Electrical Theory

Power Principles & Phase Angle

PJM State & Member Training Dept.

Objectives

- Identify the characteristics of Sine Waves
- Discuss the principles of AC Voltage, Current, and Phase Relations
- Compute the Energy and Power on AC Systems
- Identify Three-Phase Power and its configurations

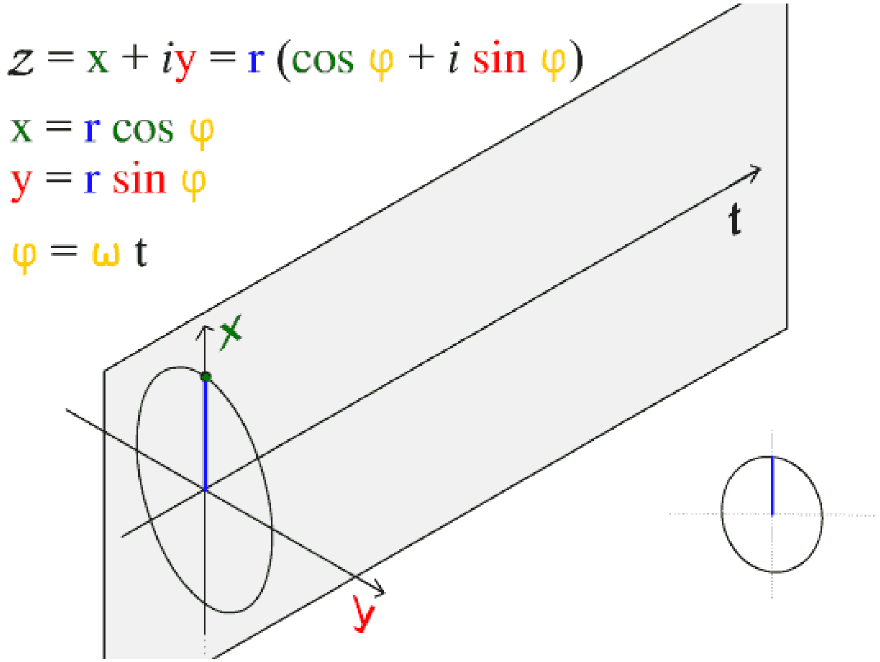
Sine Waves

Sine Waves

- Generator operation is based on the principles of electromagnetic induction, which states:

  When a conductor moves, cuts, or passes through a magnetic field, or vice versa, a voltage is induced in the conductor

- When a generator shaft rotates, a conductor loop is forced through a magnetic field, inducing a voltage



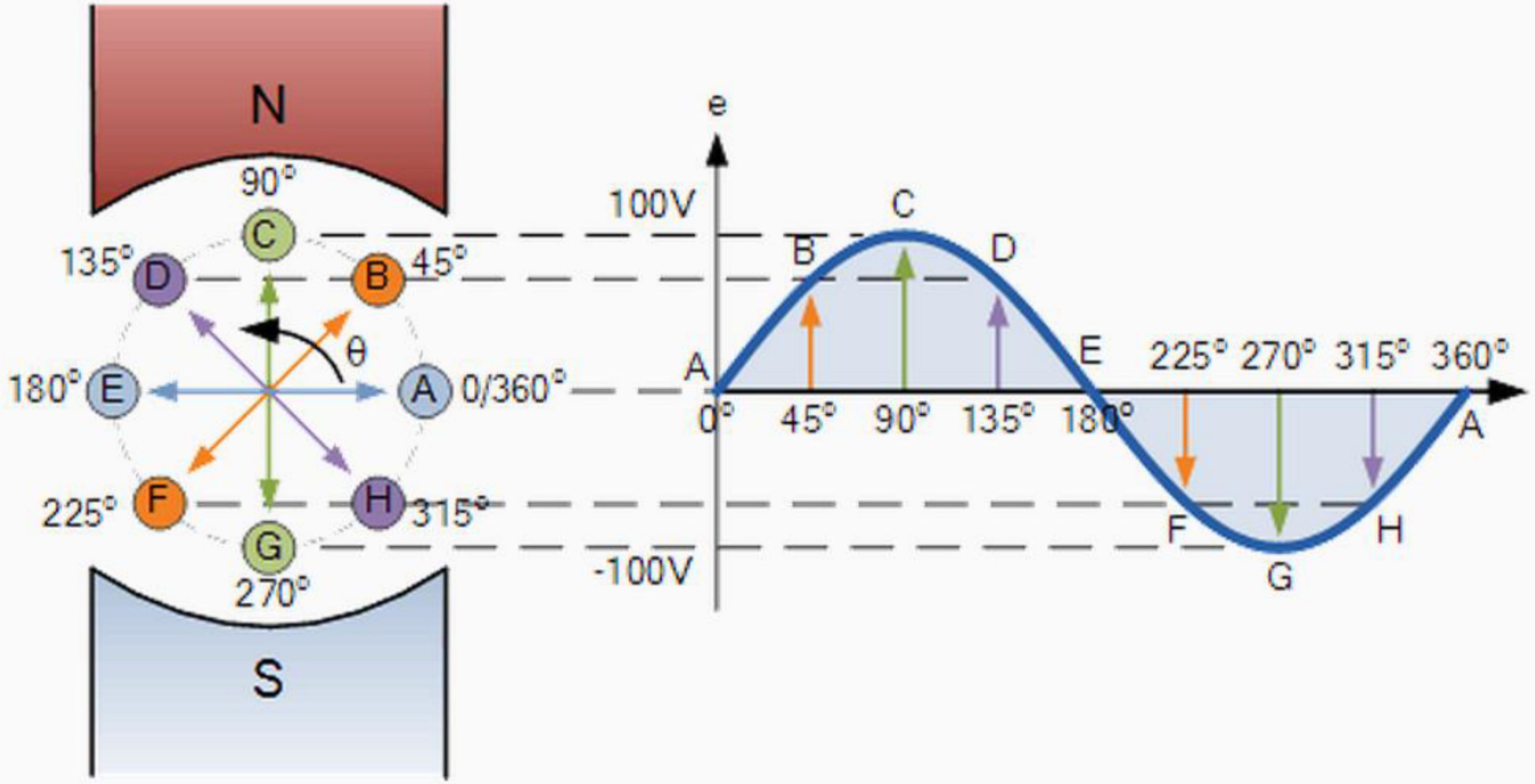
Sine Waves

- The magnitude of the induced voltage is dependent upon:
  - Strength of the magnetic field
  - Position of the conductor loop in reference to the magnetic lines of force
- As the conductor rotates through the magnetic field, the shape produced by the changing magnitude of the voltage is a sine wave

