Basics of Electricity

Electricity for Construction Engineers

ICRC

Basics of Electricity

A quick introduction course

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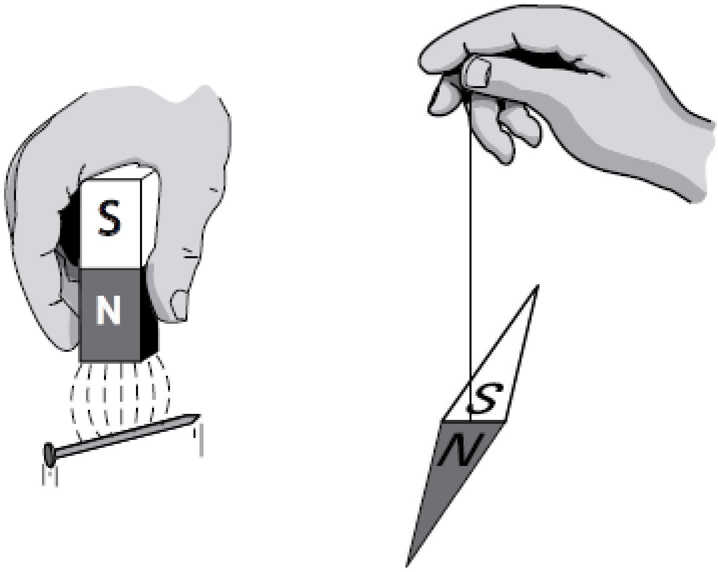
6. Magnetism

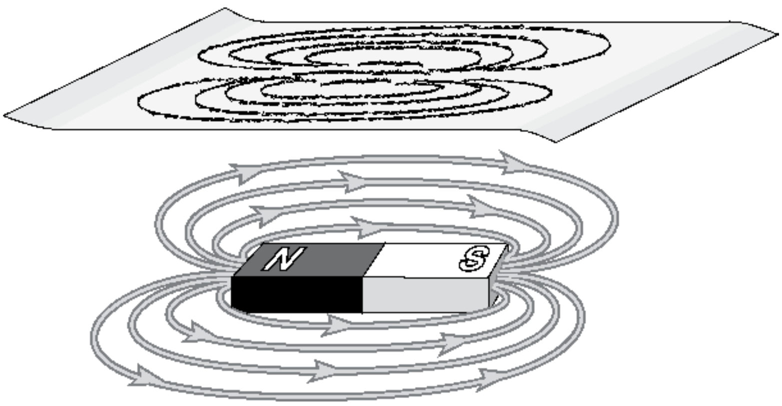
The principles of **magnetism** are an integral part of electricity. In fact, magnetism can be used to produce electric current and vice versa.

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

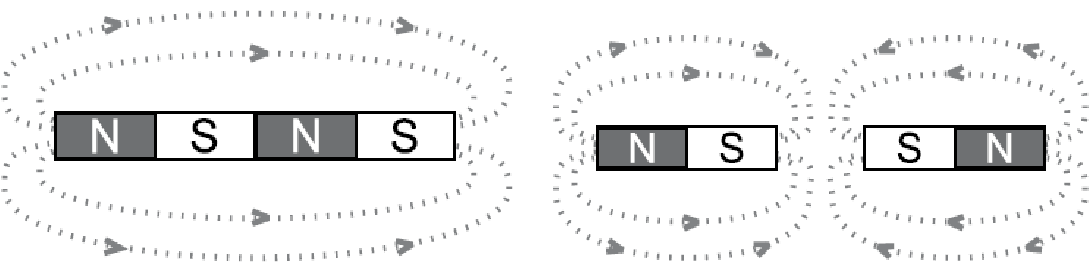
Every magnet has two **poles**, one north pole and one south pole. Invisible **magnetic lines of flux** leave the north pole and enter the south pole. While the lines of flux are invisible, the effects of magnetic fields can be made visible. When a sheet of paper is placed on a magnet and iron filings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

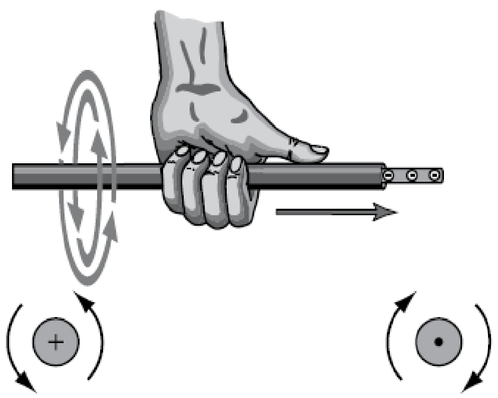


Unlike Poles Attract Like Poles Repel

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.



