Course Outline

1. Introduction to WECC
2. Fundamentals of Electricity
3. Power System Overview
4. Principles of Generation
5. Substation Overview
6. Transformers
7. Power Transmission
8. System Protection
9. Principles of System Operation

2 | Fundamentals of Electricity

- Electric Theory, Quantities and Circuit Elements
- Alternating Current
- Power in AC Circuits
- Three-Phase Circuits
- Electromechanics

Charge, Force and Voltage

Electric Theory, Quantities and Circuit Elements

- Atoms, Electrons, Charge
- Conductors and Insulators
- Current
- Voltage
- Power
- Magnetism and Electromagnetism
- Circuit Components and Resistance
- Circuit Analysis (Ohm’s and Kirchoff’s Laws)

Electric Theory, Quantities and Circuit Elements
Electricity

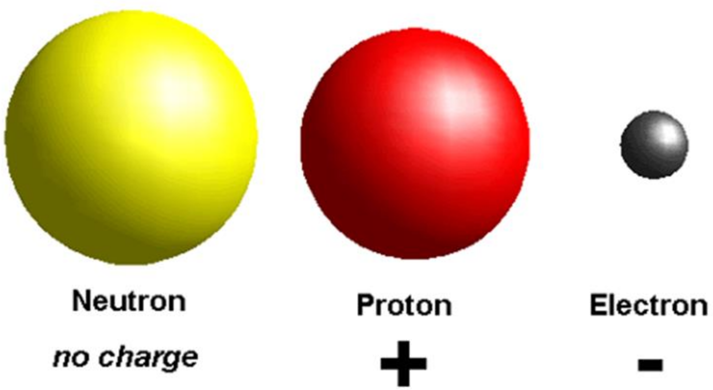
- **Electricity** is the set of physical phenomena associated with the presence and flow of electric charge. Including:

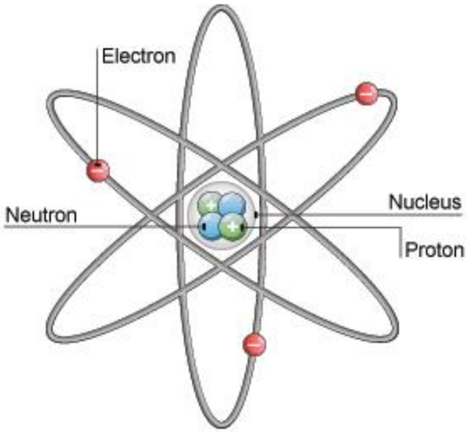
- Lightning and Static electricity
- Electromagnetic induction
- Current
- Electromagnetic radiation and radio waves

Atoms, Electrons, Charge

Electric Theory, Quantities and Circuit Elements
Atoms, Electrons, Charge

- Matter - has weight and occupies space.
- Matter is composed of atoms.

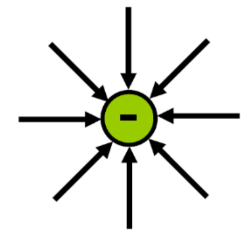




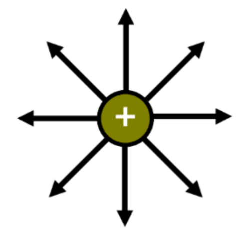
- Atoms are composed of:
  - Electrons(-) orbiting around a nucleus of Protons(+) and Neutrons.

Electric Theory, Quantities and Circuit Elements
Atoms, Electrons, Charge

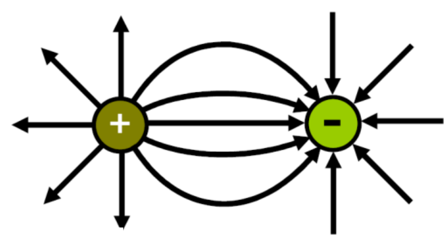
Electrons have a negative charge

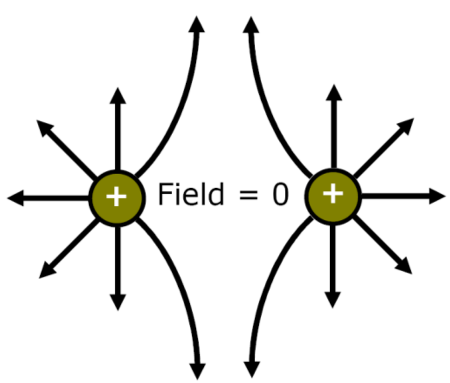


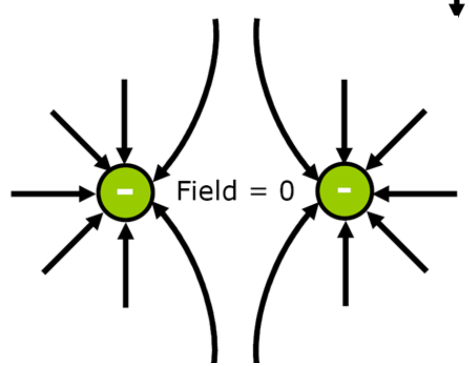
Protons have a positive charge



Opposite charges attract





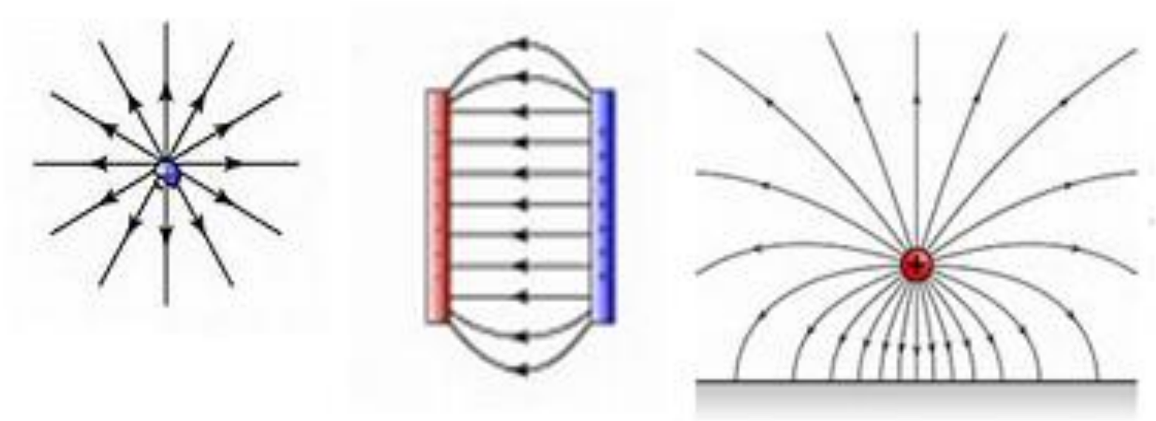


Like charges repel

Electric Theory, Quantities and Circuit Elements
Atoms, Electrons, Charge

An Electric (force) field surrounds any charged object – it spreads out - weakens with distance.

- Electric field around various shaped objects



Electric Theory, Quantities and Circuit Elements
Atoms, Electrons, Charge

- Charge is measured in Coulombs
- 1 Coulomb =1 amp per second
- The charge of one electron is -1.6 X 10^{-19} Coulombs.

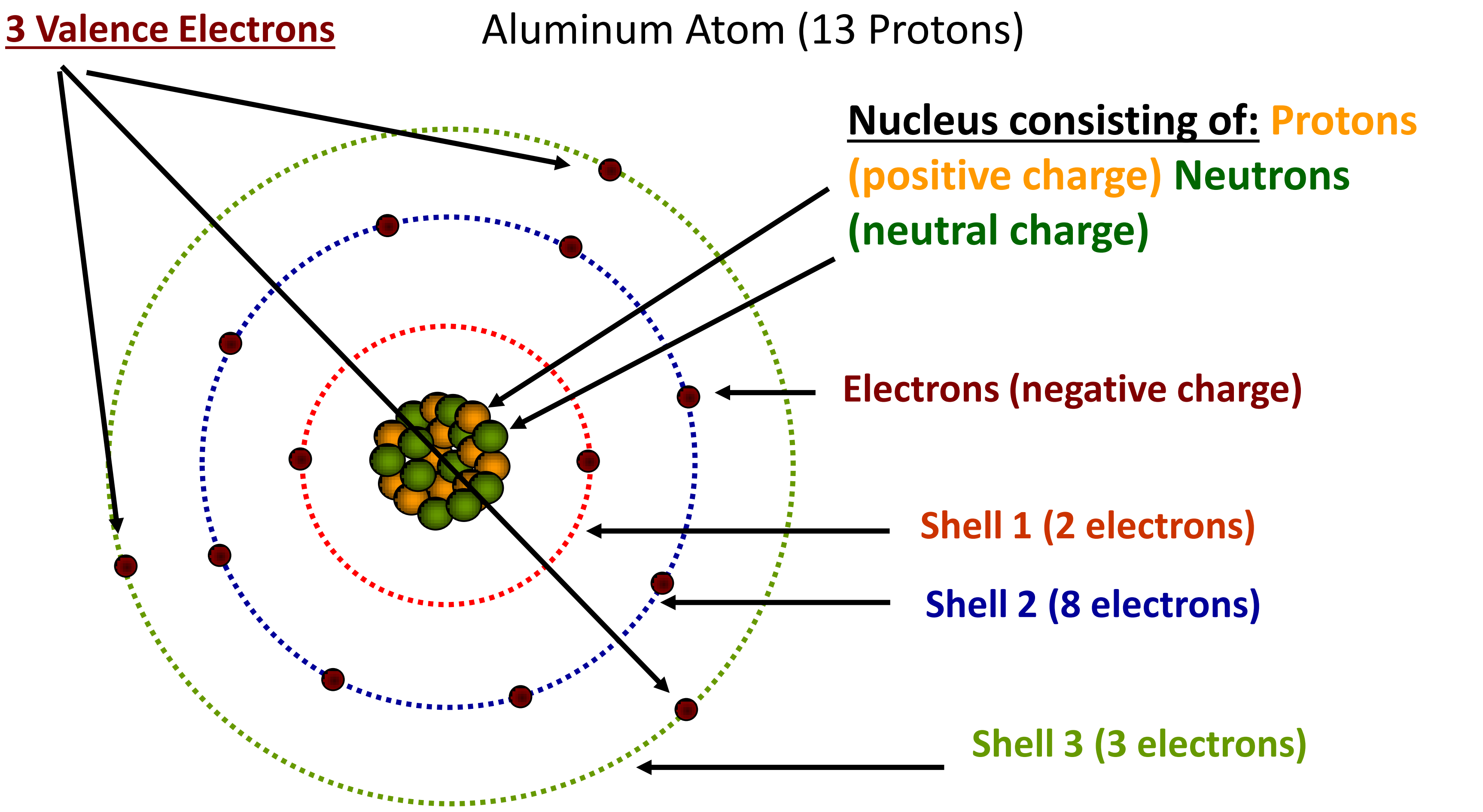
$$1\, Coulomb = \frac{1}{-1.6 * 10^{-19}} = 6.25 * 10^{18}\, Electrons$$

6,250,000,000,000,000,000 electrons!

Electric Theory, Quantities and Circuit Elements
Atoms, Electrons, Charge

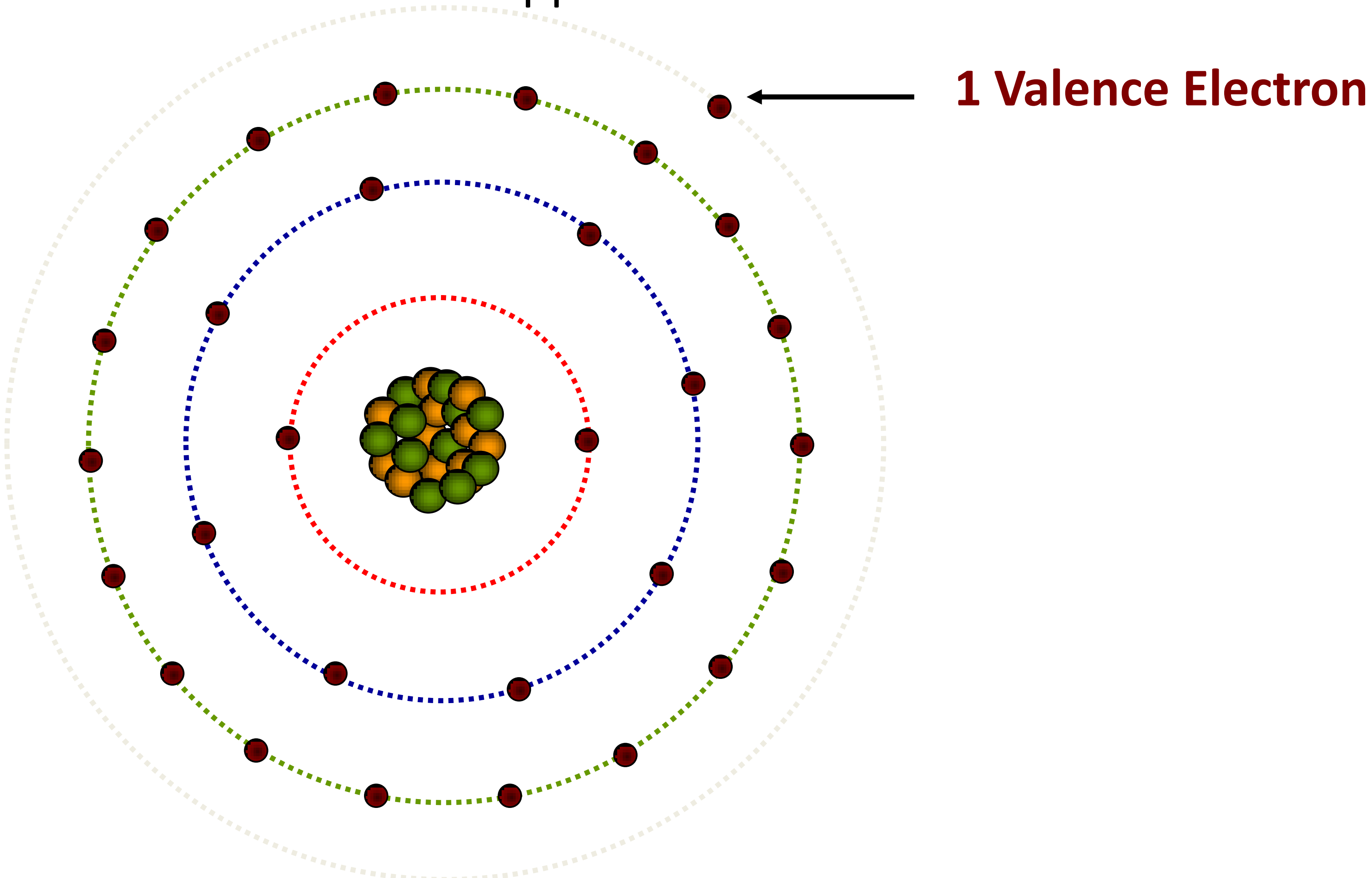
- Electrons orbiting the nucleus are organized into <u>shells</u>
- The number of protons in an atom determine what the element is
- For instance:
  - Hydrogen - 1 proton and 1 electron
  - Aluminum - 13 protons and 13 electrons

Electric Theory, Quantities and Circuit Elements
Atoms, Electrons, Charge



Electric Theory, Quantities and Circuit Elements
Atoms, Electrons, Charge

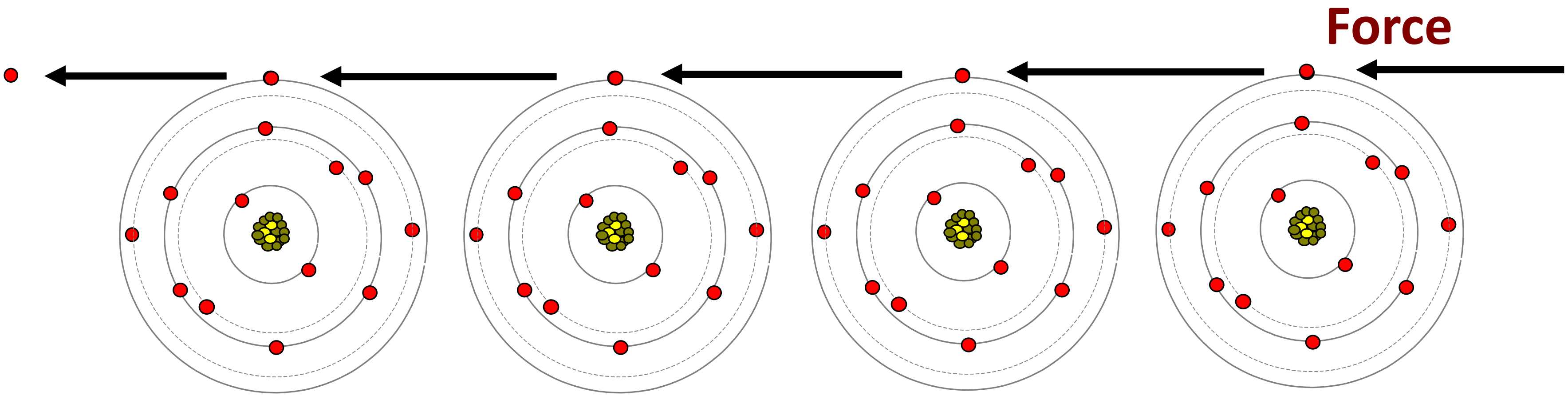
Copper Atom – 29 Protons



Electric Theory, Quantities and Circuit Elements
Atoms, Electrons, Charge

- **Free Electrons -** jump easily from one atom to another
- The number of shells, and electrons in each shell, determine how tightly they are bound to the atom
- In a good conductor the valence electrons can be easily forced to move from one atom to the next

Electric Theory, Quantities and Circuit Elements
Atoms, Electrons, Charge



An external force can cause the free electrons to move from one atom to the next.

friction (static), thermal (thermocouple), light (photocell), chemical (battery) or electromagnetic (generator)

Conductors and Insulators

Electric Theory, Quantities and Circuit Elements
Conductors and Insulators

When it comes to electricity there are generally two types of material:

- Conductors
- Insulators

Electric Theory, Quantities and Circuit Elements
Conductors and Insulators

Electric Theory, Quantities and Circuit Elements
Conductors and Insulators

A ***conductor*** is a material that has a large number of free electrons that continually jump to other atoms.

- Good electrical conductors are copper and aluminum. Gold, silver, and platinum are also good conductors, but are very expensive

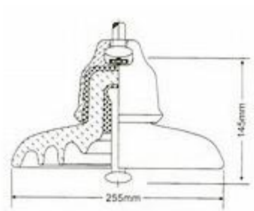
Electric Theory, Quantities and Circuit Elements
Conductors and Insulators

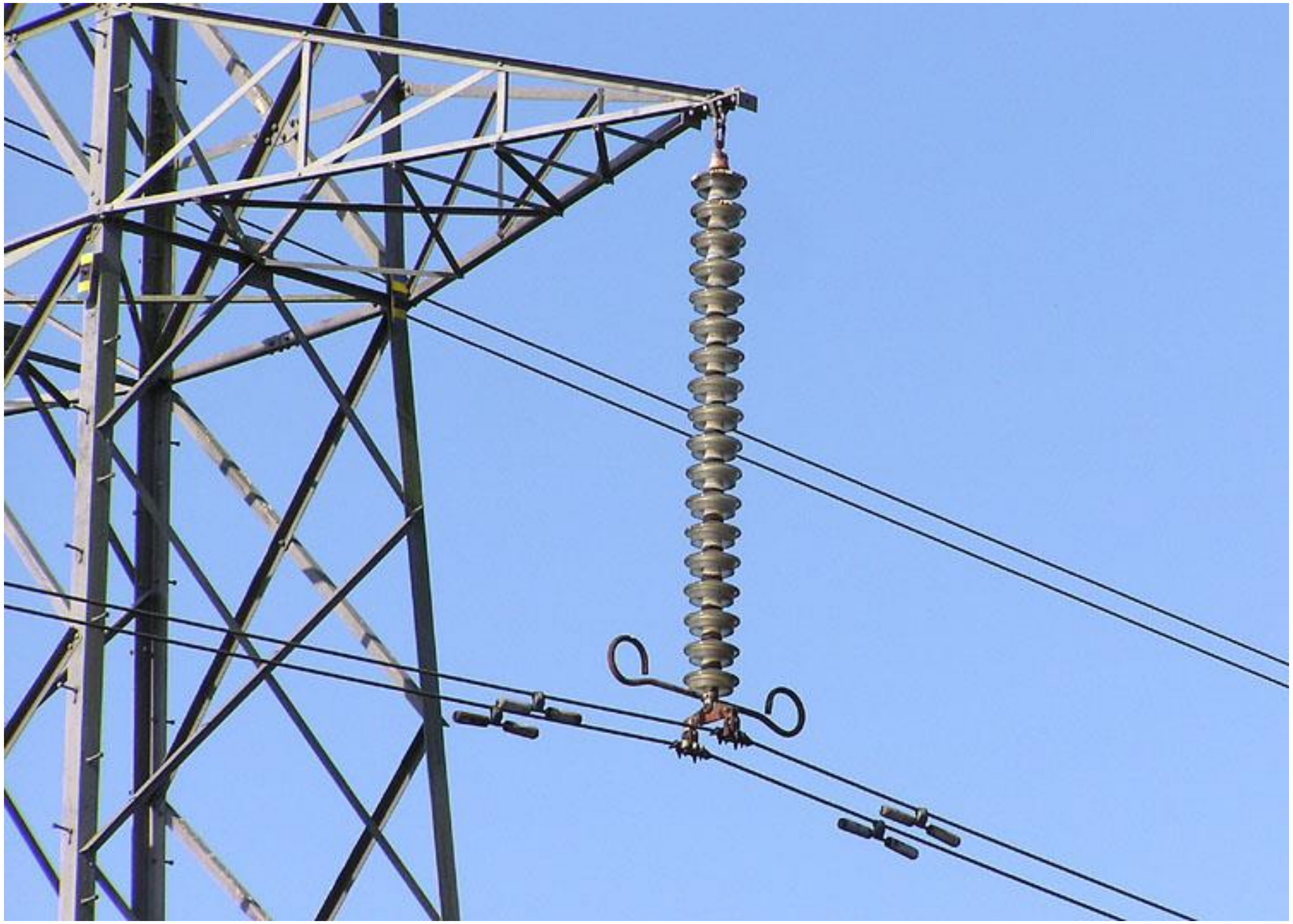
An ***insulator*** is a material that has only a few free electrons. In insulators, the electrons are tightly bound by the nucleus.

- Good electrical insulators are rubber, porcelain, glass, and dry wood

Electric Theory, Quantities and Circuit Elements
Conductors and Insulators

- Insulators prevent current from flowing
- Insulators are used to isolate electrical components and prevent current flow





Conductors and Insulators

Insulator Characteristics

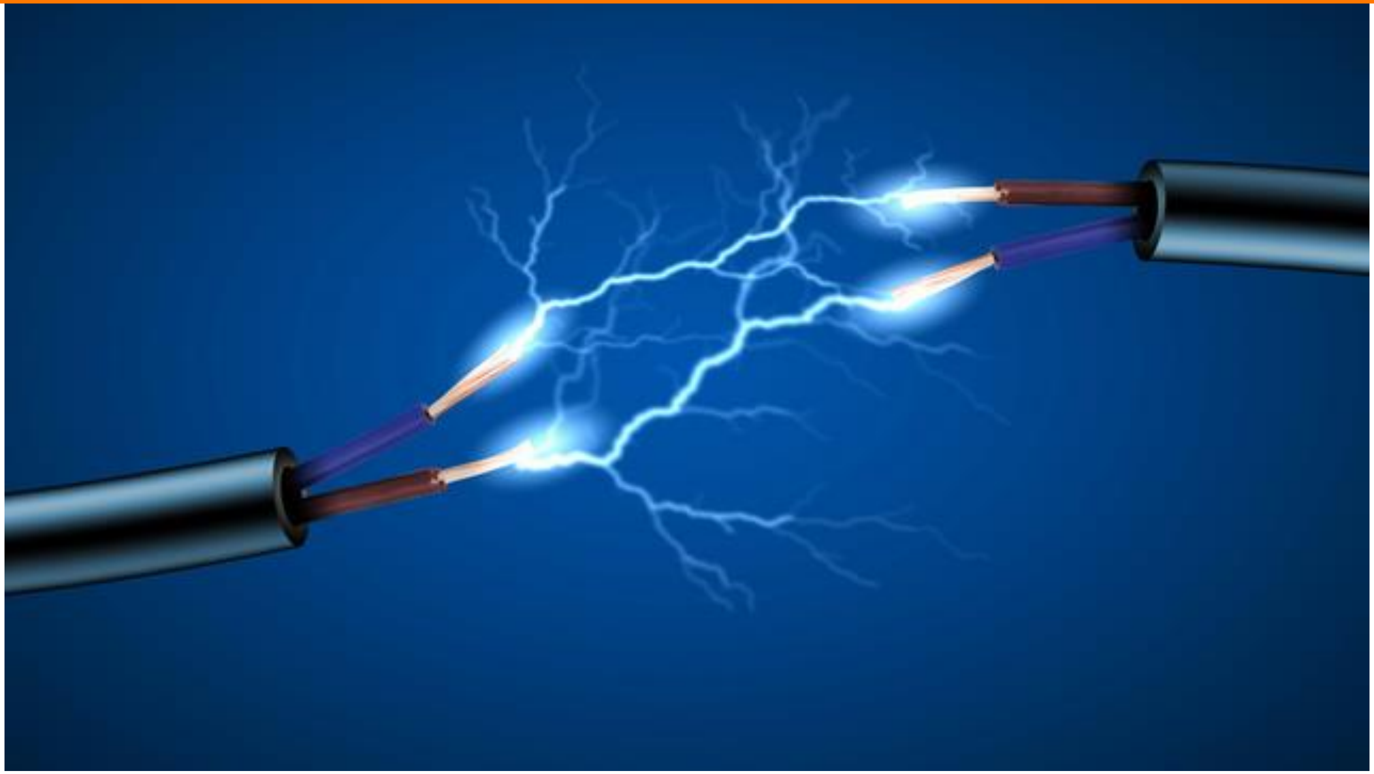
Resistance - The ability of the insulator to resist current leakage through and over the surface of the insulator material.

Dielectric Strength - The ability to withstand a maximum voltage without breakdown damage to the insulator.

Check Your Knowledge: Fundamentals of Electricity

1. In general are objects charged, or neutral? Why is that?
2. Where do you see static electricity?
3. What are good conductors? What are good insulators?
4. What decides which conductor you should use?

Current



Electric Theory, Quantities and Circuit Elements
Current

Current (I) is the movement of charge through a conductor. Electrons carry the charge.

- Unit of measurement: **Amperes (A)**
- One ampere (amp) of current is one coulomb of charge passing a point on a conductor in one second
- This measurement is analogous to “gallons or liters per second” when measuring the flow of water

Electric Theory, Quantities and Circuit Elements
Current

Direct Current (DC) flows in only one direction.

- Many uses including: Batteries, electronic circuits, LED lights, generator excitation systems and rotors, DC transmission lines – and much more

Electric Theory, Quantities and Circuit Elements
Current

Alternating Current (AC) continuously changes in magnitude and direction.

- AC is used by most lights, appliances and motors. It is used in the high voltage transmission system
- AC enables use of transformers to change voltage from high to low and back

Electric Theory, Quantities and Circuit Elements
Current

Typical Current Levels:

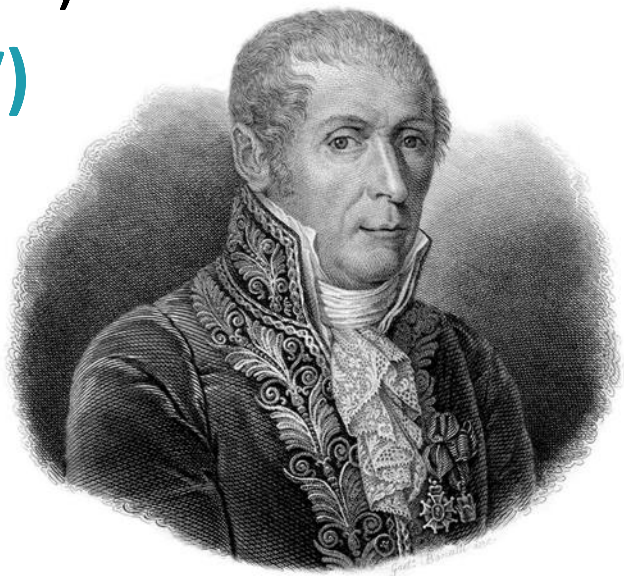
Cell phone battery charger	5/1000 Amps = 5mA = (5 milli-amps)
Sensation	.2 - .5mA
Let-go threshold	5mA
Potentially lethal	50mA
40 watt incandescent light bulb	.33 Amps
Toaster	10 Amps
Car Starter Motor	100+ Amps
Transmission line conductor	1000 Amps
Lightning Bolt or Ground Fault	20,000+ Amps

Voltage

Electric Theory, Quantities and Circuit Elements
Voltage

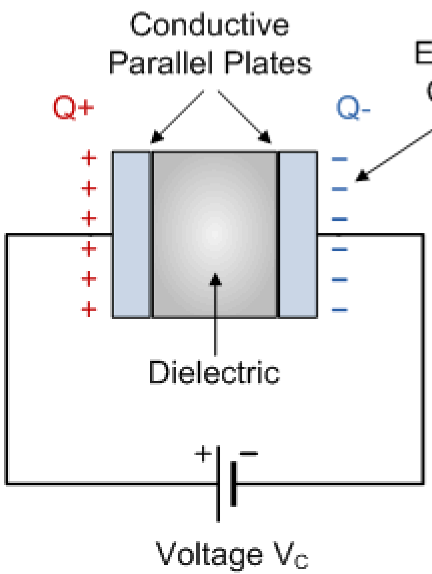
Voltage (V) is the force that causes electrons to move.

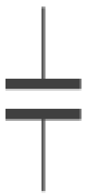
- Voltage is also referred to as potential difference or electromotive force (emf or E)
- Unit of measurement: **Volts (V)**
- Similar to "pounds per square inch" when measuring water pressure.



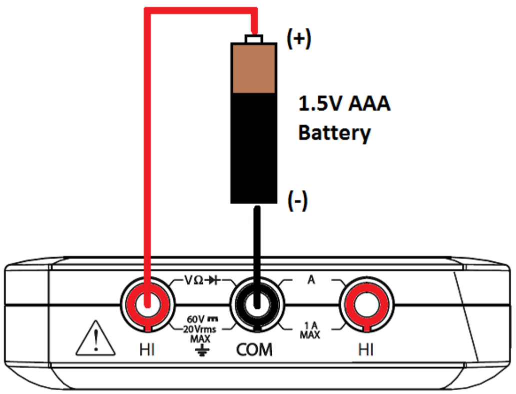
Alessandro Volta *(1745–1827)*

Electric Theory, Quantities and Circuit Elements
Voltage Sources





Symbol



Electric Theory, Quantities and Circuit Elements
Voltage

Sample Voltage Levels

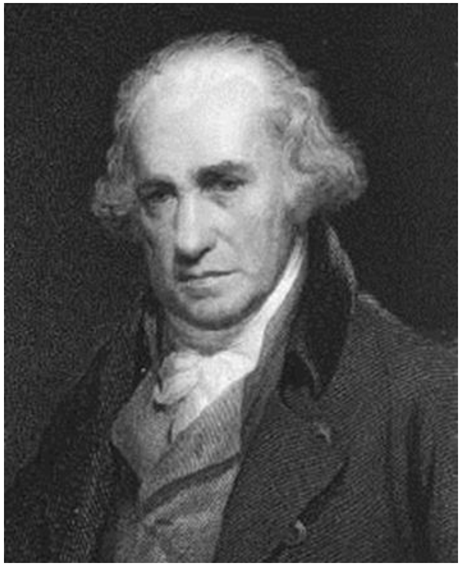
AA Battery	1.5v
Car Battery	12v
Household	120v
Distribution Feeder Circuit	12.47kV
High Voltage Line	47kV to 500kV
Lightning	1,000,000+ volts

Electric Theory, Quantities and Circuit Elements
Power

Electric Theory, Quantities and Circuit Elements
Power

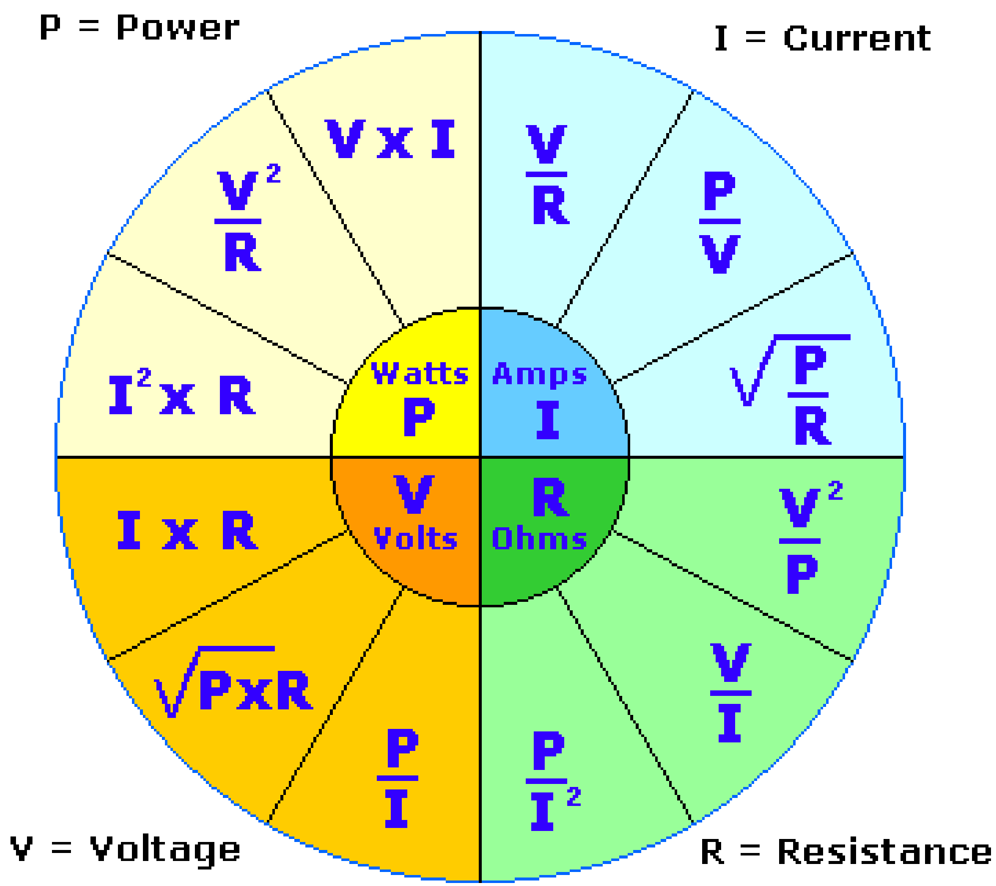
Power (P) is the *rate* at which work is being performed.

- Unit of Measurement: **watts (w)**
- Power = Voltage x Current
- This means that the electrical energy is being converted into another form of energy (e.g. heat energy, light energy, mechanical energy, etc.)



James Watt, 1736 -1819

Electric Theory, Quantities and Circuit Elements
Power



Electric Theory, Quantities and Circuit Elements
Power

Sample Power Calculation

A Toaster uses 120-volts and allows 10 amps of current to flow. How much power does it consume?

Instructions: Using the formula for power and substituting the known values, we have:

$$P = VI$$
$$P = (\_\_\_\_)(\_\_\_\_)$$
$$P = \_\_\_\_\_\_\_\_$$

Electric Theory, Quantities and Circuit Elements
Power

Sample Power Calculation

A Toaster uses 120-volts and allows 10 amps of current to flow. How much power does it consume?

Instructions: Using the formula for power and substituting the known values, we have:

$$P = VI$$
$$P = (120V)(10A)$$
$$P = 1200\,Watts$$

Electric Theory, Quantities and Circuit Elements
Power

- A “**watt**” is an instantaneous value, it is the power being used at any given instant of time

- A “**watt hour**” indicates how much power is being consumed over an hour

watt x time (in hours) = watt hours = energy

Electric Theory, Quantities and Circuit Elements
Power

Retail Power consumption is typically measured in kilowatt hours (KWh)

Kilowatts x time (in hours) = Kilowatt hours

Example:

5,000 watts used for 3 hours

5,000 = 5 kW

5 kW x 3 hours = 15 kWh

Wholesale power consumption is typically measured in megawatt hours (MWh)

Electric Theory, Quantities and Circuit Elements
Power

Example Power Use:

• Small light bulb	40 watts
• Toaster	1000 watts or 1 kW
• Household	5–10kW
• One horsepower	746 watts (.746 kW)
• Wind turbine	1,000 kW or 1.0 MW
• Power Plant	500 MW

Electric Theory, Quantities and Circuit Elements
Power

Example Power Use:

Small light bulb	40 watts
Toaster	1000 watts or 1 kilowatt (1kW)
Household	5 – 10kW
One horsepower	746 watts (.746 kW)
Wind turbine	1,000 kW or 1.0 Megawatts (MW)
Combined Cycle Power Plant	500 MW

Check Your Knowledge: Fundamentals of Electricity

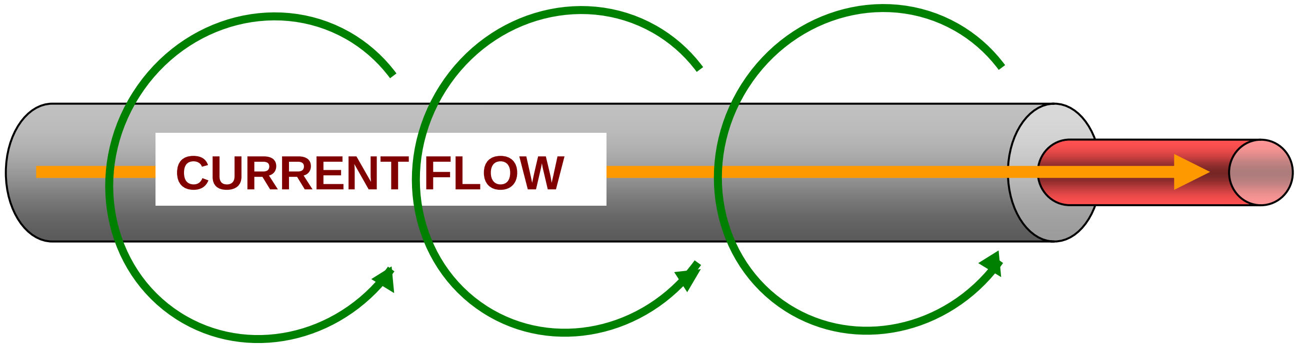
1. How many volts does a hair dryer use?
2. How many amps?
3. How many watts?
4. How many watts are consumed in a city at 7:00am where 50,000 people are simultaneously drying their hair to get ready for work?

Magnetism and Electromagnetism

Wherever an electric current exists, a ***magnetic field*** also exists.

- The magnetic field carries the invisible force of magnetism
- The magnetic field surrounds the conductor

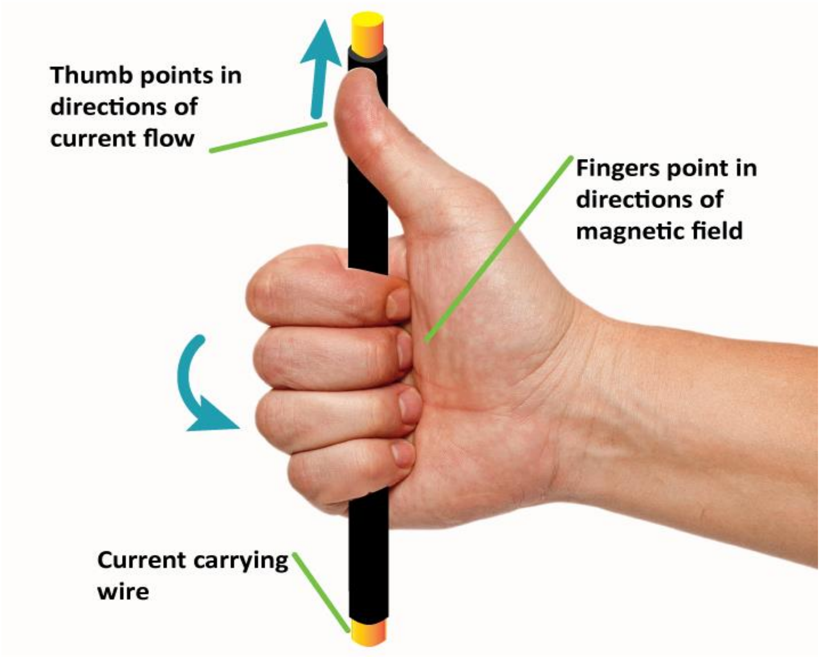
Electric Theory, Quantities and Circuit Elements
Magnetism and Electromagnetism



Whenever current flows through a conductor, a *magnetic field* is created around the conductor.

What happens when you drop a magnet in a copper tube?

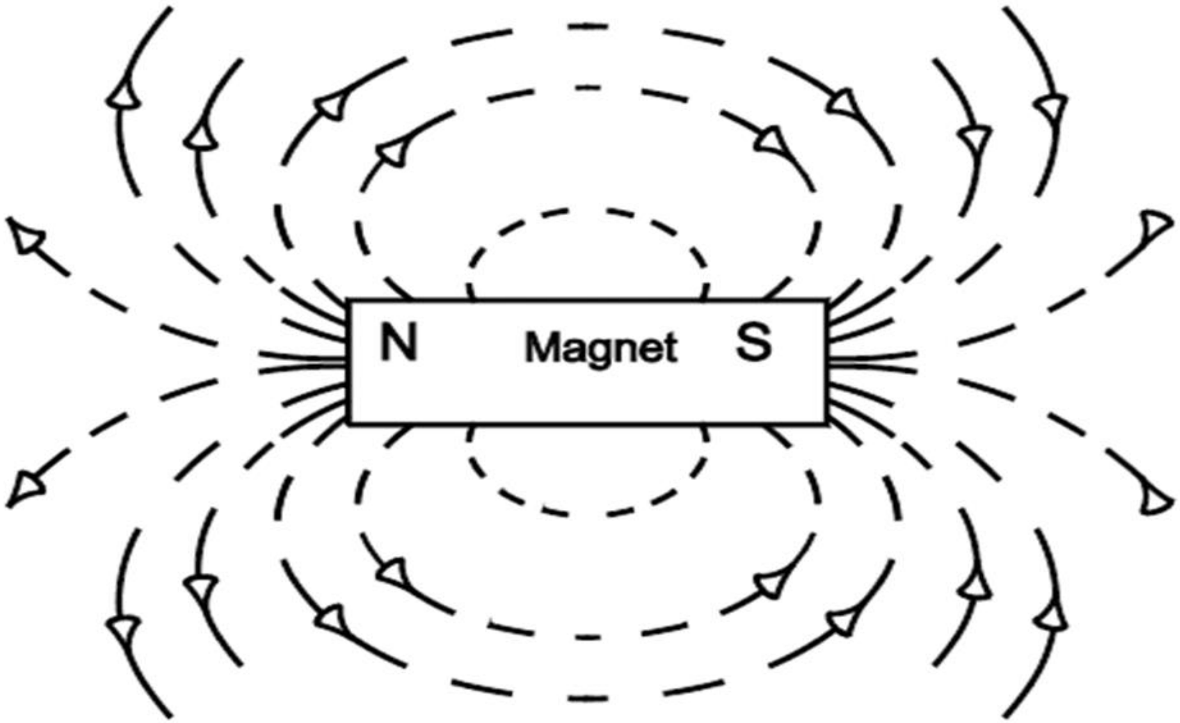
Electric Theory, Quantities and Circuit Elements
Magnetism and Electromagnetism



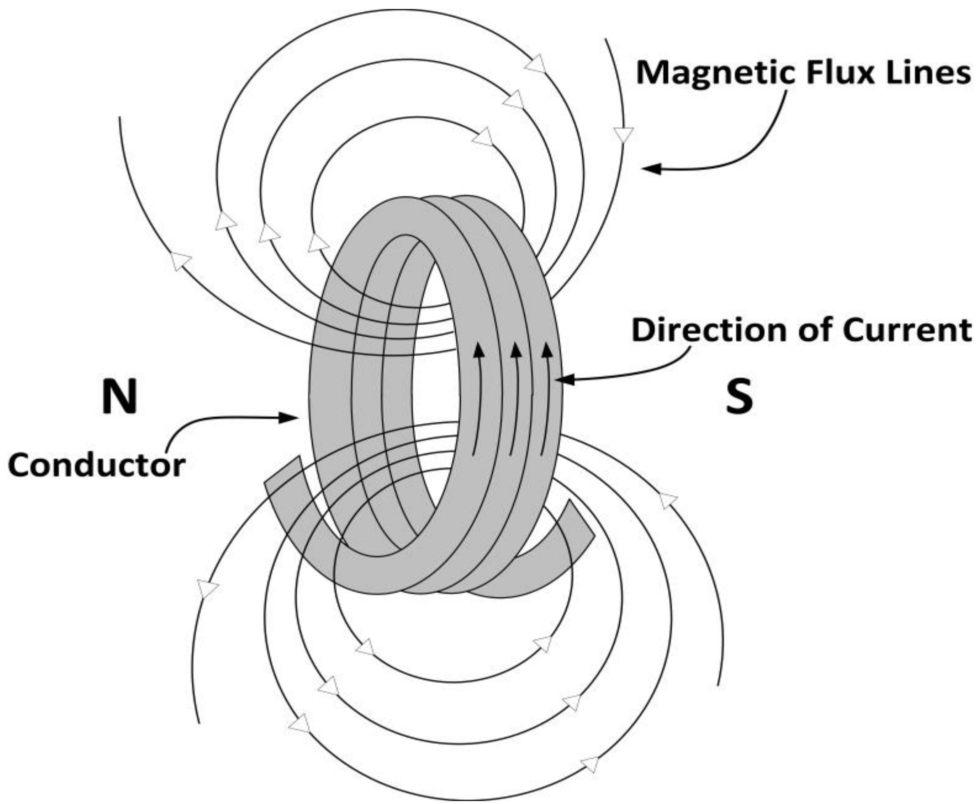
Right hand rule for <u>Magnetic Field</u> around a conductor.