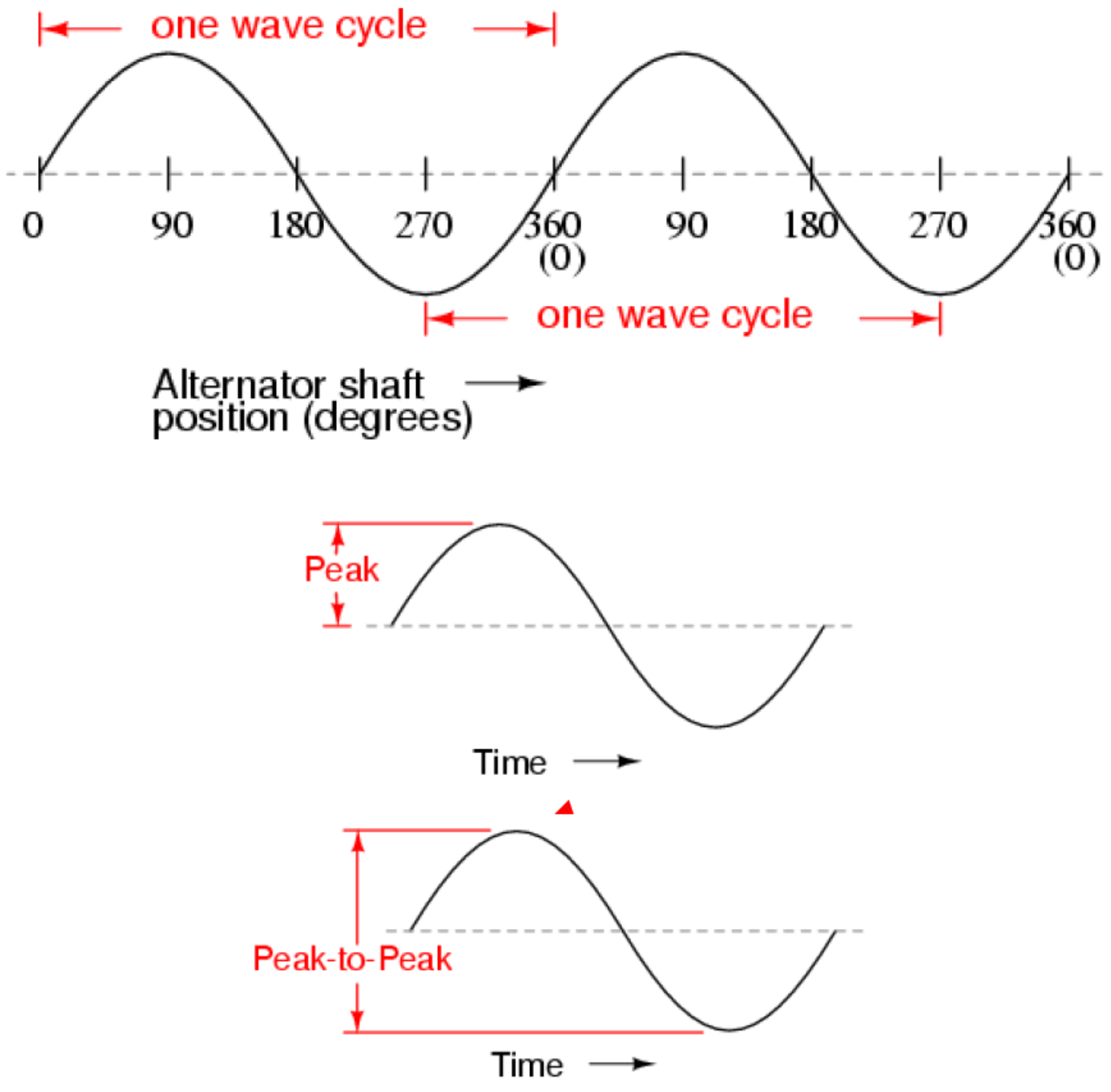
http://micro.magnet.fsu.edu/electromag/java/generator/ac.html

Sine Waves

Coil Angle (θ)	0	45	90	135	180	225	270	315	360
e = Vmax.sinθ	0	70.71	100	70.71	0	-70.71	-100	-70.71	-0



Sine Waves


one wave cycle
0
90
180
270
360
(0)
90
180
270
360
(0)
one wave cycle
Alternator shaft position (degrees)
Peak
Time
Peak-to-Peak
Time

Sine Waves

- A cycle is the part of a sine wave that does not repeat or duplicate itself
- A period (T) is the time required to complete one cycle
- Frequency (f) is the rate at which cycles are produced
- Frequency is measured in hertz (Hz), one hertz equals one cycle per second

