Introduction to Vector Diagrams

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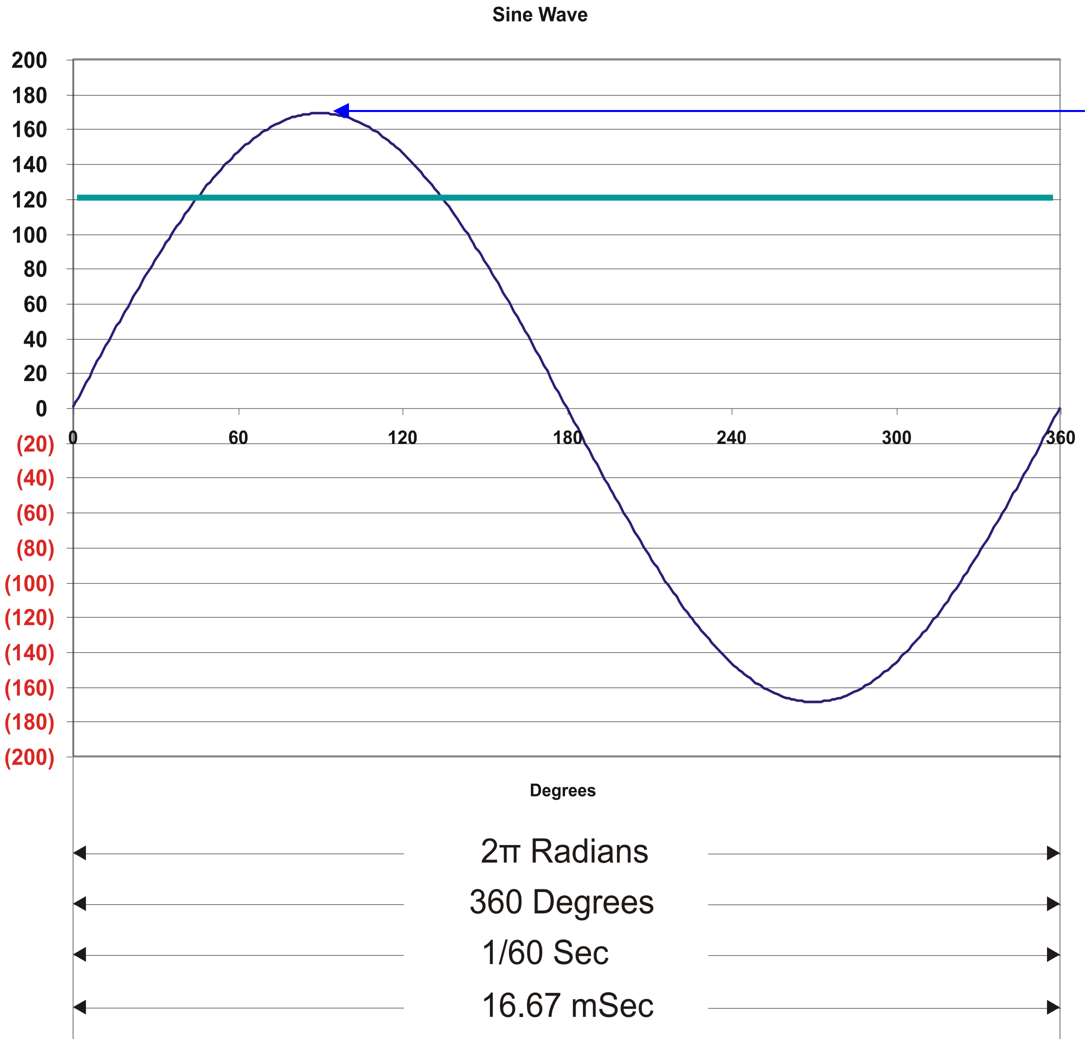
AC Theory Review – Sine Wave



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

Where Vpk is peak voltage
f is frequency
t is time
θ (theta) is phase

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

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

$$V_{rms} = 120V$$

$$V_{pk} = 169V$$

$$f = 60Hz$$

$$\theta = 0°$$

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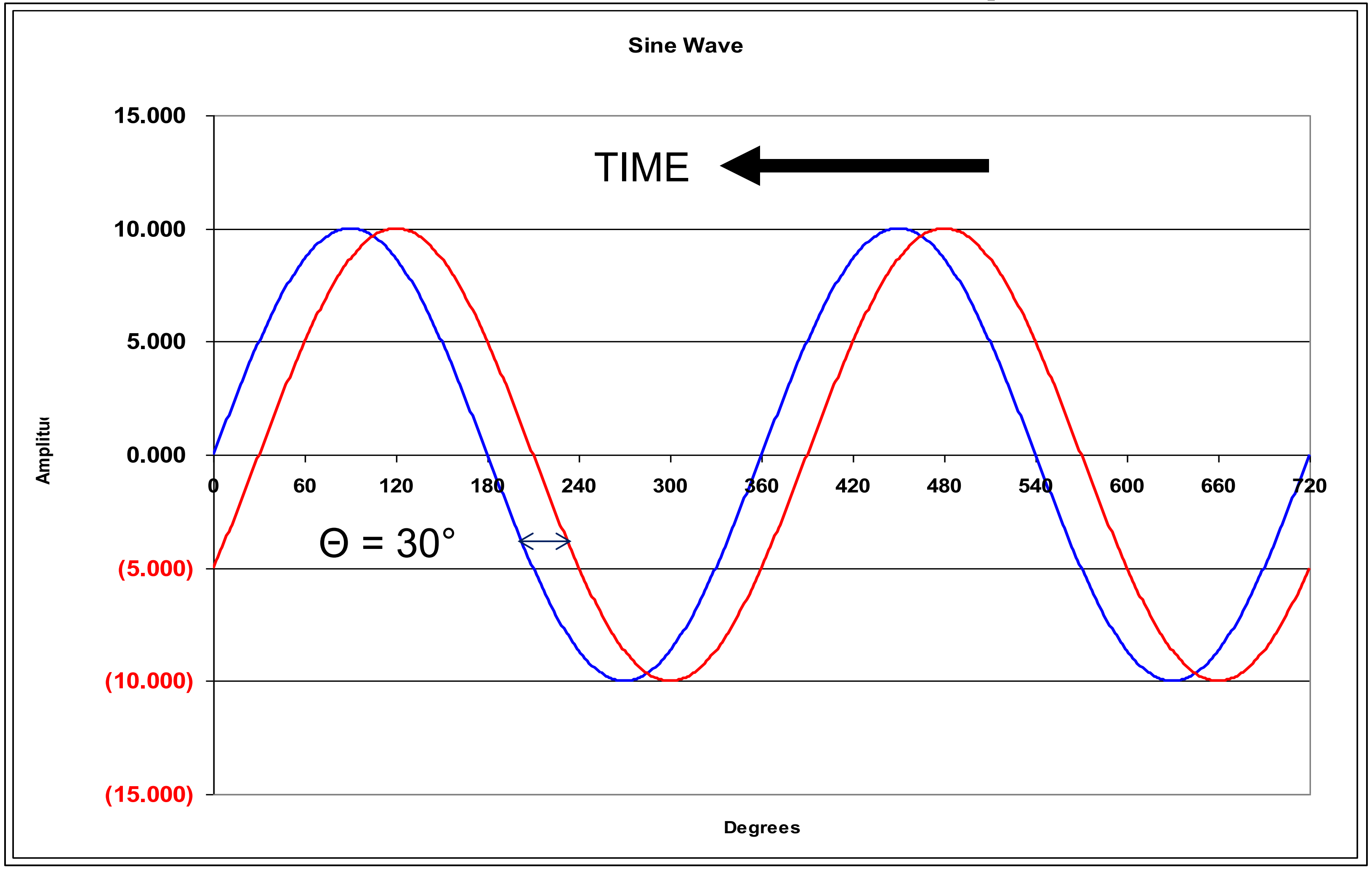
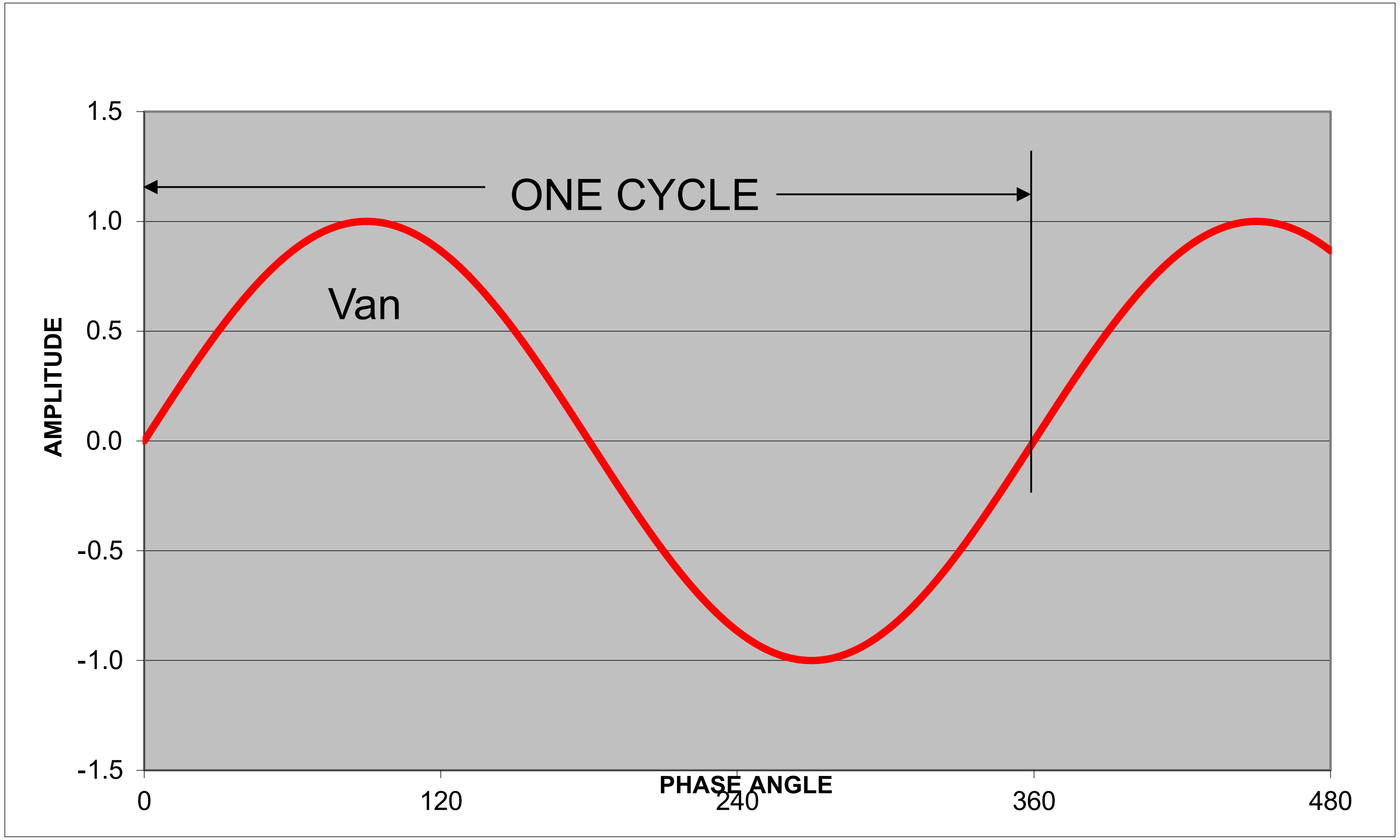
Phase Relationship