Assumes Current flows from Positive to Negative

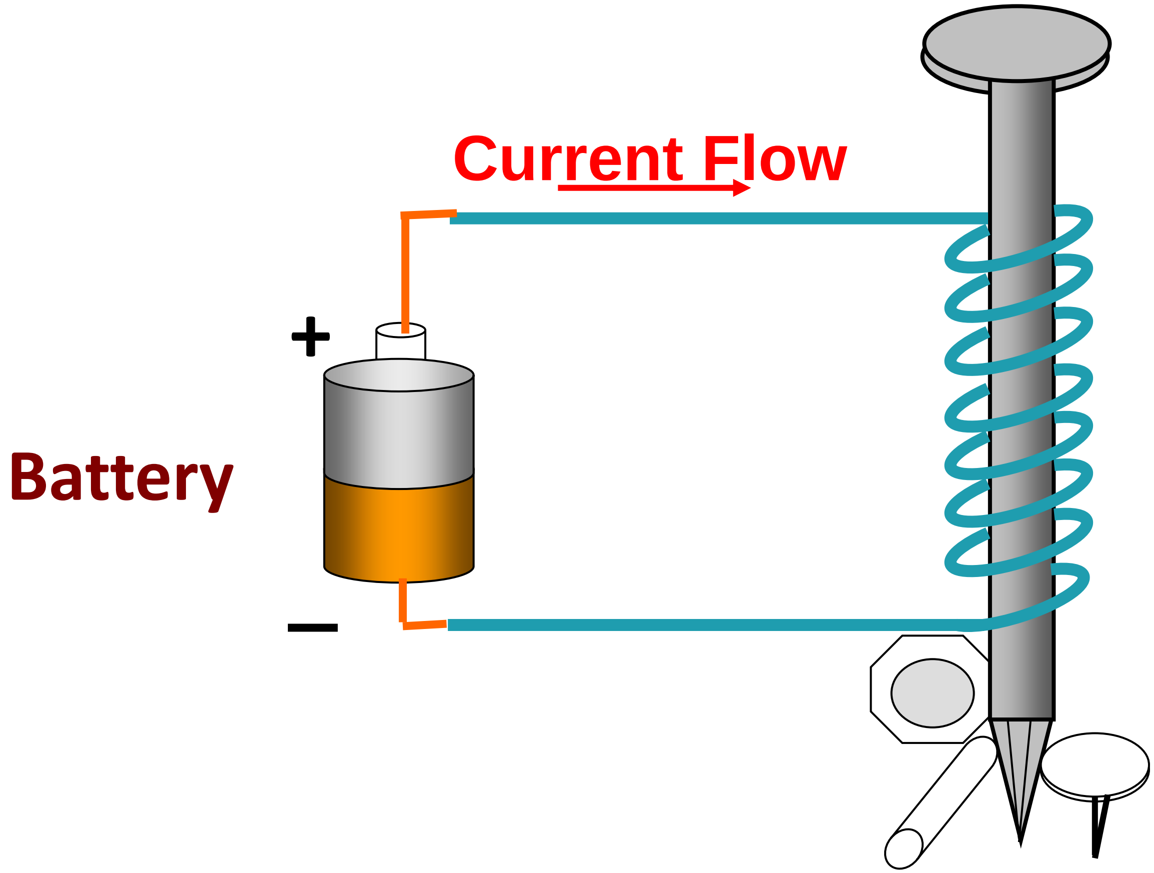
Magnetic Field Lines of Force



Electric Theory, Quantities and Circuit Elements
Magnetism and Electromagnetism



Electric Theory, Quantities and Circuit Elements
Electromagnet



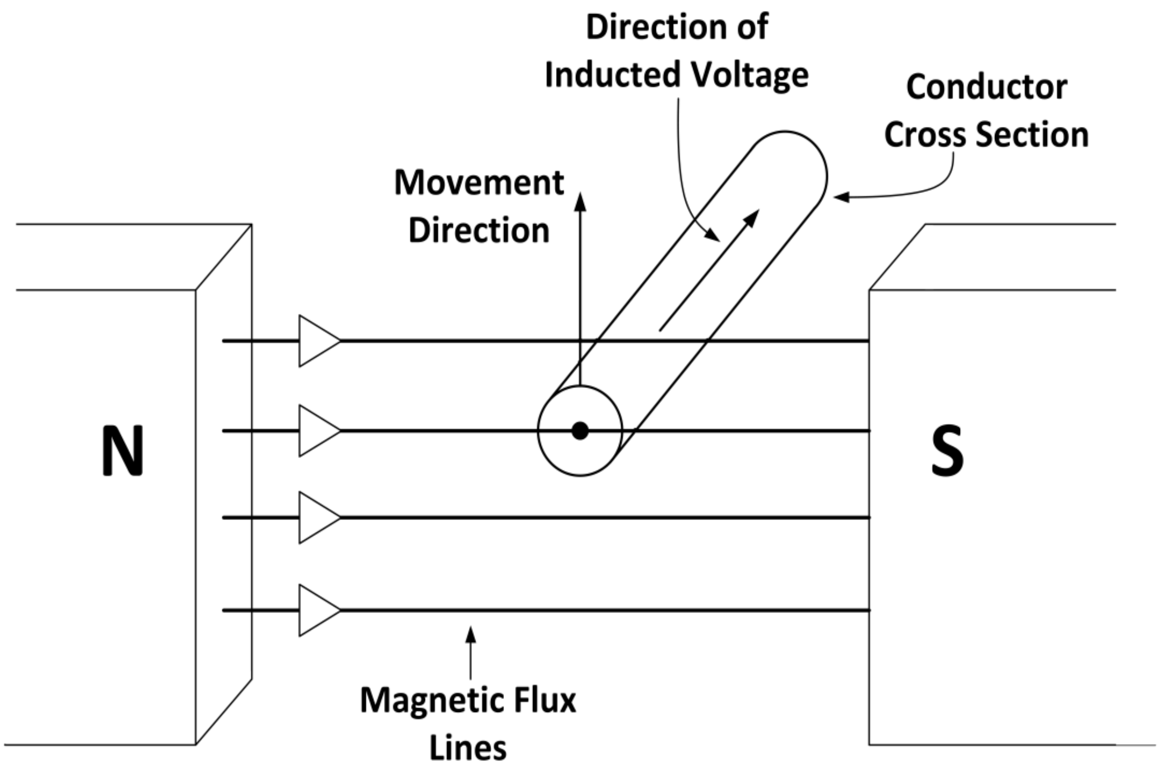
Electric Theory, Quantities and Circuit Elements
Electromagnetic Induction

In order to induce current and voltage you need 3-things:

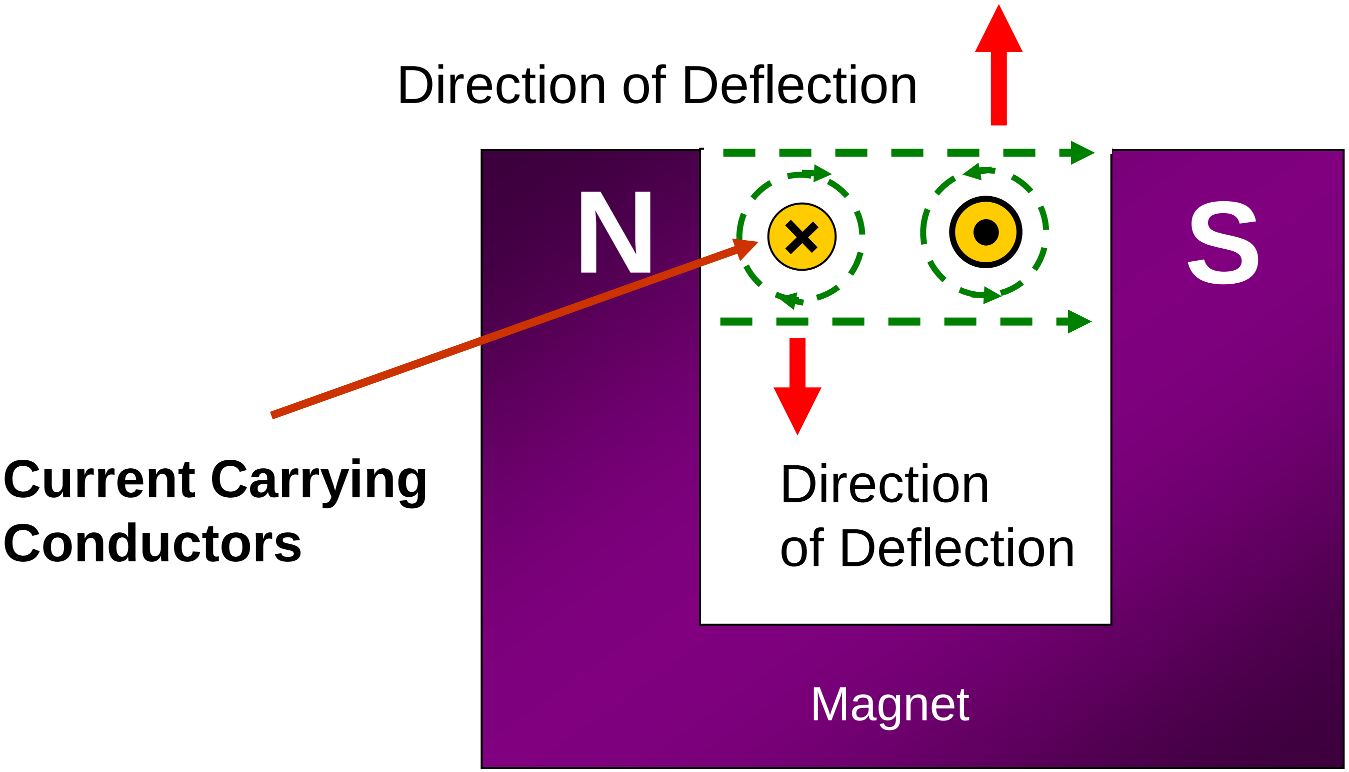
1. Conductor
2. Magnetic field
3. Relative motion between the conductor and the magnetic field.

Creation of Voltage

Electric Theory, Quantities and Circuit Elements
Magnetism and Electromagnetism



Electric Theory, Quantities and Circuit Elements
Magnetism and Electromagnetism



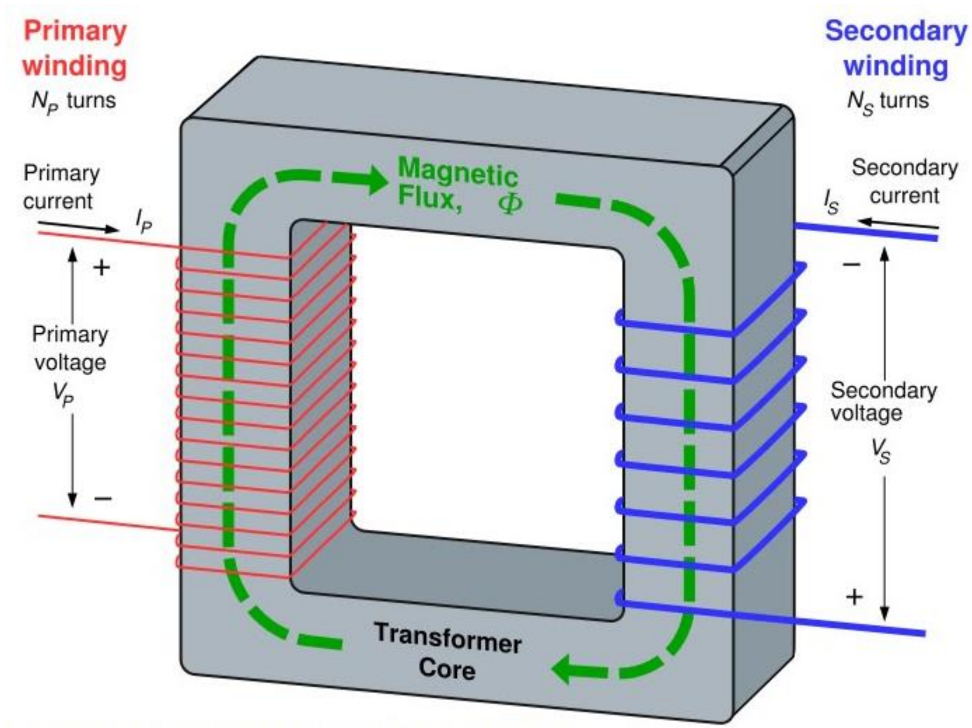
Flux Opposite Directions (cancels)

Flux the Same Direction (adds)

Electric Theory, Quantities and Circuit Elements
Magnetism and Electromagnetism

- ***Electromagnetic Induction*** creates a voltage or current in a conductor when a magnetic field changes
- In a ***transformer***, alternating current in one winding ***induces*** a changing magnetic field in the transformer ***core***
- The changing magnetic field ***induces*** an alternating voltage and current in the second winding

Basic Transformer Operation



$$V_{Primary} = \frac{Windings_{\ Primary}}{Windings_{\ Secondary}} V_{Secondary}$$

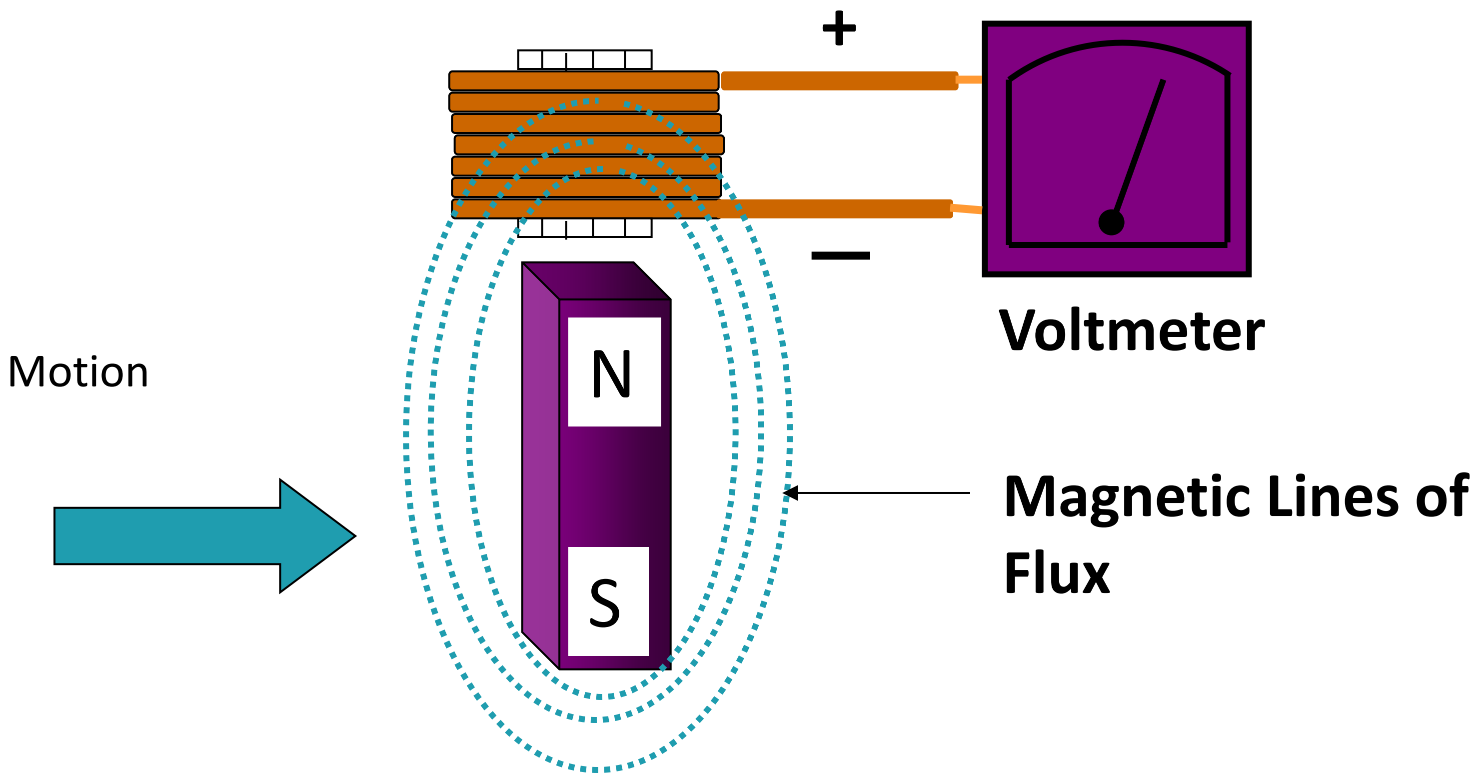
Electric Theory, Quantities and Circuit Elements
Magnetism and Electromagnetism

Generator - magnetic field of the rotor ***Induces*** a voltage in the stator windings.

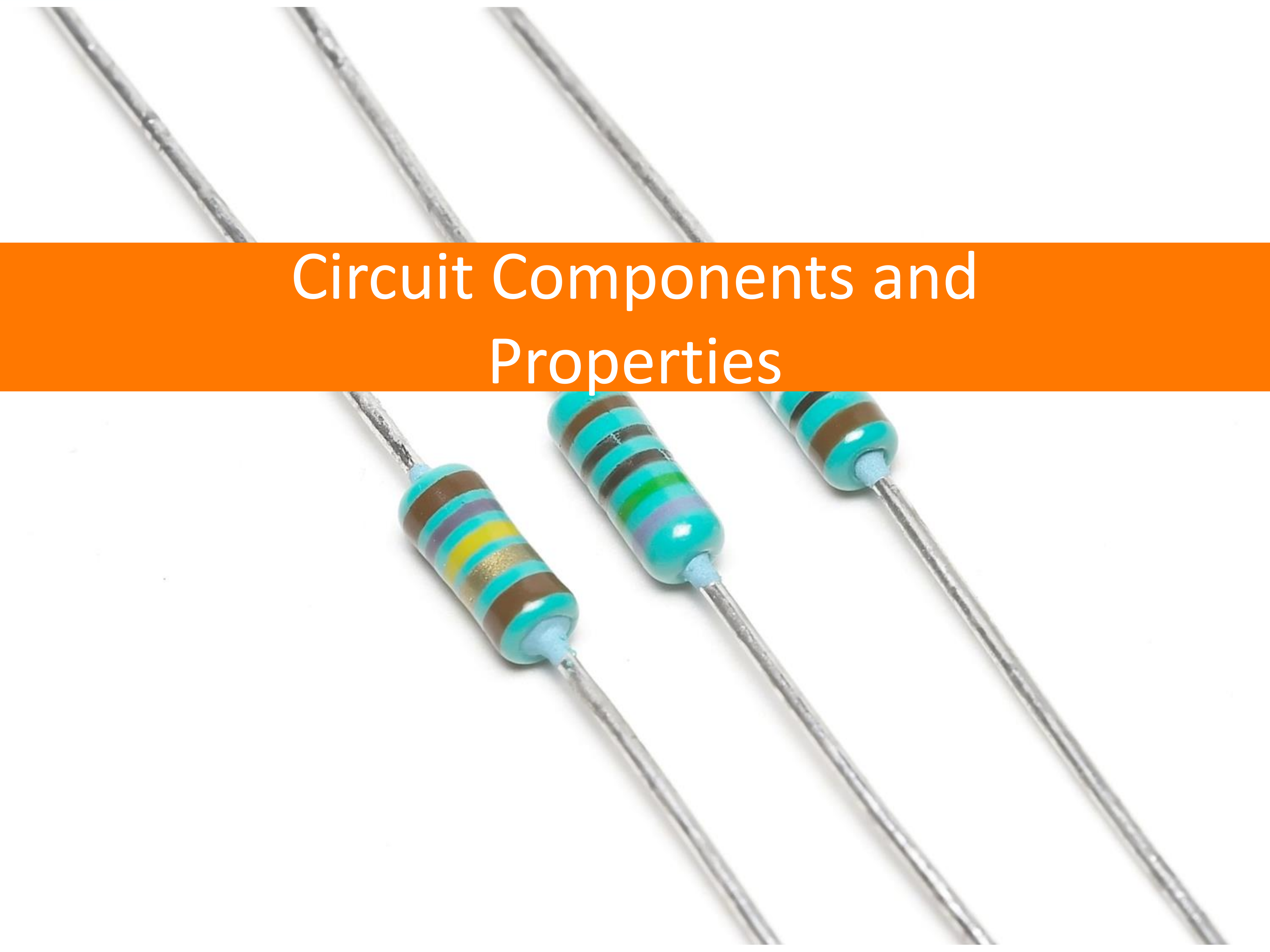
- Rotor may be a permanent magnet
- In a large generator, the ***rotor*** is a spinning electromagnet – created by current from the exciter

Electric Theory, Quantities and Circuit Elements
Electromagnetic Induction

Whenever a magnetic field is moved past a conductor a voltage is induced in the conductor



Circuit Components and Properties



Electric Theory, Quantities and Circuit Elements
Circuit Components and Properties

Resistance (R) is the property of materials that opposes or resists current by converting electric energy to heat.

- Unit of Measurement: ***ohms (Ω)***
- A ***Resistor*** provides resistance to the circuit

Georg Ohm, 1789 -1854

Electric Theory, Quantities and Circuit Elements
Circuit Components and Properties

Resistance depends on:

Resistivity

Conducting material has very low resistivity, insulators have very high resistivity.

Length

Decreasing the material's length decreases the resistance.

Cross-sectional area

Increasing the material's cross-sectional area decreases the resistance.

Temperature

The hotter the wire, the more resistance it exhibits.

Electric Theory, Quantities and Circuit Elements
Circuit Components and Properties

Inductance (L) is the property of an electrical circuit that opposes change in current. The unit of inductance is the **Henry (H)**.

- Any component that we use for its inductive property is called an **inductor**
- In the Power system, an inductor is sometimes also called a **reactor**

Electric Theory, Quantities and Circuit Elements
Circuit Components and Properties

- An **Inductor (L)** is a coil of wire that creates a magnetic field when current is applied
- The changing magnetic field of an Inductor opposes the voltage that is trying to force current in the wire
- An inductor opposes a change in current

$$V = L\frac{dI}{dt}$$

(Voltage equals Inductor size times rate-of-change of Current)

Electric Theory, Quantities and Circuit Elements
Circuit Components and Properties

Capacitance (C) is the property of an electrical circuit that opposes change in voltage.

- Unit of Measurement: **Farads(F)**

A **Capacitor** stores electrical charge.

- A Capacitor consists of two metal plates separated by an insulating layer.

$$V = 1/(2\pi f C) \int I dt$$

(Voltage builds up as current flows into the Capacitor)

Electric Theory, Quantities and Circuit Elements
Circuit Components and Properties

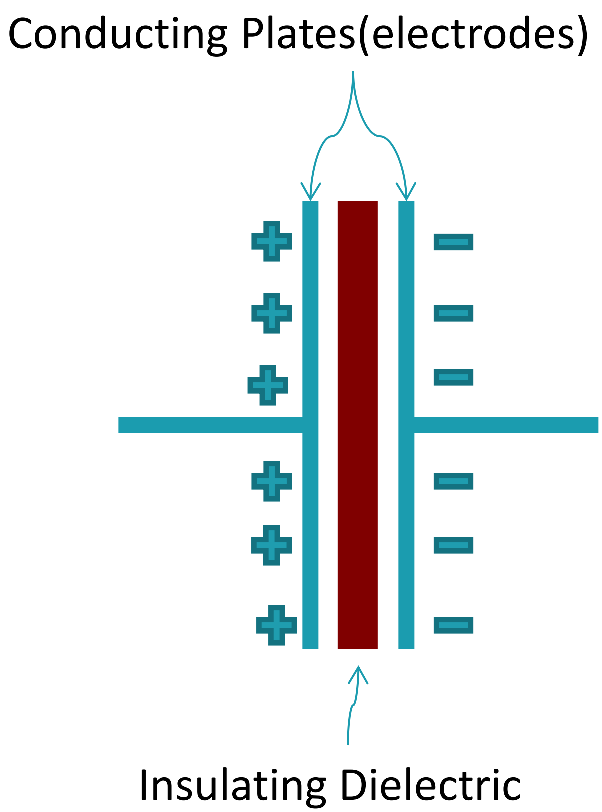
- The value of capacitance in a circuit is measured in capacitive units called farads.
- The farad is named after Michael Faraday, a 19th century British physicist, who is credited with developing the method of measuring capacitance.
- Farad determined that a capacitor has a value of one farad of capacitance if one volt of potential difference applied across its plates moved one coulomb of electrons from one plate to the other.

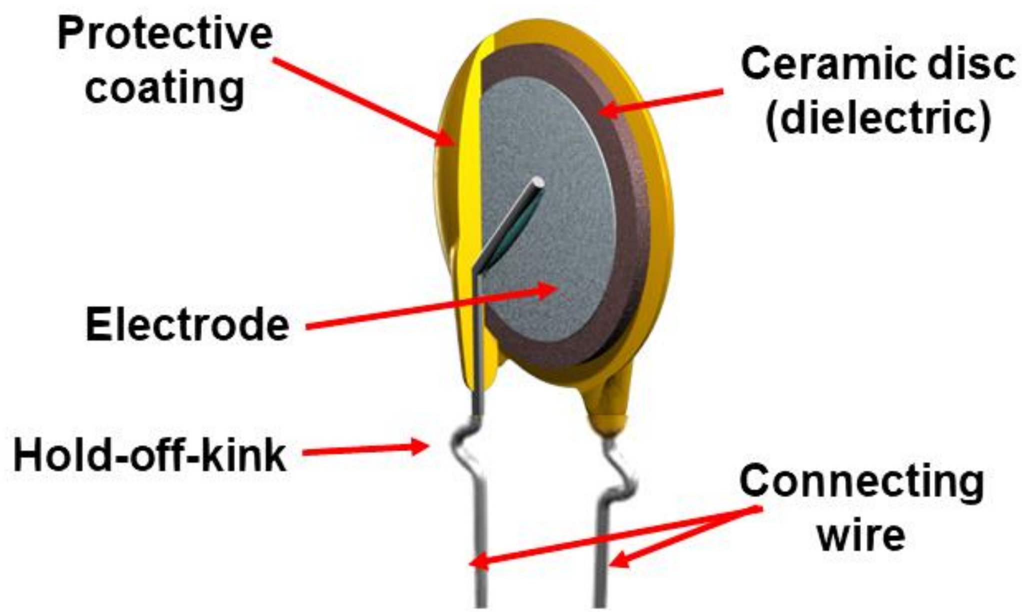
Michael Faraday

Electric Theory, Quantities and Circuit Elements
Circuit Components and Properties

- A **Capacitor** consists of two conducting metal plates with an insulating sheet of material in between.
- When current is applied across the terminals, **charge flows** from one side to the other.
- Over time as **charge builds** on the capacitor, voltage increases.

Electric Theory, Quantities and Circuit Elements
Circuit Components and Properties: Capacitor Construction





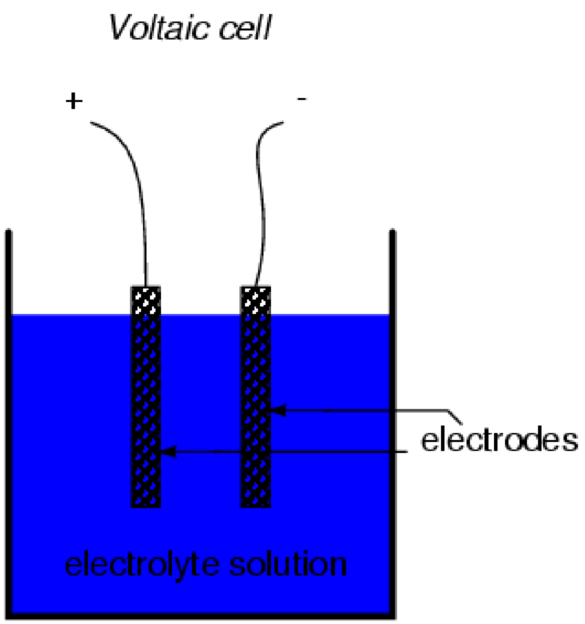
Capacitors come in all sizes and shapes…

FCC ID: H4TZX1848A. Certified to comply
with FCC Part15 SUBPART J class B limits.
RINGER Equivalence 0.3A USOC RJ11C Jacks.
complies with FCC Part 68 Rules.
29.4912 MHz
KE
9333
SC11175CV/CBF
SC22101
244N
D005/02CS
ZX6475
VER 1.0
D49151
COM1:A,C,D
COM2:B,D,E
COM3:A,C,F
COM4:B,E,F

Chemical Battery Operation

In the battery, two different metals, called ***ELECTRODES*** are placed in a chemical solution called the ***ELECTROLYTE***.

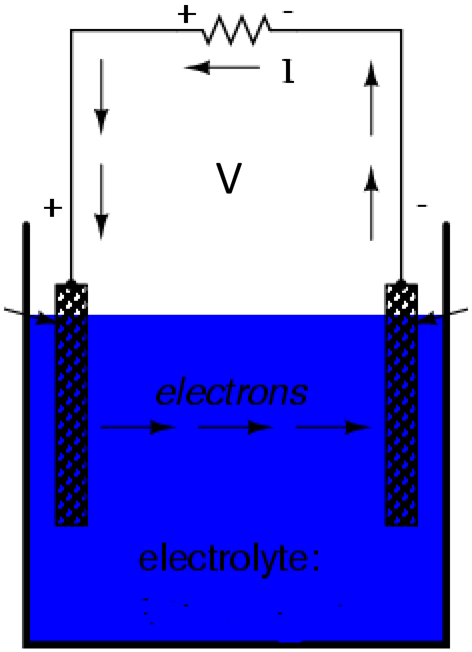
- The metals react differently.
- One loses electrons and develops a positive charge, the other attracts electrons and develops a negative charge.



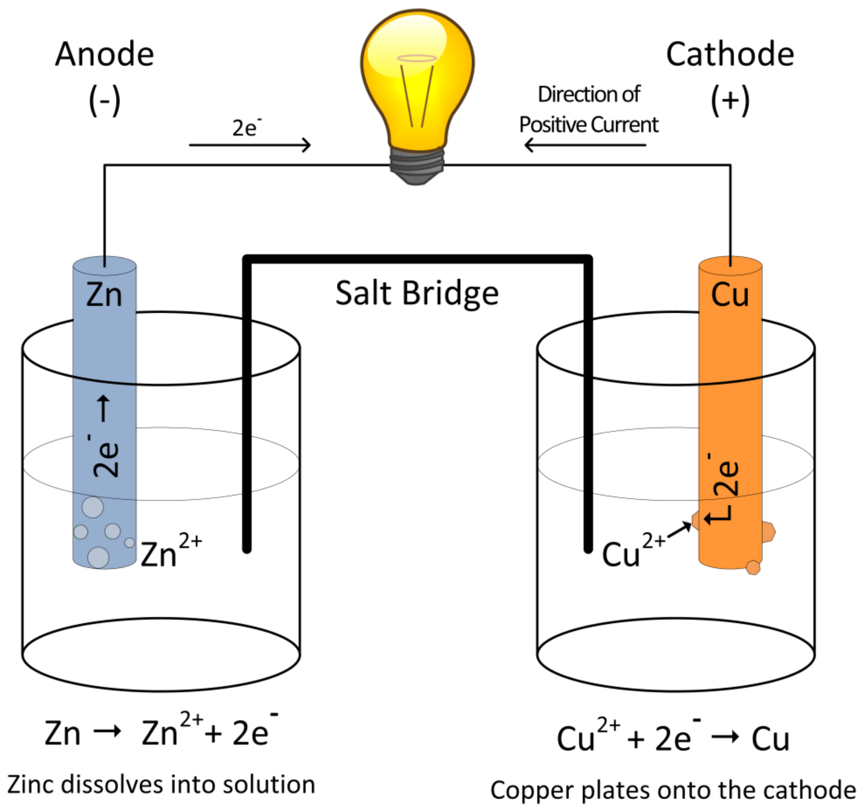
Chemical Battery Operation

This results in a DIFFERENCE IN POTENTIAL (Voltage) between the two electrodes.

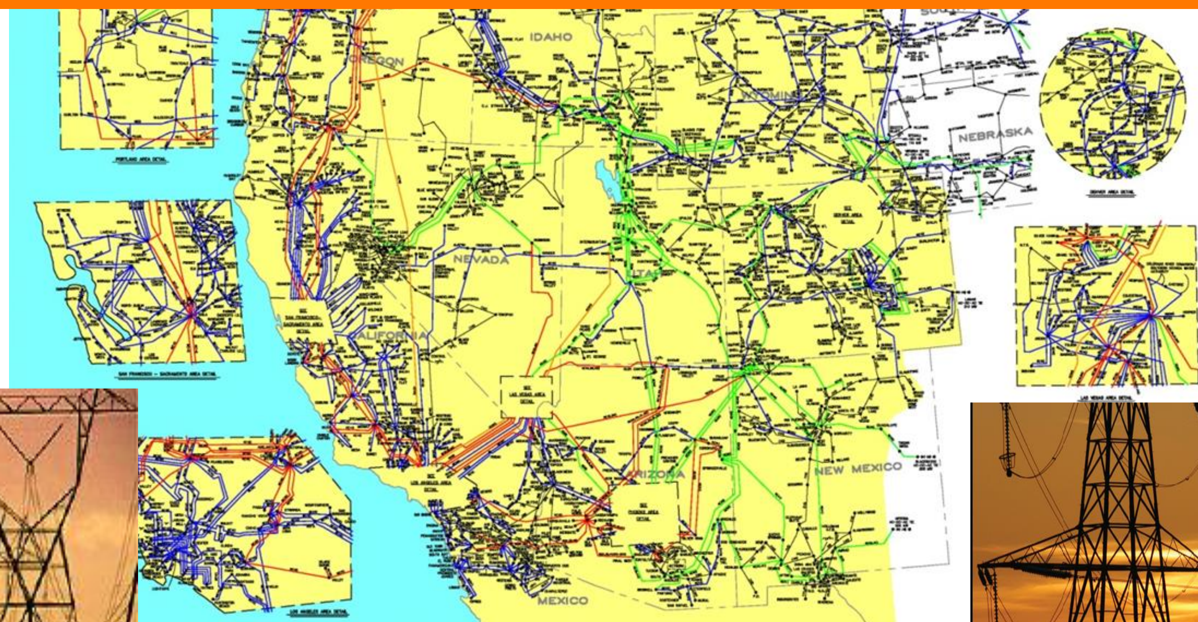
When a conductor is attached to the electrodes of the battery, electrons flow from the ***negative*** electrode to the ***positive*** electrode.



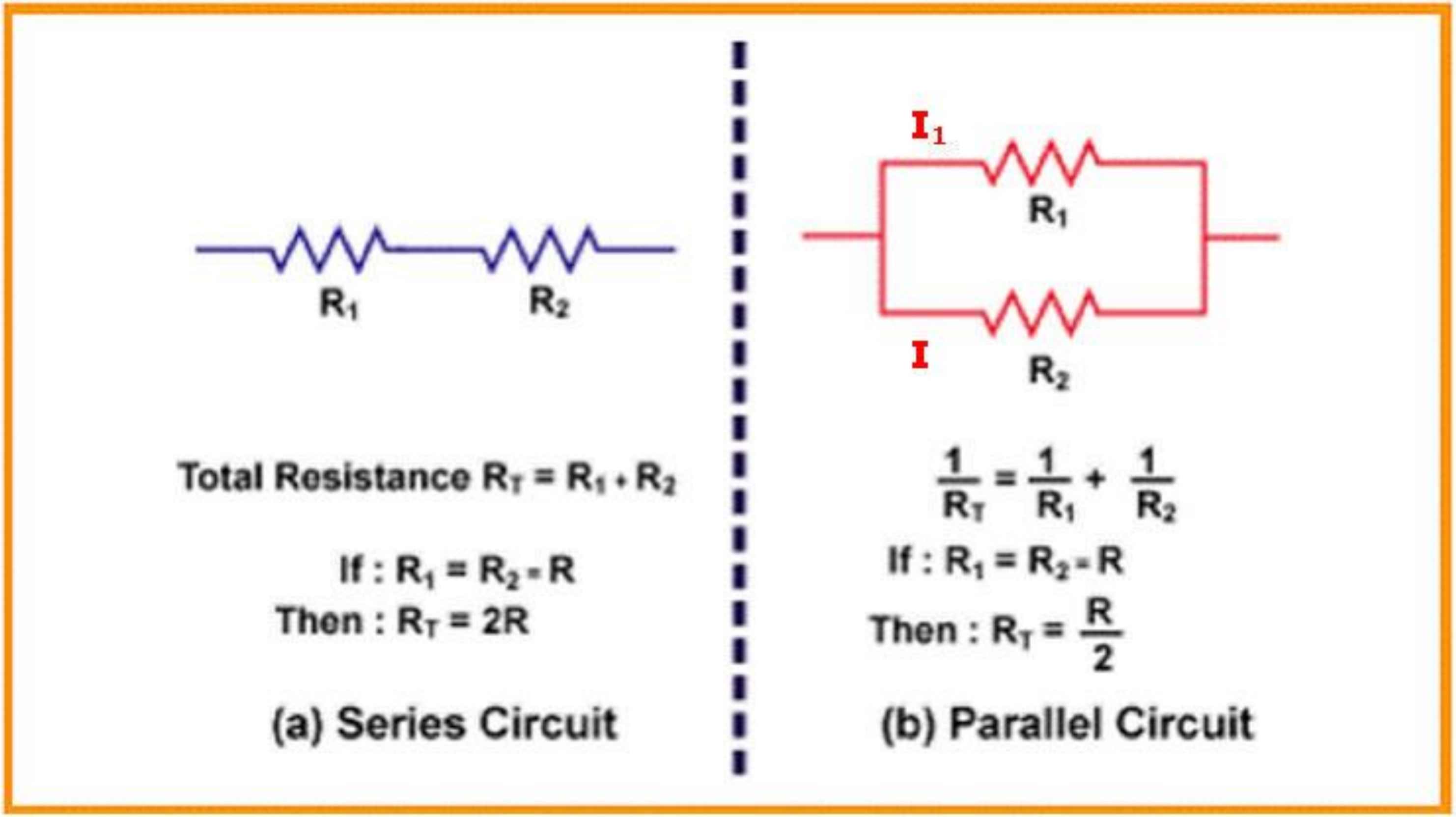
Chemical Battery Operation



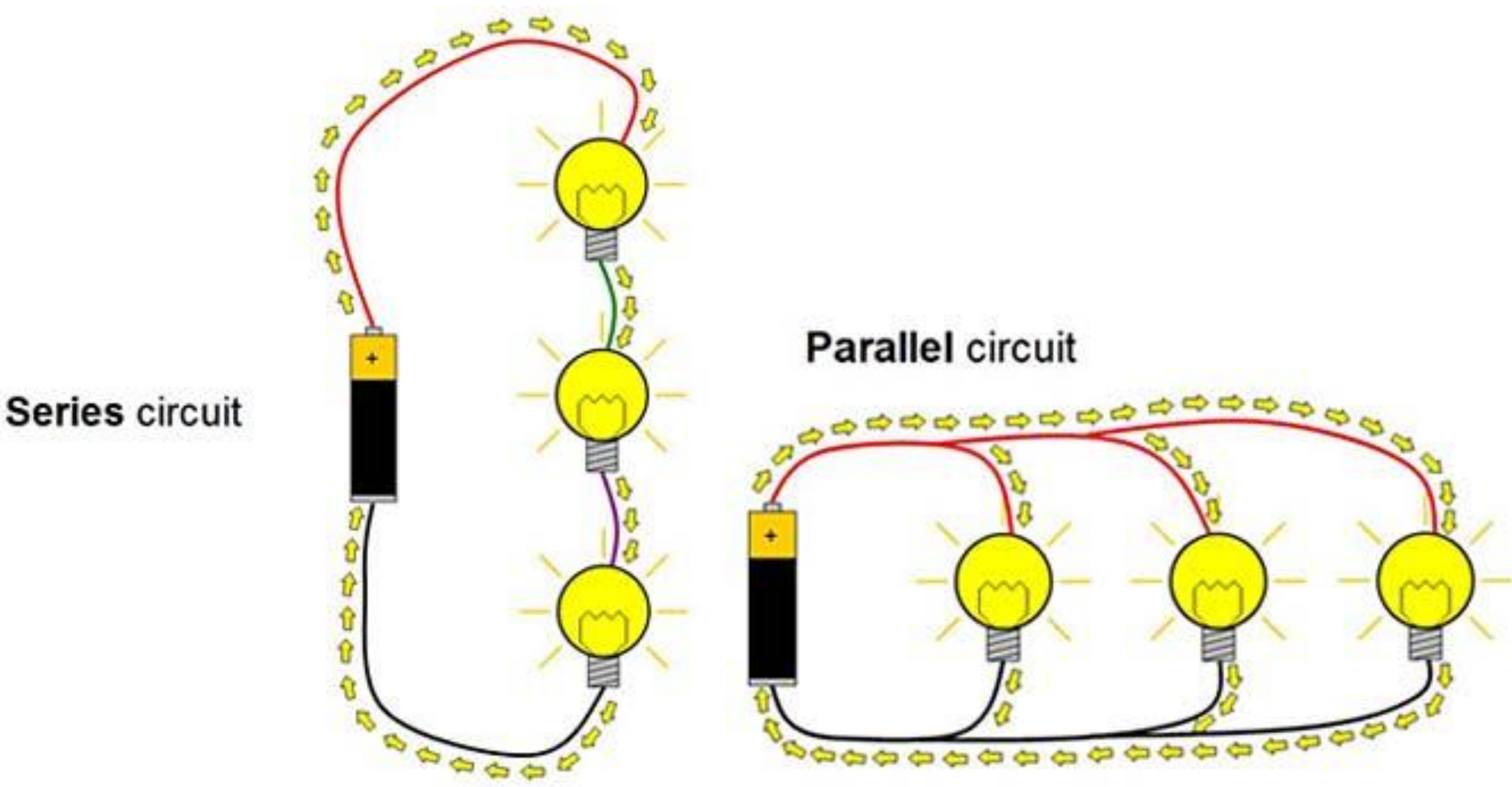
Circuit Analysis



Electric Theory, Quantities and Circuit Elements
Circuit Analysis - Series and Parallel Circuits

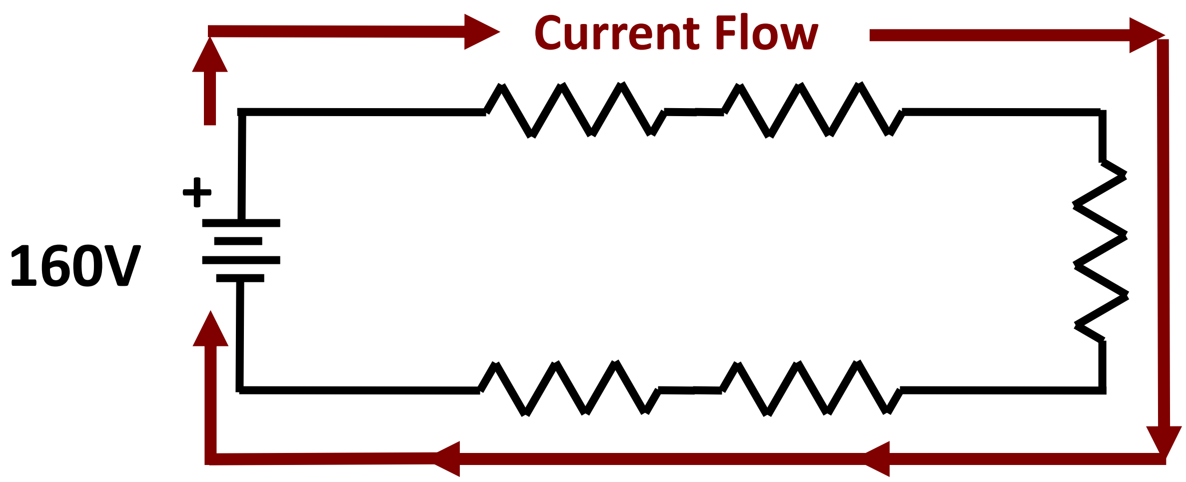


Electric Theory, Quantities and Circuit Elements
Circuit Analysis: Series and Parallel Circuits



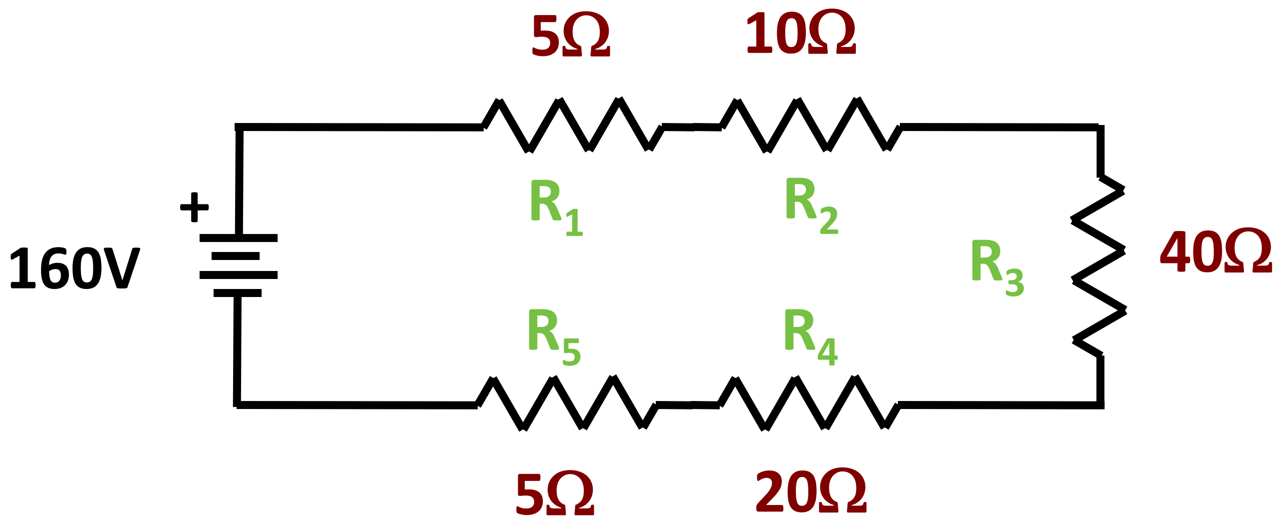
Electric Theory, Quantities and Circuit Elements
Circuit Analysis: Series Circuit

A series circuit is a circuit that has only one path for current to flow.



Electric Theory, Quantities and Circuit Elements
Circuit Analysis: Series Circuit

Total resistance of the circuit (R_T)?



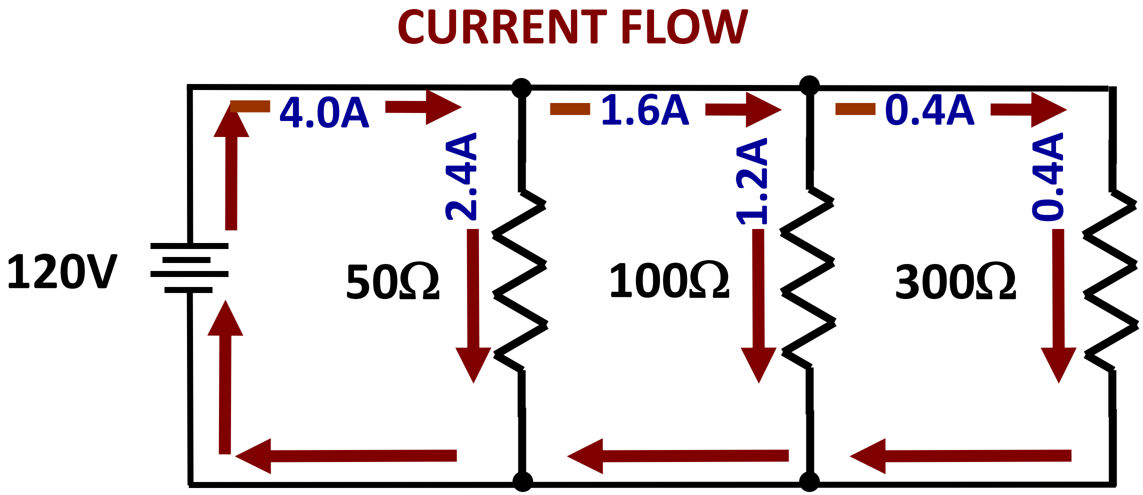
$$R_T = R_1 + R_2 + R_3 + R_4 + R_5$$

$$R_T = 5\ \Omega + 10\ \Omega + 40\ \Omega + 20\ \Omega + 5\ \Omega$$

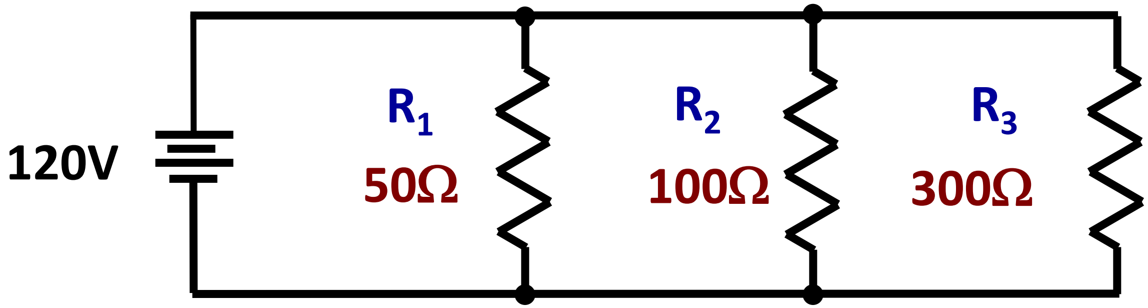
$$R_T = 80\ \Omega$$

Electric Theory, Quantities and Circuit Elements
Circuit Analysis: Parallel Circuit

A parallel circuit is a circuit that has more than one path for current to flow.



Electric Theory, Quantities and Circuit Elements
Circuit Analysis: Parallel Circuit



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

$$\frac{1}{R_T} = \frac{1}{50\Omega} + \frac{1}{100\Omega} + \frac{1}{300\Omega}$$

$$\frac{1}{R_T} = 0.02 + 0.01 + 0.0033$$

$$\frac{1}{R_T} = 0.0333 \qquad R_T = \frac{1}{0.0333}$$

$$R_T = 30\Omega$$

Ohm's Law and Kirchoff's Law

Electric Theory, Quantities and Circuit Elements
Ohm's Law

Ohm's Law:

– Voltage Drop = Current * Resistance

Kirchhoff's Laws:

– Sum of current entering a junction equals the sum of current leaving the junction.

– Sum of voltage drops equals the applied voltage.

Electric Theory, Quantities and Circuit Elements
Ohm's Law

Ohm's law, named after Mr. Georg Ohm, a German mathematician and physicist. 1789 -1854.

He defined the basic relationship between power, voltage, current and resistance.

The principles apply to AC, DC or RF (radio frequency).