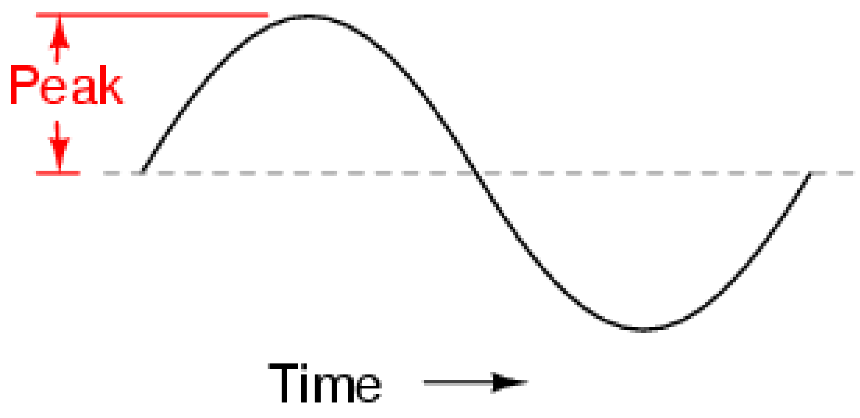
$$T = \frac{1}{f} \qquad f = \frac{1}{T}$$

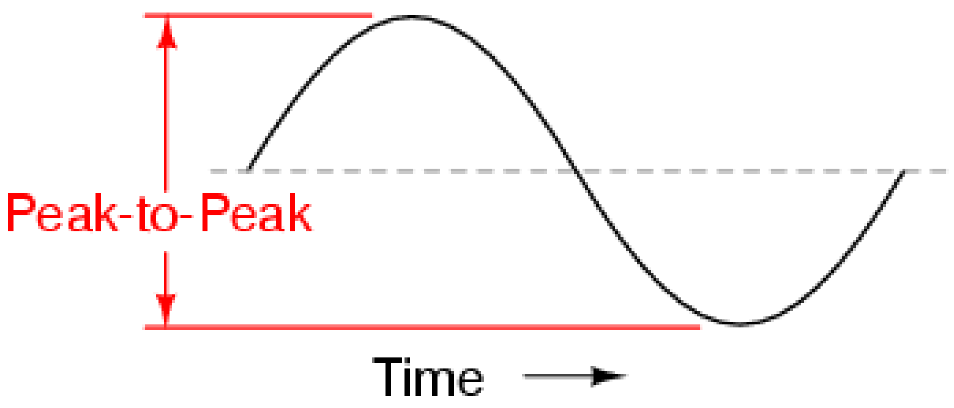
$$T = \frac{1}{60\ Hz} = .0167\ seconds$$

Sine Waves

- The amplitude of a sine wave is the value of the voltage at a specific time, it can be given in either peak or peak-to-peak values
- Peak value is the waveform's maximum value and occurs twice each cycle
- Peak-to-peak value is equal to twice the peak value:

$$E_{P\text{-}P} = 2\,(E_P)$$





Sine Waves

- Root Mean Square (RMS), or the effective value, is the amount of alternating current having the same heating effect in a resistive circuit as a given amount of direct current
- One ampere of AC RMS and one ampere of direct current produce the same power when flowing through equivalent circuits

$$I_{RMS} = 0.707(I_P)$$

Sine Waves

- The relationship between the peak value and the RMS value of voltage is similar:

$$E_{RMS} = 0.707\ (E_P)$$

- Magnitudes of AC values are usually given in terms of effective RMS values

AC Voltage and Current

AC Voltage & Current

- Review:
  - DC current flows in only one direction at a constant magnitude
  - AC current continually changes in both magnitude and direction
  - AC current flows in one direction, then flows in the opposite direction
  - If AC current is present, there must also be alternating voltage and power
    - AC voltage produces the AC current
    - AC power is produced by the AC current and AC voltage

AC Voltage & Current

- AC voltage formula: $E = E_{max} \sin \theta$

  where:

  E = value of the induced EMF (volts)

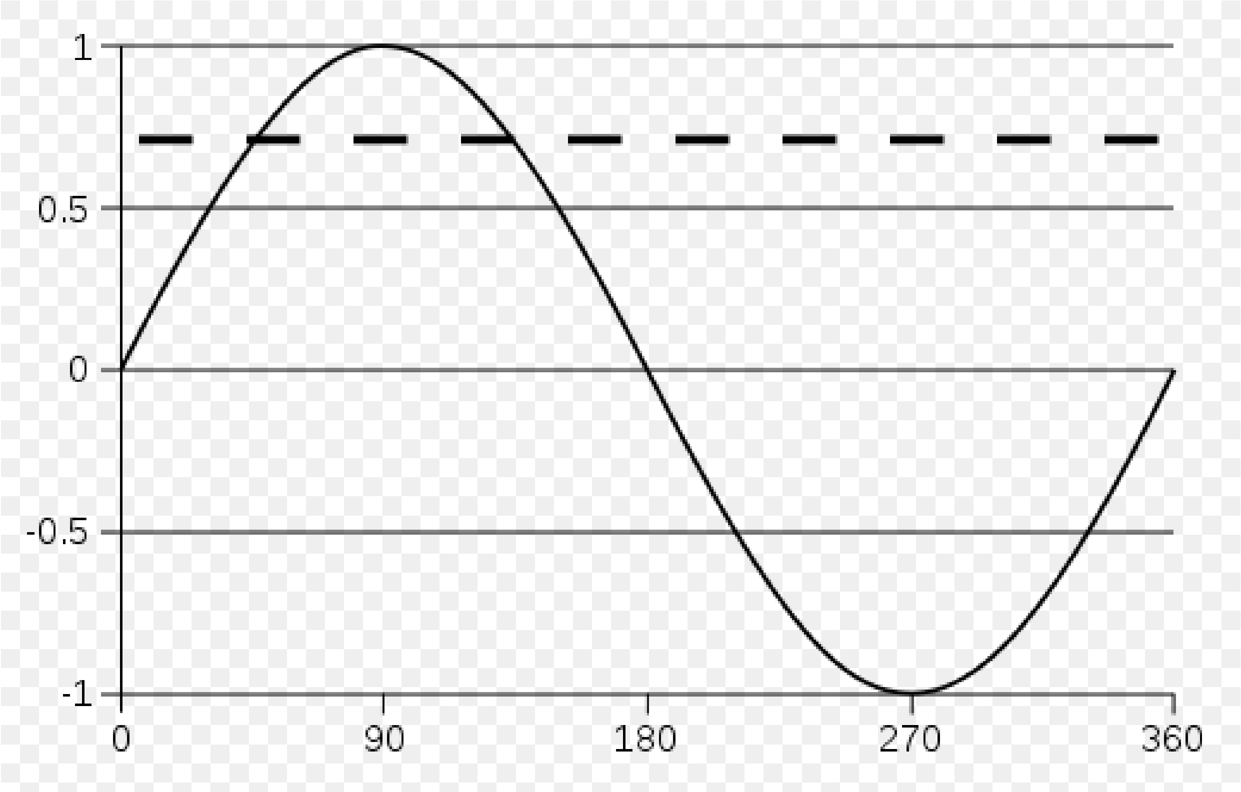
  E_{max} = maximum induced EMF (volts)