Current is lagging Voltage by 30˚

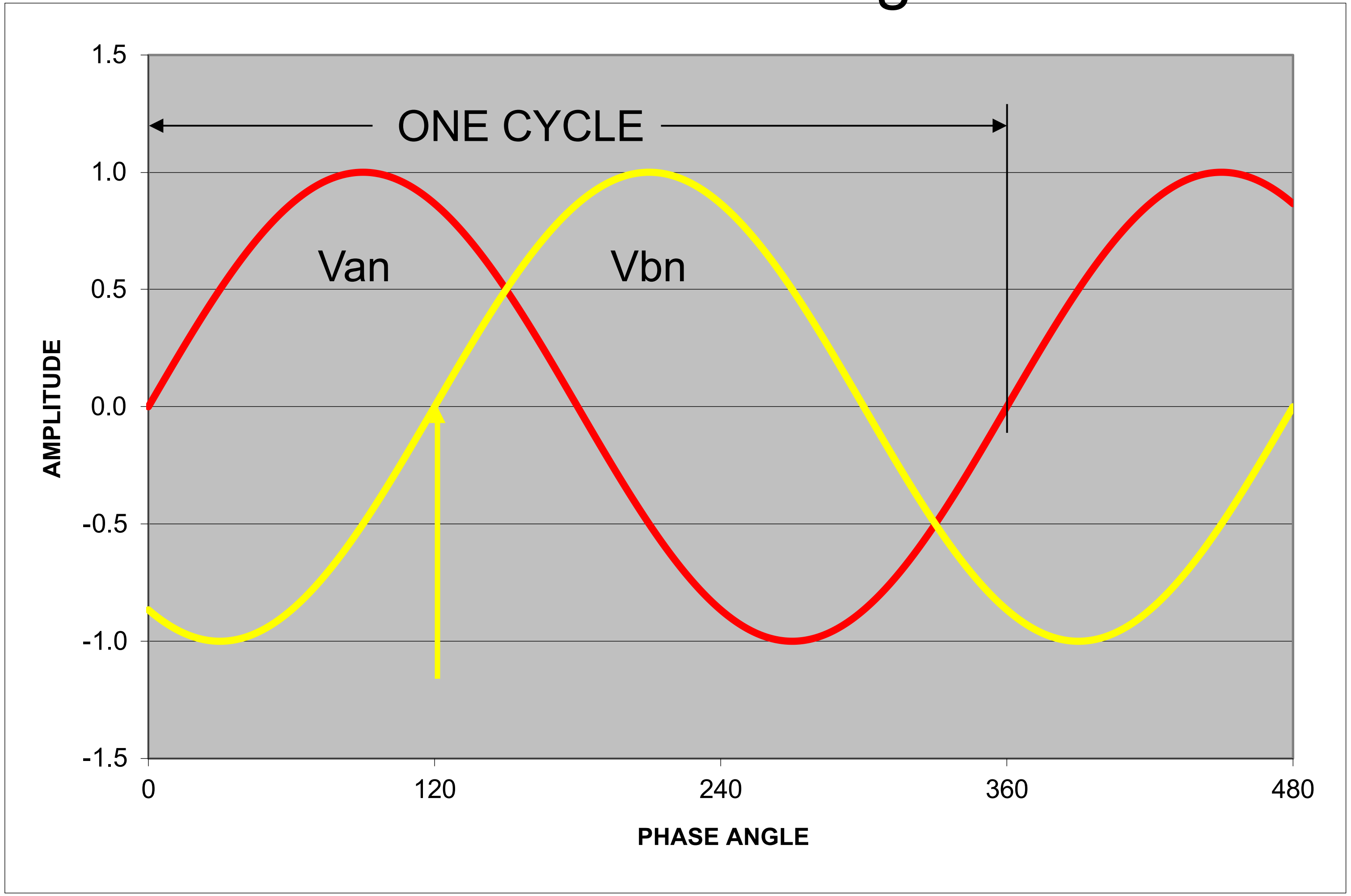
Three Phase Theory

Single Phase - Voltage Plot



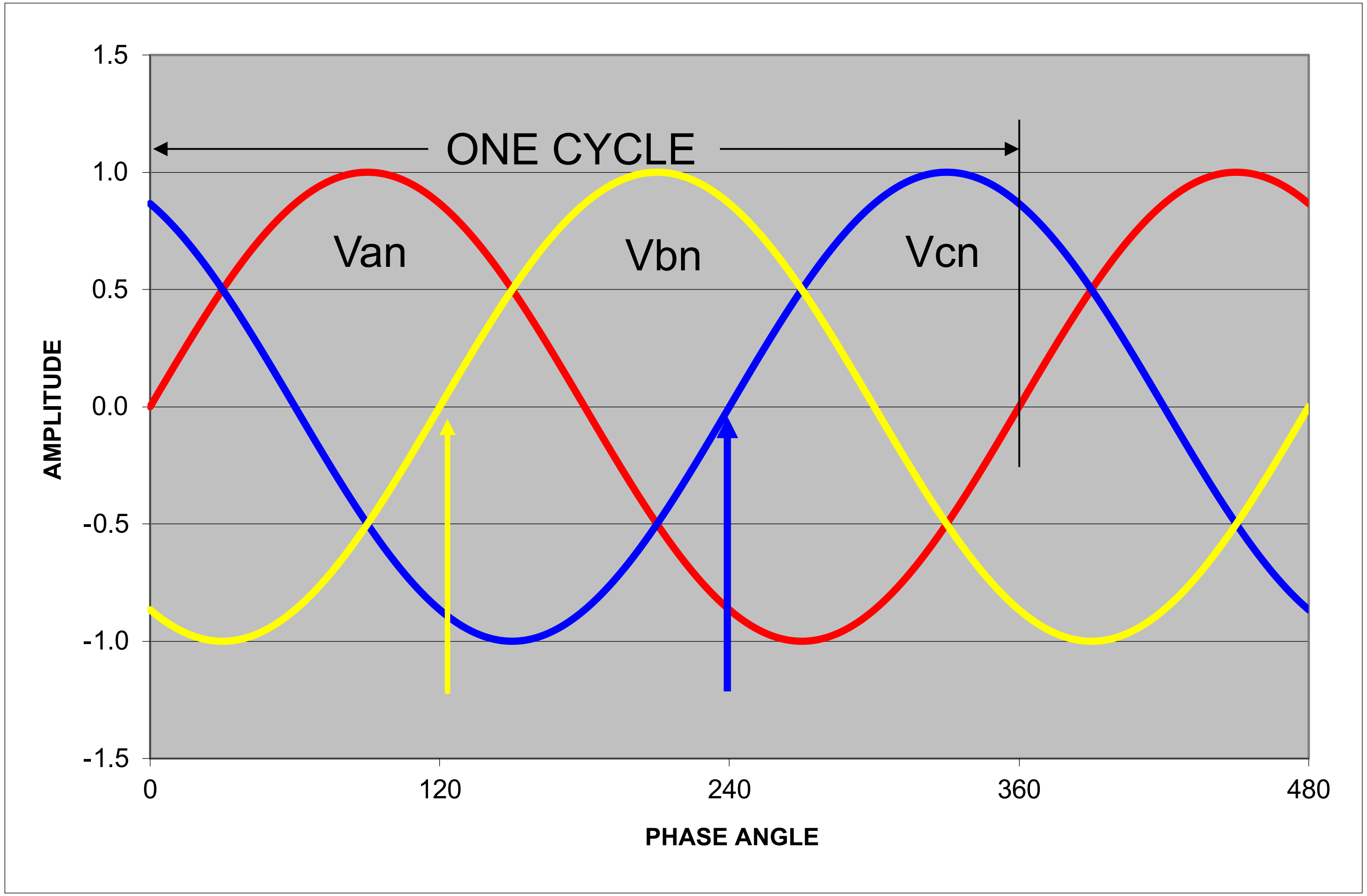
Three Phase Theory

Two Phases - Voltage Plot



Three Phase Theory

Three Phase - Voltage Plot

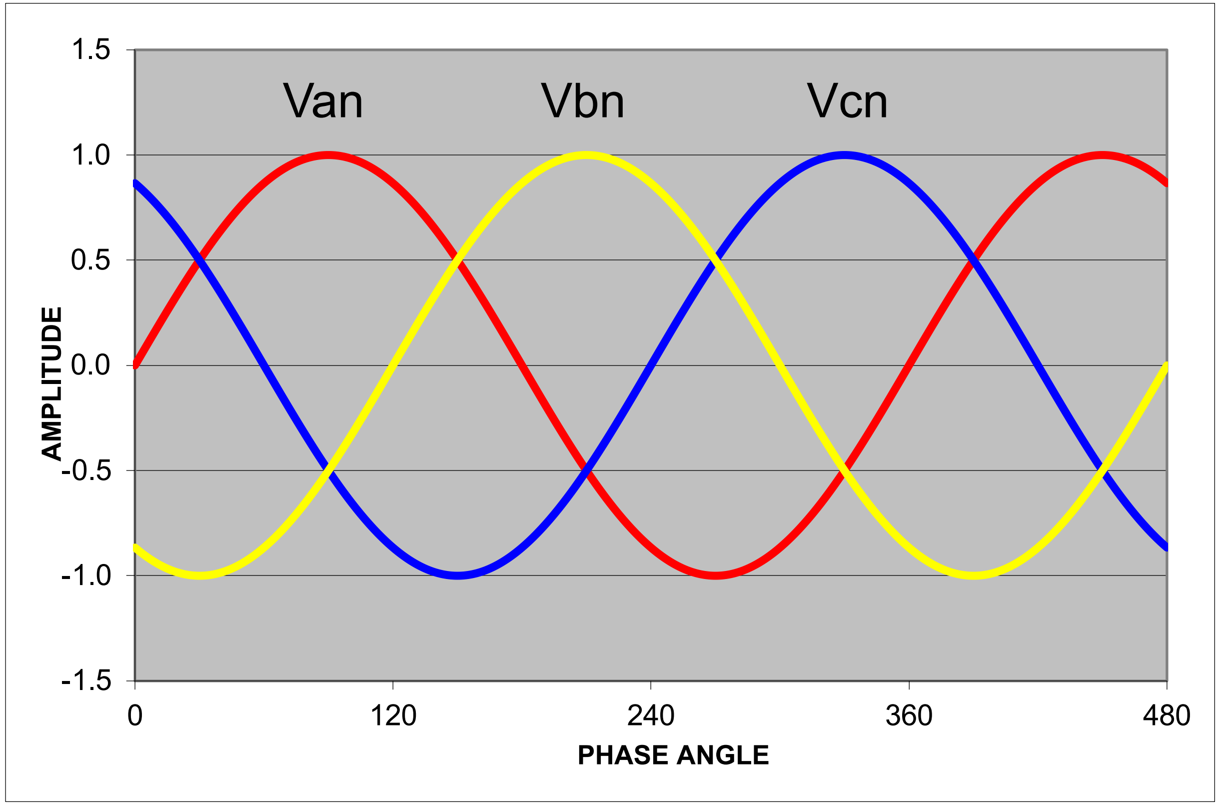


Three Phase Power

At the Generator

Three voltage vectors each separated by 120°.

Peak voltages essentially equal.



Most of what makes three phase systems seem complex is what we do to this simple picture in the delivery system and loads.

Three Phase Power

Basic Concept – Phase Rotation

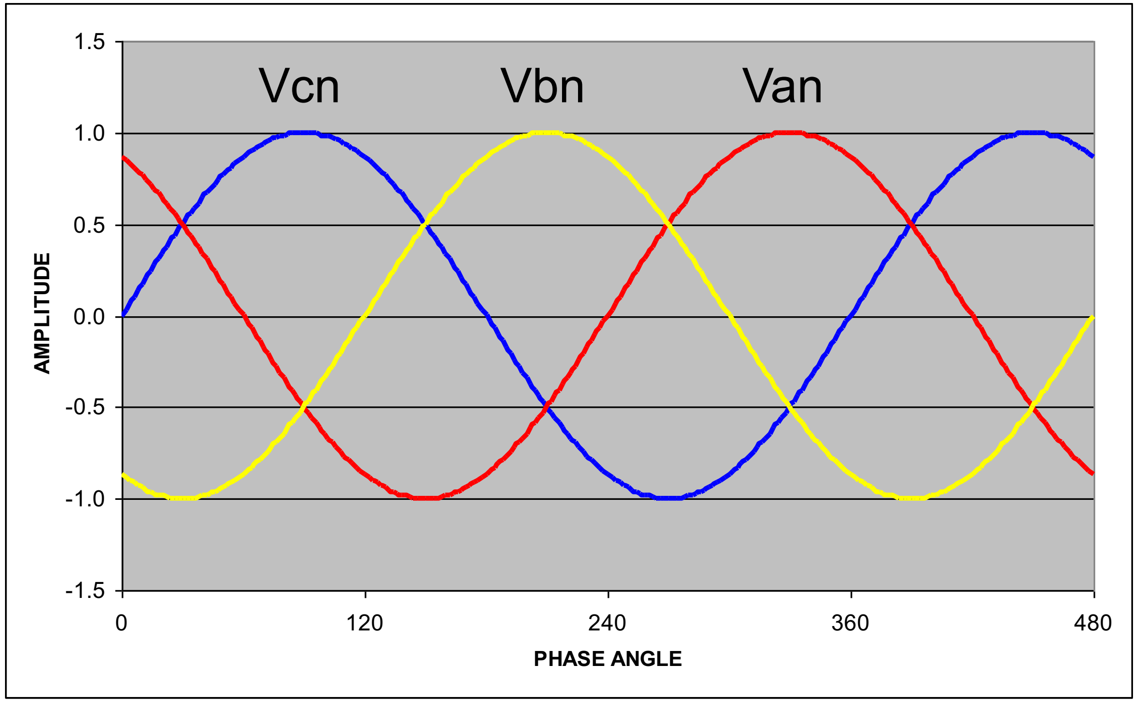
Phase Rotation:

The order in which the phases reach peak voltage.

There are only two possible sequences:

A-B-C (previous slide)

C-B-A (this slide)



Phase rotation is important because the direction of rotation of a three phase motor is determined by the phase order.

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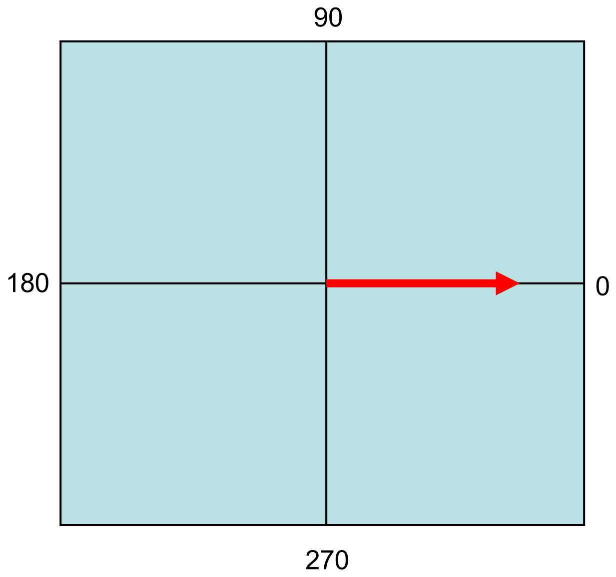
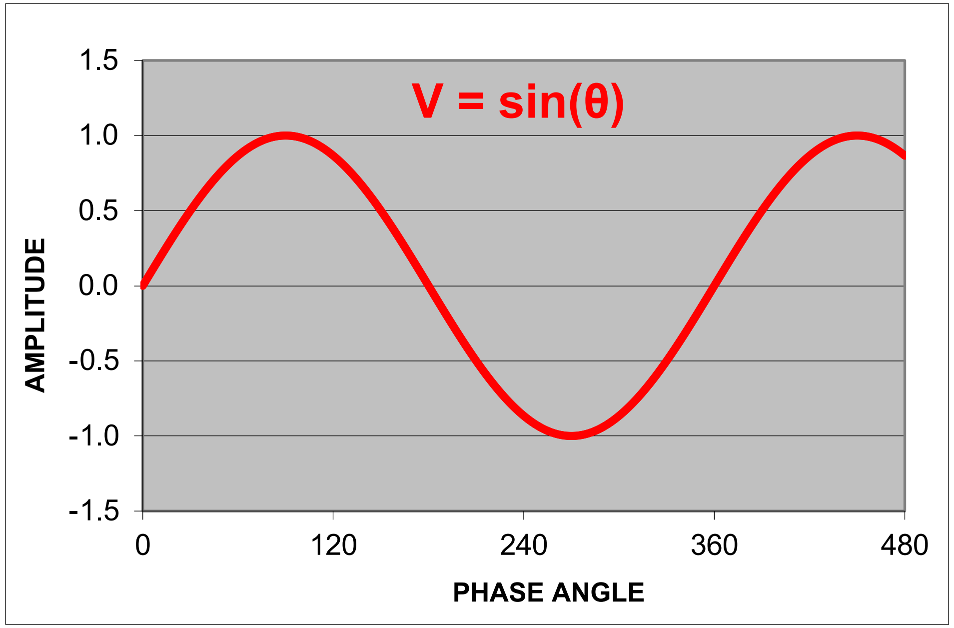
Three Phase Theory

Phasors and Vector Notation

- Phasors are a graphical means of representing the amplitude and phase <u>relationships</u> of voltages and currents.