Electric Theory, Quantities and Circuit Elements
Ohm's Law

V = IR

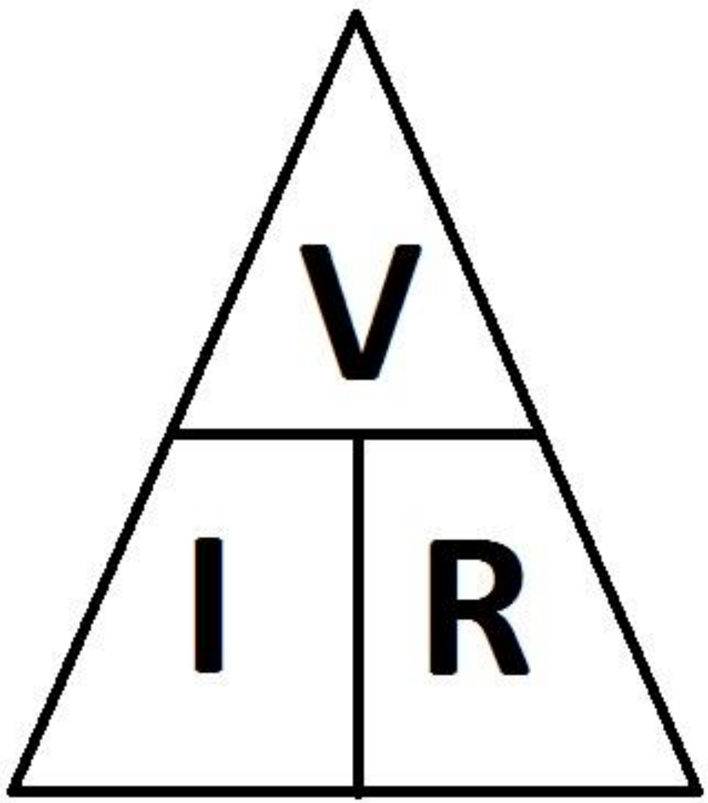
I = V/R

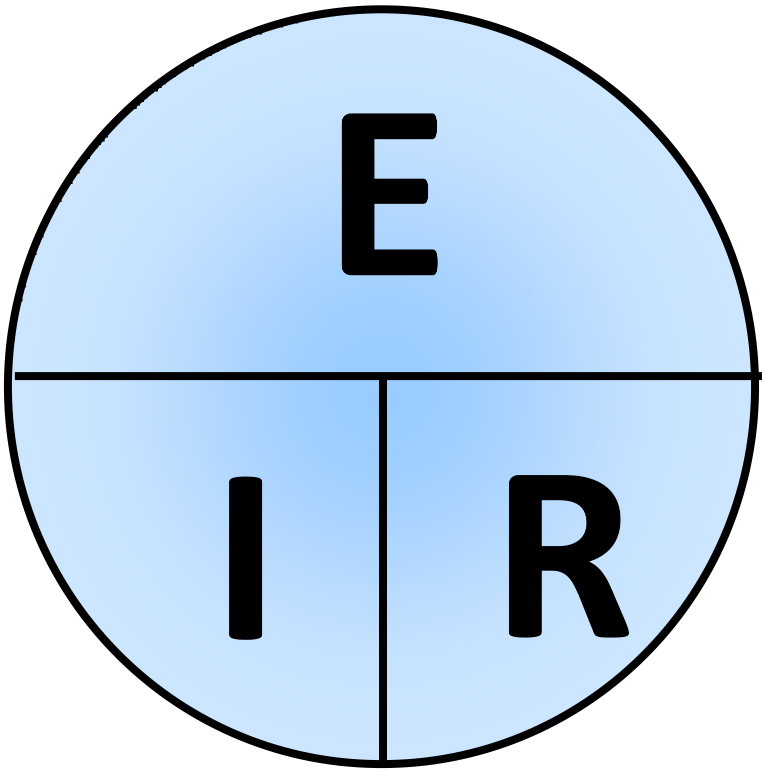
R = V/I

Where:

V = Voltage	***in Volts***
I = Current	***in Amps***
R = Resistance	***in Ohms***

Electric Theory, Quantities and Circuit Elements
Ohm’s Law: Pie or Triangle

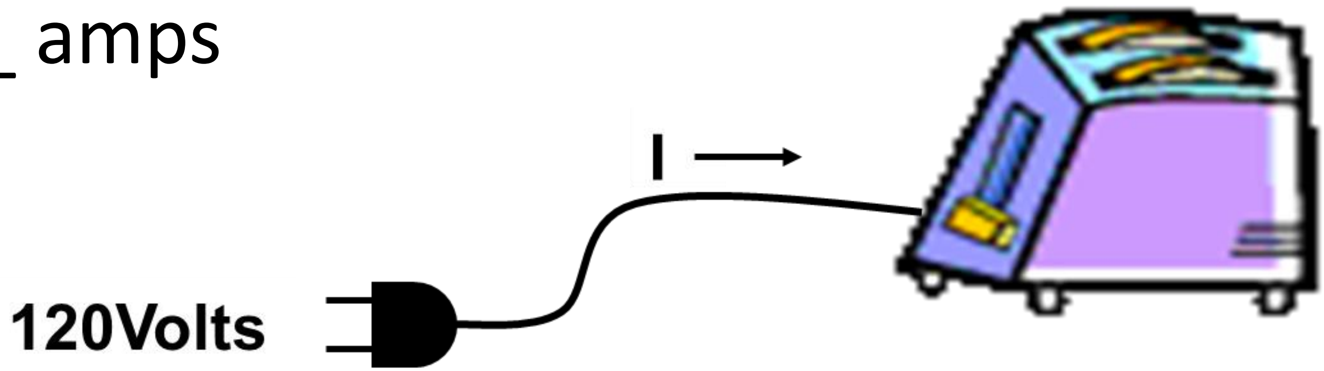


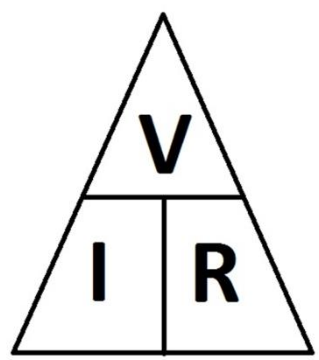


Electric Theory, Quantities and Circuit Elements
Quick question

How much current is flowing in the toaster circuit?

I = __ amps

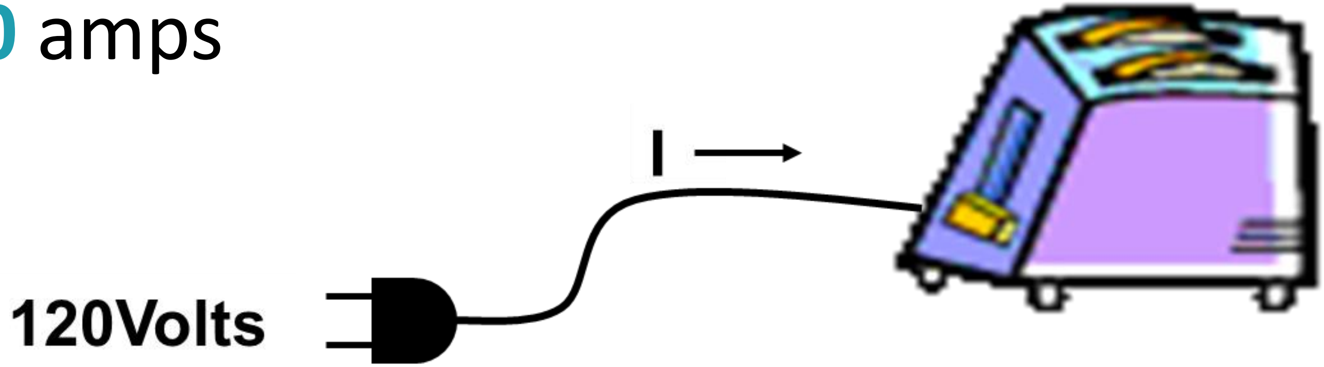


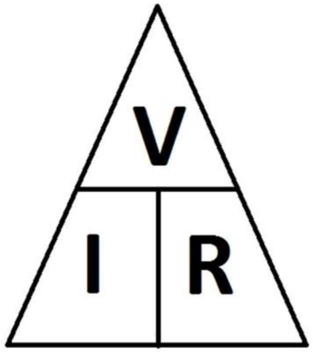


Electric Theory, Quantities and Circuit Elements
Quick question

How much current is flowing in the toaster circuit?

I = **10** amps



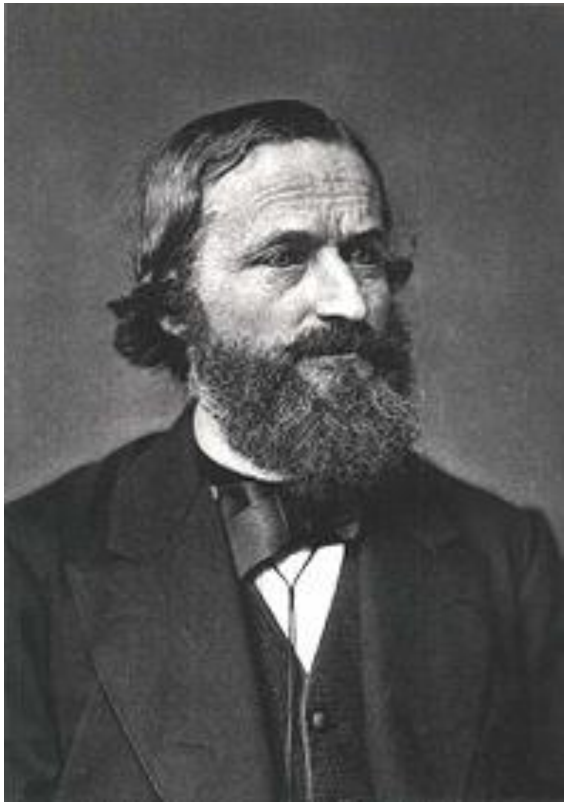


Electric Theory, Quantities and Circuit Elements
Kirchoff's Law

Kirchhoff's Current Law: the sum of the currents entering a junction equals the sum of the currents leaving a junction.

- For series circuits - the current is the same at all points
- For parallel circuits - the total current in a parallel circuit is equal to the sum of the currents in each branch

Electric Theory, Quantities and Circuit Elements
Kirchoff's Law



Gustav Kirchoff was a German Physicist 1824 – 1887.

He developed laws for circuit analysis as well as other laws for "black body" radiation and thermochemistry.

Electric Theory, Quantities and Circuit Elements
Kirchoff's Law

Kirchhoff's Voltage Law states:

- The voltage difference across a resistor is called a voltage drop
- In series circuits, the sum of the voltage drops around the circuit is equal to the applied voltage
- In parallel circuits, the voltage drops across all the branches are the same

Check Your Knowledge: Fundamentals of Electricity

1. A blow drier uses 120 Volts and draws 10 amps. What is its resistance?
2. How much power does it use?
3. How much would it cost to run the blow drier for one hour?
4. If you had two similar blow dryers plugged in to the wall – would they be in series or parallel?
5. How many amps total would they use?
6. If you re-wired the blow dryers to put one in series with the other, what would be the total resistance?
7. How much current would flow through the circuit?
8. What would the voltage across each dryer be?
9. What would be the total power used?

Alternating Current

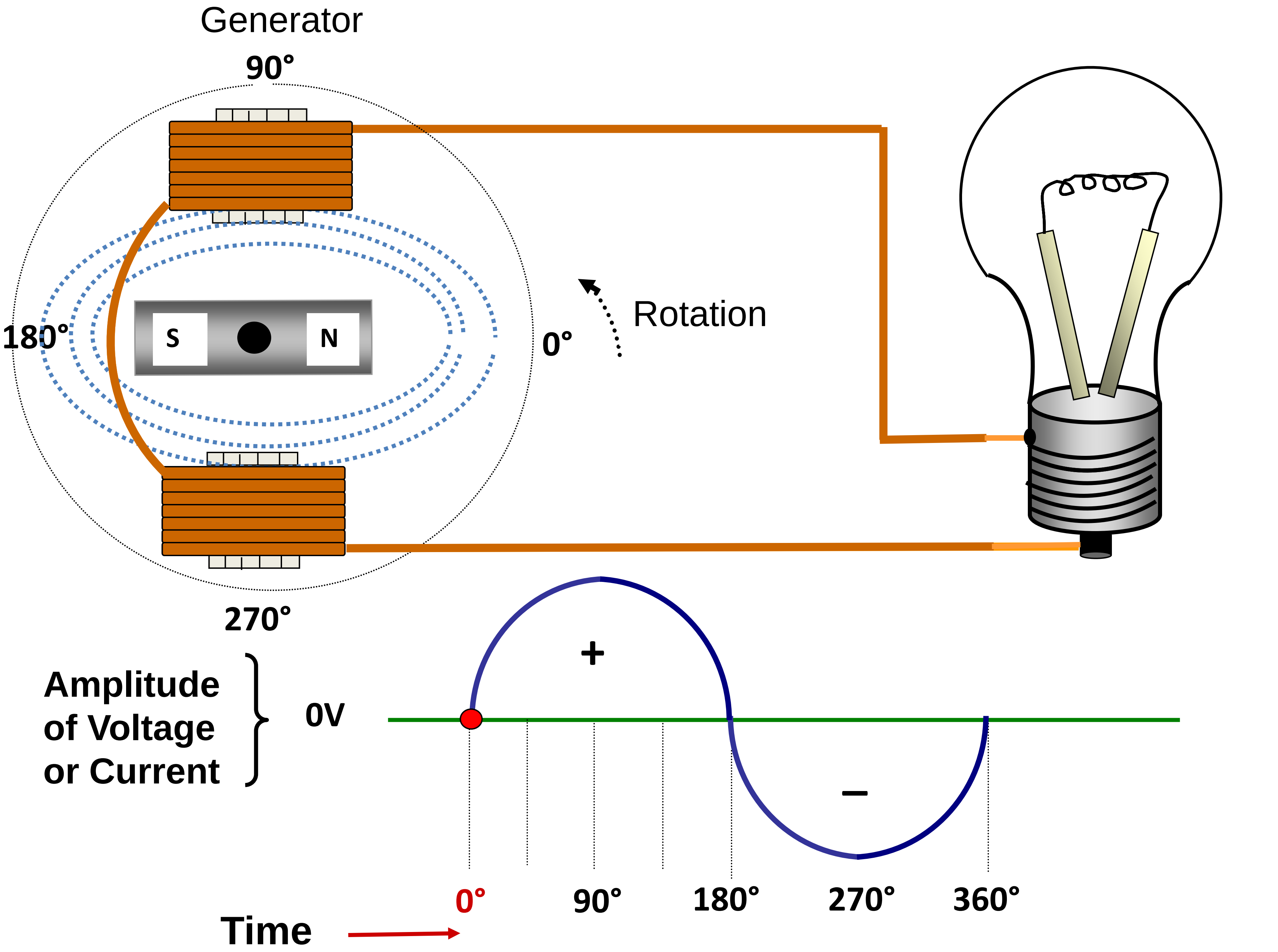
- Generating AC Current
- Sine Waves
- RMS Values
- Phase Relationship
- Right Triangle Relationships
- Impedance–Resistance, Inductance, Capacitance

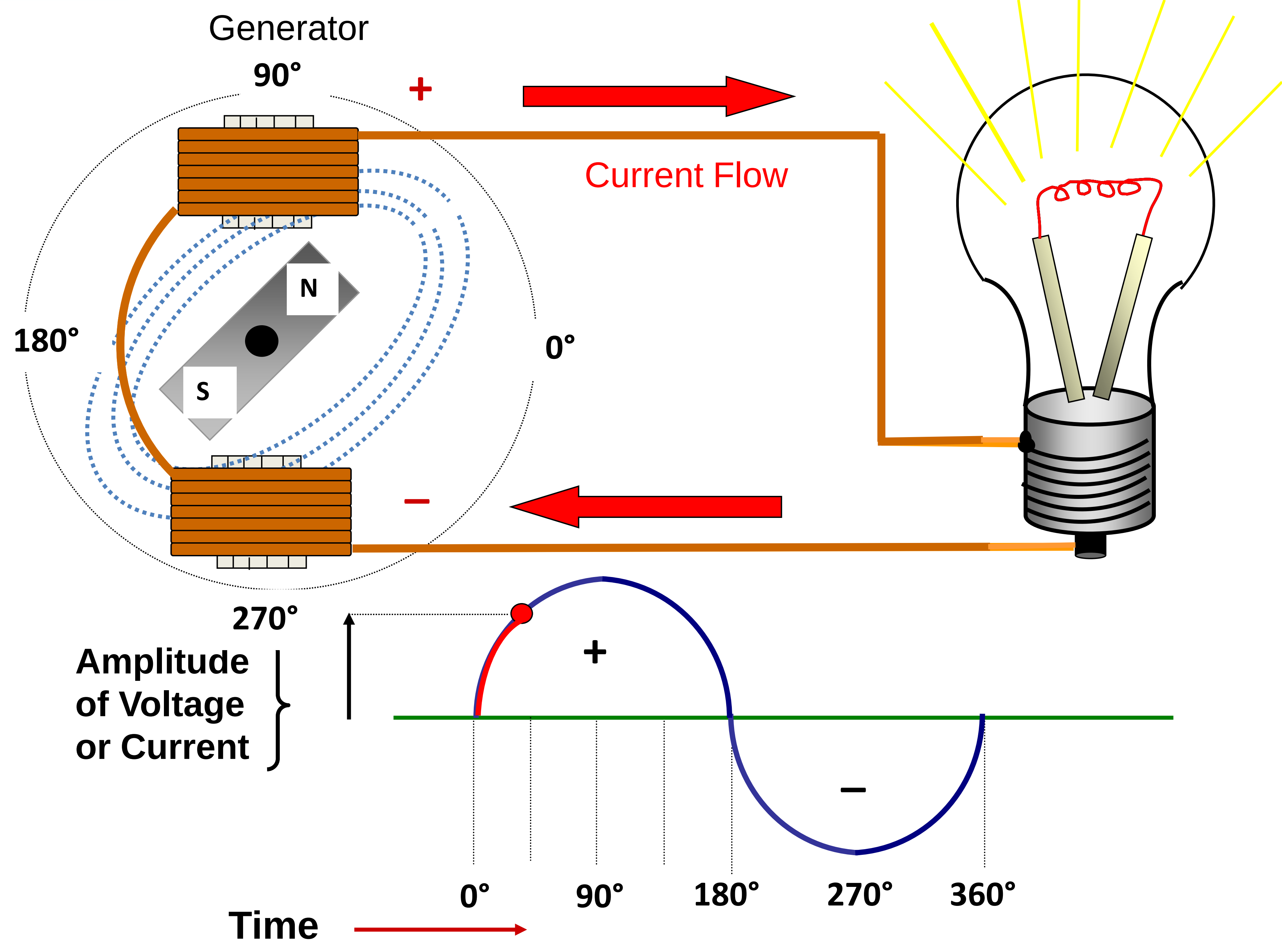
Alternating Current (AC)

Alternating Current (AC) periodically changes direction of flow and magnitude.

- AC voltage produces an alternating current
- AC power is produced by alternating current and alternating voltage

Generating AC Current


Generator
90°
180°
S
N
0°
Rotation
270°
Amplitude
of Voltage
or Current
0V
+
–
0°
90°
180°
270°
360°
Time


Generator
90°
+
Current Flow
180°
N
S
0°
−
270°
Amplitude
of Voltage
or Current
+
−
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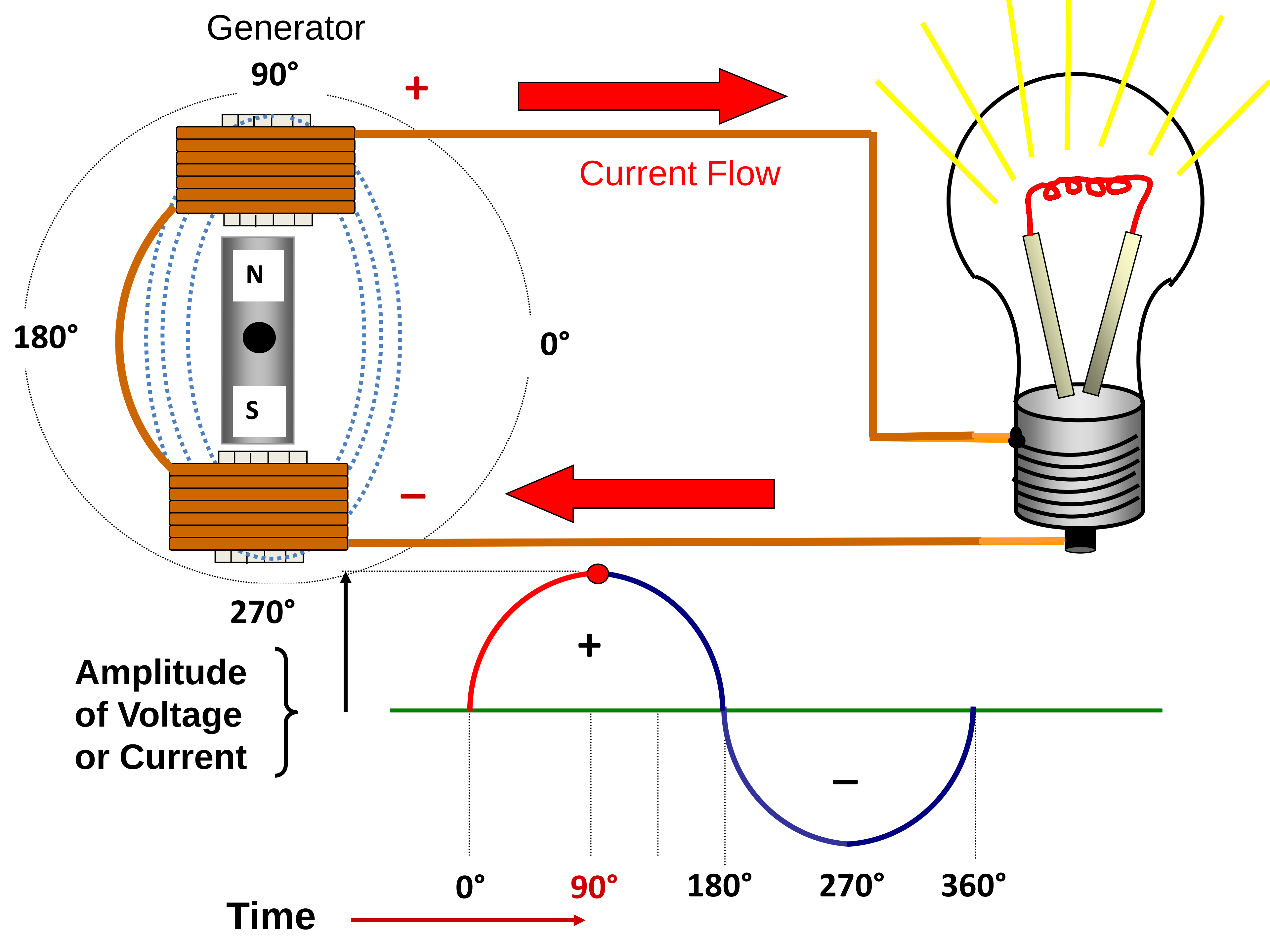
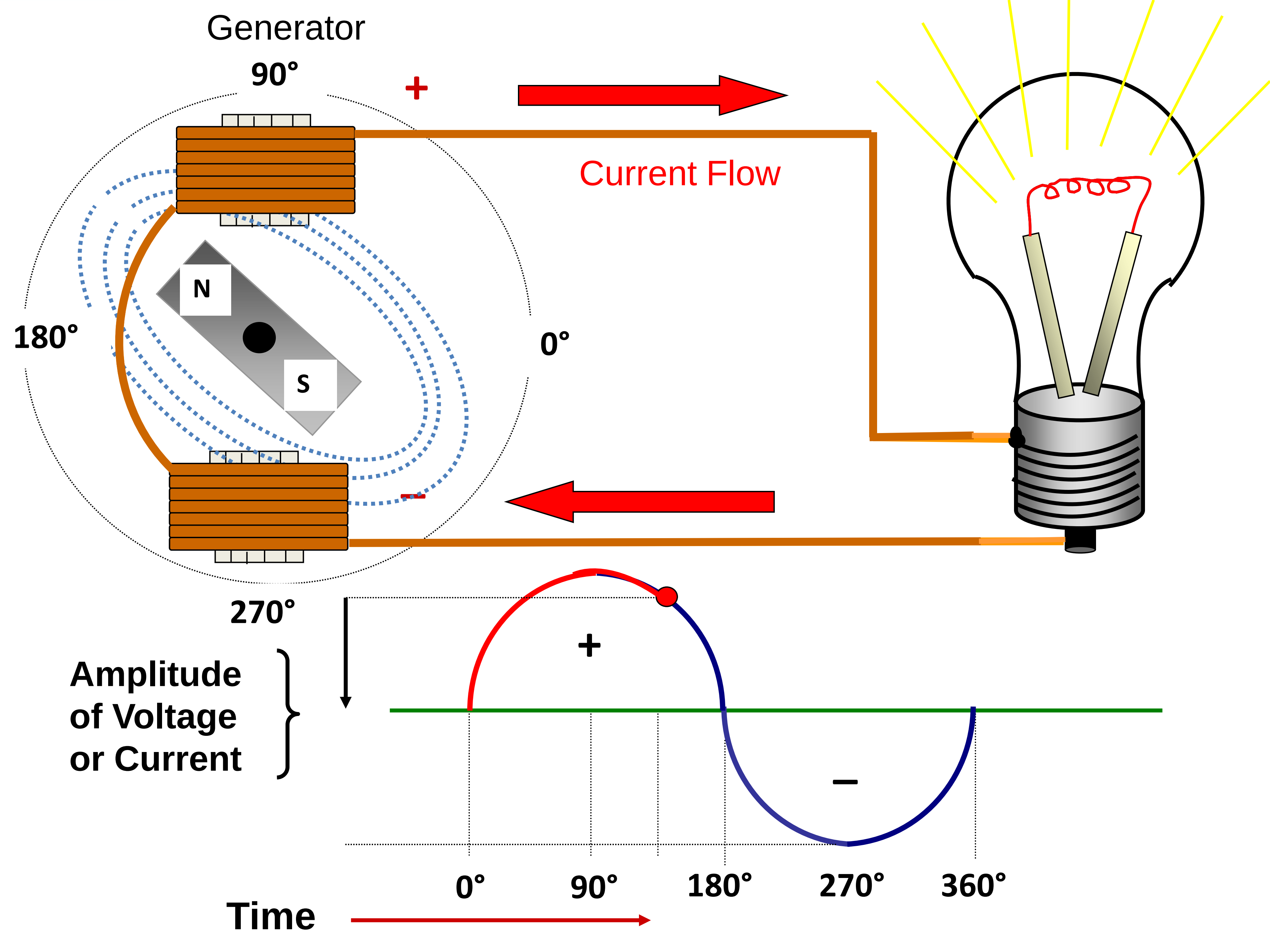
180°
270°
360°
Time


Generator
90°
+
180°
0°
N
S
270°
–
Current Flow
Amplitude of Voltage or Current
+
–
0°
90°
180°
270°
360°
Time



Generator
90°
+
Current Flow
180°
N
S
0°
–
270°
Amplitude
of Voltage
or Current
+
–
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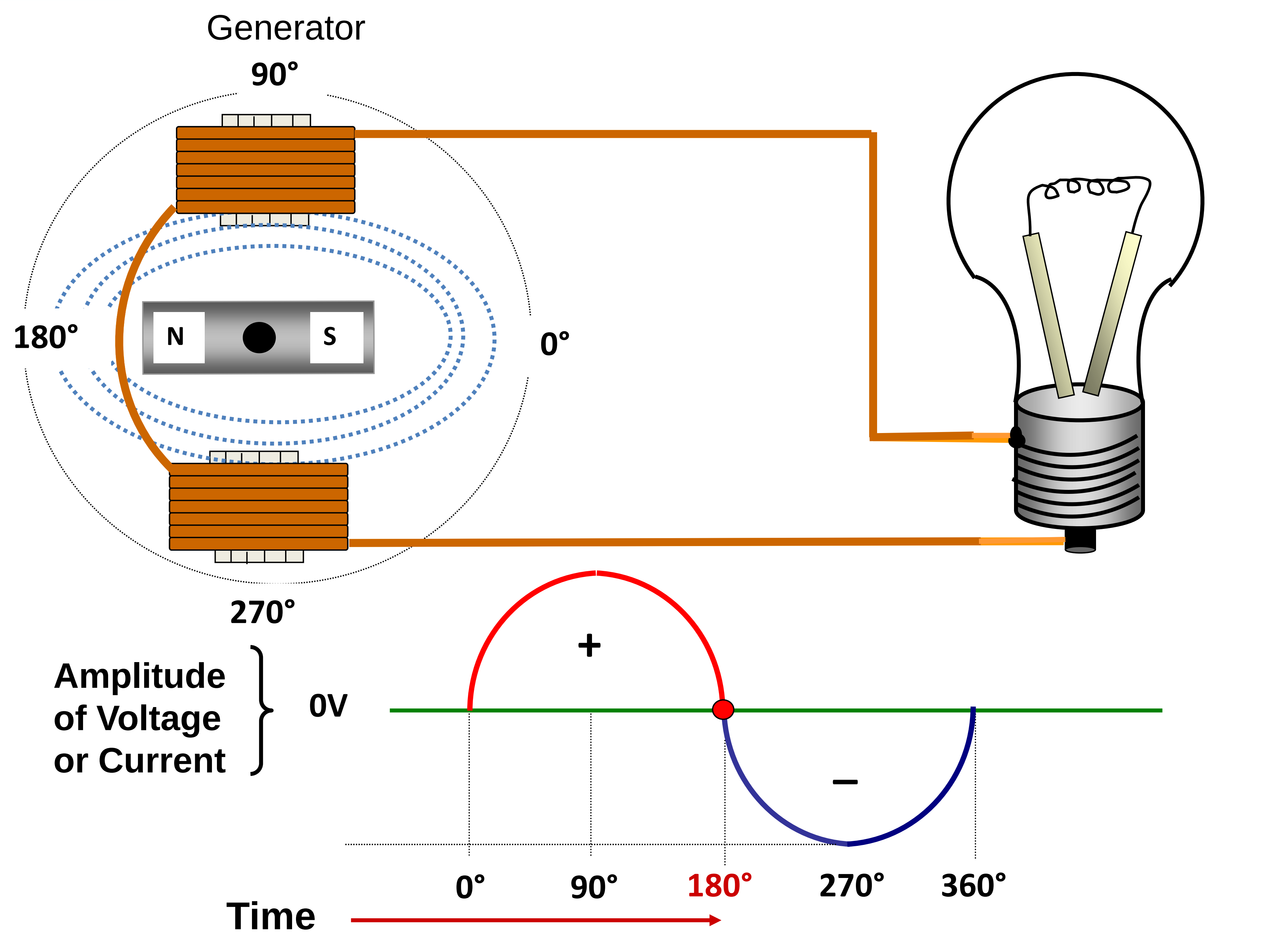
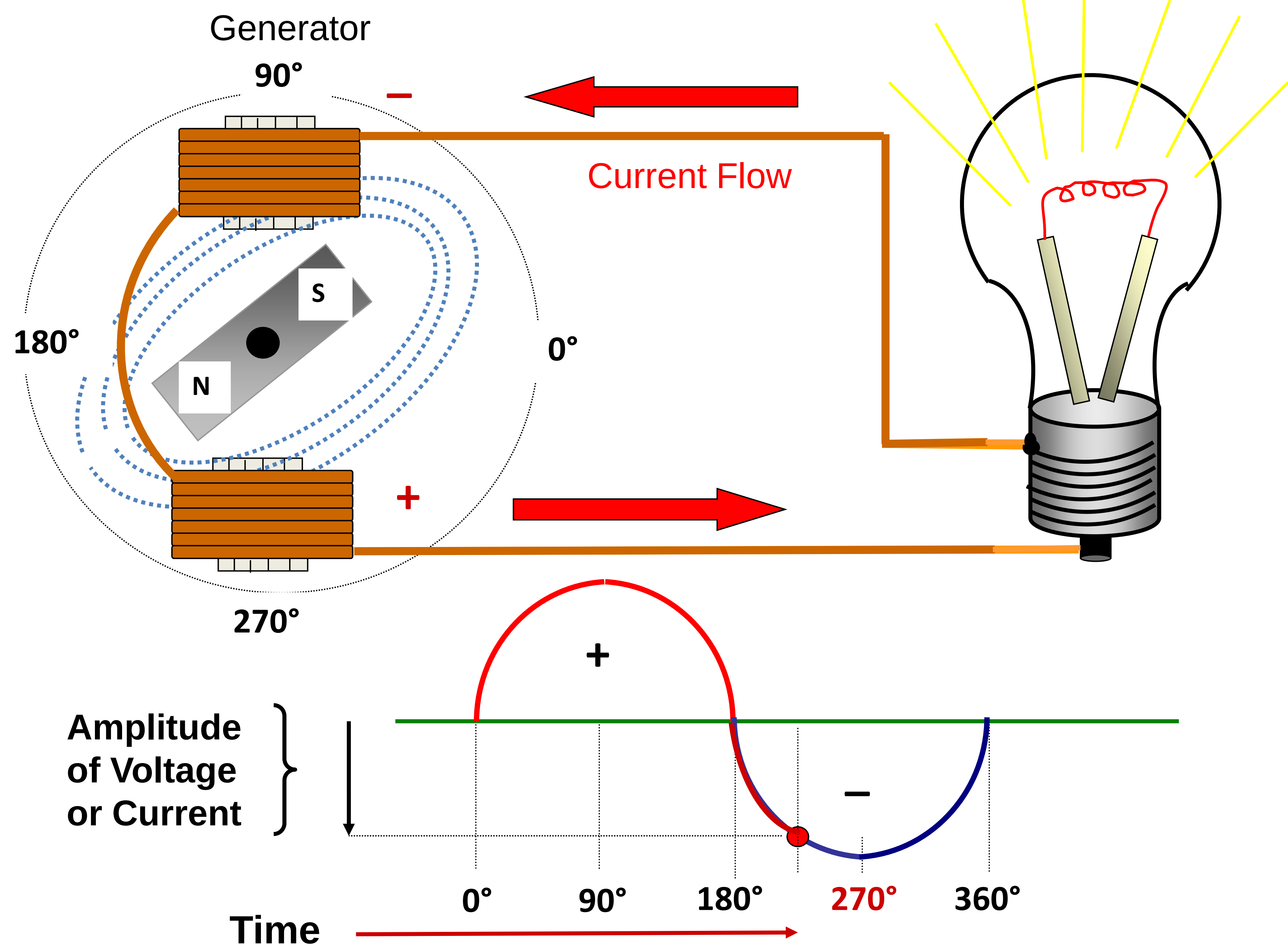
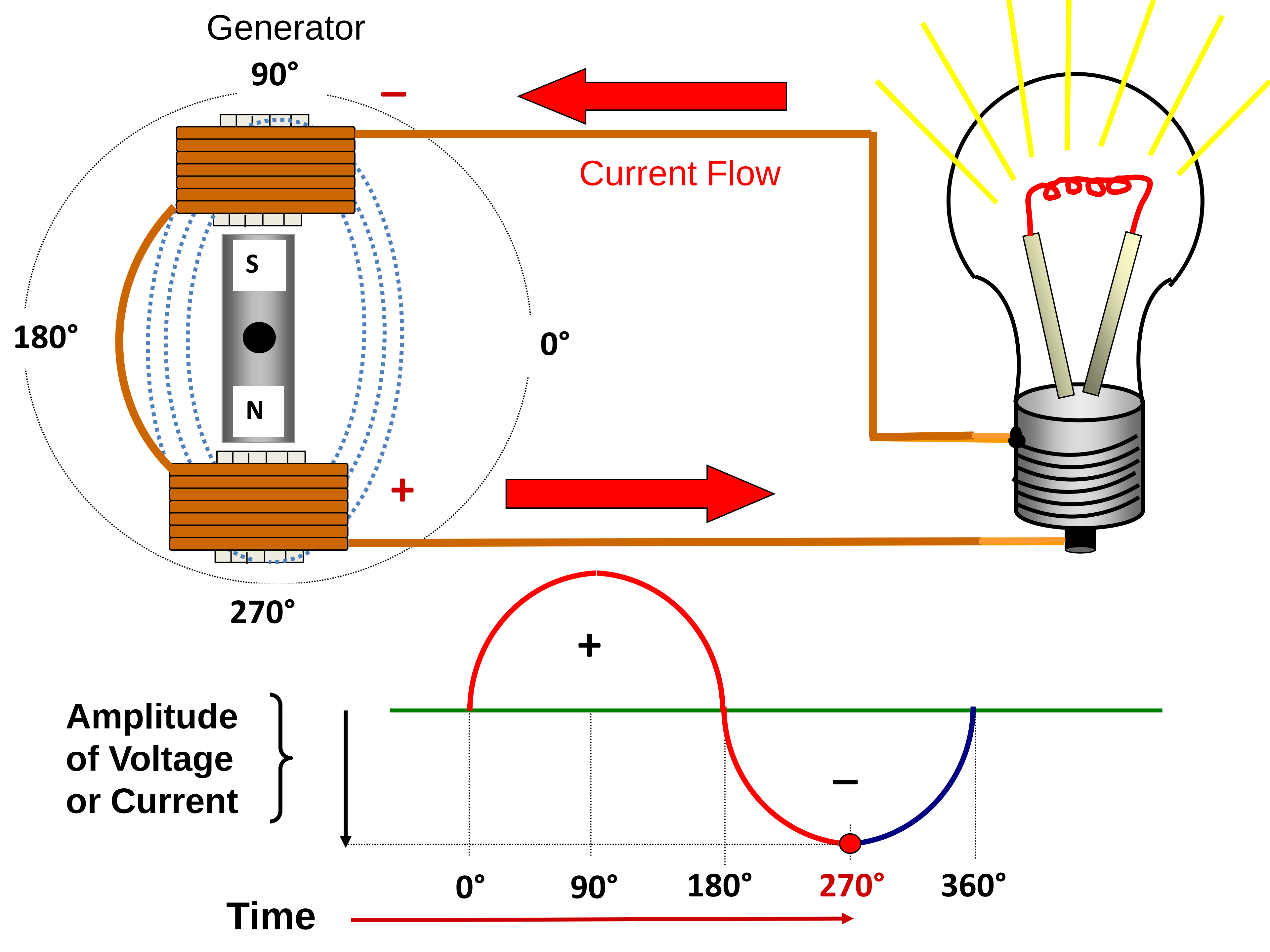
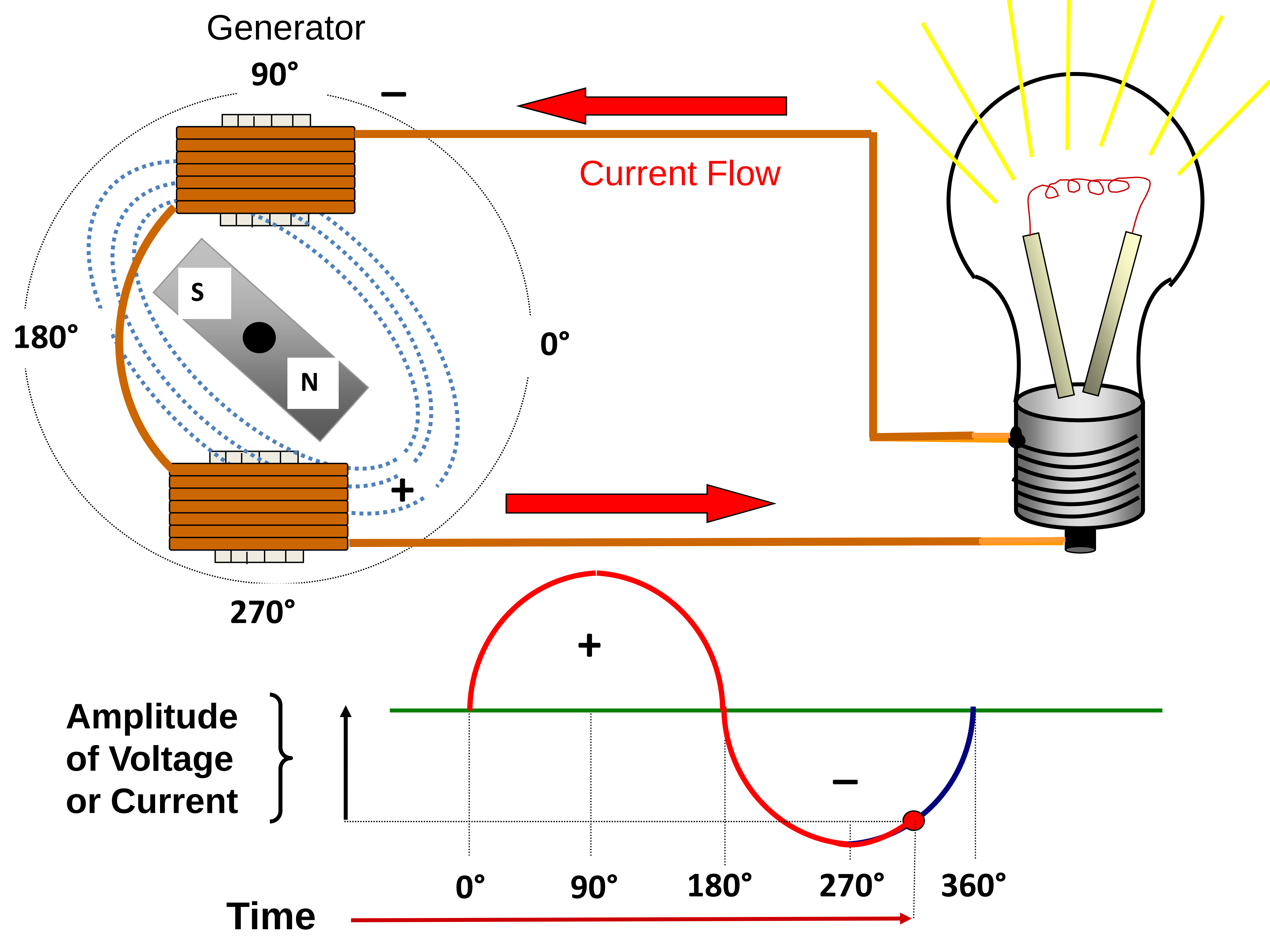
90°
180°
270°
360°
Time

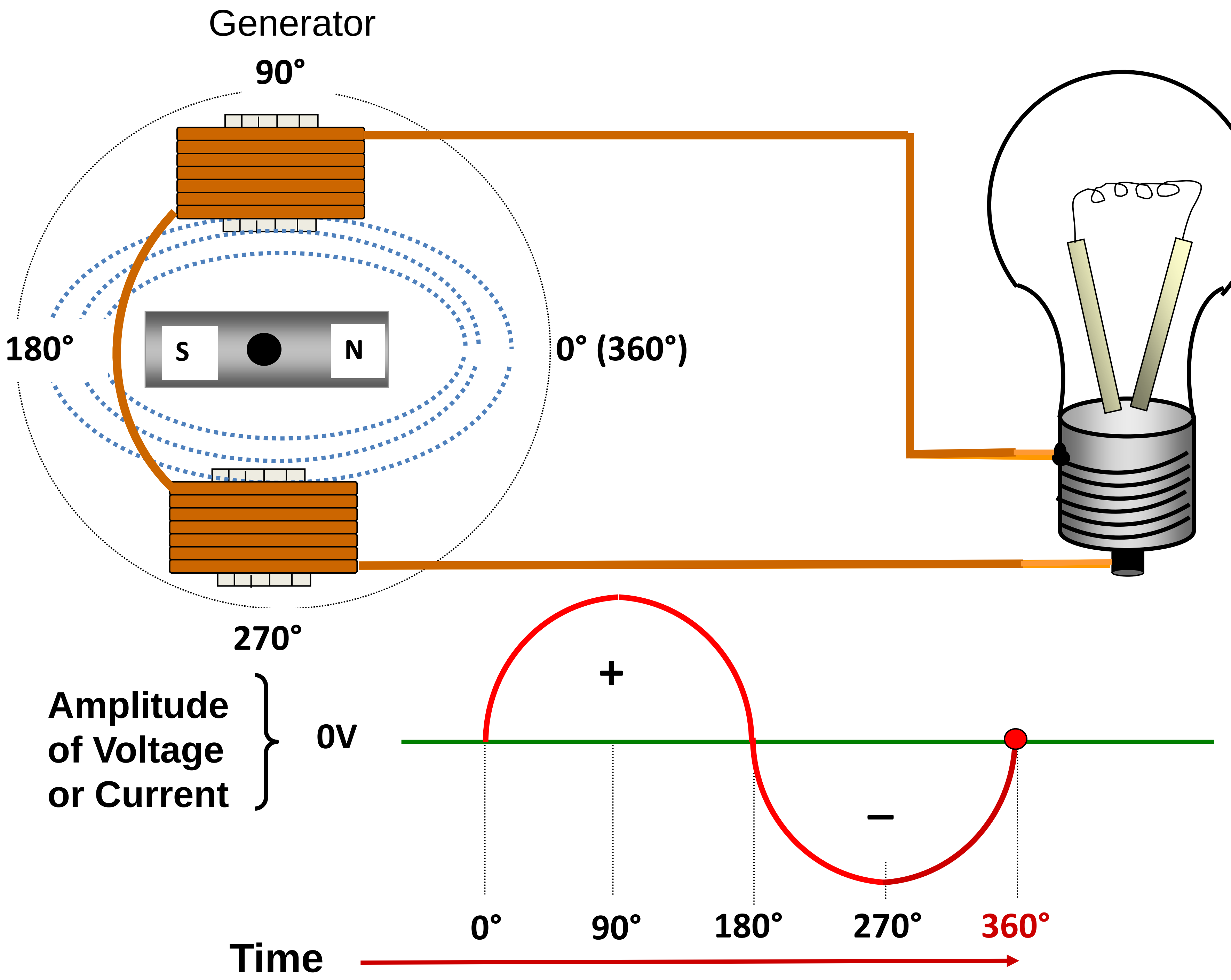

Generator
90°
180°
N
S
0°
270°
Amplitude of Voltage or Current
0V
+
–
0°
90°
180°
270°
360°
Time



Generator
90°
–
Current Flow
180°
S
N
0°
+
270°
+
Amplitude
of Voltage
or Current
–
0°
90°
180°
270°
360°
Time


Generator
90°
–
Current Flow
180°
S
N
0°
+
270°
+
Amplitude
of Voltage
or Current
–
0°
90°
180°
270°
360°
Time

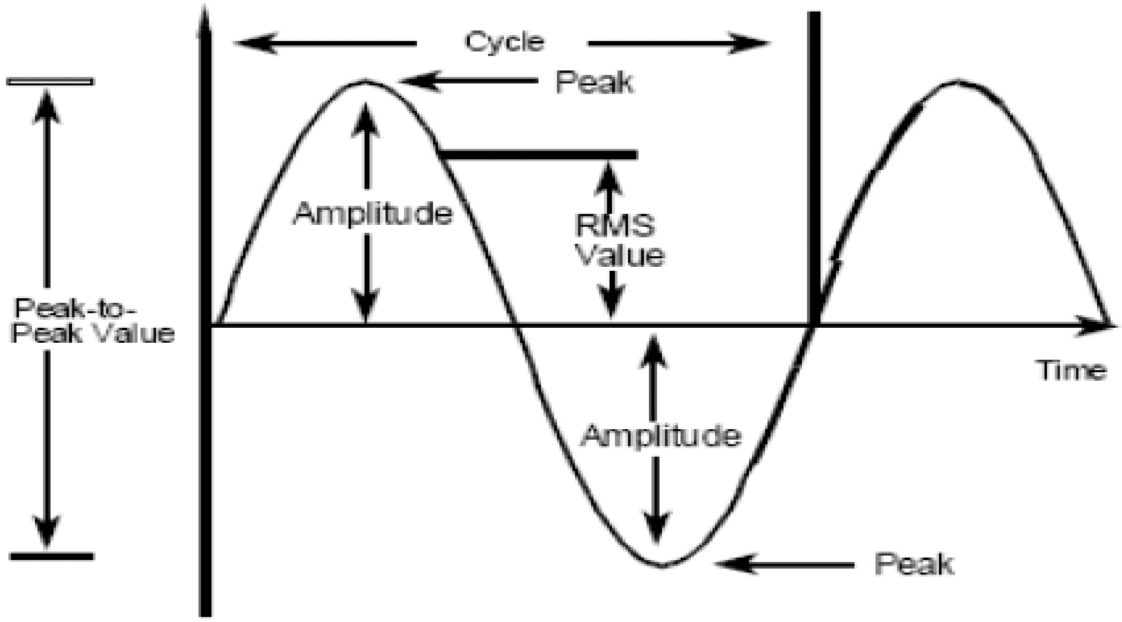

Generator
90°
–
+
180°
0°
270°
S
N
Current Flow
Amplitude
of Voltage
or Current
+
–
0°
90°
180°
270°
360°
Time


Generator
90°
180°
S
N
0° (360°)
270°
Amplitude of Voltage or Current
0V
+
–
0°
90°
180°
270°
360°
Time

Sine Waves

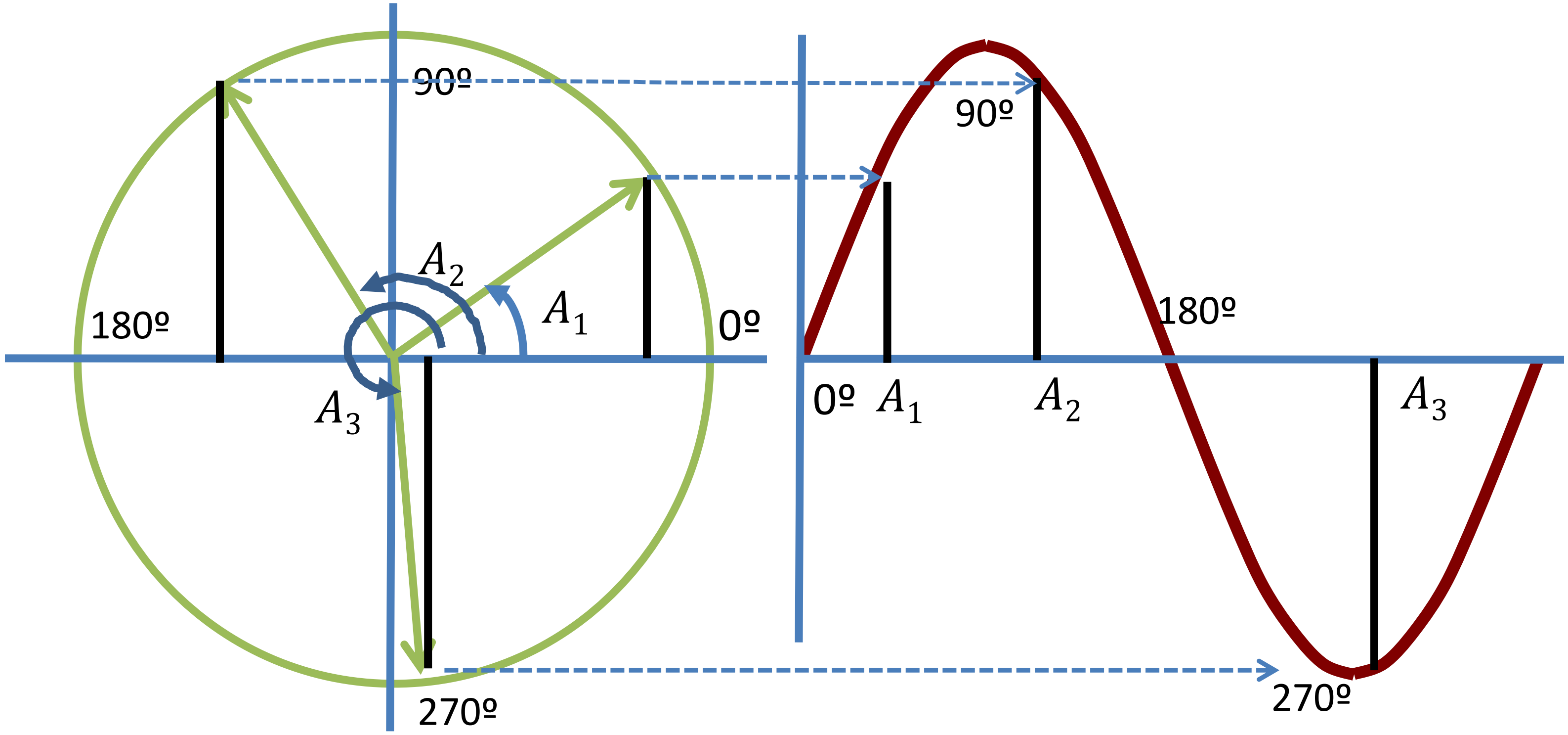
Alternating Current (AC)
Sine Waves

A Sine Wave is a curve that describes a smooth repetitive oscillation.