  θ = angle from the reference (degrees)

- E_{max} is also referred to as amplitude or peak voltage (E_P)

AC Voltage & Current

- The instantaneous voltage at any given point along the sine wave is equal to: $E = E_{max} \sin \Theta$



AC Voltage & Current

- AC instantaneous current formula :

$$I = (I_{max})(\sin\theta)$$

- Rotation of the conductor in the field produces an EMF, but current will not flow unless the circuit path is closed

AC Voltage & Current

- Advantages of AC power over DC power:
  - Easier to transform one AC voltage level to another
  - Efficiency of power transmission much better at higher voltages
  - AC motors are less complex than DC motors and require less maintenance (no brushes or commutators)

AC Voltage & Current

- Advantages of DC power over AC power:
  - AC losses associated with series inductance and line charging due to capacitance are eliminated
  - HVDC lines require only two power conductors rather than three required for AC facilities
  - HVDC lines can tie two AC power systems having dissimilar characteristics (50 Hz to 60 Hz)

Phase Relations

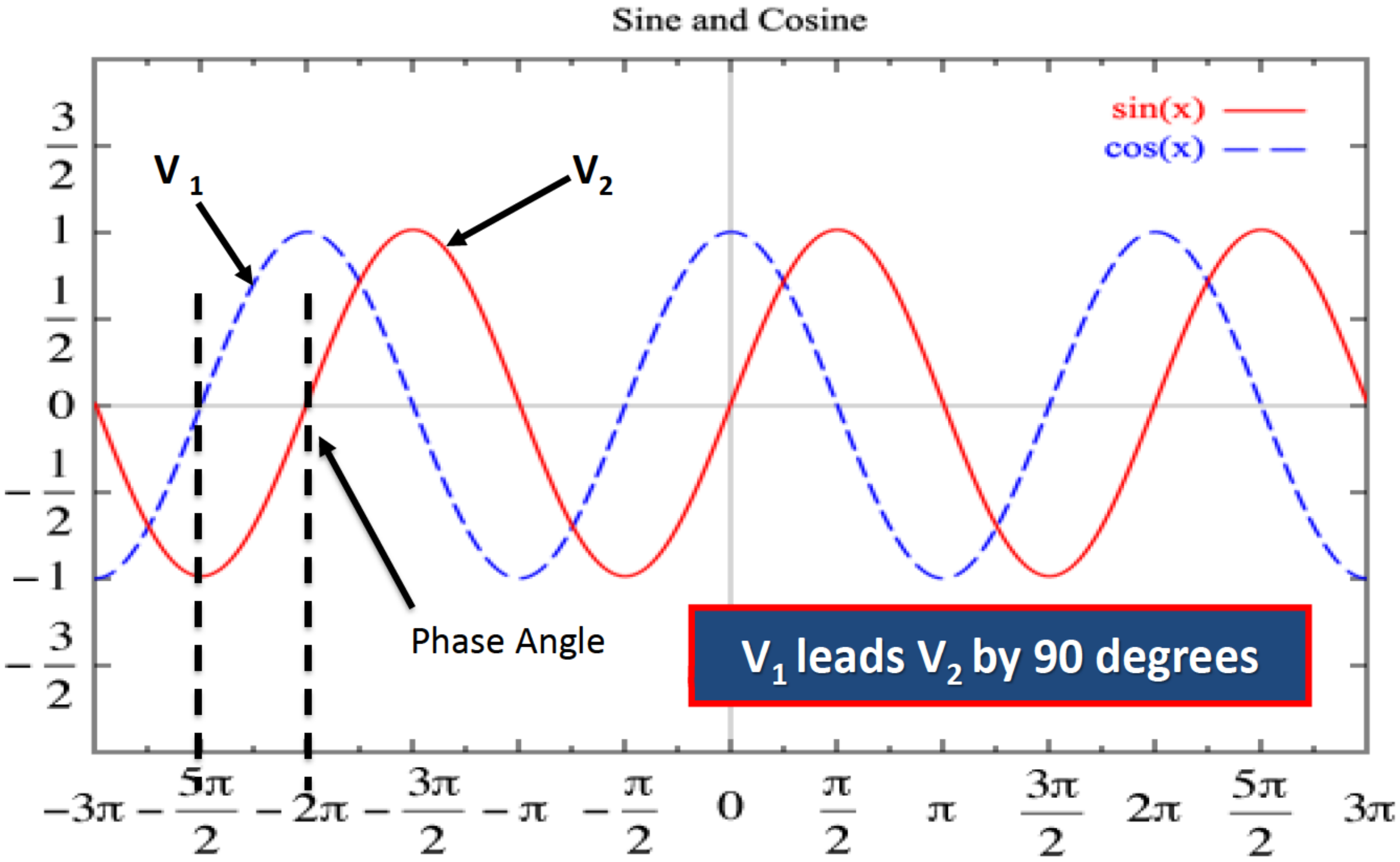
Phase Relations

- Sine waves with the same frequency have what is termed as phase relations

- A Phase relation, or phase angle, is the angular difference between sine waves of the same frequency

- Phase angle is the portion of a cycle that has elapsed since another wave passed through a given value

