Introduction to Power Factor

And Vector Diagrams

POWERMETRIX

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Focus of this Presentation

- Review basic power concepts as they relate to Power Factor (PF)
- What is a vector diagram?
- How do different loads affect PF?
- How does low power factor lead to lost revenue?
- Show the vector diagram for each meter form and service type
- See how vector diagrams help identify meter site errors that can recover lost revenue

AC Theory Review – an AC Generator

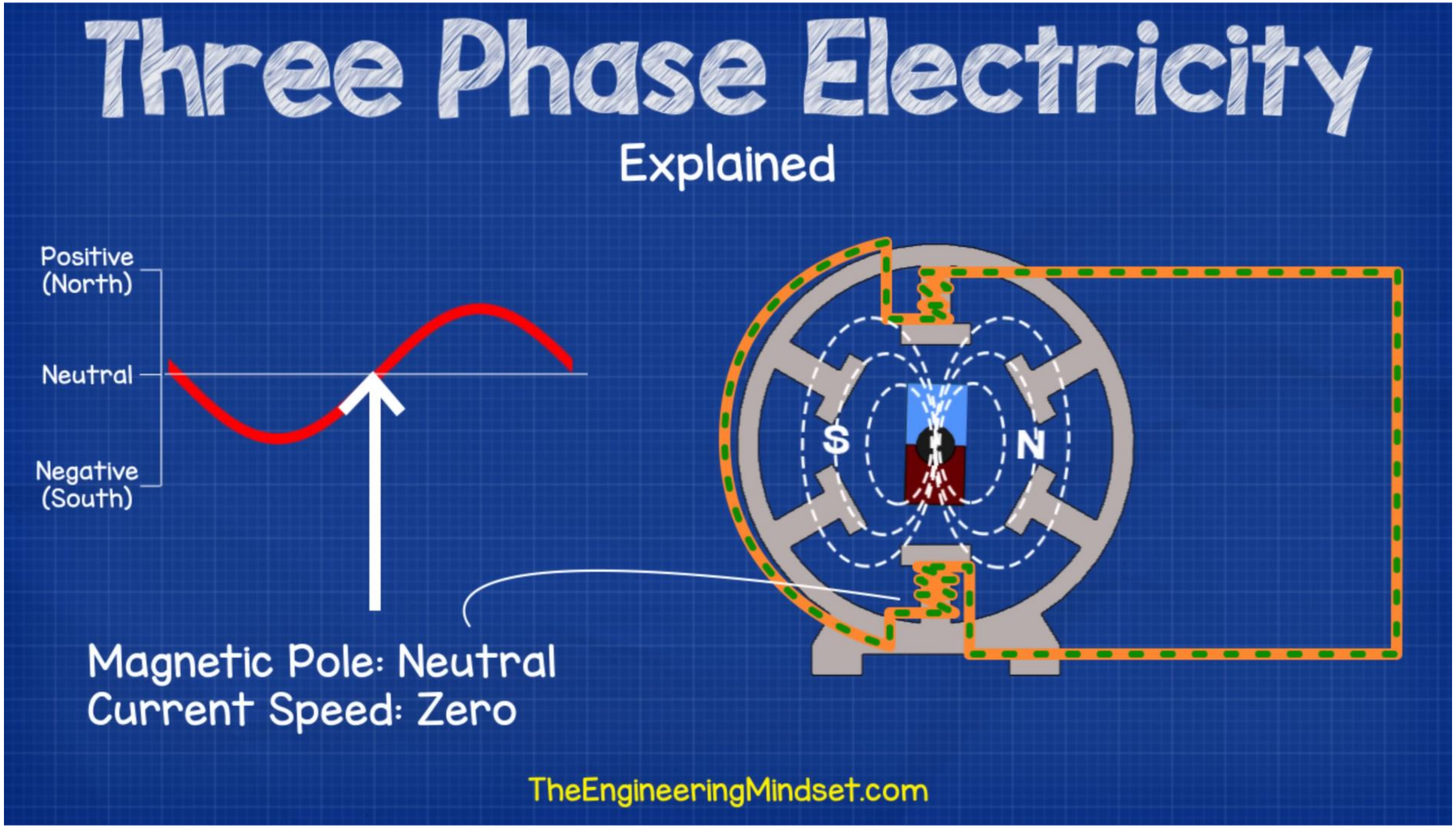

Figure Credit: https://theengineeringmindset.com/three-phase-electricity-explained/

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AC Theory Review – an AC Generator

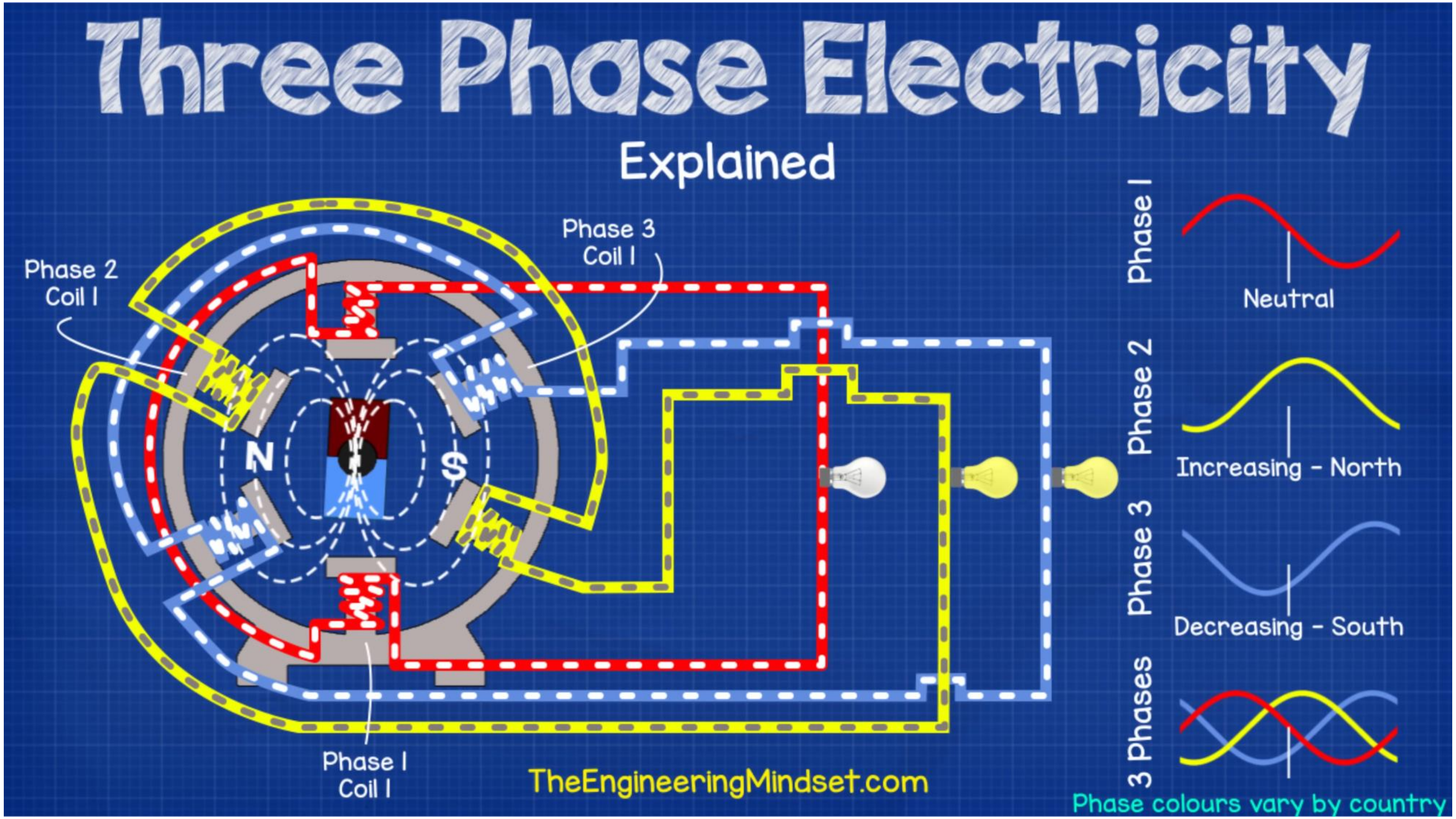

Figure Credit: https://theengineeringmindset.com/three-phase-electricity-explained/

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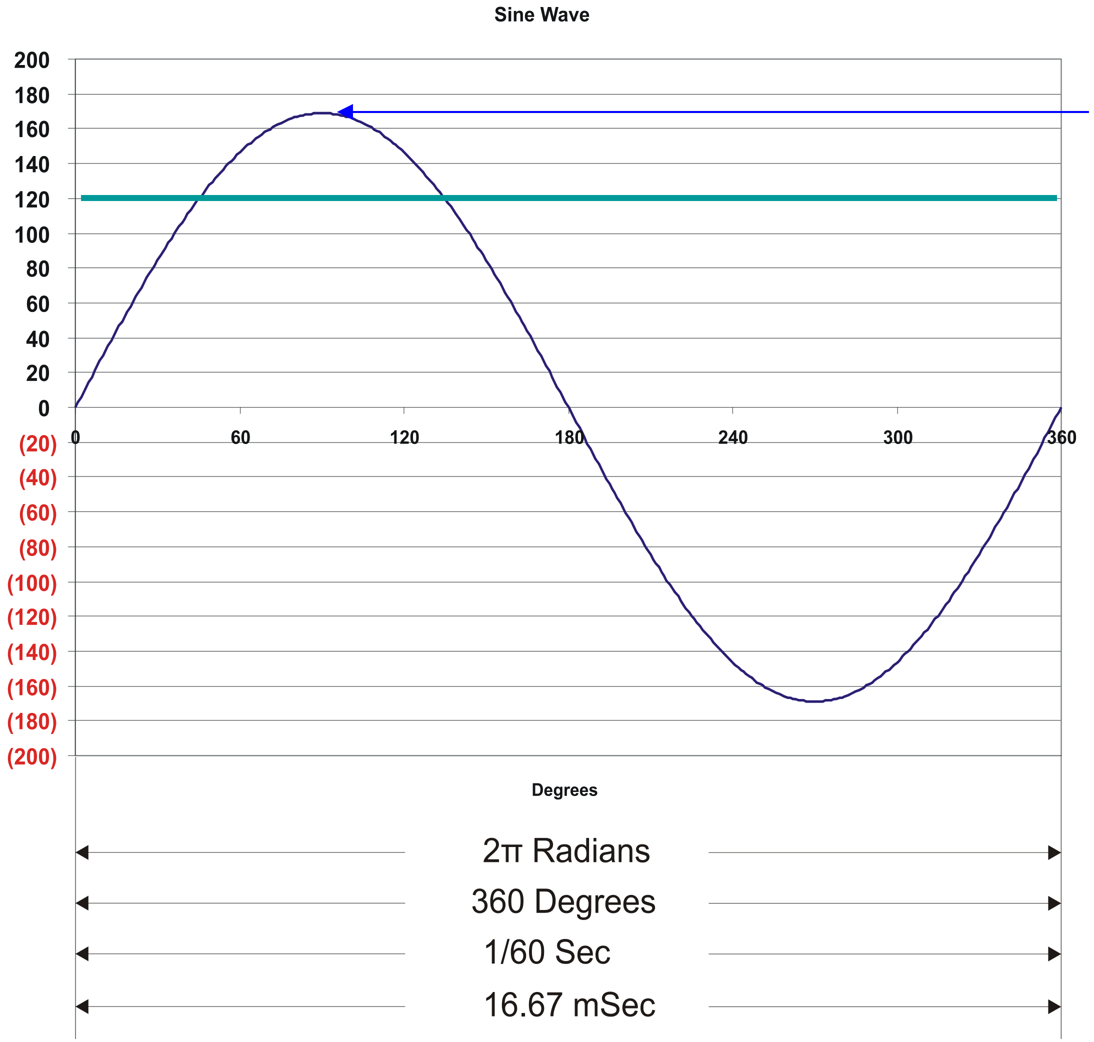
AC Theory Review – Sine Wave



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

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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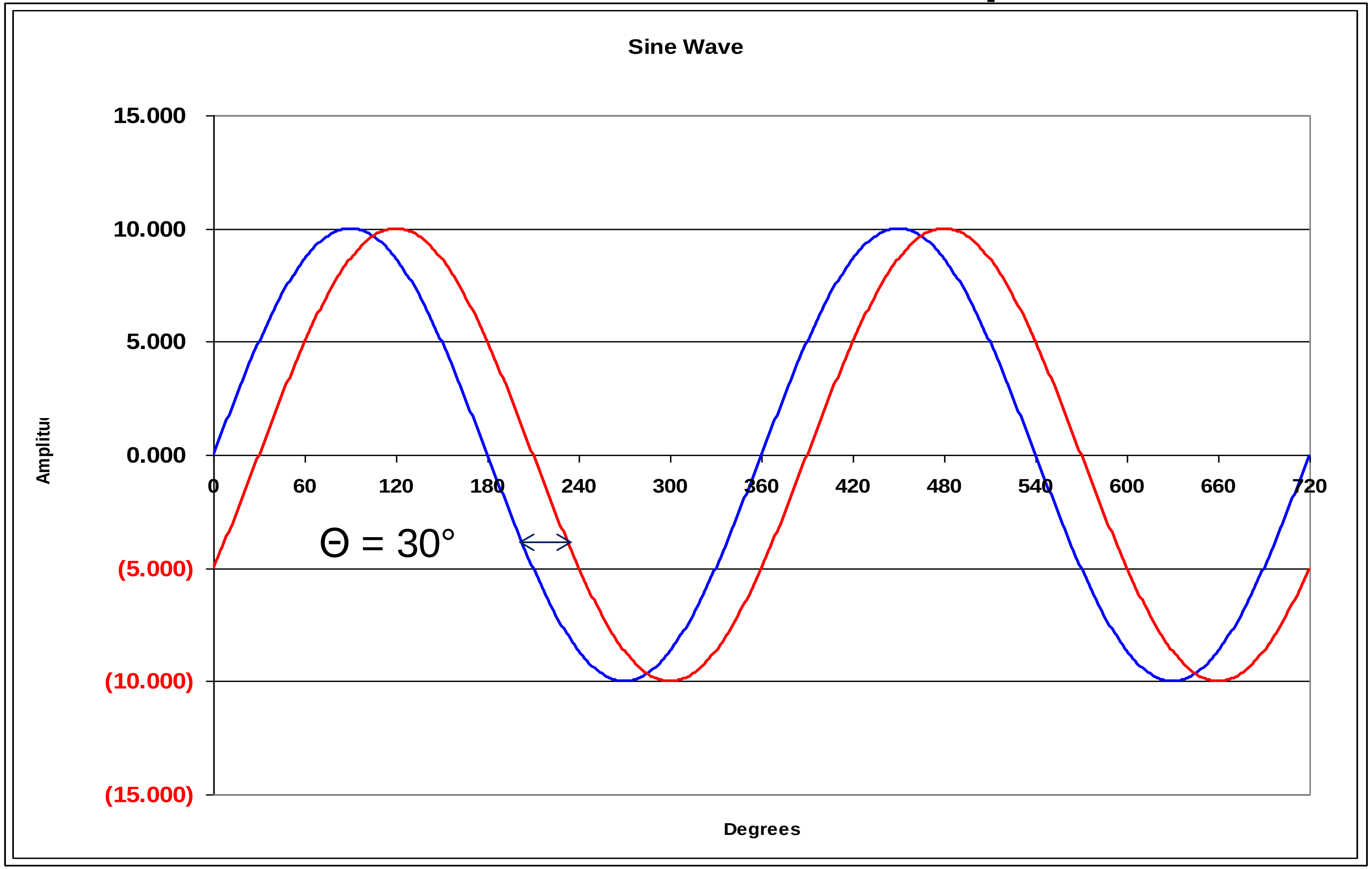
Phase Relationship