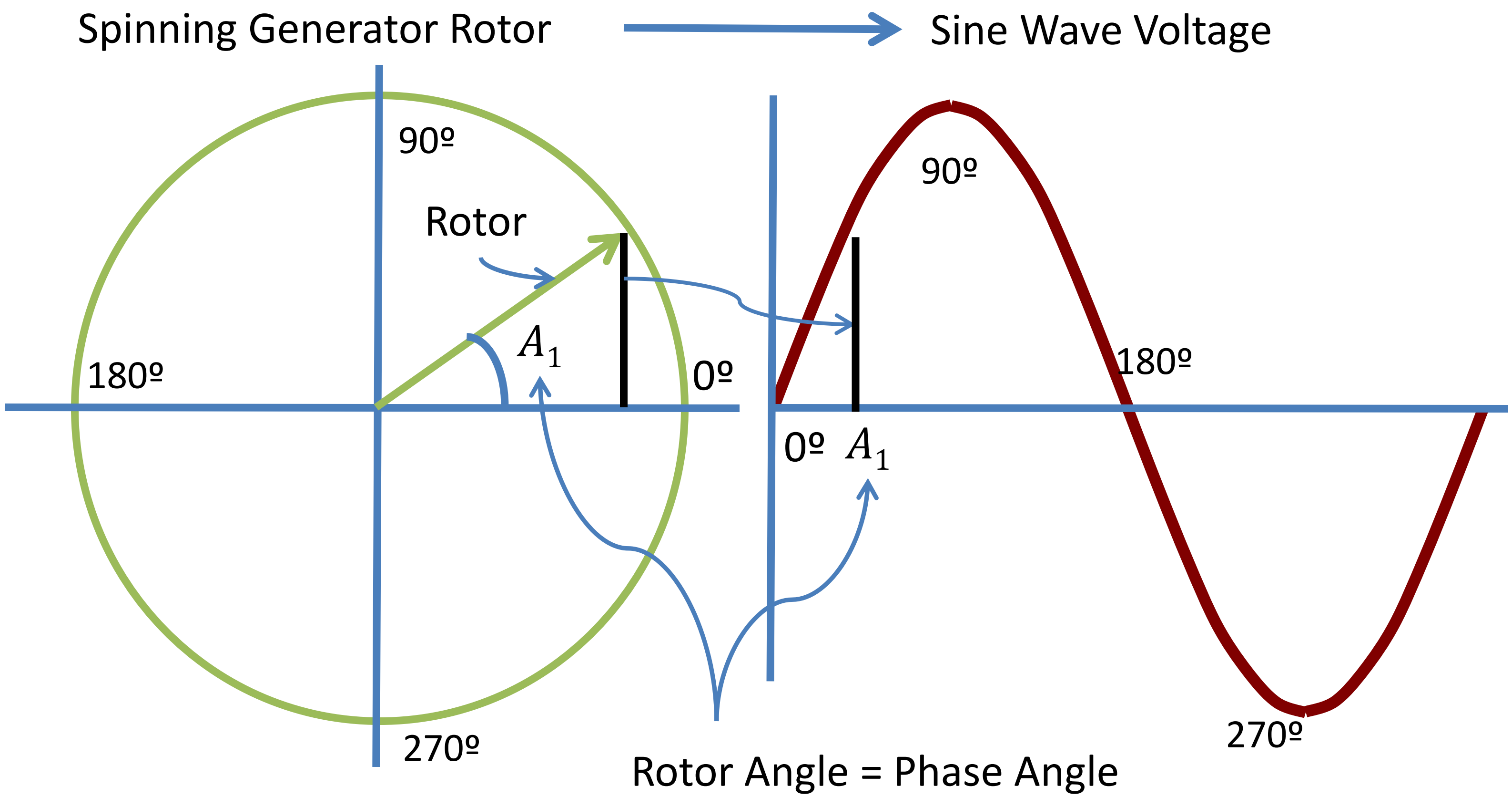
Alternating Current (AC)
Sine Waves

A Sine Wave shows the height of the circle at a given angle.



Alternating Current (AC)
Sine Waves

Spinning Generator Rotor creates a Sine Wave Voltage



Alternating Current (AC)
Sine Waves

A Cycle is the part of a waveform that does not repeat or duplicate itself. In the time it takes to complete one cycle, the current:

- ✓ builds from zero to the maximum amplitude in one direction
- ✓ decays back to zero
- ✓ builds to the maximum amplitude in the opposite direction
- ✓ decays back to zero again

Alternating Current (AC) Sine Waves

- The Period (T) is the time required to complete one cycle
- Frequency (f) is the rate at which the cycles are produced
- Frequency is measured in Hertz (Hz). One hertz equals one cycle per second

Alternating Current (AC)
Sine Waves

Frequency (f) and period (T) are related by the following equations:

$$f = 1/T$$

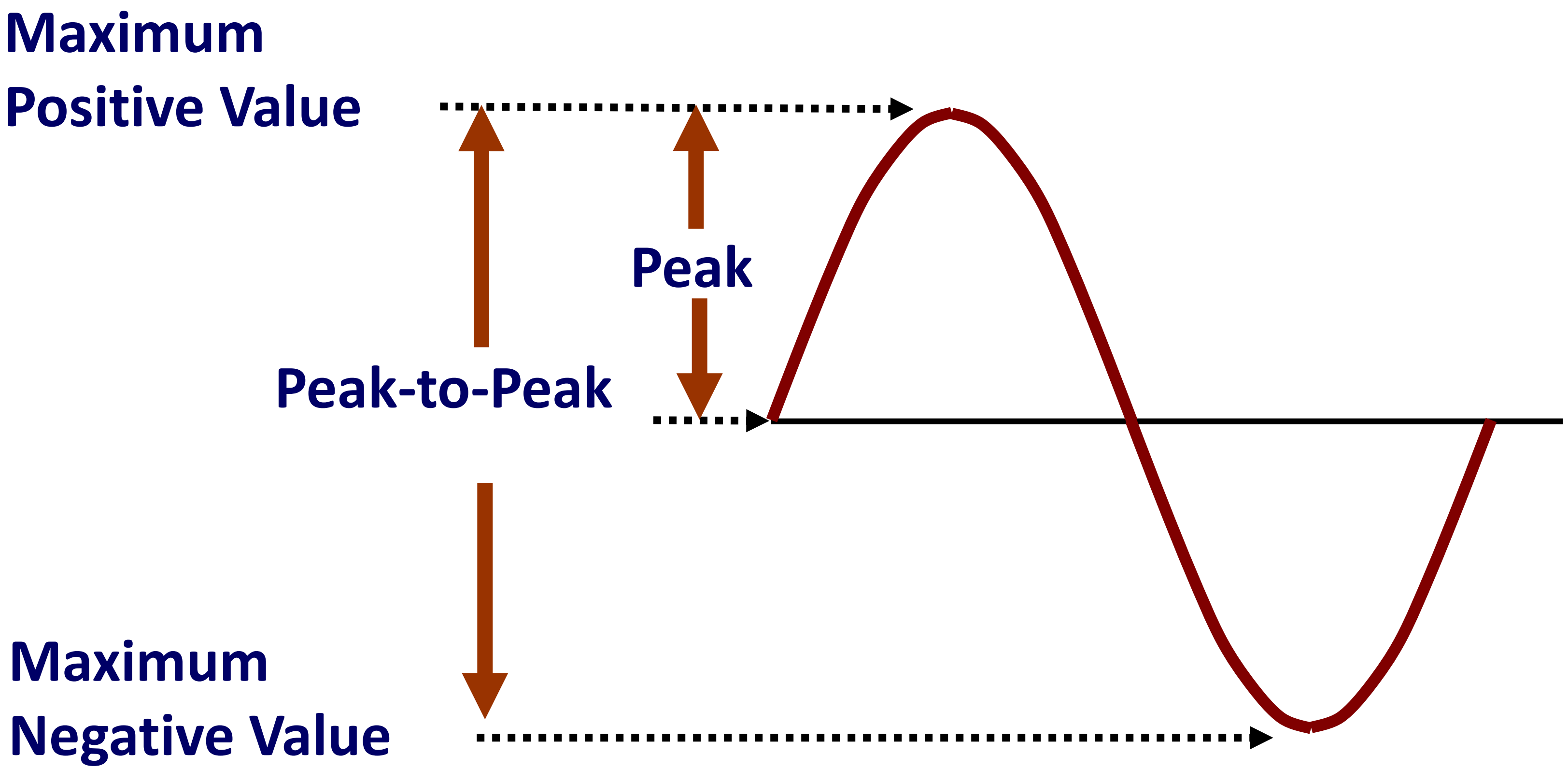
$$T = 1/f$$

Alternating Current (AC)
Sine Waves

Amplitude

- peak
- peak-to-peak
- RMS (Effective Value)

Alternating Current (AC)
AC Power Sine Wave



RMS Values

Alternating Current (AC)
RMS (Effective) Value

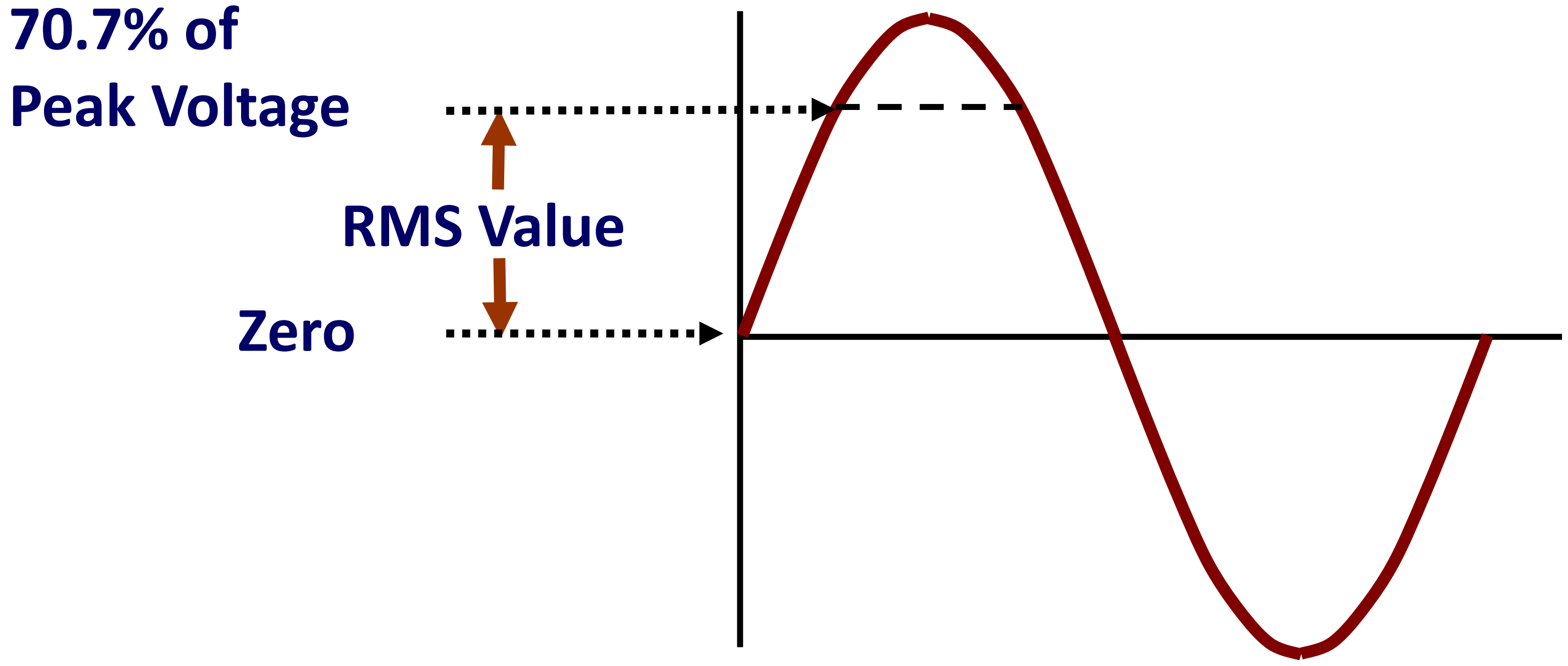
- The **effective** or **root mean square (RMS)** is the amount of AC current or voltage that has the same effect as a given amount of DC current or voltage in producing heat in a resistive circuit
- Effective value (RMS) is the most common way of specifying the amount of AC
- One amp of effective AC and one amp of DC produce the same power when flowing through equal resistors

Alternating Current (AC)
RMS Values

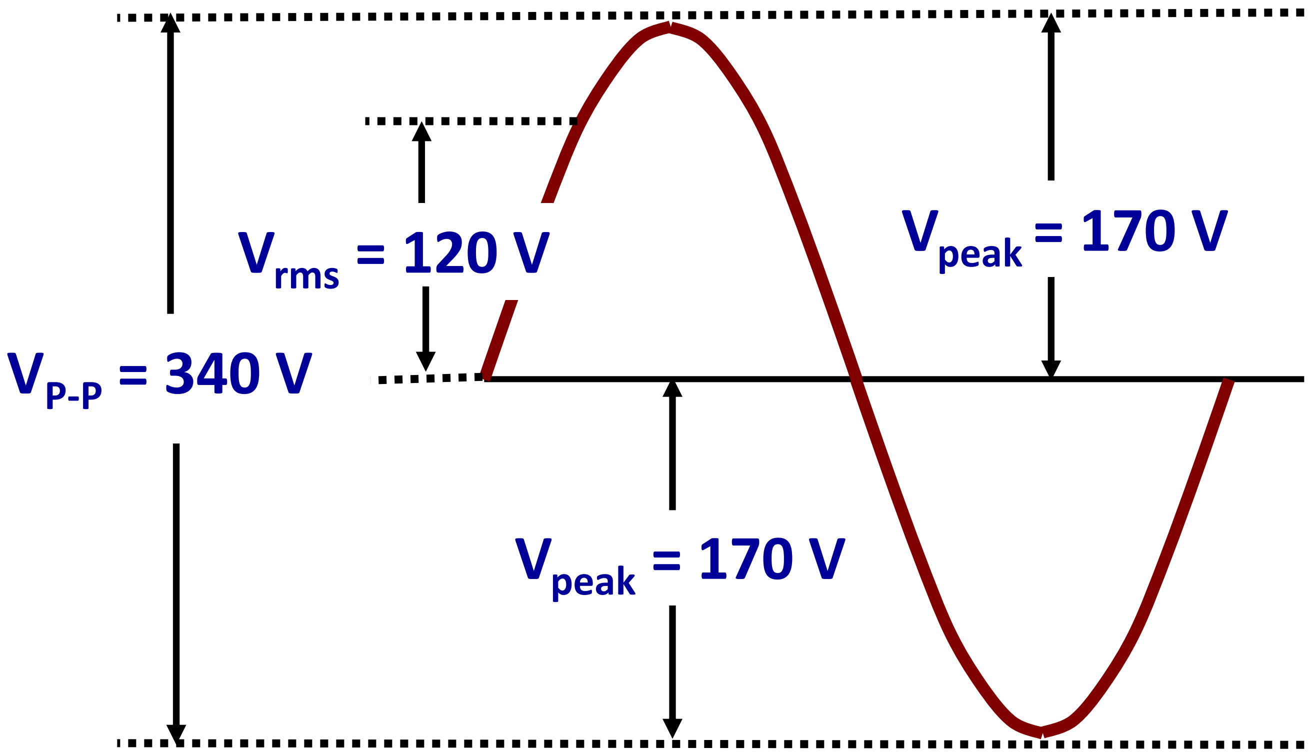
- The Root Mean Square (RMS) Value is the Effective value
- To calculate the RMS value of a waveform, **Square** the instantaneous values over one period, average them to provide the **Mean**, and take the square **Root** of the mean
- RMS value is 70.7% of Peak value

$$I_{rms} = \frac{\sqrt{2}}{2} I_p = .707\ I_p$$

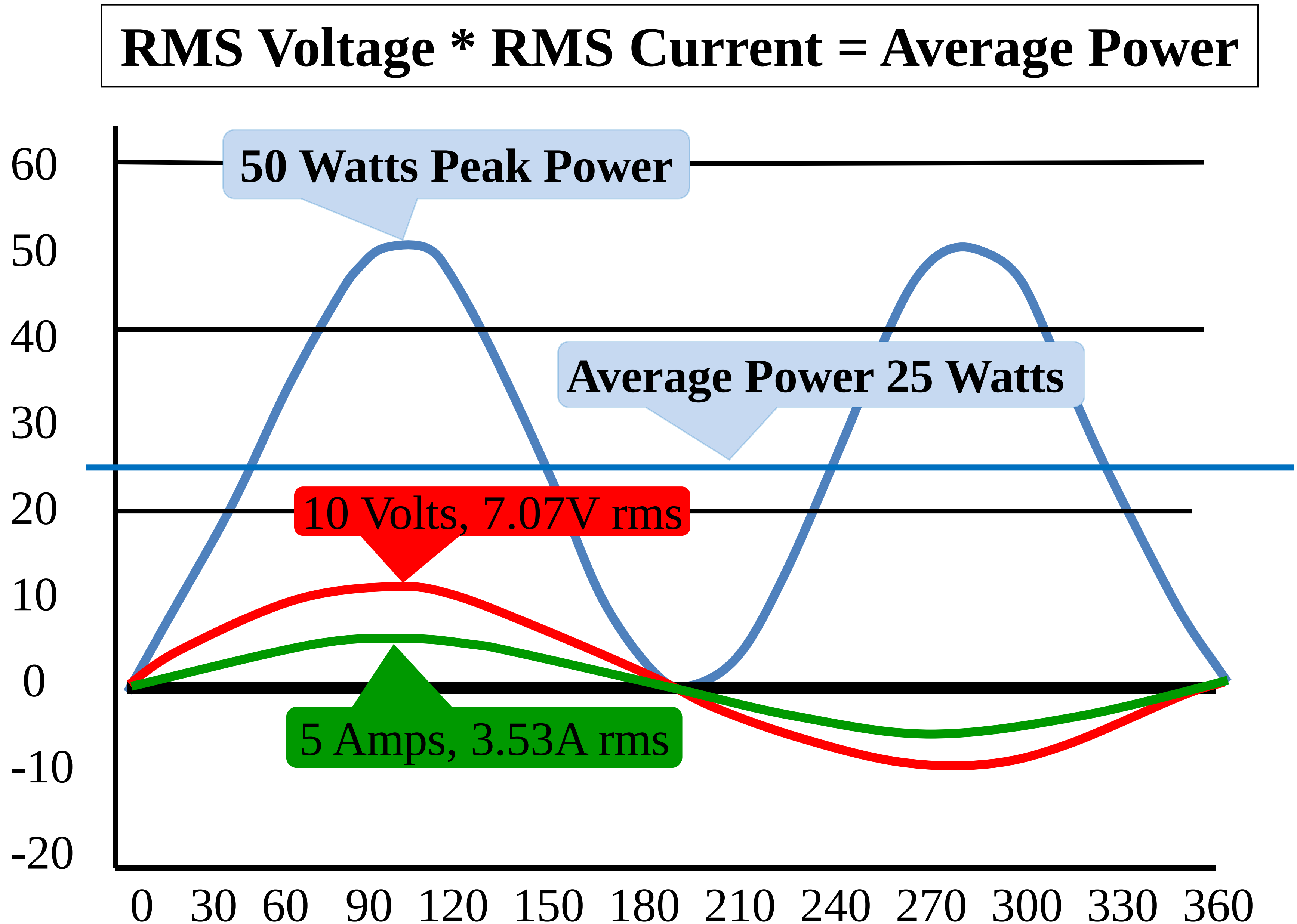
Alternating Current
RMS (Effective) Value



Alternating Current
Household Voltage



$$V_{RMS} = .707 \times 170\ V = 120.2\ V$$



RMS Voltage * RMS Current = Average Power
50 Watts Peak Power
Average Power 25 Watts
10 Volts, 7.07V rms
5 Amps, 3.53A rms
60
50
40
30
20
10
0
-10
-20
0 30 60 90 120 150 180 210 240 270 300 330 360

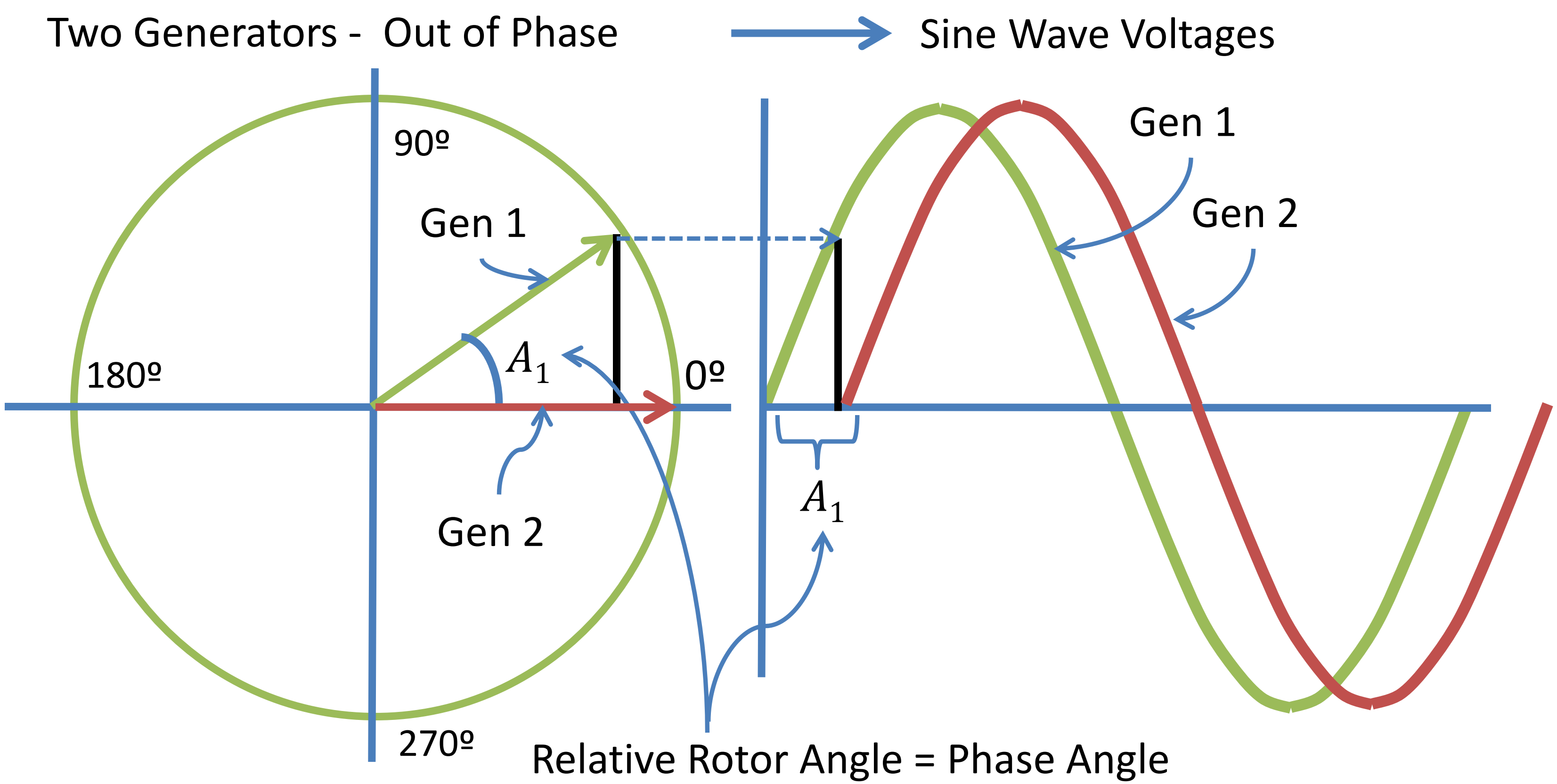
Phase Relationship

Alternating Current (AC)
Phase Relations

Phase Angle is the angle difference between two sine waves with the same frequency

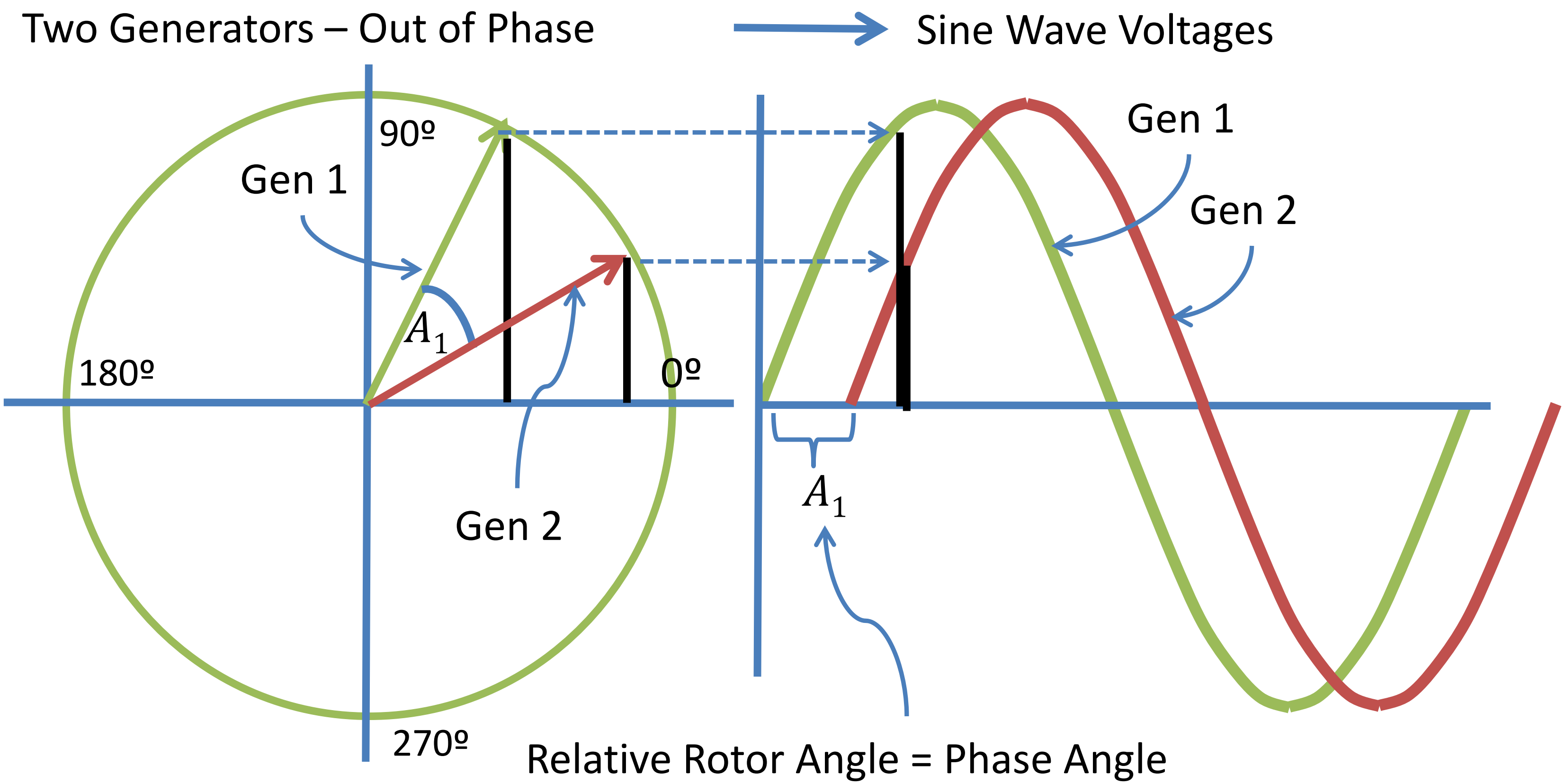
- Phase Angle is sometimes called ***phase relation***
- ***Phase angle*** is the portion of a cycle that has elapsed since another wave passed through a given value

Alternating Current (AC)
Phase Angle Between Two Generators



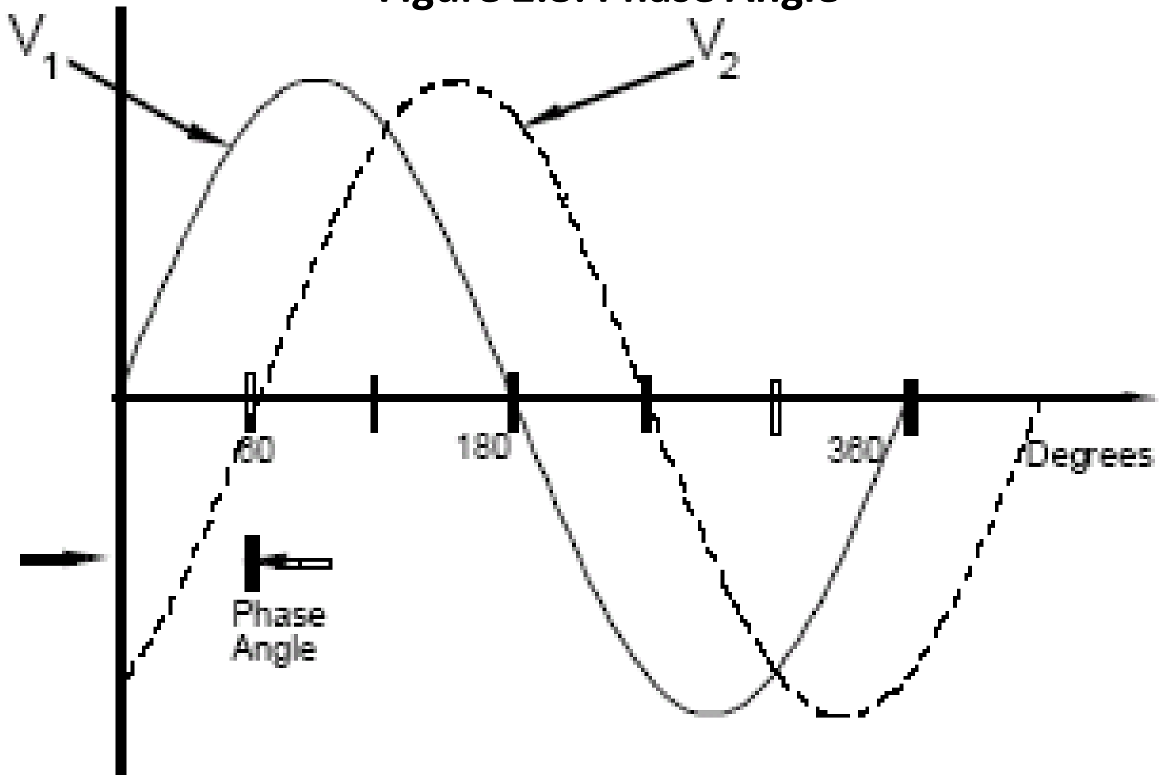
Alternating Current (AC)
Phase Angle Between Two Generators

Angle between Generators stays the same while they both rotate



Alternating Current (AC) Phase Relations

Figure 2.8: Phase Angle



V_1 = Generator #1
V_2 = Generator #2

Alternating Current (AC)
Phase Angle Between Two Generators

In-Phase **-** the phase angle between two generators is zero degrees

- The generated voltages cross zero at the same time

Alternating Current (AC)
Phase Angle Between Two Generators

Out-of-Phase means that the phase angle between two generators is not zero degrees.

- The generated voltages cross zero at different times
- Only applies if the two waveforms have the same frequency

Alternating Current (AC)
Phase Relations

A **phasor** is a line representing a rotating quantity (voltage or current) for which:

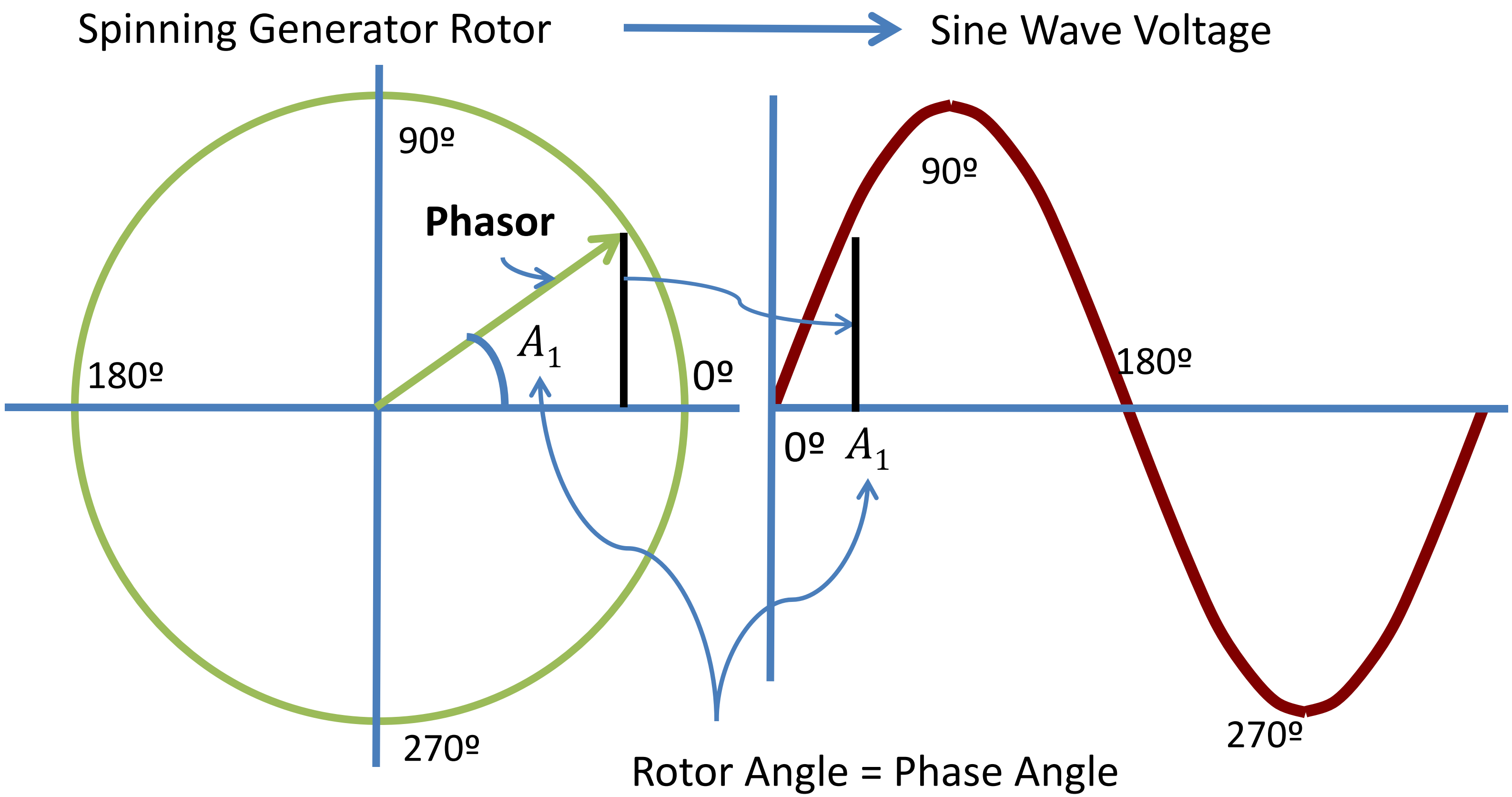
- ✓ Length represents magnitude
- ✓ Direction represents the phase angle (in electrical degrees)
- ✓ Zero electrical degrees are on the right side of the horizontal axis
- ✓ Rotation is counterclockwise

Alternating Current (AC) Phase Relations

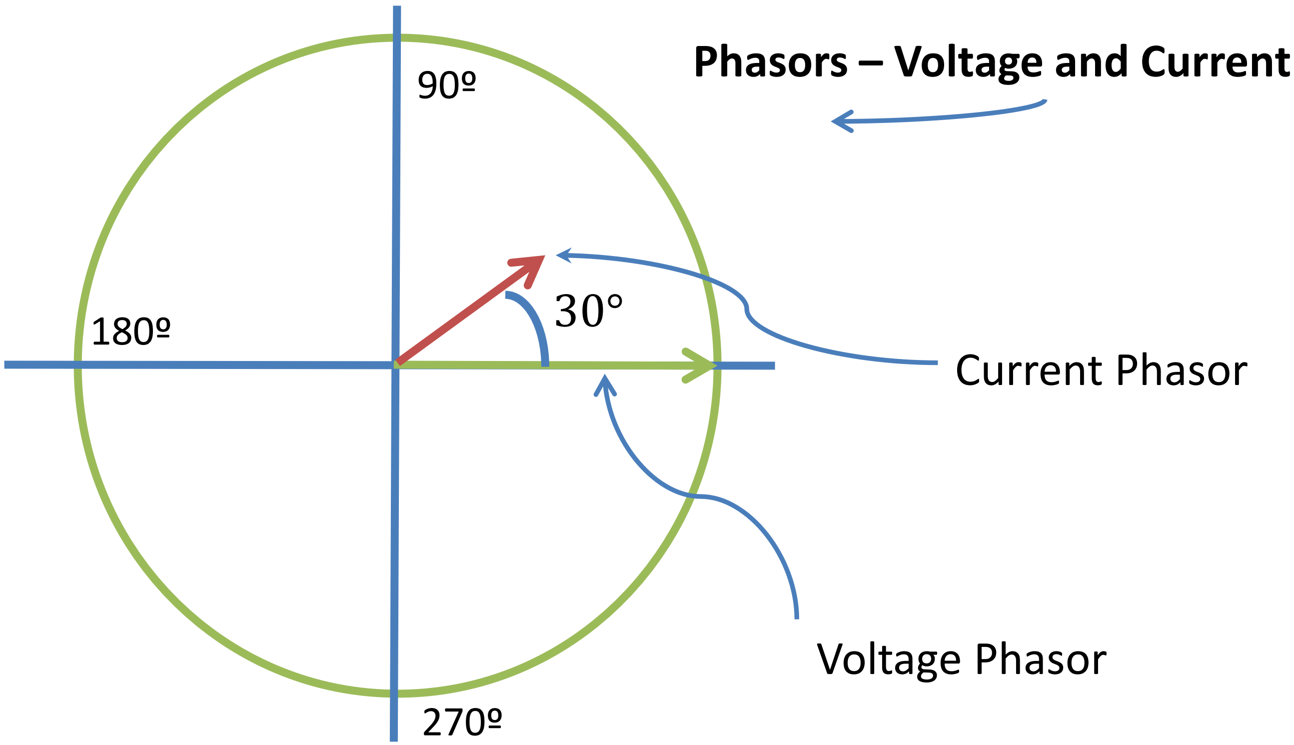
A **phasor** is similar to an arrow drawn on the end of a spinning shaft

- A strobe light flashes once each time the shaft does a full revolution

Alternating Current (AC)
Phase Relations



Alternating Current (AC)
Phase Relations

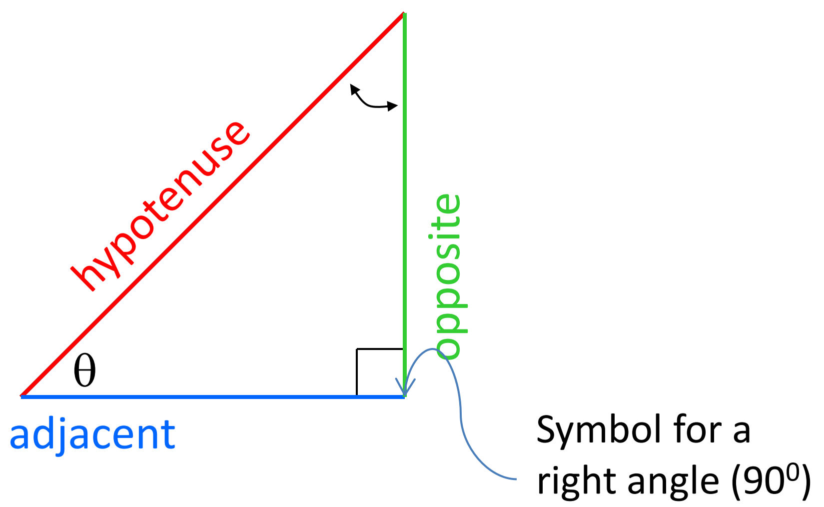


Since phasors rotate in a counterclockwise direction, the phasor diagram above shows the current leading the voltage by 30º.

Right Triangle Relationships

Alternating Current (AC)
Right Triangles

A Right Triangle has one corner with a 90º Angle.



Alternating Current (AC)
Right Triangles

The right triangle can be used to represent:

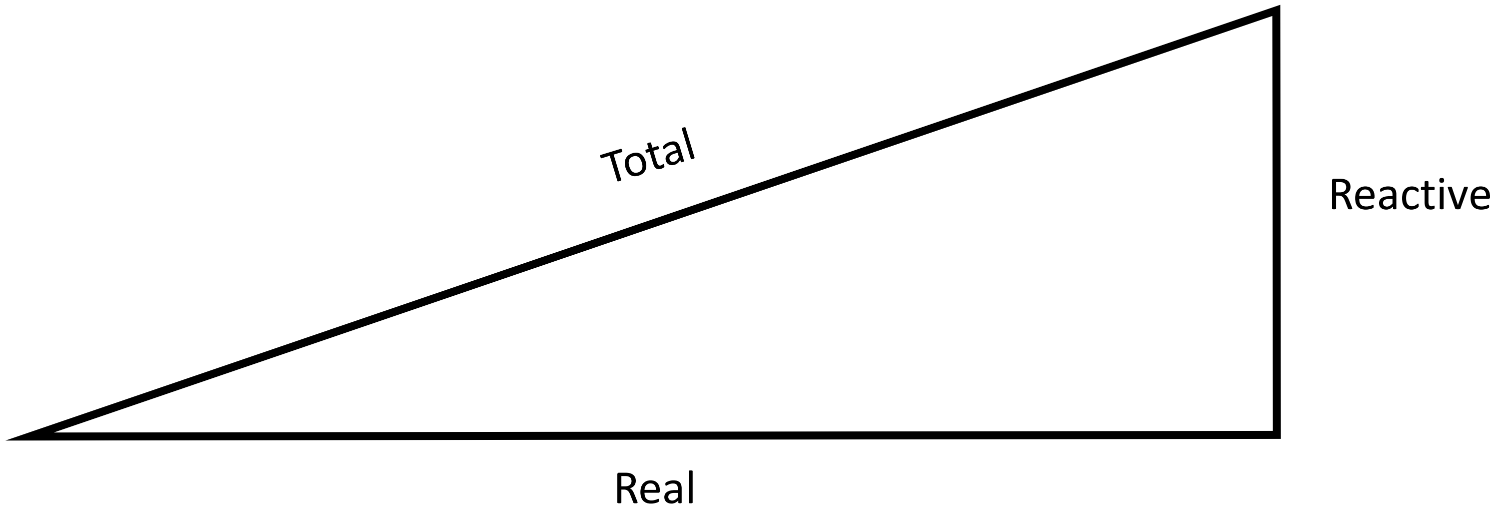
– Resistance vs Reactance

– Real versus Reactive portion of Current and Voltage

– Real and Reactive Power

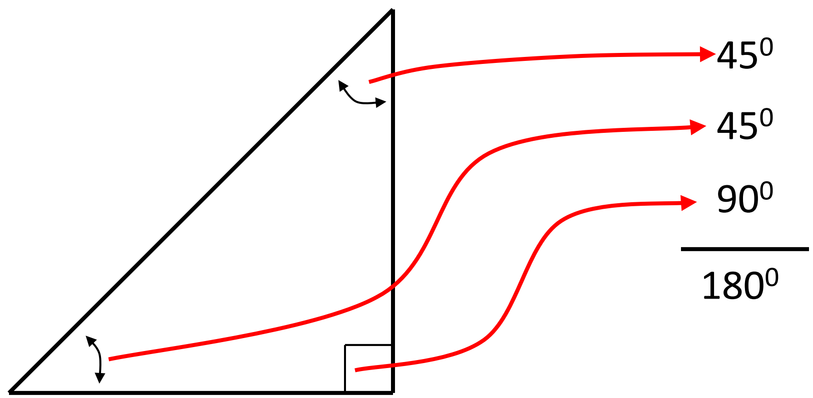
Alternating Current (AC)
Right Triangles

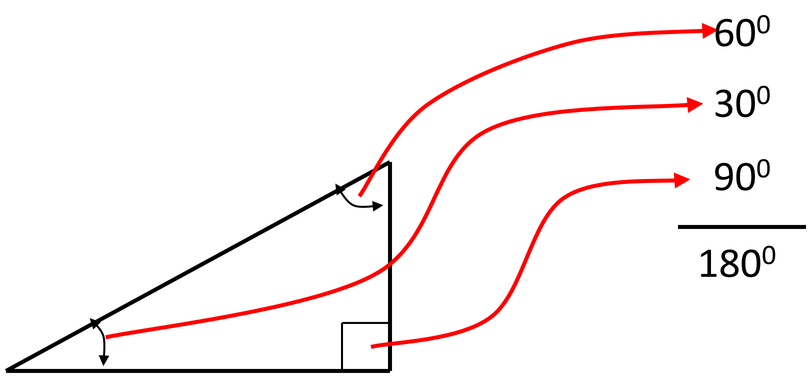
The right triangle can be used to represent the resistive, reactive, and Resulting total.



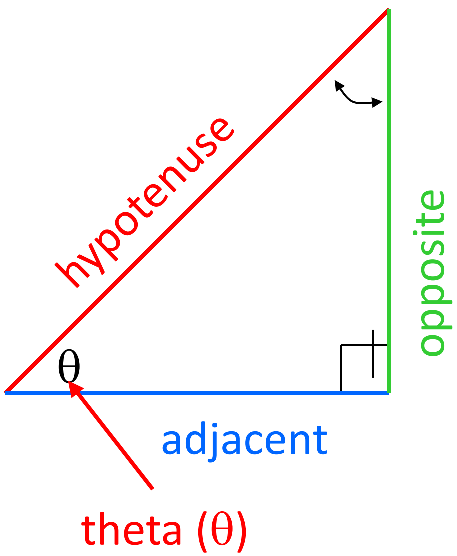
Alternating Current (AC)
Right Triangles

Angles total 180º



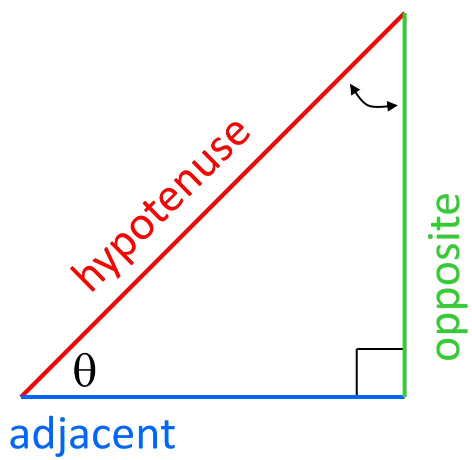


Alternating Current (AC)
Right Triangles



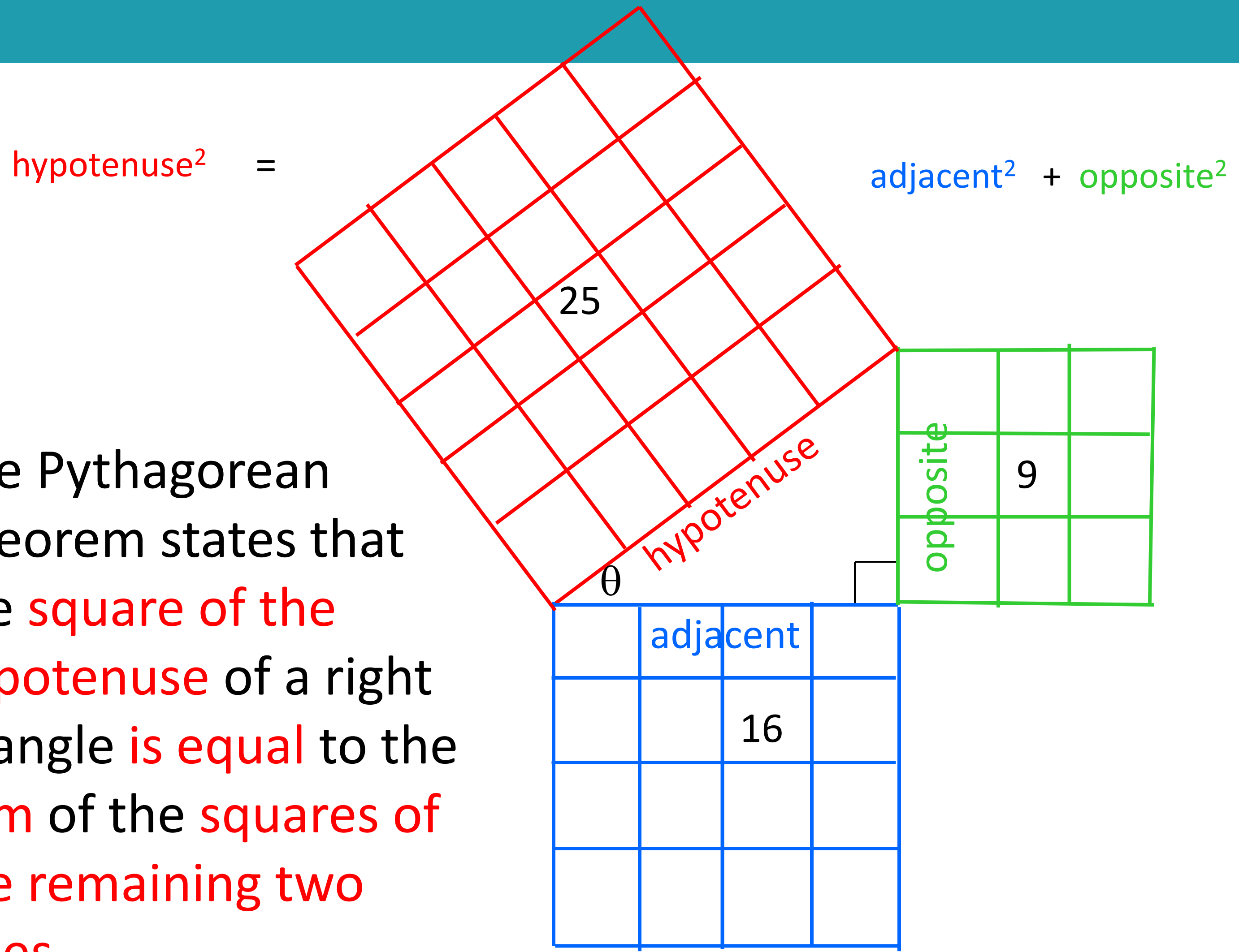
Right Triangles

Pythagorean Theorem



The Pythagorean Theorem states that the square of the hypotenuse of a right triangle is equal to the sum of the squares of the remaining two sides.