Phase Relations



Phase Relations

- In-phase means the phase difference between two variables is equal to zero degrees
- Out-of-phase means that the phase difference between two variables is not zero degrees
- Phase difference only applies to waveforms that have the same frequency (each waveform should complete one cycle in the same amount of time)
- Angle θ is used when comparing the phase angle difference between voltage and current
- Angle δ is used when comparing the phase angle difference between two voltage curves or two current curves

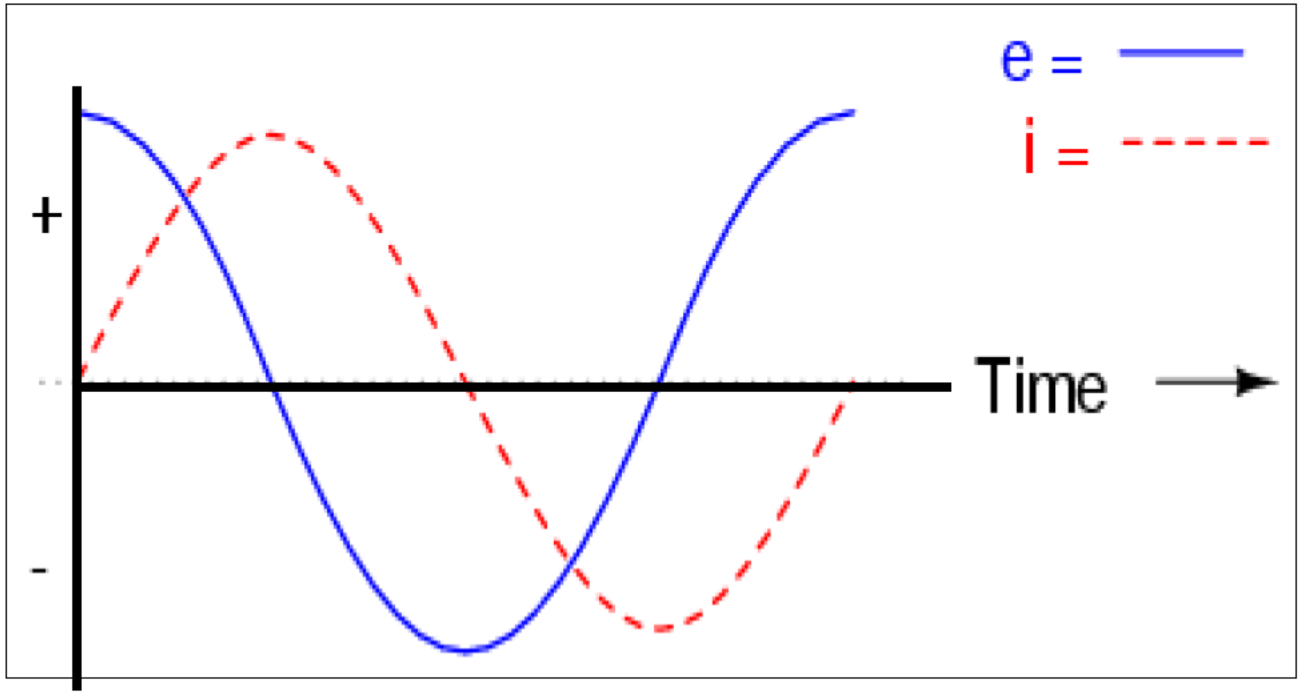
Review

- Are the waves both the same frequency?

  Yes

- Does the voltage lead or lag the current?

  Voltage leads the current



Energy and Power on AC Systems

Energy & Power

- The power that flows in a power system is composed of active and reactive power. Both components are necessary to serve customer loads
- Power is the rate of performing work
- Power is also the rate at which energy is used or dissipated
- The measure of electricity’s ability to perform work is the watt

AC and DC Power

- For a DC circuit, the power consumed is the sum of the I^2R heating in the resistors
  - Power is equal to the source power
- For an AC circuit, the power consumed is also the sum of the I^2R heating in the resistors
  - The power consumed is not always equal to the source power because of the capacitance and inductance in the circuit
- Power consumption always refers to the I^2R heating in the resistors, reactance consumes no power

AC and DC Power

- When an amount of positive charge (q) moves from a higher potential to a lower potential, its potential energy decreases
  (voltage potential)

$$P = \frac{Change\ in\ energy}{Time\ interval} \times Voltage$$

- The change in energy per unit of time is the current (I) in the device

AC and DC Power

- When an electric charge flows from point A to point B in a circuit, leading to a current (I), and the voltage between the points is (E), the electric power associated with this current and voltage is:

$$P = EI$$

- The charge can either lose or gain electric potential energy and must be accompanied by a transfer of energy to some other form (conservation of energy)

Real Power

- Many devices are essentially resistors that become hot when provided with sufficient electric power
- The power consumed by the resistance of a circuit is called "Real" or "Active" power
- Real power is the useful or working energy

$$P = EI$$

$$P = I^2R$$

$$P = E^2/R$$

- Real Power (P) is expressed in watts

Real Power

- Monthly electric bills specify the cost of energy consumed during a month
- Energy is the product of power and time, and is computed by expressing power in kilowatts (kW) and time in hours
- Energy consumption commonly uses the units of kilowatt-hour (kWh)

Electric Energy

- Electric energy is used or produced when electric power is applied over a period of time

$$E_n = Pt$$

where,

E_n = energy in watt hours

P = power in watts

t = time in hours

Power in Resistive Circuits

- In a pure resistive circuit, current and voltage are in phase
- Active power is the rate used to perform work such as lighting a room, heating a building or turning a motor shaft
- In a generating station, more fuel must be added to the prime mover to increase the active power output
- In a transmission system, when power in a resistance is dissipated as heat (I^2R), this is considered a loss
- The general equation for real power in all types of circuits is:

$$P = EI \cos \theta$$

Reactive Power

- Reactance in an AC circuit causes a phase shift between current and voltage
- If a circuit contains only inductance, or only capacitance, a maximum phase shift of 90° occurs between the current and voltage
- Most circuits have a combination of resistance and reactance resulting in a phase shift of less than 90°
- This combination of resistance and reactance is referred to as Impedance (Z)