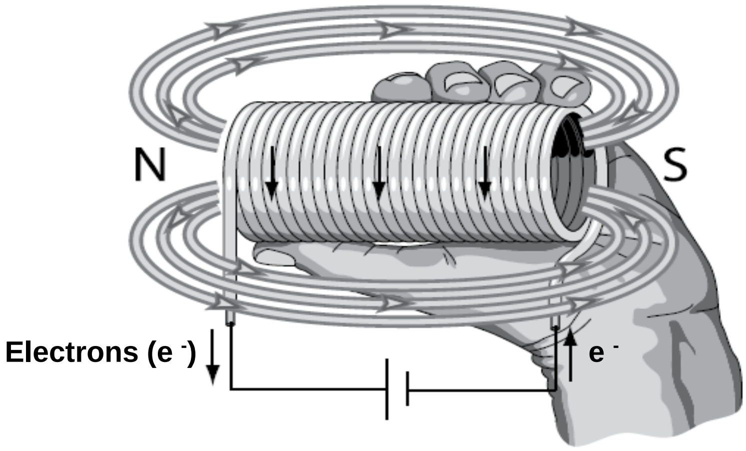
Electron Flow Away From You Causes Counterclockwise Magnetic Flux

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 or flux.

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 electrical flow, the fingers point in the direction of _____________________.

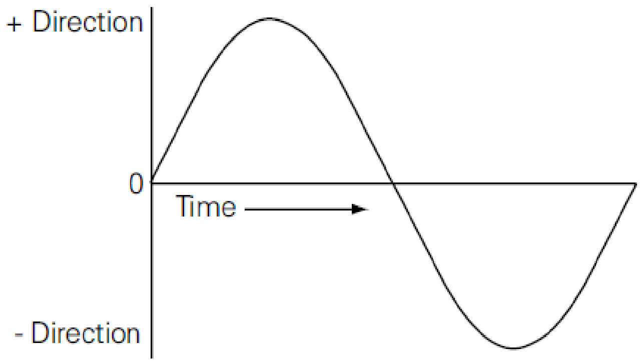
7. Alternating Current

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.

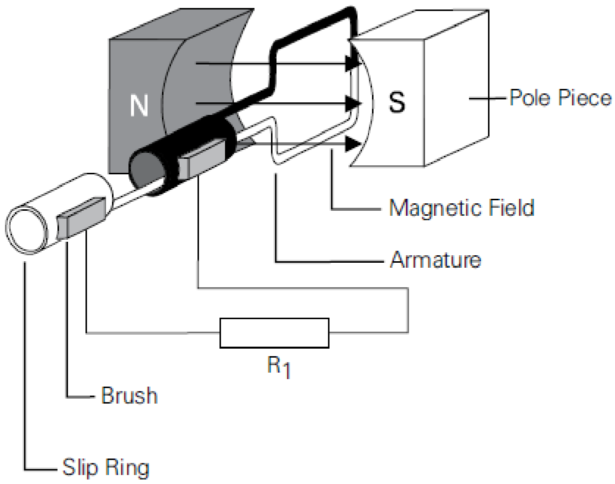
Basic AC Generator

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

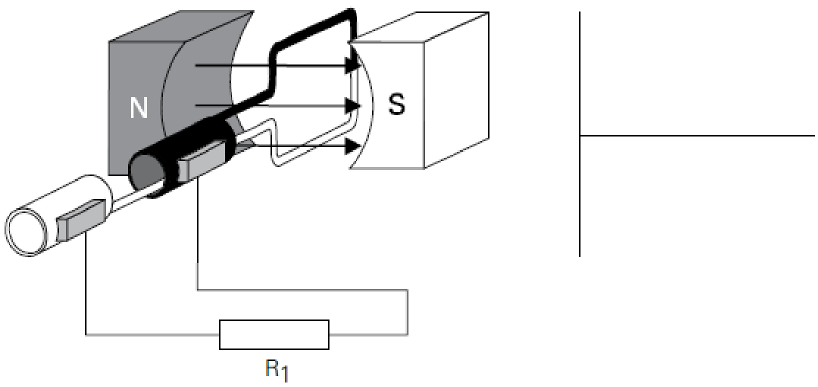
An **armature** is any number of conductive wires wound in loops which rotates through the magnetic field. For simplicity, one loop is shown below. When a conductor is moved through a magnetic field, a voltage is induced in the conductor: the voltage produced is due to the opposite of the variation of the magnetic flux. 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 rub against the slip rings to conduct current from the armature to a resistive load.