Right Triangles

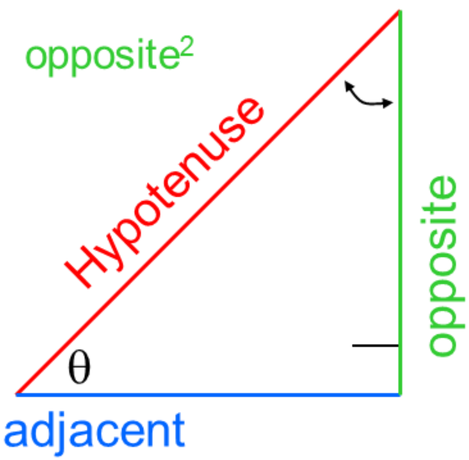


The Pythagorean Theorem states that the square of the hypotenuse of a right triangle is equal to the sum of the squares of the remaining two sides.

Alternating Current (AC)
Right Triangles

Pythagorean Theorem

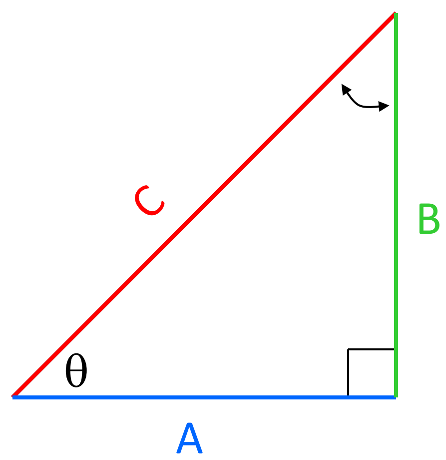
hypotenuse^2 adjacent^2 opposite^2



Alternating Current (AC)
Right Triangles

Pythagorean Theorem

$C^2 = A^2 + B^2$



$C^2 = A^2 + B^2$

or

$A^2 = C^2 - B^2$

or

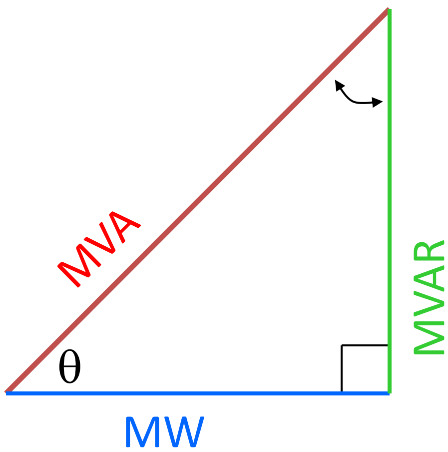
$B^2 = C^2 - A^2$

Using our formula, we could find the value of any side if we know the value of the other two sides.

Alternating Current (AC)
Right Triangles

Pythagorean Theorem

$MVA^2 = MW^2 + MVAR^2$



$MVA^2 = MW^2 + MVAR^2$

$MW^2 = MVA^2 - MVAR^2$

$MVAR^2 = MVA^2 - MW^2$

Generators produce Mega-Watts and Mega-Vars.
Use the right triangle to find the values.

Alternating Current (AC)
Right Triangles

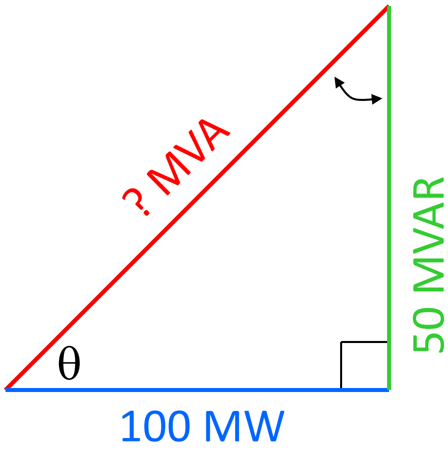
Pythagorean Theorem

$MVA^2 = 100^2 + 50^2$

$MVA^2 = 10{,}000 + 2{,}500$

$MVA^2 = 12{,}500$

$MVA = 111.8$



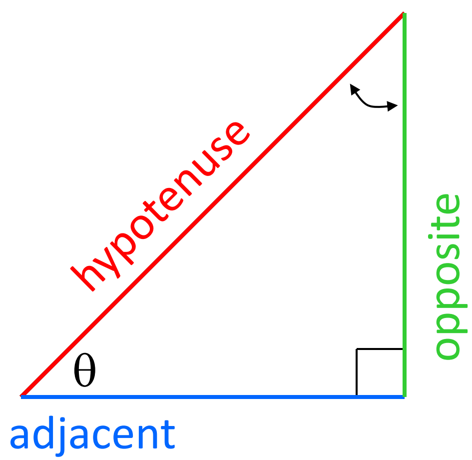
If a generator was producing 100 MW and 50 MVAR we could calculate the MVA using our formula.

Alternating Current (AC)
Right Triangles

Sine and Cosine

$$\text{Sine } \theta = \frac{\text{opposite}}{\text{hypotenuse}}$$

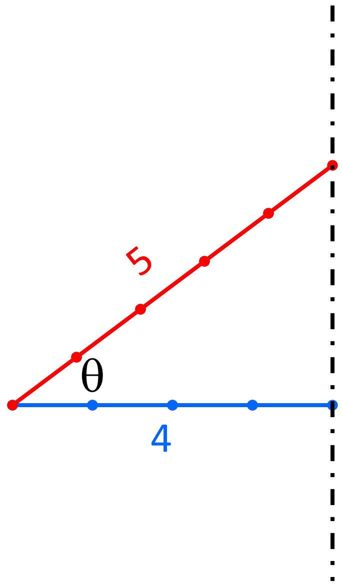
$$\text{Cosine } \theta = \frac{\text{adjacent}}{\text{hypotenuse}}$$



Alternating Current (AC)
Right Triangles

Sine and Cosine

$$\text{cosine } \theta = \frac{4}{5}$$



This ratio of Adjacent side to Hypotenuse establishes the slope of the angle

Alternating Current (AC)
Right Triangles

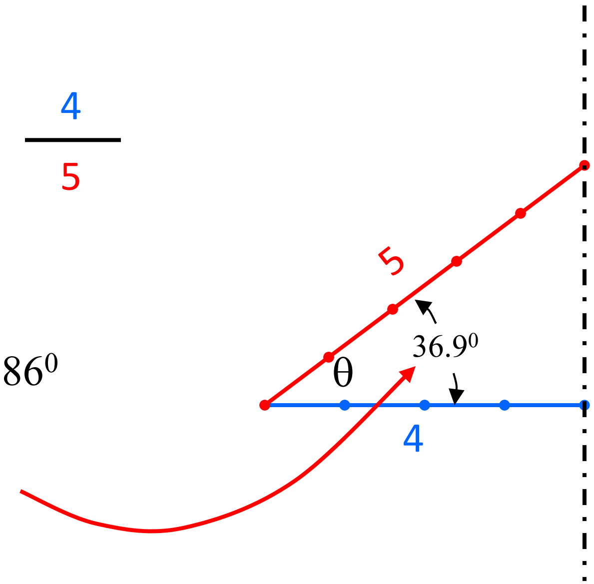
Sine and Cosine

$$\text{cosine } \theta = \frac{4}{5}$$

$$\text{cosine } \theta = 0.8$$

$$\text{arccosine } 0.8 = 36.86^0$$

$$\theta = 36.9^0$$



Determine the angle theta using the inverse of the cosine of theta the arccosine.

Alternating Current (AC)
Right Triangles

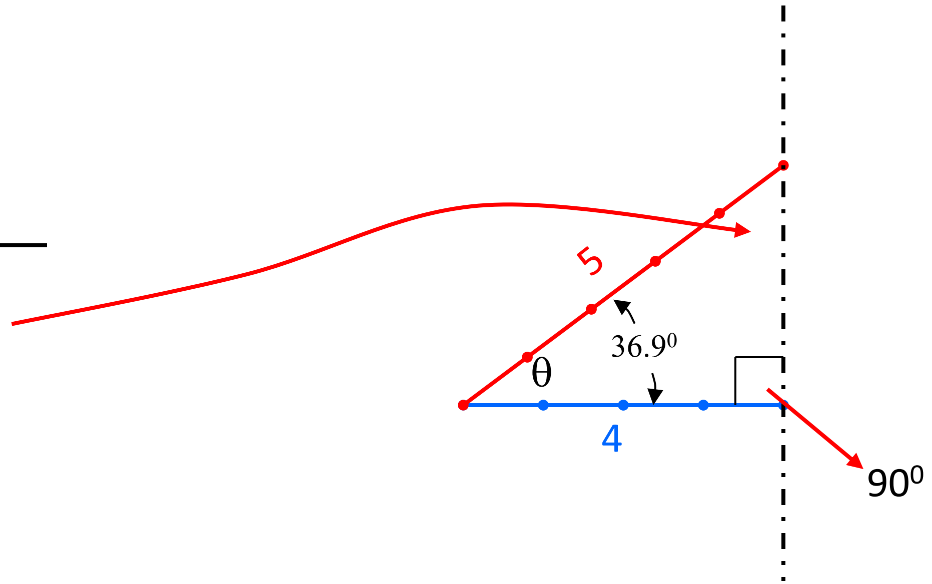
Sine and Cosine

180⁰

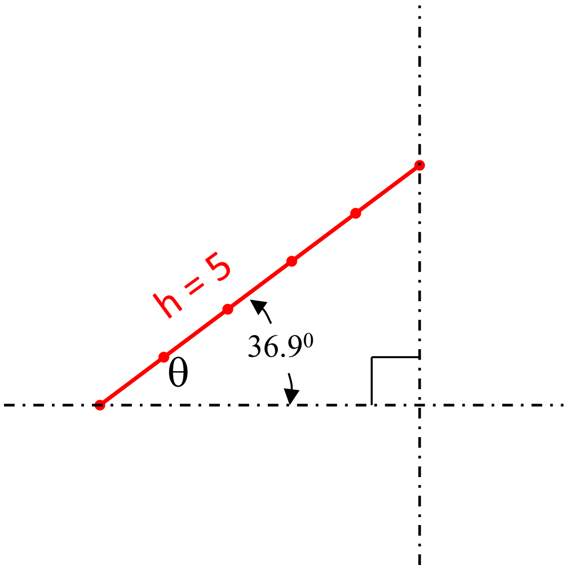
90⁰

36.9⁰

53.1⁰



Alternating Current (AC)
Right Triangles



We can solve for all angles and sides given only one side and one angle

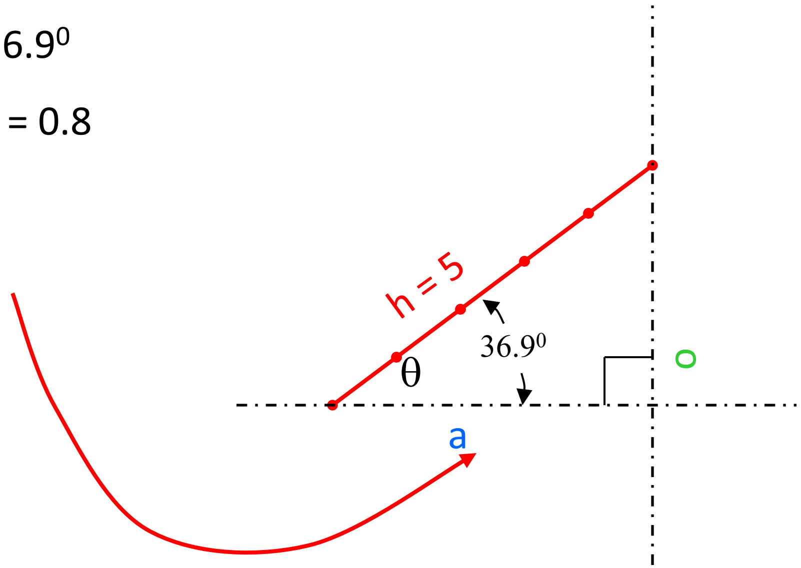
Alternating Current (AC)
Right Triangles

arccosine $\theta = 36.9^0$

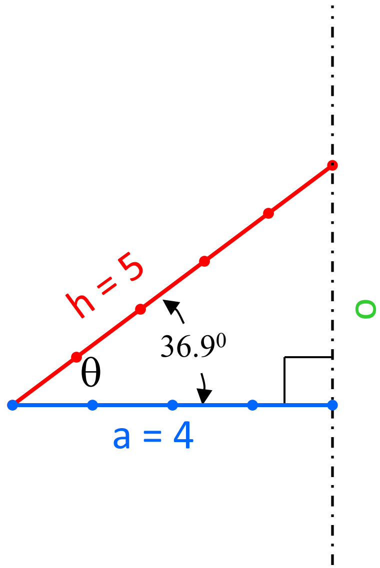
cosine θ (36.9) = 0.8

a = 0.8 X 5

a = 4



Alternating Current (AC)
Right Triangles



$o^2 = h^2 - a^2$

$o^2 = 25 - 16$

$o^2 = 9$

$o = 3$

OR

$O = 5 \sin(36.9) = 3$

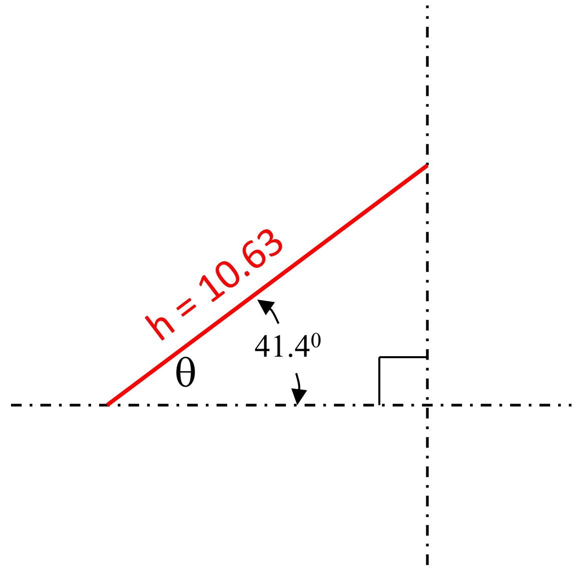
Alternating Current (AC)
Right Triangles

Summary

- A right triangle has one right angle (**90º**)
- The sum of the angles of any triangle equals **180^0**
- The sides of a right triangle are named the **hypotenuse, adjacent** and **opposite** side.
- The hypotenuse of any right triangle will always be the longest side.
- The **square of the hypotenuse** is equal to the **sum of the squares of the remaining two sides**
- The **sine** equals the ratio of the opposite side to the hypotenuse
- The **cosine** equals the ratio of the adjacent side to the hypotenuse

Alternating Current (AC)
Right Triangles

Practice Question

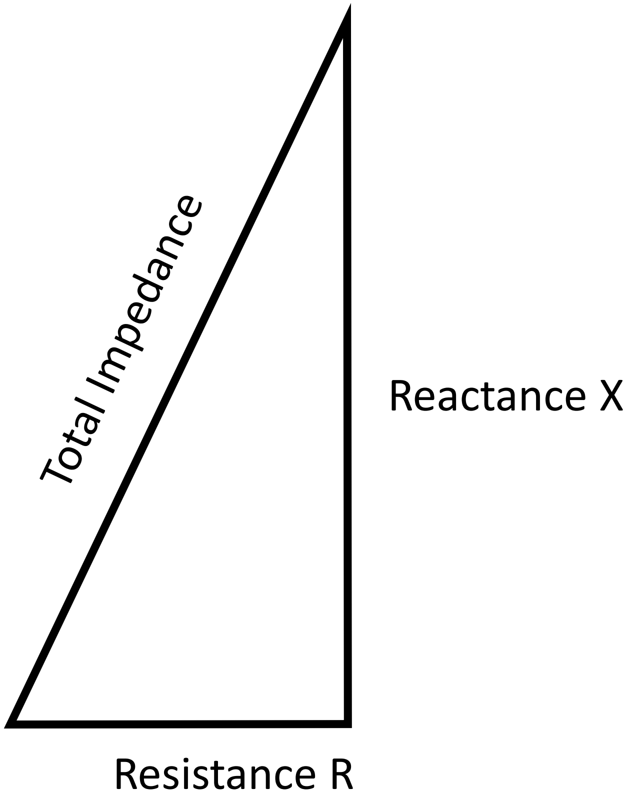


Solve the unknown sides and angles of this right triangle using the methods we have learned in this module on right triangles.

Alternating Current (AC)
Right Triangles

Application to Electricity

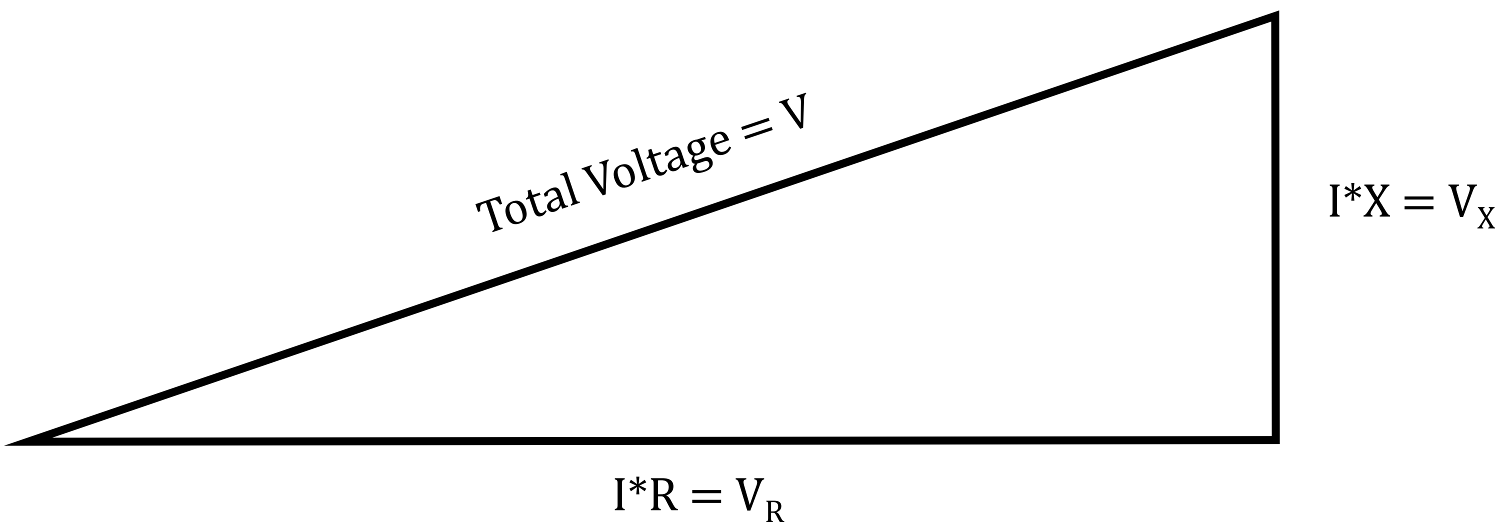
Resistive, Reactive, and Total Impedance



Alternating Current (AC)
Right Triangles

Application to Electricity

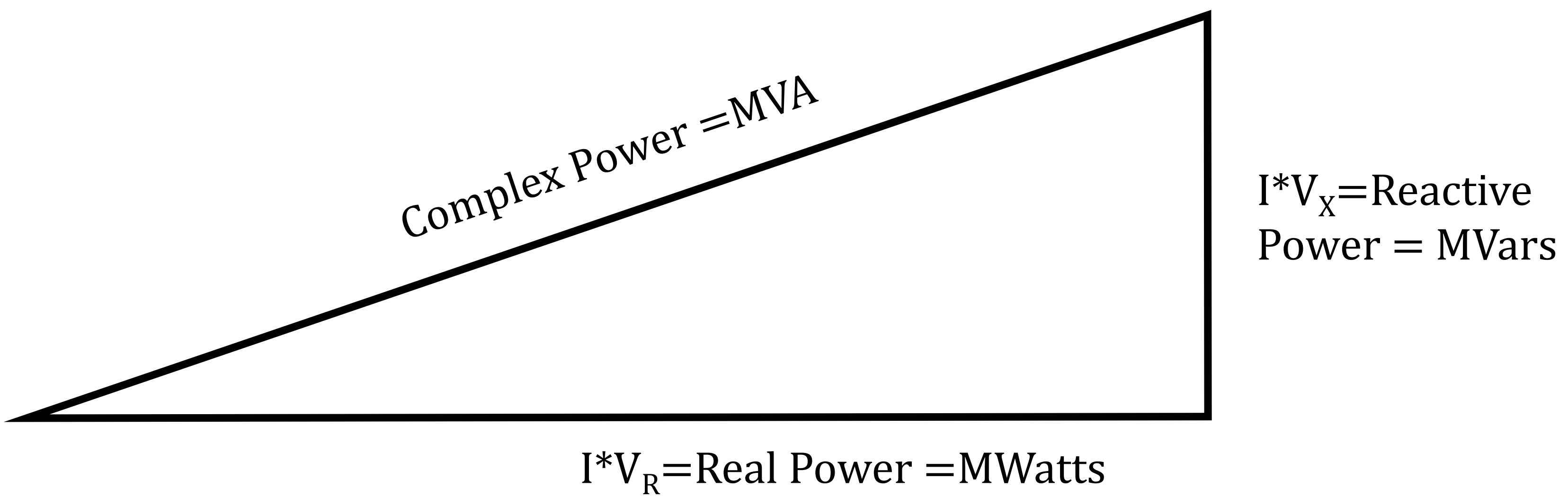
Total Voltage drop equals the voltage drop across resistor squared plus voltage drop across reactor squared.



Alternating Current (AC)
Right Triangles

Application to Electricity

Apparent Power = Real Power + Reactive Power (Vars)



Check Your Knowledge: Fundamentals of Electricity

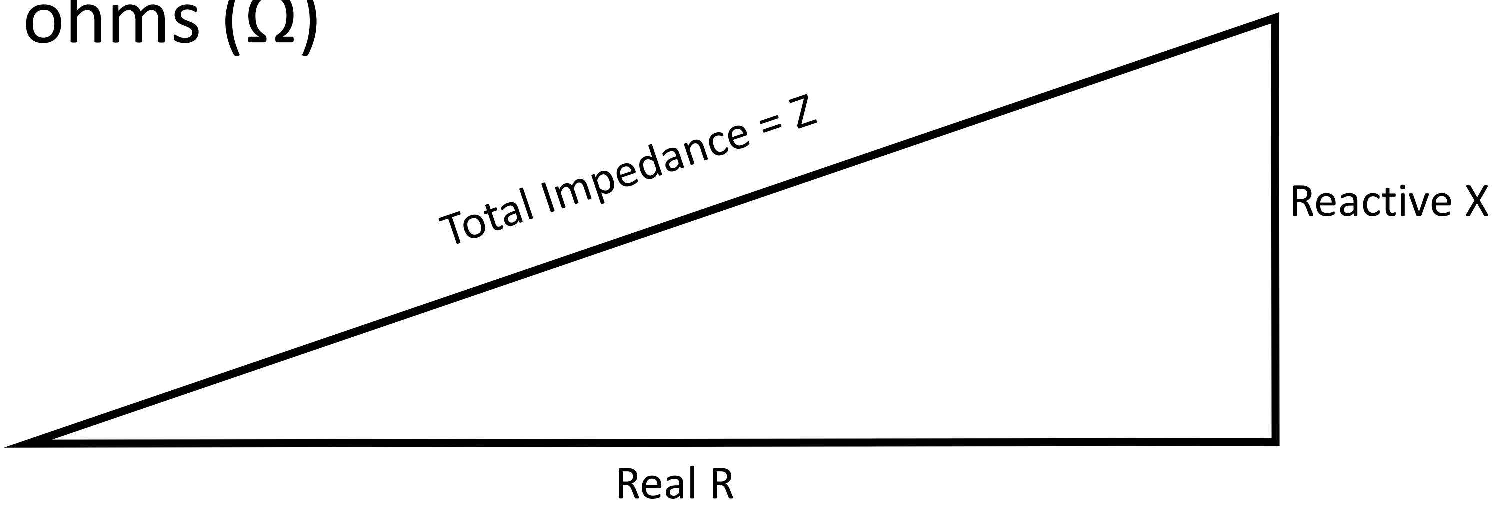
1. In a right triangle with the adjacent side equal to 5 and the opposite side equal to 12, what is the length of the hypotenuse?
2. Can you prove graphically that the Pythagorean Theorem is true?
3. What is the sine of 45 degrees?
4. With a hypotenuse of one and an adjacent side of .5, what is the angle? The opposite side?

Impedance
Resistance, Inductance, Capacitance

Alternating Current (AC) Impedance

Impedance (Z) is the total opposition to current.

- Impedance is the vector sum of the resistance and reactance
- Impedance is represented by a Z and measured in ohms (Ω)



Alternating Current (AC)
Impedance

- Impedance of ***resistors*** is independent of whether the current is AC or DC
- Impedance of ***inductors*** and ***capacitors*** depends on the rate-of-change or frequency of the voltage

Alternating Current (AC)
Impedance

- Impedance of capacitors and inductors is also called reactance
- Reactance depends on frequency

$X_C = \frac{1}{2\pi f C}$ - Current Leads the Voltage

$X_L = 2\pi f L$ - Voltage Leads the Current

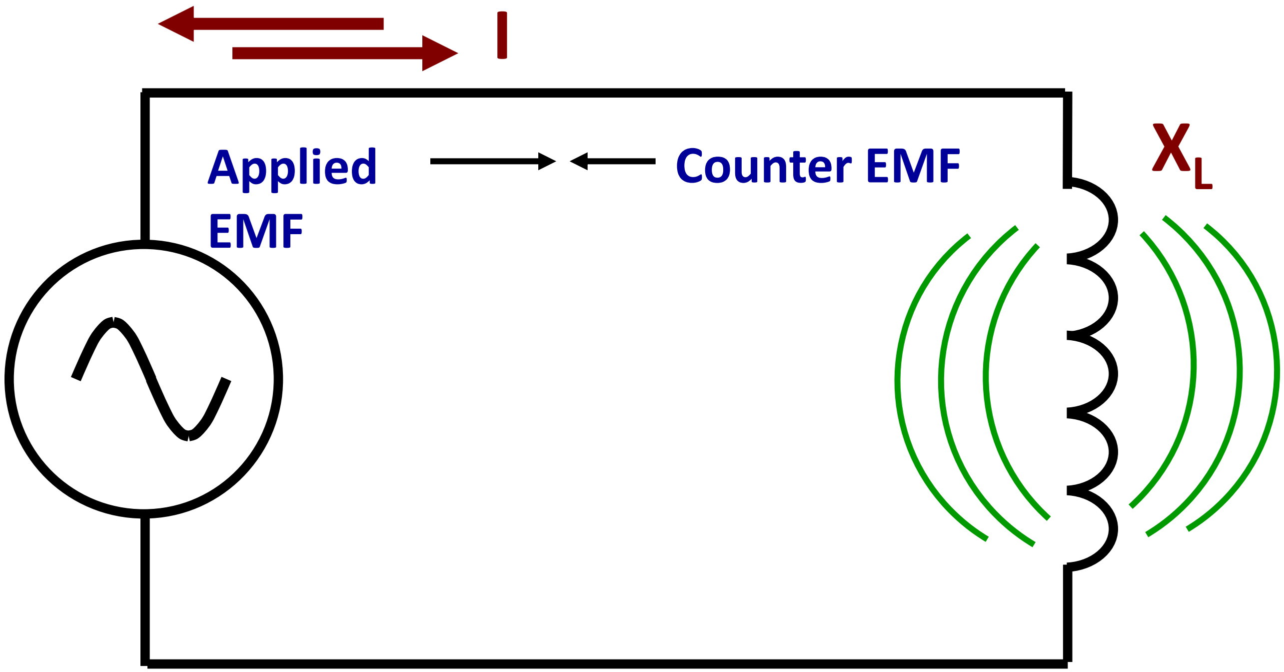
Alternating Current (AC) Impedance

Inductive Reactance(X_L) opposes change in current. It is measured in ohms(**Ω**).

- Reactance does not convert the electrical energy into heat energy
- The reactor **temporarily stores the energy** in the expanding magnetic field, then gives it back when the field collapses

Alternating Current (AC) Impedance

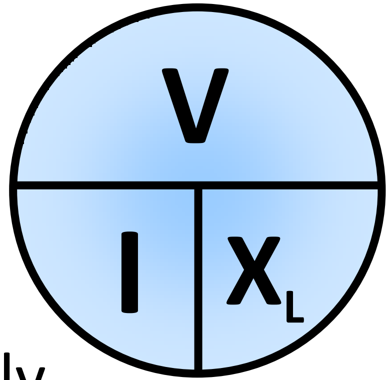
Inductors are devices that oppose *changes* in current flow using a magnetic field.



Alternating Current (AC)
Impedance

This form of Ohm's Law applies to inductive reactance:

$$V = IX_L$$

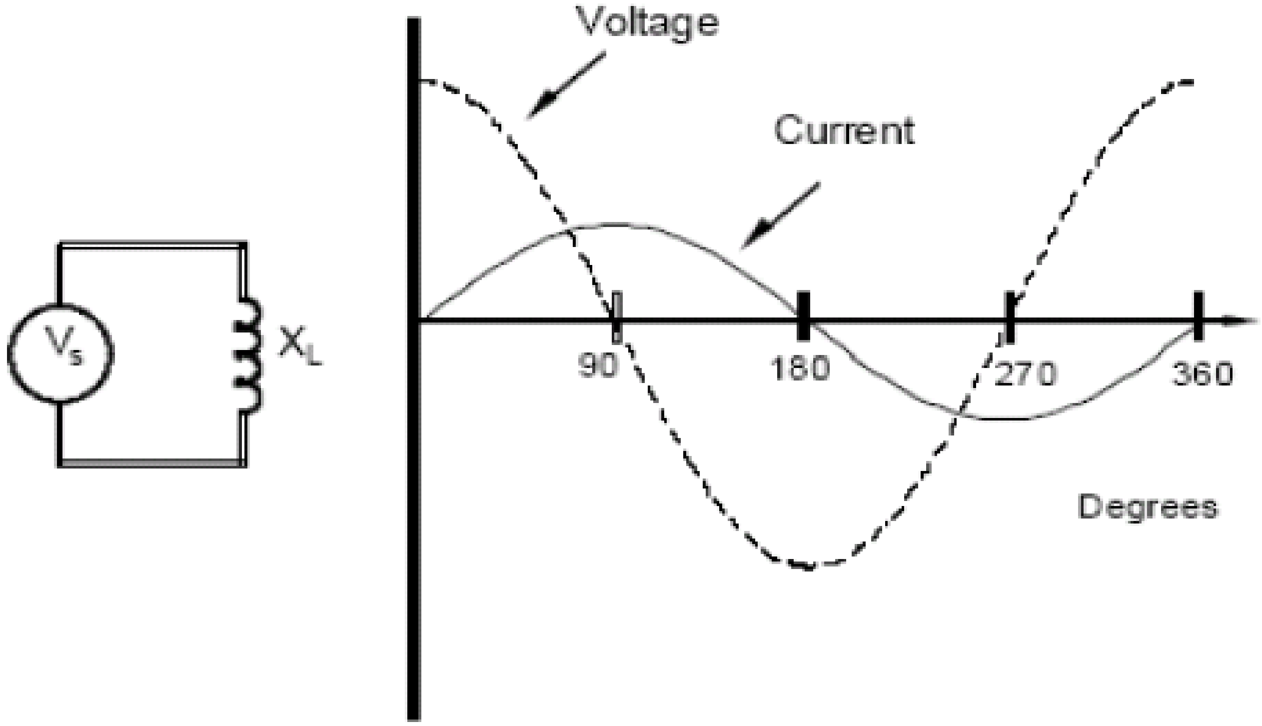


Where:

- V and I = Voltage and current, respectively
- $X_L = 2\pi f L$= Inductive Reactance
- π = Constant (approximately 3.14)
- f = Frequency
- L = Inductance

The Current lags the voltage by 90º

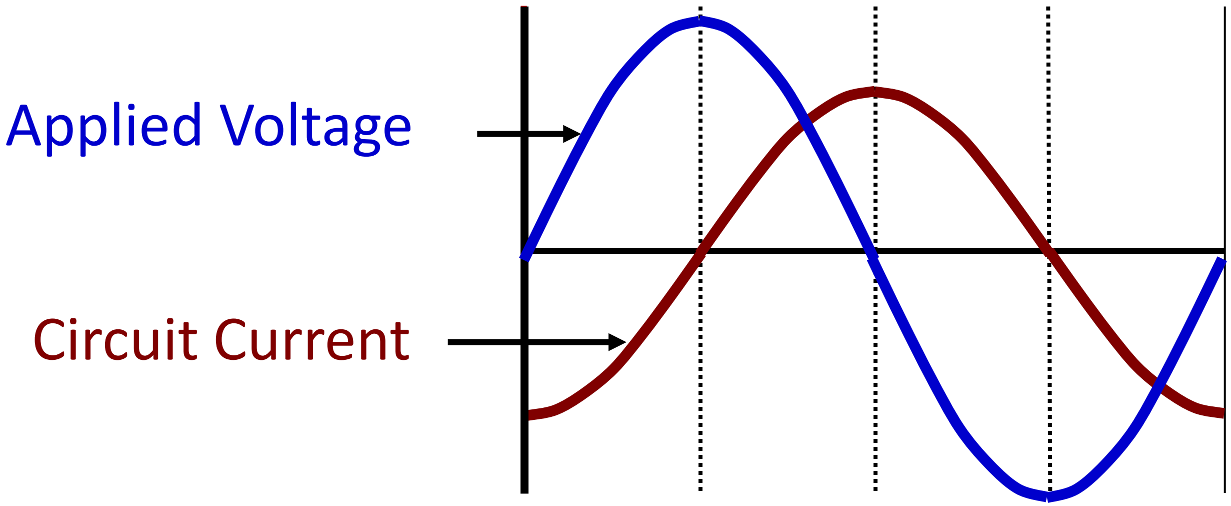
Inductance



The current lags the voltage by 90º in this example.

Alternating Current (AC)
Inductance

Current Lags Voltage by a Maximum 90°



The maximum amount that the inductance can cause the current to lag behind the voltage is 90°

Alternating Current (AC)
Impedance

ELI the ICE man

(A catchy memorable phrase)

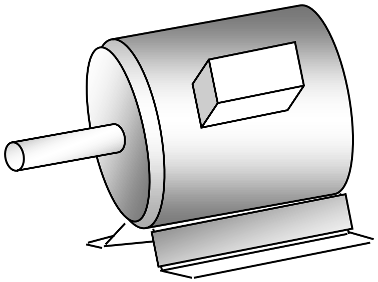
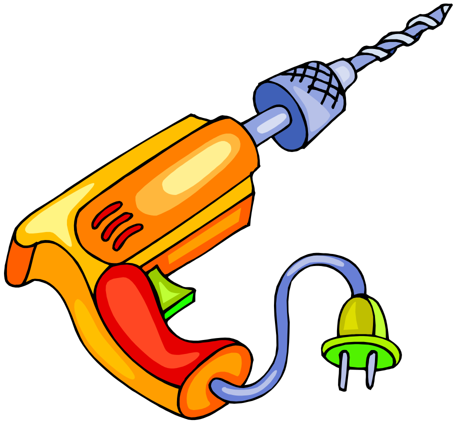
Voltage leads the current in an inductive circuit.

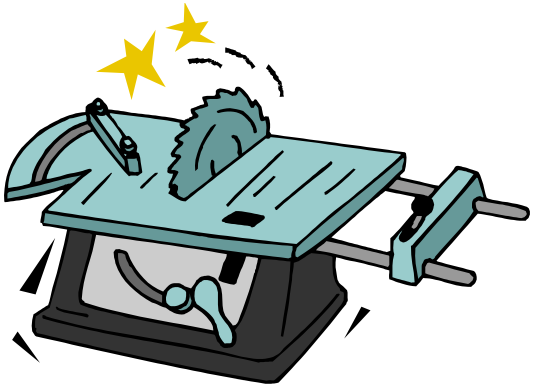
E L I

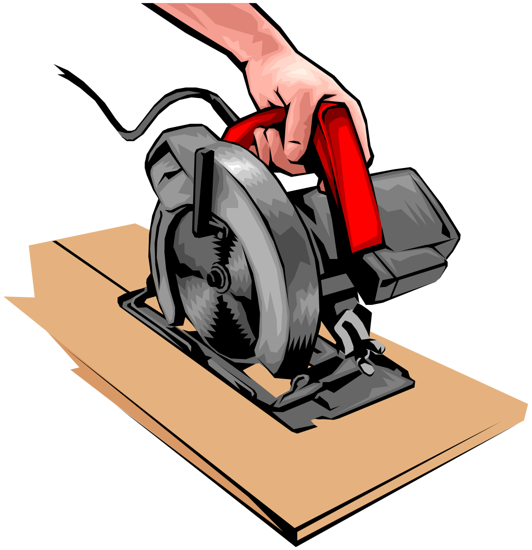
E = Voltage L = Inductance I = Current

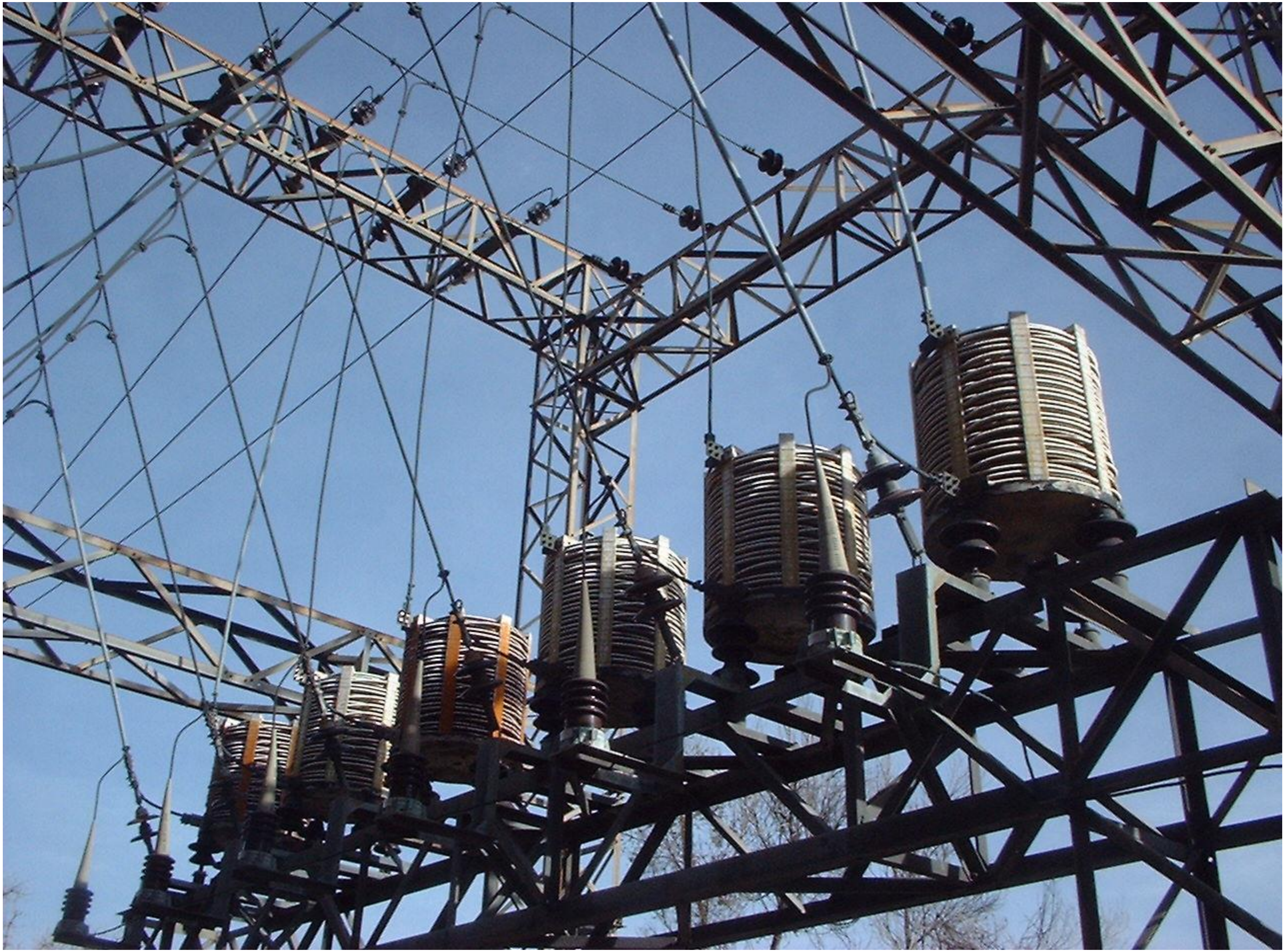
(The hard part is remembering why I=Current and E=Voltage)

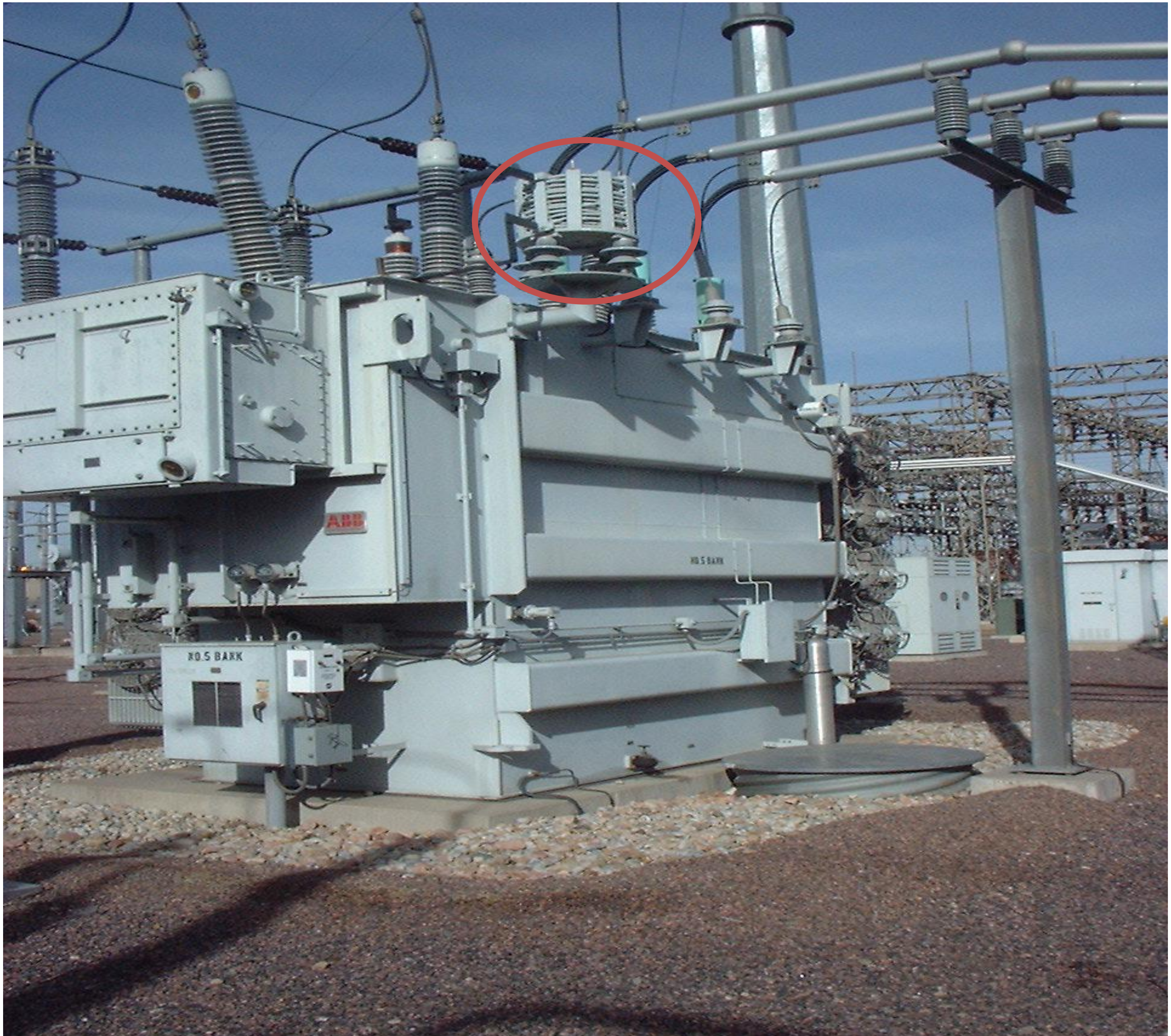
Inductive loads









ABB

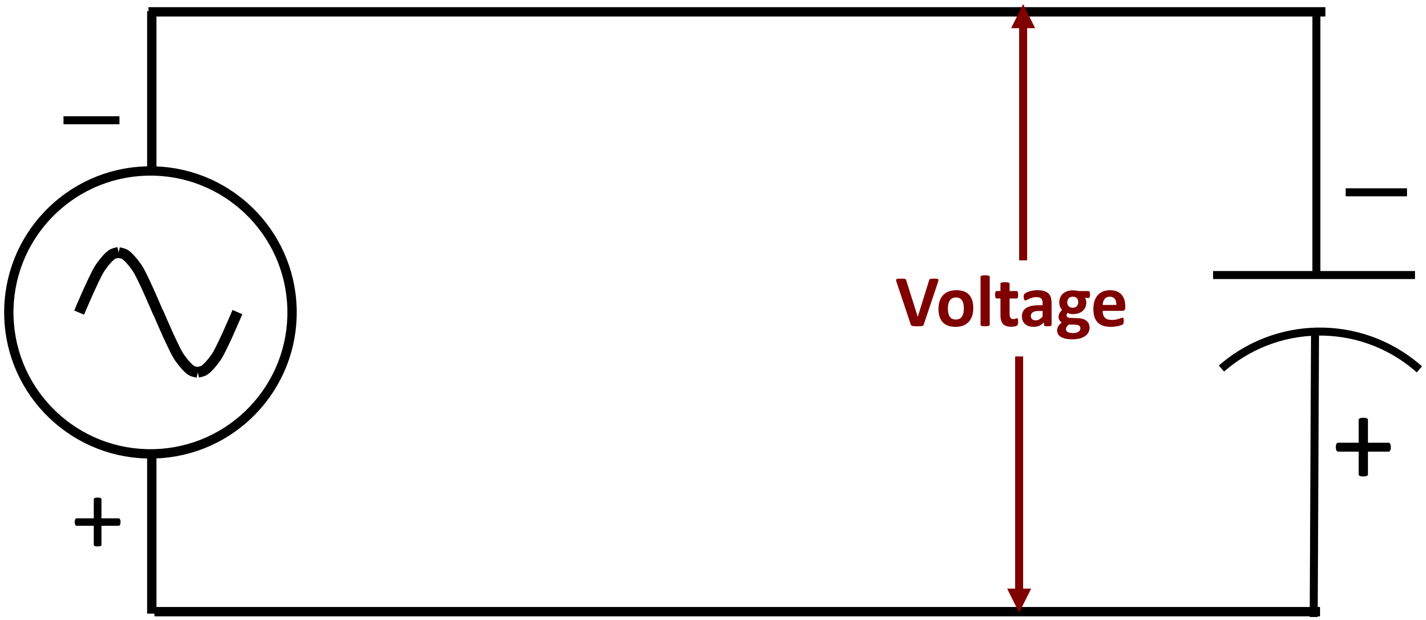
Alternating Current (AC) Impedance

Capacitive Reactance (X_c) opposes change in voltage. It is measured in ohms(**Ω**).

- Reactance does not convert the electrical energy into heat energy
- The capacitor **temporarily stores the energy** in the electric field between its plates, then gives it back when the field collapses

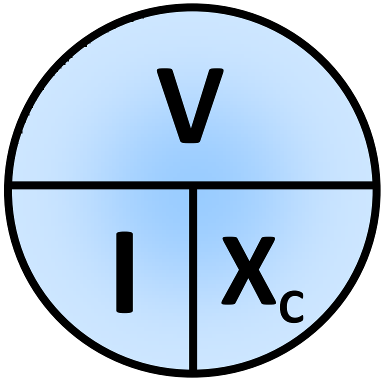
Alternating Current (AC)
Impedance

Capacitors are devices that store electrical charge.
They *oppose a change of voltage.*



Alternating Current (AC) Impedance

The following form of Ohm's Law applies to capacitive reactance:



$$V = IX_C$$

Where:

- V and I = Voltage and current, respectively.
- $X_C = 1/(2\pi f C)$= Capacitive Reactance
- π = Constant (approximately 3.14)
- f = Frequency
- C = Capacitance

Current can lead the voltage by up to 90º.

Alternating Current (AC)
Impedance

Similar to inductive reactance, capacitive reactance depends on frequency.

- Increasing the frequency *decreases* the capacitive reactance.

Definition: Susceptance

- There are times when using the reciprocal of X_C makes calculations easier
- The reciprocal of X_C is B_C and is called ***susceptance***

So now: $I = VB_C$

Alternating Current (AC)
Impedance

ELI the ICE man

(A catchy memorable phrase)

Current leads the voltage in a capacitive circuit.