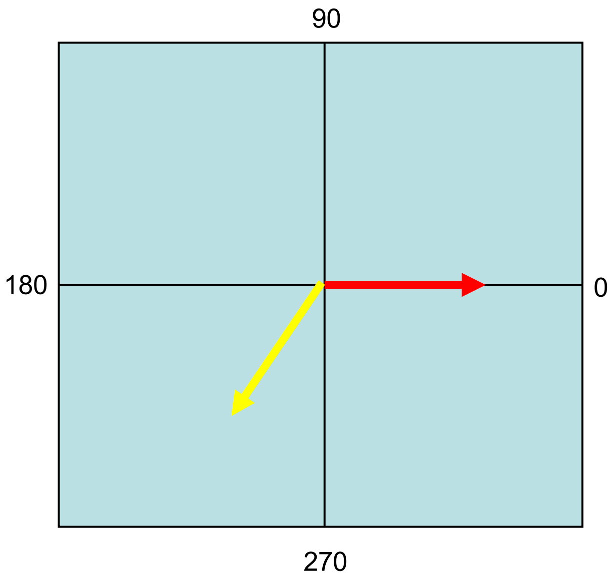


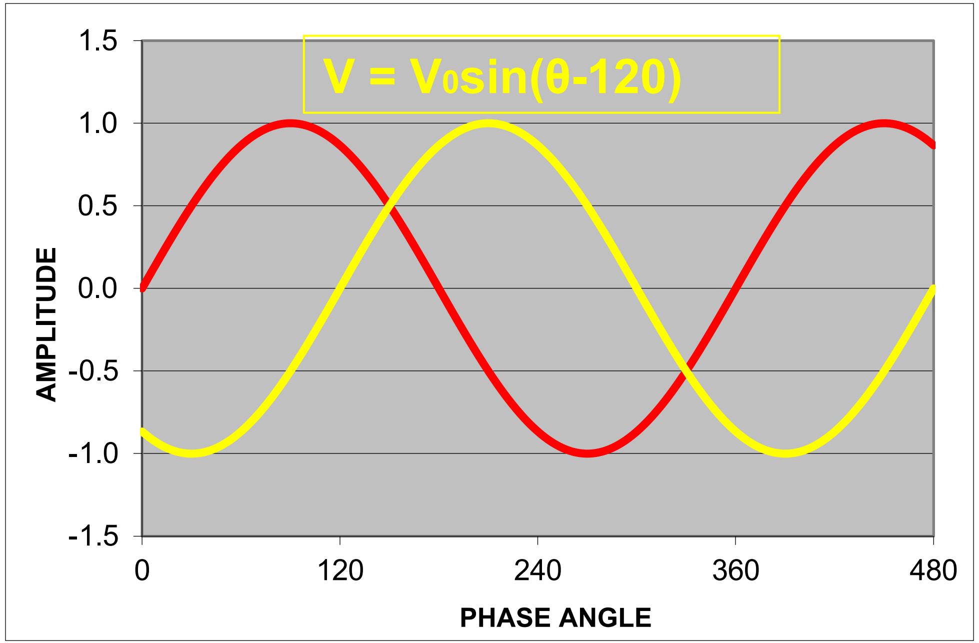


Three Phase Power

Phasors and Vector Notation

- As stated in the Handbook of Electricity Metering, by common consent, counterclockwise phase rotation has been chosen for general use in phasor diagrams.

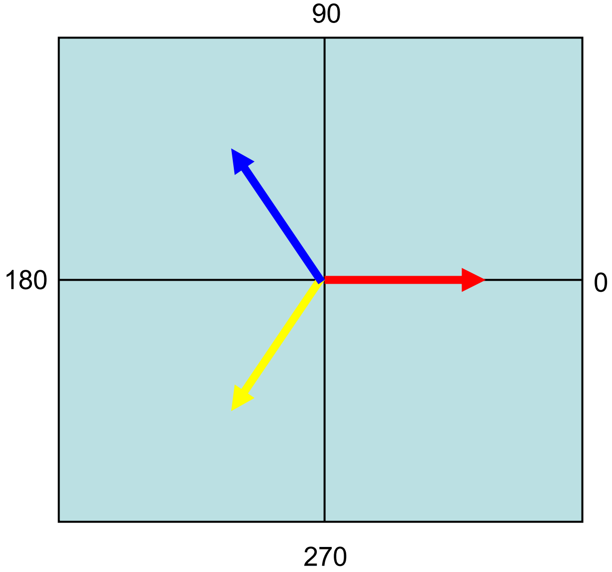


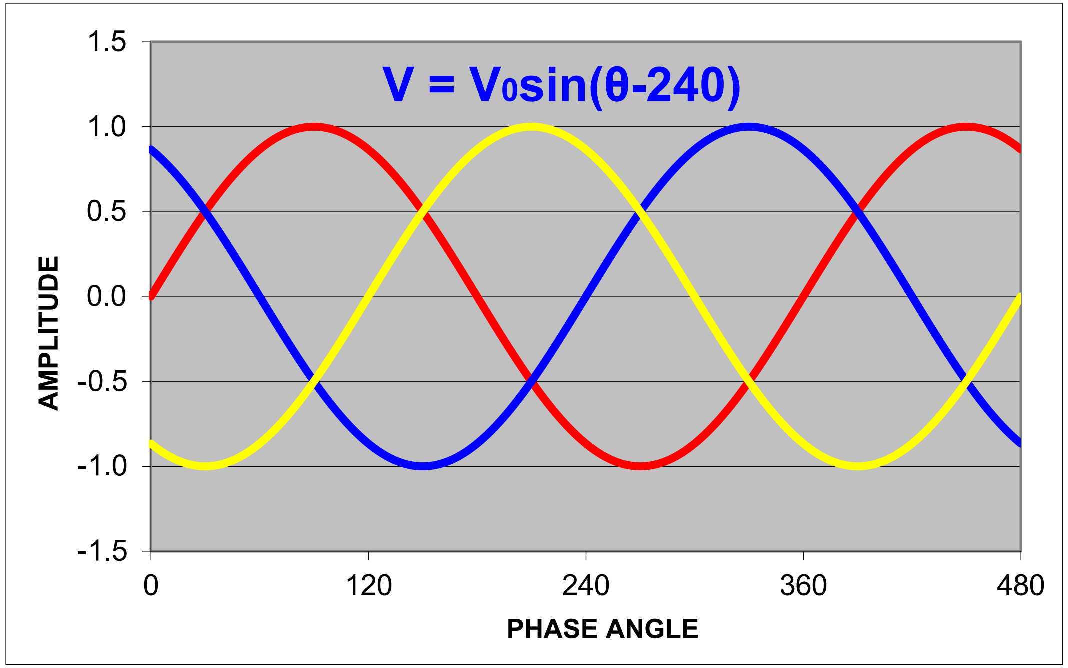


Three Phase Power

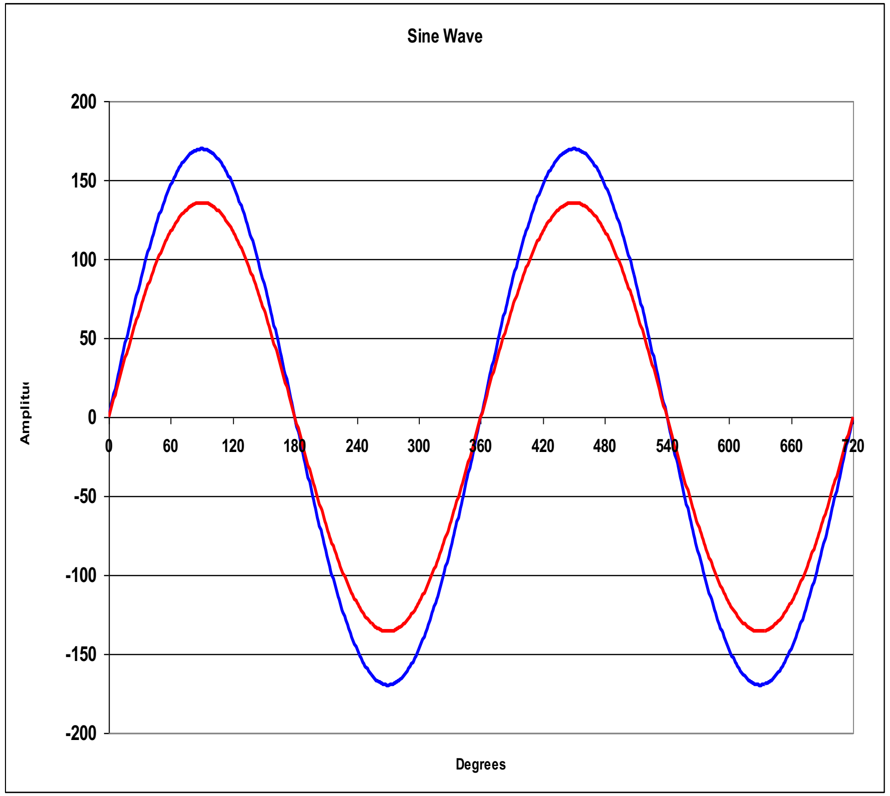
Phasors and Vector Notation

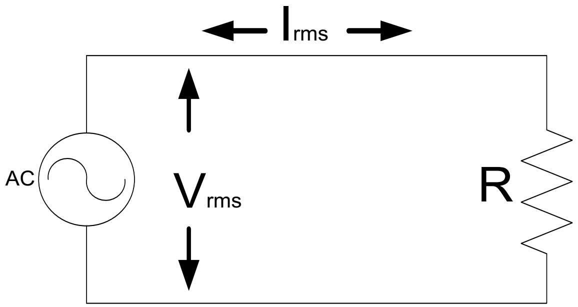
- The phasor diagram for a simple 3-phase system has three voltage phasors equally spaced at 120° intervals.
- Going clockwise the order is A – B – C.

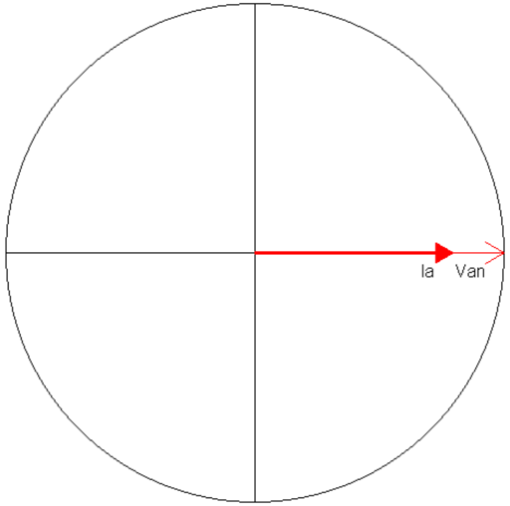




Resistive Load







A purely resistive load has ZERO phase angle. The voltage and current vectors overlap.

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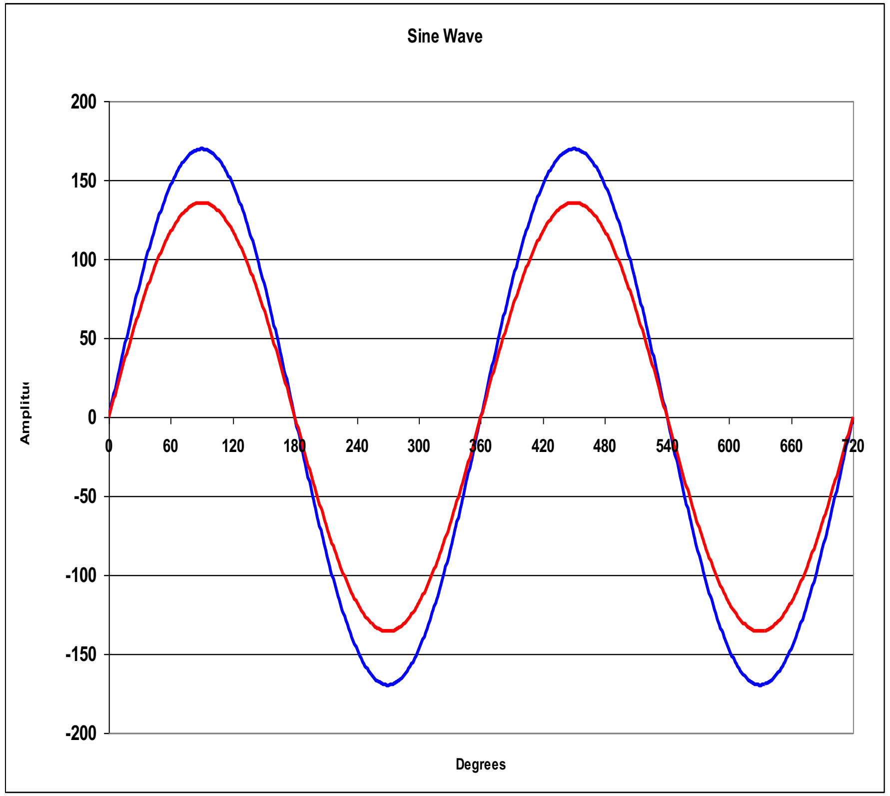
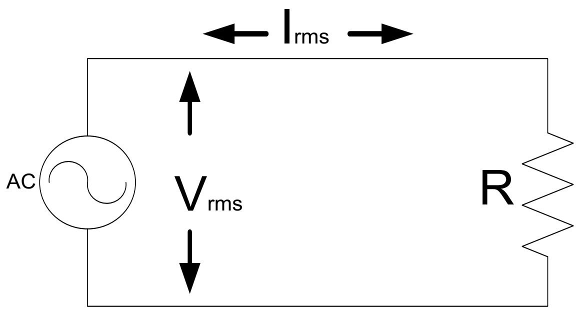
Resistive Load