Current is lagging Voltage by 30˚

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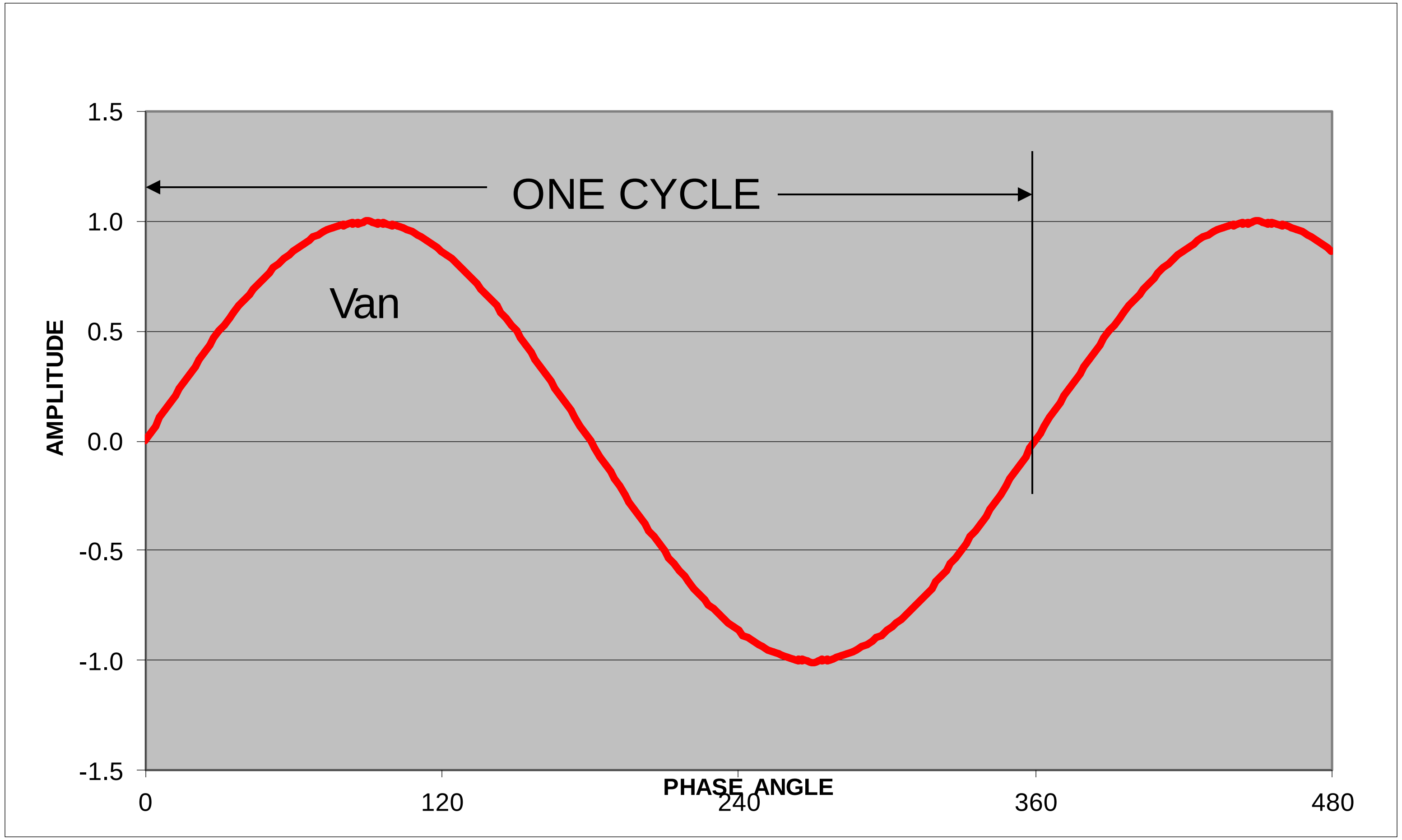
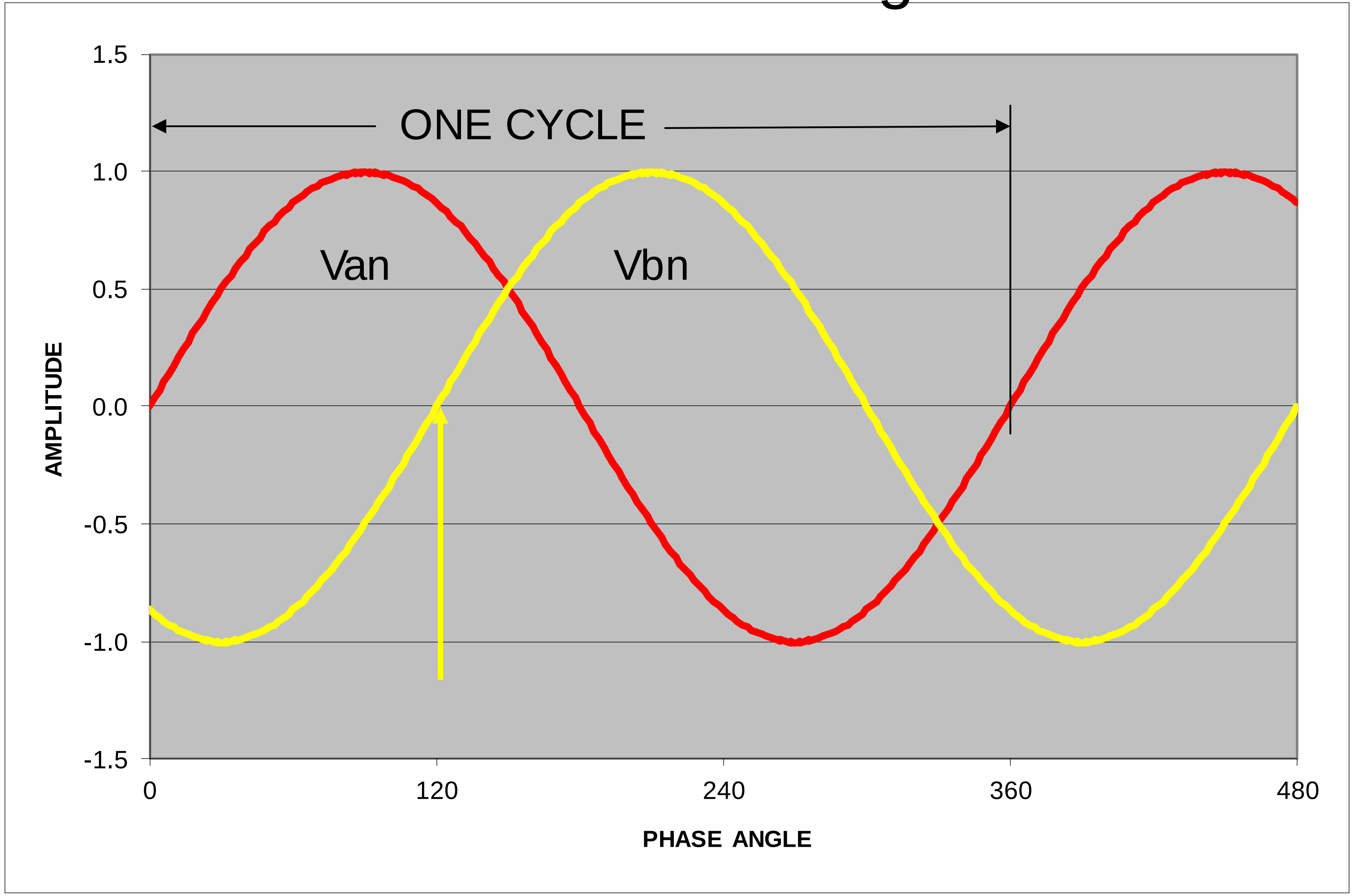
Three Phase Theory

Single Phase - Voltage Plot



Three Phase Theory

Two Phases - Voltage Plot



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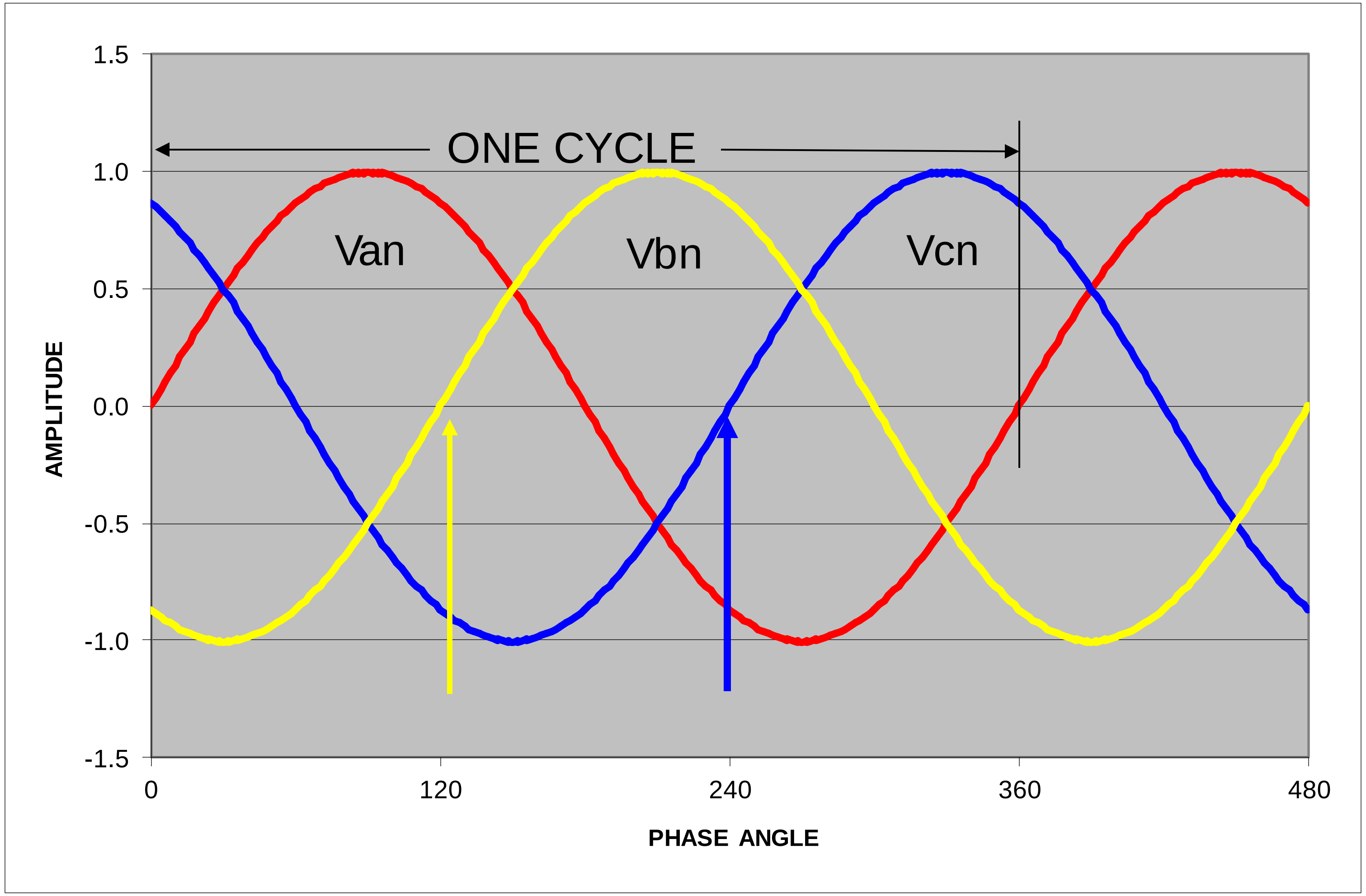
Three Phase Theory

Three Phase - Voltage Plot



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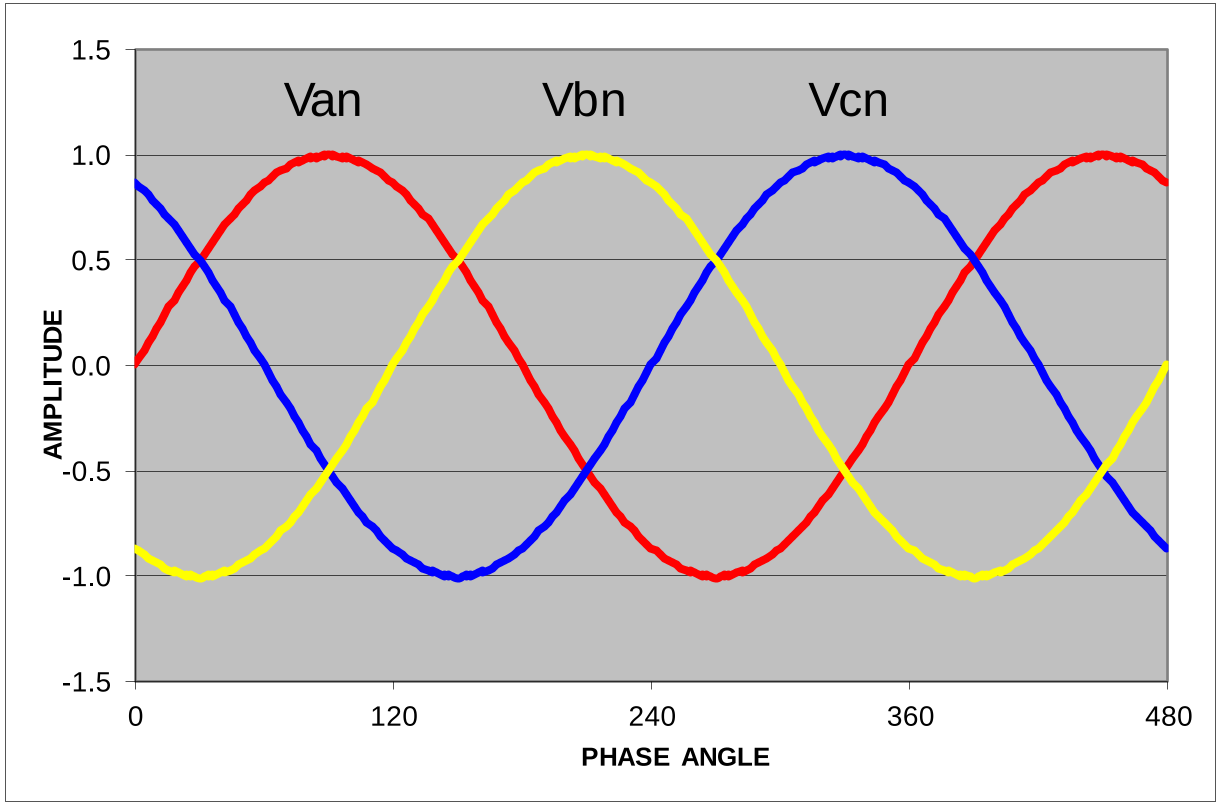
Three Phase Power

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

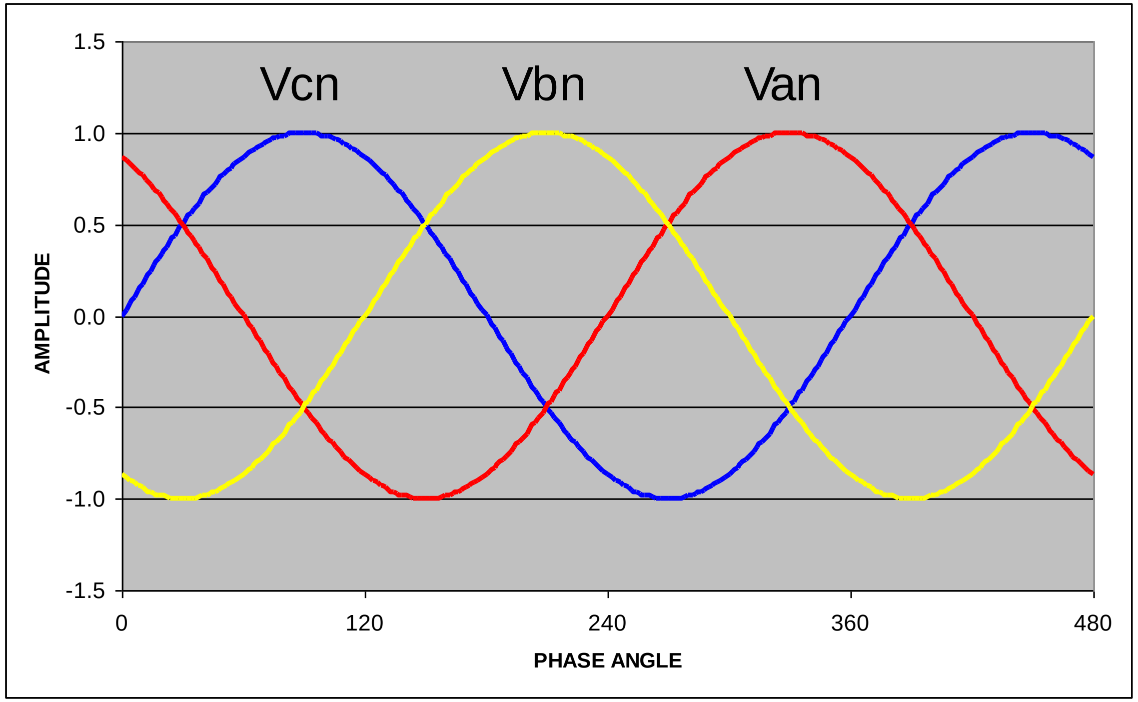
Phase Rotation:

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)

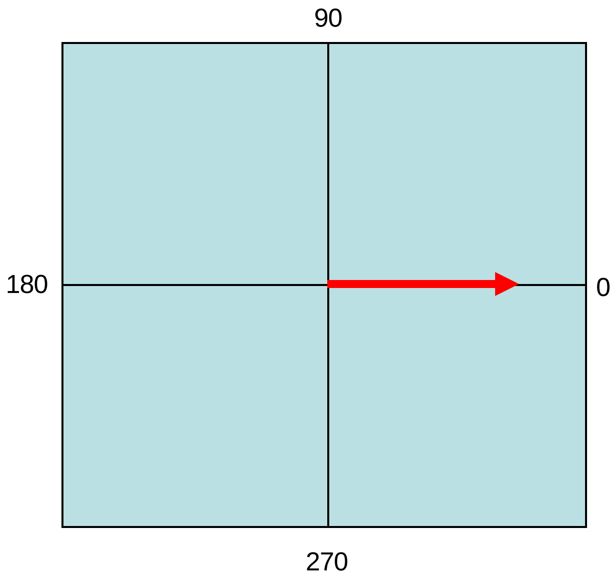


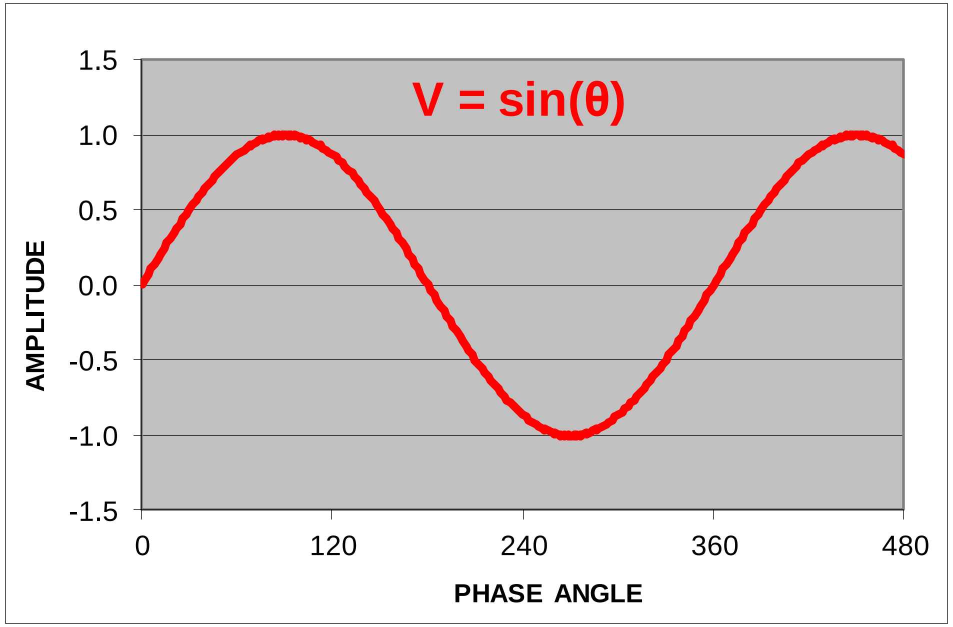
Phase rotation is important because the direction of rotation of a three phase motor is determined by the phase order.