Rotating elements called **rotor** :
- ✓ Armature
- ✓ Slip rings

Static elements called **stator** :
- ✓ Magnet (Pole Piece)
- ✓ Brushes
- ✓ Load

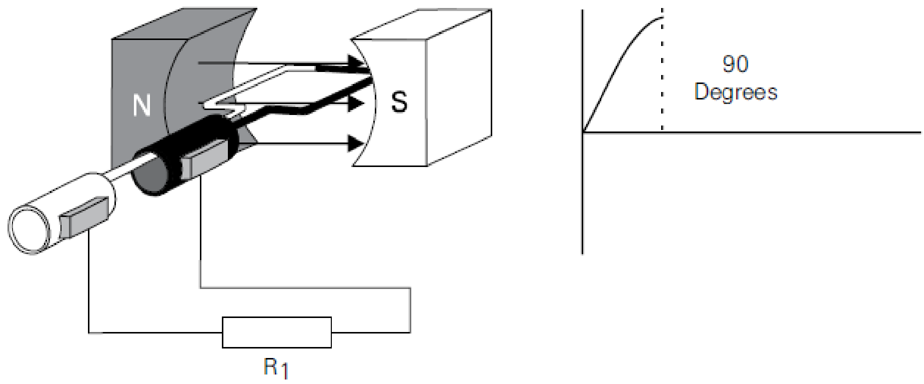


An armature rotates in the magnetic field. In an initial position of zero degrees, the armature surface is perpendicular to the magnetic field, so that the magnetic flux through the armature is at a maximum, and the change in magnetic flux is zero as the rotor rotates. In this case, no voltage is induced.



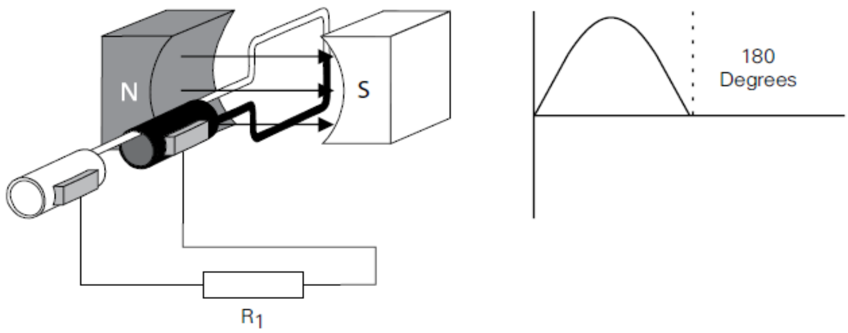
Generator Operation from Zero to 90 Degrees

As the armature rotates from zero to 90 degrees, the conductors cross fewer and fewer flux lines, so that the magnetic flux through the armature decreases, and the change in magnetic flux increases to the maximum. The voltage increases to the maximum.



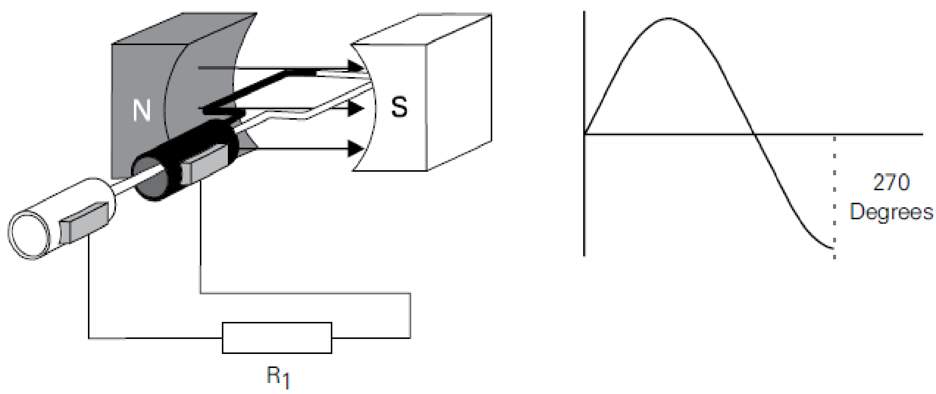
Generator Operation from 90 to 180 Degrees

The armature continues to rotate from 90 to 180 degrees, crossing now more and more lines of flux, but in the opposite direction. Magnetic flux through the armature decreases below zero to a minimum value, and magnetic flux variation decreases to zero. The induced voltage decreases from a maximum positive value to zero.