E L I

I = Current **C = Capacitance** **E = Voltage**

(The hard part is remembering why I=Current and E=Voltage)

Check Your Knowledge: Fundamentals of Electricity

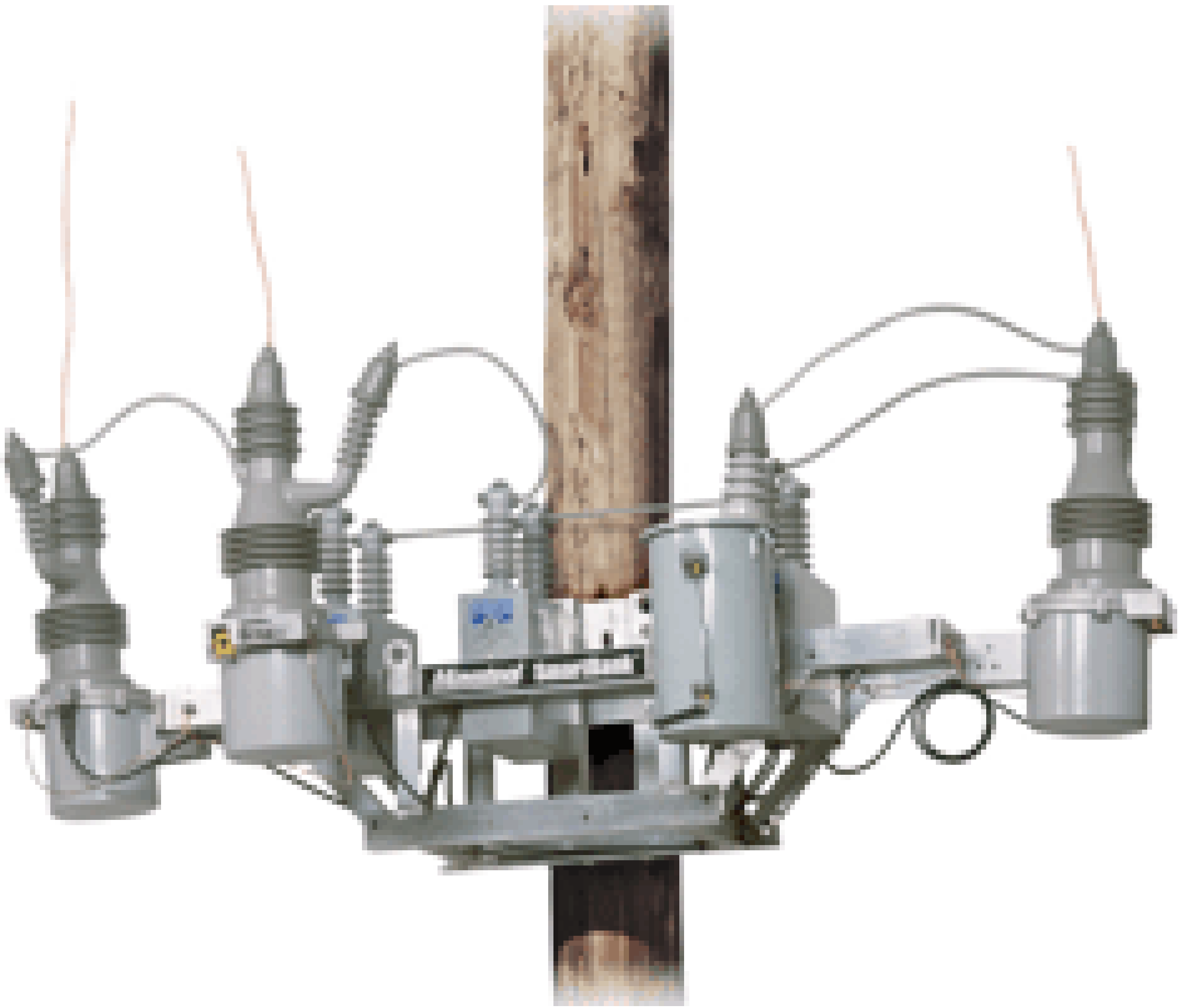
1. With a Voltage of 120 volts, Resistance of 10Ω and Inductive Reactance of 5Ω. What is the current?

2. Does the current lead or lag the voltage?

3. What is the angle between the current and the voltage legs of the triangle?

Power in AC Circuits

- Resistive Circuits - Watts
- Reactive Circuits – VARS
- Complex Power
- Power Triangle
- Power Factor
- VARs – Effect on Voltage
- Voltage Collapse



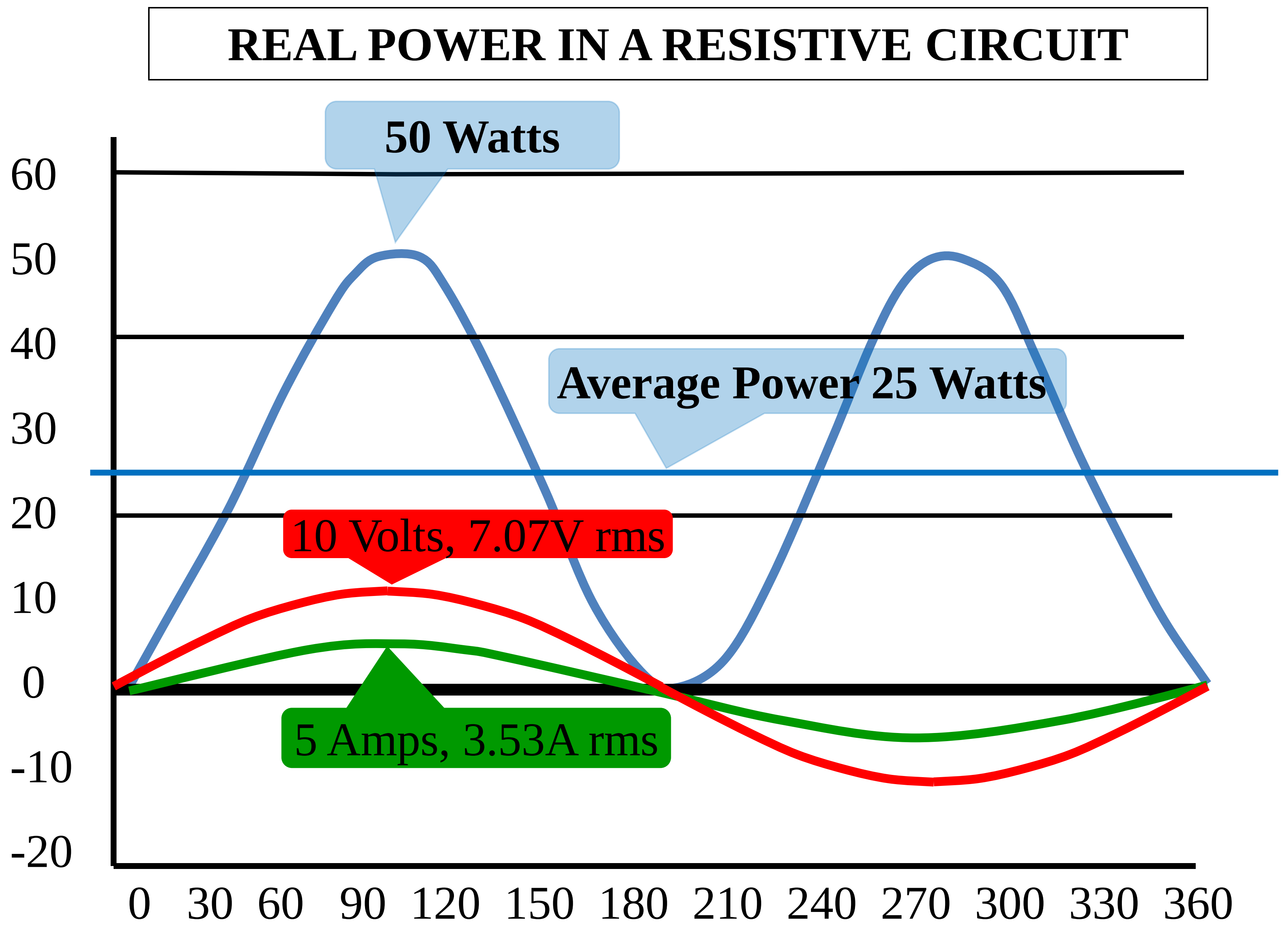
Power Capacitors

Resistive Circuits - Watts

Power in AC Circuits
Resistive Circuits

Power is the rate at which work is performed it is measured in ***watts***.

- In a resistive circuit, the current and voltage are in phase.
- ***Real Power*** is the power consumed by the resistance in a circuit.


REAL POWER IN A RESISTIVE CIRCUIT
50 Watts
Average Power 25 Watts
10 Volts, 7.07V rms
5 Amps, 3.53A rms
60
50
40
30
20
10
0
-10
-20
0 30 60 90 120 150 180 210 240 270 300 330 360

Power in AC Circuits
Resistive Circuits

Real power is calculated using the following equations:

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

$$P = \frac{VV}{R} = \frac{V^2}{R}$$

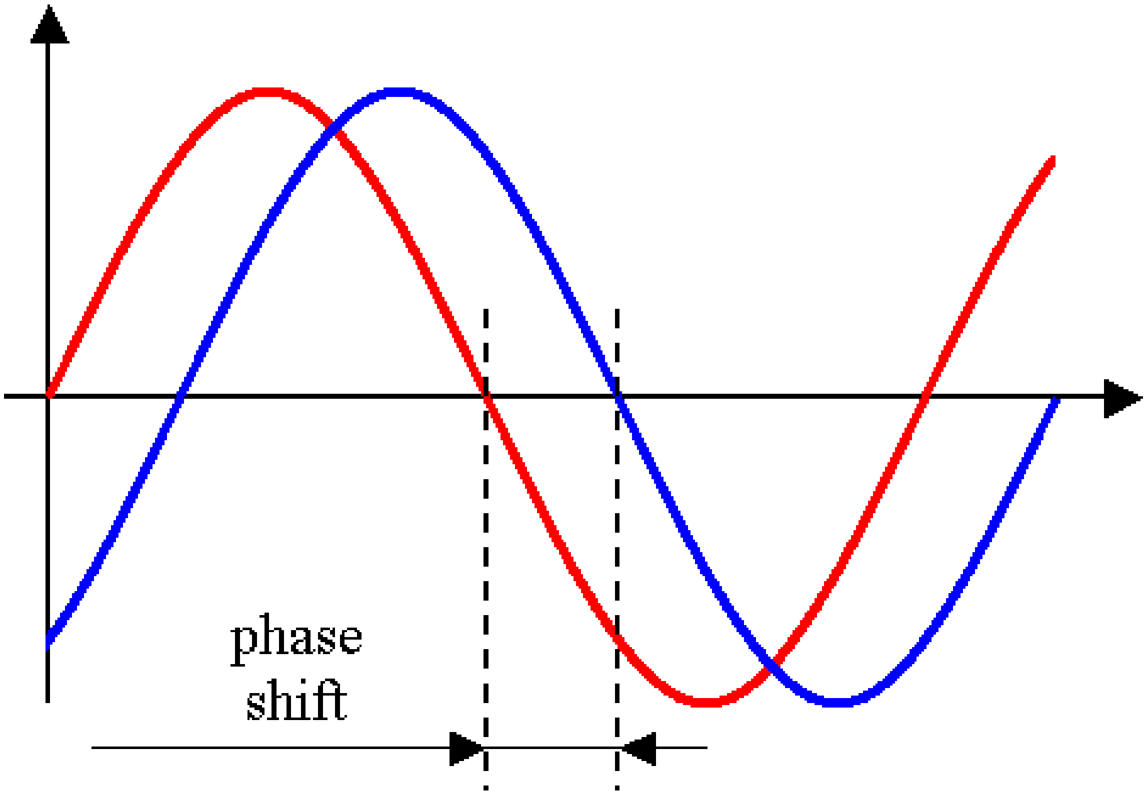
Power in AC Circuits
Resistive Circuits

- **Losses** are dissipated as heat in transmission lines and transformers
- **I^2R = Heating Losses**
- Most circuits are not entirely resistive – they contain reactance

Reactive Circuits - VARs

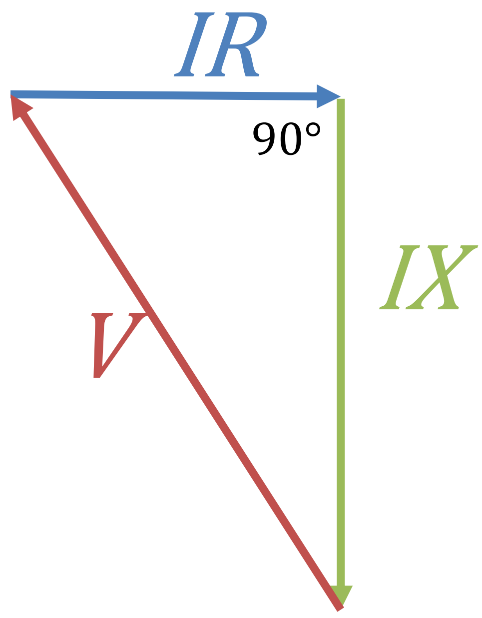
Power in AC Circuits
Reactive Circuits

Reactance causes a phase shift between voltage and the current.



Power in AC Circuits
Reactive Circuits

$$V = IR + IX < 90°$$



Note: Reactive Impedance of a Transmission line is much larger then the resistance.

Power in AC Circuits
Reactive Circuits

Reactive Power ***is the power used to support the magnetic and electric fields*** found in inductive and capacitive loads throughout a power system.

- Reactive power is measured in volt-amps-reactive (Vars)

Complex Power

Power in AC Circuits
Complex Power

Complex Power = Real Power + Reactive Power.

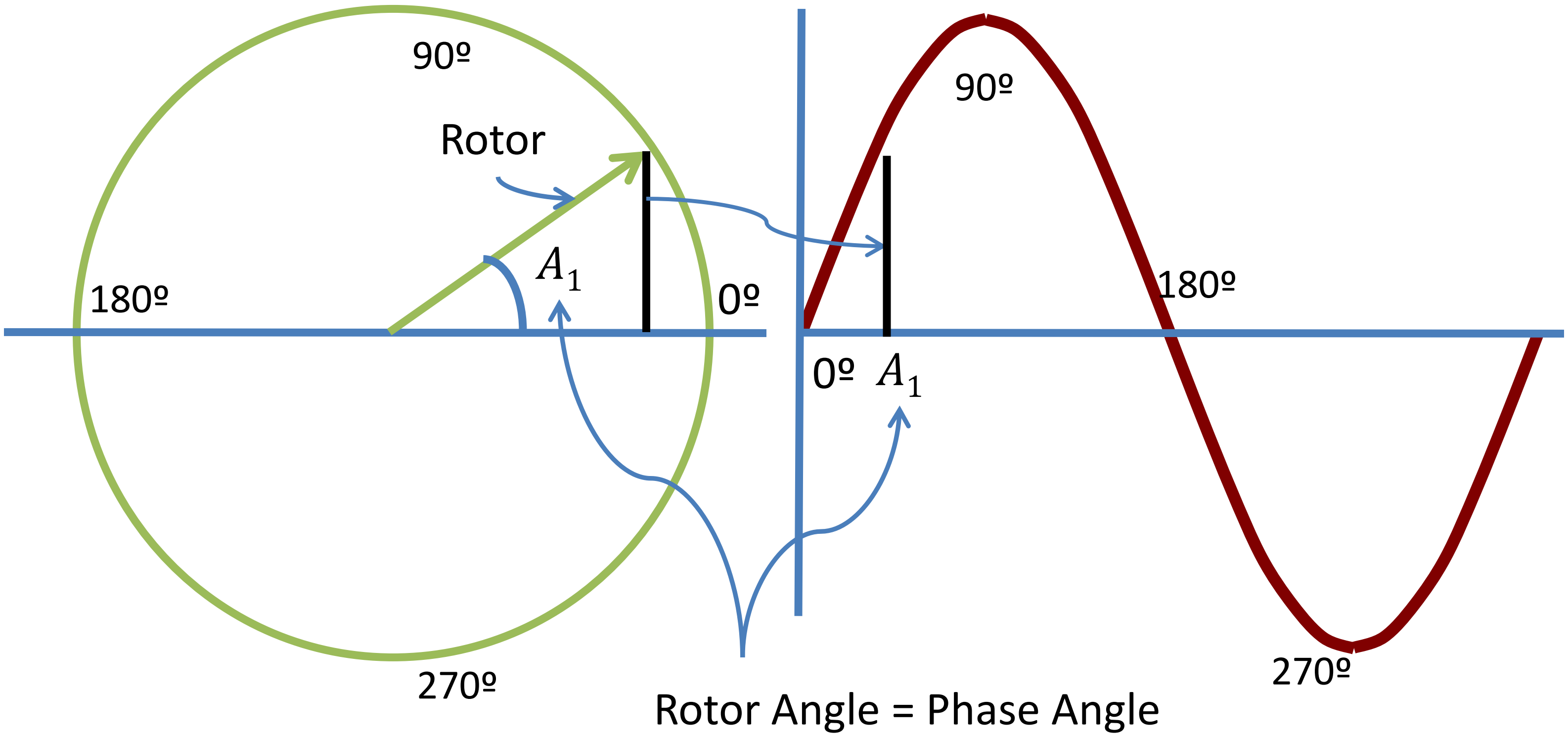
- Unlike resistors; inductors and capacitors do not consume power, they store and release energy
- In a resistive circuit, the current and voltage are in phase. But that is not the case in a reactive circuit

Power in AC Circuits
Complex Power

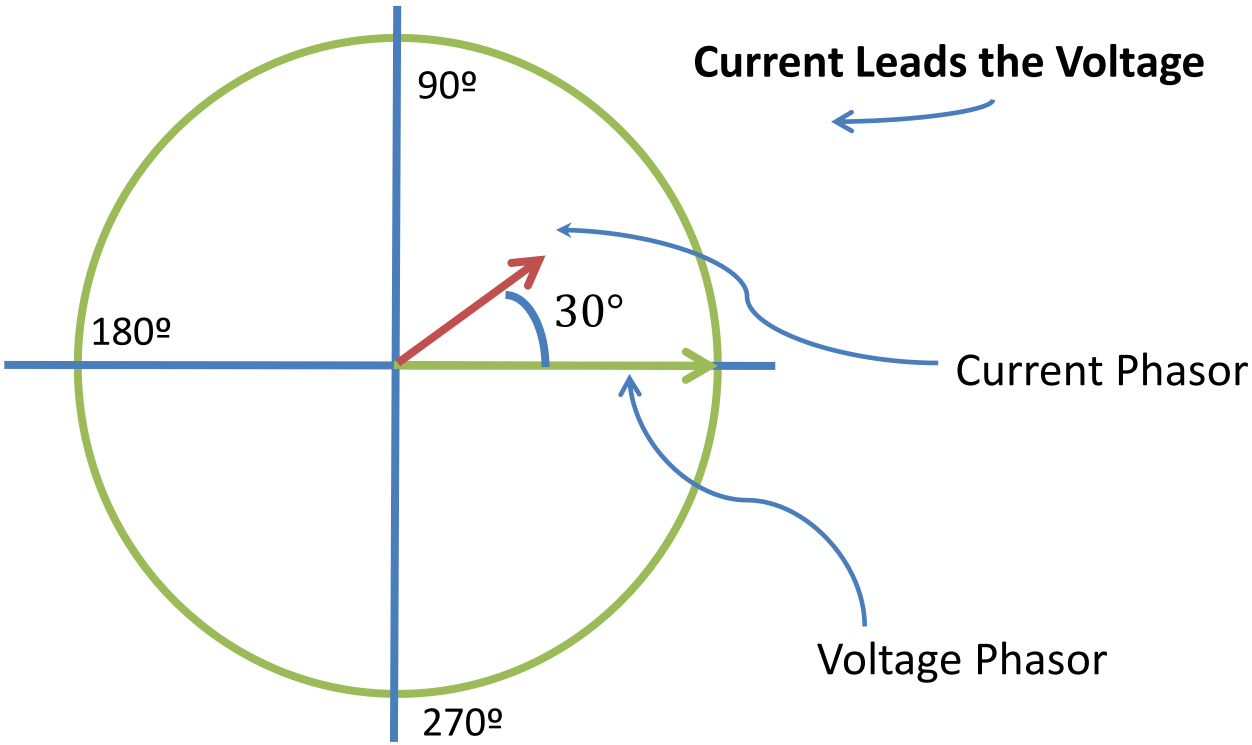
- **Reactive Power** supports the magnetic and electric fields found in inductive and capacitive loads
- Reactive power is measured in ***volt-amperes reactive (Vars)***

Power in AC Circuits
Complex Power

We use phasors and **right triangle relationships** to break the current and voltage into resistive and reactive parts.



Power in AC Circuits
Complex Power

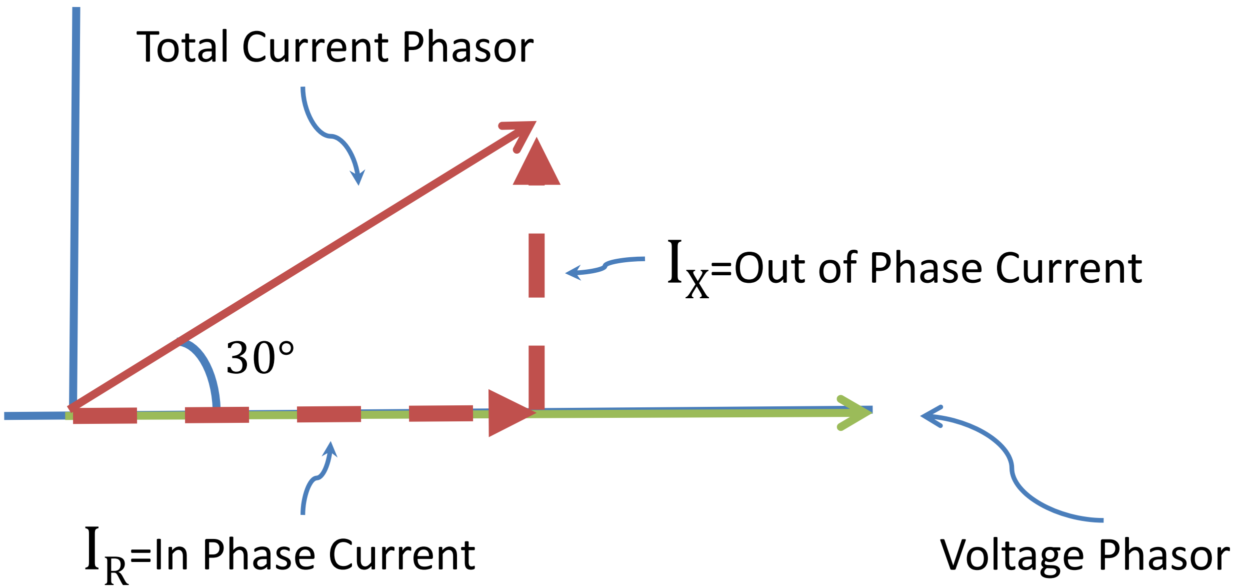


Current **leads** Voltage by 30º

Capacitive Circuit

Power in AC Circuits
Complex Power

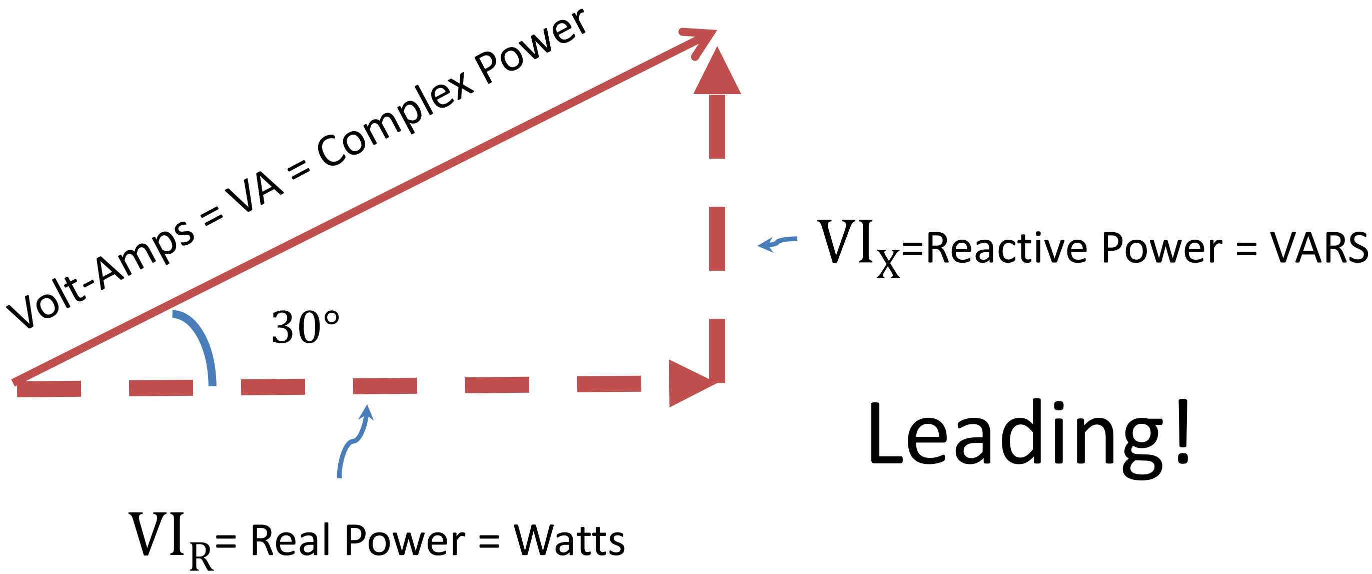
Part of the Current is in-phase with the voltage. Part of the Current is out-of-phase with the voltage.



Current leads Voltage by 30º

Power in AC Circuits
Complex Power

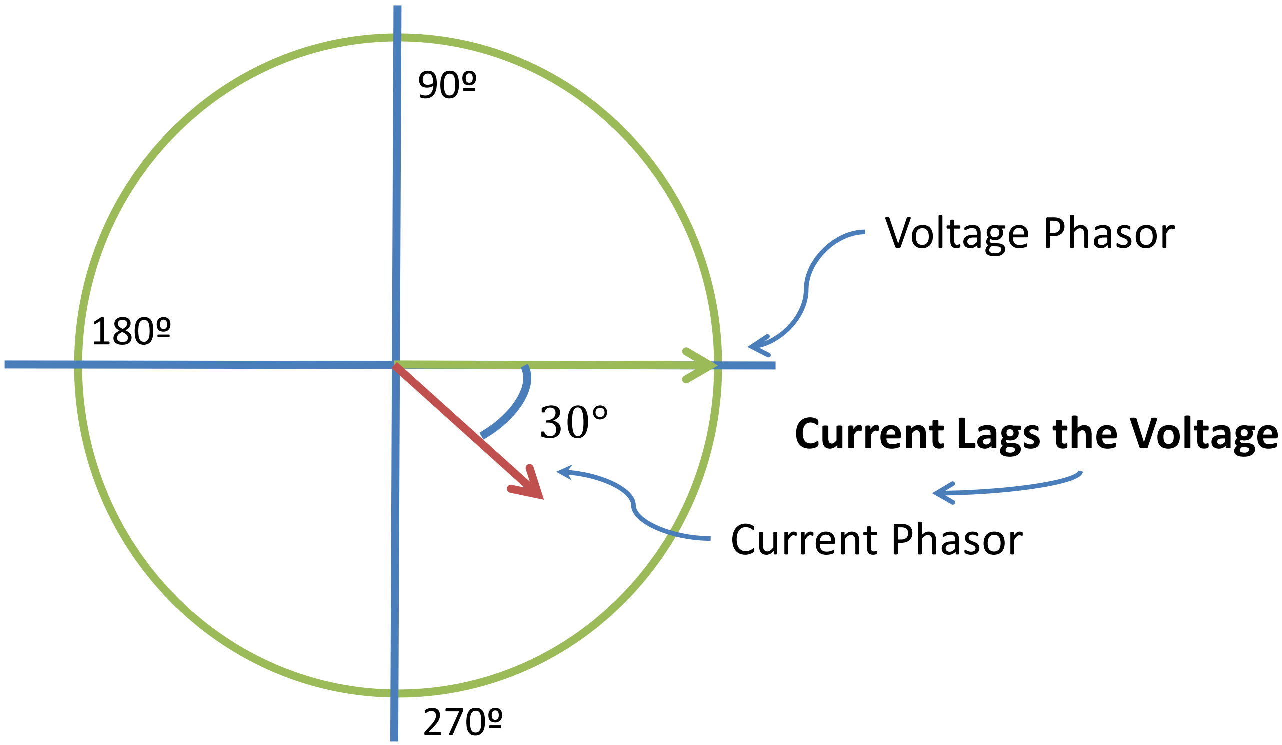
Part of the Current is in-phase with the voltage. Part of the Current is out-of-phase with the voltage.



Leading!

Current leads Voltage by 30º

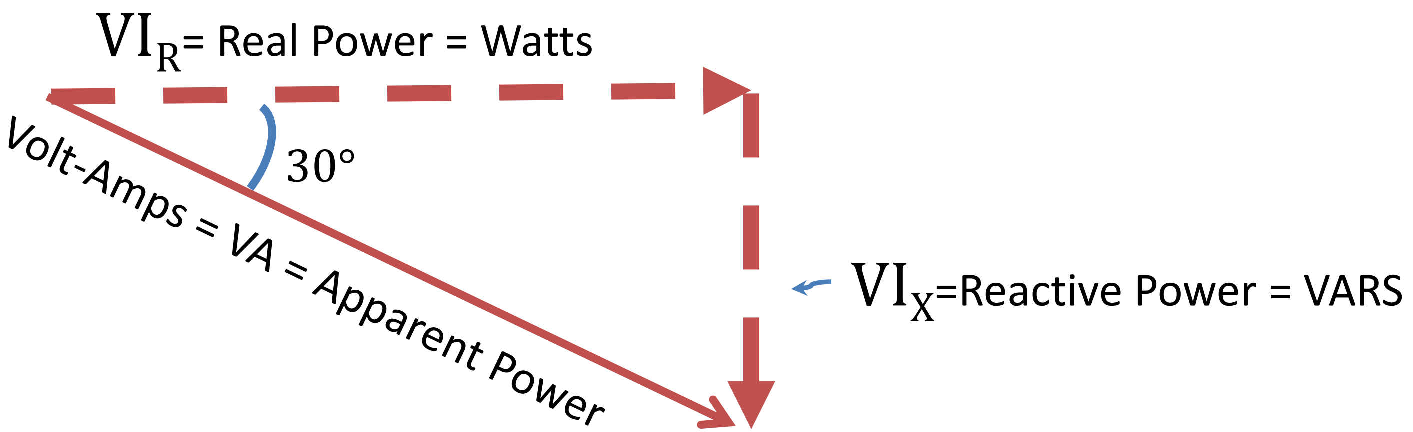
Power in AC Circuits
Complex Power



Current **Lags** Voltage by 30º

Inductive Circuit

Power in AC Circuits
Complex Power



Lagging

Inductive Circuit

Current Lags Voltage by 30º

Power in AC Circuits
Complex Power

- When voltage and current are not in phase or in sync, there are two components:
  - Real or active power is measured in Watts
  - Reactive (sometimes referred to as imaginary) power is measured in VARs
- The combination (vector product) is Complex Power or Apparent Power
- The term "Power" normally refers to active power

Power in AC Circuits
Complex Power

Real power does the work; it does the heating, lighting, and turning of motors, etc.

It is measured in **Watts**

Power in AC Circuits
Complex Power

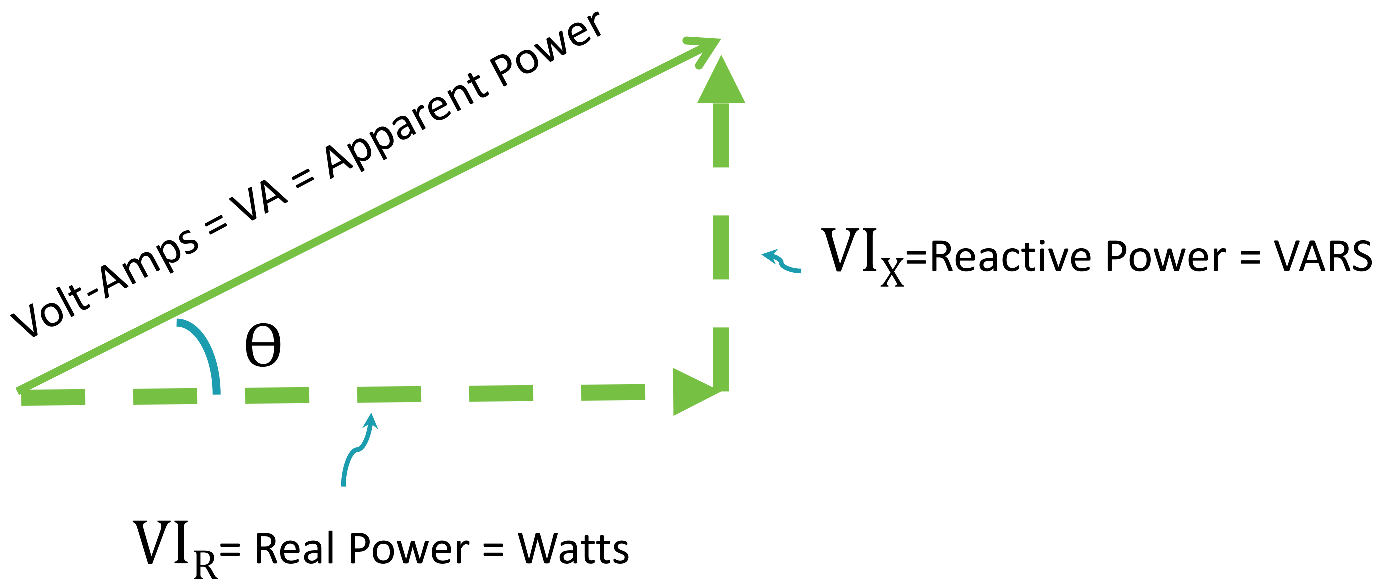
Reactive power supports magnetic and electric fields required for AC systems to function.

It is measured in:

Volt-**A**mperes-**R**eactive (**VARs**)

Power Triangle

Power in AC Circuits
Power Triangle



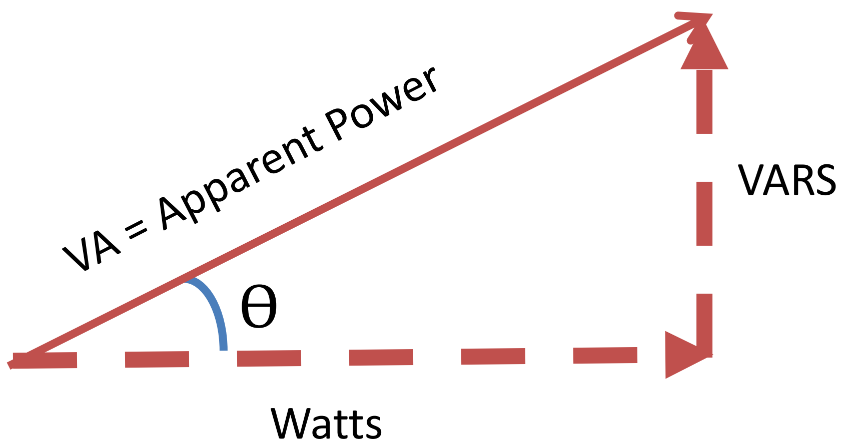
Angle between Apparent Power and Real Power is θ

Power Factor

Power in AC Circuits
Power Factor

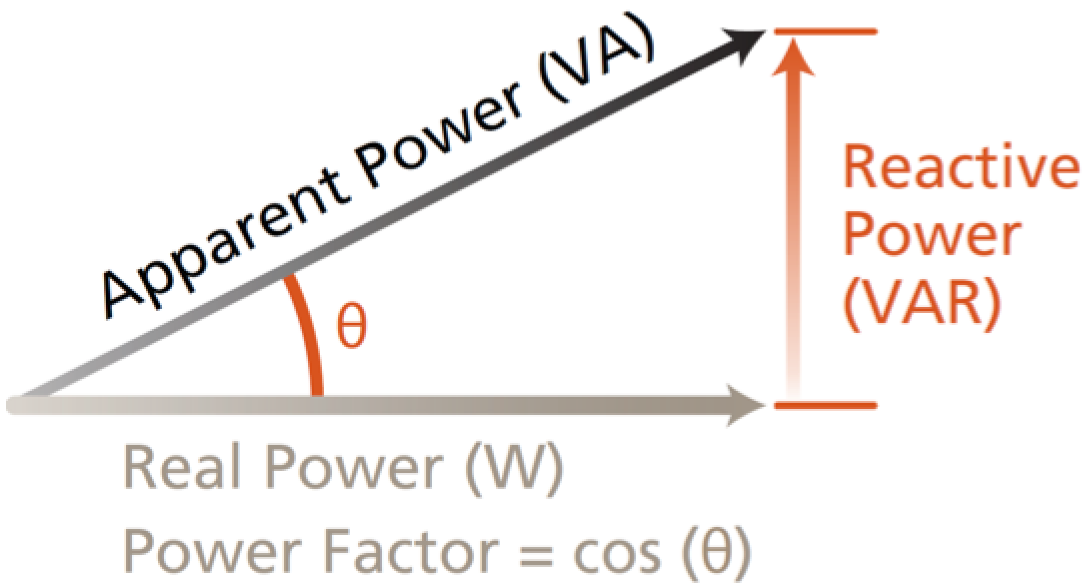
Power Factor (PF) is the ratio of real power to apparent power.

$$\text{Power factor} = \frac{Watts}{VA}$$



Power in AC Circuits
Power Factor

The Power Factor (cos ϴ) = Real/Apparent



Power in AC Circuits
Power Factor

To serve Manufacturer A, the utility must provide the following volt-amperes.

$$P_{app} = \frac{P}{PF}$$

$$P_{app} = \frac{2{,}000{,}000}{.6}$$

$$P_{app} = 3{,}333{,}333.3$$

$$P_{app} = 3.3\text{MVA}$$

Power in AC Circuits
Power Factor

To serve this load, the utility's conductors must be able to carry the following current:

$$I = \frac{P_{app}}{V}$$

$$I = \frac{3{,}333{,}333.3\ \text{VA}}{4{,}700\ \text{V}}$$

$$I = 709.2\ \text{A}$$

Power in AC Circuits
Power Factor

Manufacturer B uses the same real power (2 MW) as Manufacturer A and, therefore, pays the same amount to the utility.   However, Manufacturer B requires a different amount of apparent power.

$$P_{app} = \frac{P}{PF}$$

$$P_{app} = \frac{2,000,000}{.97}$$

$$P_{app} = 2,061,856\ VA$$

$$P_{app} = 2.1 MVA$$

Power in AC Circuits
Power Factor

And, the current drawn by Manufacturer B is:

$$I = \frac{P_{app}}{V}$$

$$I = \frac{2{,}061{,}856 \text{ VA}}{4{,}700 \text{ V}}$$

$$I = 439 \text{ A}$$

Power in AC Circuits
Power Factor

Manufacturer B draws much less current to obtain the same real power.

Utilities design their transmission and distribution systems based on the apparent power and the current they must deliver.

Since utilities bill their customers for the true power used, utilities encourage the use of high-power factor systems.

VARs – Effect on Voltage

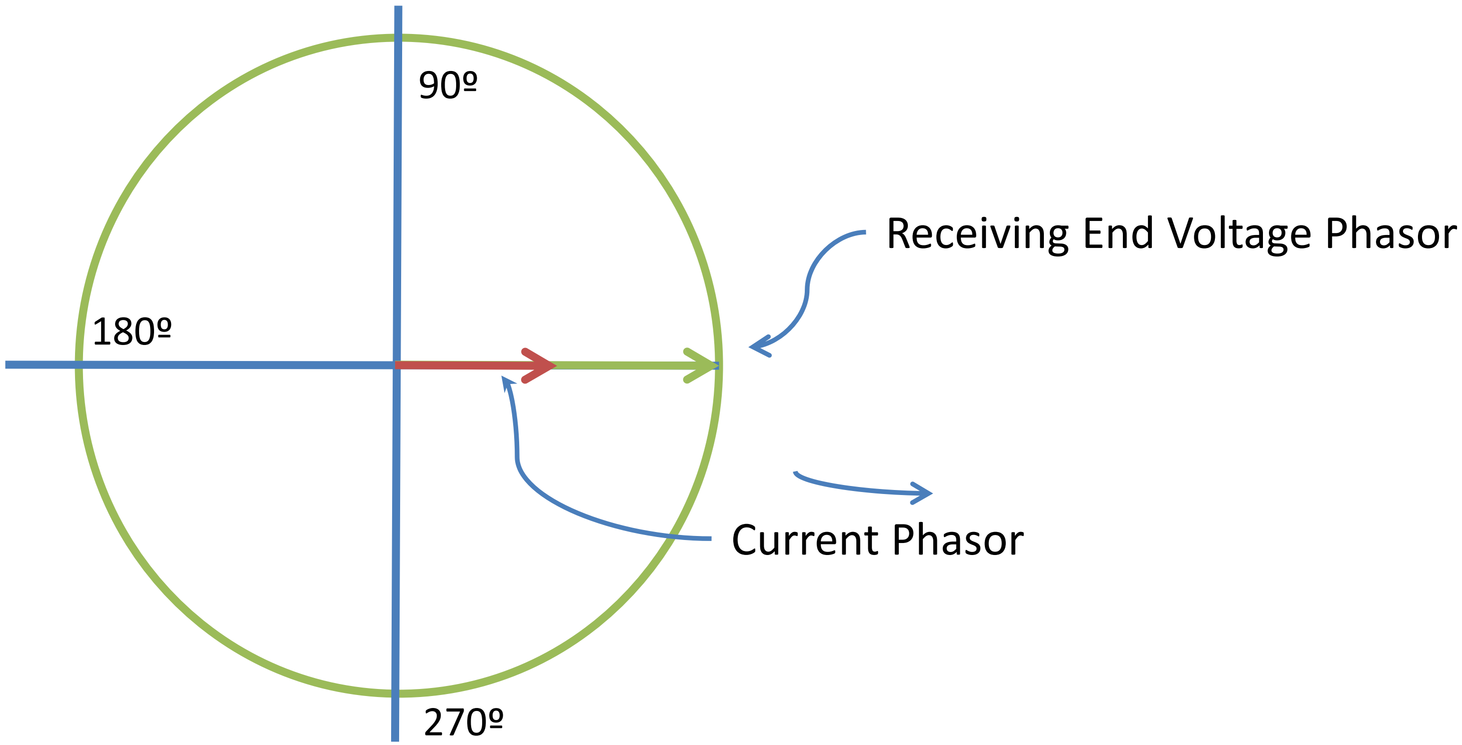
Power in AC Circuits
VAR Effect on Voltage Control

Reactive power supply is the most important element in controlling voltage.

Why?

If I put a lagging reactive current that is 90º out of phase through a reactive line impedance that is 90º out of phase, it results in a 180º voltage drop.