Three Phase Theory

Phasors and Vector Notation

- Phasors are a graphical means of representing the *amplitude* and *phase* relationships of voltages and currents.

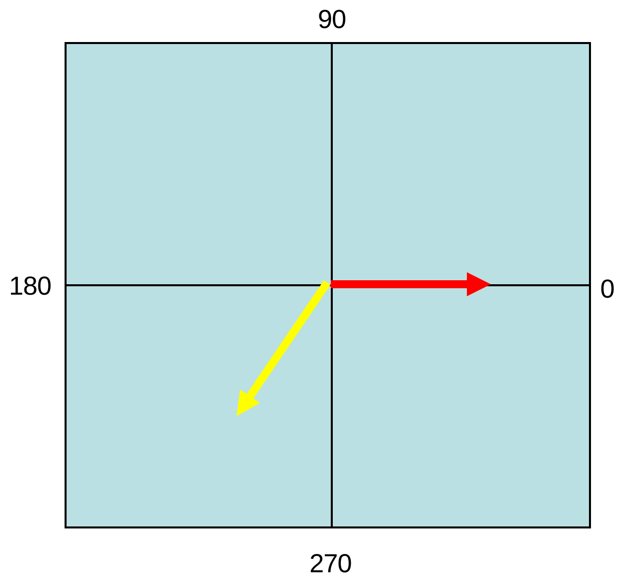


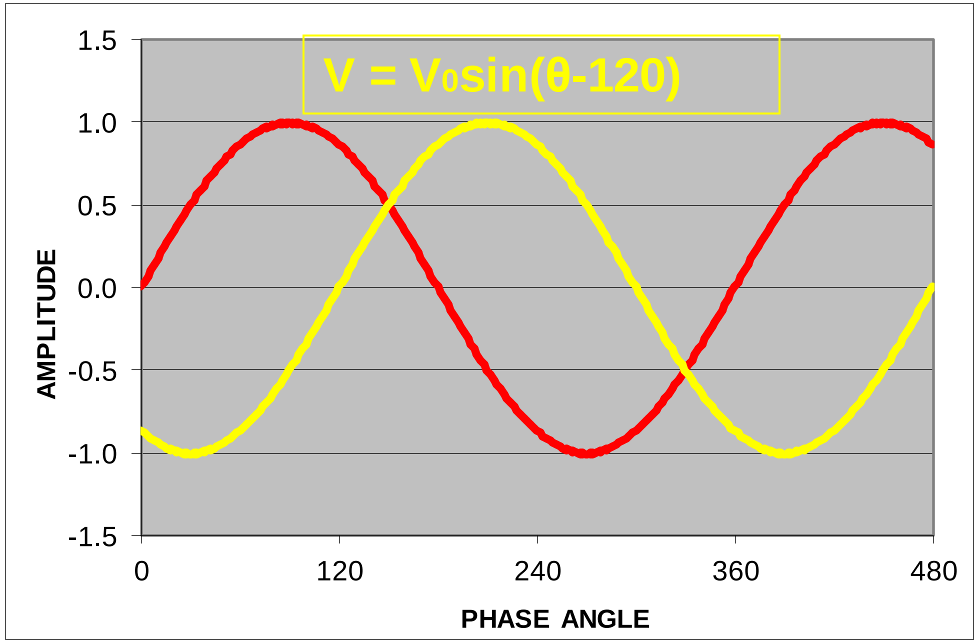


Three Phase Power

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.





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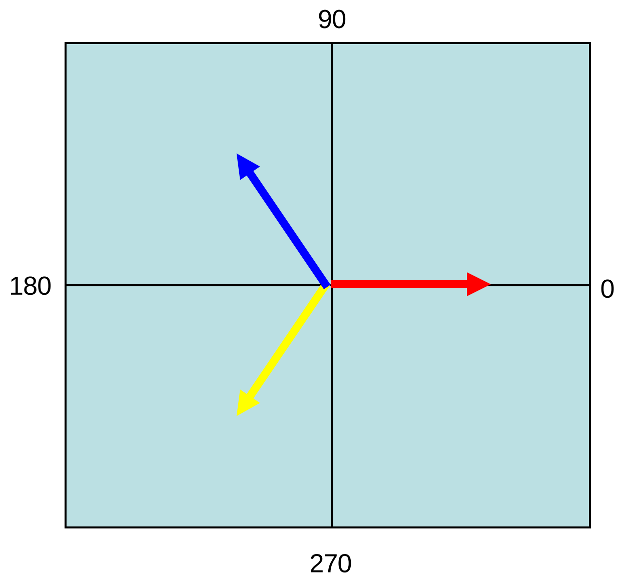
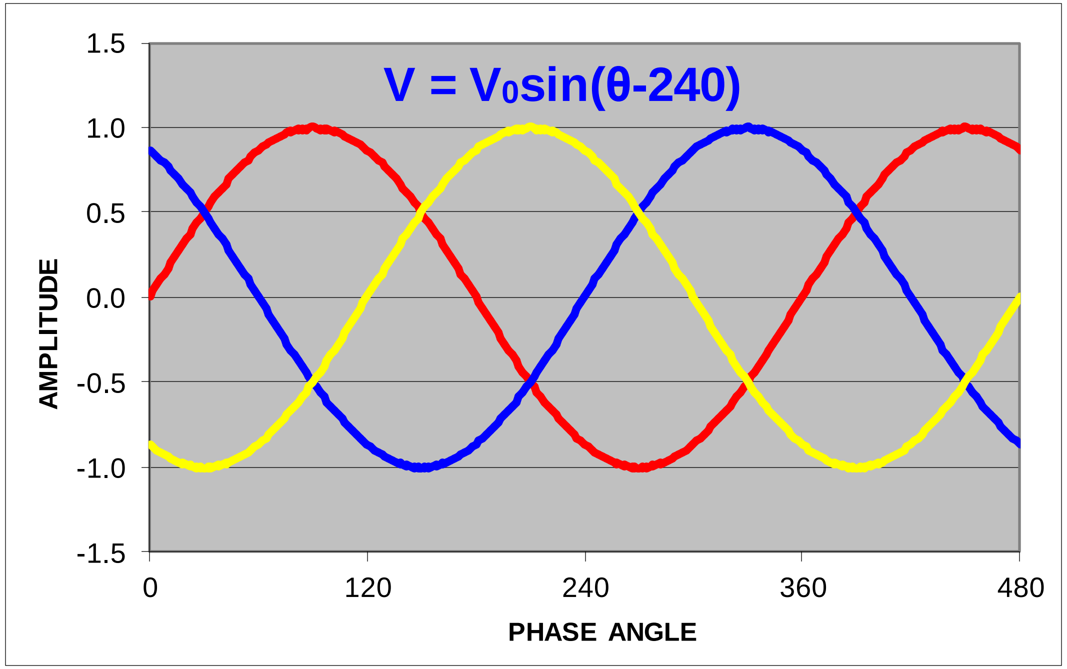
Three Phase Power

Phasors and Vector Notation

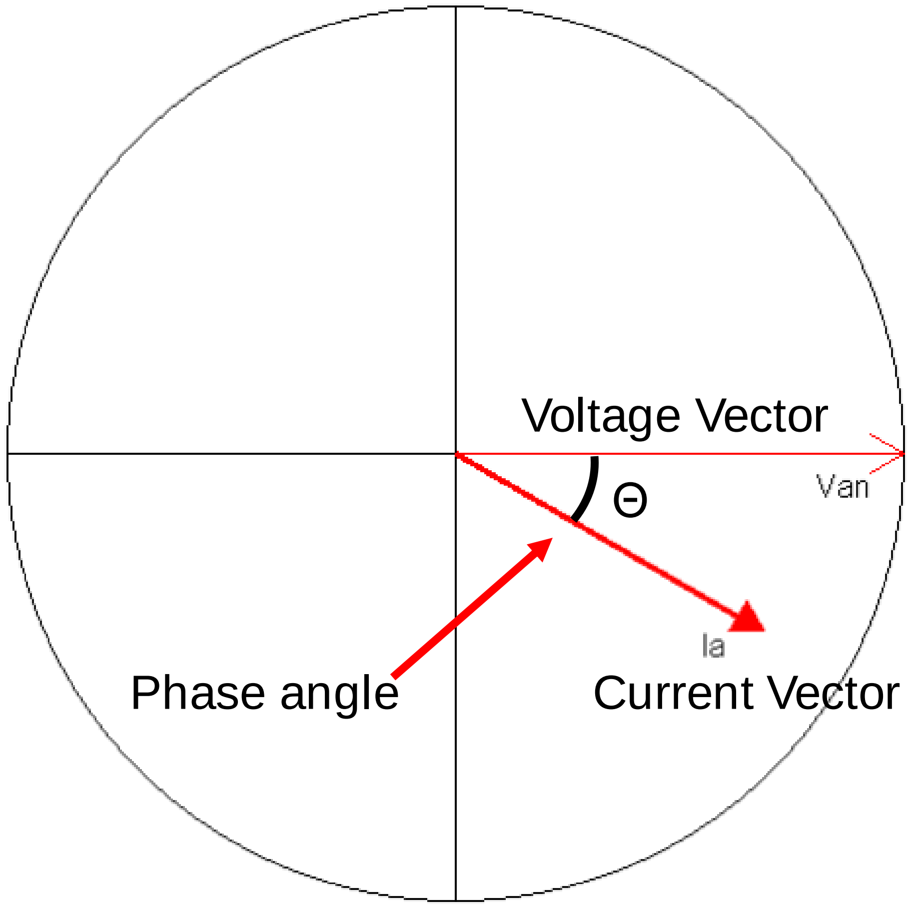
- The phasor diagram for a simple 3-phase system has three voltage phasors equally spaced at 120° intervals.
- Going clockwise the order is A – B – C.





Voltage and Current Vectors

- Vector diagrams normally have a voltage and current vector for each phase
- The voltage vector is lighter and has an open arrow
- The current vector is darker and has a closed arrow
- The PF is the cosine of the angle between the voltage and current
- PF = cos Θ



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Voltage and Current Vectors

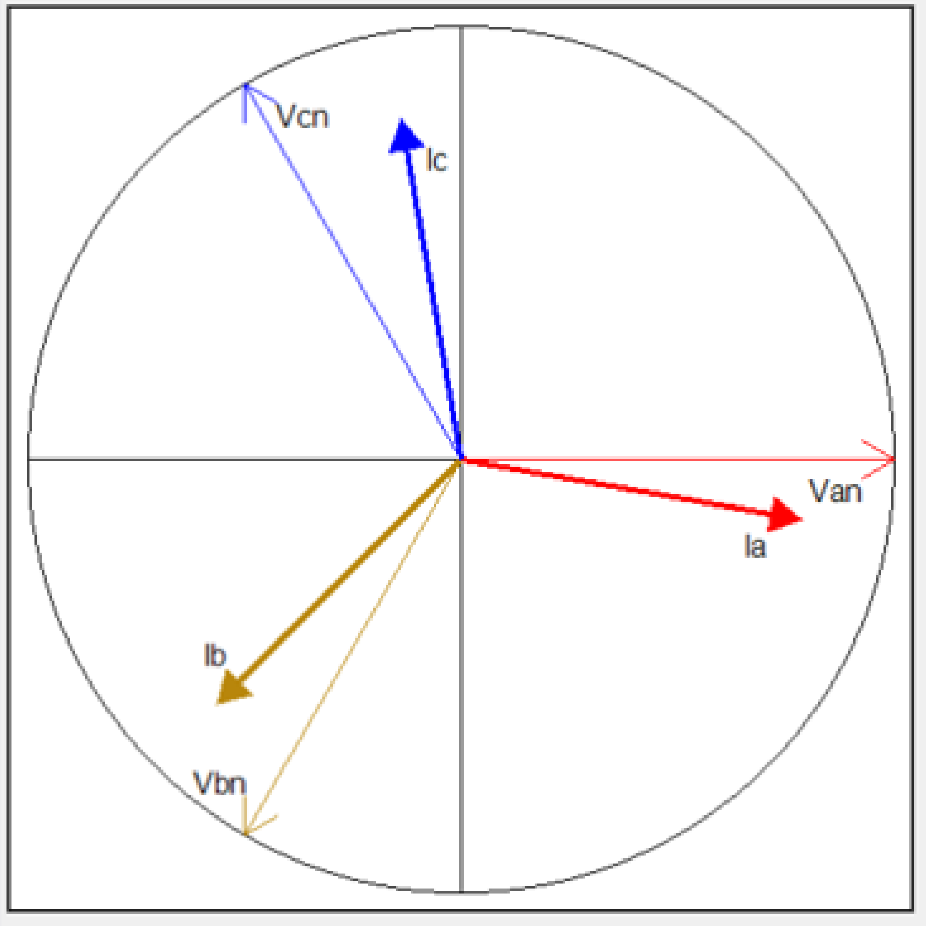
- Vector sets are color coded by phase
- Typical colors are

A – Red

B – Yellow

C – Blue

- Colors can vary from utility to utility



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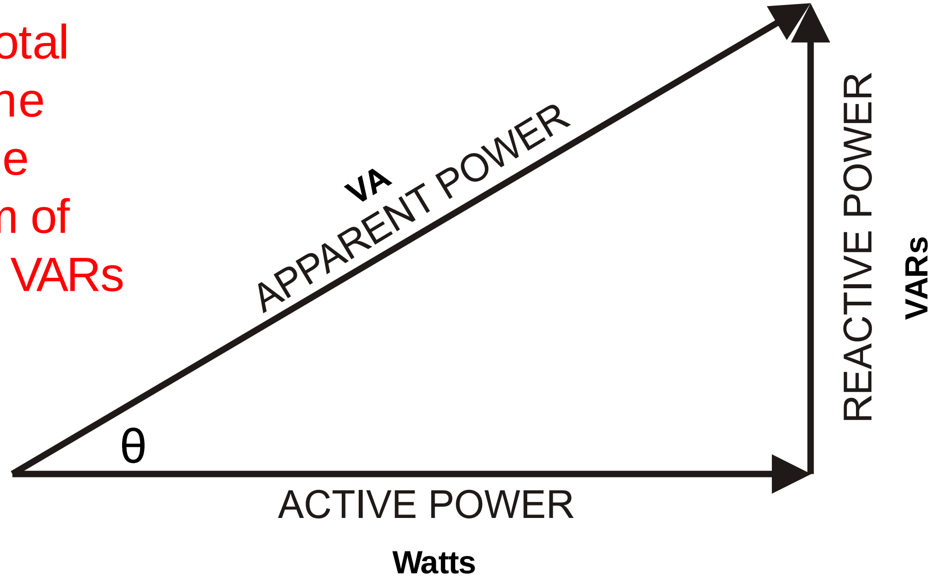
Introducing the "Power Triangle"