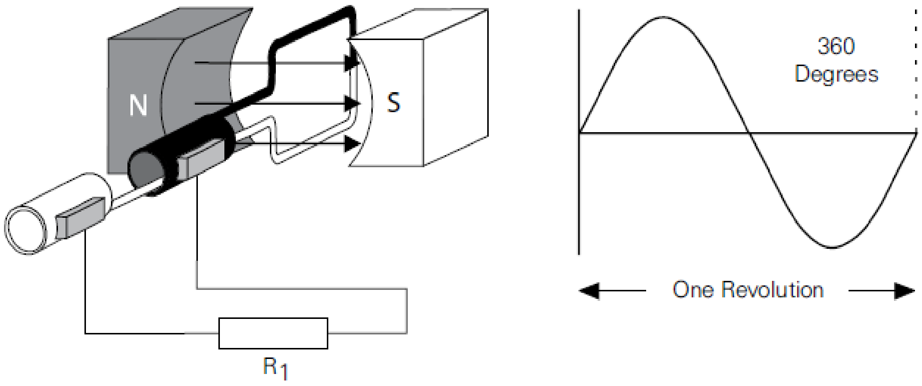
Generator Operation from 180 to 270 Degrees

As the armature continues to rotate from 180 degrees to 270 degrees, the conductors cross fewer and fewer flux lines, still in the opposite direction, and voltage is induced in the negative direction, reaching a minimum at 270 degrees.



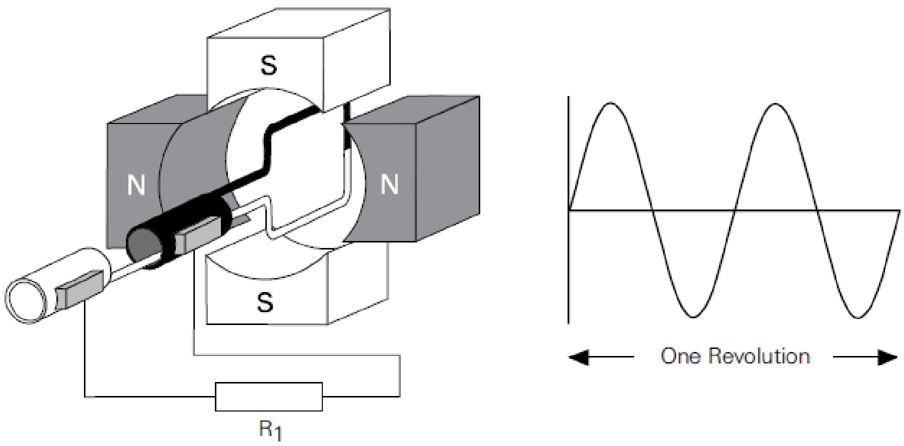
Generator Operation from 270 to 360 Degrees

As the armature continues to rotate from 270 to 360 degrees, induced voltage decreases from a minimum 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

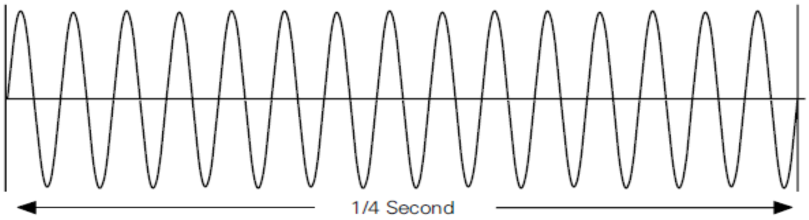
An AC generator produces one cycle per revolution for each pair of poles. Increasing the number of poles means increasing the number of cycles performed in a revolution. A two-pole generator performs one cycle per revolution and a four-pole generator performs two cycles per revolution.



Frequency

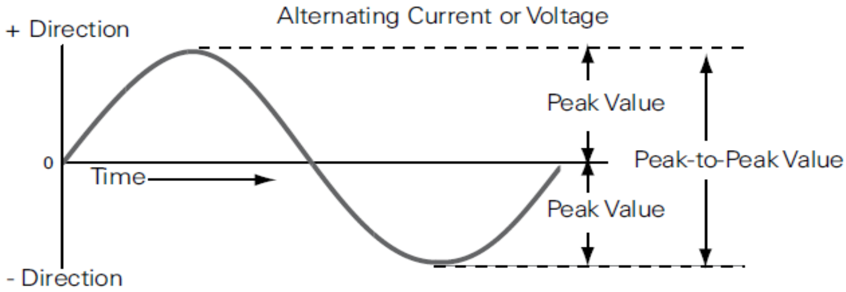
The number of cycles per second of voltage induced in the armature is the **frequency** of the generator. If a two-pole generator armature rotates at a speed of 60 revolutions per second, the generated voltage has a frequency of 60 cycles per second. The recognized unit for frequency is **hertz**, abbreviated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