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

Reactive Power

- Reactive Power (Q) is used to support the magnetic and electric fields found in inductive and capacitive loads

- Reactive Power is measured in volt amperes reactive (VARs)

- Unlike resistors, which consume power, inductors and capacitors store and release energy but do not consume power

- In order to calculate power in a circuit containing both real and reactive power, we must use vectors and right triangle relationships

Apparent Power

- Apparent Power (S) is the power that appears to be present when voltage and current are measured separately regardless of the phase angle
- Apparent Power is the product of voltage and current

$$S = VI = VoltAmperes\ (VA)$$

- Real power does not equal apparent power if a circuit contains both resistance and reactance
- Real power and apparent power differ by cosine θ

Power Factor

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

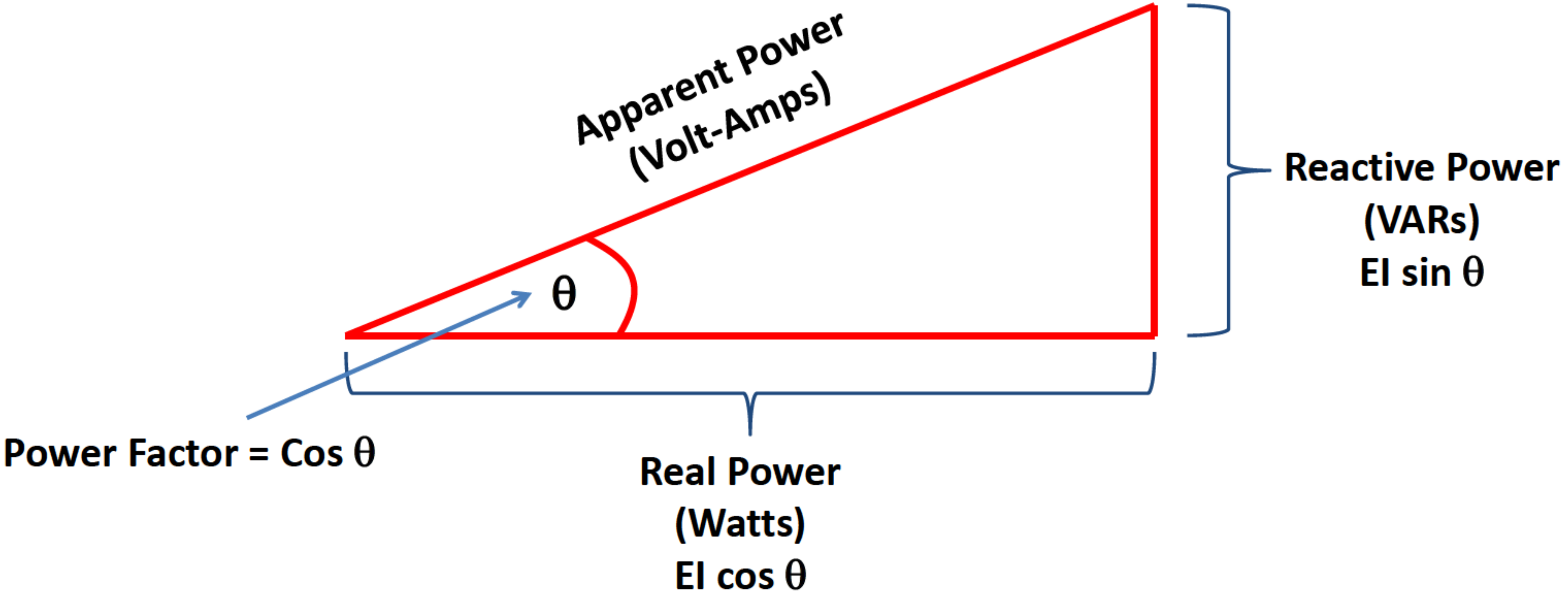
$$PF = \cos\theta = \frac{P}{S} = \frac{Watts}{Volt\ Amps}$$

- Power Factor indicates the amount of apparent power (total current and voltage) that is actually doing the work or producing the real power

- Power Factor can be any value between 0 and 1

Power Triangle

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



Power Factor

- If real power equals apparent power, voltage and current are in-phase, and the resulting power factor is 1
- If real power does not equal apparent power, and voltage and current are out-of-phase by 90^{o}, the power factor is 0
- If real power does not equal apparent power, and voltage and current are out-of-phase between 0^{o} and 90^{o}, power factor will be between 0 and 1

