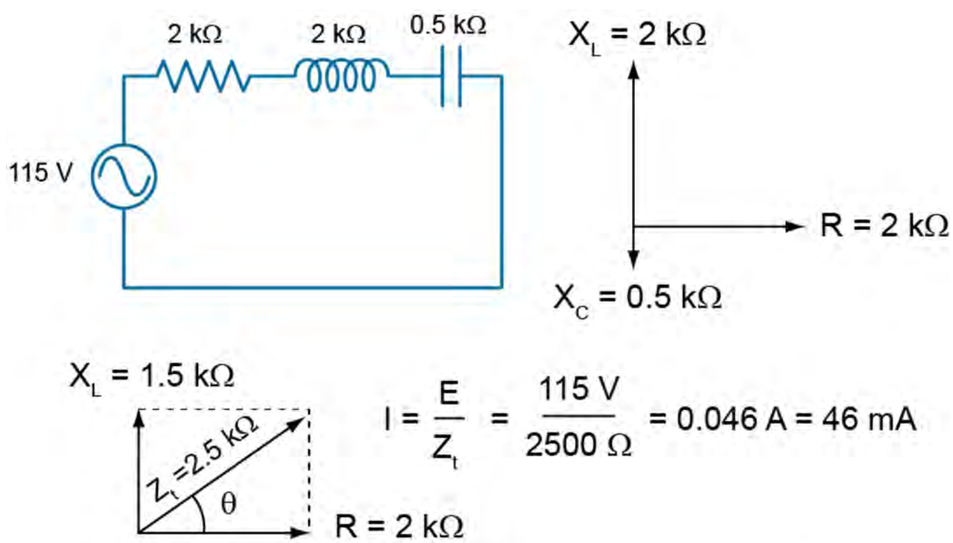
Many circuits contain values of resistance, inductance, and capacitance in parallel. One method for determining the total impedance for a parallel circuit is to begin by calculating the total current.

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 using the formula shown in the accompanying illustration. Once the total current is known, the total impedance can be calculated using Ohm's law.

Keep in mind that because both inductive reactance and capacitive reactance are dependent upon frequency, if the frequency of the source voltage changes, the reactances and corresponding currents 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.

Power in an AC Circuit



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

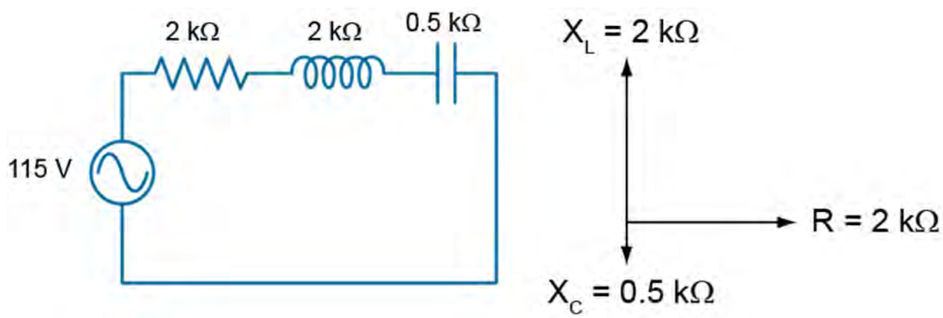
Apparent Power = $IE = 0.046\ A \times 115\ V = 5.29\ VA$

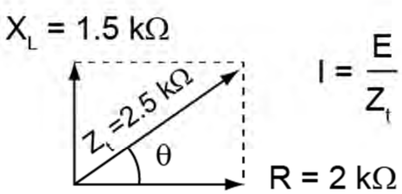
In resistive circuits, power is dissipated in heat. This is called true power or effective power because it is the rate at which energy is used. True power is equal to the current squared times the resistance. The unit for true power is the watt.

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-amperes reactive.

The vector sum of true power and reactive power is called apparent power. Apparent power is also equal to the total current multiplied by the applied voltage (P = IE). The unit for apparent power is the volt-ampere (VA).

Power Factor





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

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

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

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

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

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

$$\text{True Power} = IE\cos\theta = 0.046\ \text{A} \times 115\ \text{V} \times 0.8 = 4.232\ \text{W}$$

Power factor is the ratio of true power to apparent power in an AC circuit. 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 accompanying illustration, the power factor is 0.8. This means that the circuit uses 80 percent of the energy supplied by the source and returns 20 percent to the source.

True power is equal to the apparent power times the power factor. This is I times E times the cosine of the phase angle.