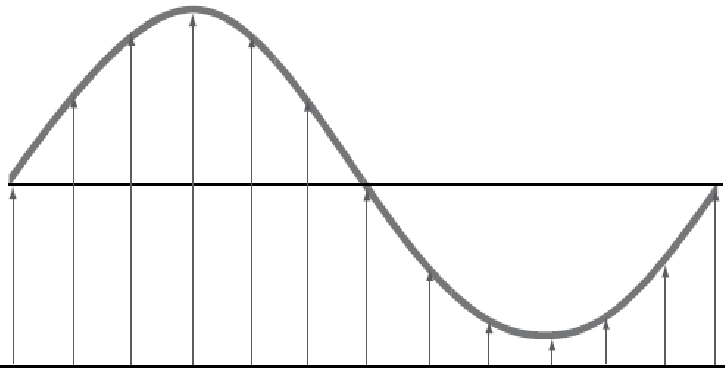
The effective value is also referred to as the **RMS value**. This name is derived from the root-mean-square mathematical process used to calculate the effective value of a waveform.

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)** or **current (i)** at any point on the sine wave is equal to the peak value multiplied by 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 or sin ϕ, where the Greek letters **theta (θ)** or **phi (ϕ)** represent the angle.

Instantaneous Value of Alternating Current or Voltage

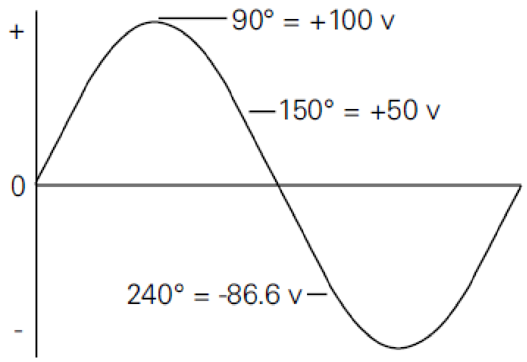


Angle	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	36
Sin θ	0.000	0.500	0.866	1.000	0.866	0.500	0.000	-0.500	-0.866	-1.000	-0.866	-0.500	0.

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 = 170x0.5 = 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 sinewave 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.
5. The peak voltage for a sine wave with an effective voltage of 240 V is ___________ V.

8. Inductance and Capacitance

Inductance

The circuits studied to this point have been resistive. However, resistance and voltage are not the only circuit properties that influence current flow. **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, as the henry is a relatively large unit, inductance is often rated in millihenries or microhenries.

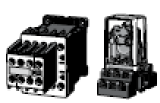
Unit	Symbol	Equivalent Measure
millihenry	mh	1 mh = 10^{-3} h = 0.001 h
microhenry	µh	1 µh = 10^{-6} h = 0.000001 h

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.

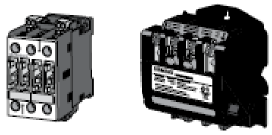
Any change in current causes a corresponding change in the magnetic field surrounding the conductor. Current is constant for a regulated DC source, except when the circuit is turned on and off, or when there is a load change. However, alternating current is constantly changing, and inductance is continually 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 electromagnetic force (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.

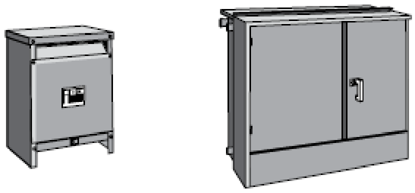
All electrical products have inductance, but the products shown below are examples of products that are primariliy inductive.



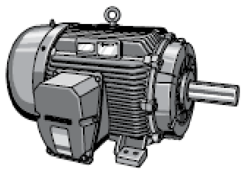
Control Relays



Contactors

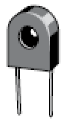


Transformers



Electric Motor

Inductors are components manufactured to have a specific inductance.



Inductor

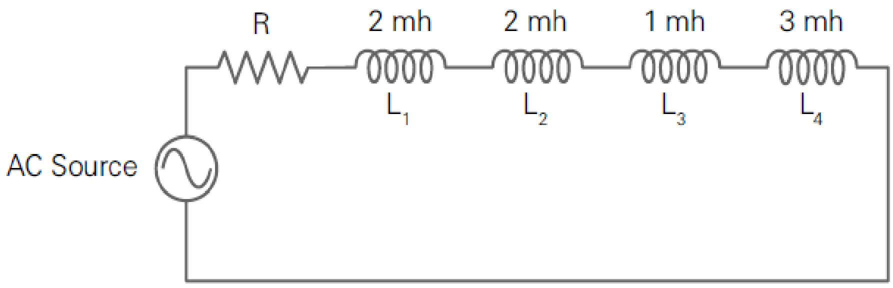
Schematic Symbols

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

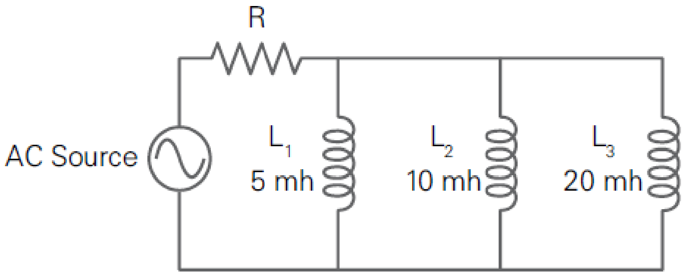
In the following circuit, an AC source supplies electrical power to four inductors. Total inductance of series inductors is equal to the sum of the inductances.