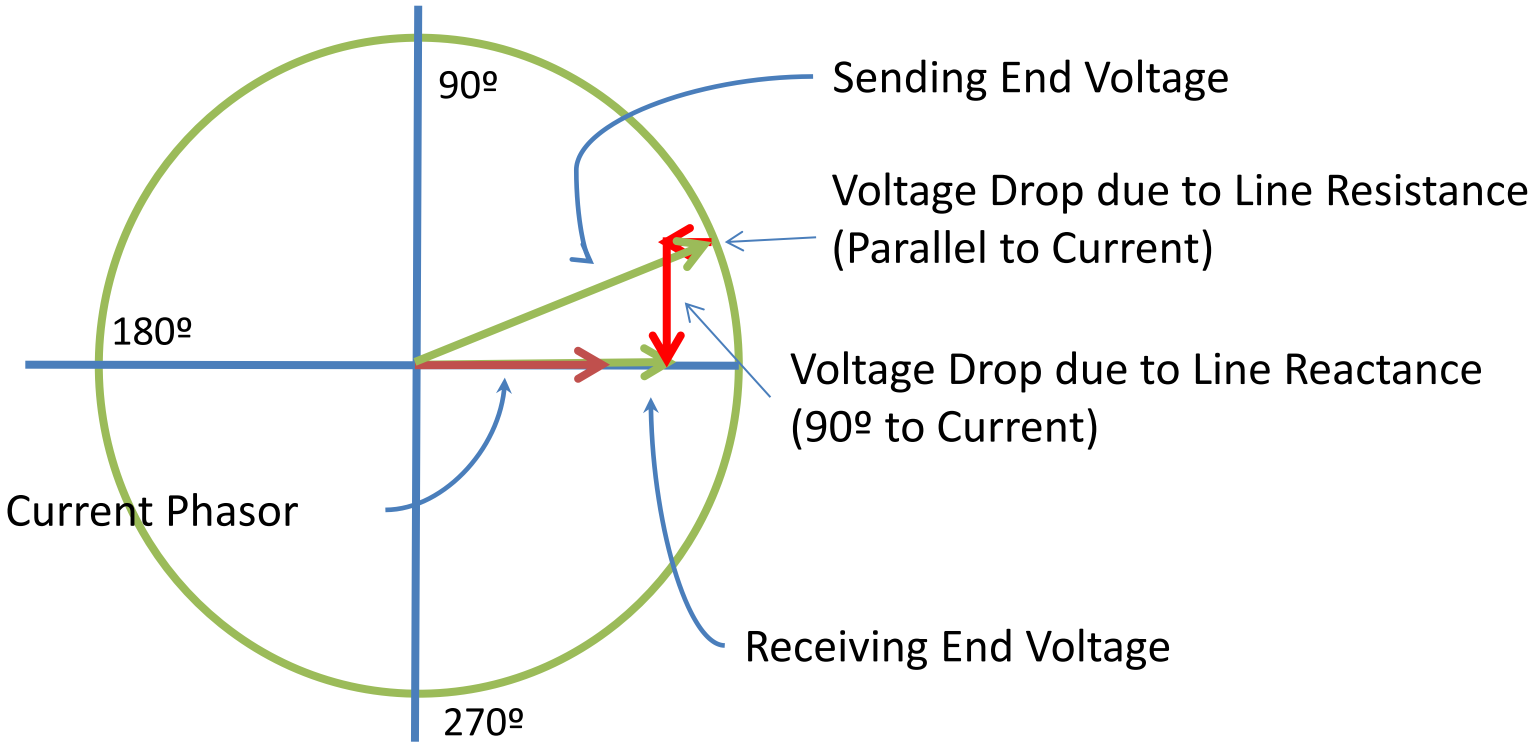
Power in AC Circuits
VAR effect on Voltage Control



Current **In Phase with** Voltage

Resistive Load

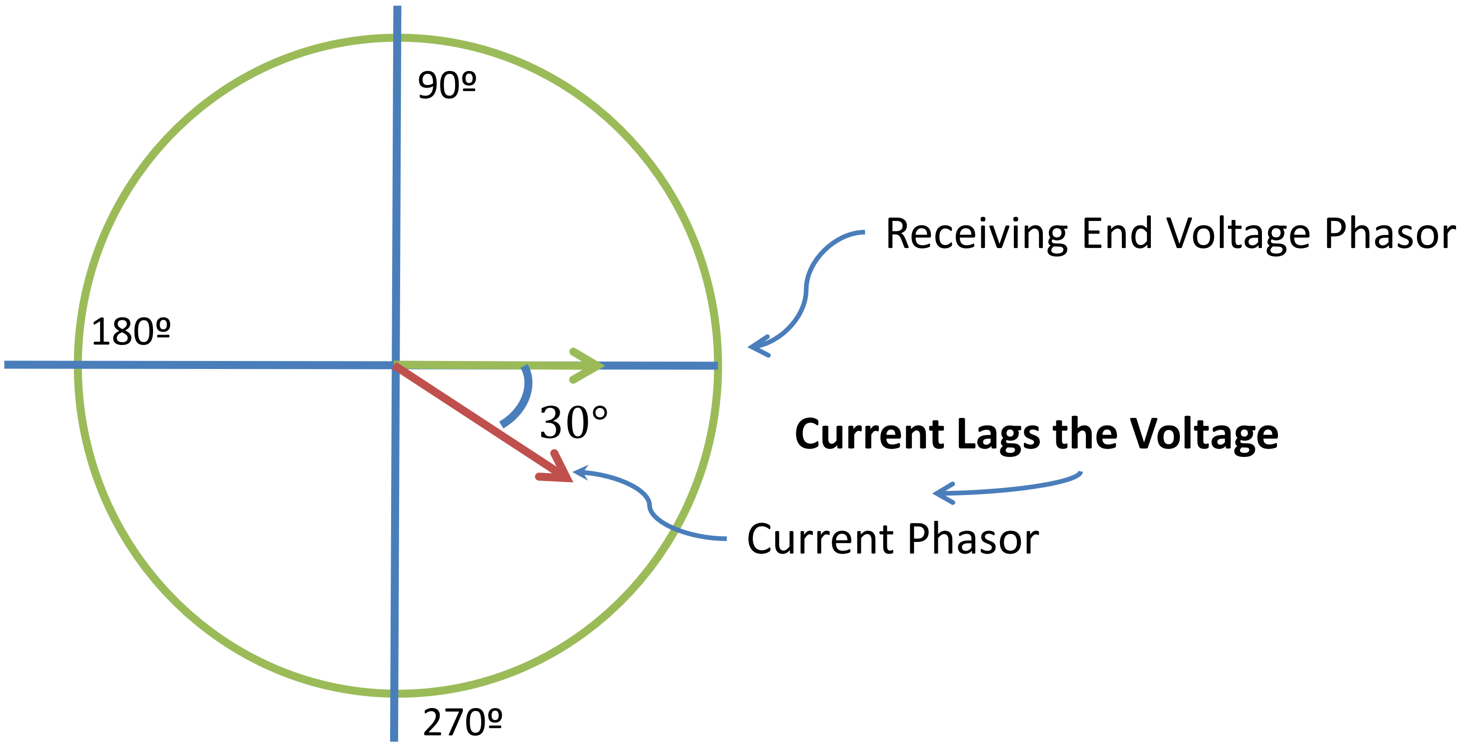
Power in AC Circuits
VAR effect on Voltage Control



Current **In Phase with** Voltage

Resistive Load

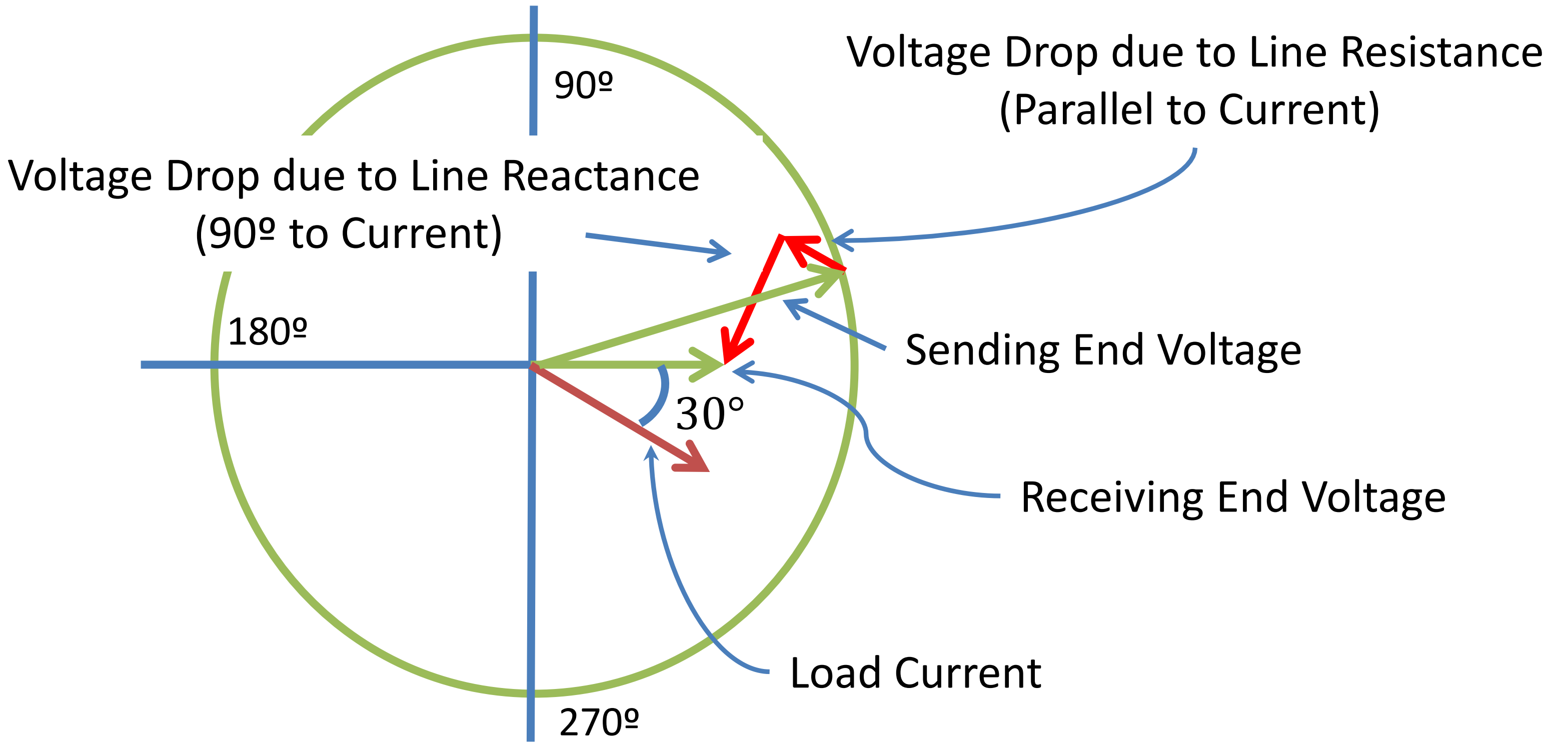
Power in AC Circuits
VAR effect on Voltage Control



Load Current **Lags** Voltage by 30º

Inductive Load

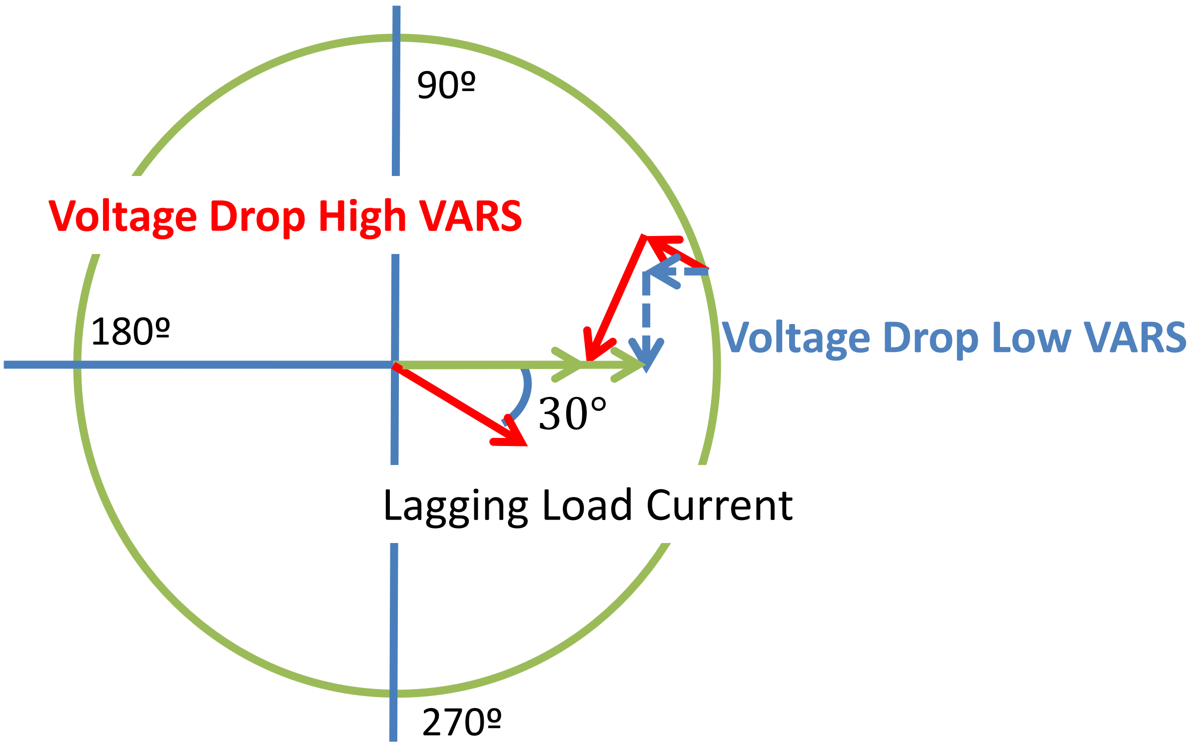
Power in AC Circuits
VAR effect on Voltage Control



Current **Lags** Voltage by 30º

Inductive Load

Power in AC Circuits
VAR effect on Voltage Control



Power in AC Circuits
VAR Effect on Voltage Control

Voltage fluctuates due to:

Load

- Consumes VARs
- More load, more VARs used

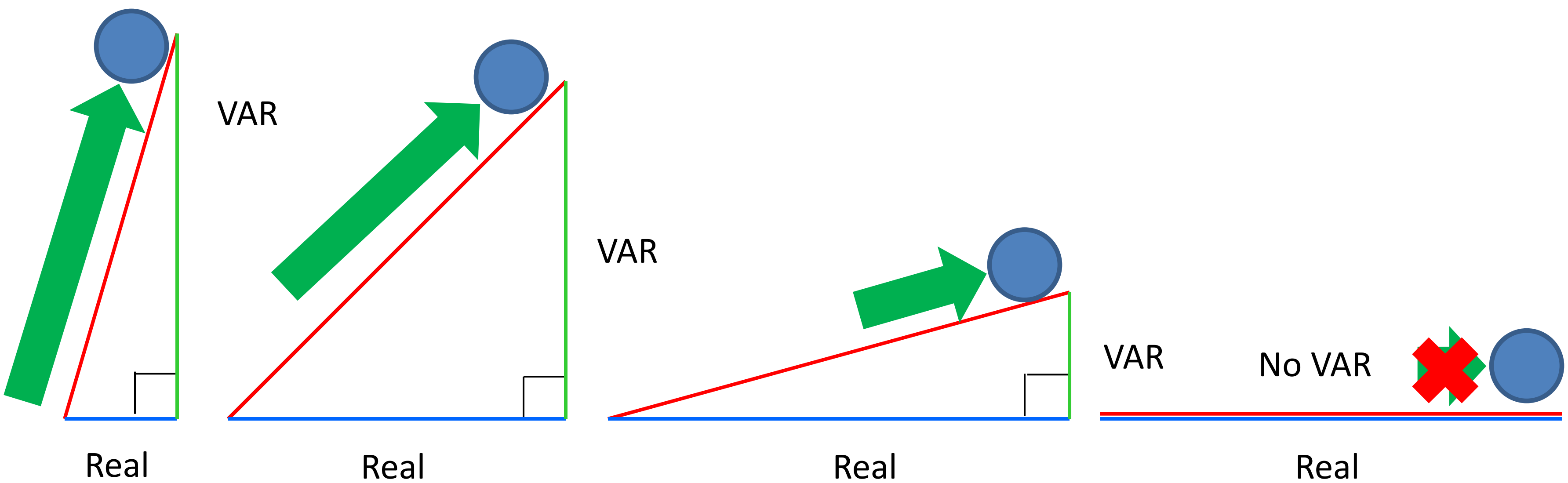
Lines – inductive impedance

- More load, more VAR losses
- Loss of a transmission line means other lines load heavier and we experience even more VAR losses

Voltage Collapse

Power in AC Circuits
Voltage Collapse

Voltage Collapse – when the grid system experiences an uncontrollable reduction in voltage due to a deficiency in reactive power (VARS).



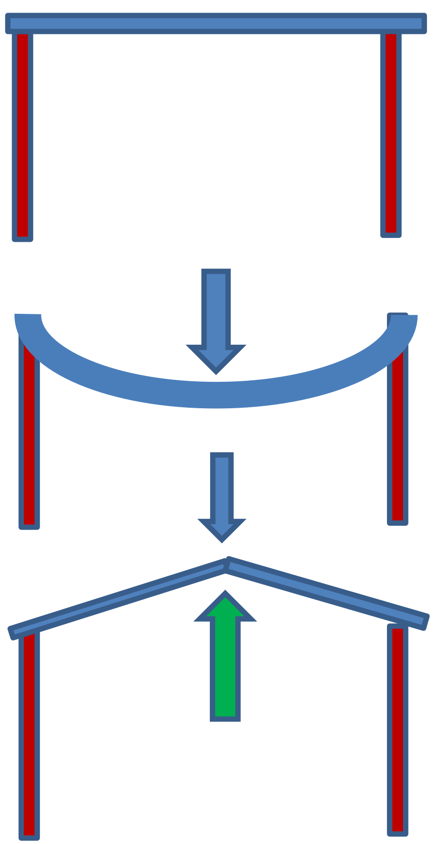
Power in AC Circuits
WHAT are VARs?

System Operator and Engineering Terms

- Volt Amp Reactive
- Reactive Power
- Imaginary Power
- Part of Complex Power
- Part of Apparent Power

Power in AC Circuits
WHAT are VARs?

VAR analogy --- Building a roof



Flat roof with no vertical load is OK (Voltage is OK)

Flat roof with vertical load (VARS) Sags (Voltage Sags)

Slanted roof with **VARS** added to compensate for load **VARS** is ok

Power in AC Circuits
WHAT are VARs?

- VARs support the system and pull down or push up the voltage
- When circuits result in the current **leading** the voltage, voltage rises as VARs increase
- When circuits result in the current **lagging** the voltage, voltage decreases as VARs are consumed

Power in AC Circuits
Why do WE need Reactive Power

"Reactive power (VARs) is required to maintain the voltage to deliver active power (watts) through transmission lines. Motor loads and other loads require reactive power to convert the flow of electrons into useful work. When there is not enough reactive power, the voltage sags down and it is not possible to push the power demanded by loads through the lines."

("Signatures of the Blackout of 2003", Roger C. Dugan et. al.)

Power in AC Circuits
Importance of Reactive Power

- Refers to the circulating power in the grid that does no useful work
- Results from energy storage elements in the power grid (mainly inductors and capacitors)
- It must be controlled to prevent voltage problems.
- Reactive power levels have an effect on voltage collapse
- The reactive power flow should be minimized to reduce losses. This ensures that the system operates efficiently

Power in AC Circuits
Reactive Power is a Byproduct of AC systems

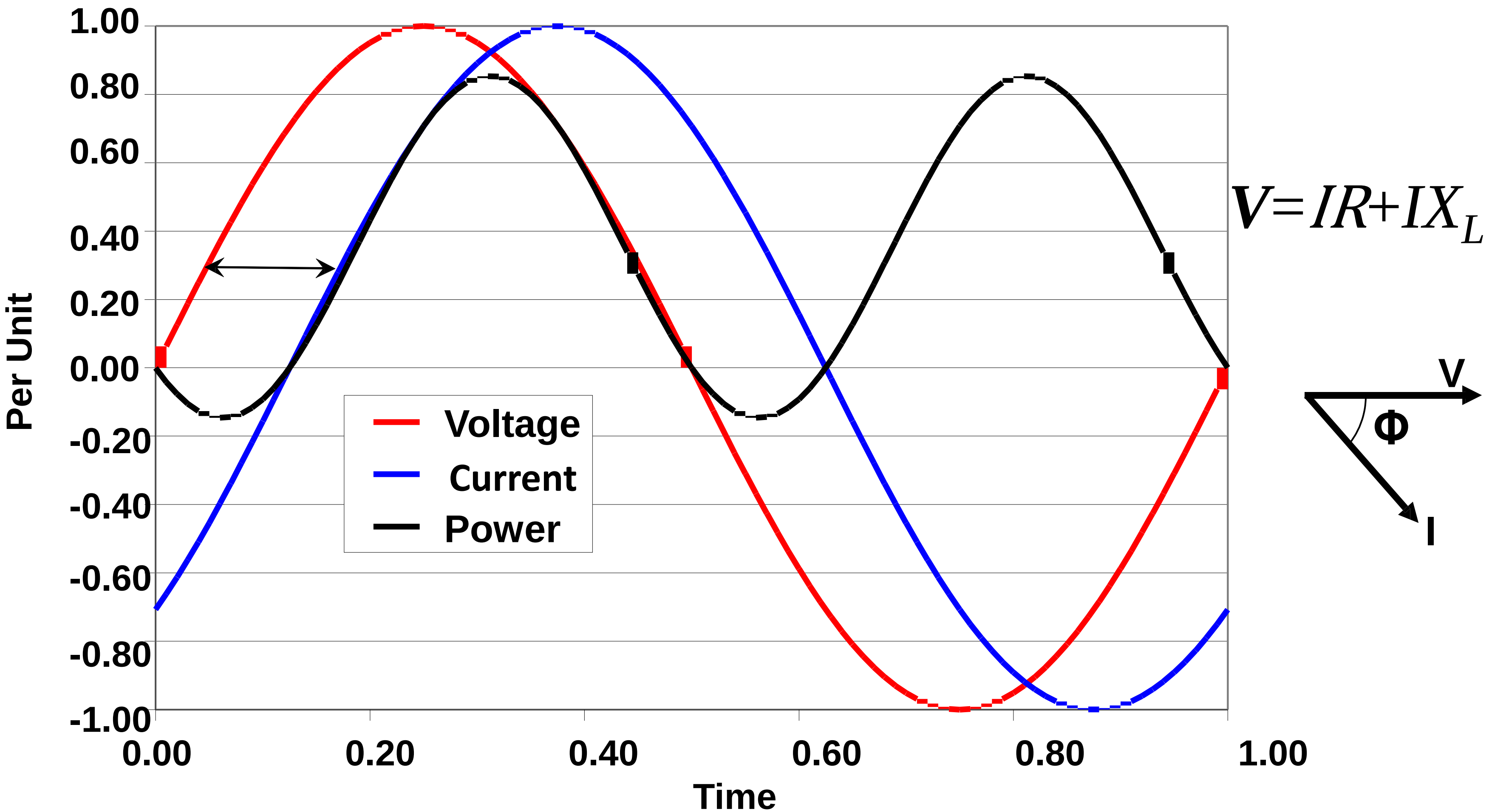
- Transformers, transmission lines, and motors require reactive power.
- Transformers and transmission lines introduce inductance as well as resistance.
    - Both oppose the flow of current
- Must raise the voltage higher to push the power through the inductance of the lines.
    - Unless capacitance is introduced to offset inductance
- The farther the transmission of power, the higher the voltage needs to be raised.

Power in AC Circuits
Reactive Power & Power Factor

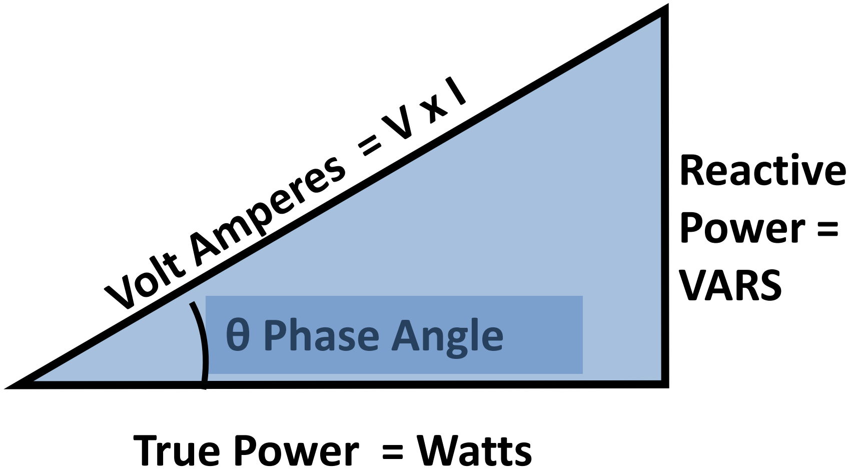
- Reactive power is present when the voltage and current are not in phase
  - One waveform leads the other
  - Phase angle not equal to Zero Degrees
  - Power factor less than unity
- Measured in volt-ampere reactive (VAR)
- Produced when the current waveform leads voltage waveform (Leading power factor)
- Vice versa, consumed when the current waveform lags voltage (lagging power factor)

AC Voltage & Current Phase Shift due to Inductance

Current Lags Voltage



Power Triangle



Volt-Amperes = (**VA**) = Apparent Power

Watts = (**W**) = True Power

Vars = (**VARS**) = Volt-Amperes Reactive

Power Factor = (**PF**) = Watts/(Volt Amperes)

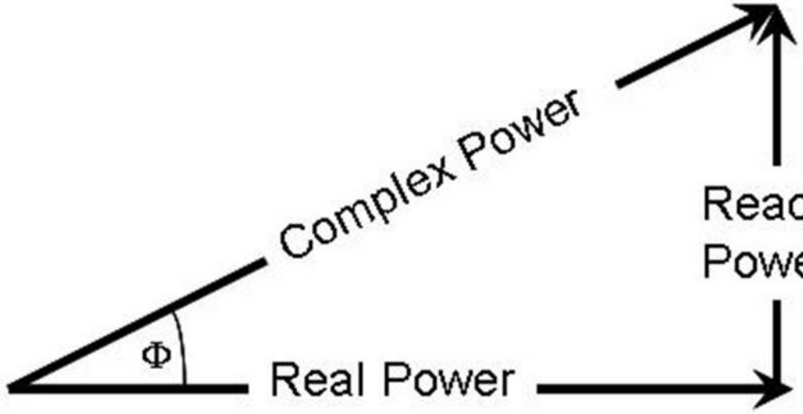
Phase Angle = Θ = $\cos^{-1}$ (PF) = Angular displacement between voltage & current

Power in AC Circuits
Power Triangle

$$\text{Complex Power} = \sqrt{(\text{Real Power})^2 + (\text{Reactive Power})^2}$$

$$\text{Real Power} = \text{Complex Power} \times \text{Cos}(\Phi)$$

$$\text{Power Factor} = \text{Cos}(\Phi) = \frac{\text{Real Power}}{\text{Complex Power}}$$



Power in AC Circuits
Reactive Power Limitations

- Reactive power does not travel very far
- Usually necessary to produce it close to the location where it is needed
- A supplier/source close to the location of the need is in a much better position to provide reactive power
  - versus one that is located far from the location of the need
- Reactive power supplies are closely tied to the ability to deliver real or active power

Check Your Knowledge: Fundamentals of Electricity

1. In a Resistive Load the current A) Leads, B) Lags, C) is in phase with the voltage. T/F?
2. A load consists of a 4 ohms resistor in parallel with a 3 ohm reactor with a voltage of 10 volts.
   a. What is the total Impedance?
   b. Current?
   c. Real Power?
   d. Reactive Power?
   e. Power Factor?

Three-Phase Circuits

- Definition and Advantages
- Three Phase Connections

WYE vs. Delta

Definition and Advantages

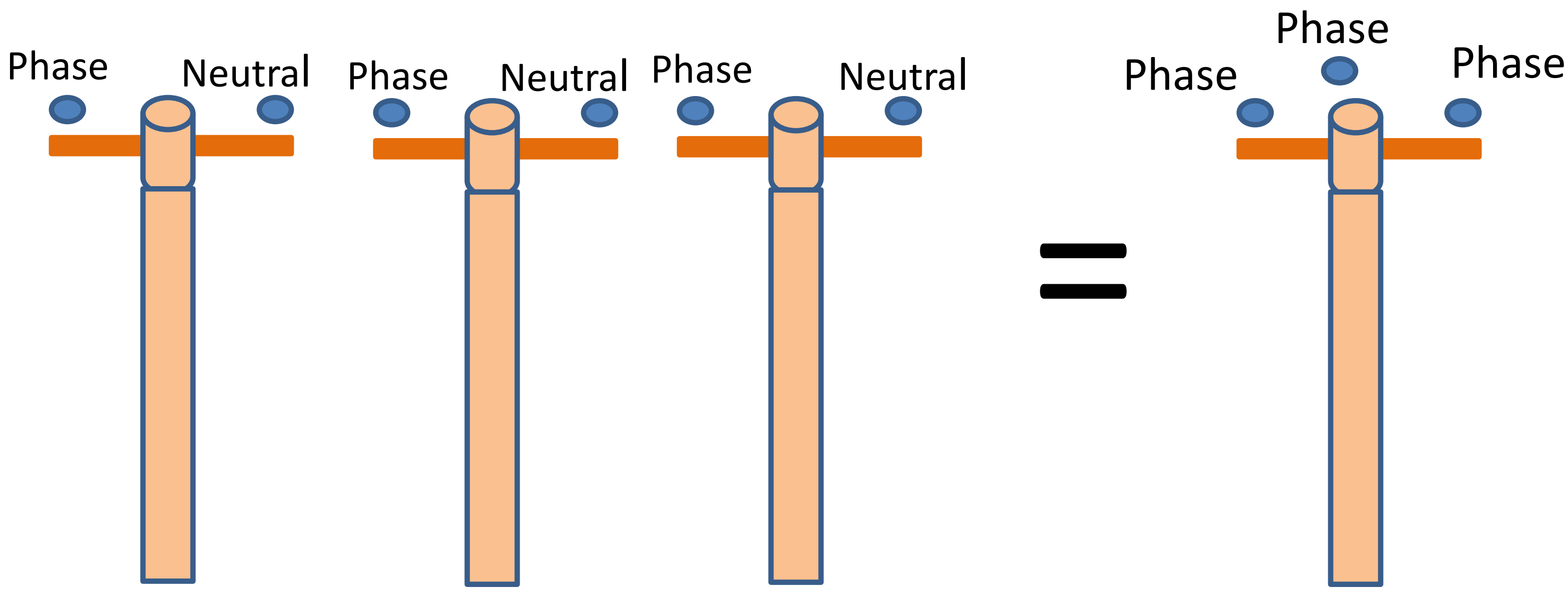
Three-Phase Circuits
Definition and Advantages

- Almost all electricity is generated and distributed as ***three-phase*** rather than single-phase
- Cost of three-phase is less than single-phase
- Uses fewer conductors
- Reduces Losses

Three-Phase Circuits
Definition and Advantages

3 – Single Phase Lines

1 – 3 Phase Line

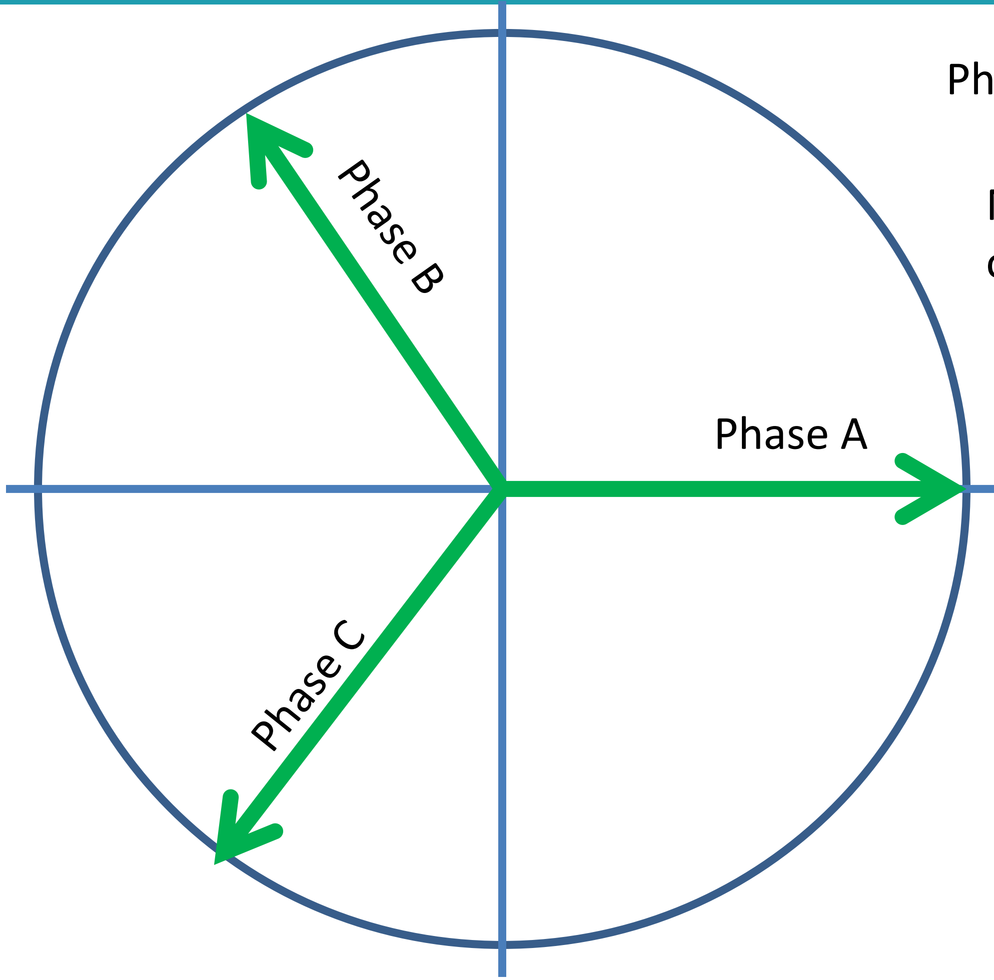


Six Conductors

Three Conductors

Neutral Current – returns on other two phases

Three-Phase Circuits
Definition and Advantages



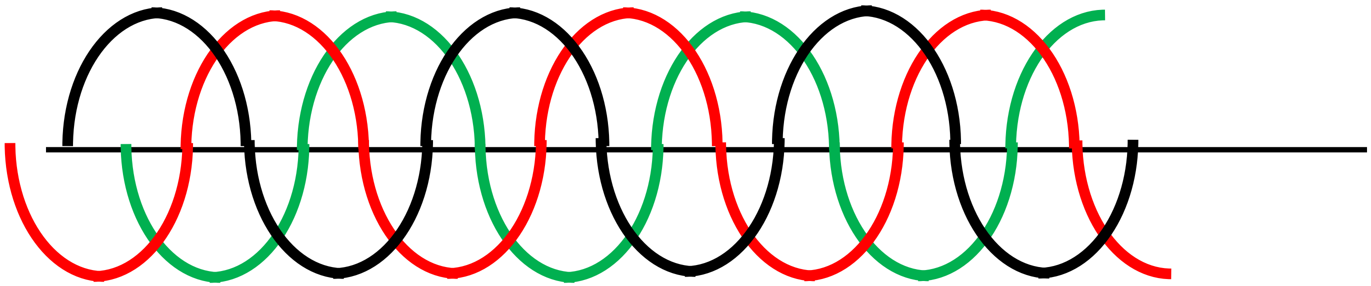
Phase A= - (Phase B +Phase C)

Neutral Current – returns on other two phases

Three-Phase Circuits
Definition and Advantages

- More constant load on the generator shaft.
- Single-phase load on the generator shaft goes from zero to maximum power and back to zero with each cycle.
- With three-phase current, at least two of the phases provide current (and therefore, power) at any instant.
- Load on a three-phase generator never reduces to zero. This uniform load allows smoother operation of the generator…

Three-Phase Circuits
Definition and Advantages



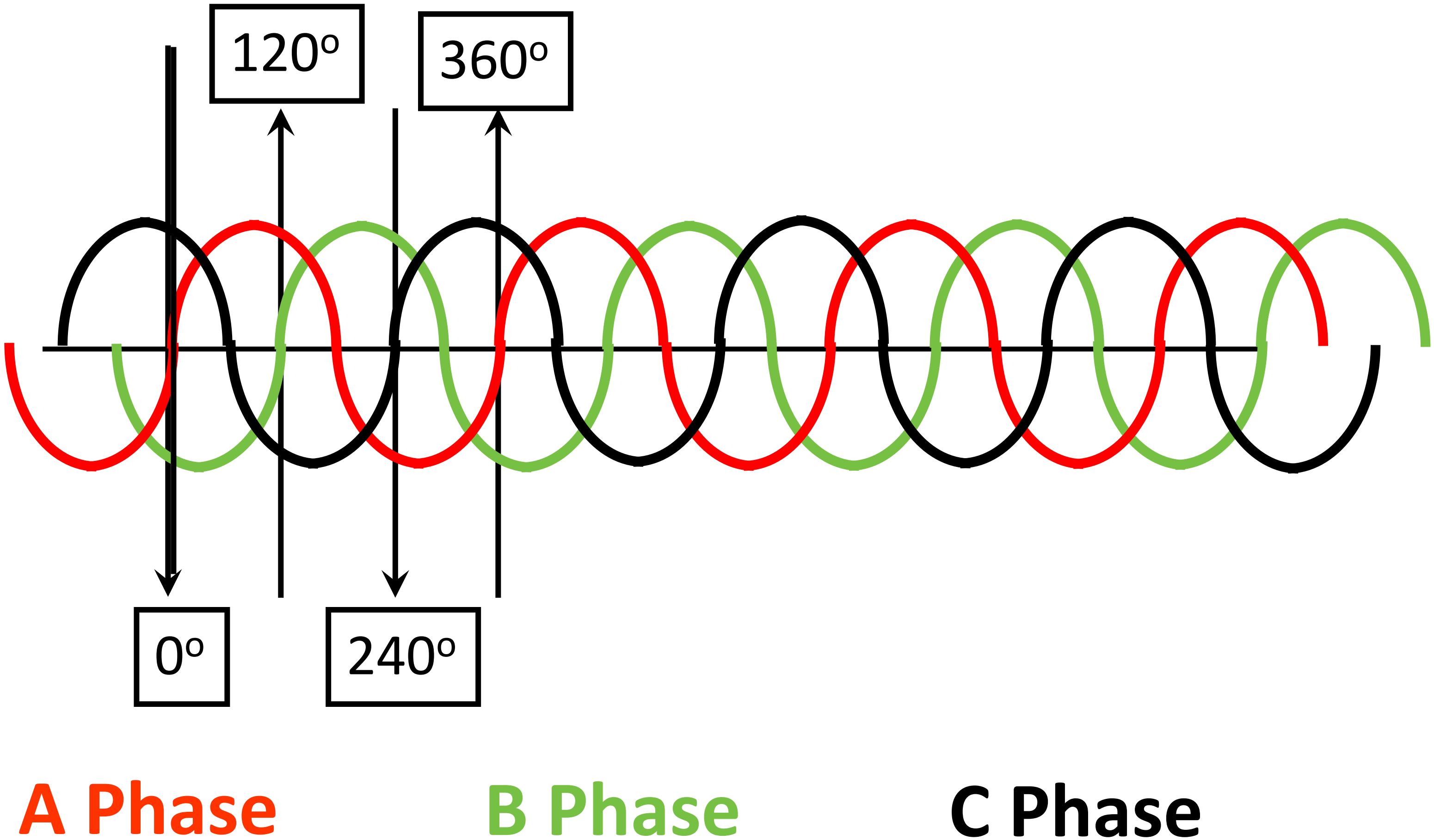
A Phase B Phase C Phase

Three-Phase Circuits
Definition and Advantages

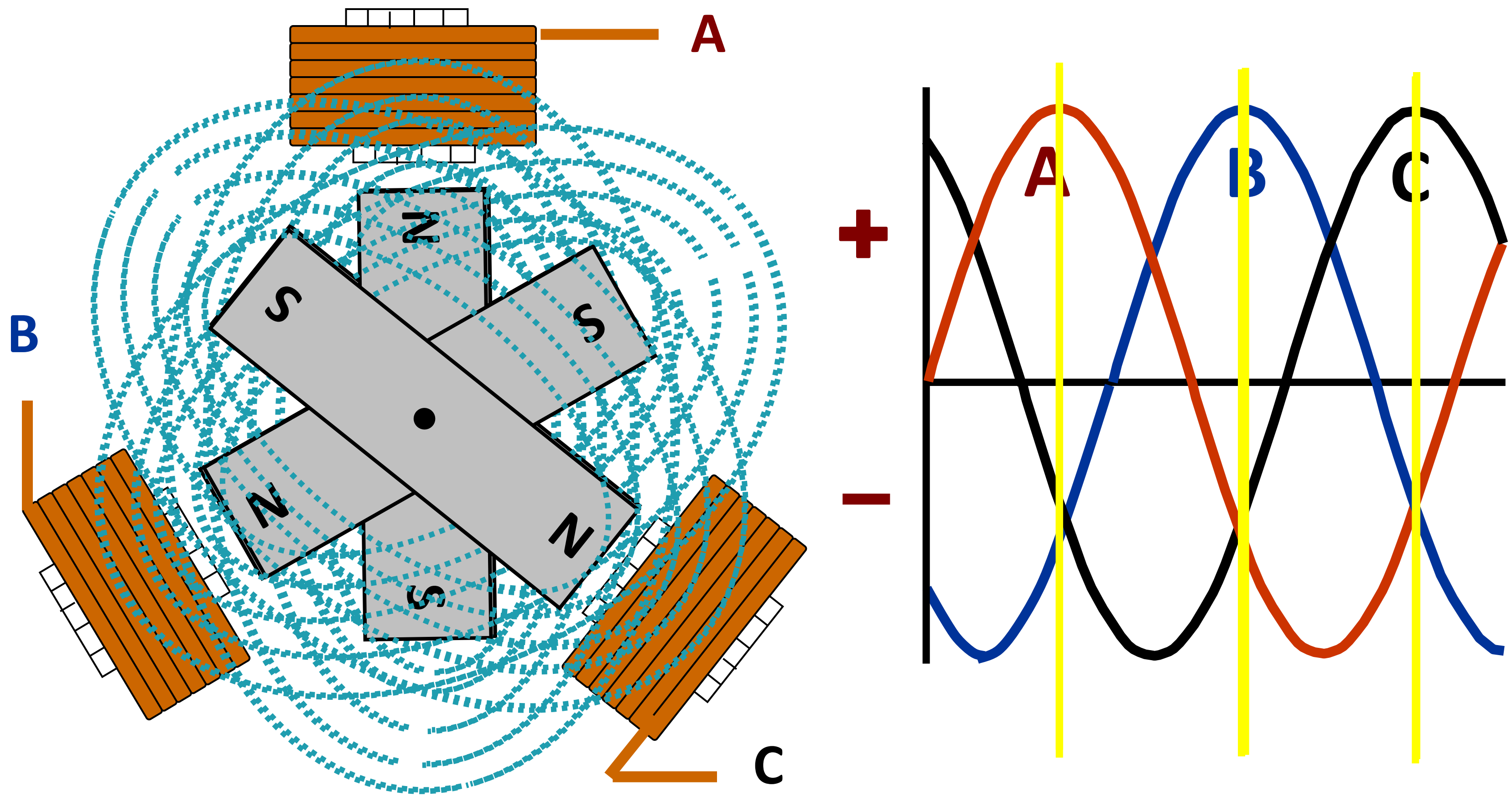
In a three-phase circuit:

- An AC voltage generator produces three evenly spaced sinusoidal voltages, identical except for a phase angle difference of 120º
- Three conductors transmit the electric energy. The conductors are called phases and are commonly labeled A Phase, B Phase, and C Phase
- Each phase conductor carries its own phase current

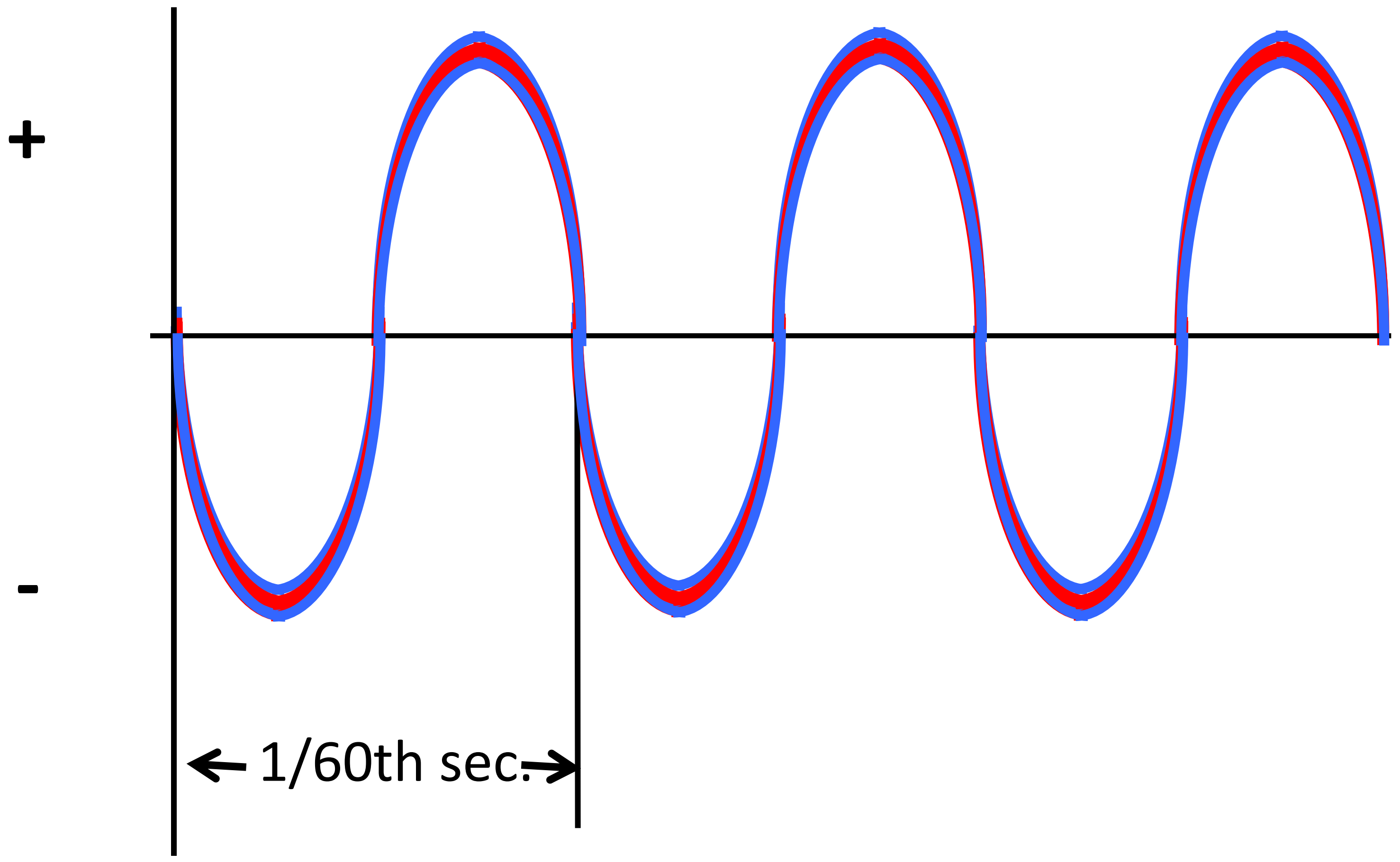
Three-Phase Circuits
Three-Phase Power



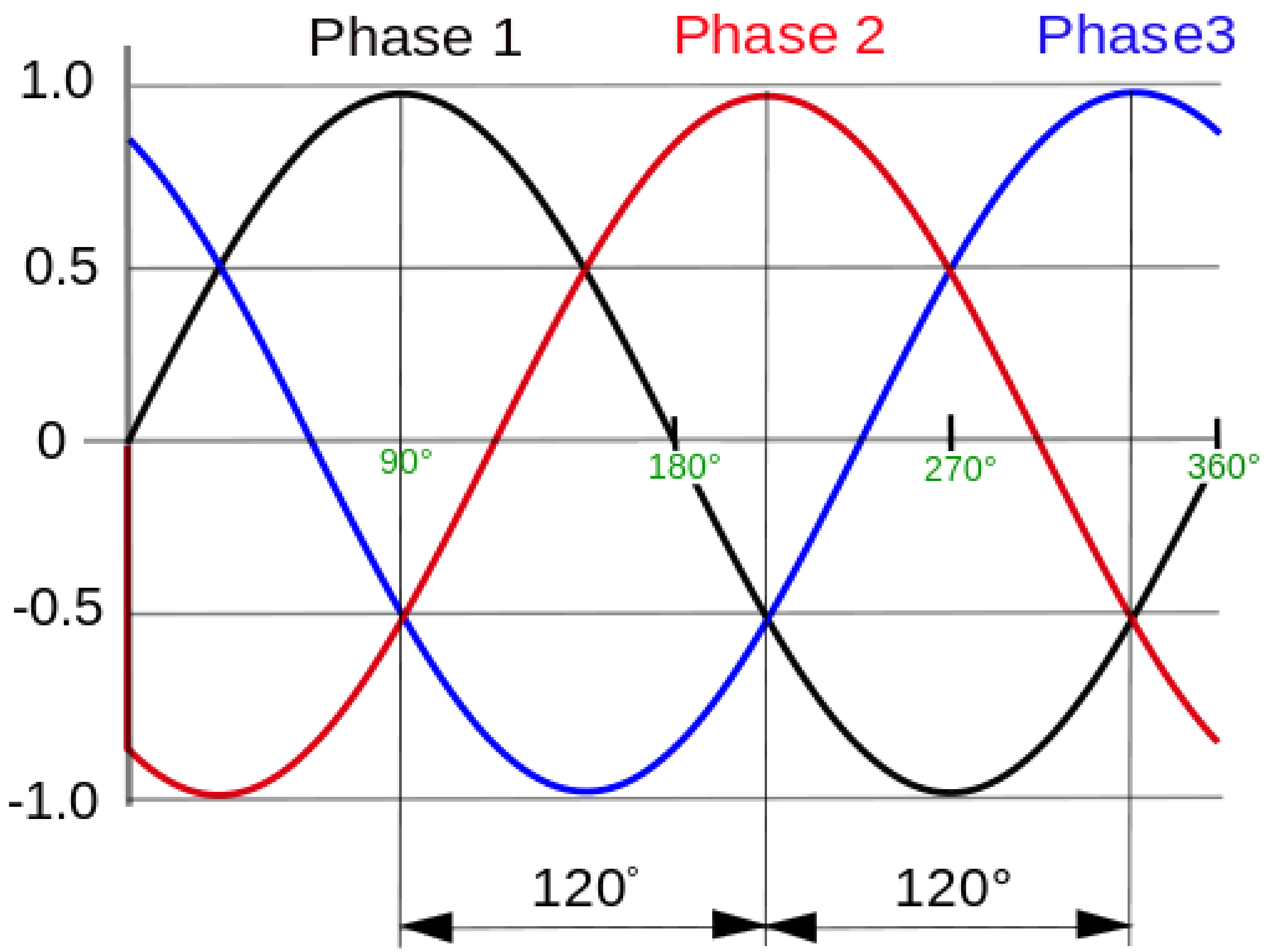
Three-Phase Circuits
Generating 3-Phase Power Waves



Three-Phase Circuits vs. Single Phase Power



Three-Phase Circuits
Three-Phase Power



Three-Phase Circuits
Interconnected 3-Phase Power

In an AC interconnection, all connected utilities see the same electrical frequency and all generators operate in synchronism with each other.

Three-Phase Circuits
Definition and Advantages

- **Definition:** **Phase-to-Phase and Line Voltages**
- The voltages between the outputs of the generator are called the ***line voltages (sometimes called phase-to-phase voltages).***
- The line voltages are equal to the phase voltages.
- When a Delta-connected generator is loaded, current flows in the loads, lines, and phase windings.

Three-Phase Circuits

Three-Phase Circuits
Three Phase Connections

The line currents are not equal to the phase currents, because each line carries current from two phases. The currents from any two phases are 120° out of phase.