(Sinusoidal Waveforms)

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



VARs – non-useful power that is required to drive the inductance or capacitance of the system

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

If $V = Sin(\omega t)$ and $I = Sin(\omega t - \theta)$ (the load is linear)
then

Active Power =	$VICos(\theta)$	Watts
Reactive Power =	$VISin(\theta)$	Volt-Amp Reactive (VAR)
Apparent Power =	VI	Volt-Amp (VA)

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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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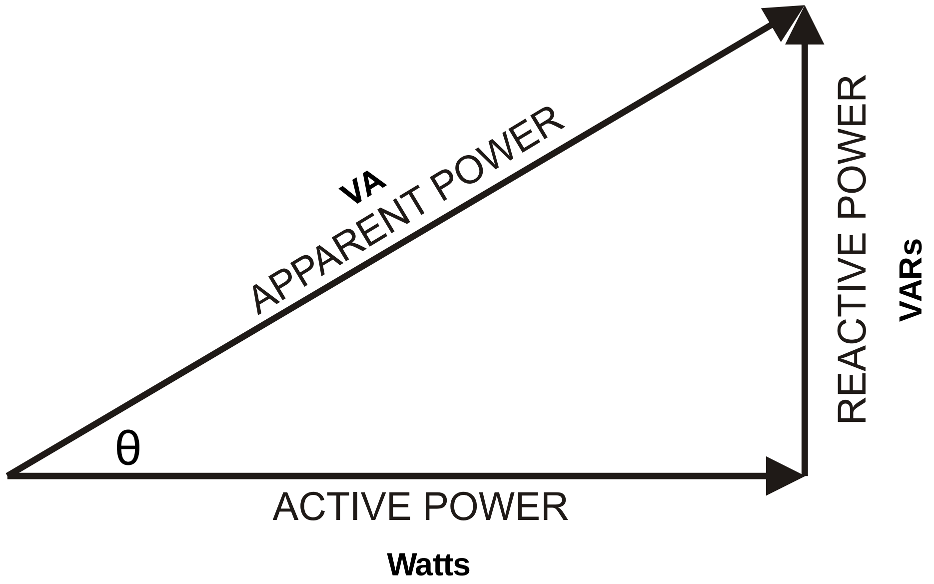
Power Factor Definition



Power Factor = Active / Apparent Power

= Watts / VA

= *Cos*(θ)

Power Factor can range from 1 to 0

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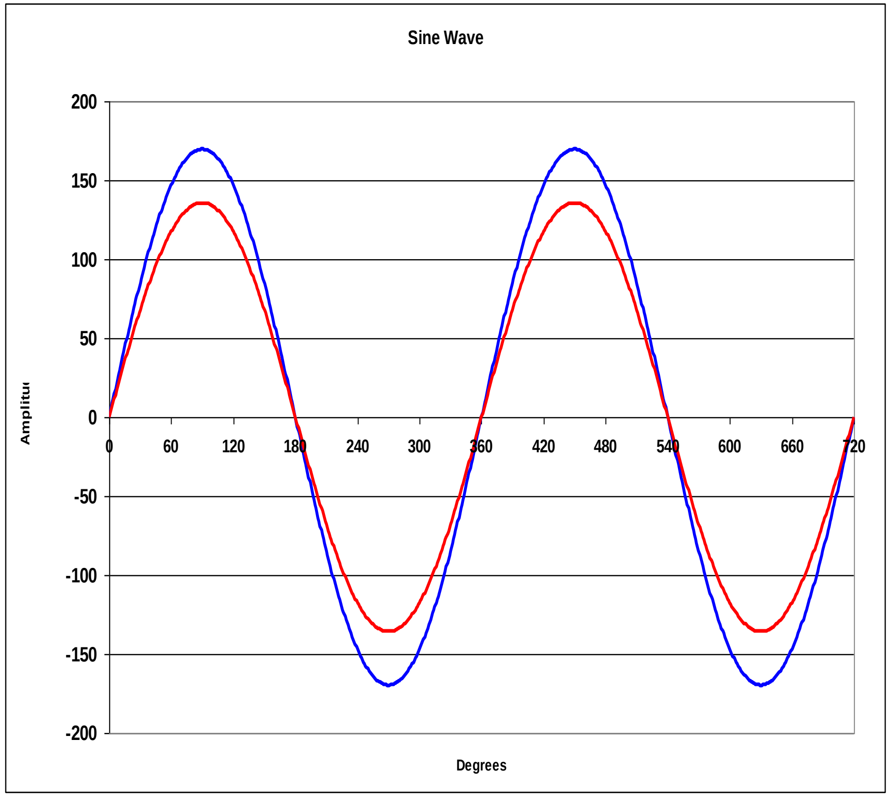
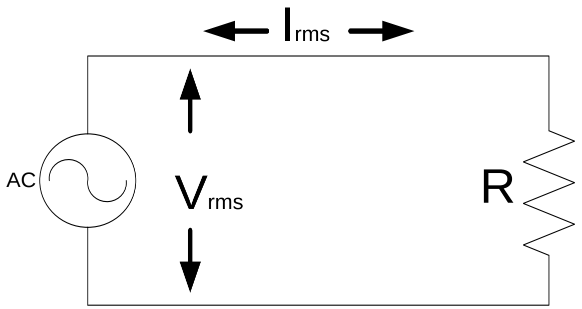
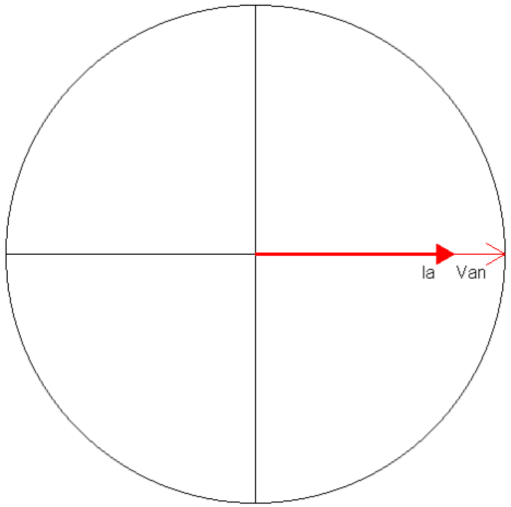
Resistive Load

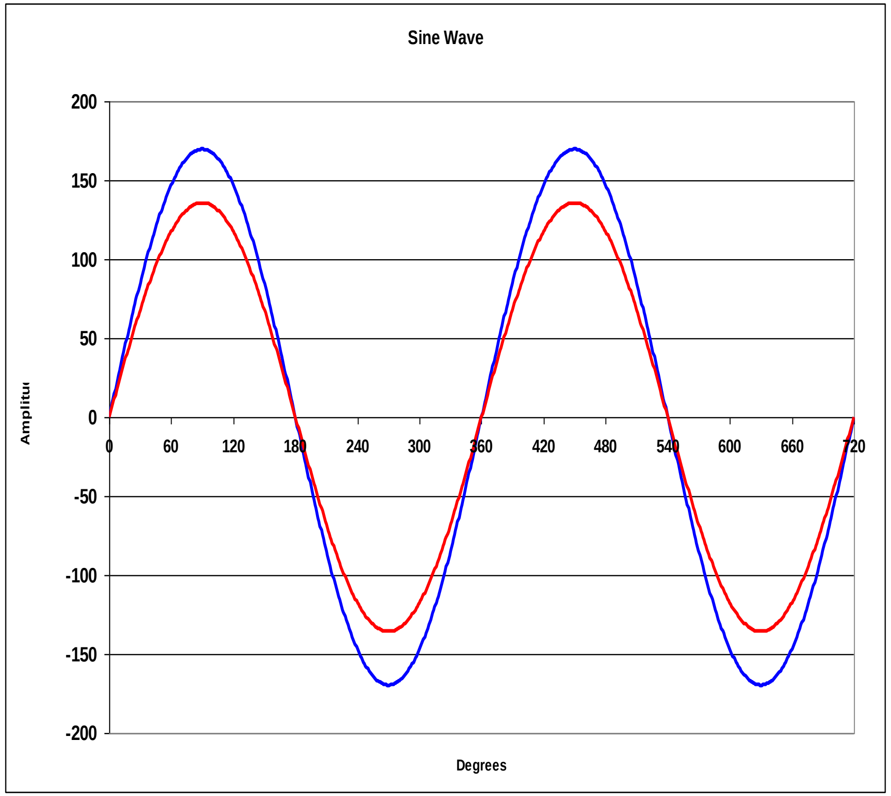


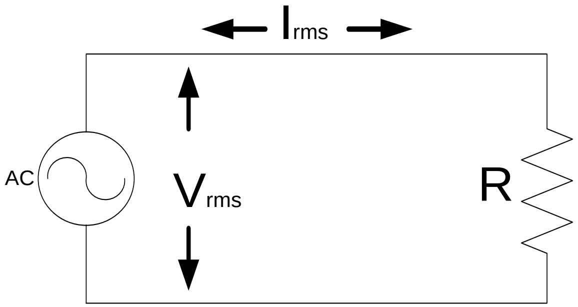




A purely resistive load has current and voltage “in phase”; i.e. ZERO phase angle

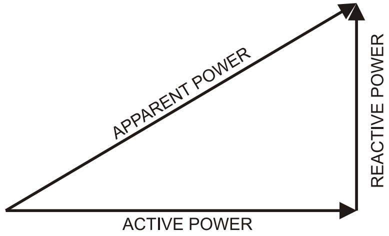
Resistive Load





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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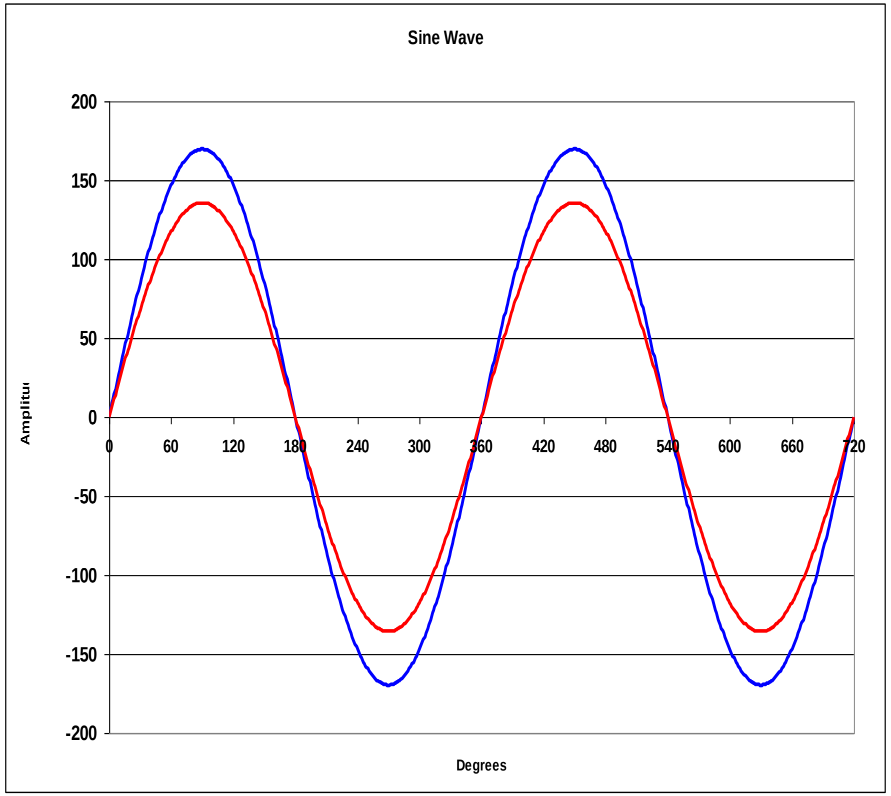
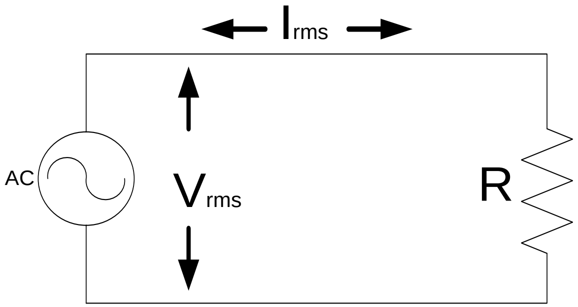
Resistive Load



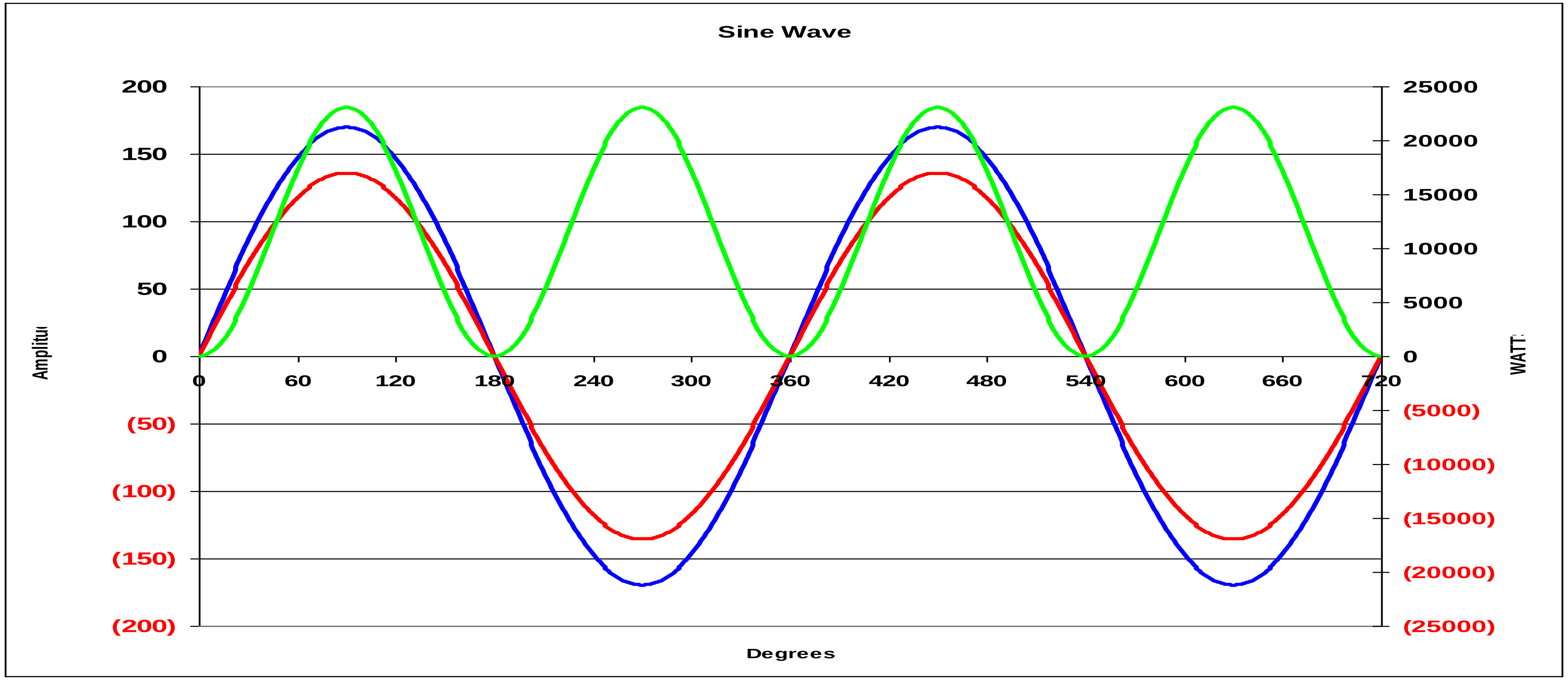


A purely resistive load will:

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

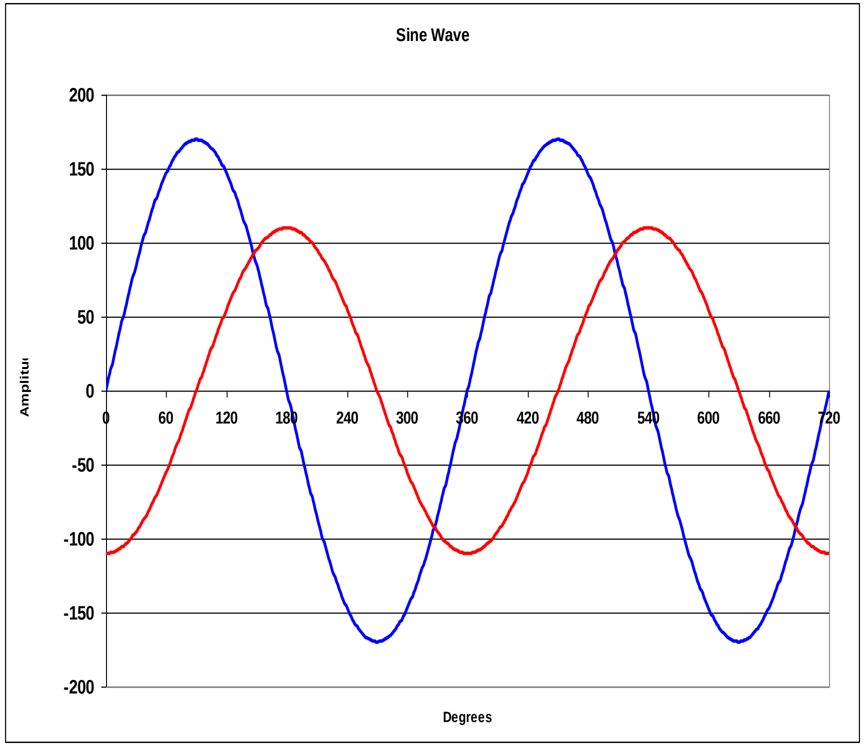
Resistive Load

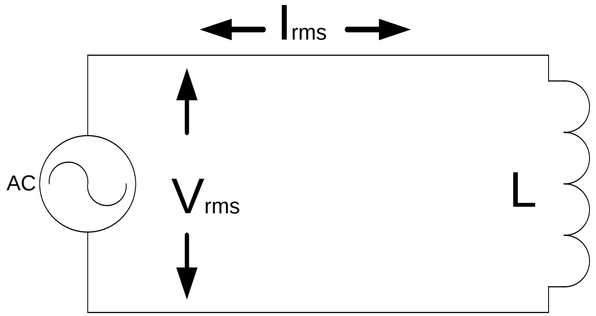
For a resistive load: $p = vi = 2VISin^2(\omega t) = VI(1 - Cos(2\omega t))$

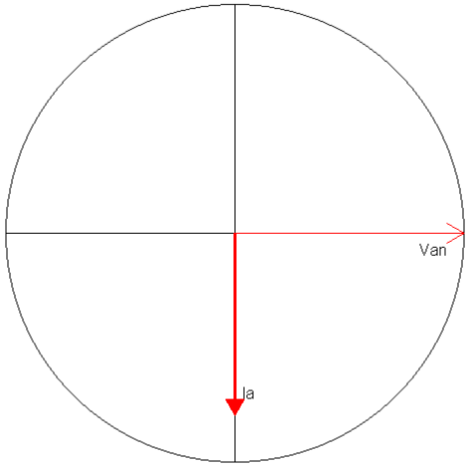


A resistive load consumes only Watts, so the power will always be delivered (positive).