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

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.

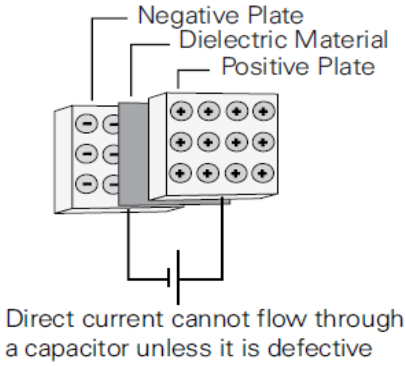


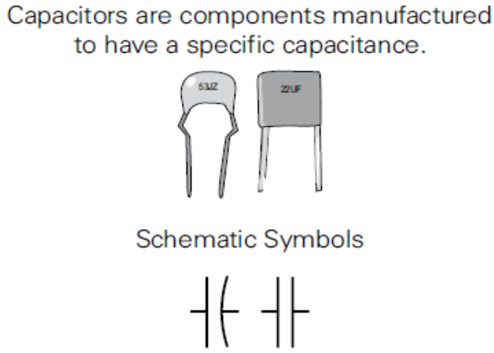
$$\frac{1}{L_t} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} = \frac{1}{5\text{ mh}} + \frac{1}{10\text{ mh}} + \frac{1}{20\text{ mh}} = \frac{4}{20\text{ mh}} + \frac{2}{20\text{ mh}} + \frac{1}{20\text{ mh}} = \frac{7}{20\text{ mh}}$$

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

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.





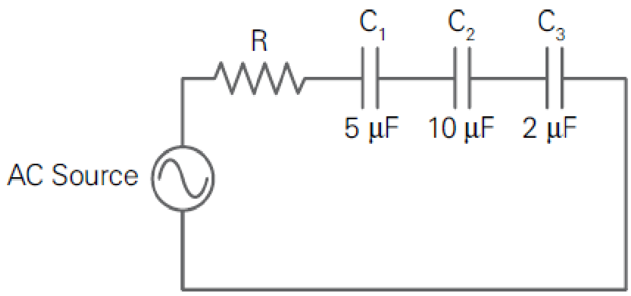
When a voltage is applied to the plates of a capacitor, electrons are forced onto one plate and removed from the other. This charges the capacitor. Direct current cannot flow through the dielectric material because it is an insulator; however, the electric field created when the capacitor is charged is felt through the dielectric. Capacitors are rated according to 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, as the farad is a large unit, capacitors are often rated in microfarads (µF), nanofarads (nF) or picofarads (pF).

Unit	Symbol	Equivalent Measure
microfarad	µF	1 µF = 10^{-6} F = 0.000001 F
nanofarad	nF	1 nF = 10^{-9} F = 0.000000001 F
picofarad	pF	1 pF = 10^{-12} F = 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.

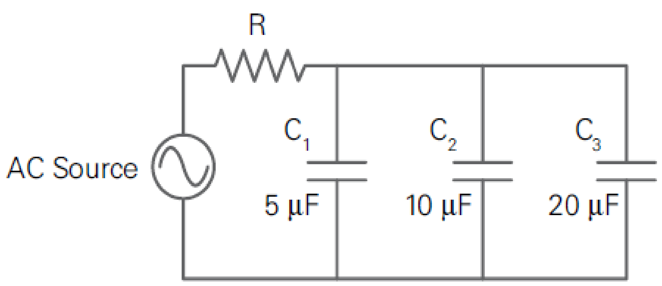


$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_3} + \frac{1}{C_2} = \frac{1}{5\ \mu F} + \frac{1}{10\ \mu F} + \frac{1}{2\ \mu F} = \frac{2}{10\ \mu F} + \frac{1}{10\ \mu F} + \frac{5}{10\ \mu F} = \frac{8}{10\ \mu F}$$

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

Capacitors in Parallel

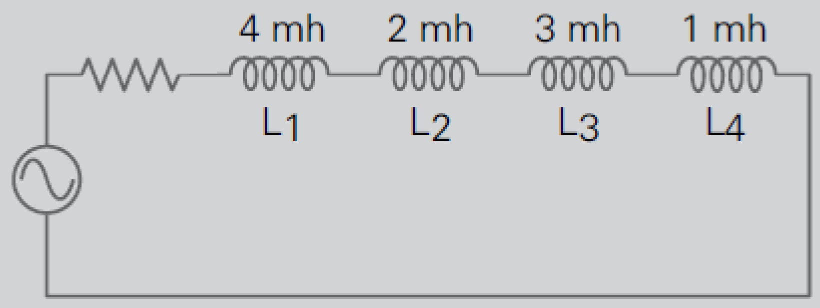
Adding capacitors in parallel increases circuit capacitance. In the following circuit, an AC source supplies electrical power to three capacitors. Total capacitance is determined by adding the values of the capacitors.