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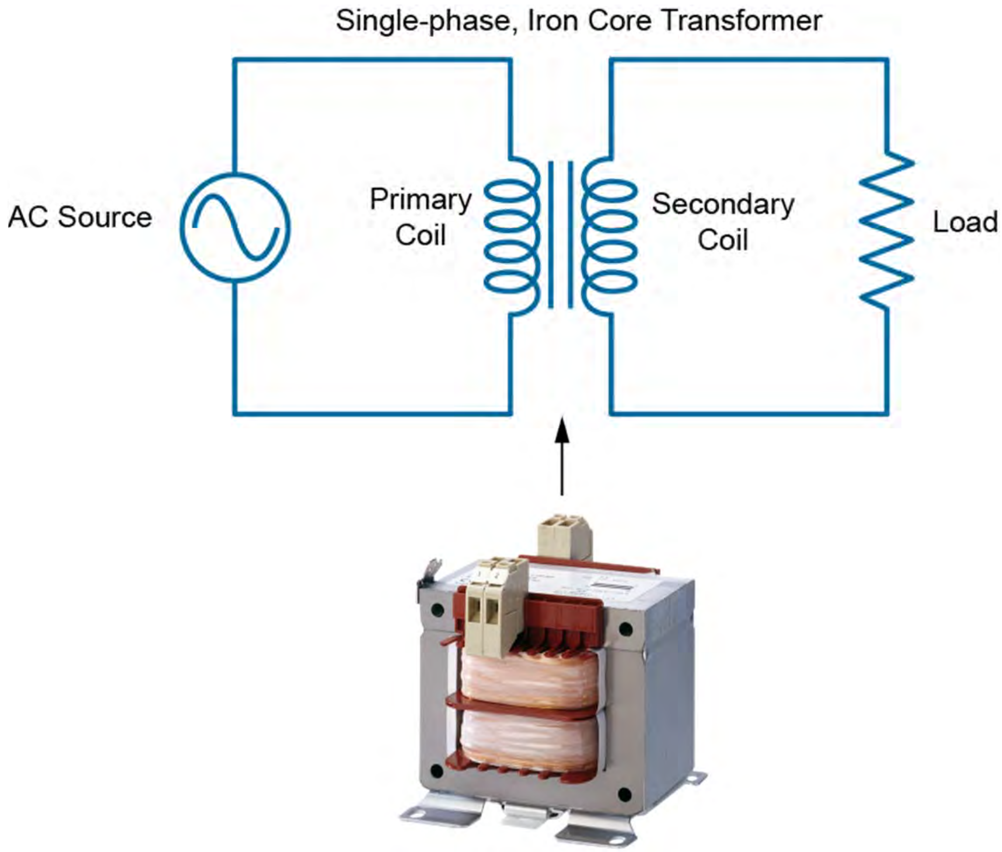
This chapter covers the following topics:

- Alternating Current Basics
- Inductance and Capacitance
- AC Circuits
- **Transformers**

Transformers



Transformers are electromagnetic devices that transfer electrical energy from one circuit to another by mutual induction. They are frequently used to step up or step down a voltage. Because direct current cannot flow from one transformer winding to another, transformers can also be used to provide DC isolation from one circuit to another.

A single-phase transformer has two coils, a primary coil and a secondary coil. Energy is transferred from the primary to the secondary via mutual induction.

The accompanying illustration shows an AC source connected to the primary coil. The magnetic field produced by the primary induces a voltage in the secondary coil, which supplies power to a load.

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 coil. To maximize the amount of coupling, both coils are often wound on the same iron core, which provides a good path for the lines of flux. The following discussions of step-up and step-down transformers apply to transformers with an iron core.

Transformer Turns Ratio

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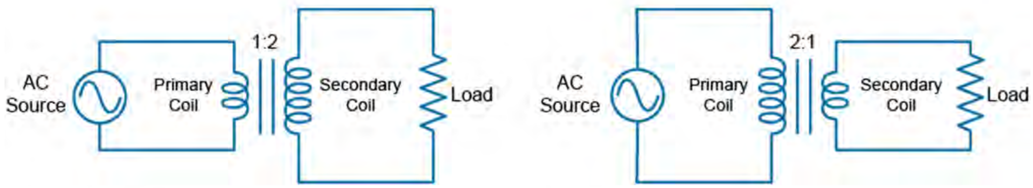
<u>Step-up Transformer Example</u>

Primary Voltage (E_P) = 120 V
Primary Current (I_P) = 10 A
Number of Primary Turns (N_P) = 900
Secondary Voltage (E_S) = 240 V
Secondary Current (I_S) = 5 A
Number of Secondary Turns (N_S) = 1800

