Introduction to Power Factor

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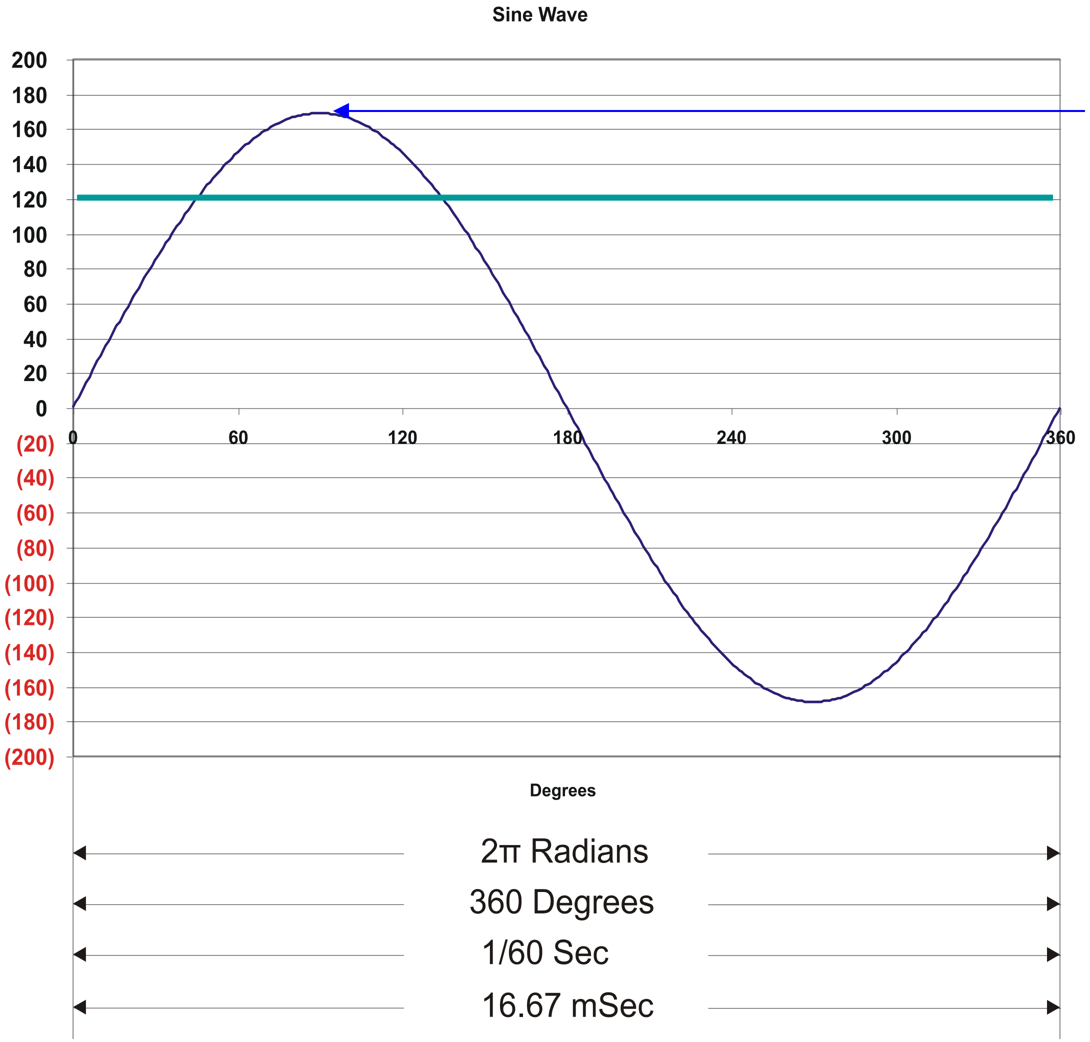
Focus of this Presentation

- Review basic power concepts as they relate to Power Factor (PF)
- Show how resistive, inductive, and capacitive loads affect PF
- Give examples of PF calculations for wye and delta service types

AC Theory Review – Sine Wave



$$V = V_{pk} Sin(2\pi ft - \theta)$$

$$V_{pk} = \sqrt{2} V_{rms}$$

$$V_{rms} = 120V$$

$$V_{pk} = 169V$$

$$\theta = 0°$$

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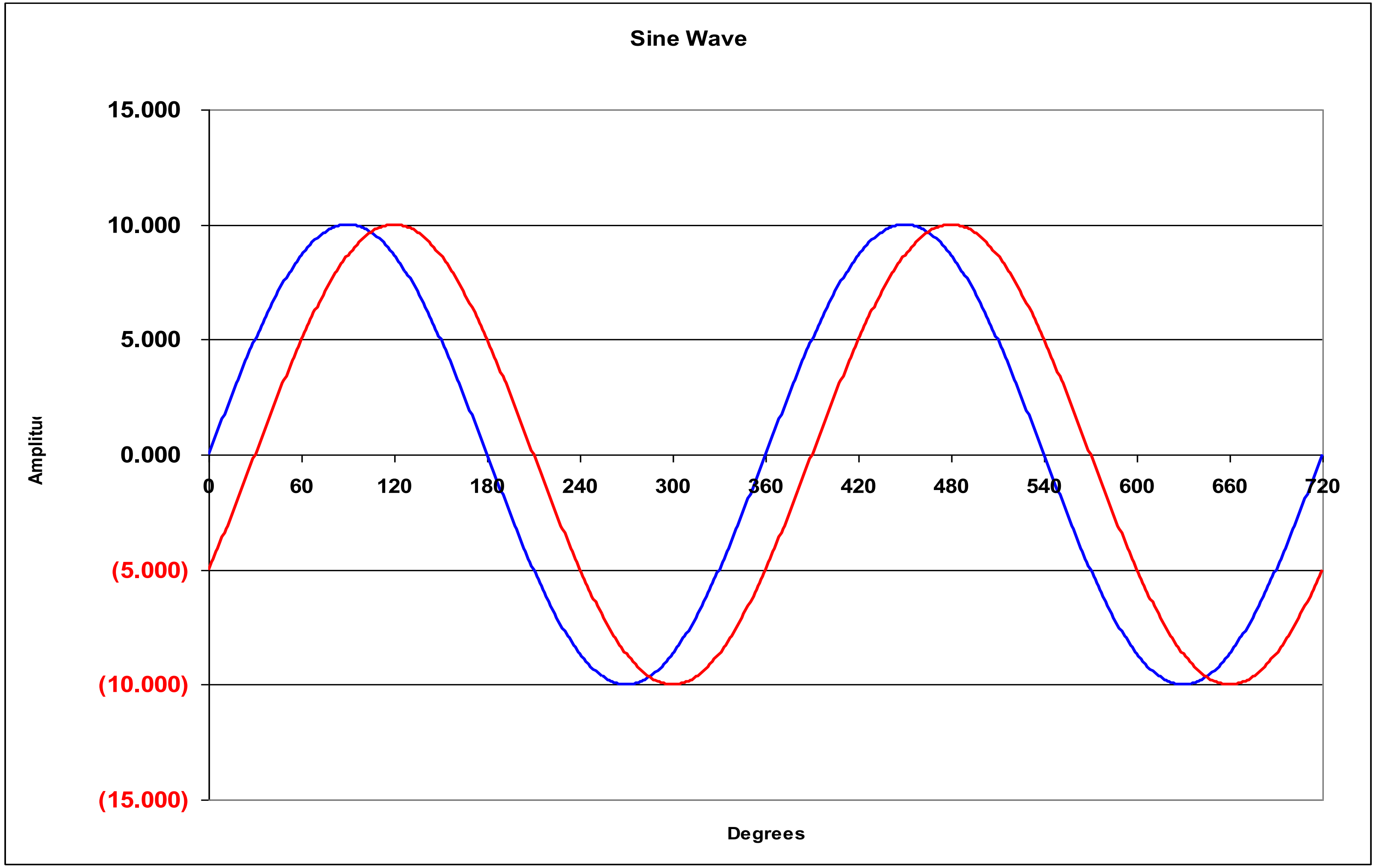
AC Theory Review - Phase



$V = 10Sin(2\pi ft)$

$V = 10Sin(2\pi ft - 30)$

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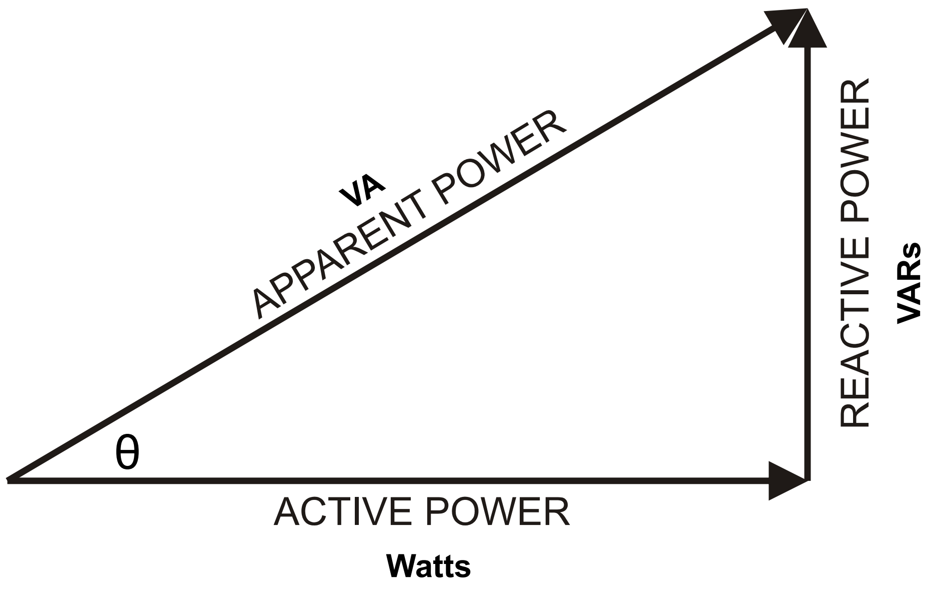
Power Triangle

(Sinusoidal Waveforms)



If V = Sin(ωt) and I = Sin(ωt - θ) (the load is linear)
then

Active Power =	VI*Cos*(θ)	Watts
Reactive Power =	VI*Sin*(θ)	Volt-Amp Reactive (VAR)
Apparent Power =	VI	Volt-Amp (VA)

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Watt, VAR, and VA

Watt - useful power that does real work at the load – light a bulb or turn a motor

VAR – non-useful power that is required to drive the inductance or capacitance of a power line

VA – the total power in the system; the vector sum of Watts and VARs

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Watt, VAR, and VA

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Power Factor Definition:

Power Factor represents the ratio of active power (Watts) to the total power (VA) in a system.

It is a representation of the percentage of useful work being done.

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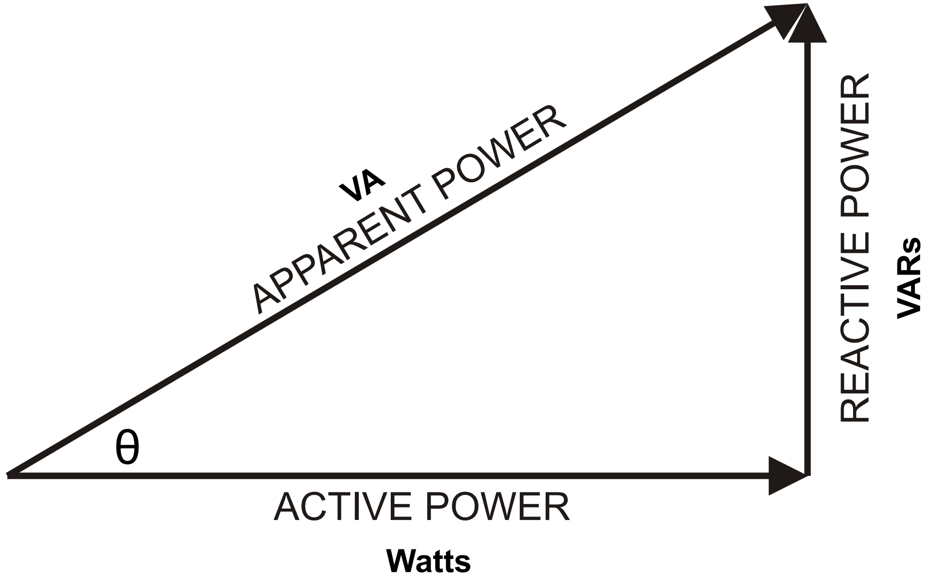
Power Factor Definition



Power Factor = Active / Apparent Power

= Watts / VA

= $Cos(\theta)$

Power Factor can range from 1 to 0

Intro to Power Factor

Power – VA

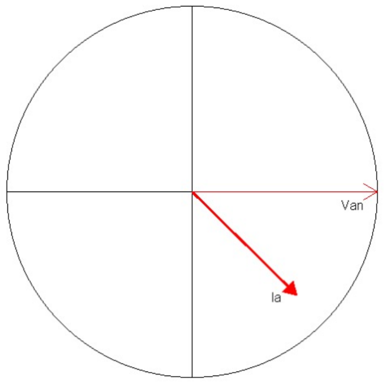
For a 120 Volt service drawing 13 Amps at 0.5 PF (60°)

How much power is being drawn?

Power = 120 x 13 x 0.5 = 780 Watts

How many VA are being drawn?

VA = 120 x 13 = 1560 Volt-Amperes



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Intro to Power Factor

Power – VA

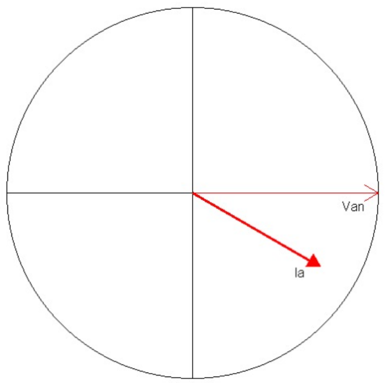
For a 120 Volt service drawing 13 Amps at 0.866 PF (30°)

How much power is being drawn?