Power Factor

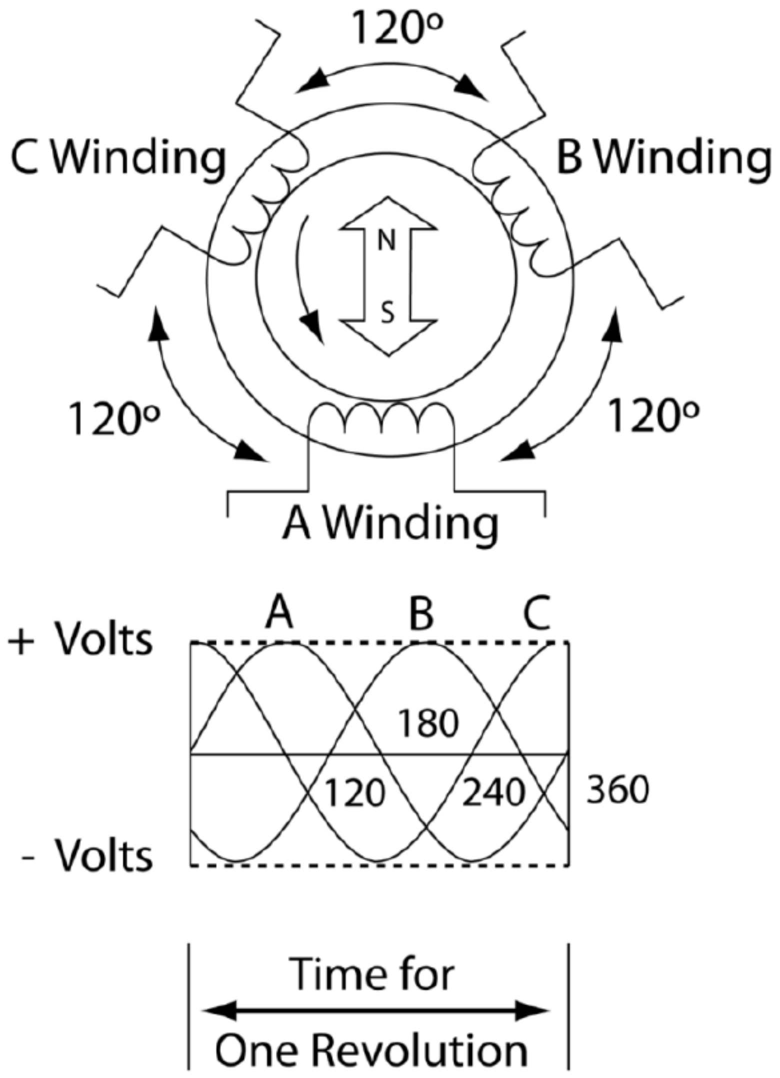
- Why is power factor so important?
  a) High power factor enables motors and other equipment to provide their rated power, without drawing excess current
  b) Electric energy transfer is more efficient with higher power factors
     - The power system can transmit and distribute more real power, without having to increase current-carrying capabilities of utility equipment

Three-phase Power

Three-Phase Power

- A system is balanced when the impedances in a three-phase system are identical in magnitude and phase
- Voltage, line current, real power, apparent power, reactive power, and power factor are identical in a balanced system for all three phases
- An AC generator produces three evenly-spaced sine wave voltages, each with a phase angle difference of 120^{o}
- Three conductors or phases transmit the energy, and each phase carries its own phase current

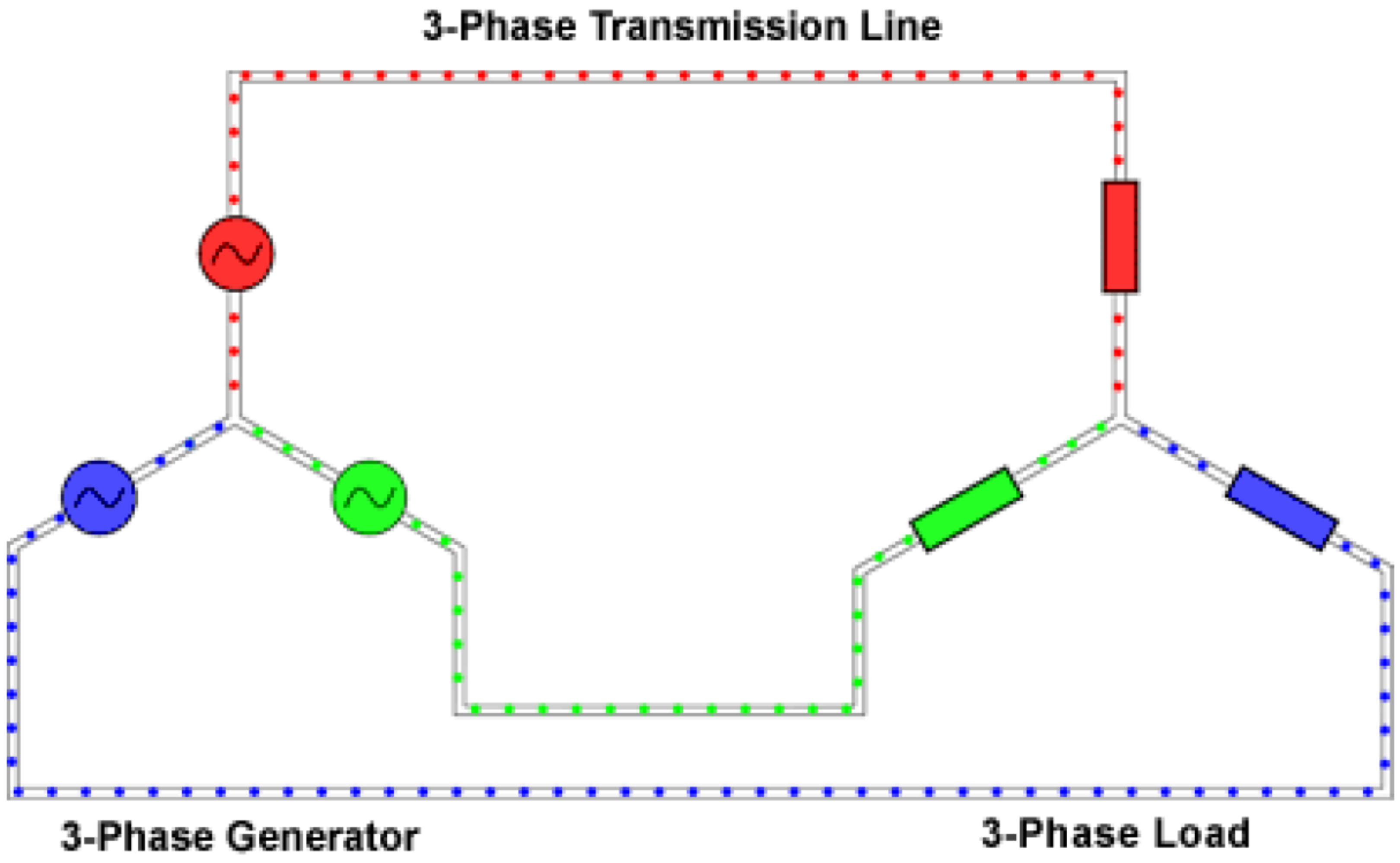
Three-Phase Power



Three-Phase Power

- Utilities use three-phase systems because:
  - Cost of a three-phase transmission line is less than a single-phase line
  - A three-phase system provides a more constant load on the generator (at least two phases are providing current and power at any instant) allowing smoother operation