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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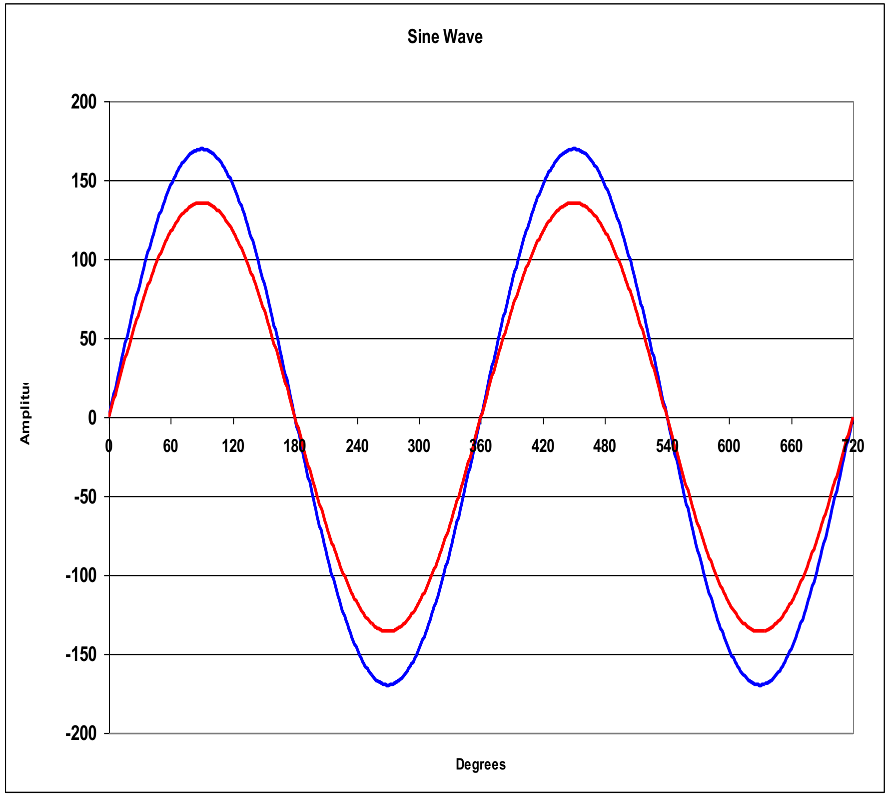
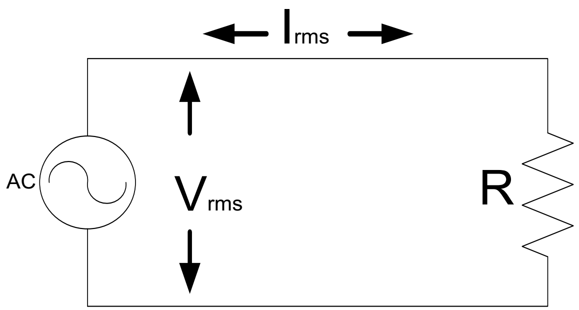
Resistive Load





A purely resistive load will:

- Only create Watts
- Create NO VARs
- Have a PF = 1 and phase angle of 0°

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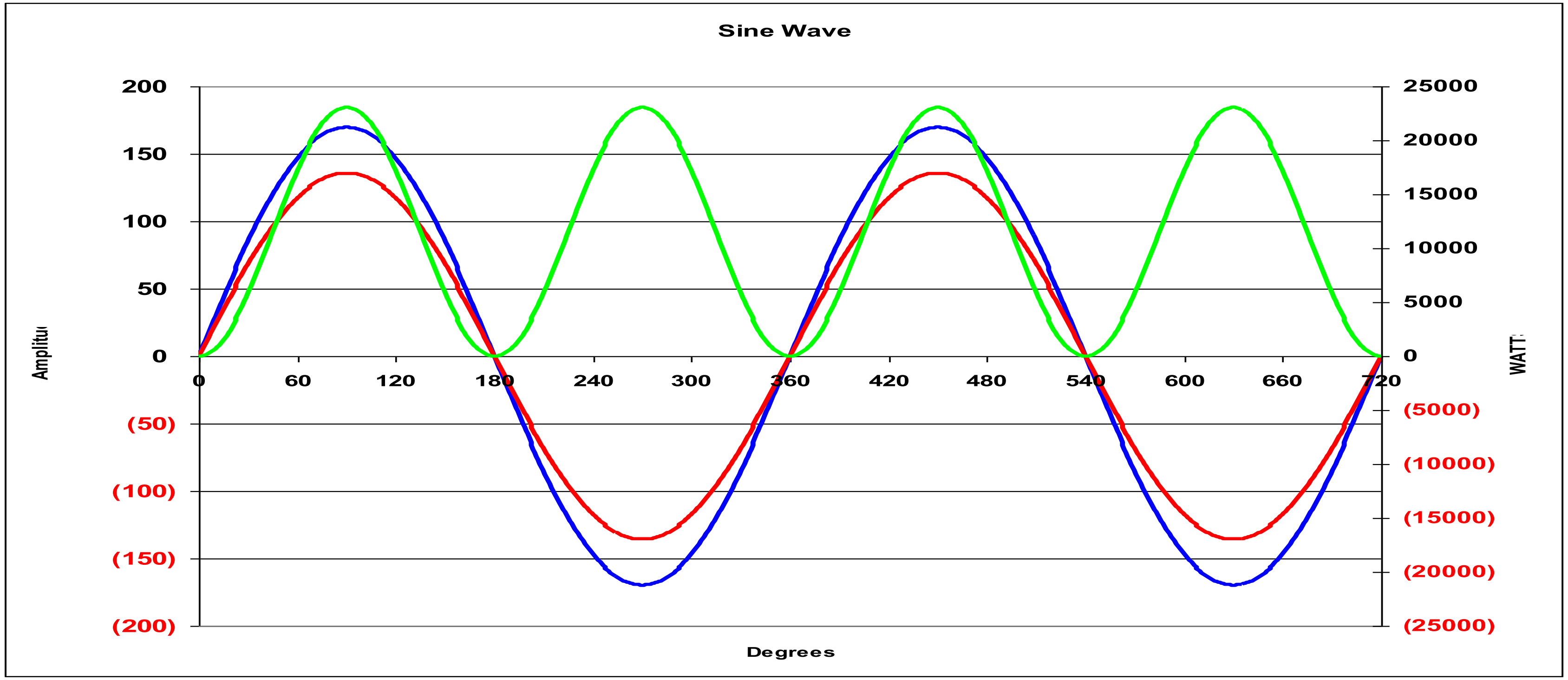
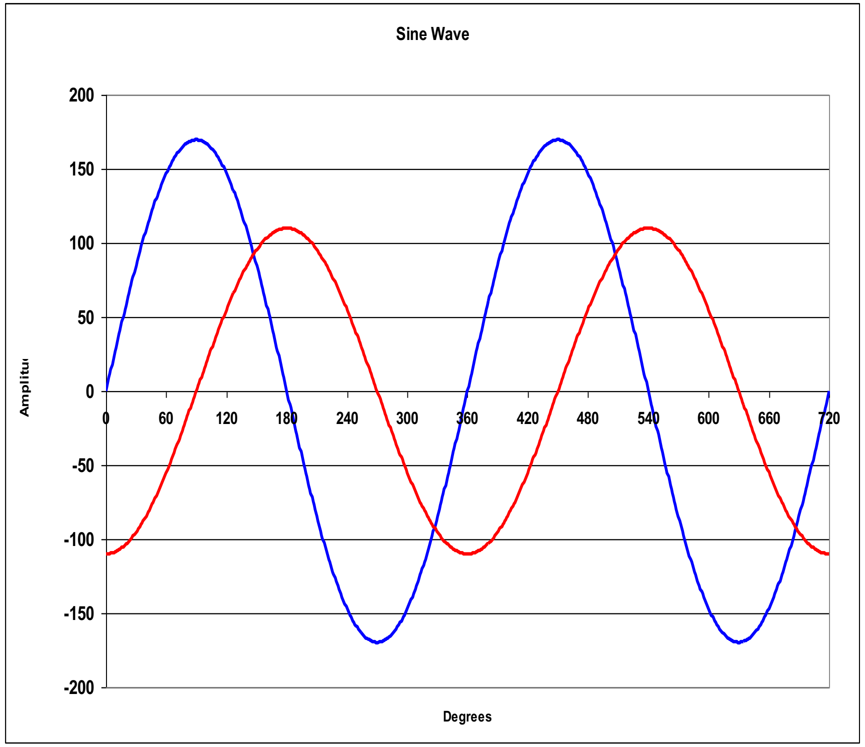
Resistive Load

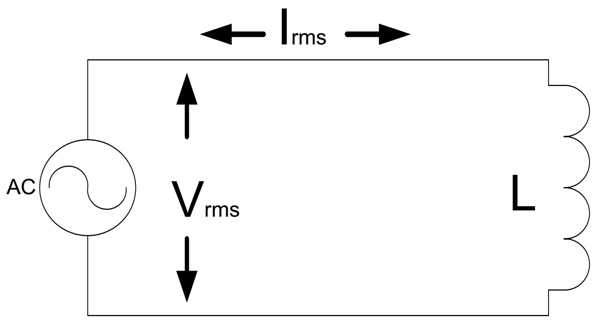
For a resistive load: $p = vi = 2VISin^2(\omega t) = VI(1 - Cos(2\omega t))$

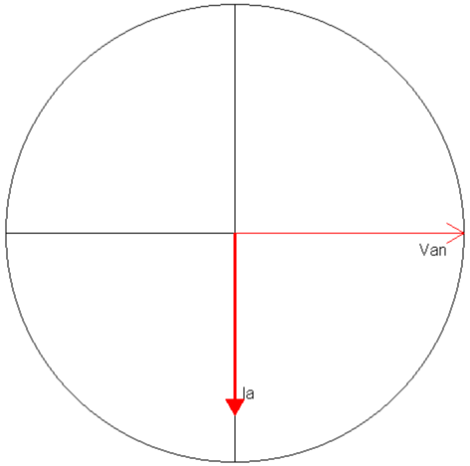


A resistive load consumes only Watts, so the power will always be delivered (positive).

Inductive Load

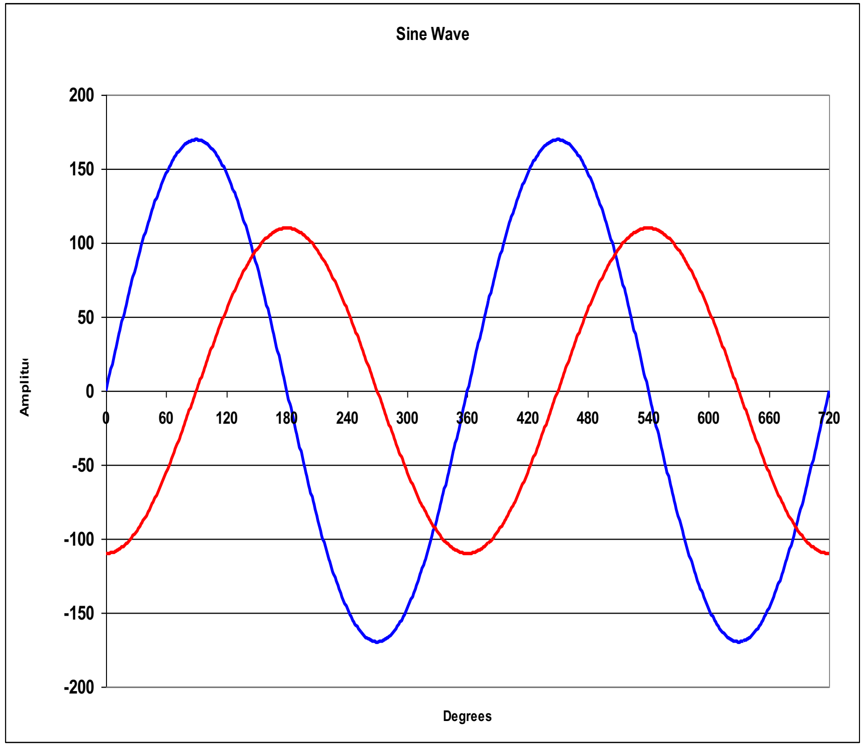


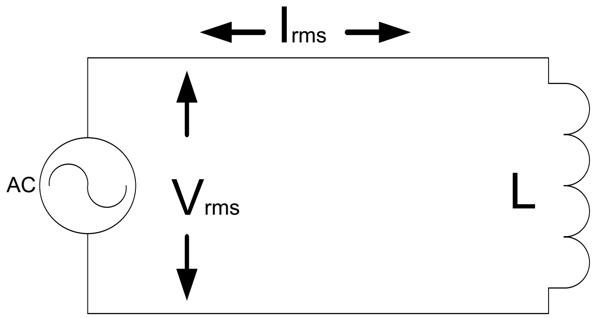




A purely inductive load has +90° phase angle. Clockwise vectors are LAGGING as current lags voltage.