Power = 120 x 13 x 0.866 = 1351 Watts

How many VA are being drawn?

VA = 120 x 13 = 1560 Volt-Amperes



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Intro to Power Factor

Power – VA

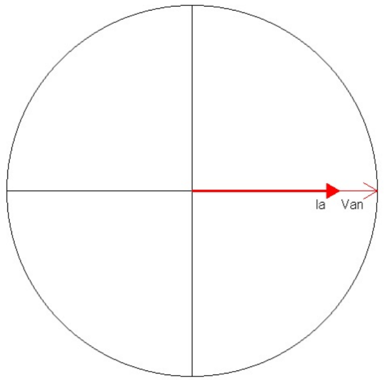
For a 120 Volt service drawing 13 Amps at 1.0 PF (0°)

How much power is being drawn?

Power = 120 x 13 x 1.0 = 1560 Watts

How many VA are being drawn?

VA = 120 x 13 = 1560 Volt-Amperes



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Power Factor, Watts, and VA

For our 120V, 13A system

Phase Angle	PF	Watts	VA
60	0.5	780 W	1560 VA
30	0.866	1351 W	1560 VA
0	1.0	1560 W	1560 VA

As PF get closer to 1, the Watt value gets closer to the VA value! This means more real power is being consumed!

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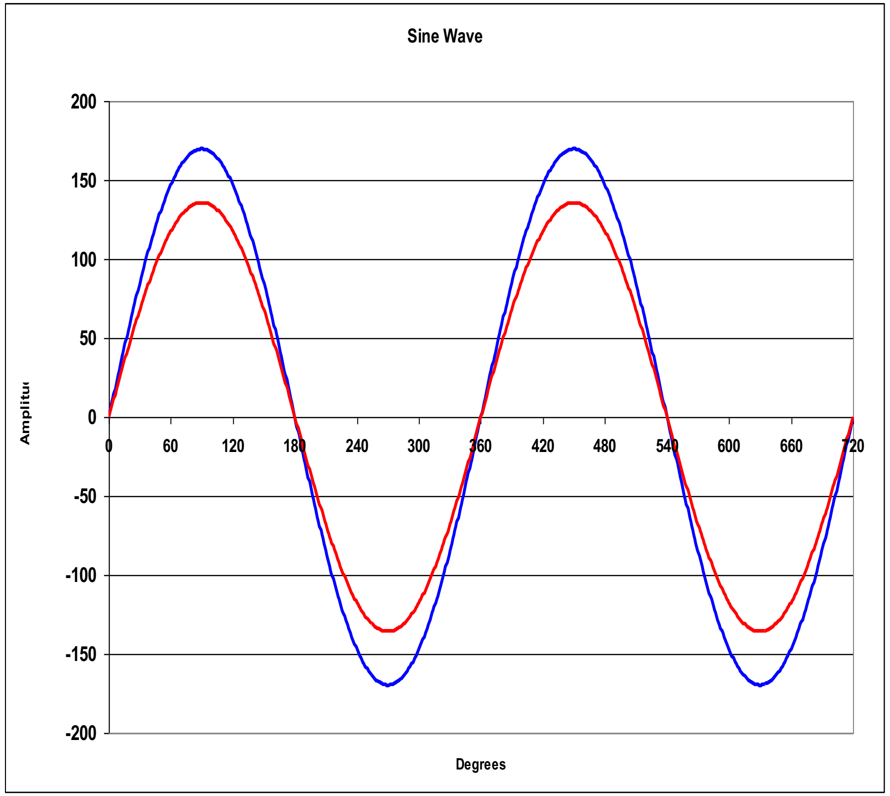
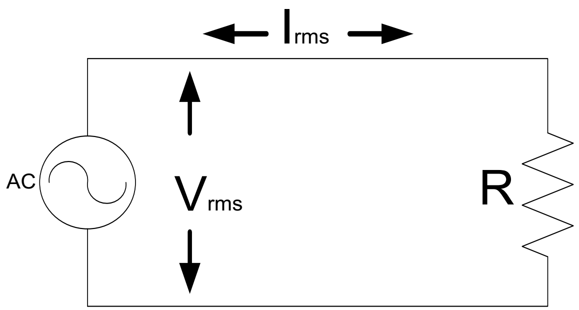
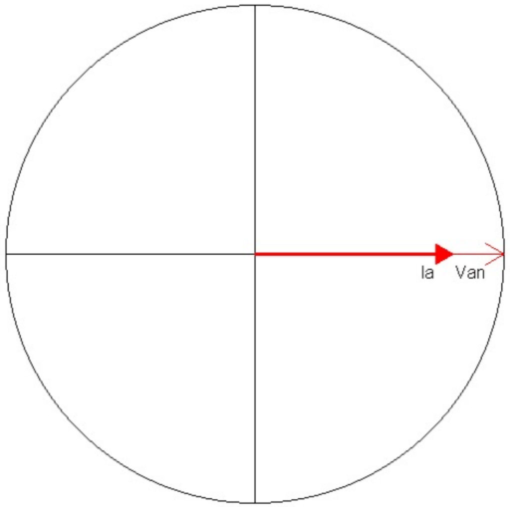
Resistive Load

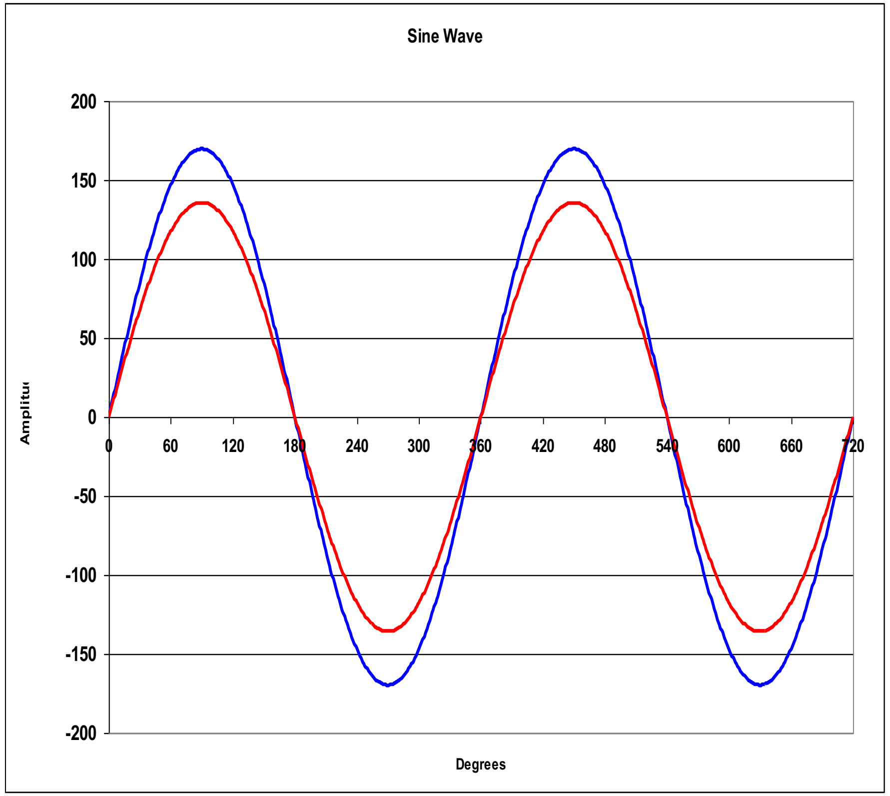


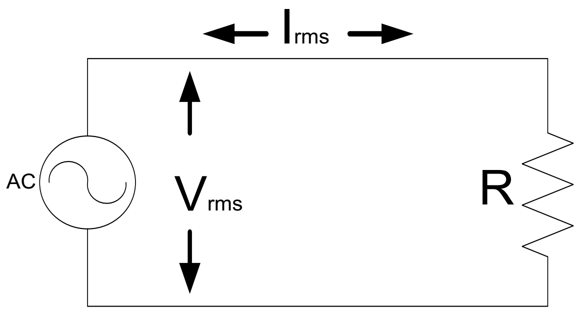




A purely resistive load has ZERO phase angle

Resistive Load





Resistive Example:
V = 120V
I = 10A
Θ = 0°
Cos 0° = 1
Sin 0° = 0

Active Power (W) = V I cos (θ) = 120 * 10 * 1 = 1200 W
Reactive Power (VAR) = V I sin (θ) = 120 * 10 * 0 = 0 VAR
Apparent Power (VA) = V I = 120 * 10 = 1200 VA

PF = W / VA = cos (θ) = 1

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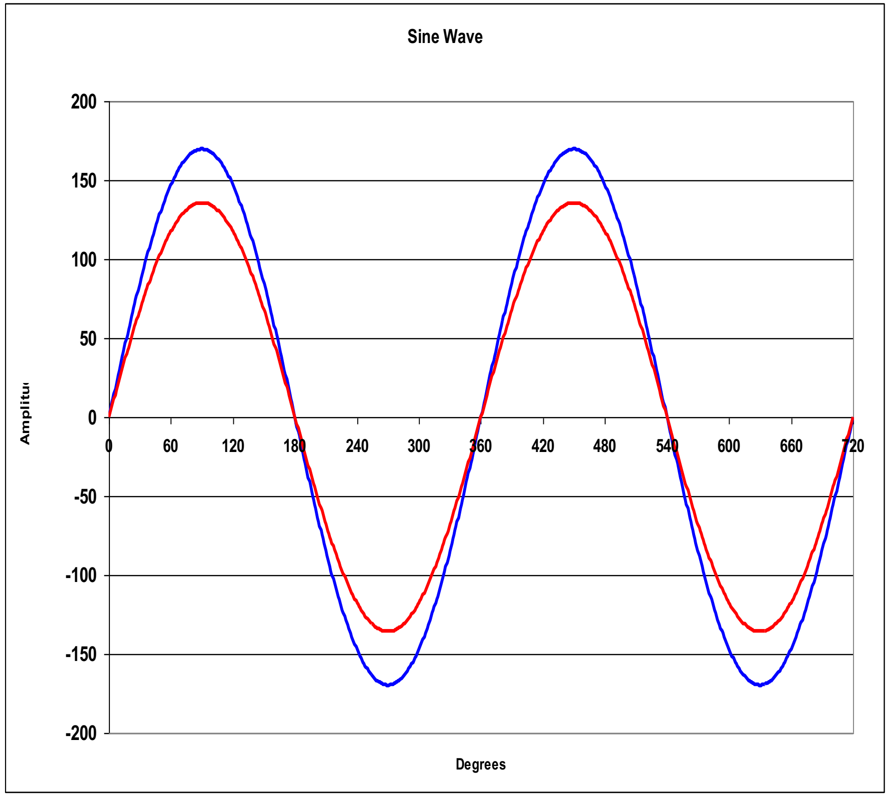
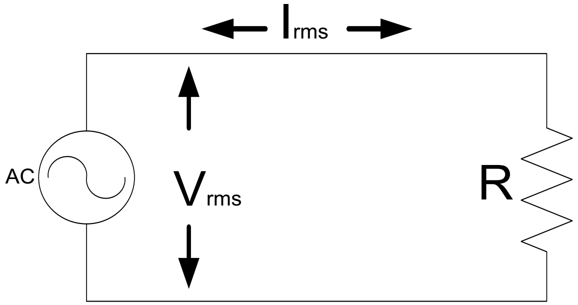
Resistive Load



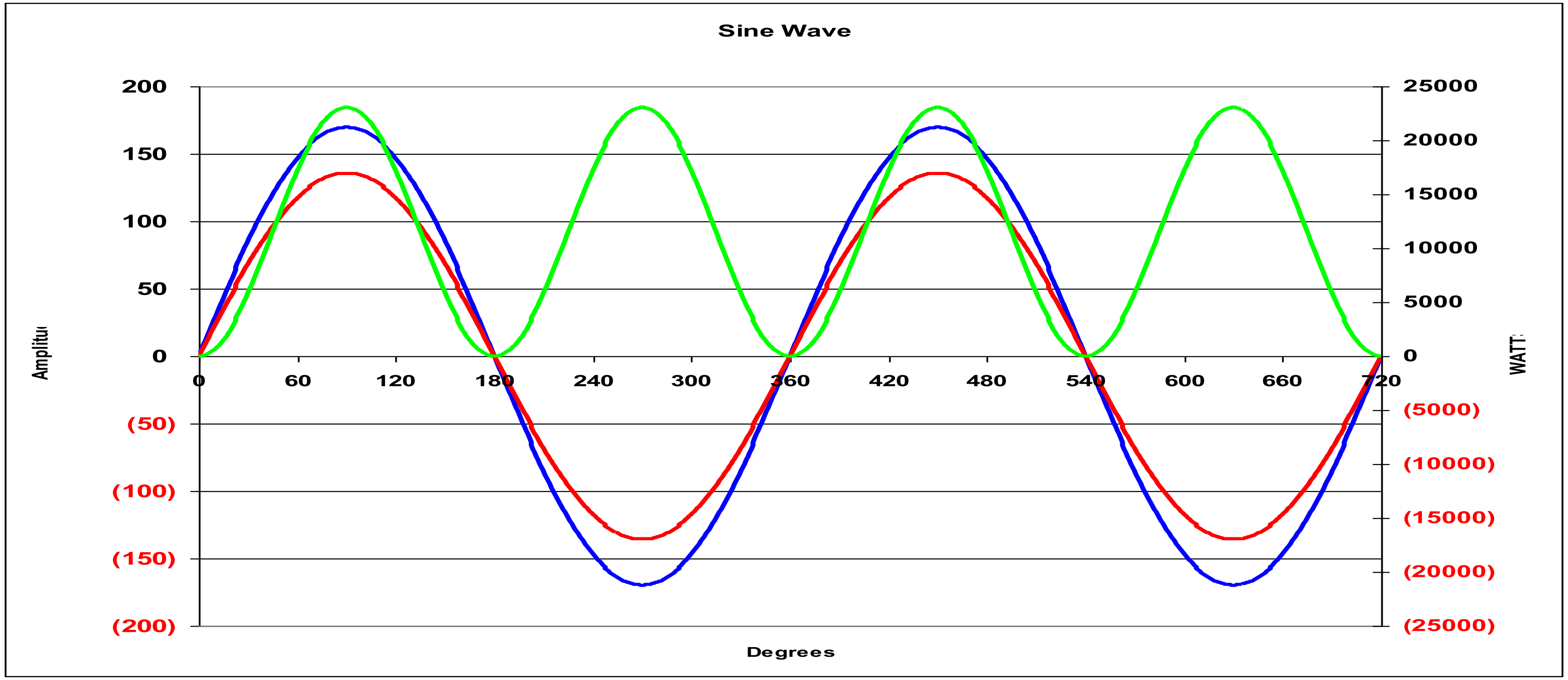


A purely resistive load will:

- Only create Watts
- Create NO VARs
- Have a PF = 1

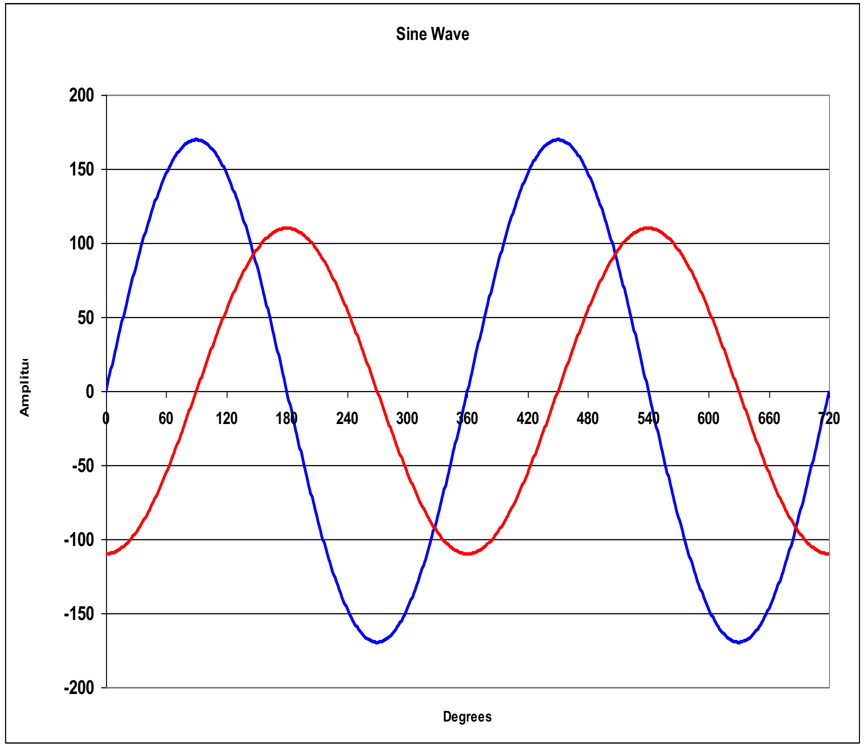
Resistive Load

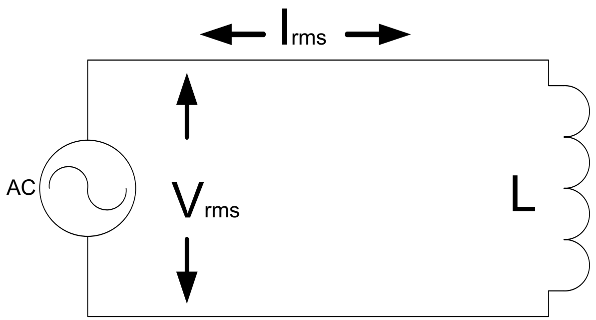
For a resistive load: $p = vi = 2VISin^2(\omega t) = VI(1 - Cos(2\omega t))$

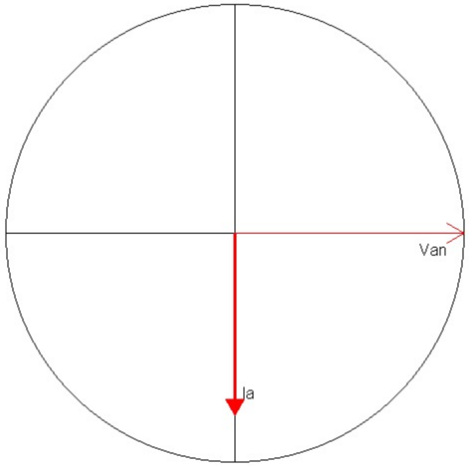


A resistive load consumes only Watts, so the power will always be delivered (positive).

Inductive Load

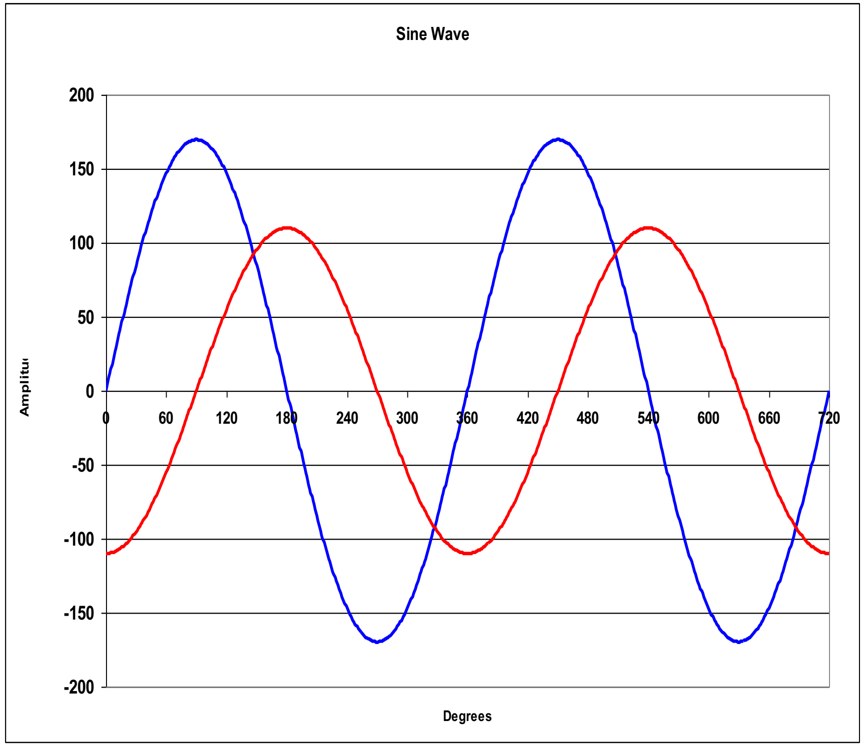


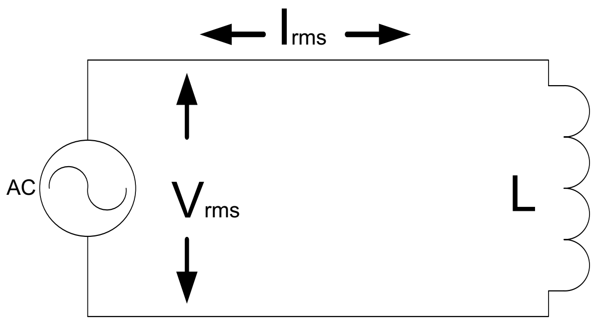




A purely inductive load has +90° phase angle

Inductive Load





Inductive Example:
V = 120V
I = 10A
Θ = 90°
Cos 90° = 0
Sin 90° = +1

Active Power (W) = V I cos (θ) = 120 * 10 * 0 = 0 W
Reactive Power (VAR) = V I sin (θ) = 120 * 10 * +1 = +1200 VAR
Apparent Power (VA) = V I = 120 * 10 = 1200 VA

PF = W / VA = cos (θ) = 0

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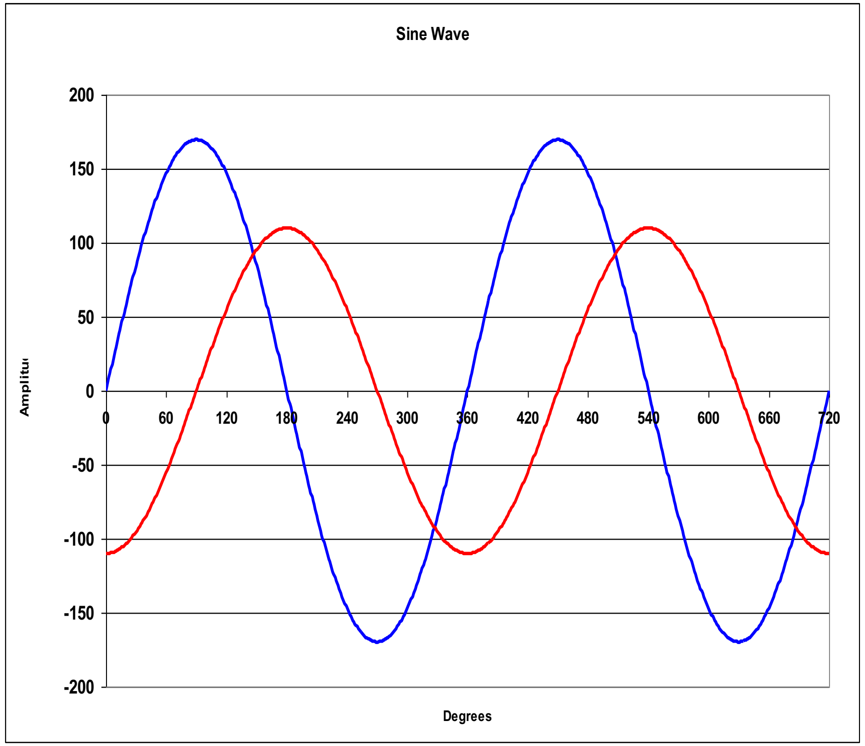
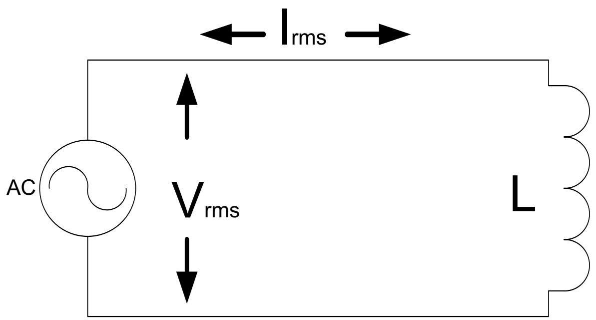
Inductive Load



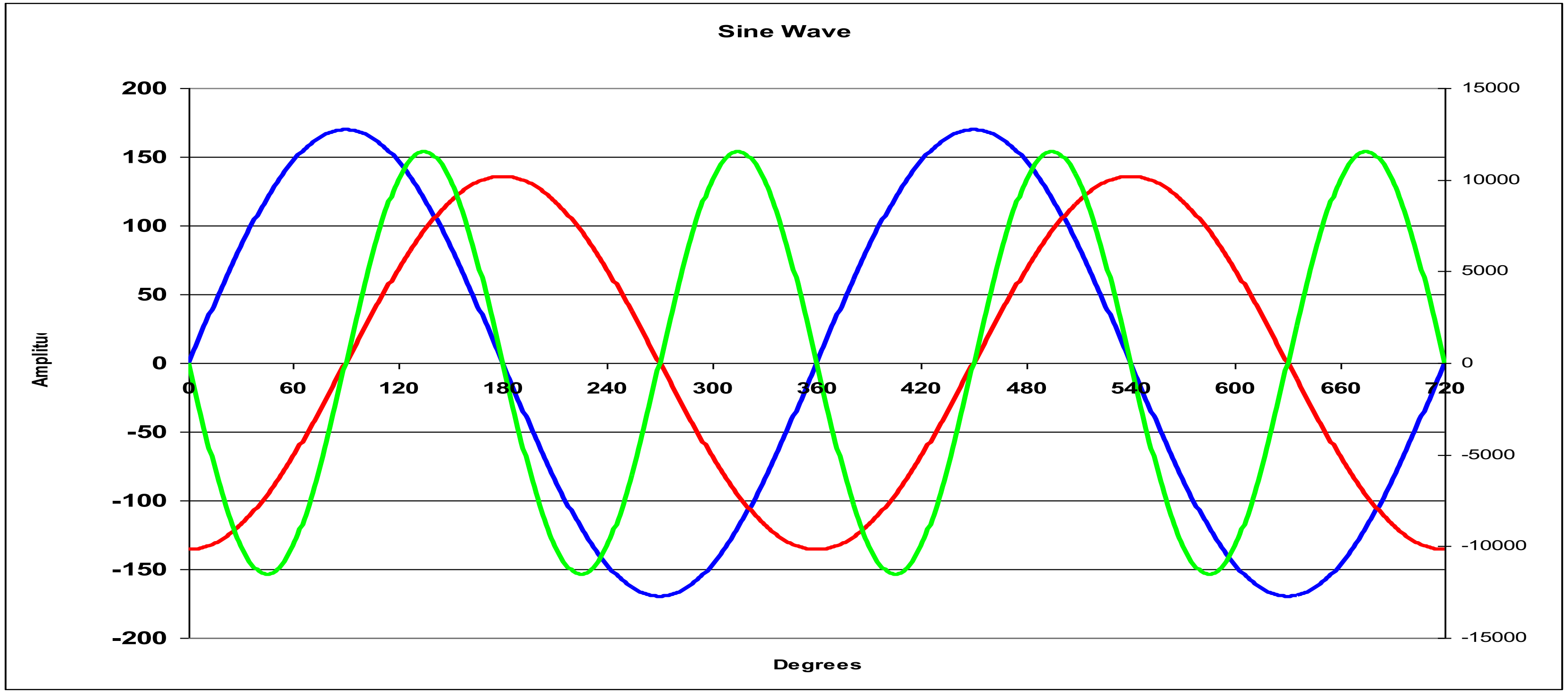


A purely inductive load will:

- Only create positive VARs
- Create NO Watts
- Have a PF = 0

Inductive Load

For an inductive load: $p = vi = 2VISin(\omega t)Sin(\omega t - 90) = -VISin(2\omega t)$



An inductive load consumes receives and delivers equal amounts of power, so the net active power (Watts) is ZERO
And the reactive load is 100%!