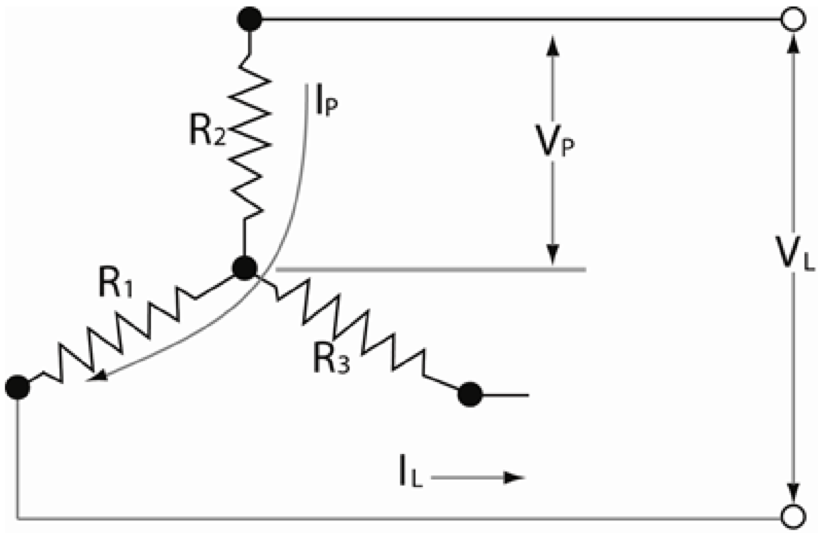
Three-Phase Power



Three-Phase Power

- In a three-phase system, there are two ways to specify voltage:
  - Phase Voltage (Line-to-Ground)
  - Line Voltage (Line-to-Line)
- In a three-phase system, there are two basic types of winding connections:
  - Delta connection
  - Wye connection

Wye Connection



3-Phase Wye (Balanced Load)

$$I_P = I_L$$

$$E_P = E_L / 1.73$$

$$W_{WYE} = E_L^2 / R = 3(E_P) / R$$

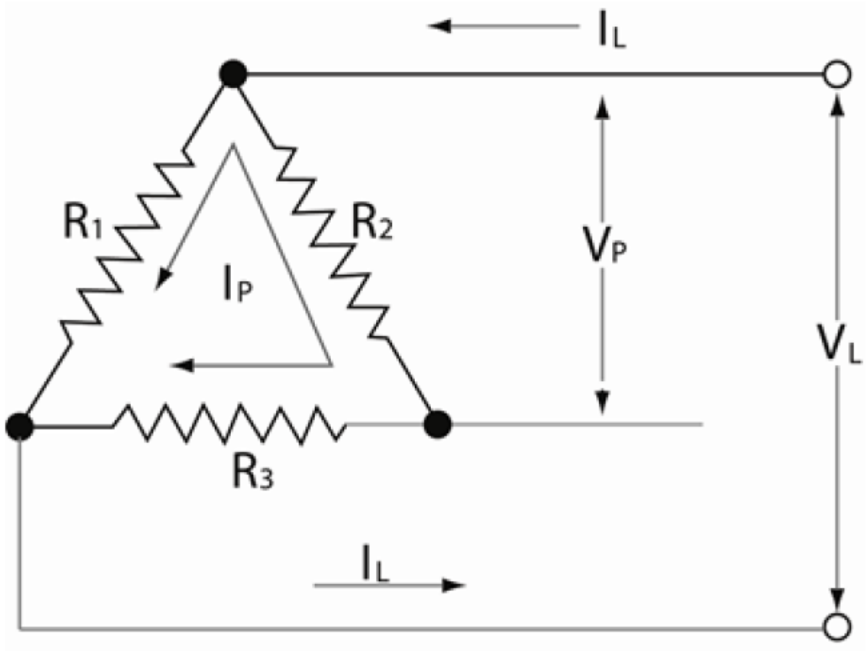
$$W_{WYE} = 1.73 E_L I_L$$

Wye Connection

- Coils are connected together at a common or neutral point (one wire for each voltage and a neutral)
- Line voltages are 120° out of phase with each other
- Line currents equal Phase currents $I_L = I_P$
- Line voltages do not equal Phase voltages
- Voltage between any two lines is the result of two phase voltages being 120 degrees out of phase

$$E_L = E_P(1.732)$$
$$208\,V = (120\,V)(1.732)$$

Delta Connection



3-Phase Delta (Balanced Load)

$$I_P = I_L / 1.73$$

$$E_P = E_L$$

$$W_{Delta} = 3(E_L^2) / R$$

$$W_{Delta} = 1.73 E_L I_L$$

Delta Connection

- Ends of the coils are connected together
- No current flows in the phase windings until a load is connected because the sum of the voltages on any two of the phases is equal and opposite to the other phase
- Line voltage is equal to the Phase voltage $E_L = E_P$
- Line current is not equal to Phase current because each line carries current from two phases and are 120^o out of phase

$$I_L = (1.732)(I_P)$$

- There is no neutral

Wye or Delta Connection

- The power that is dissipated by each phase of either a delta **or** wye connected load is:

Power per phase (P_P):

$$P_P = (E_P I_P)\cos\theta$$

or

$$P_P = \frac{(E_L I_L)\cos\theta}{\sqrt{3}}$$

3Ø Power ($P_{3\emptyset}$):

$$P_{3\emptyset} = 3P_p$$

or

$$P_{3\emptyset} = \sqrt{3}E_L I_L \cos\theta$$

Questions?

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