Inductive Load





Inductive Example:

V = 120V

I = 10A

Θ = 90°

Cos 90° = 0

Sin 90° = +1

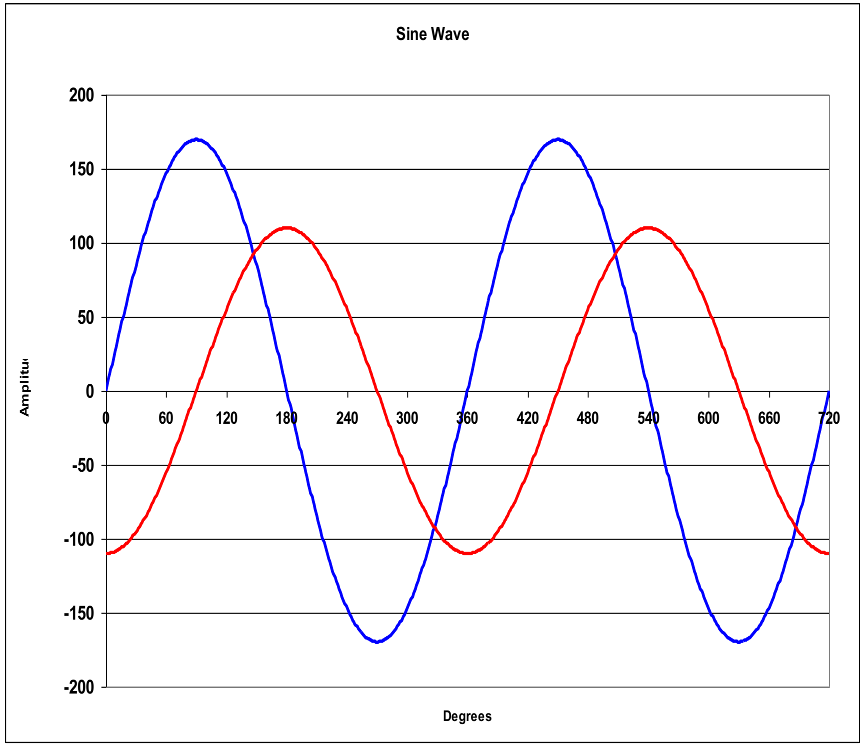
Active Power (W) = V I cos (θ) = 120 * 10 * 0 = 0 W

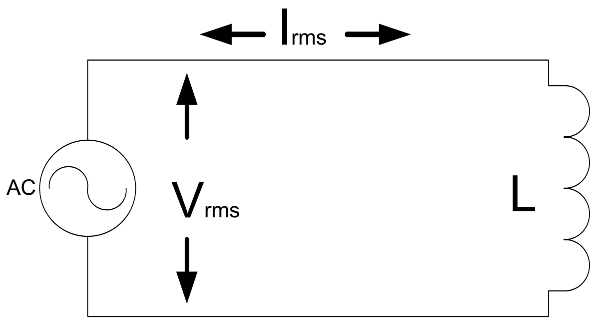
Reactive Power (VAR) = V I sin (θ) = 120 * 10 * +1 = +1200 VAR

Apparent Power (VA) = V I = 120 * 10 = 1200 VA

PF = W / VA = cos (θ) = 0

Inductive Load



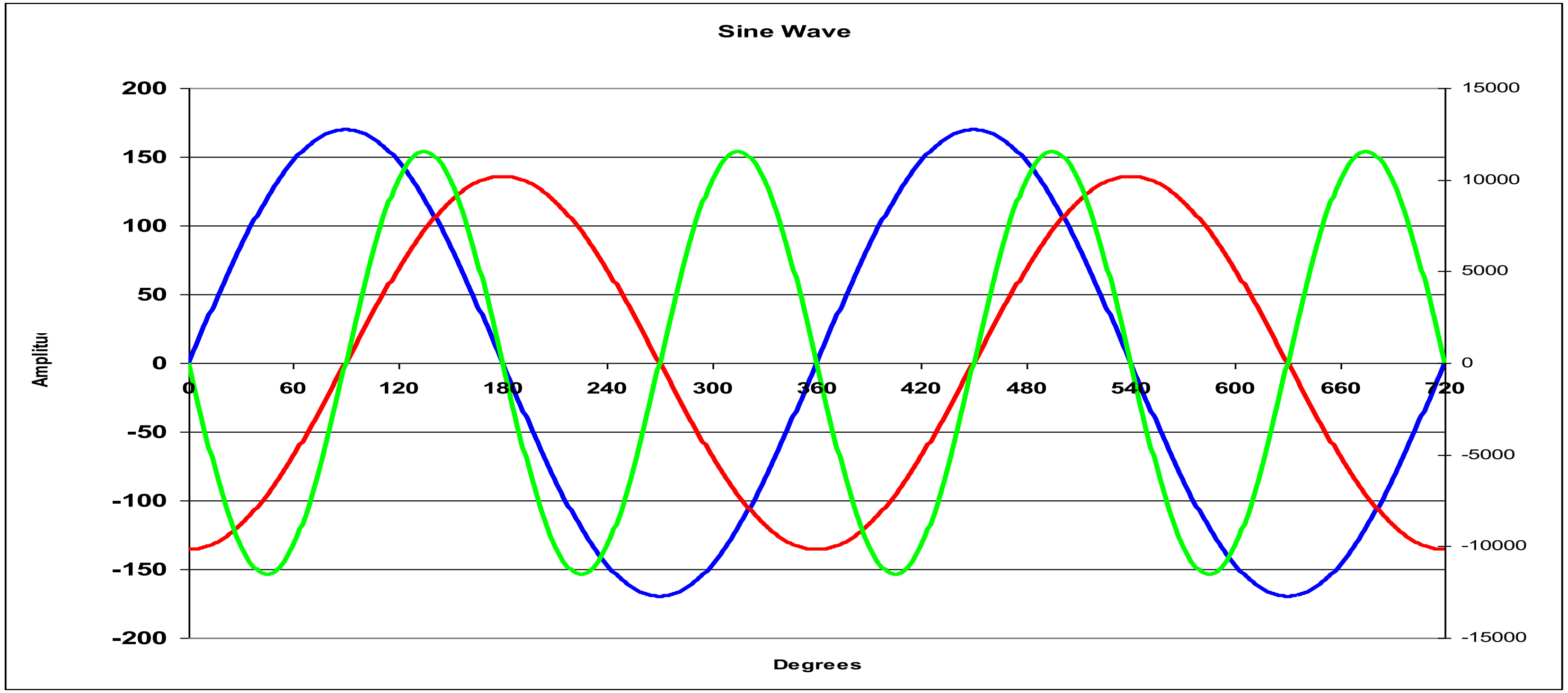


A purely inductive load will:

- Only create positive VARs
- Create NO Watts
- Have a PF = 0 and phase angle of 90° lagging

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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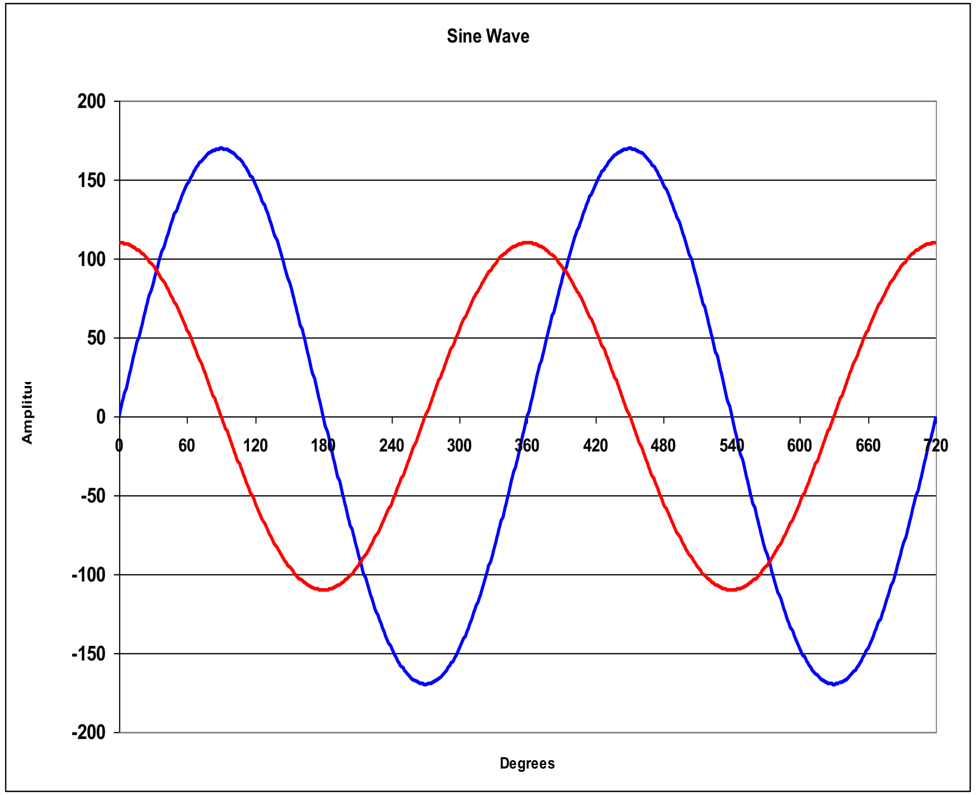
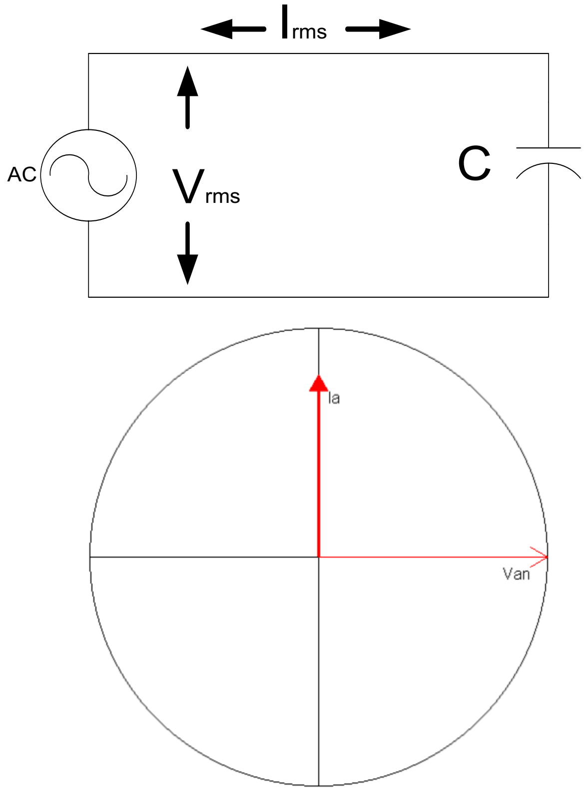
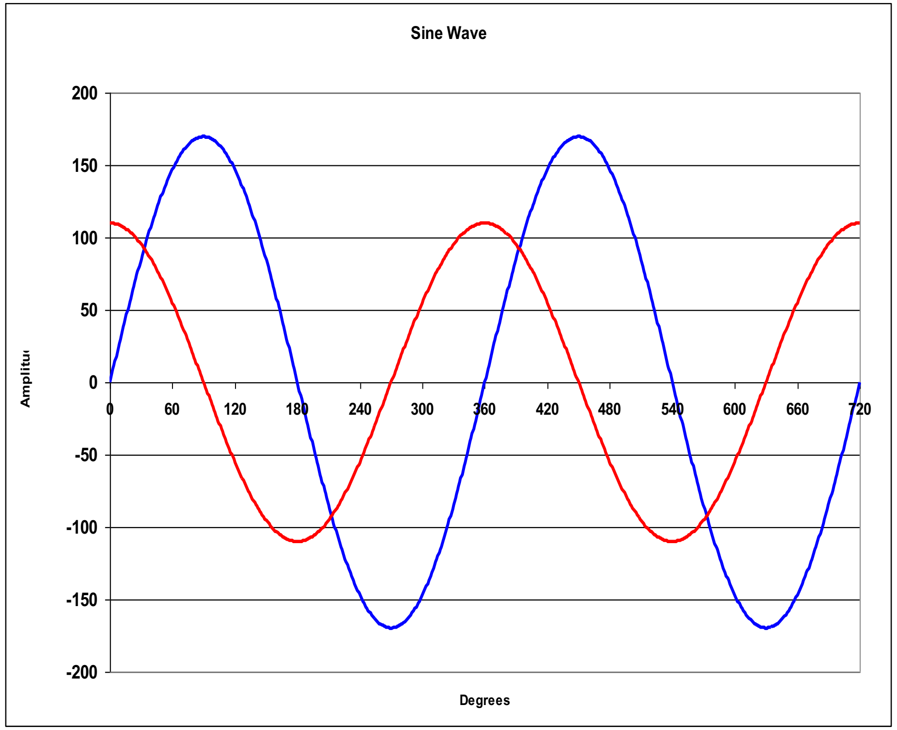
Capacitive Load

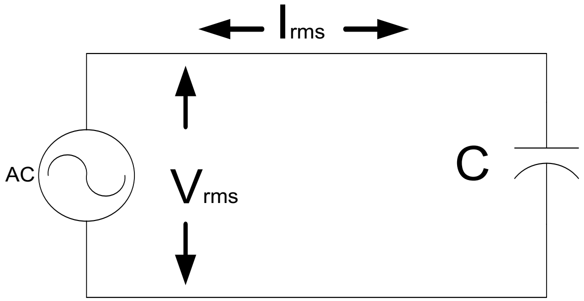




A purely capacitive load has -90° phase angle. Counter-clockwise vectors are LEADING as current leads voltage.

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

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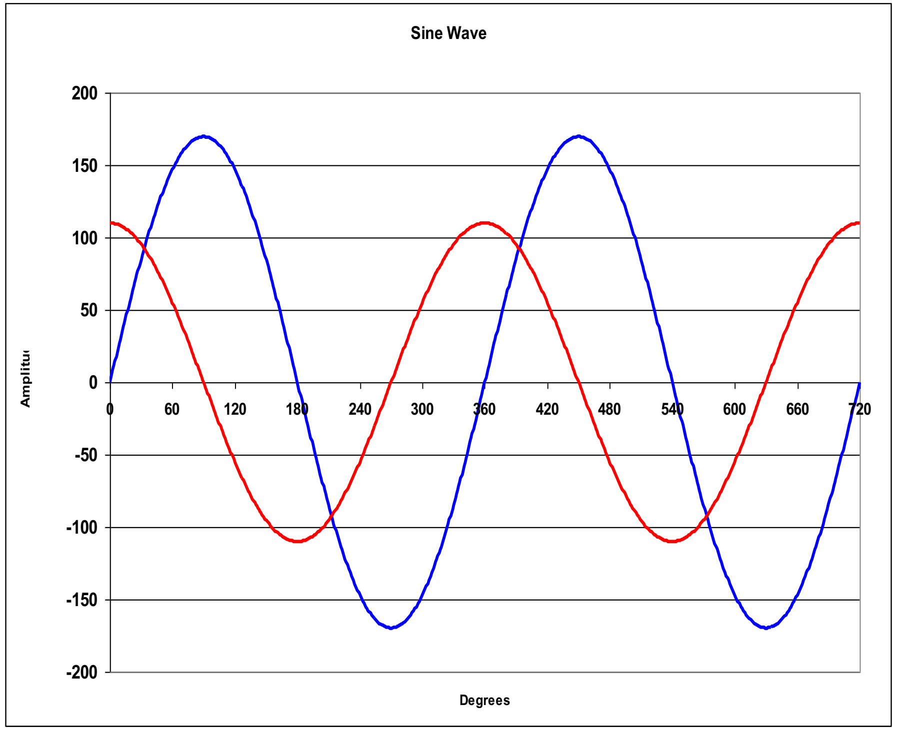
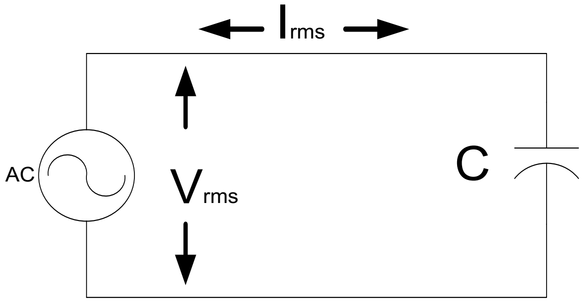
Capacitive Load