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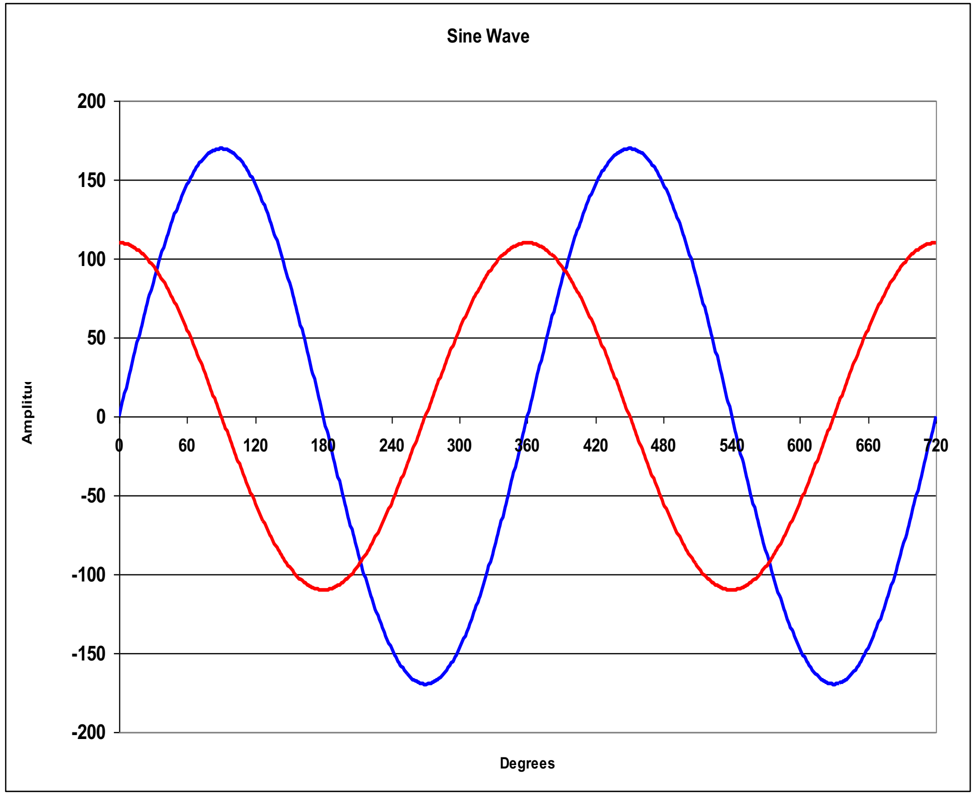
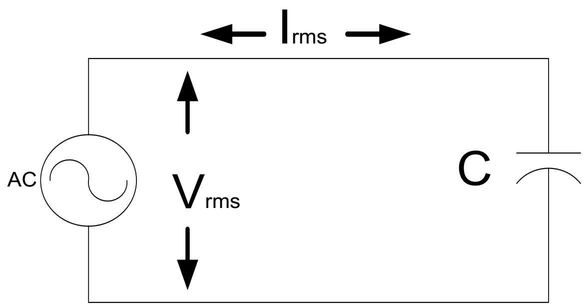
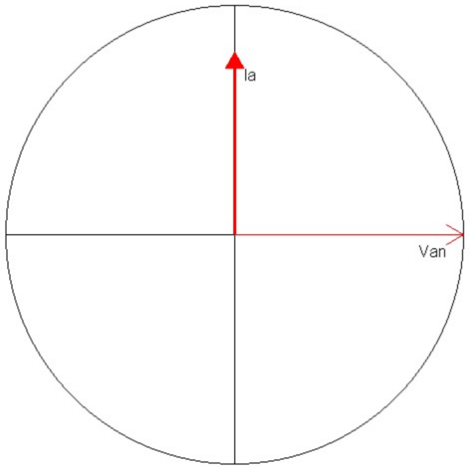
Capacitive Load

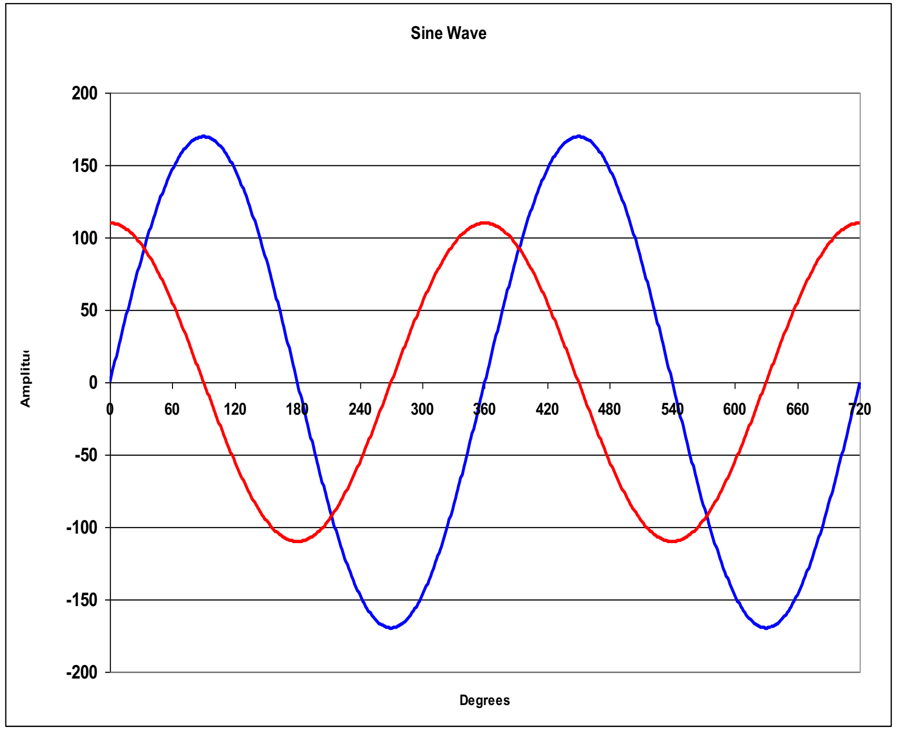


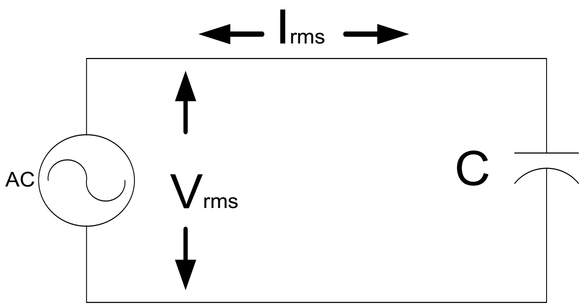




A purely capacitive load has -90° phase angle

Capacitive Load



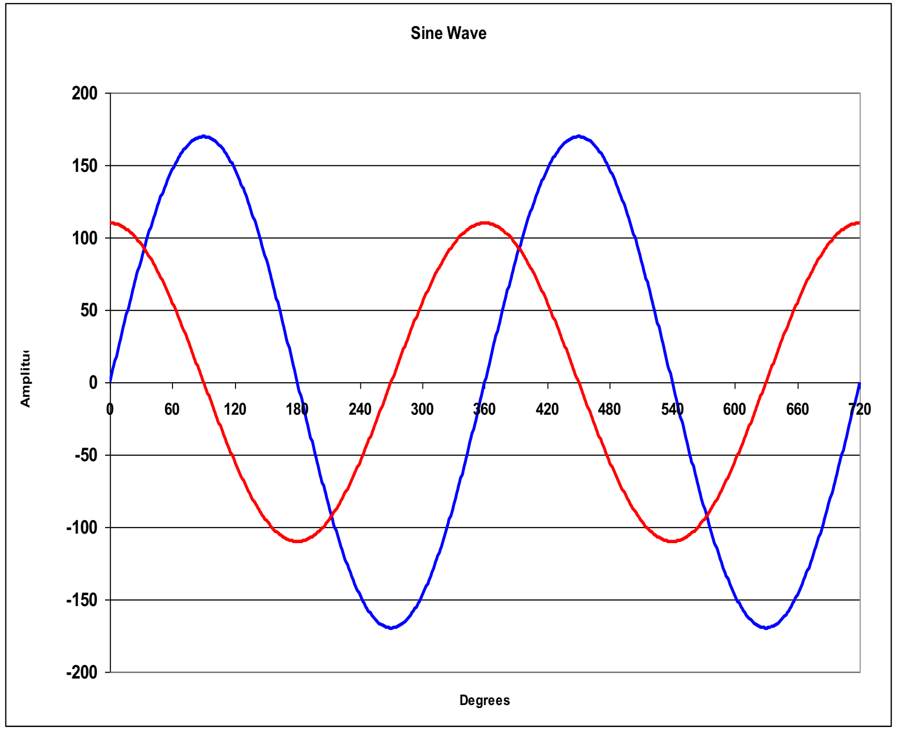


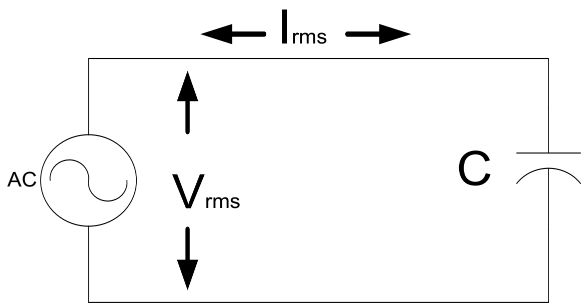
Inductive Example:
V = 120V
I = 10A
Θ = -90°
Cos -90° = 0
Sin -90° = -1

Active Power (W) = V I cos (θ) = 120 * 10 * 0 = 0 W
Reactive Power (VAR) = V I sin (θ) = 120 * 10 * -1 = -1200 VAR
Apparent Power (VA) = V I = 120 * 10 = 1200 VA

PF = W / VA = cos (θ) = 0

Capacitive Load



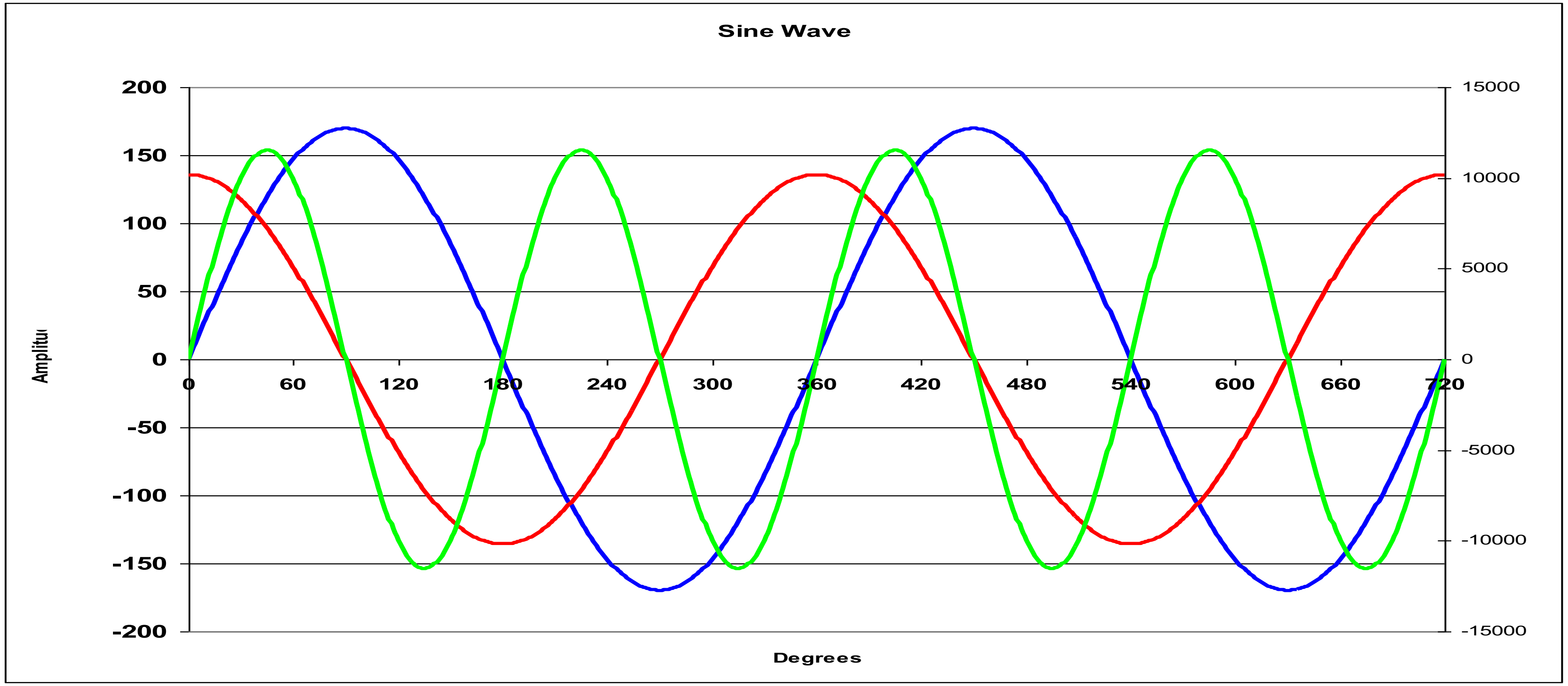


A purely capacitive load will:

- Only create negative VARs
- Create NO Watts
- Have a PF = 0

AC Theory – Instantaneous Power

For a capacitive load: $p = vi = 2VISin(\omega t)Sin(\omega t + 90) = VISin(2\omega t)$



$V = 120\sqrt{2}Sin(2\pi ft)$

$I = 96\sqrt{2}Sin(2\pi ft + 90)$

$P = 11520Sin(2\pi ft)$

P = 0 Watts

Inductance Vs Capacitance

- More inductance creates more VAR, less W, and lower PF
- Capacitance is added to an inductive load to reduce VAR, raise W, and raise PF
- Ideally, we want all loads to have a PF = 1

+

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Delivered vs Received Power

Positive Watts are DELIVERED
from the Utility to the Consumer

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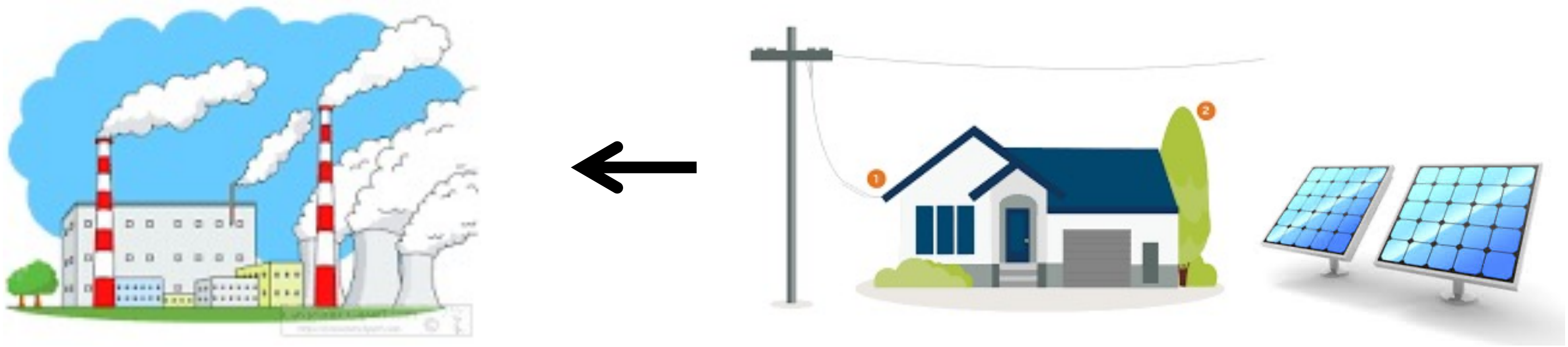
Delivered vs Received Power



Negative Watts are RECEIVED by the Utility from the Consumer

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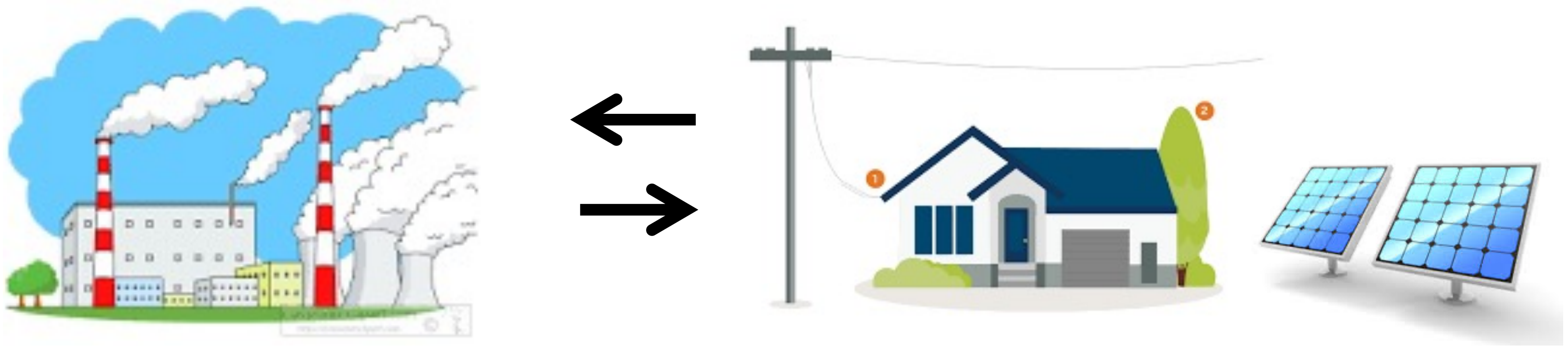
Delivered vs Received Power



Positive and Negative VARs flow in both directions

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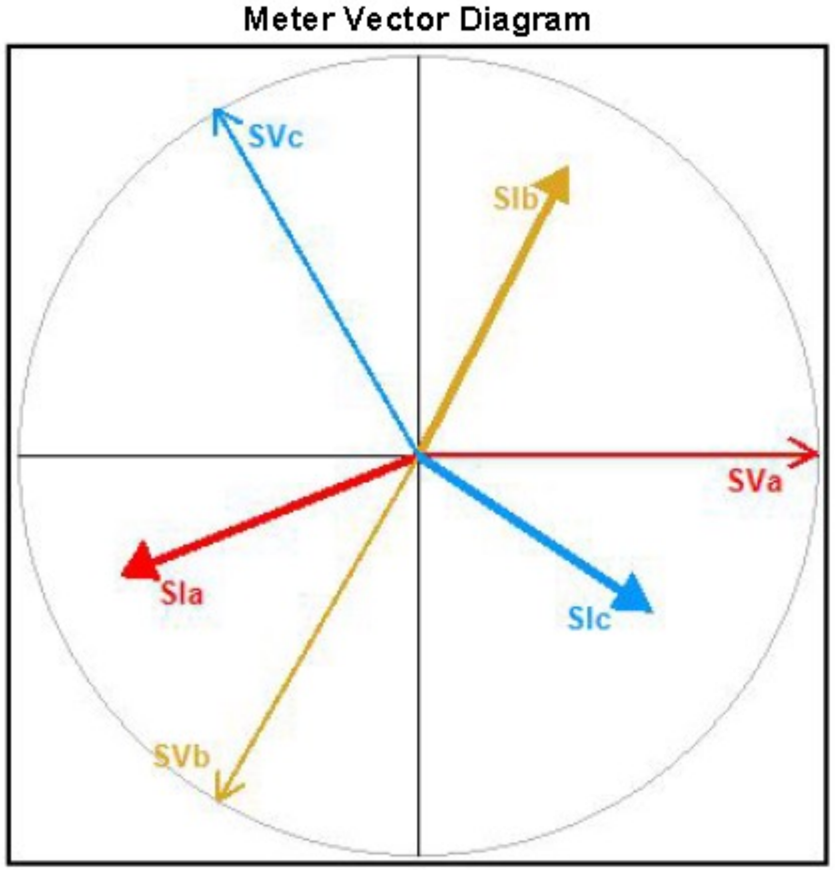
Negative Power Factor?

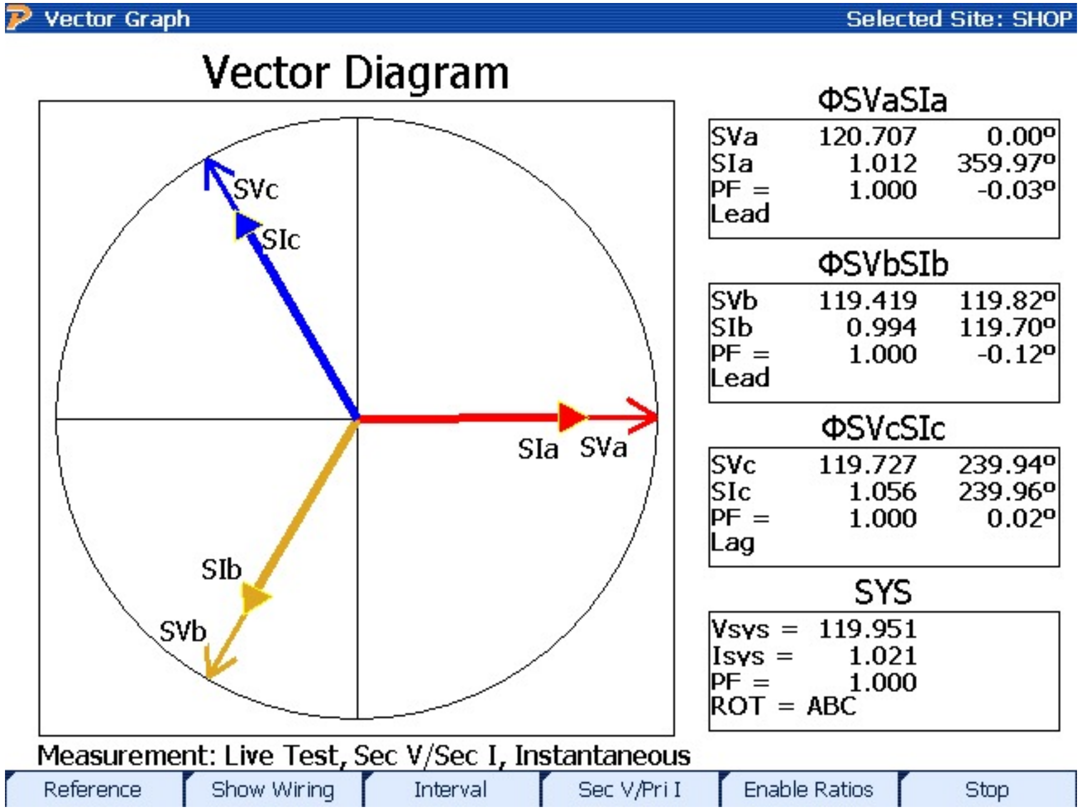


- The vector diagram for a renewable site may have current vectors 180° out when the site is generating power.
- Whr, VARhr, and PF may also be negative when generating power.
- The sign of PF will follow Watts

3 Phase, 4-Wire “Y” Service

0° = Unity Power Factor

- Three Voltage Phasors
- 120° Apart
- Three Current Phasors
- Aligned with Voltage at PF=1



System PF = Average of A, B, and C phase PF

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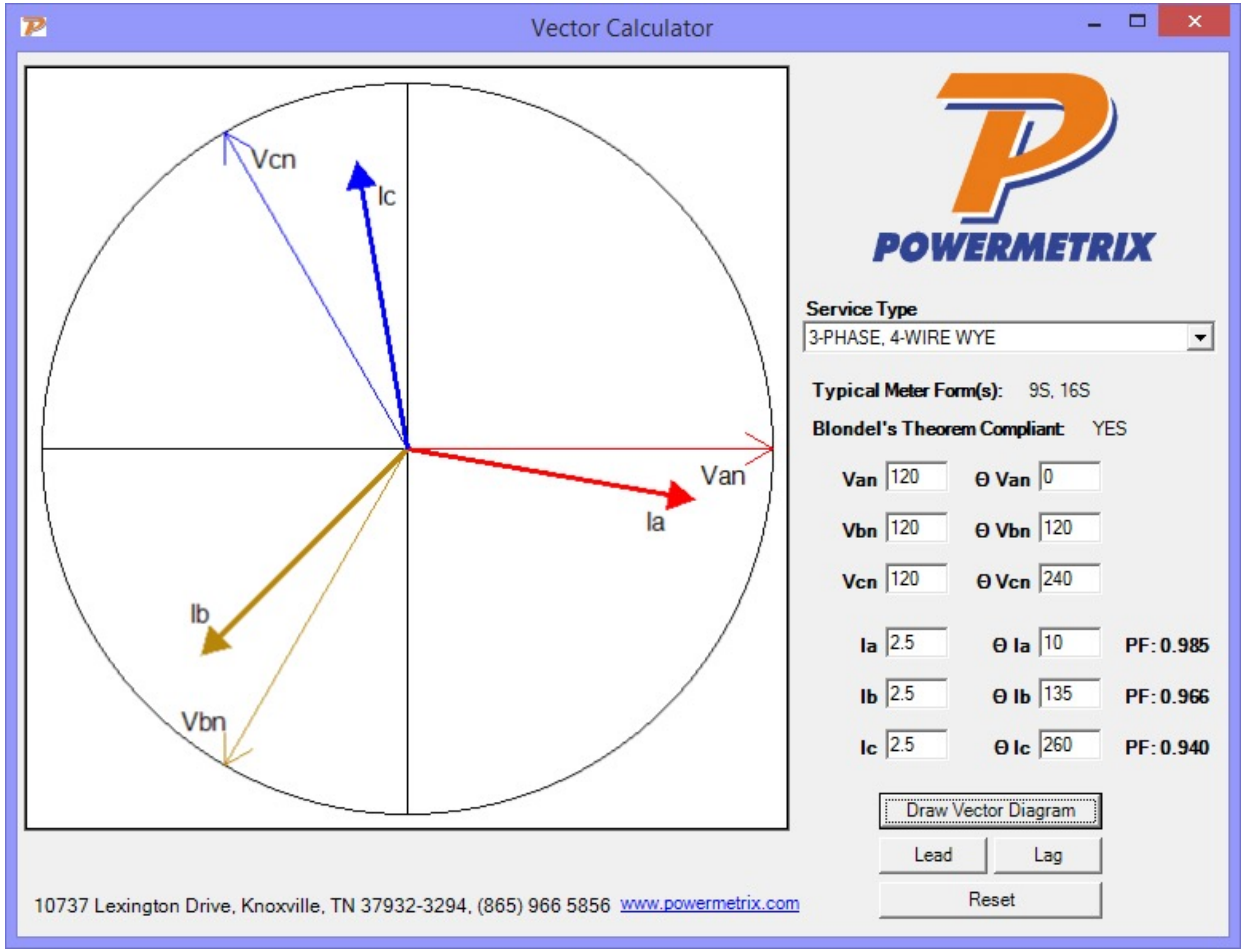
3 Phase, 4-Wire Wye