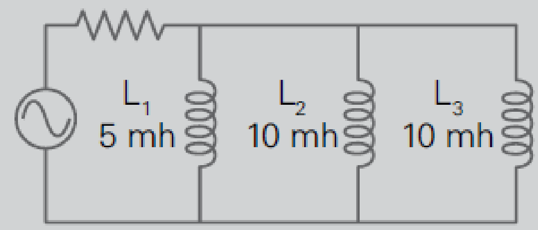
$$C_t = C_1 + C_2 + C_3 = 5\ \mu F + 10\ \mu F + 20\ \mu F = 35\ \mu F$$

Review 6

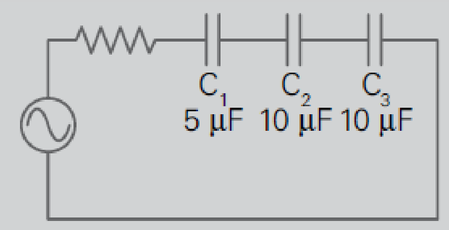
1. The total inductance for this circuit is __________ mh.



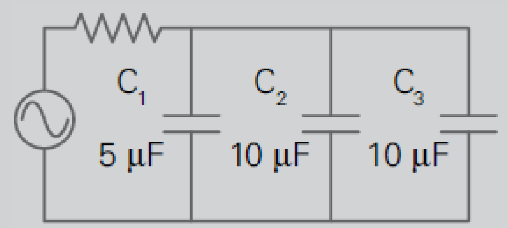
2. The total inductance for this circuit is __________ mh.



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



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



9. 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 50 Hz circuit containing a 10 mh inductor, the inductive reactance is:

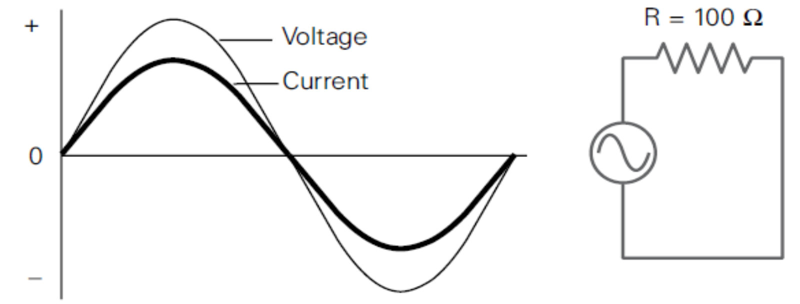
$X_L = 2\pi fL = 2 \times 3.14 \times 50\ \text{Hz} \times 0.010\ \text{h} = 3.14\ \Omega$

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:

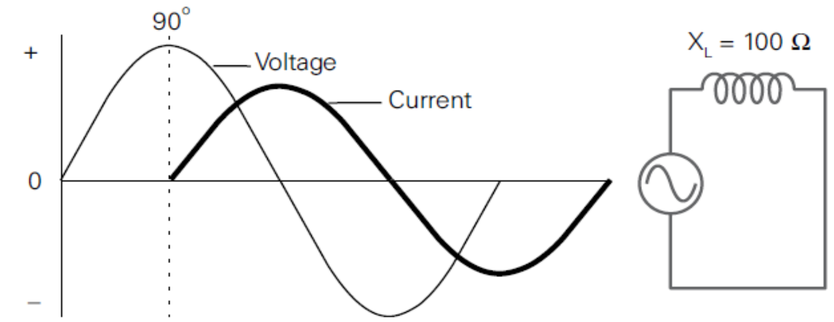
$$\mathrm{I} = \frac{E}{Z} = \frac{10\ V}{3.14\ \Omega} = 3.18\ \mathrm{A}$$