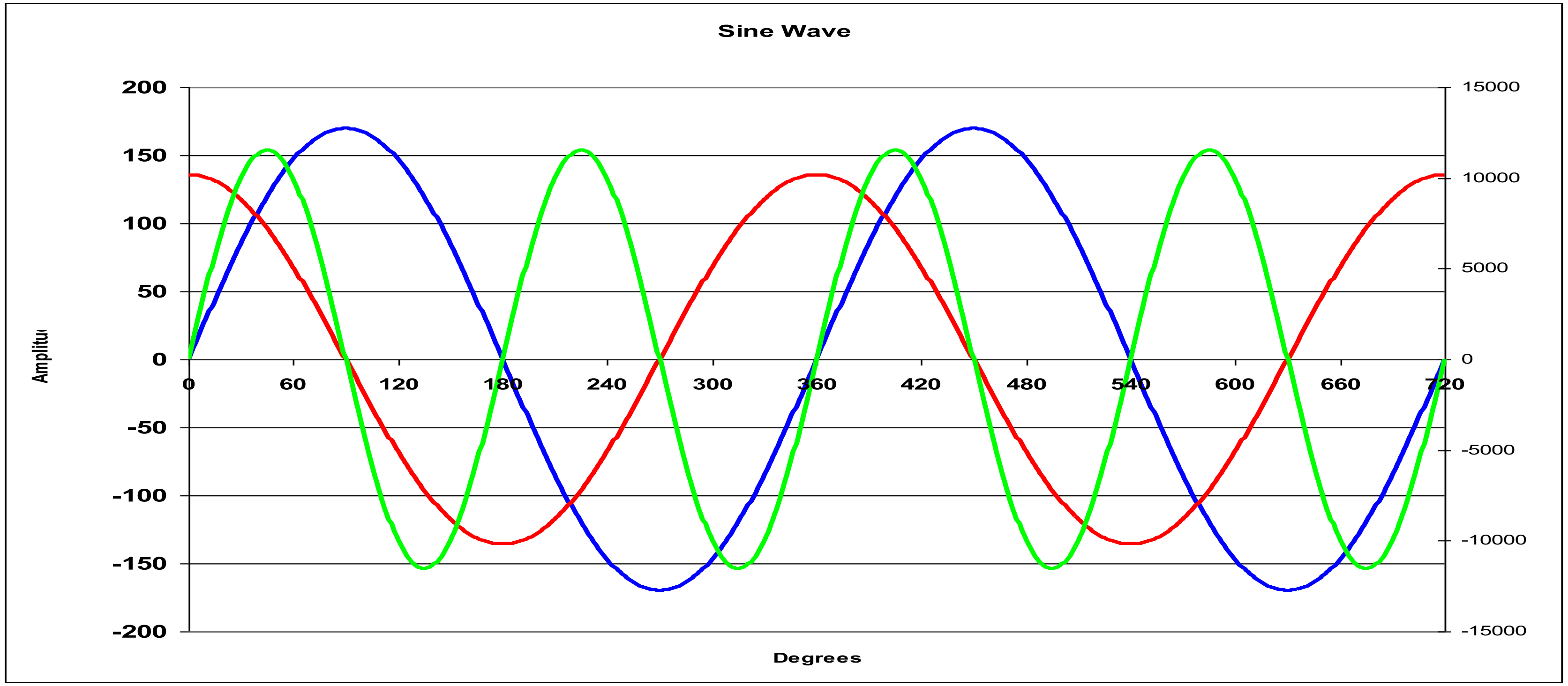


A purely capacitive load will:

- Only create negative VARs
- Create NO Watts
- Have a PF = 0 and phase angle of 90° leading

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

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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

+

=

Power Factor, Watts, and VARs

For a 120V, 10A System

Phase Angle	PF	Watts	VAR	VA
0	1	1200 W	0 VAR	1200 VA
30	0.866	1039 W	600 VAR	1200 VA
60	0.5	600 W	1039 VAR	1200 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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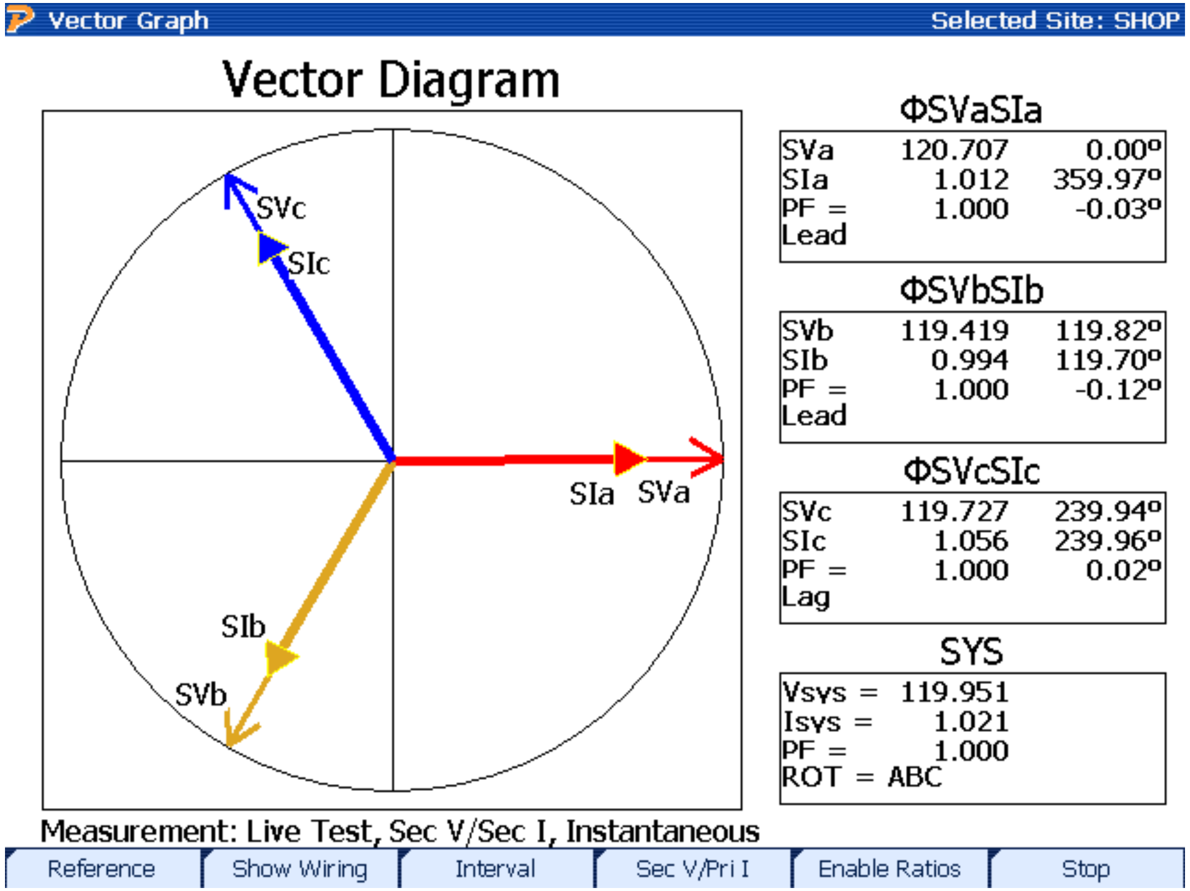
3 Phase, 4-Wire "Y" Service

0° = Unity Power Factor

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



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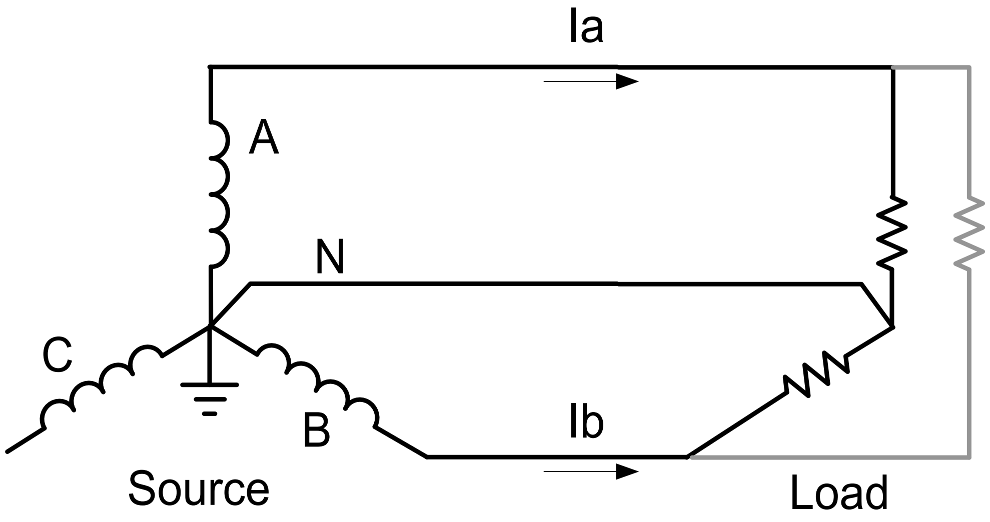
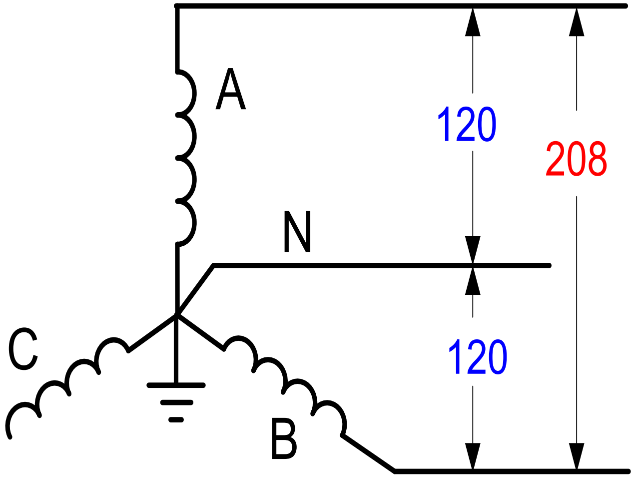
2 Phase, 3-Wire "Y" Service

"Network Connection"

Single phase variant of the service.





Two voltage sources with their returns connected to a common point.

Provides 208 rather than 240 volts across "high side" wires.

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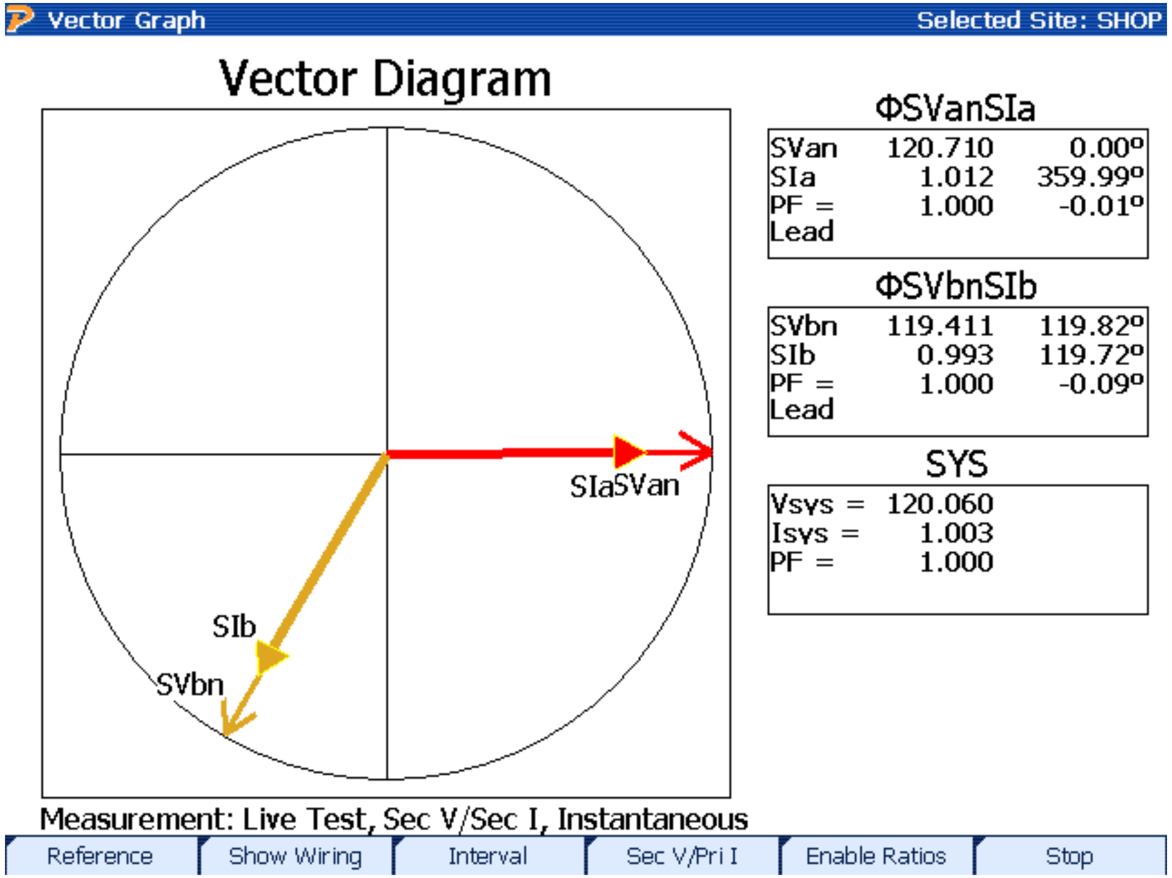
2 Phase, 3-Wire “Network” Service