<u>Step-down Transformer Example</u>

Primary Voltage (E_P) = 240 V
Primary Current (I_P) = 5 A
Number of Primary Turns (N_P) = 1800
Secondary Voltage (E_S) = 120 V
Secondary Current (I_S) = 10 A
Number of Secondary Turns (N_S) = 900



$$\frac{N_P}{N_S} = \frac{E_P}{E_S} = \frac{I_S}{I_P} \qquad E_S = \frac{N_S E_P}{N_P} \qquad I_S = \frac{N_P I_P}{N_S} \qquad Z_P = \left(\frac{N_P}{N_S}\right)^2 Z_L$$

Z_P = Impedance of the Primary
Z_L = Impedance of the Load

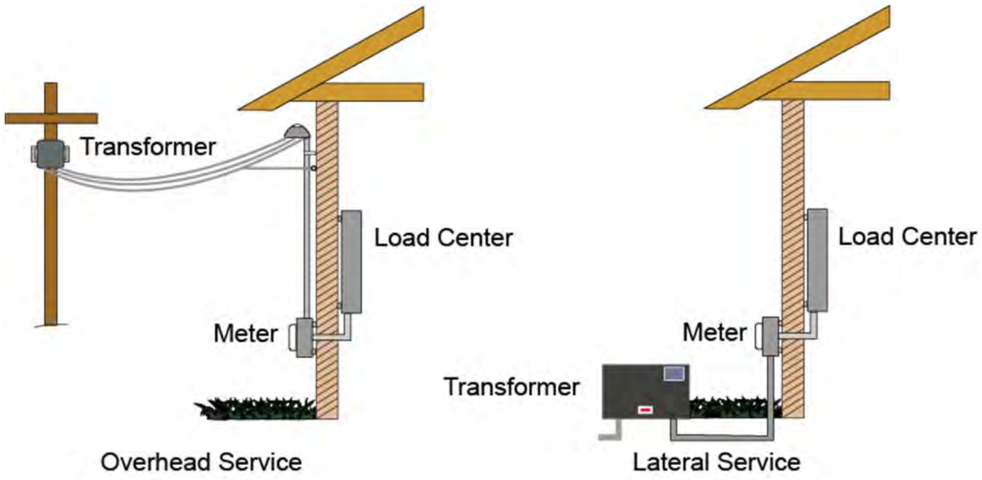
There is a relationship between primary and secondary voltage, current, and impedance and the ratio of transformer primary turns to secondary turns.

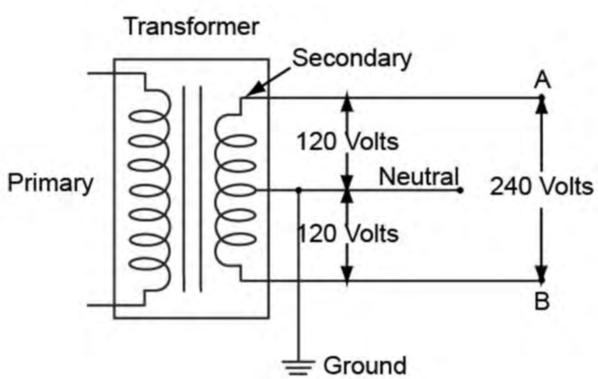
When the primary has fewer turns than the secondary, voltage is stepped up from primary to secondary. For the circuit on the left, the transformer secondary has twice as many turns as the primary, and voltage is stepped up from 120 VAC to 240 VAC. Because the impedance of the load is also higher than the impedance of the primary, current is stepped down from 10 amps to 5 amps.

When the primary has more turns than the secondary, voltage is stepped down from primary to secondary. For the circuit on the right, the primary coil has twice as many turns as the secondary coil, and voltage is stepped down from 240 VAC to 120 VAC. Because the impedance of the load is lower than the impedance of the primary, the secondary current is stepped up from 5 amps to 10 amps.

Transformers are rated for the amount of apparent power they can provide. Because values of apparent power are often large, the transformer rating is frequently given in kVA (kilovolt-amps).