Current and Voltage Phases

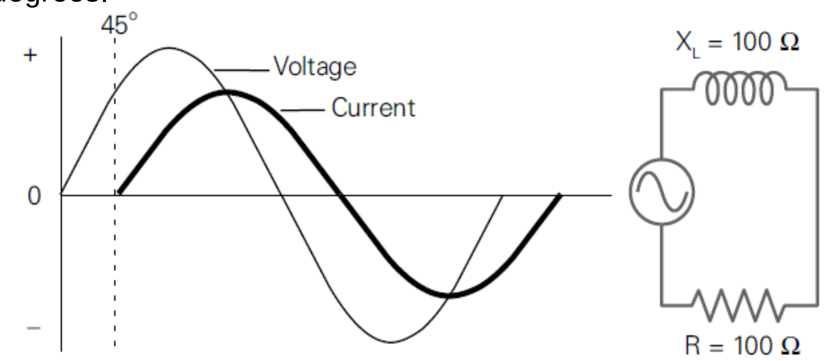
In a purely resistive AC circuit, current and voltage are said to be **in phase** because they rise and fall at the same time as shown in the following example.



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.

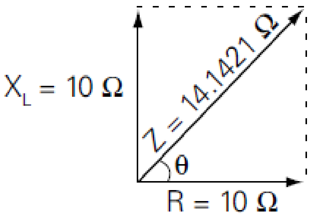
$$Z = \sqrt{R^2 + {X_L}^2}$$

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

$$Z = \sqrt{10^2 + 10^2} = \sqrt{200} = 14.1\ \Omega$$

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** or **ϕ**. 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 **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.

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

The capacitive reactance for a 50 Hz circuit with a 10 μF capacitor is calculated as follows.

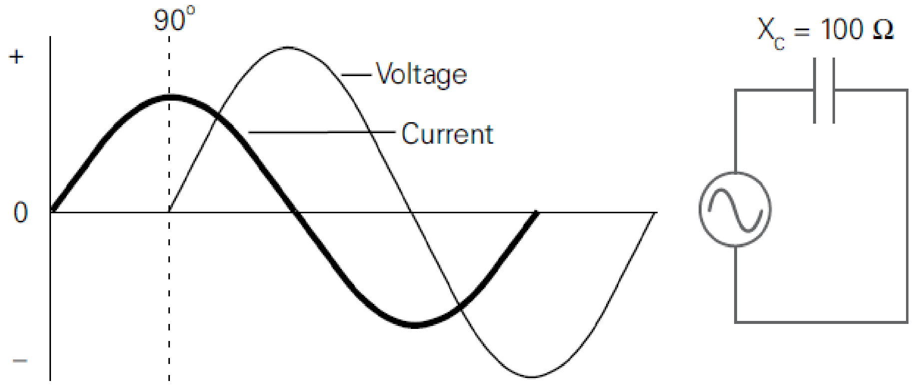
$$X_C = \frac{1}{2\pi f C} = \frac{1}{2 \times 3.14 \times 50\ Hz \times 0.00001\ F} = 318\ \Omega$$

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.

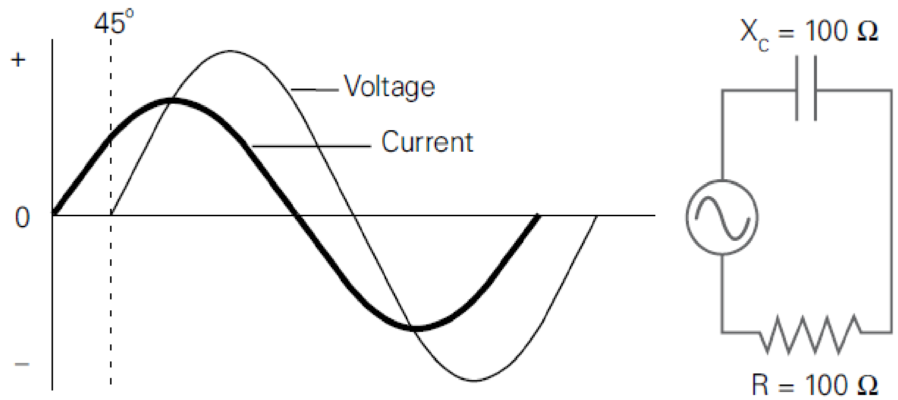
$$I = \frac{E}{Z} = \frac{10\ V}{318\ \Omega} = 0.0314\ A$$

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

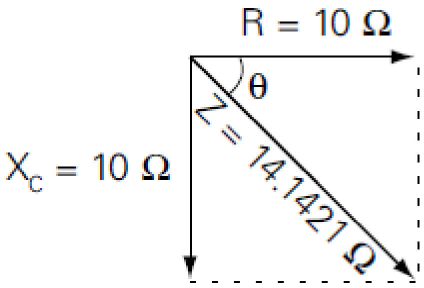
The following formula is used to calculate impedance in a circuit with resistance and capacitive reactance.

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

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

$$Z = \sqrt{10^2 + 10^2} = \sqrt{200} = 14.1\ \Omega$$

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 or ϕ. 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.