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



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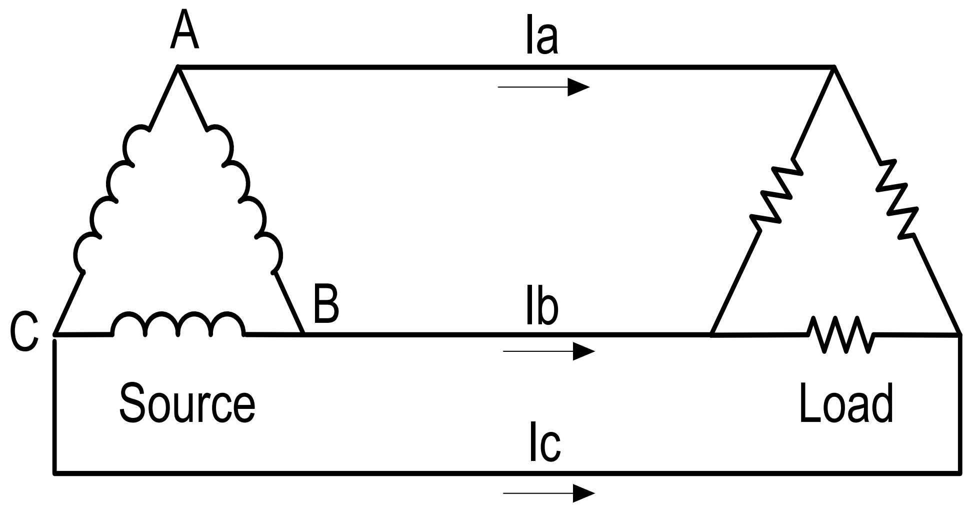
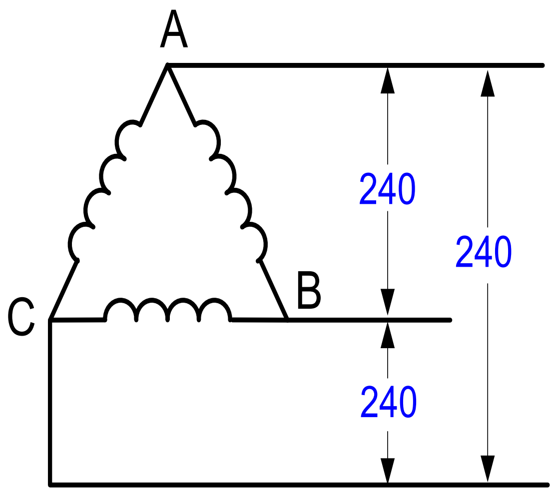
3 Phase, 3-Wire Delta Service

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





•Voltages normally measured relative to phase B.

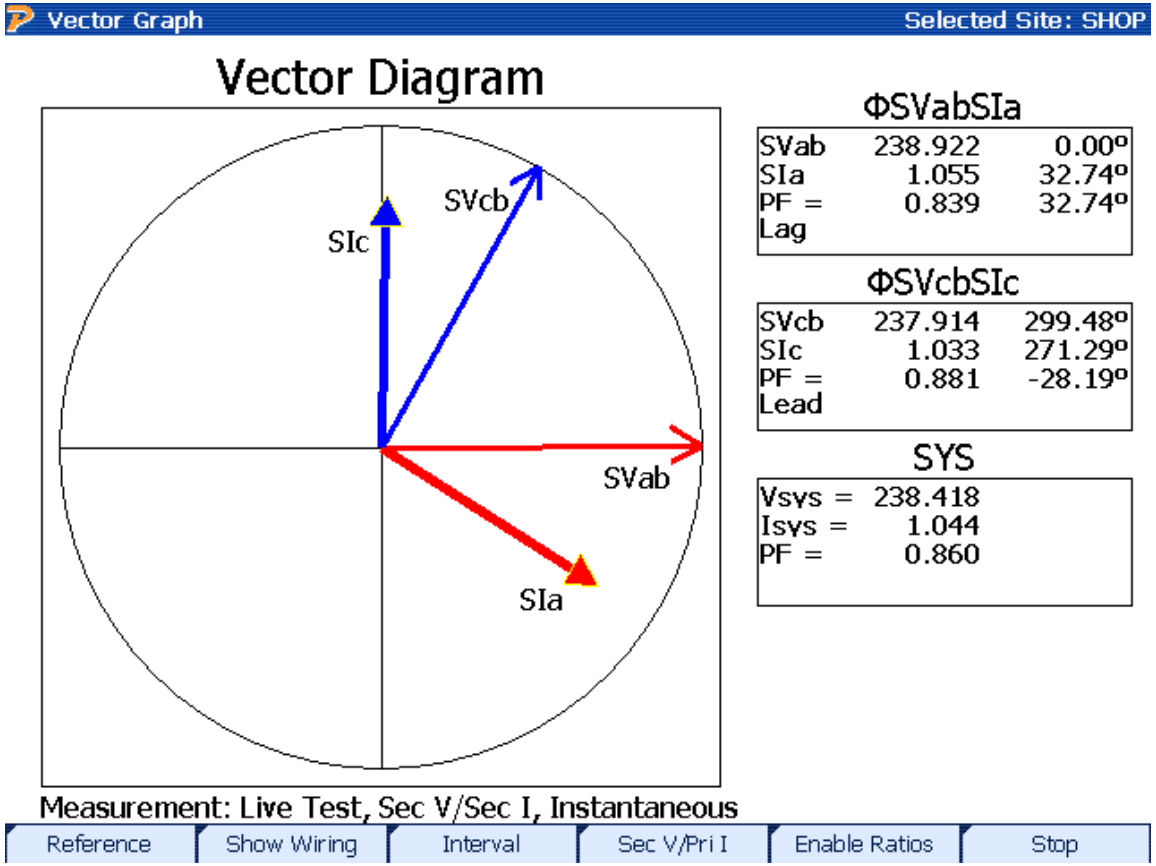
•Voltage and current vectors do not align.

•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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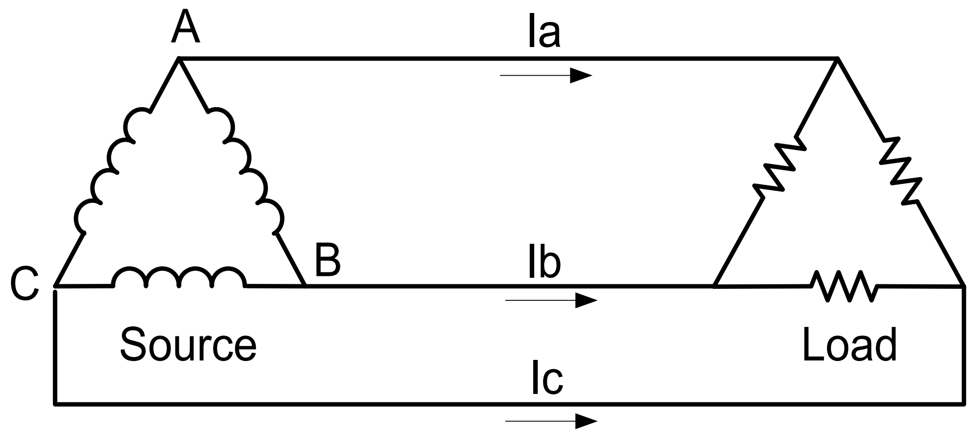
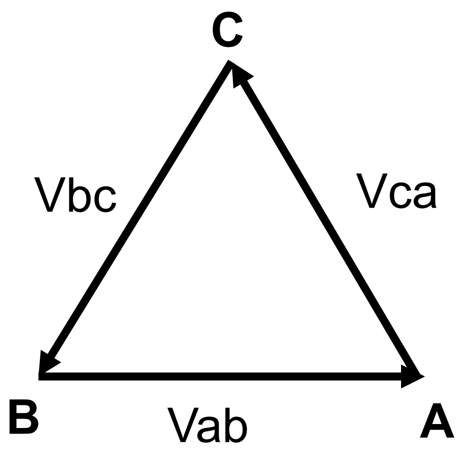
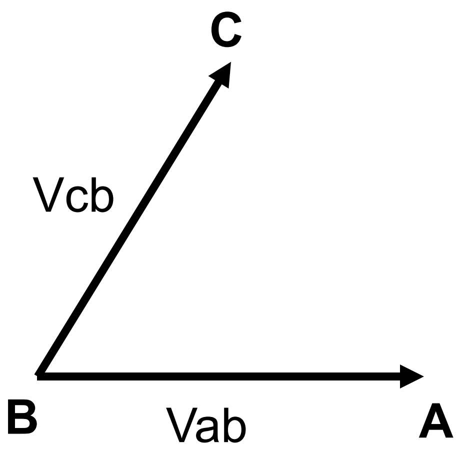
3 Phase, 3-Wire Delta Service

Understanding the Diagram

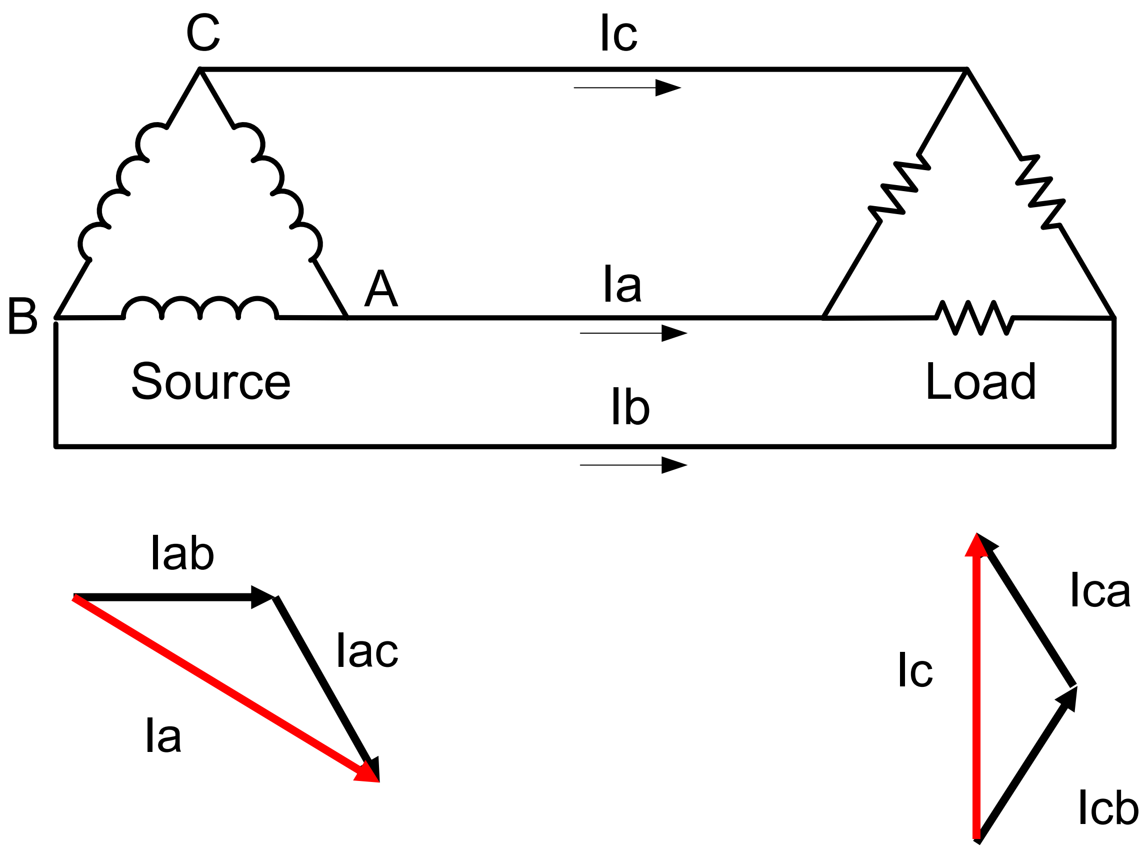






3 Phase, 3-Wire Delta Service

Understanding the Diagram



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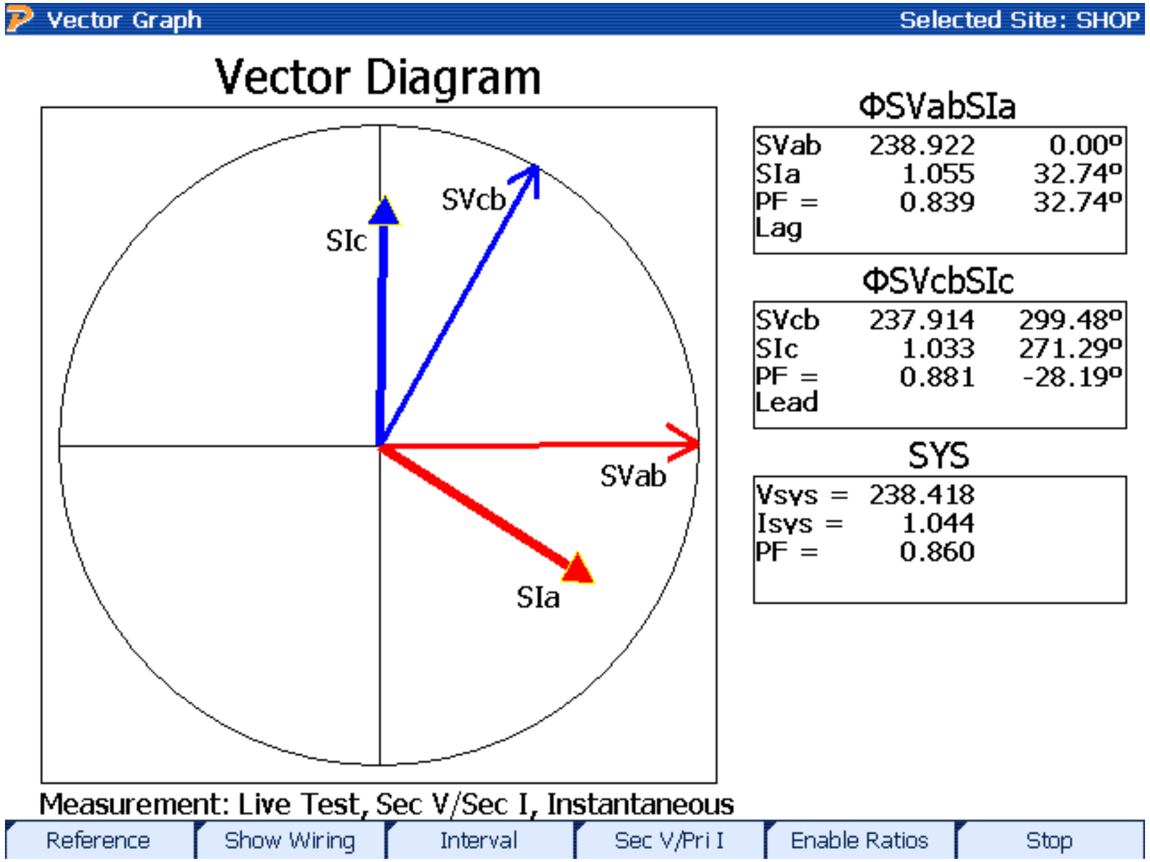
3 Phase, 3-Wire Delta Service