Inductive Load

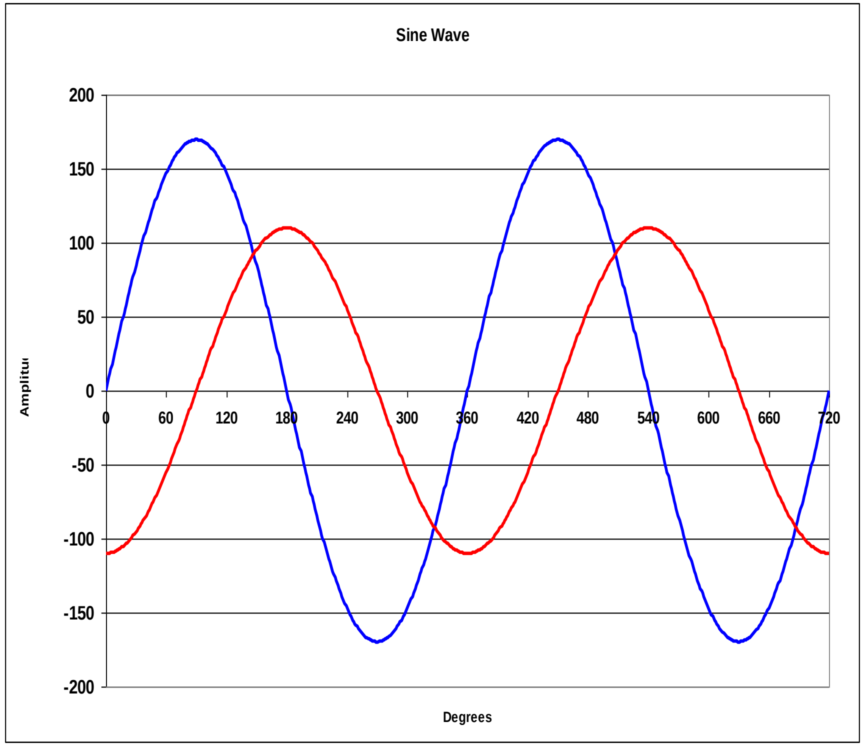


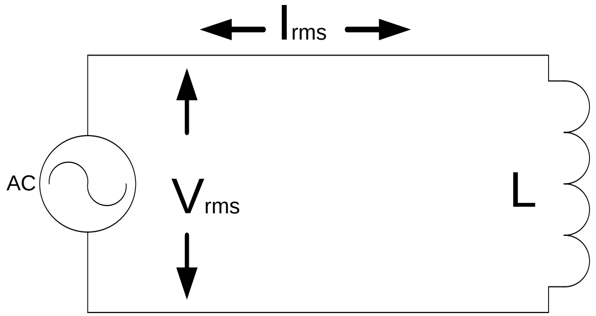




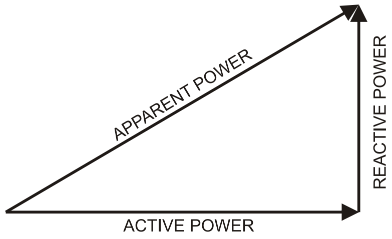
A purely inductive load has current “lagging” the voltage by 90° phase angle

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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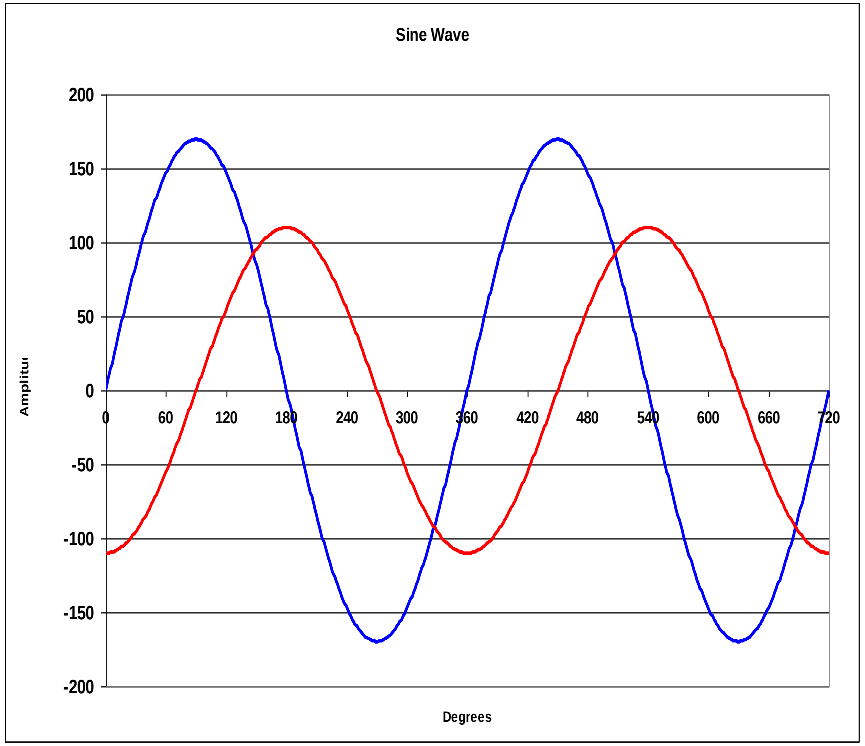
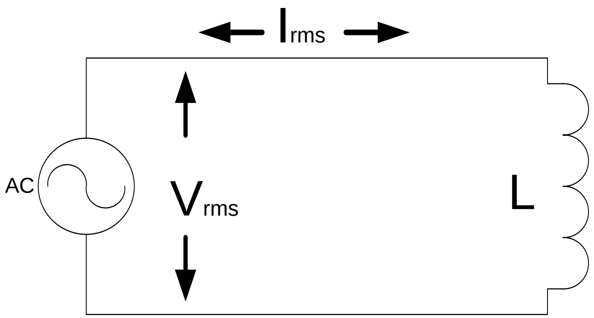
Inductive Load





A purely inductive load will:

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

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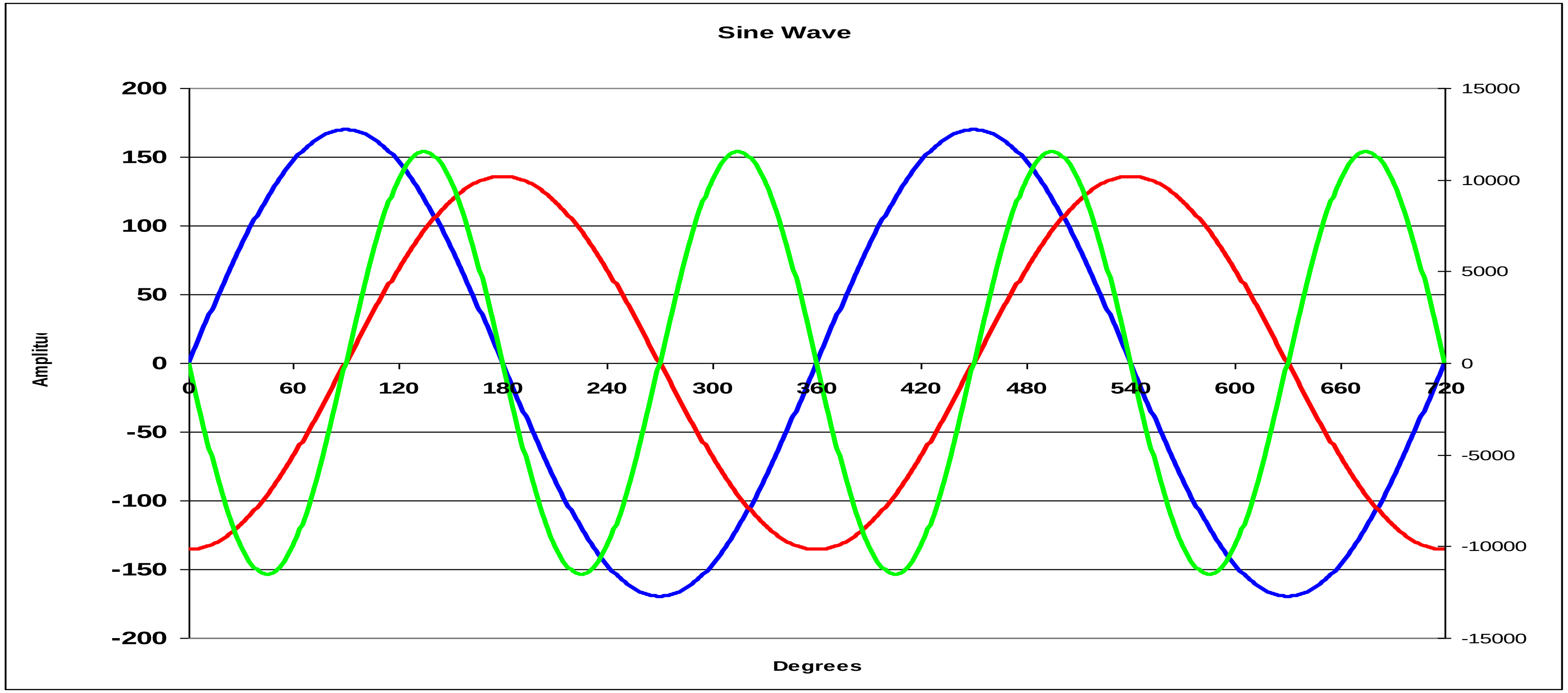
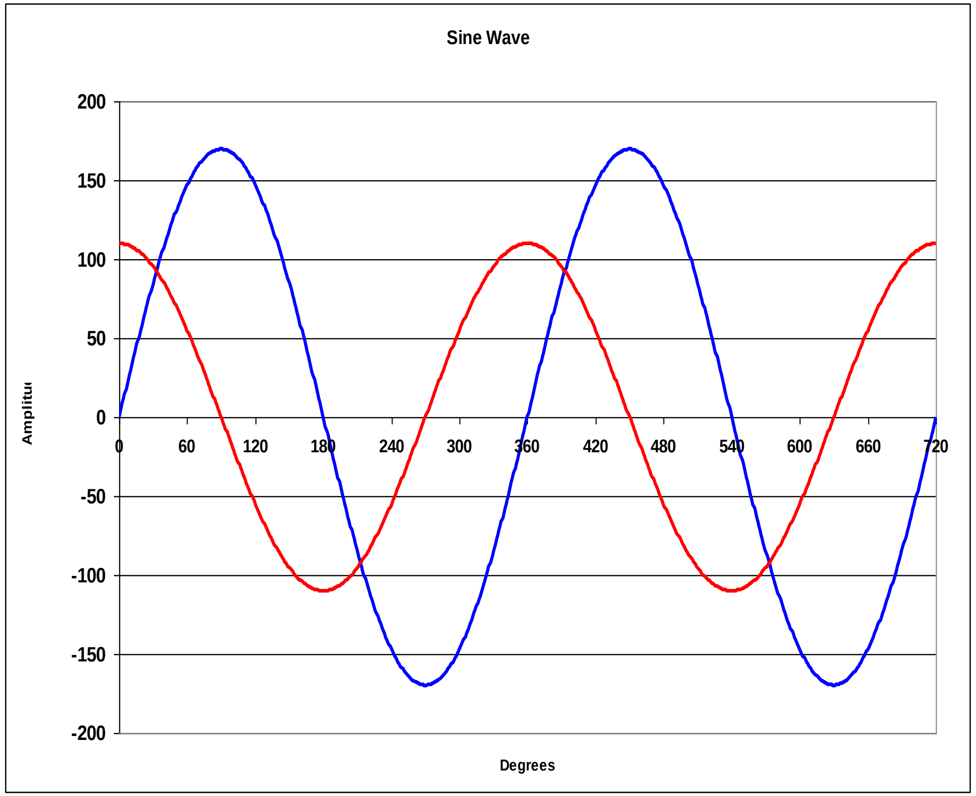
Inductive Load

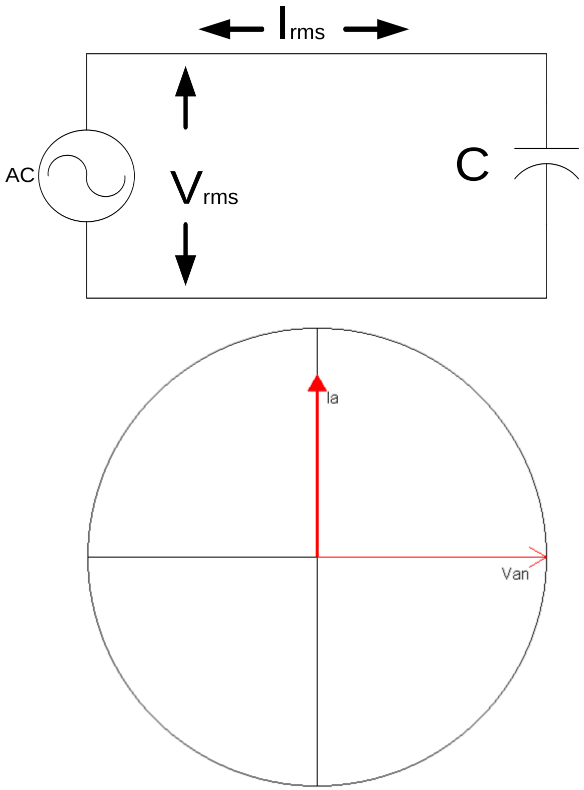
For an inductive load: $p = vi = 2VISin(\omega t)Sin(\omega t - 90) = -VISin(2\omega t)$



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%!