System PF = Average of A, B, and C = 0.964

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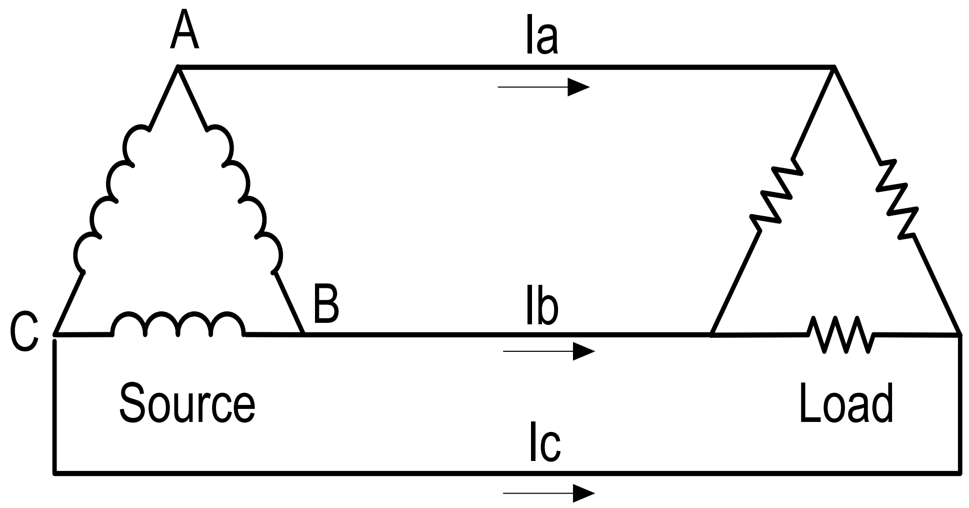
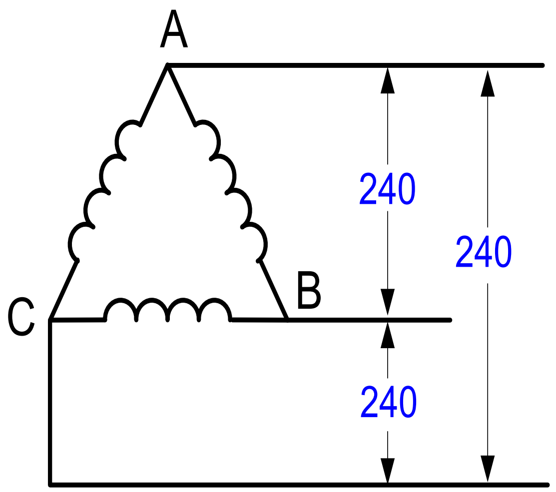
3 Phase, 3-Wire Delta Service

Common service type for industrial customers. This service has NO neutral.



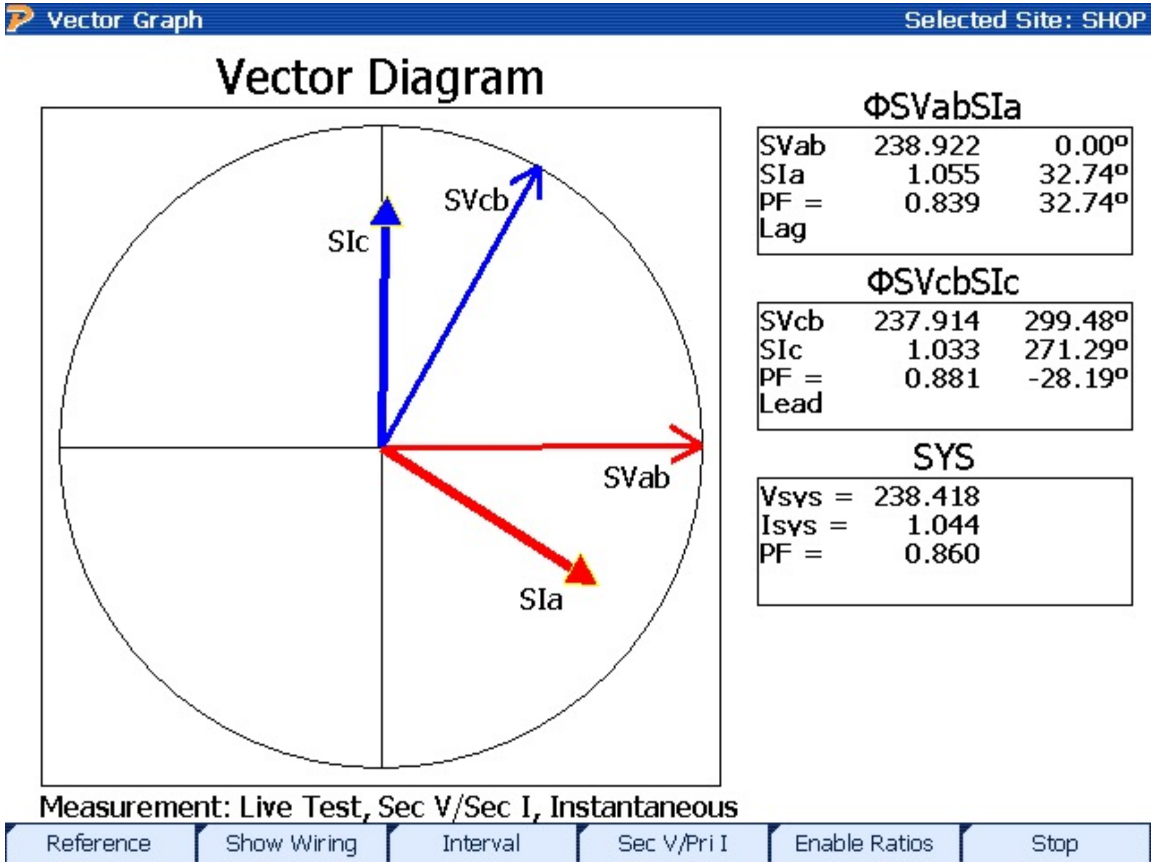


- Voltages normally measured relative to phase B.
- Voltage and current vectors do not align.
- Service is provided even when a phase is grounded.

3 Phase, 3-Wire Delta Service

Resistive Loads

- Two Voltage Phasors
- 60° Apart
- Two Current Phasors
- For a resistive load one current leads by 30° while the other lags by 30°



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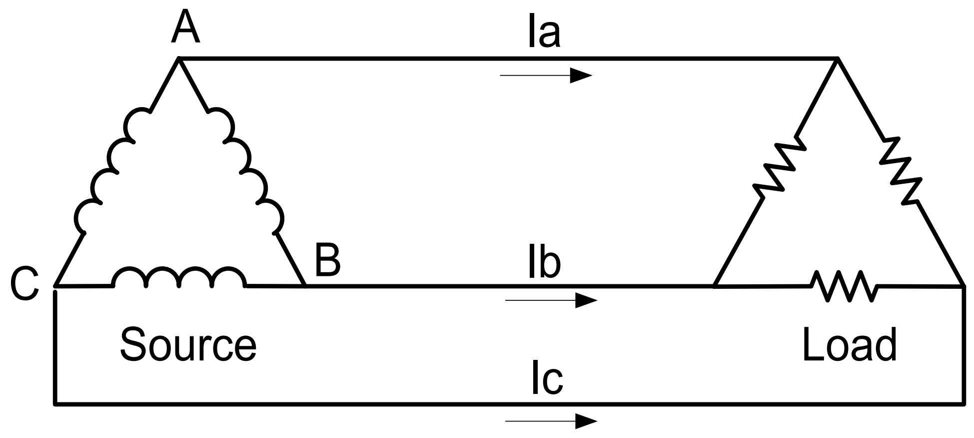
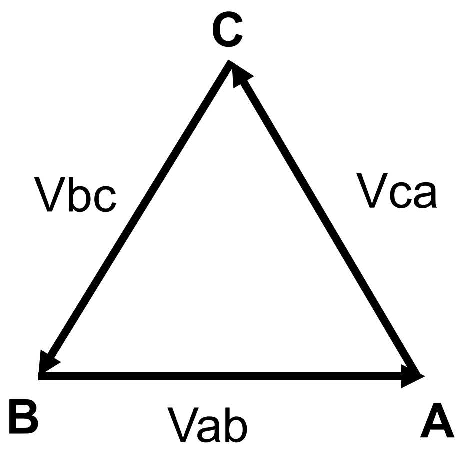
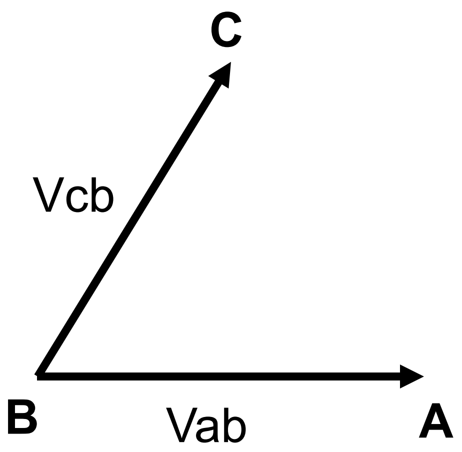
3 Phase, 3-Wire Delta Service

Understanding the Diagram







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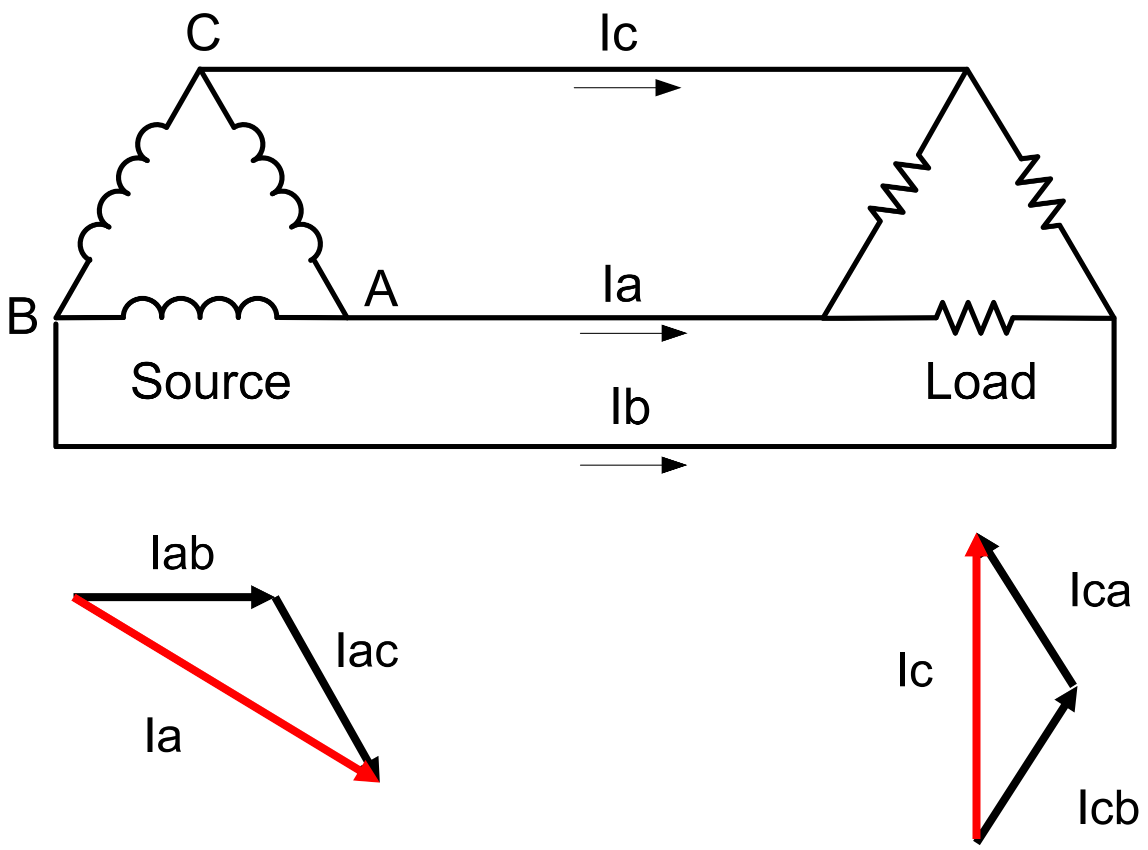
3 Phase, 3-Wire Delta Service

Understanding the Diagram



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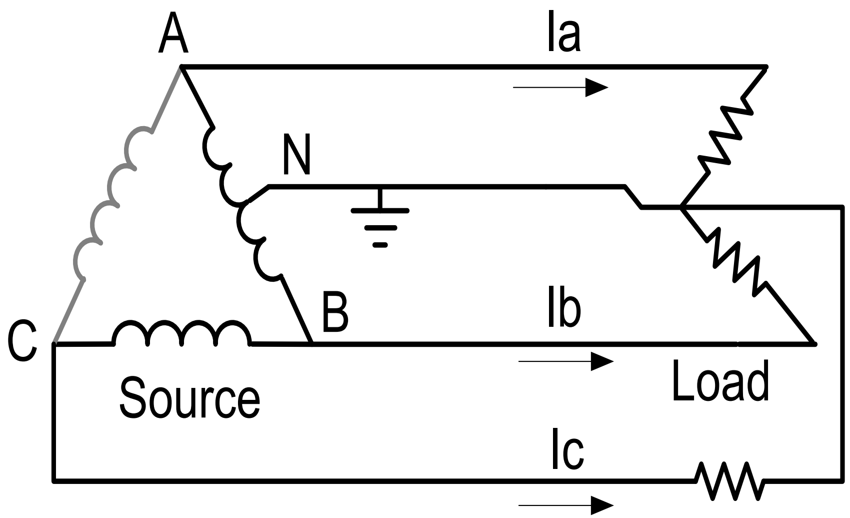
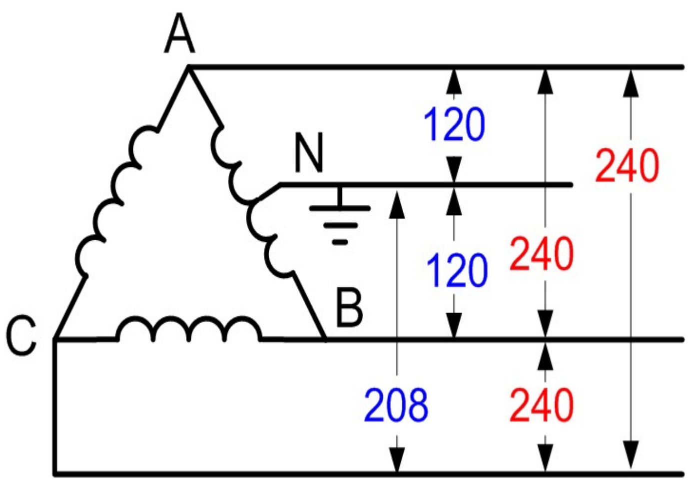
3 Phase, 4-Wire Delta Service

Common service type for industrial customers. Provides a residential like 120/240 service (lighting service) single phase 208 (high side) and even 3 phase 240 V.