Resistive Load

- 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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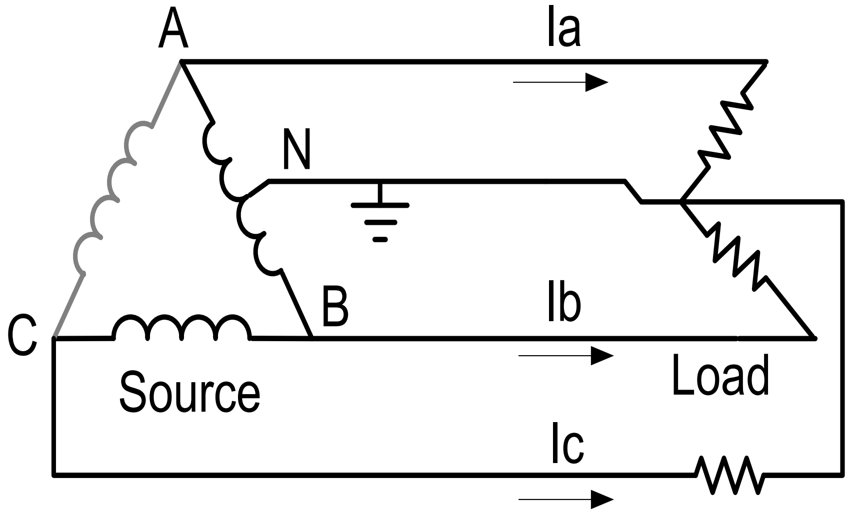
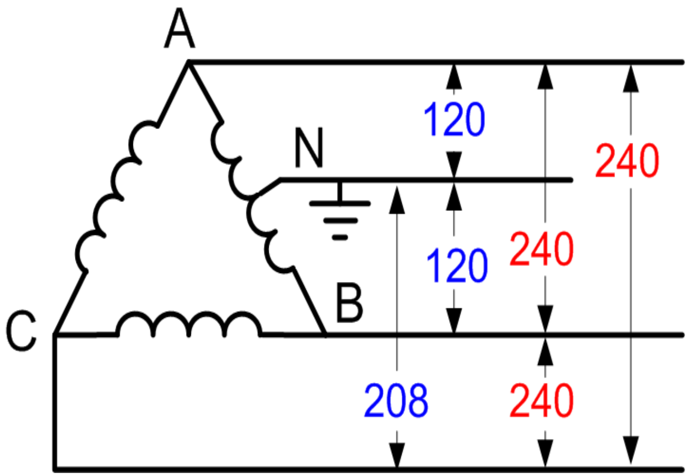
3 Phase, 4-Wire Delta Service

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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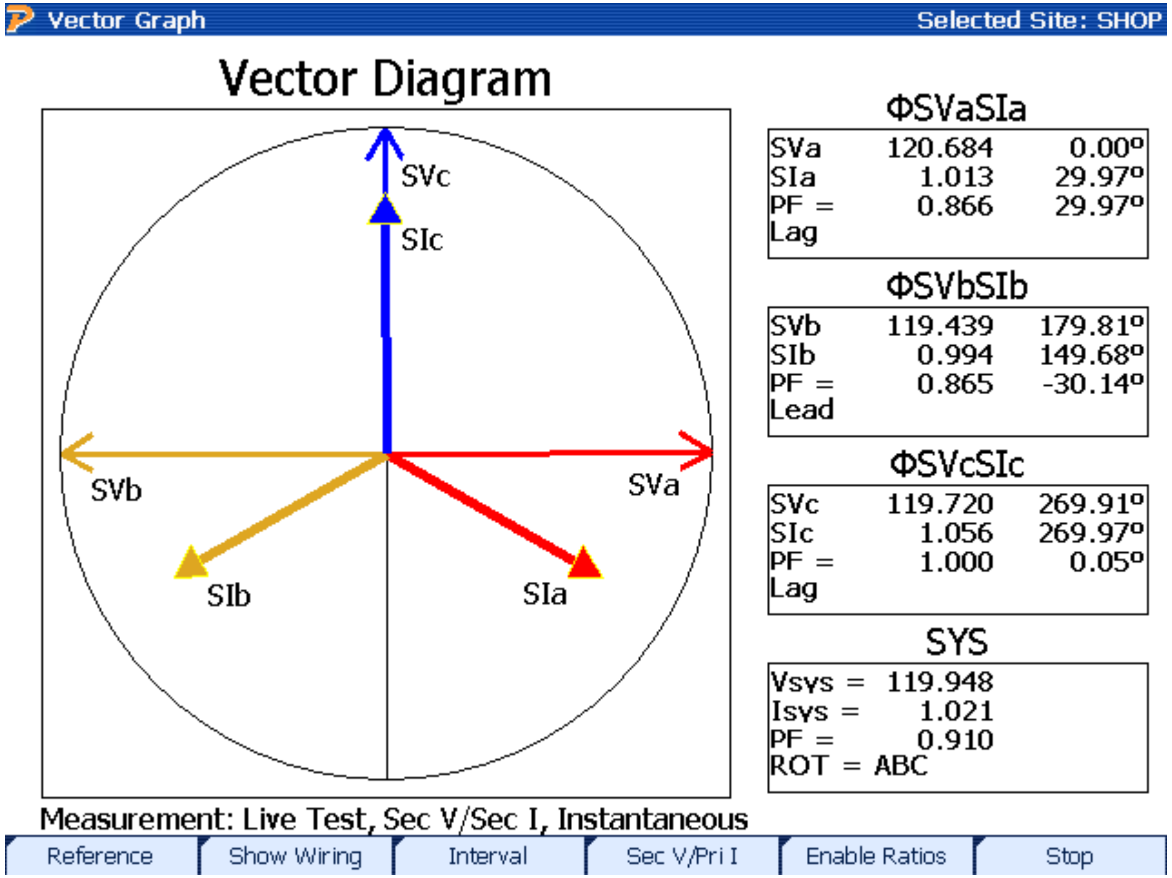
3 Phase, 4-Wire Delta Service

Resistive Load

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



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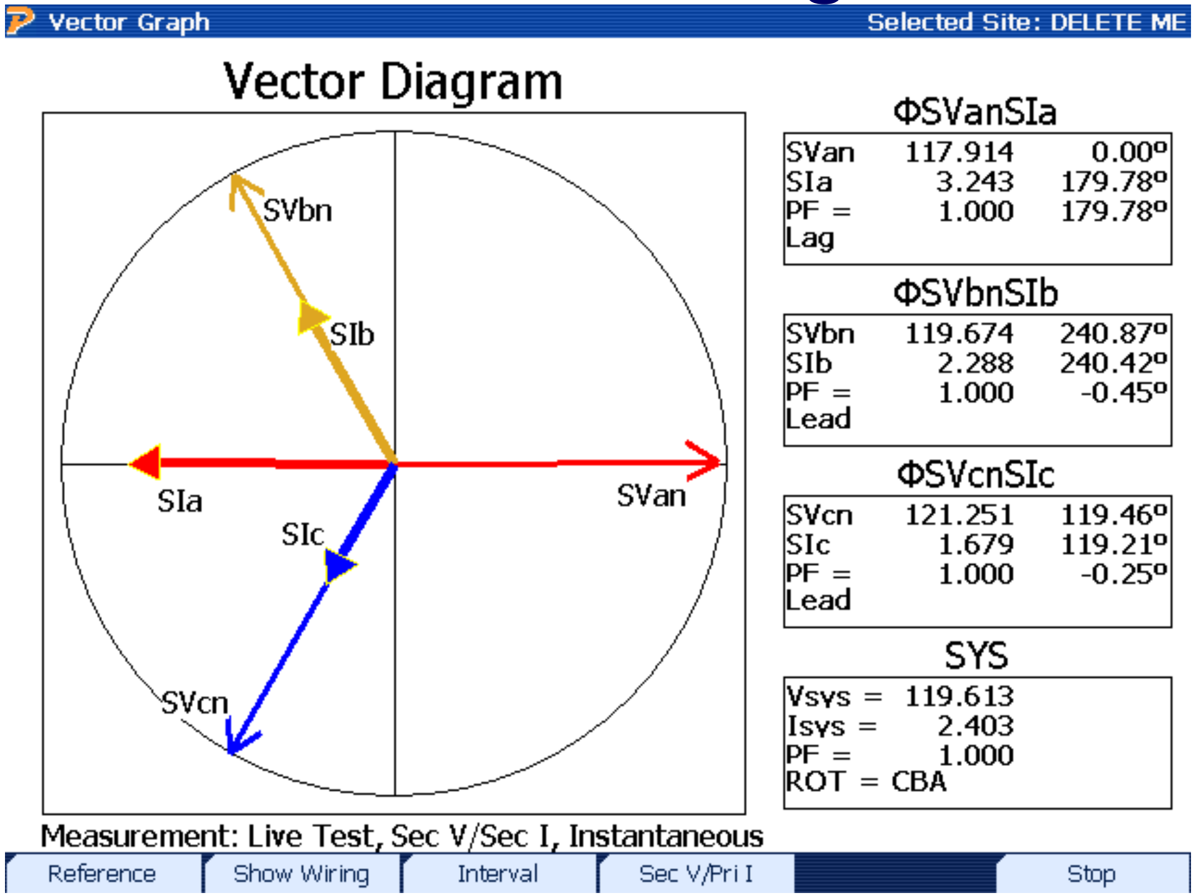
Troubleshooting with Vectors

What's Wrong?



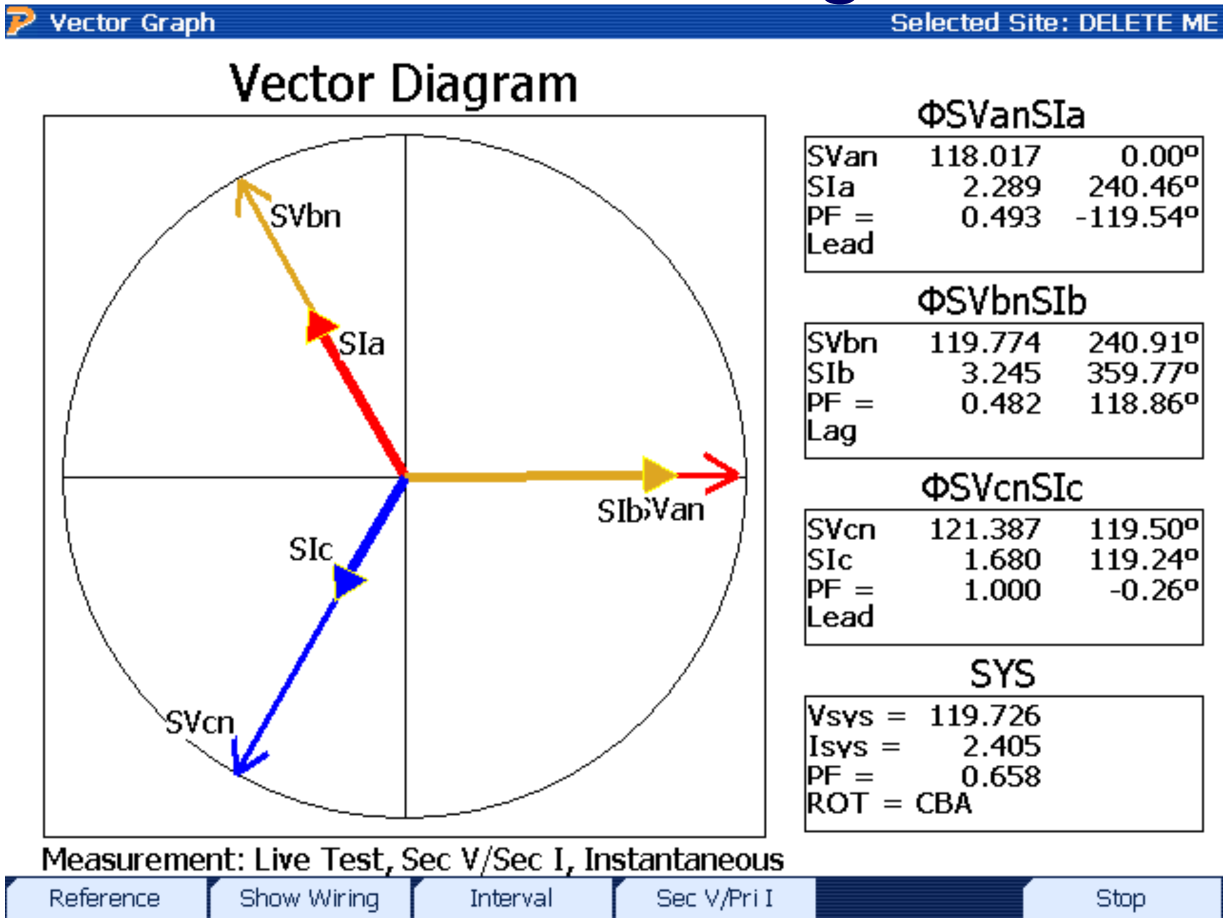
Phase A CT reversed.

Backwards CT = ??? $$$

- kW = Va * Ia * Cos θ + Vb * Ib * Cos θ + Vc * Ic * Cos θ
- Cos 180 on phase A makes this NEGATIVE power!
- Reading will be 66% low assuming a balanced current load!

Troubleshooting with Vectors

What's Wrong?



Phase A & B CTs swapped.

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Swapped Wire = ??? $$$

- kW = Va * Ia * Cos θ + Vb * Ib * Cos θ + Vc * Ic * Cos θ

- Cos 120 on phase A and B makes this NEGATIVE power!

- Reading will be 0W assuming a balanced current load!

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