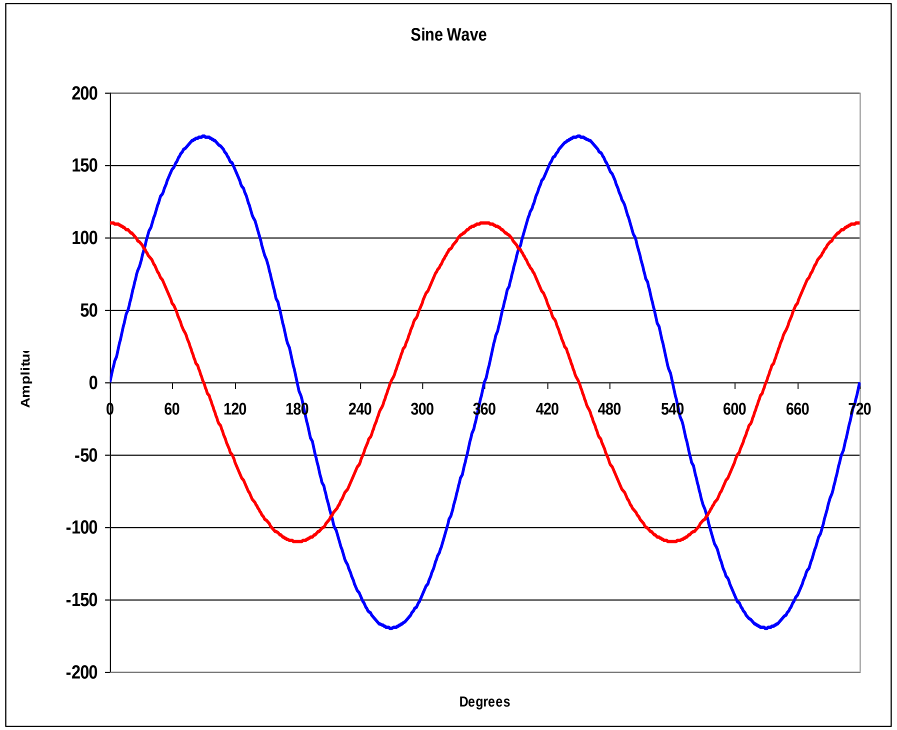
Capacitive Load

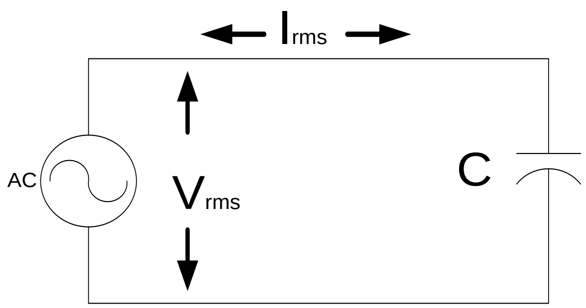




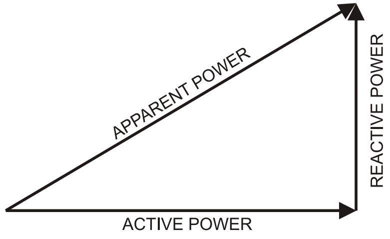
A purely capacitive load has the current "leading" the voltage by 90 degrees phase angle

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

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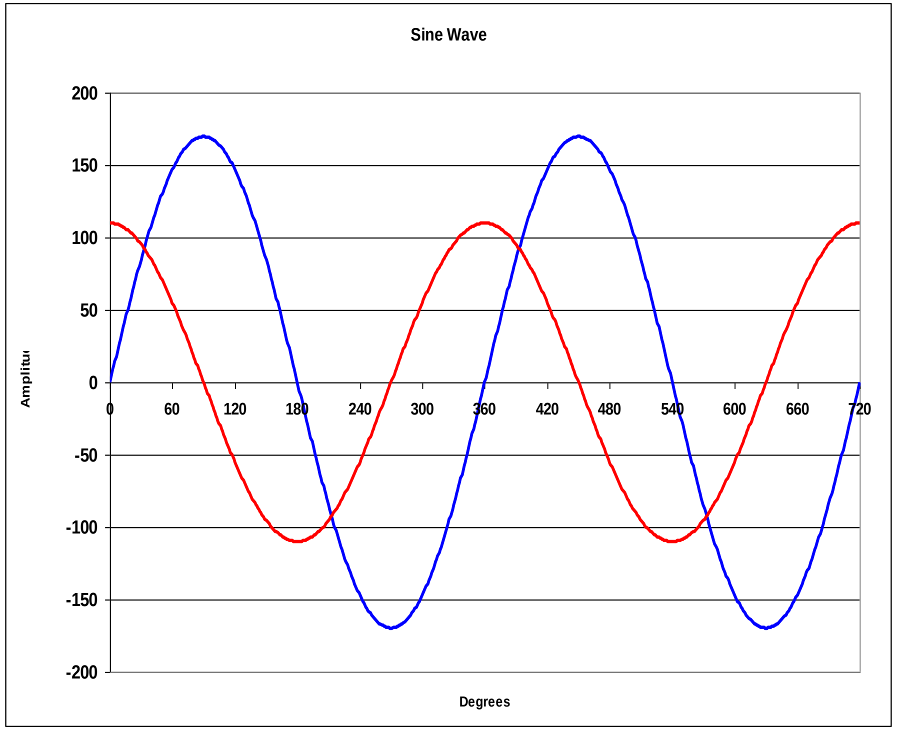
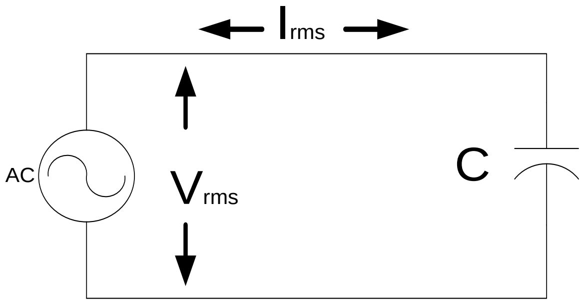
Capacitive Load



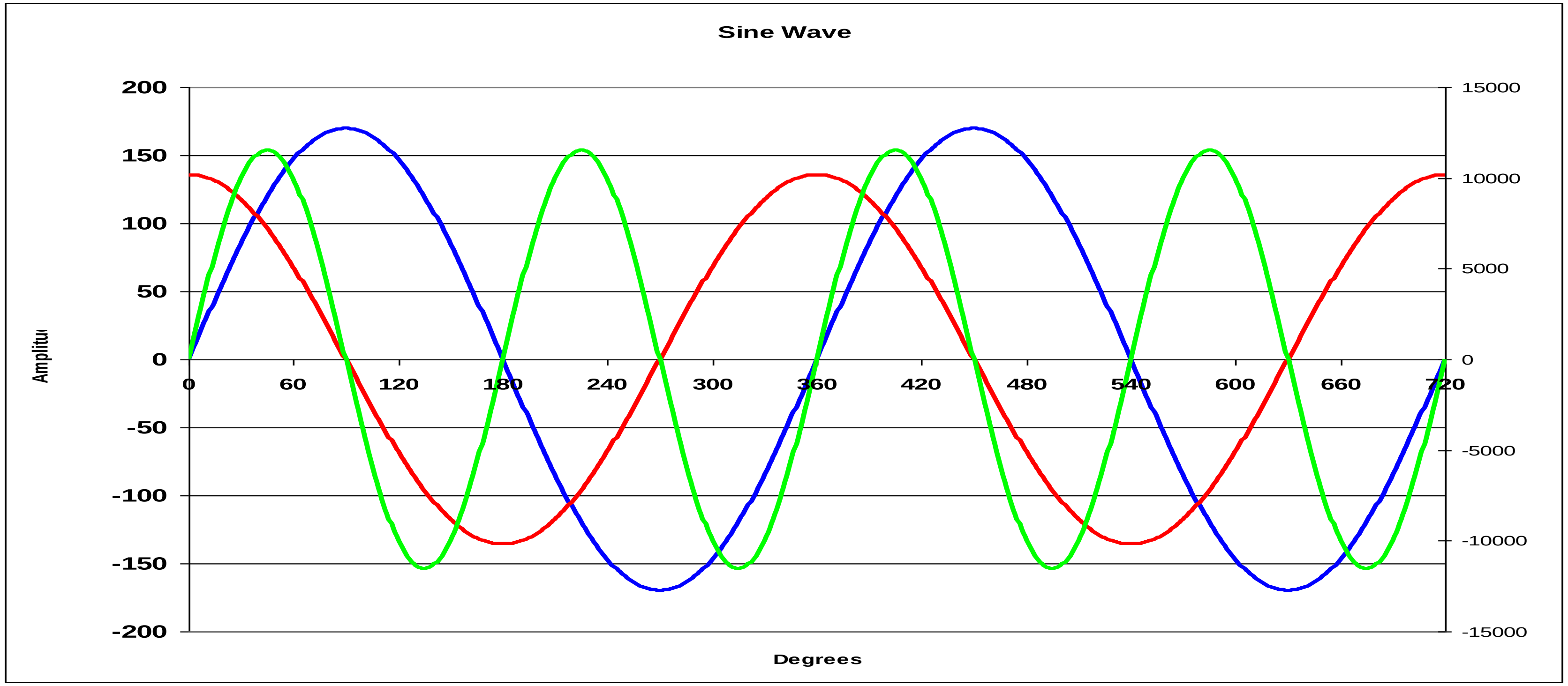


A purely capacitive load will:

- 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

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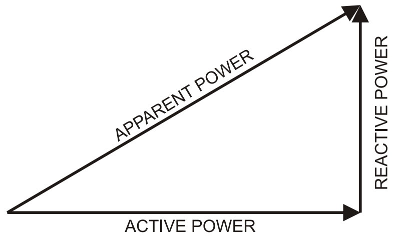
Inductance Vs Capacitance

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



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Power Factor Examples

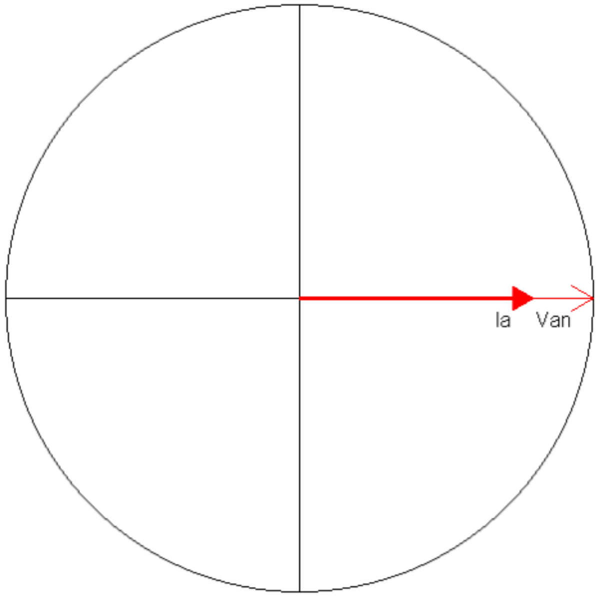
Power – VA

For a 120 Volt service drawing 10 Amps at 1.0 PF (0°)

How much power (in Watts) is being drawn?

Power = V x A x PF

120 x 10 x 1.0 = 1200 Watts



How many VA are being drawn?

VA = V x A

120 x 10 = 1200 Volt-Amperes

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Power Factor Examples

Power – VA

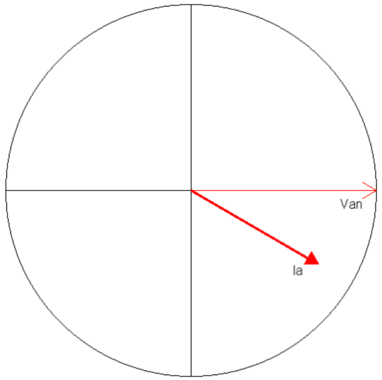
For a 120 Volt service drawing 10 Amps at 0.866 PF (30°)

How much power is being drawn?

Power = 120 x 10 x 0.866 = 1039 Watts

How many VA are being drawn?

VA = 120 x 10 = 1200 Volt-Amperes



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Power Factor Examples

Power – VA

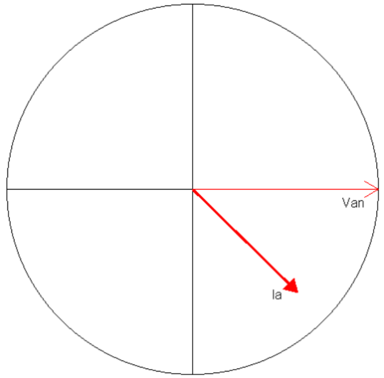
For a 120 Volt service drawing 10 Amps at 0.5 PF (60°)

How much power is being drawn?

Power = 120 x 10 x 0.5 = 600 Watts

How many VA are being drawn?

VA = 120 x 10 = 1200 Volt-Amperes



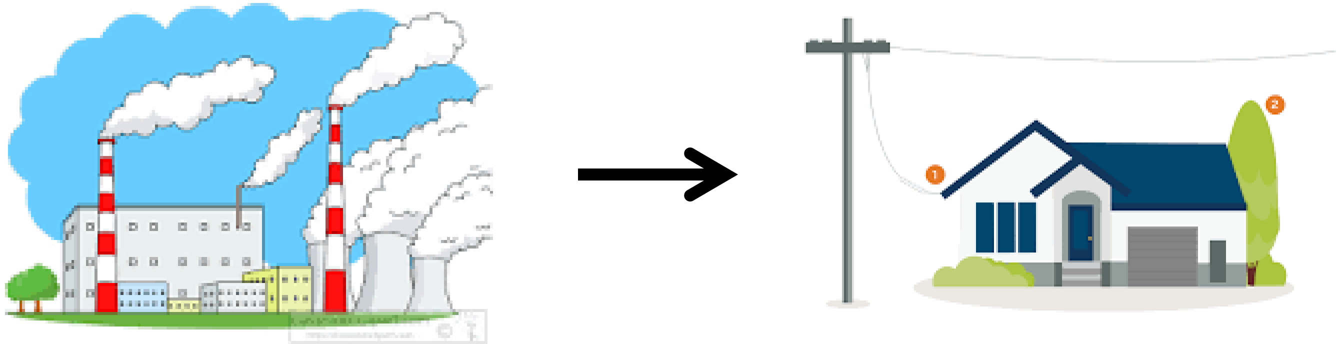
Power Factor, Watts, and VA

For our 120V, 10A system

Phase Angle	PF	Watts	VA
0	1.0	1200 W	1200 VA
30	0.866	1039 W	1200 VA
60	0.5	600 W	1200 VA

As PF get closer to 1, the VA generated by the utility gets closer to the Watts required to drive useful work at the site! This means less VARs have to be generated. This also means the utility can more adequately "right-size" assets (wires, transformers, and substations)!

Delivered vs Received Power



Positive Watts are DELIVERED from the Utility to the Consumer

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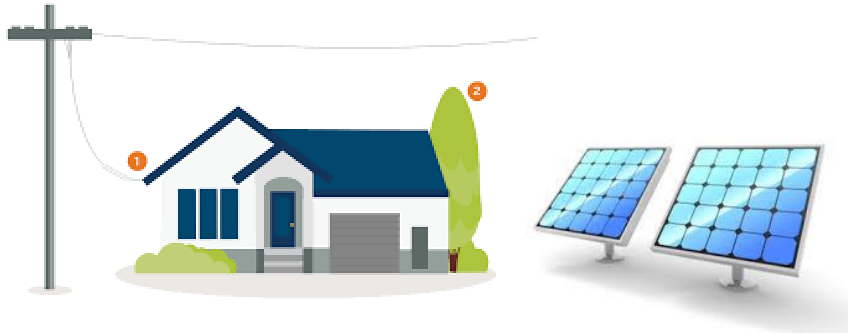
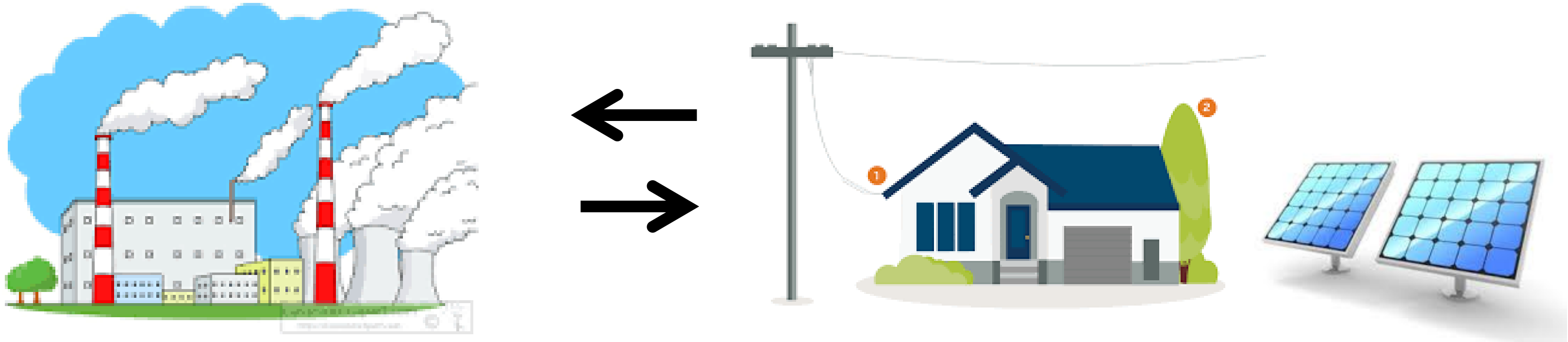
Delivered vs Received Power



Negative Watts are RECEIVED by the Utility from the Consumer

Delivered vs Received Power



Positive and Negative VARs flow in both directions

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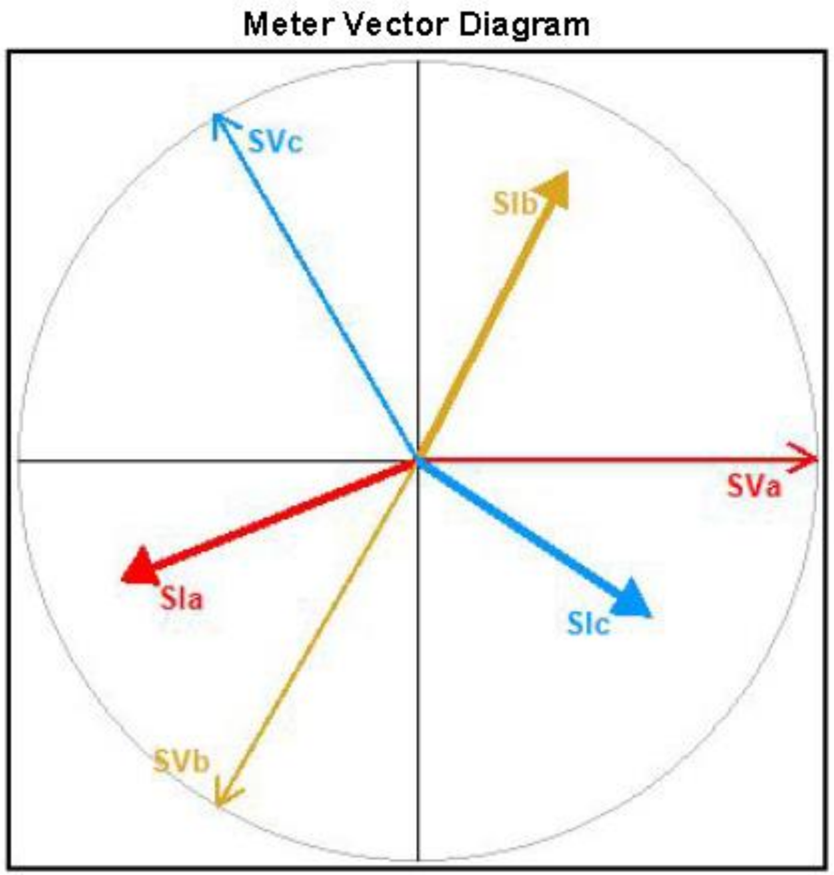
Negative Power Factor?