- Voltage phasors form a “T” 90° apart
- Currents are at 120° spacing
- In 120/120/208 form only the “hot” (208) leg has its voltage and current vectors aligned.

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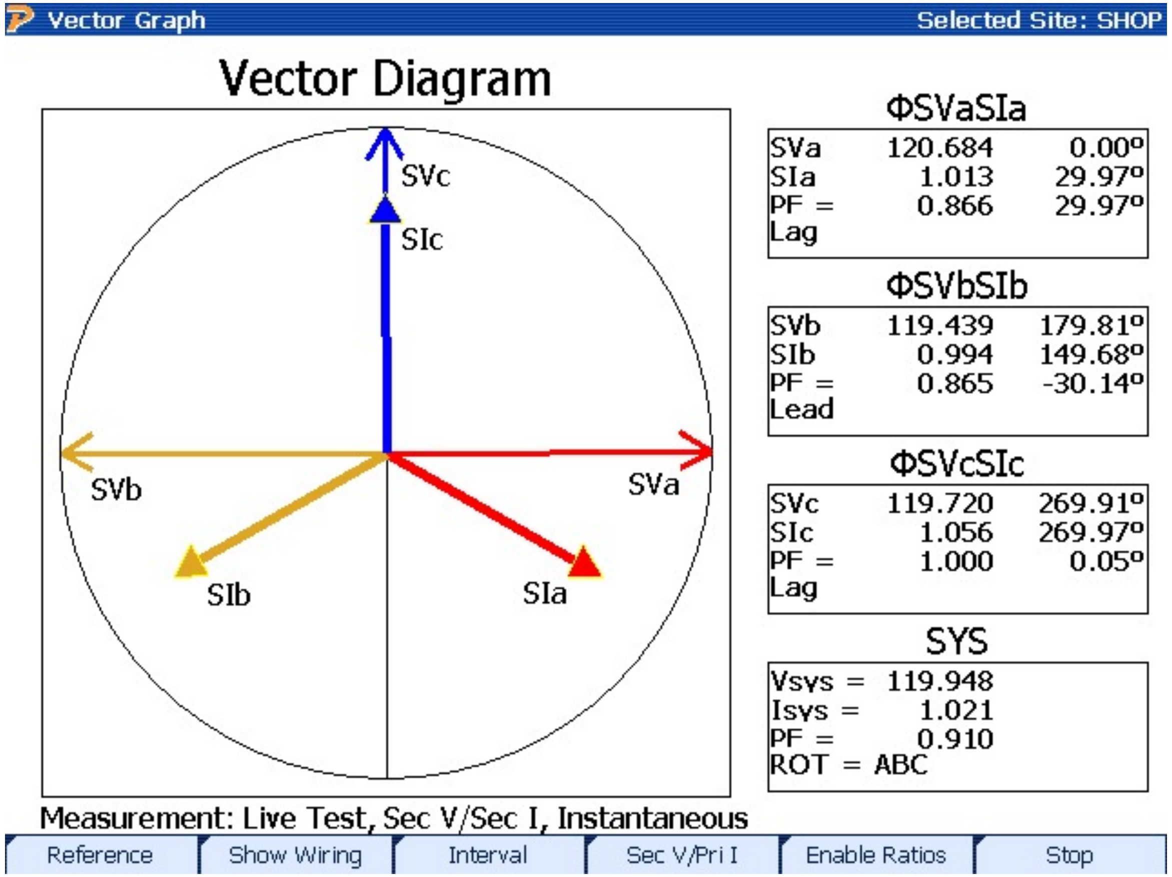
3 Phase, 4-Wire Delta Service

Resistive Load

- Three Voltage Phasors
- 90° Apart
- Three Current Phasors
- 120° apart



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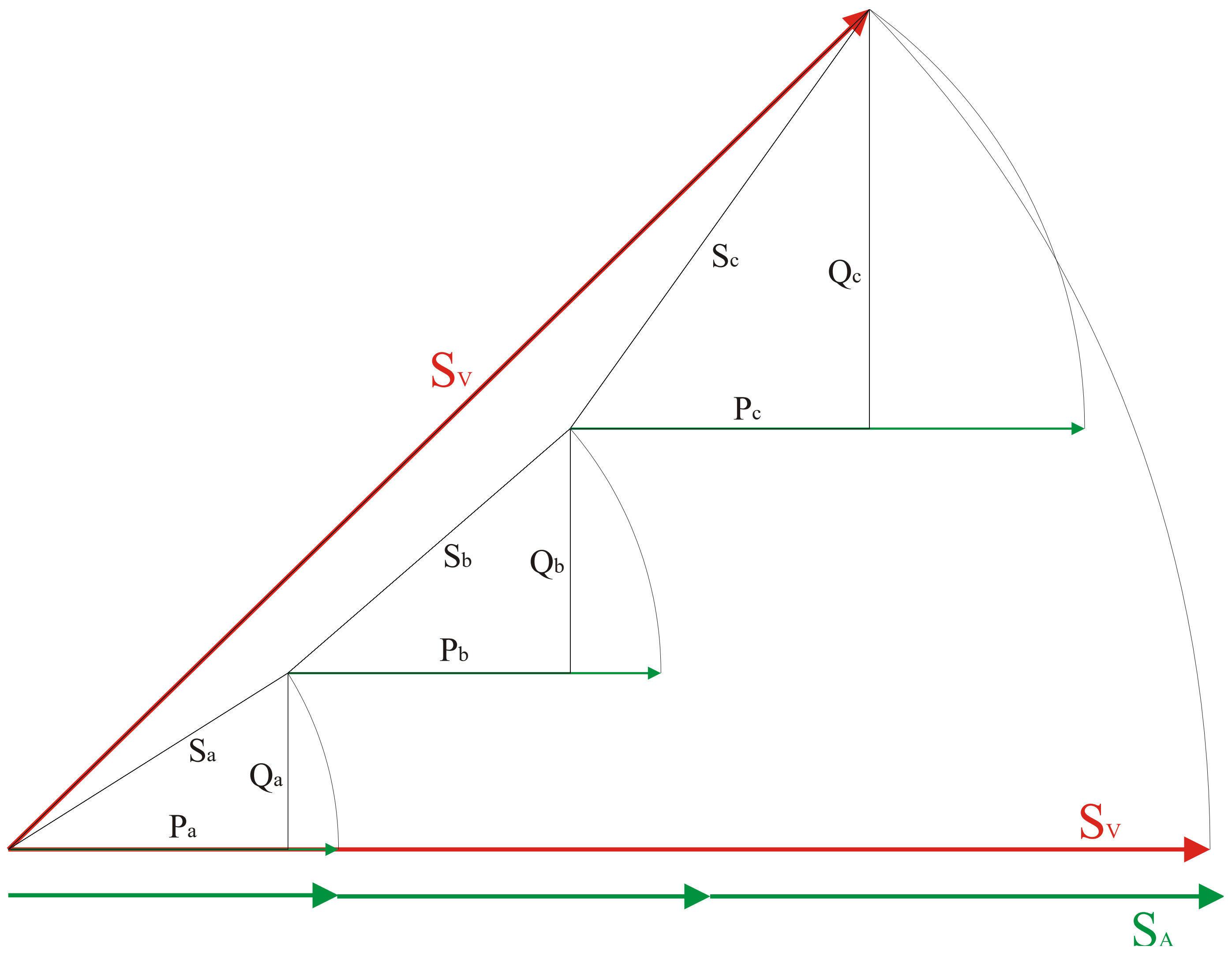
3 Phase Power Measurement

- We have discussed how to measure and view power quantities (W, VARs, VA) in a single phase case.
- How do we combine them in a multi-phase system?
- Two common approaches:
  - Arithmetic
  - Vectorial

3 Phase Power Measurement



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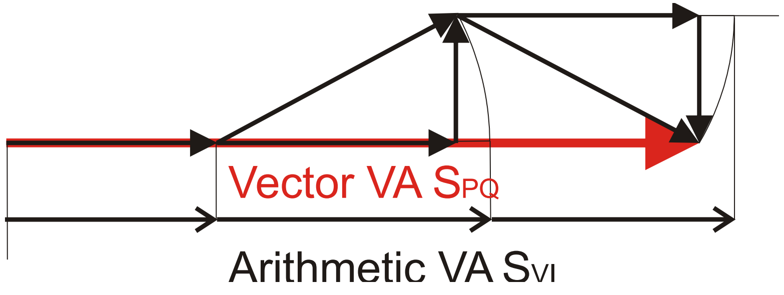
3 Phase Power Measurement

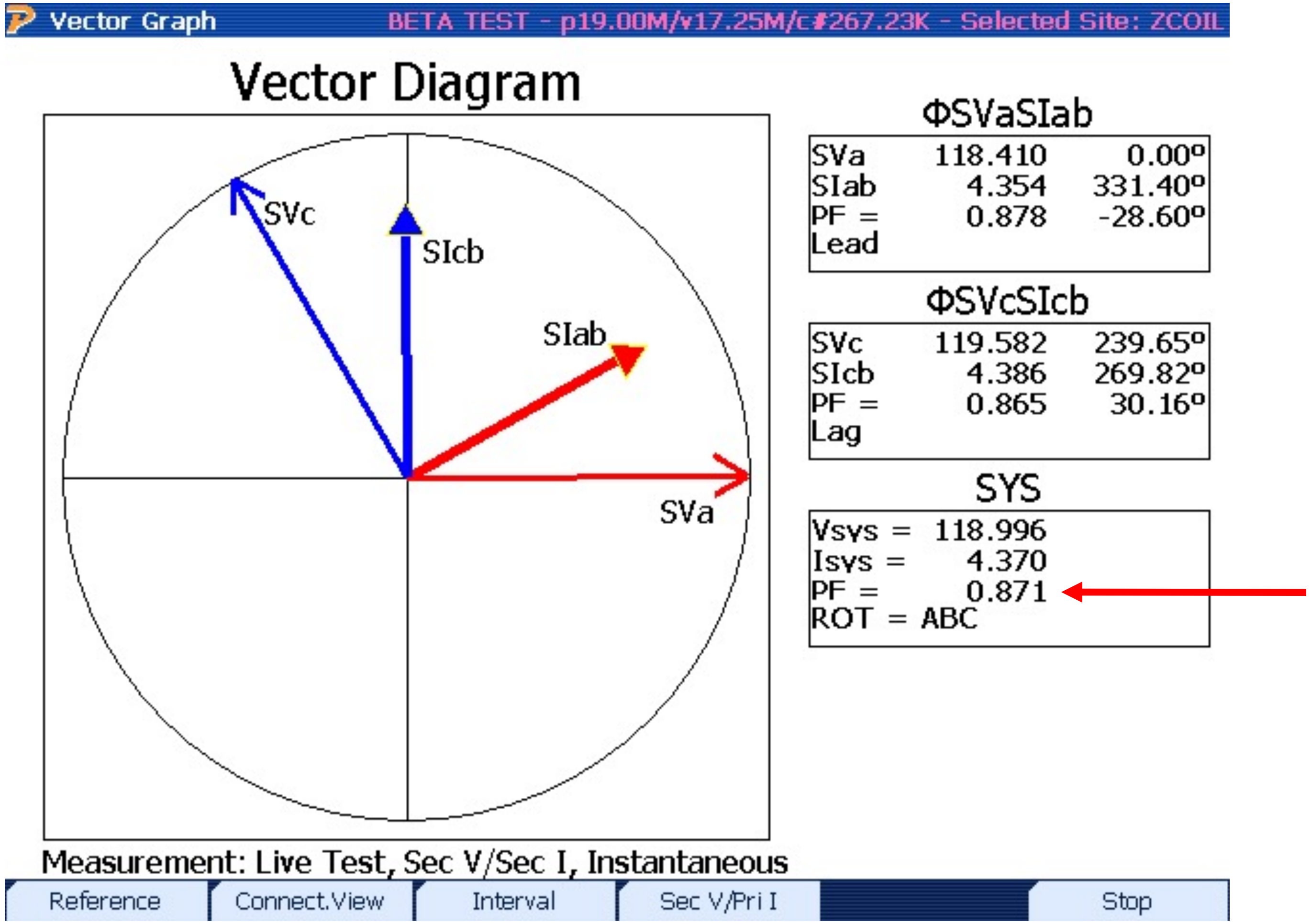
- VAR and VA calculations can lead to some strange results:
  - If we define

$$VA = \sqrt{(W_A + W_B + W_C)^2 + (Q_A + Q_B + Q_C)^2}$$

PH	W	Q	VA
A	100	0	100
B	120	55	132
C	120	-55	132
Arithmetic VA			364
Vector VA			340