Residential Transformers



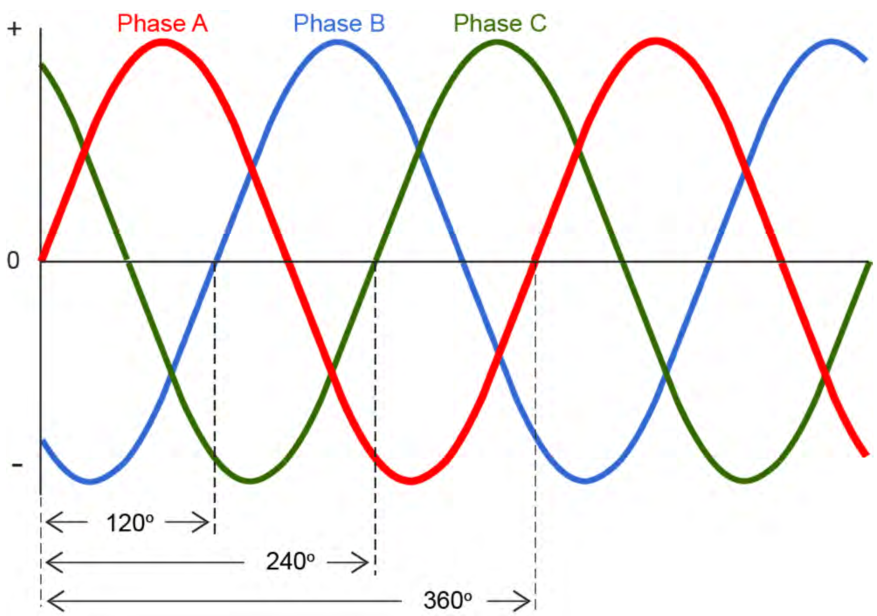


The most common power supply system used in residential applications in the United States today is a single-phase, three-wire supply system.

In this system, the voltage between either hot wire and neutral is 120 volts and the voltage between the two hot wires is 240 volts.

The 120-volt supply is used for general-purpose receptacles and lighting. The 240 volt supply is used for heating, cooling, cooking, and other high-demand loads

Three-Phase Power

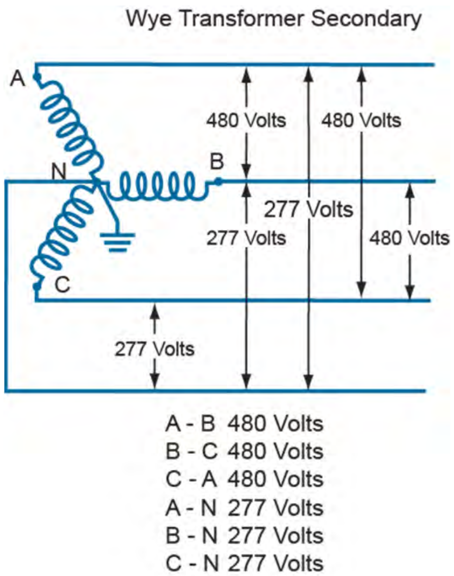


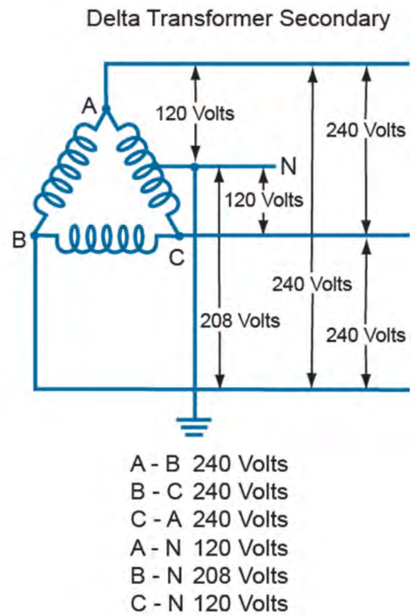
Up till now, we have been talking only about single-phase AC power. Single-phase power is used where power demands are relatively small, such as for a typical home.

However, power companies generate and distribute three-phase power. Three-phase power is used in commercial and industrial applications.

Three-phase power, as shown in the accompanying 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





Transformers used with three-phase power require three interconnected coils in both the primary and the secondary. These transformers can be connected in either a wye or a delta configuration. The type of transformer and the actual voltage depend on the requirements of the power company and the needs of the customer.

The accompanying illustration shows the secondary of a wye-connected transformer and the secondary of a delta-connected transformer. These are only examples of possible distribution configurations, the specific voltages and configurations vary widely depending upon the application requirements.

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Course Completion

This course covered the following topics:

Introduction

Chapter 1 – Direct Current

- Direct Current Basics
- DC Circuits
- Magnetism

Chapter 2 – Alternating Current

- Alternating Current Basics
- Inductance and Capacitance
- AC Circuits
- Transformers

This course has covered the topics shown on the left. Thank you for your efforts. You can complete this course by taking the final exam and scoring at least 70%.