- 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

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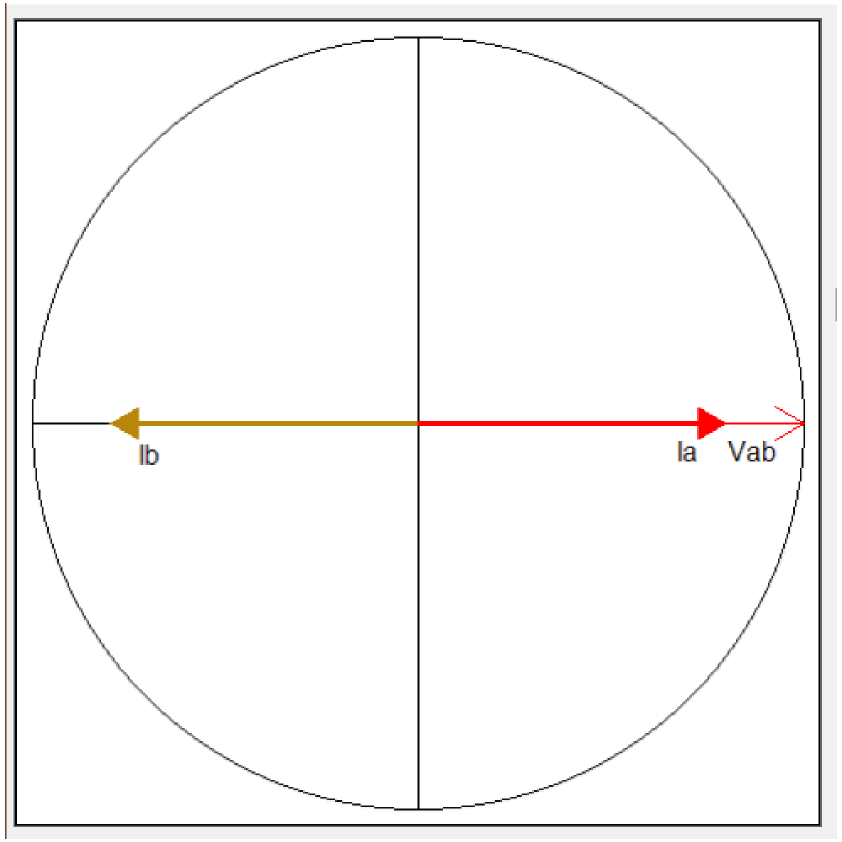
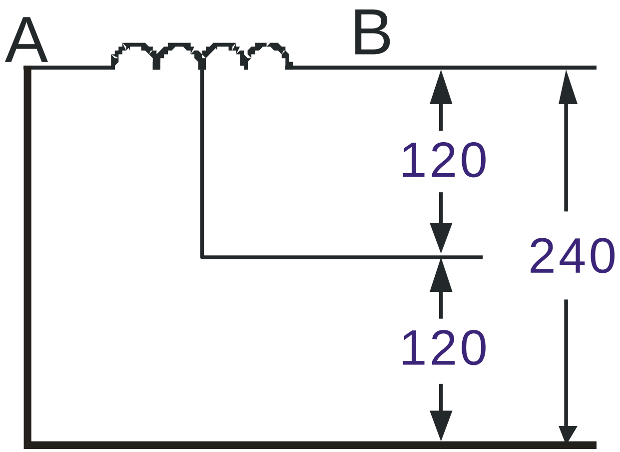
Single Phase – 3 Wire Service

0° = Unity Power Factor

- One Voltage Phasor
- Vab is phase-phase
- Two Current Phasors, 180° apart
- Aligned with Voltage at PF=1
- 2S or 4S





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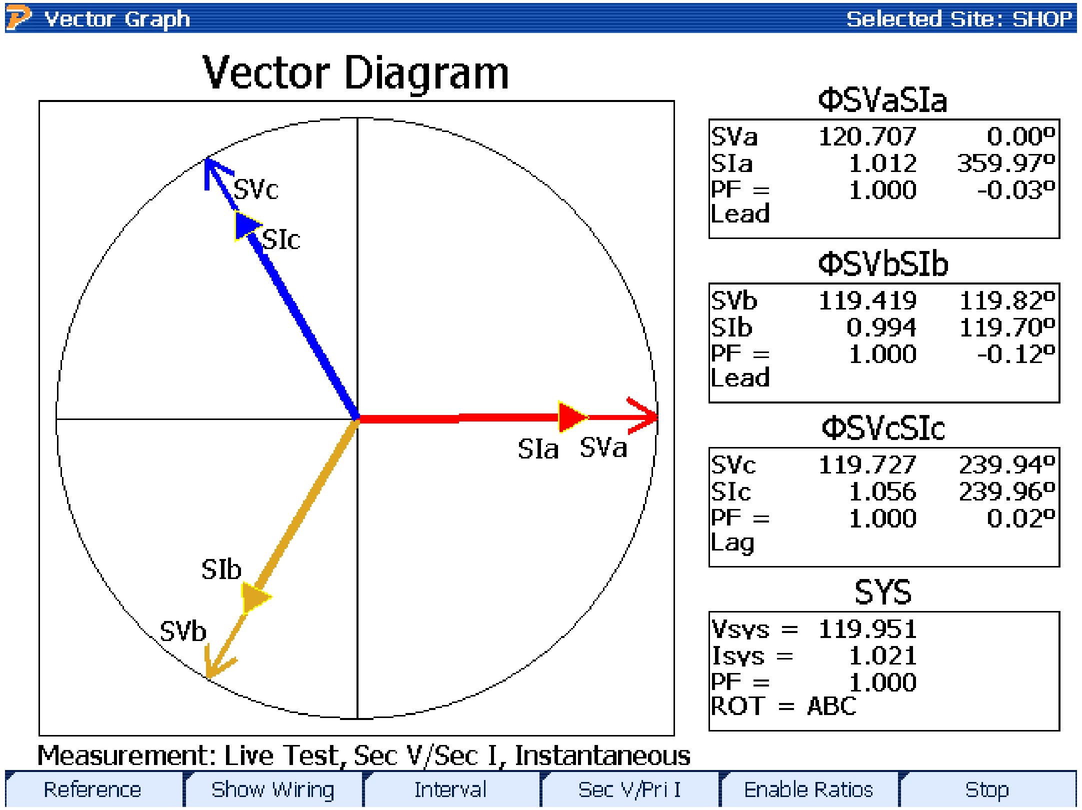
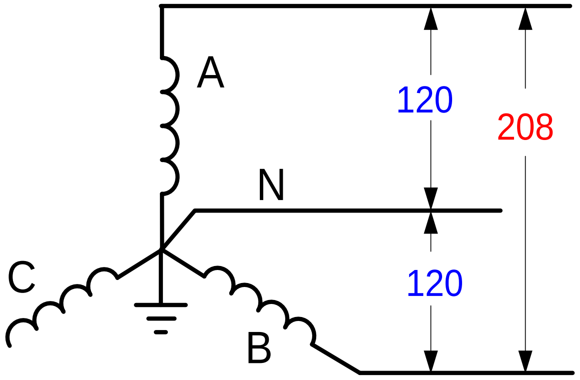
3 Phase, 4-Wire “Y” Service

0° = Unity Power Factor

- Three Voltage Phasors
- 120° Apart
- Three Current Phasors
- Aligned with Voltage at PF=1
- 9S or 16S





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

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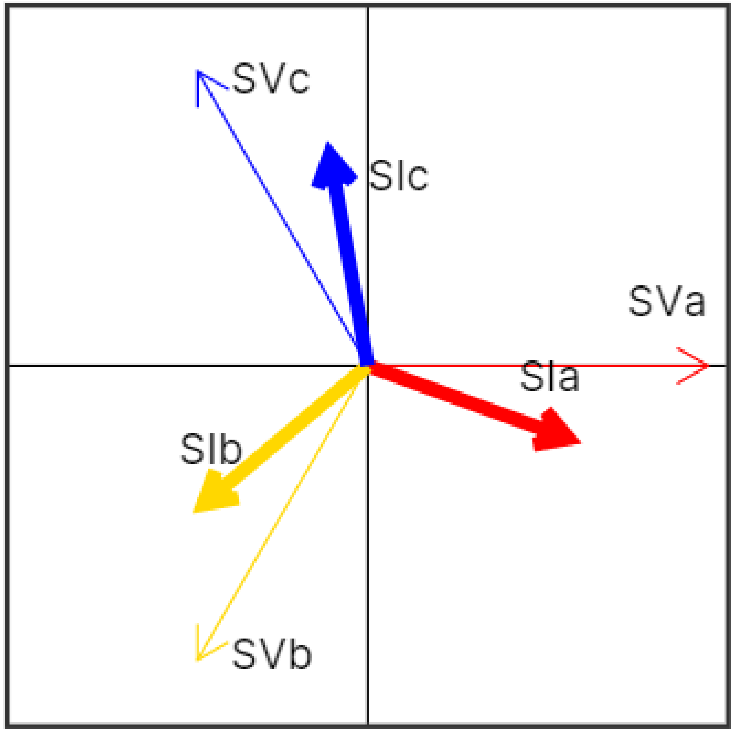
3 Phase, 4-Wire Wye

Meter Vector Diagram



Phase	Voltage	V-Phase	Phase	Current	I-Phase	VI-Phase	PF
SVa	120.451	0.000	SIa	2.447	19.891	19.891	0.940
SVb	120.348	120.051	SIb	2.464	139.886	19.834	0.941
SVc	120.332	240.010	SIc	2.461	259.820	19.810	0.941
Vn	0.000		In	0.000			
VSys	120.377		ISys	2.457			0.941

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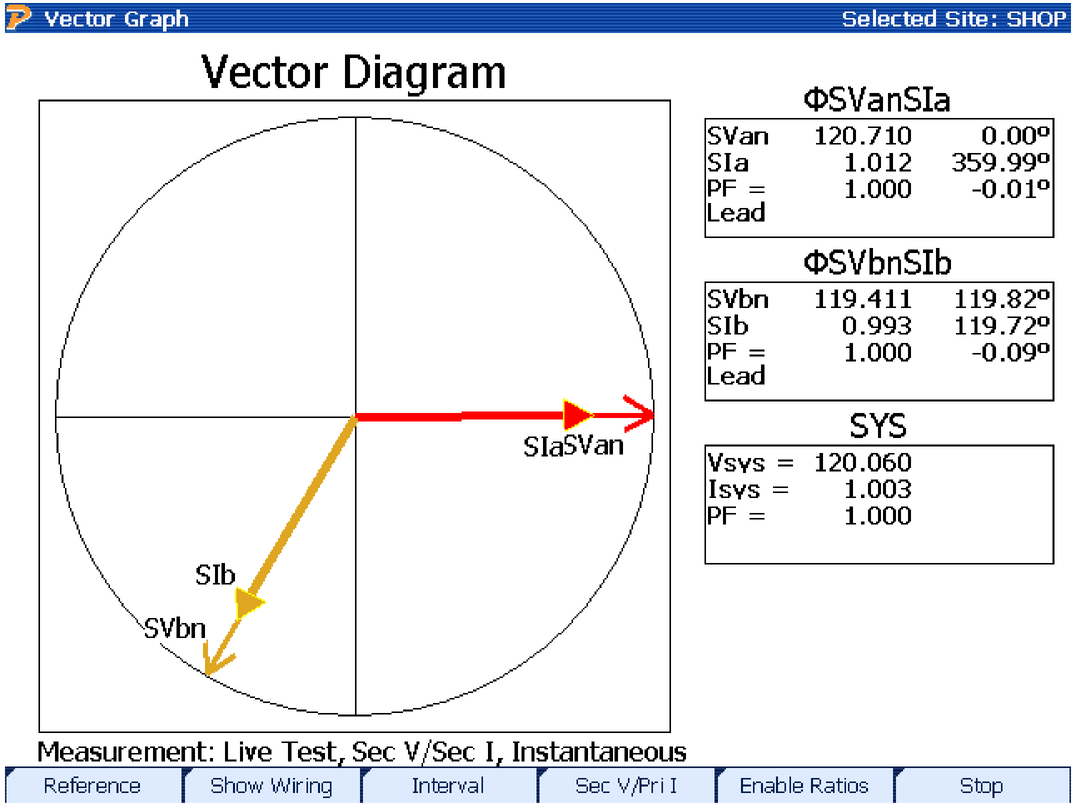
2 Phase, 3-Wire "Network" Service

0° = Unity Power Factor

- Two Voltage Phasors
- 120° Apart
- Two Current Phasors
- Aligned with Voltage at PF=1
- 5S or 12S



Network is only 2 phases of a 4 wire-Wye

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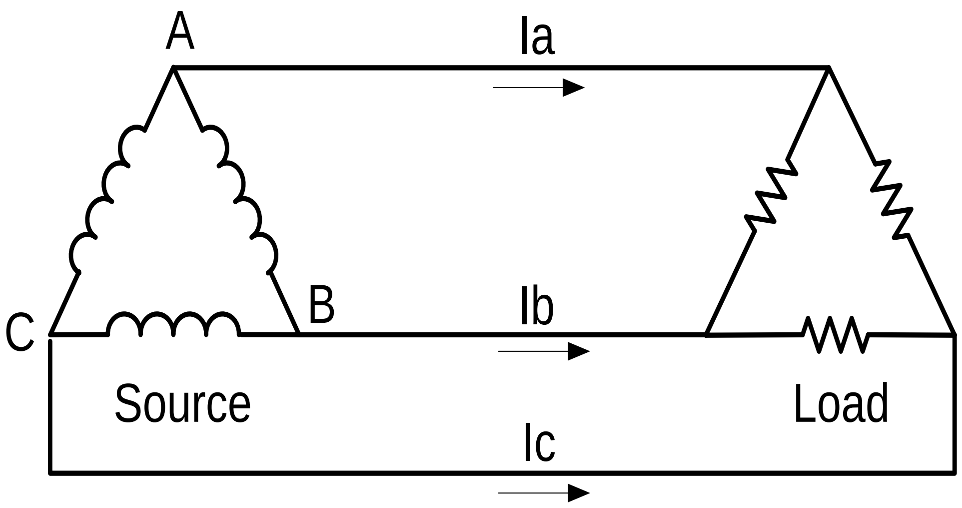
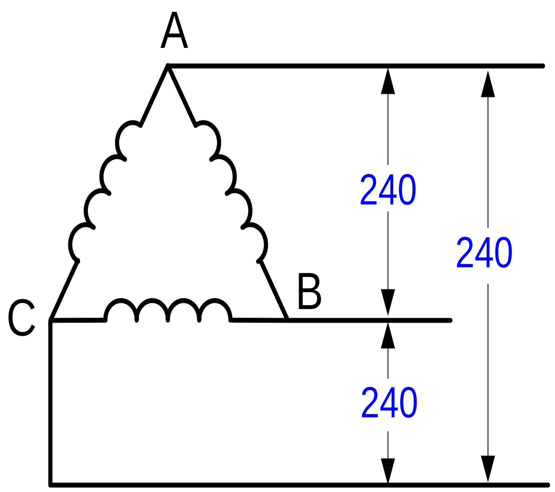
3 Phase, 3-Wire Delta Service