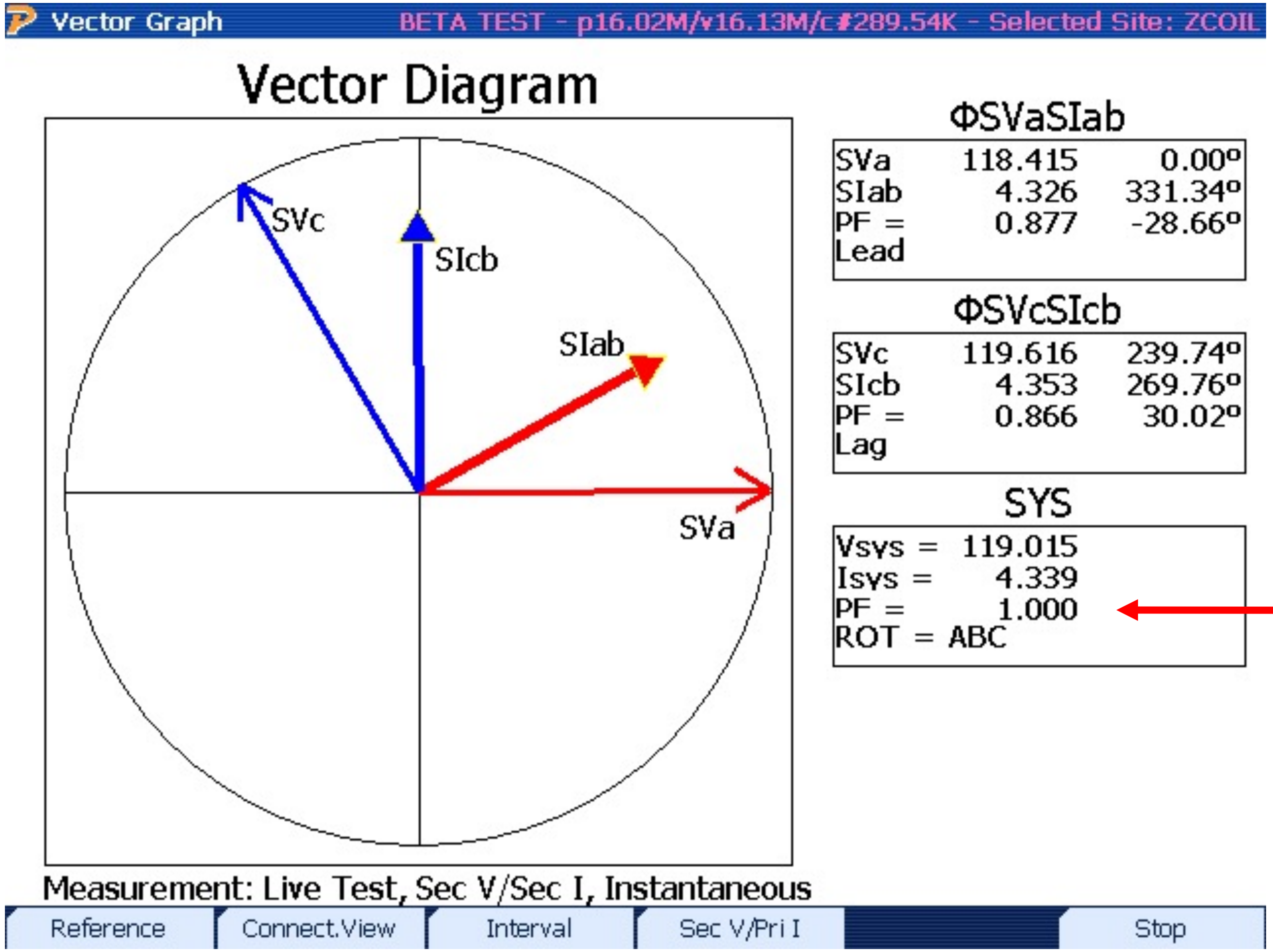


3 Phase Power Measurement



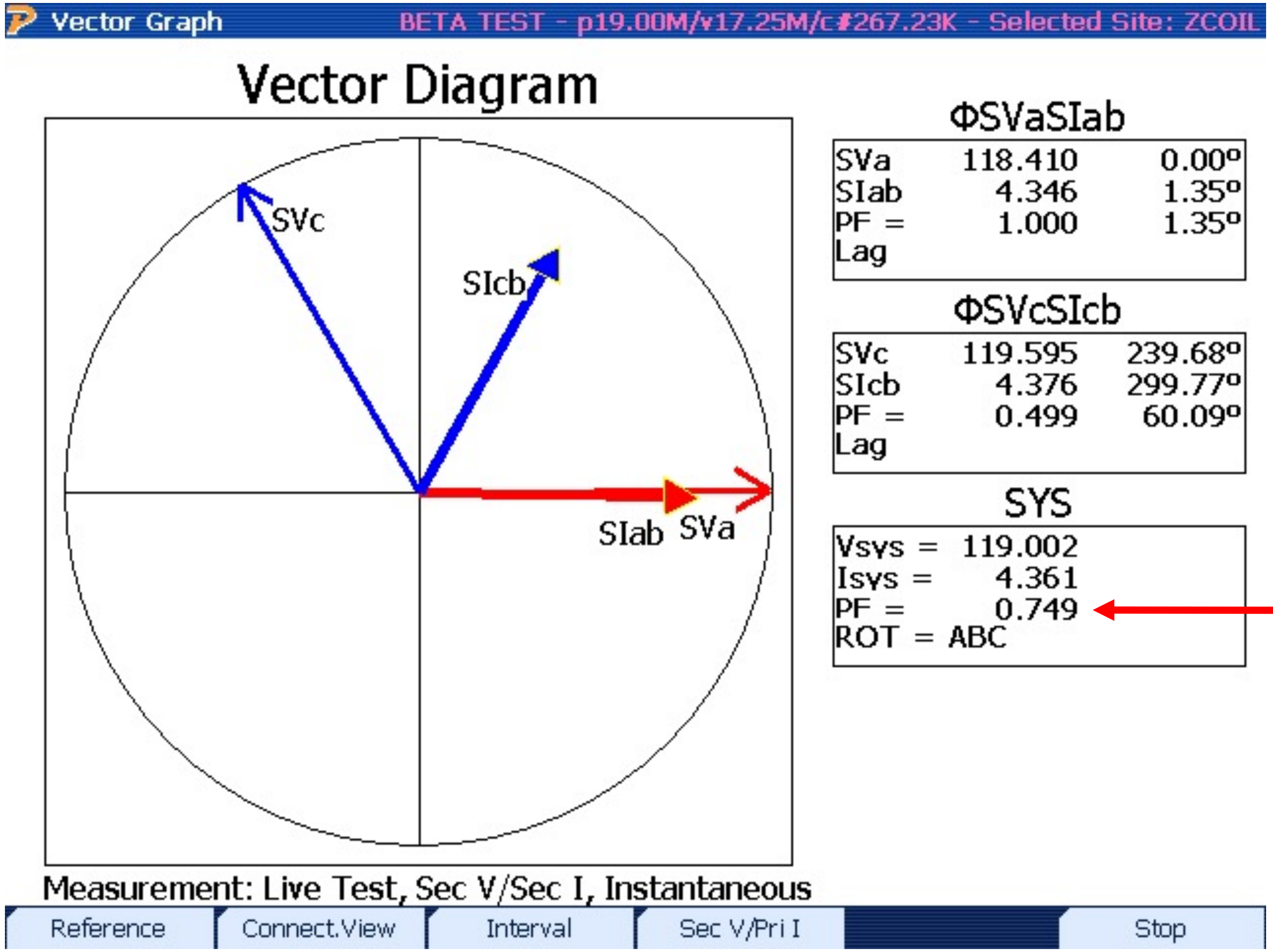
Arithmetic Calculation - Form 6 – 4 Wire Y Site
Voltages and Currents Aligned at 0°

3 Phase Power Measurement



Vector Calculation - Form 6 – 4 Wire Y Site
Voltages and Currents Aligned at 0°

3 Phase Power Measurement



Arithmetic Calculation - Form 6 – 4 Wire Y Site

Currents All shifted by 30°

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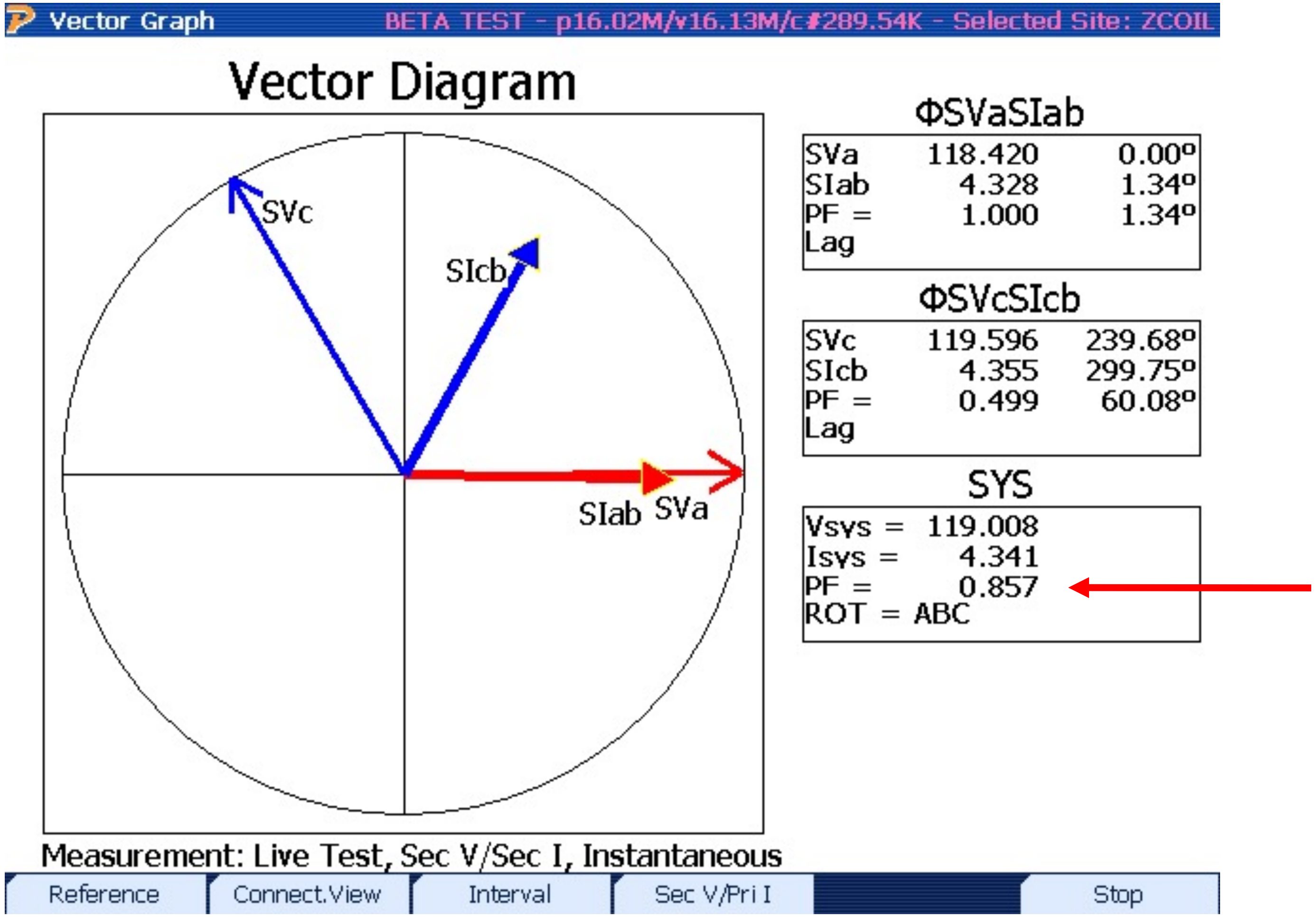
3 Phase Power Measurement



Vector Calculation - Form 6 – 4 Wire Y Site
Currents All shifted by 30°

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Displacement and Distortion Power Factor

Displacement and Distortion PF are used in systems that are non-linear (contain harmonics)

Displacement PF = cos (θ_1) where "1" represents the fundamental frequency (60Hz) ONLY

Distortion PF = $1/\sqrt{1+THD^2}$

True PF = Displacement PF * Distortion PF

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Total Harmonic Distortion (THD)

THD is a measurement of the ratio of the sum of the harmonic power to the power of the fundamental frequency.

$$\mathrm{THD} := \frac{\sqrt{\sum_{n=2}^{4} (V_n)^2}}{V_1}$$

This is an equation for a waveform with 3 harmonics.
V_1 is the fundamental (60Hz)
V_2 is the 2^{nd} harmonic (120Hz)
V_3 is the 3^{rd} harmonic (180Hz)
V_4 is the 4^{th} fundamental (240Hz)

Summary

- Power Factor is the ratio of useful power (Watts) to total power (VA) in a system
- PF decreases with inductance, and increase with capacitance
- An ideal system has a PF = 1, which represents 100% active, useful power being delivered to the load
- PF calculations may differ depending on the metering

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