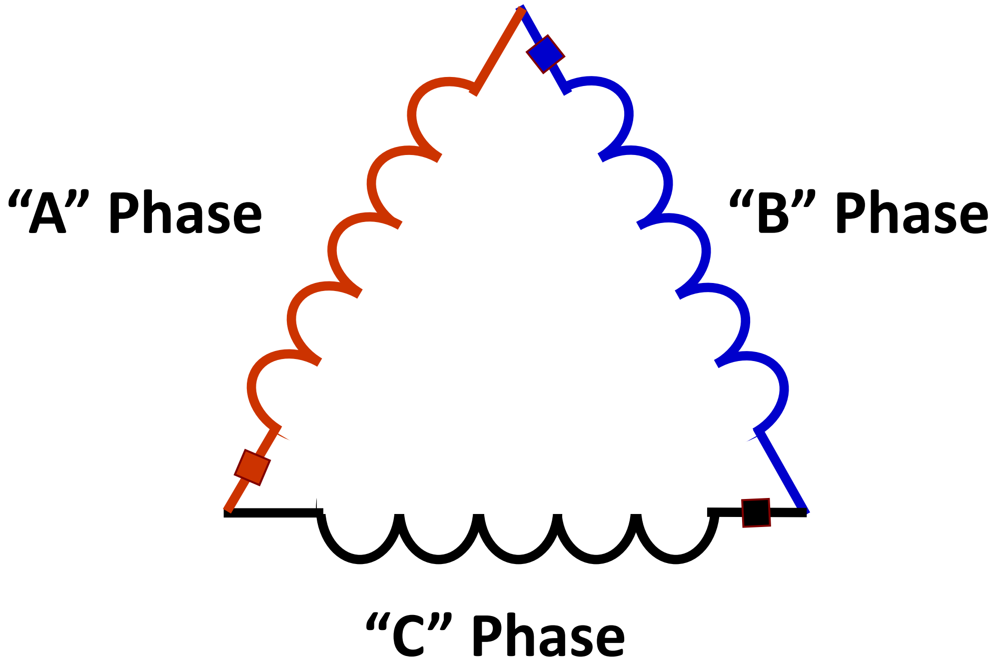
$I_{line} = \sqrt{3}\ I_{phase}$

$I_{line} = 1.732\ I_{phase}$

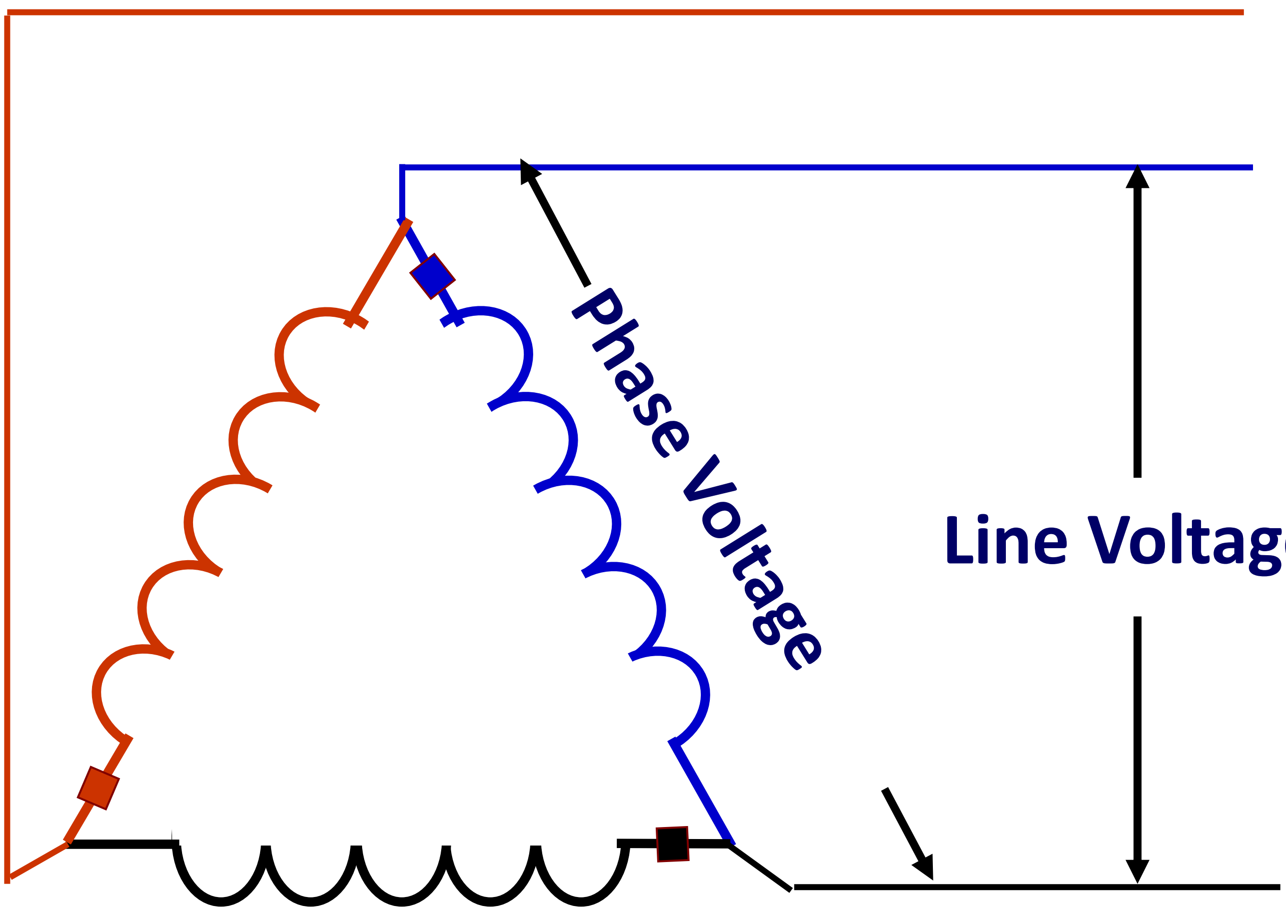
($\sqrt{3}$ is approximately 1.732)

Three-Phase Circuits
Three Phase Connections

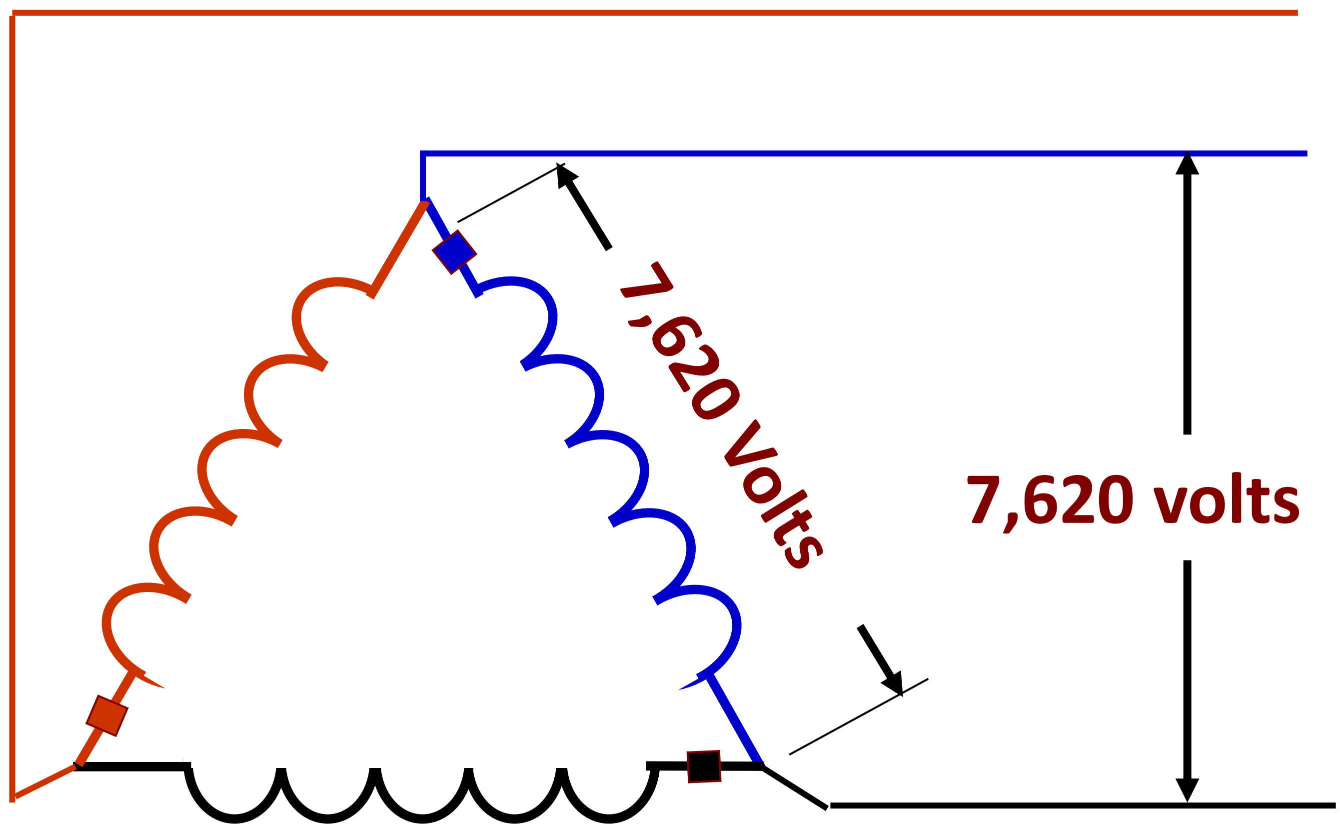
“Delta” Connection



Three-Phase Circuits
Three Phase Connections

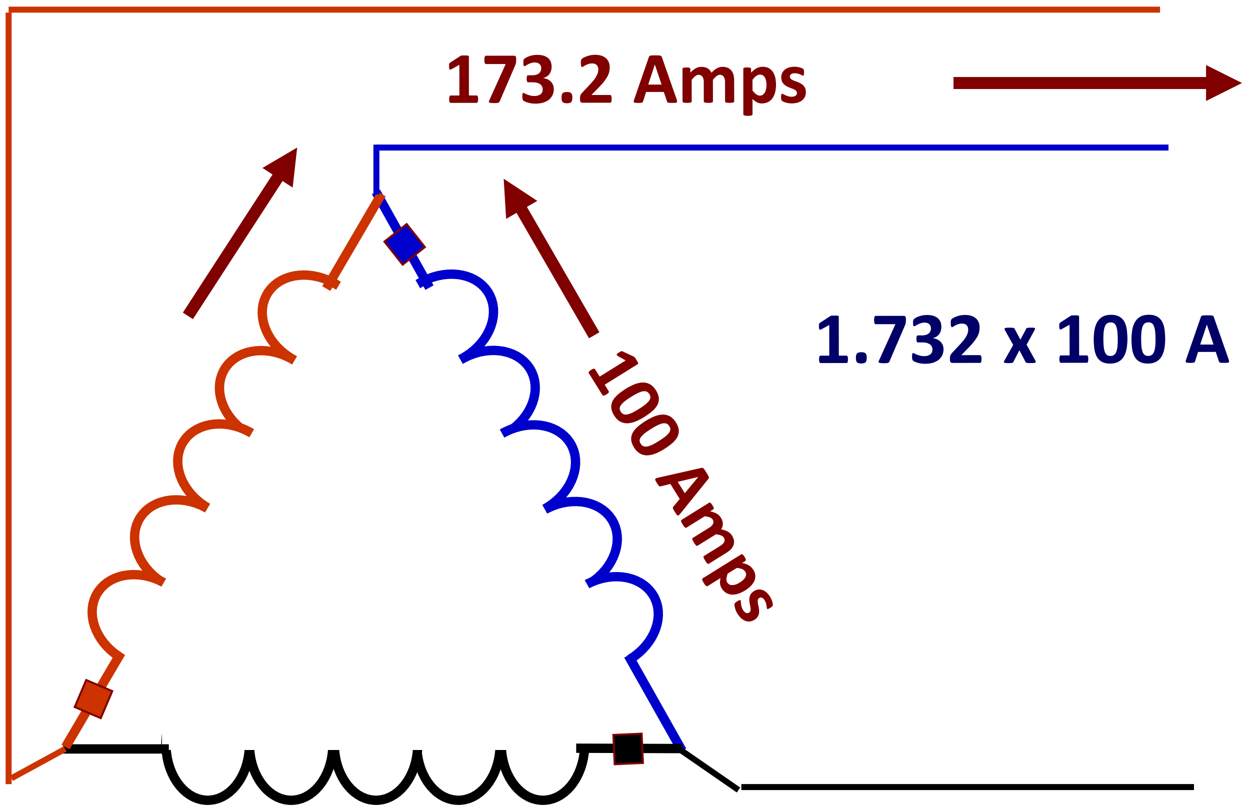


Three-Phase Circuits
Three Phase Connections



Phase Voltage = Line Voltage

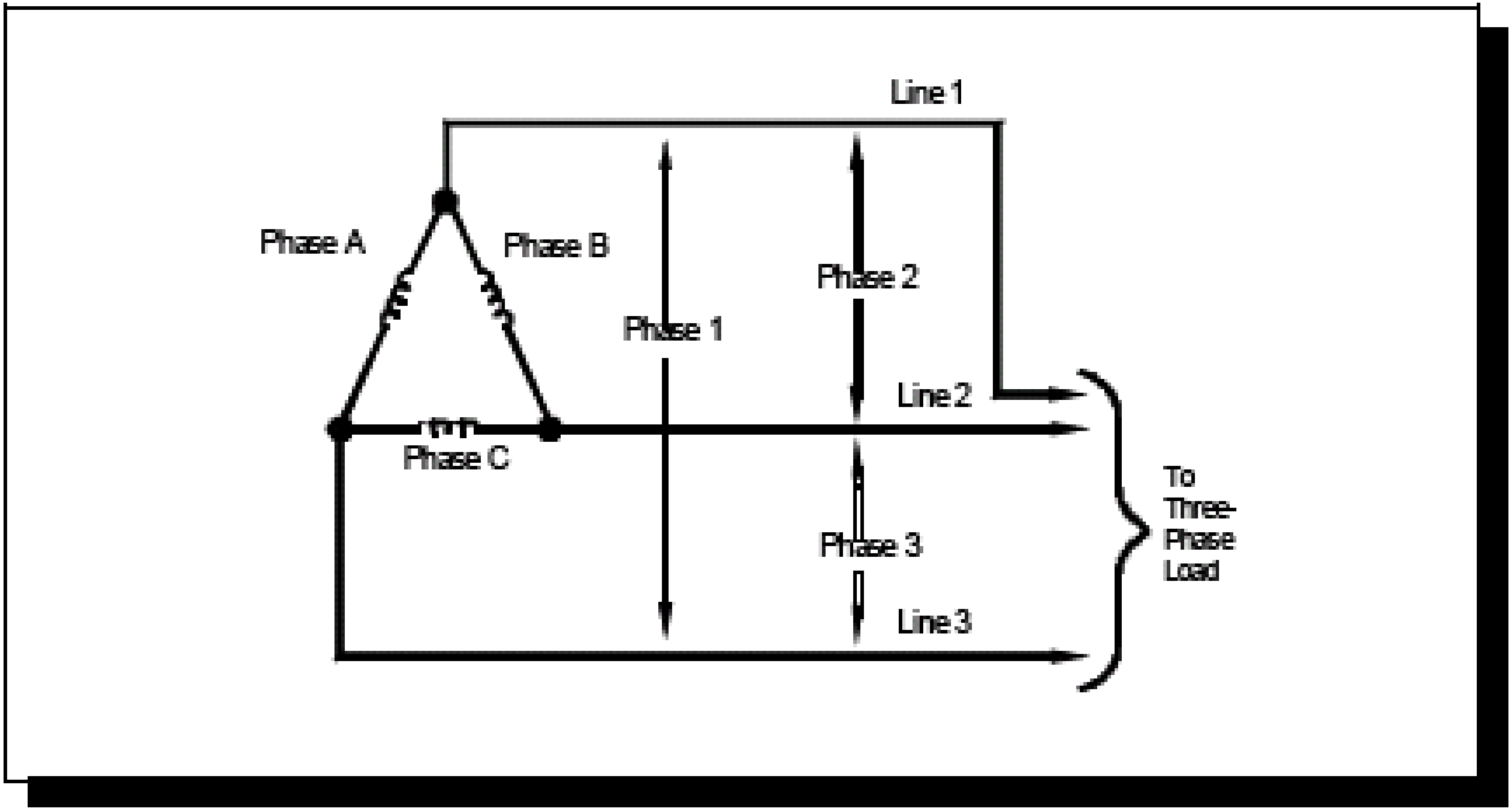
Three-Phase Circuits
Three Phase Connections



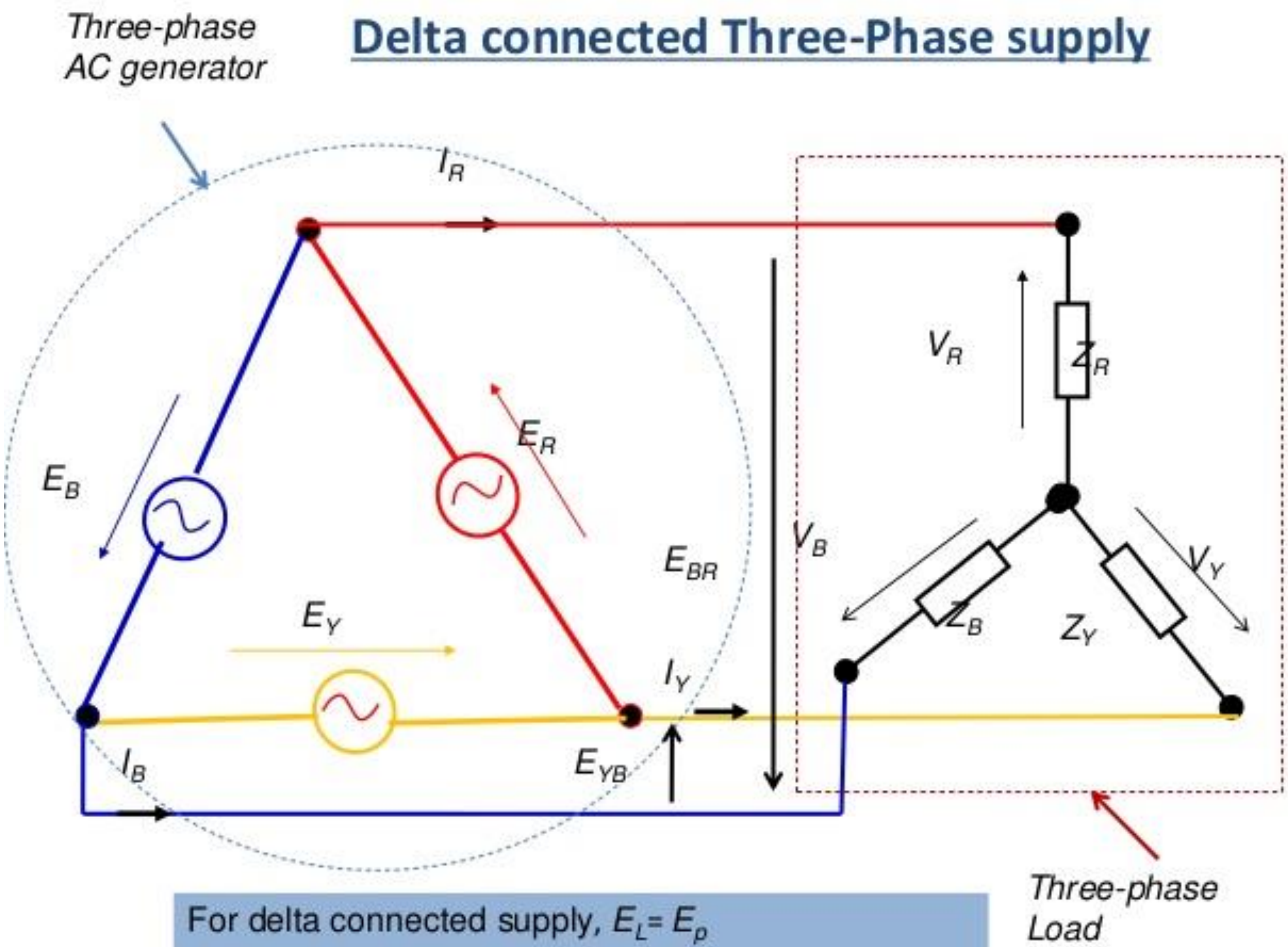
1.732 x 100 A = 173.2 A

Line Current = Phase Current x √3 = PC x 1.732

Three-Phase Circuits
Three Phase Connections

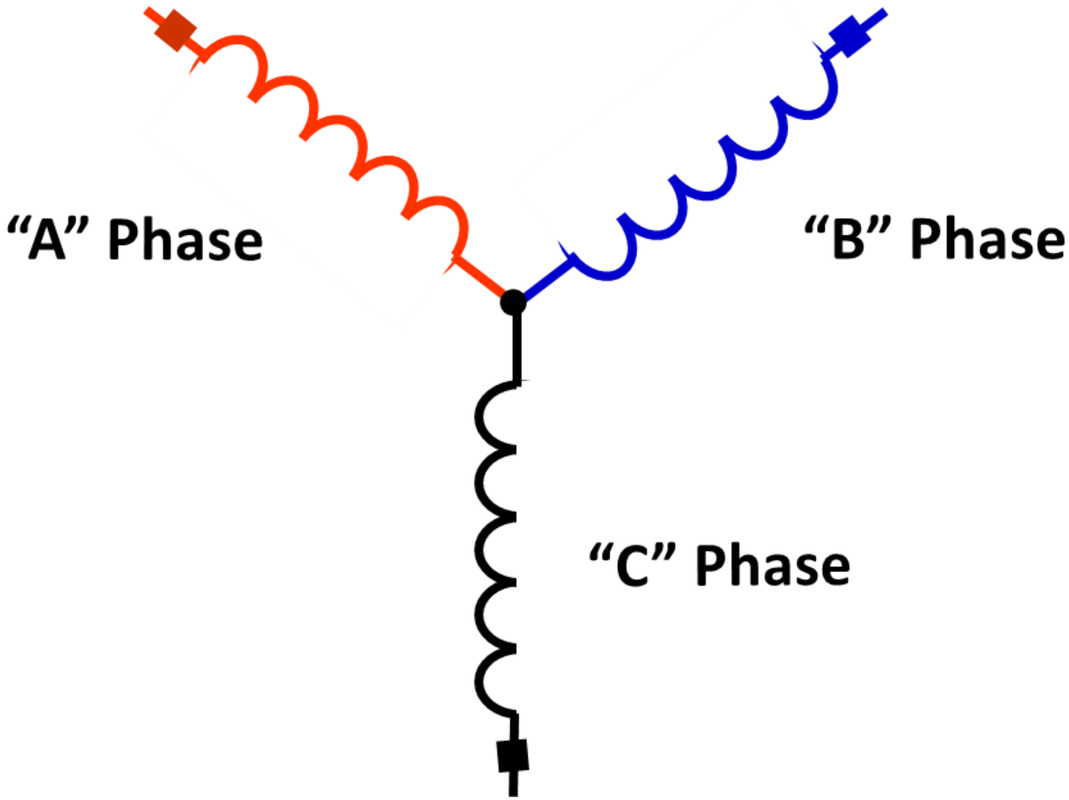


Three-Phase Circuits
Three Phase Connections

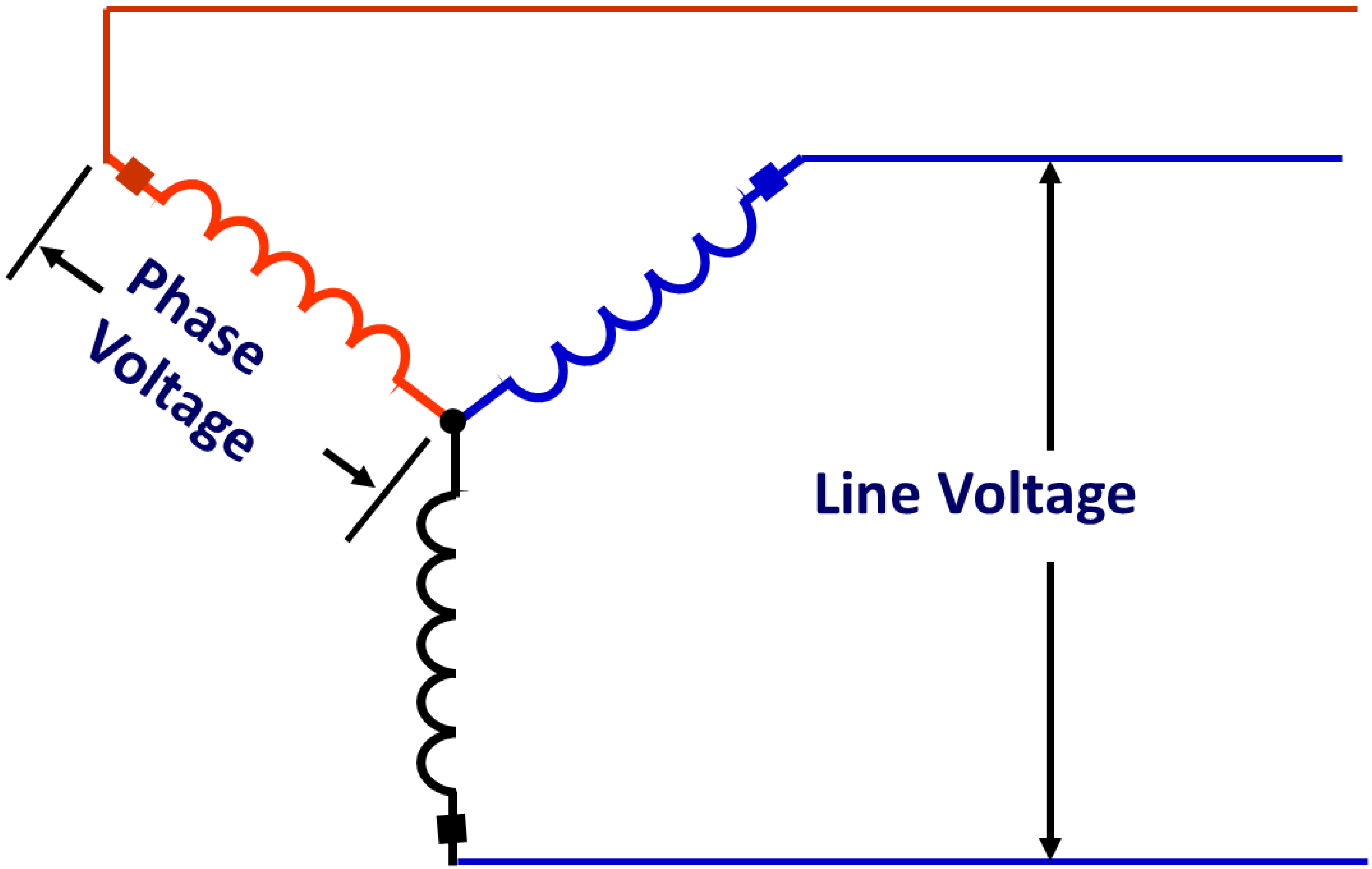


For delta connected supply, $E_L = E_p$

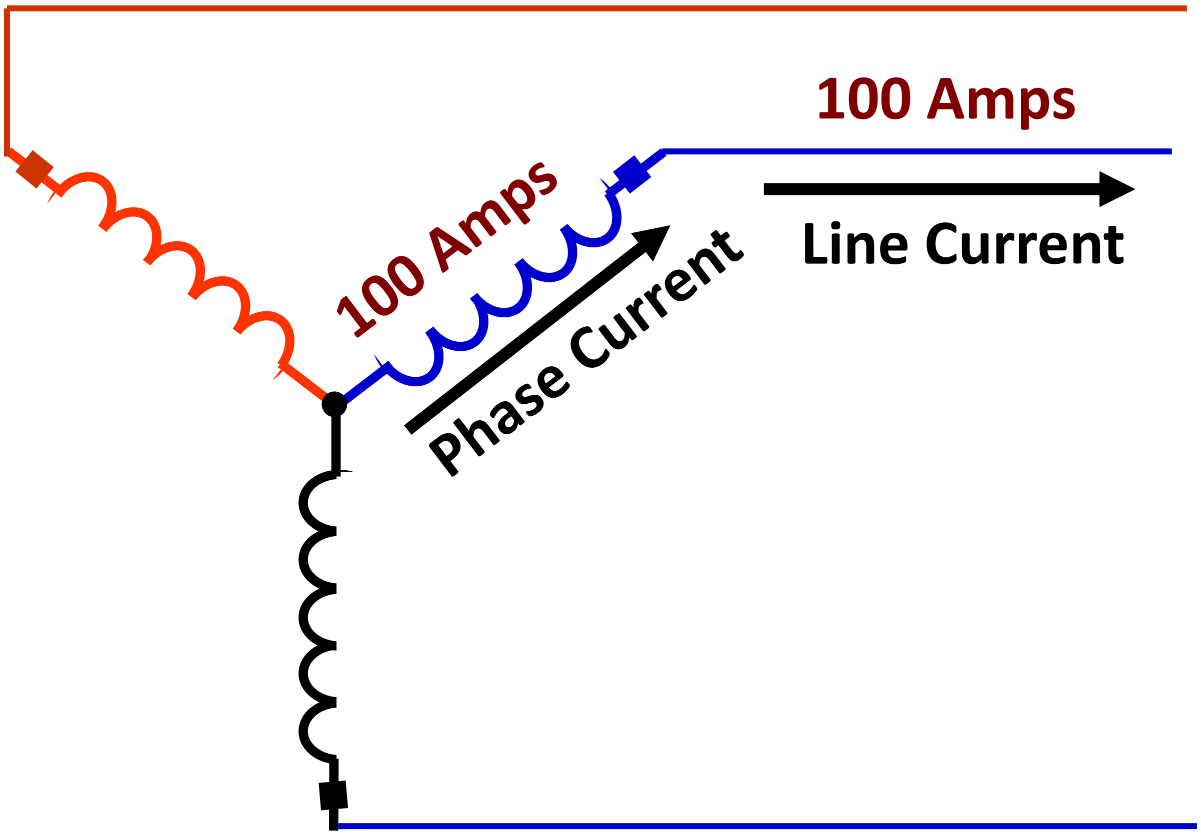
“WYE” Connection



Three-Phase Circuits
Three Phase Connections

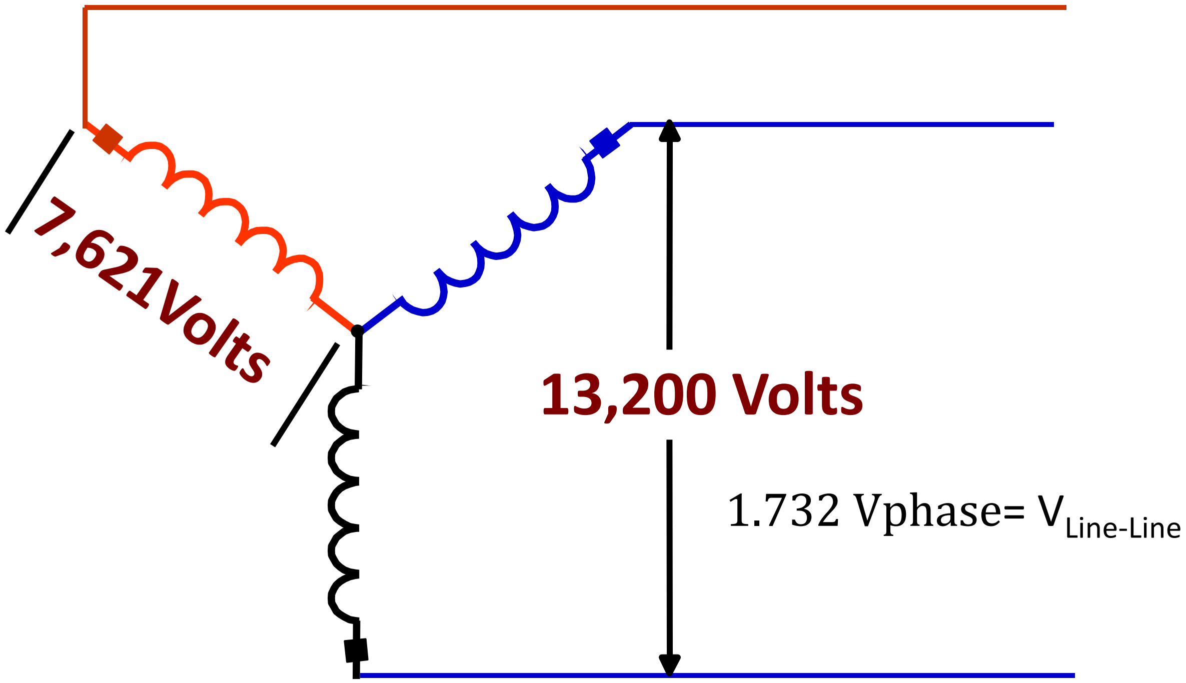


Three-Phase Circuits
Three Phase Connections



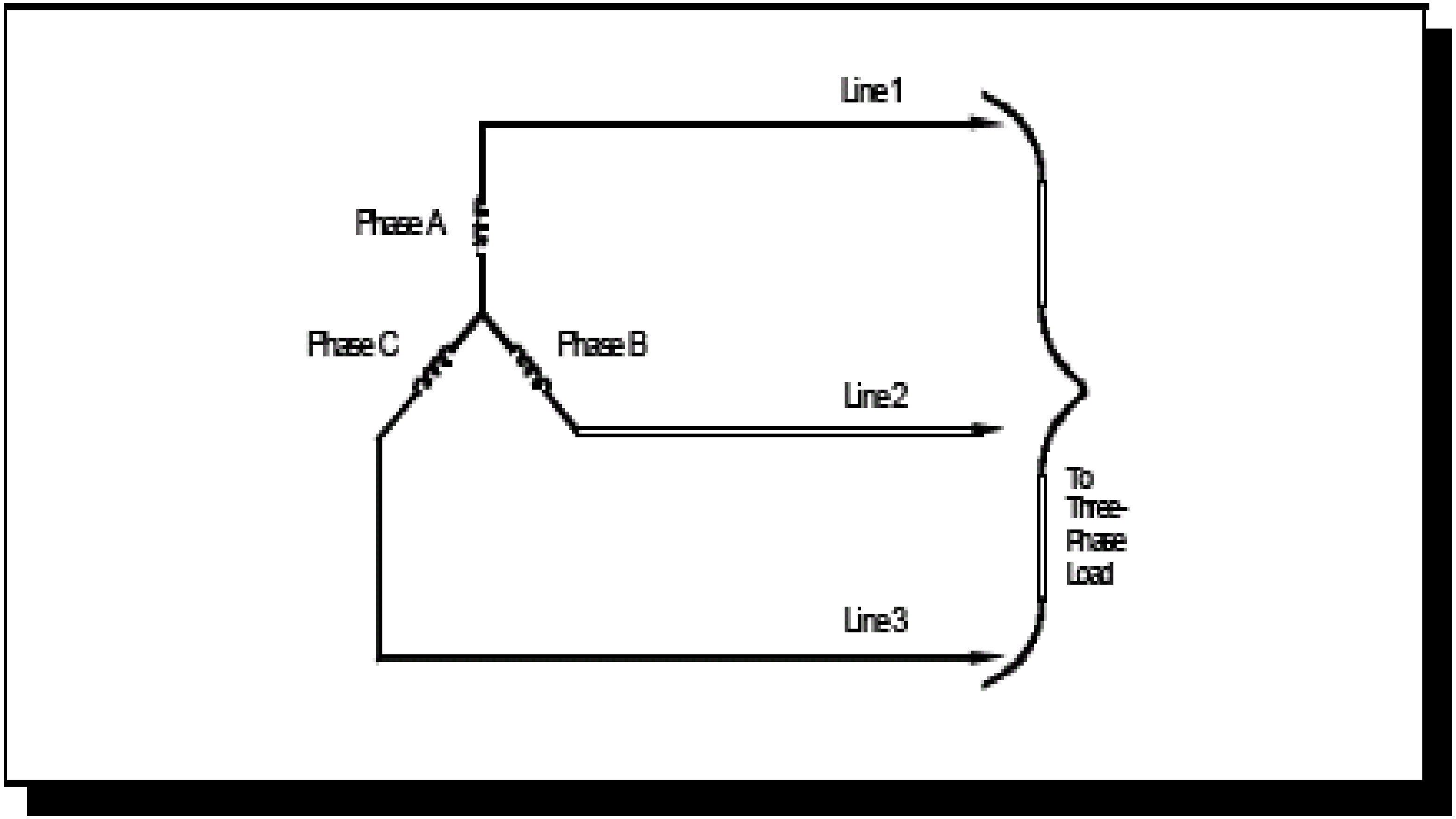
Phase Current = Line Current

Three-Phase Circuits
Three Phase Connections



Line Voltage = Phase Voltage x √3 = PV x 1.732

Three-Phase Circuits
Three Phase Connections



Electromechanics

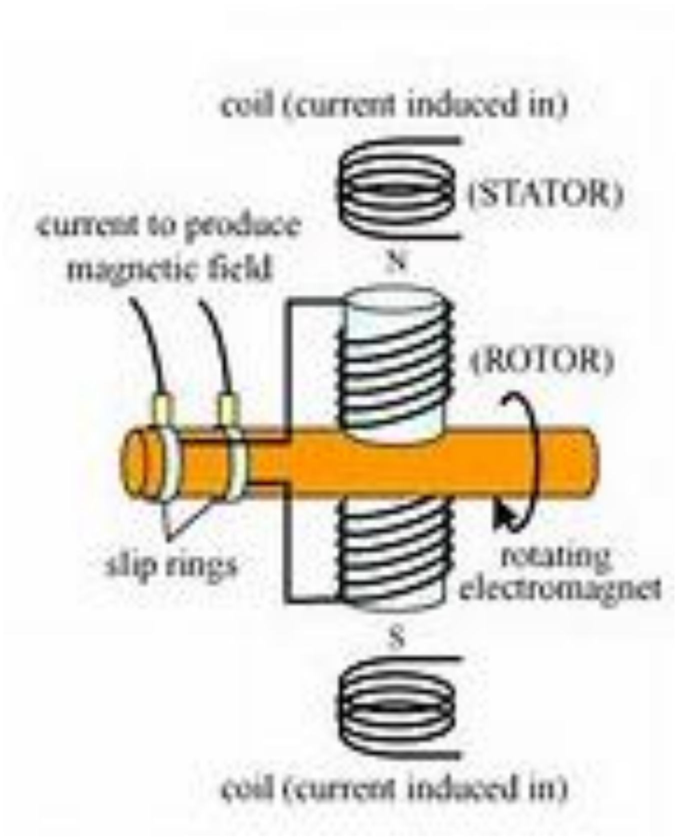
- Definition
- Generators
- Motors
- Synchronous Condenser

Electromechanics
Definition

Electromechanical Energy Conversion is used by generators and motors.

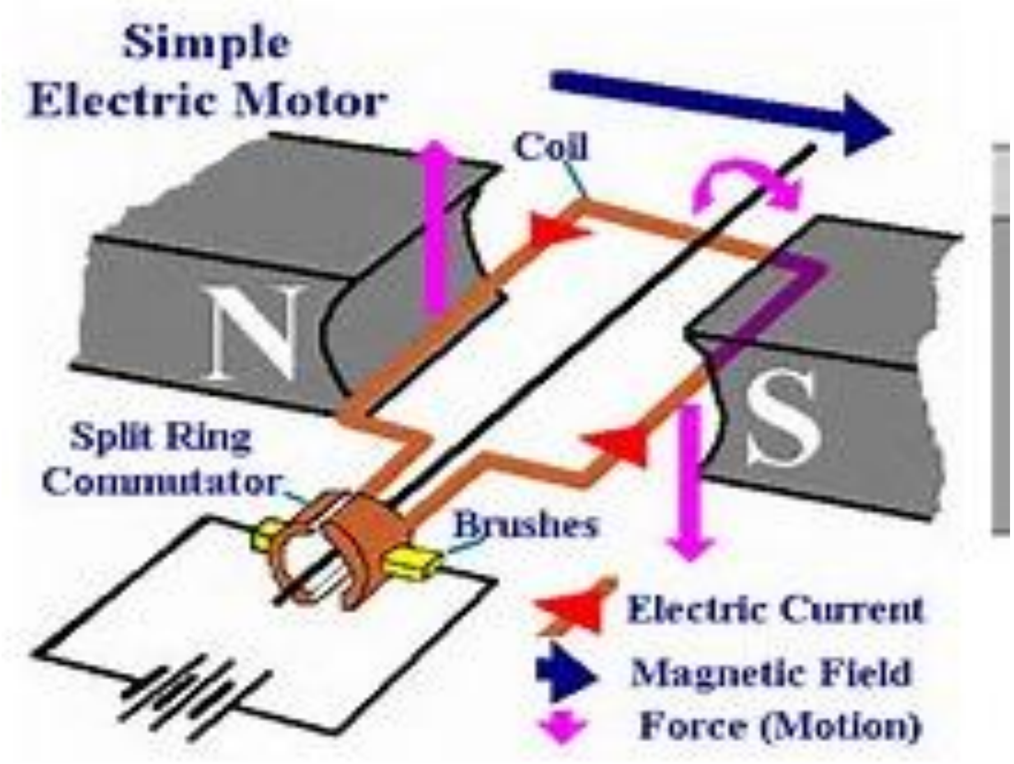
- This process transforms mechanical energy into electrical energy and vice versa

A simple Generator



Electromechanics
Motors

A simple Motor



Generators and Motors

Electromechanics
Generators and Motors

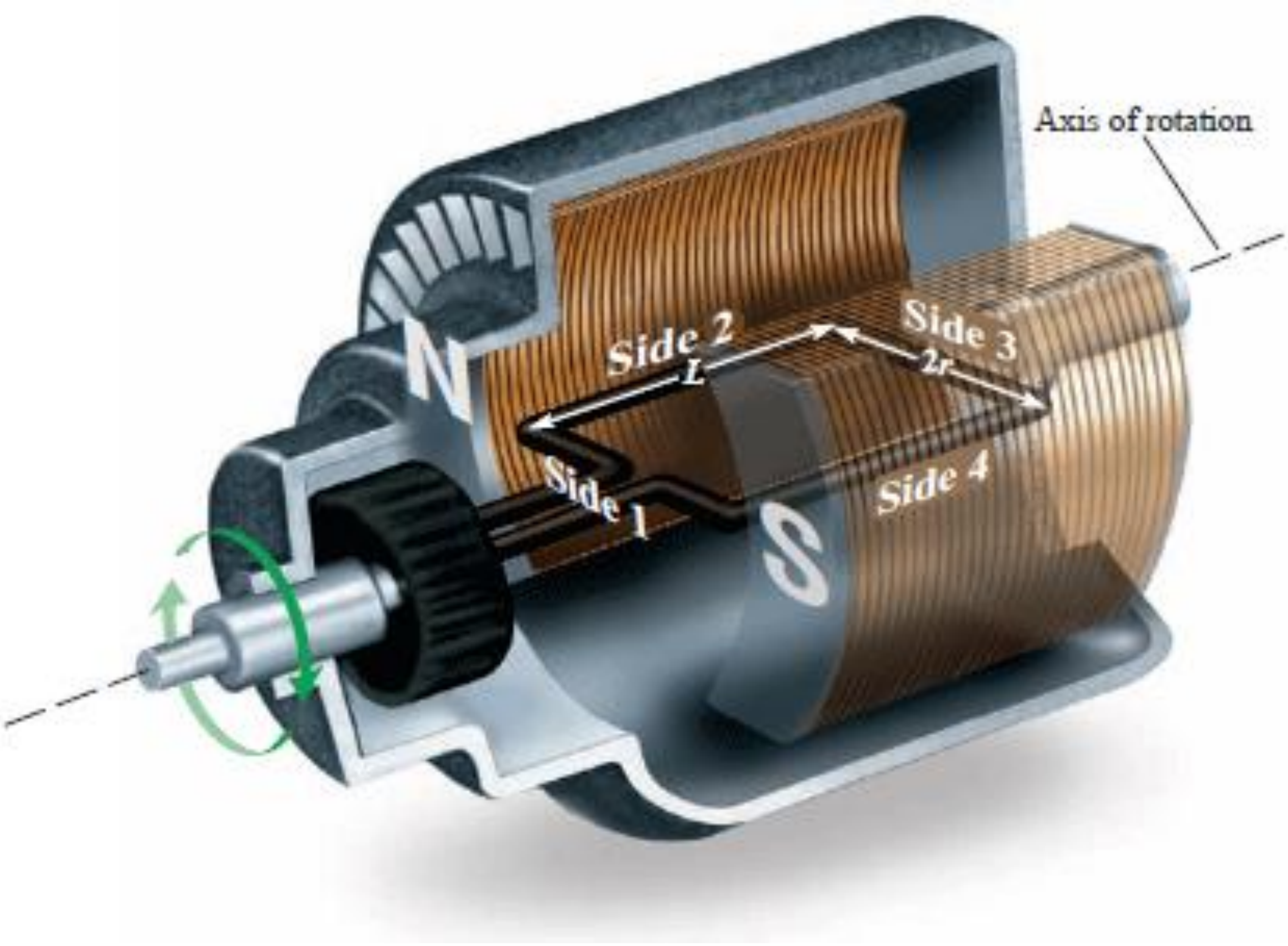
A ***generator*** converts mechanical energy into electrical energy.

- A voltage is induced in stator conductors as the magnetic flux from the rotor moves past them

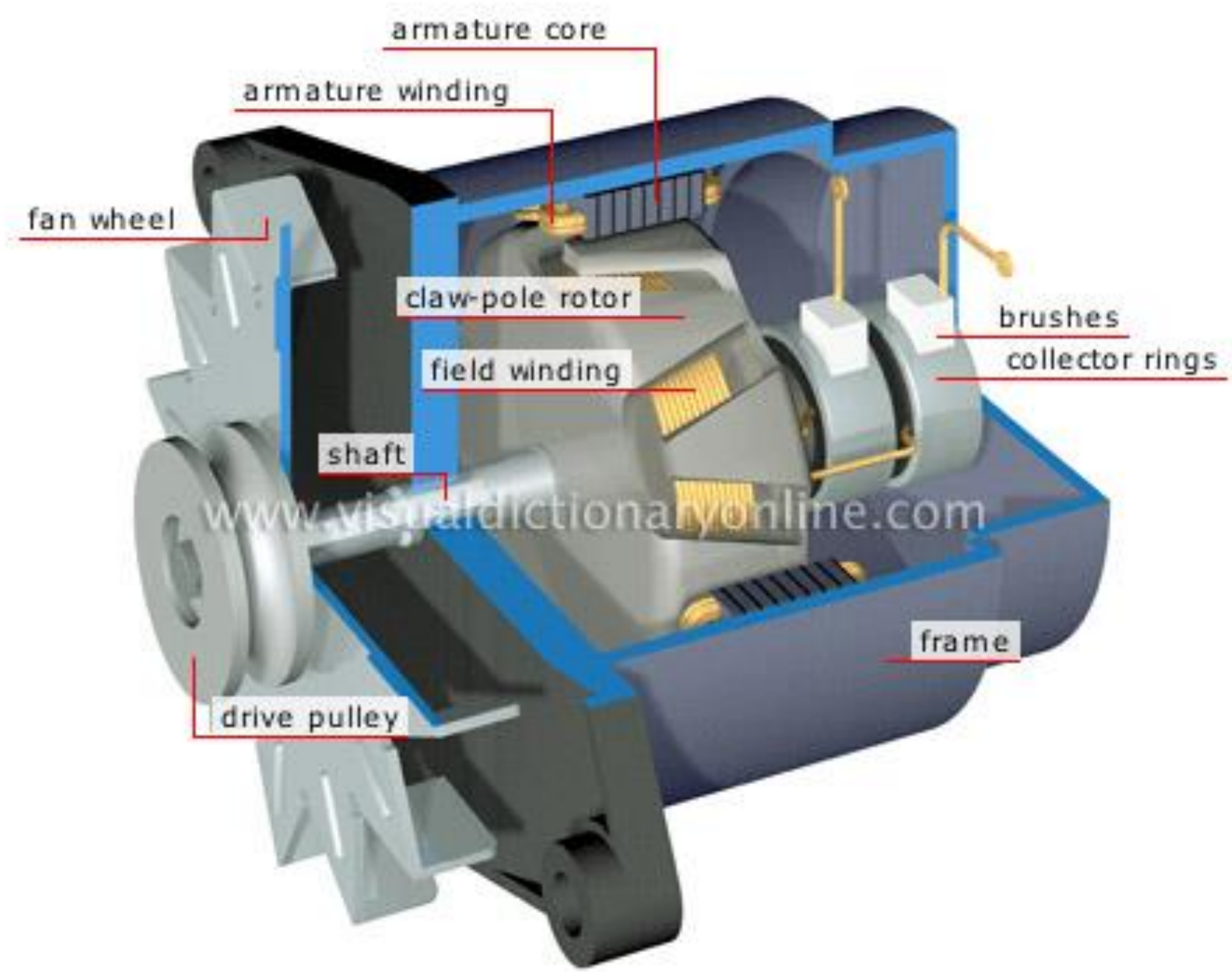
A ***motor*** converts electrical energy into rotary motion.

- Current-carrying conductors in the rotor experience a force at right angles to the magnetic field of the motor

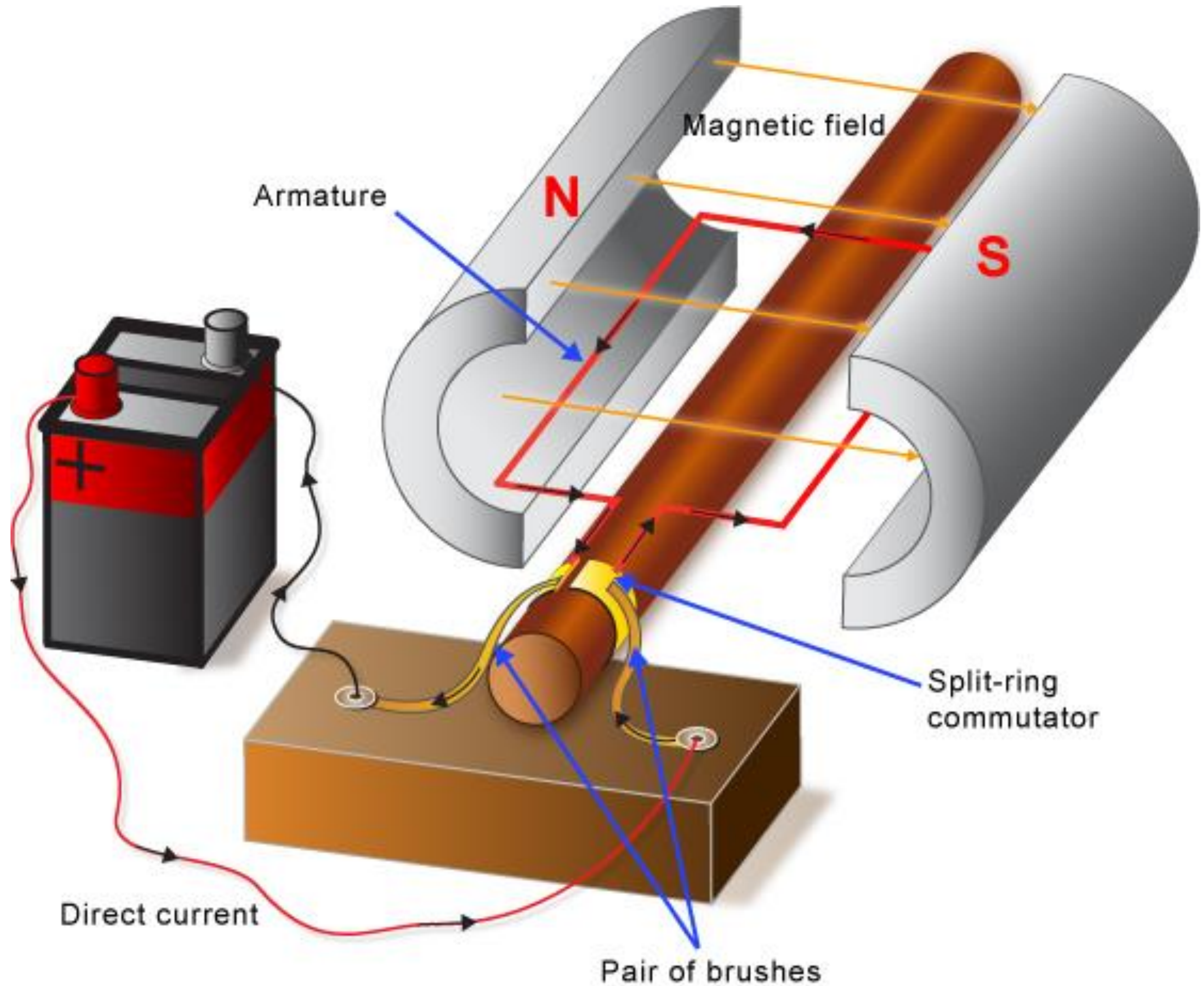
Electromechanics
Generators



Electromechanics
Generators



Electromechanics
Motors



Sychronous Condenser

Electromechanics
Synchronous Condenser

A ***synchronous condenser*** is a large synchronous motor.

- A synchronous condenser is used to generate or absorb VARs
- Operators can control whether it produces or consumes VARs

Check Your Knowledge: Fundamentals of Electricity

1. A conductor is a material that has only a few free valance electrons that continually jump to other atoms. T/F?
2. What are two materials that are good electrical conductors?
3. An insulator is a material that has a large number of free valance electrons that continually jump to other atoms. T/F?
4. What are two materials that are good electrical insulators.
5. Whenever current flows in a conductor, what invisible force surrounds the conductor?
6. In an inductive circuit, does the current *lead or lag* the voltage?
7. What is impedance?