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



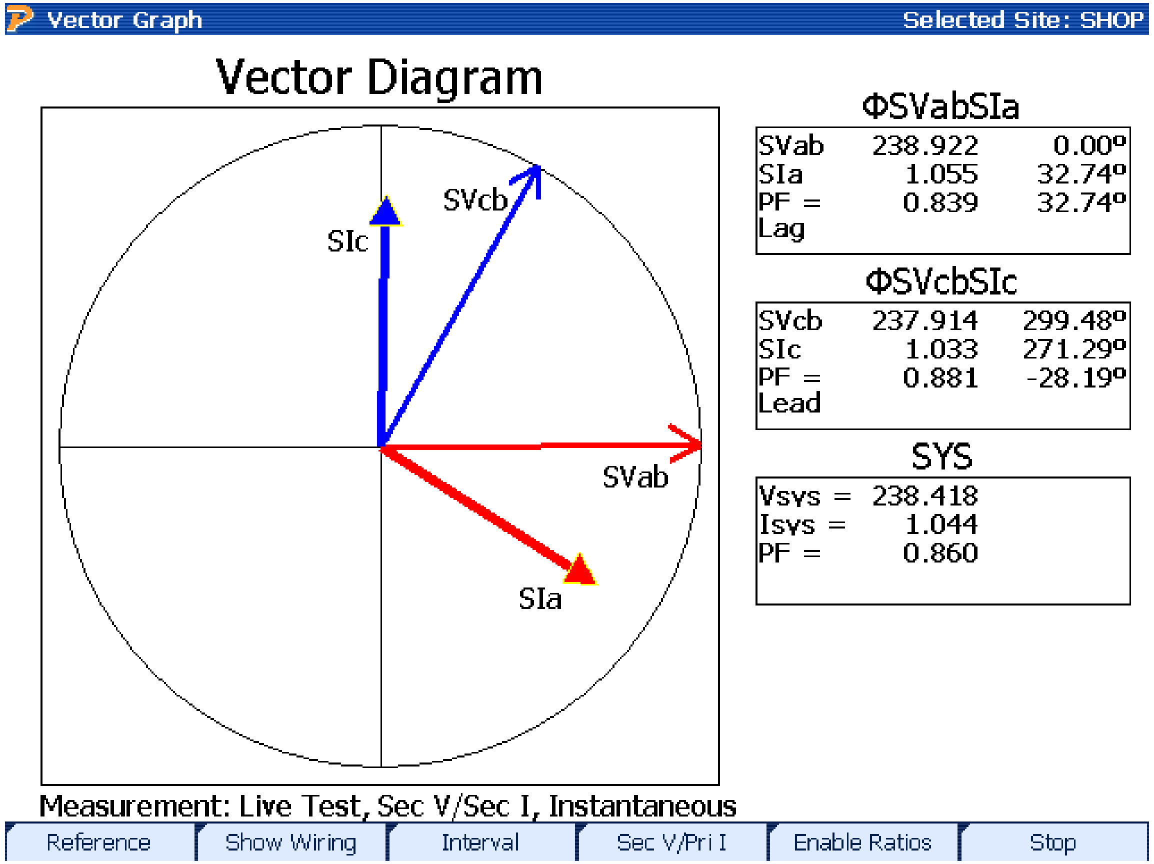


- Voltages normally measured relative to phase B.
- Voltage and current vectors do not align.
- Service is provided even when a phase is grounded.

3 Phase, 3-Wire Delta Service

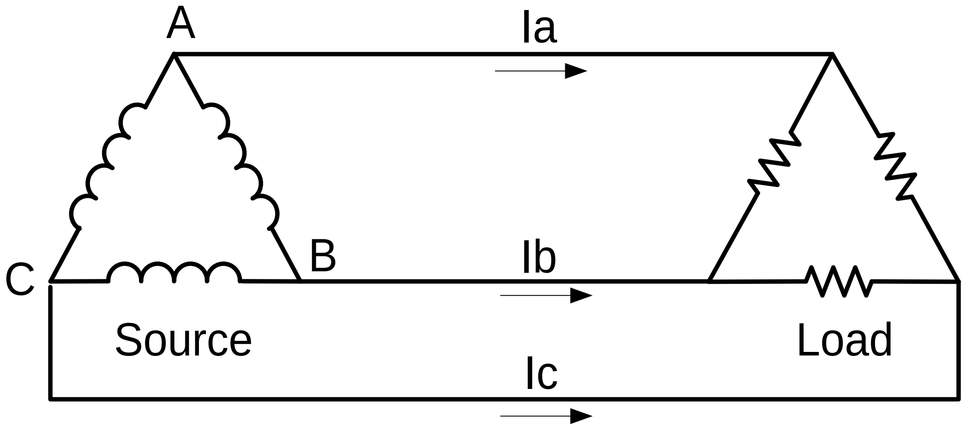
Resistive Loads

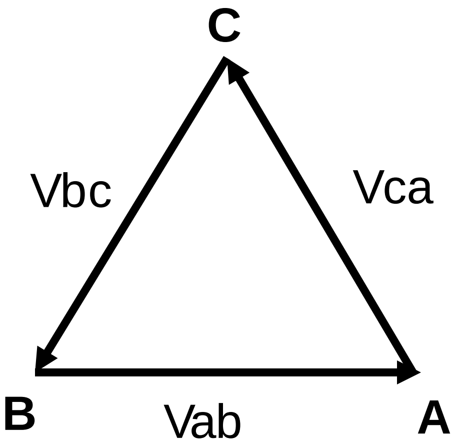
- Two Voltage Phasors
- 60° Apart
- Two Current Phasors
- For a resistive load one current leads by 30° while the other lags by 30°
- 5S or 12S

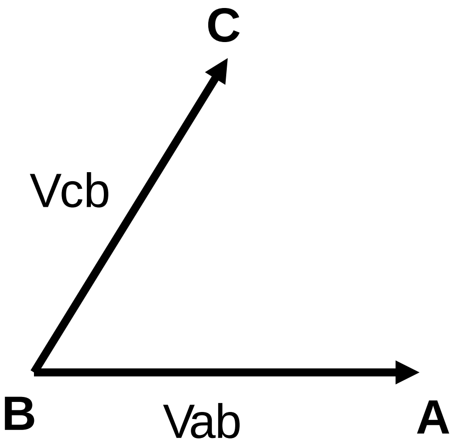


3 Phase, 3-Wire Delta Service

Understanding the Diagram

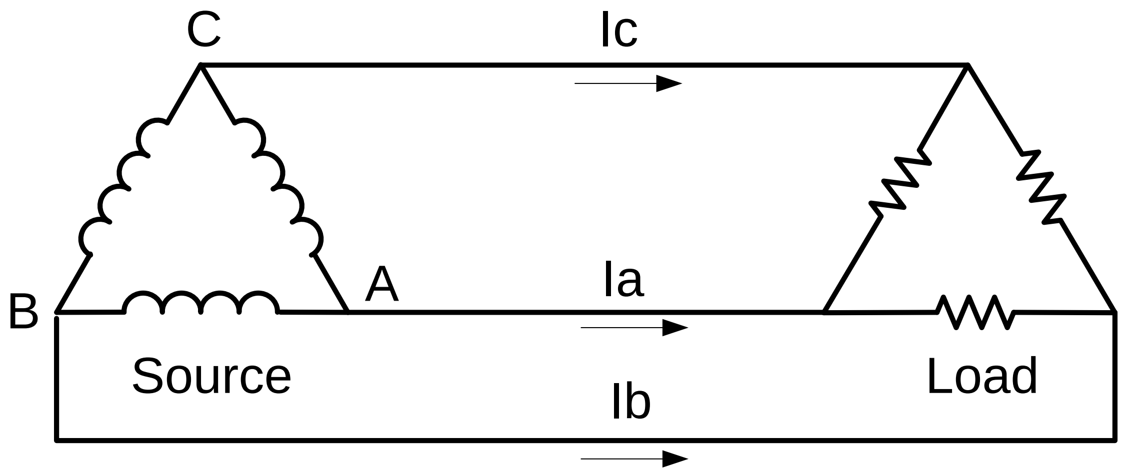


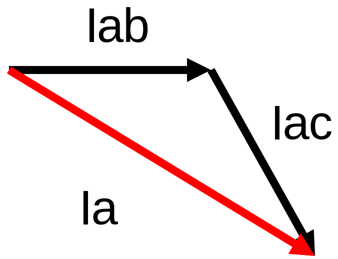


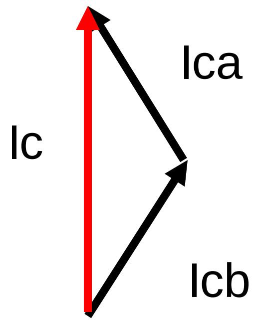


3 Phase, 3-Wire Delta Service

Understanding the Diagram







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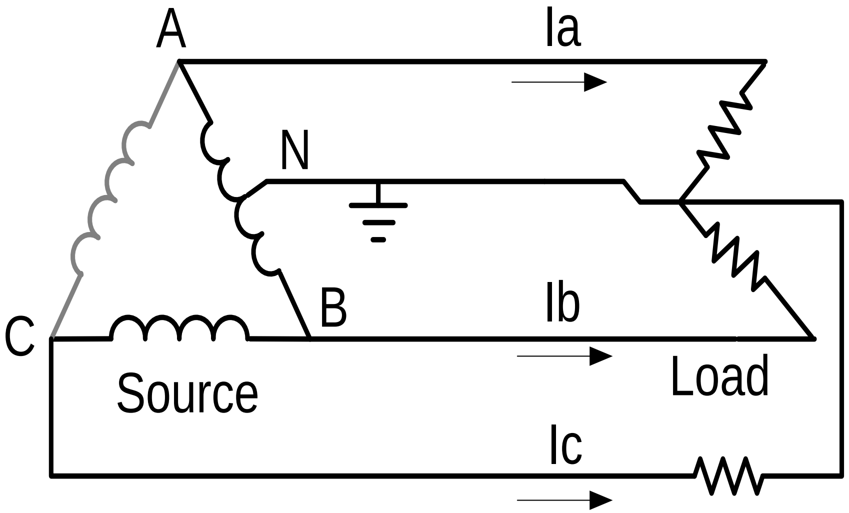
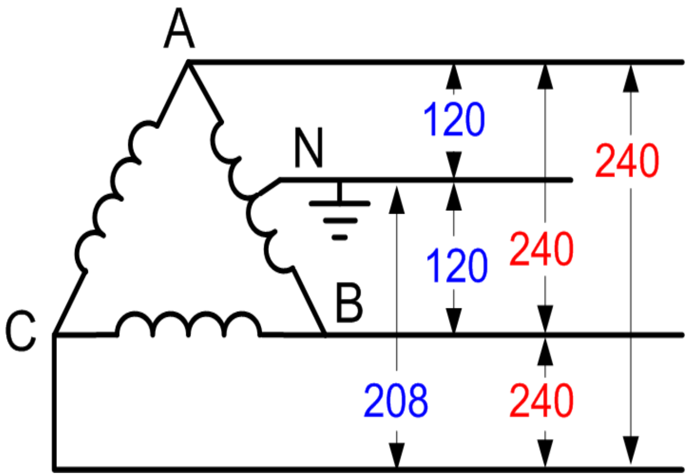
3 Phase, 4-Wire Delta Service

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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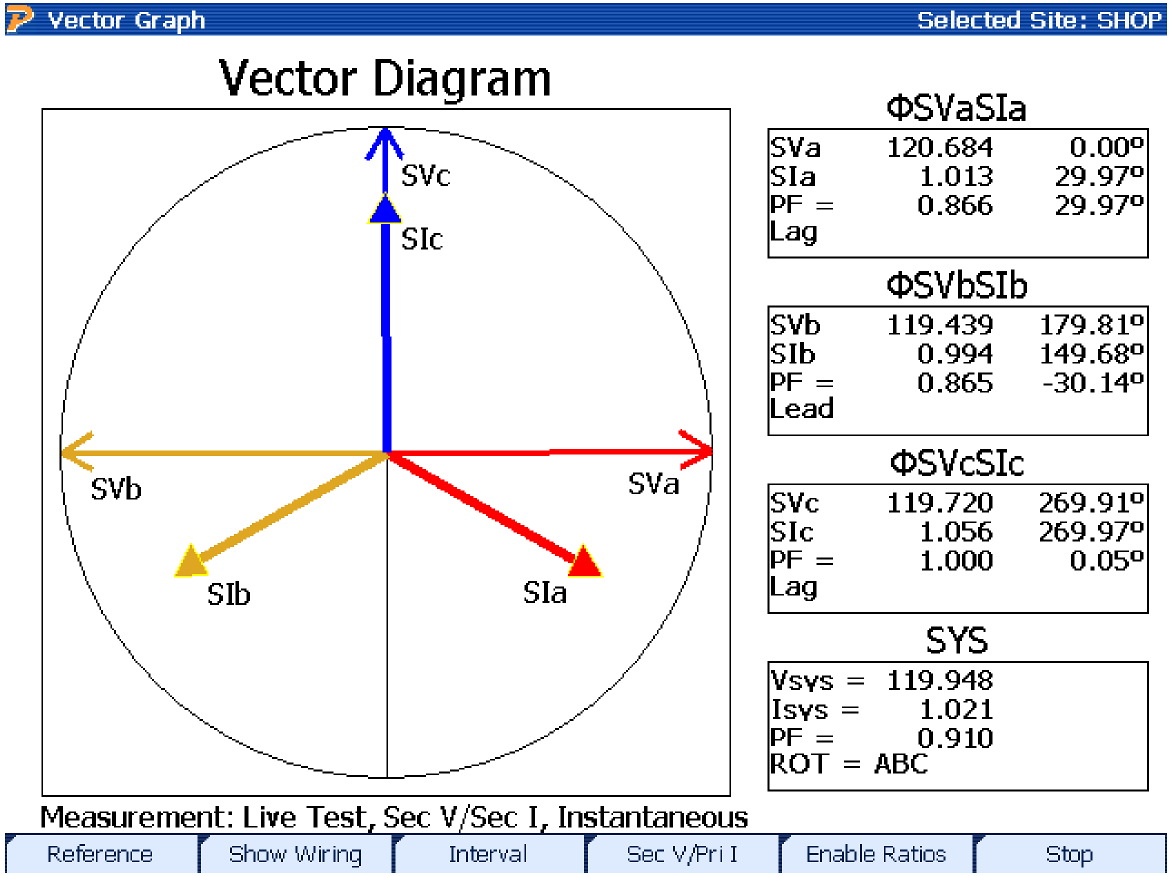
3 Phase, 4-Wire Delta Service

Resistive Load

- Three Voltage Phasors
- 90° Apart
- Three Current Phasors
- 120° apart
- 9S or 16S



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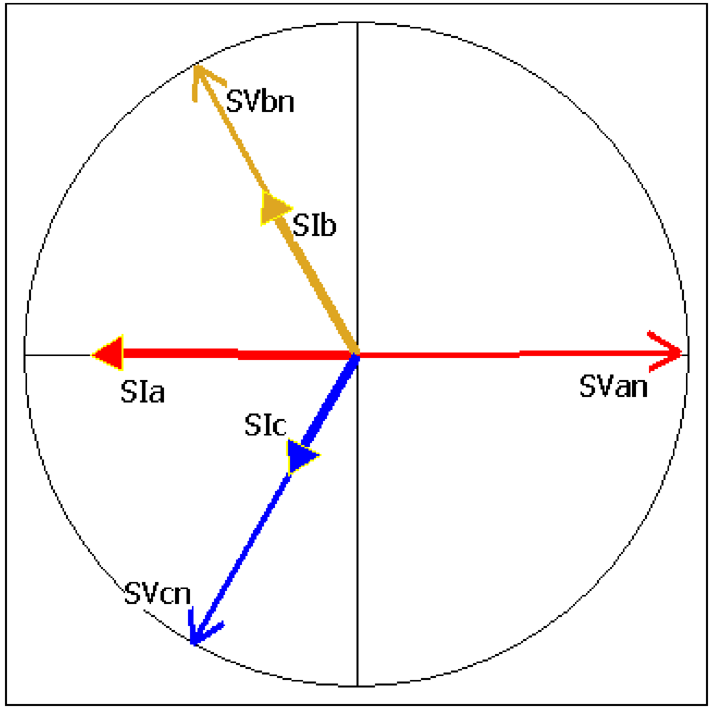
Troubleshooting with Vectors

What's Wrong?

Vector Graph — Selected Site: DELETE ME

Vector Diagram



Measurement: Live Test, Sec V/Sec I, Instantaneous

ΦSVanSIa

SVan	117.914	0.00º
SIa	3.243	179.78º
PF =	1.000	179.78º
Lag		

ΦSVbnSIb

SVbn	119.674	240.87º
SIb	2.288	240.42º
PF =	1.000	-0.45º
Lead		

ΦSVcnSIc

SVcn	121.251	119.46º
SIc	1.679	119.21º
PF =	1.000	-0.25º
Lead		

SYS

Vsys =	119.613
Isys =	2.403
PF =	1.000
ROT =	CBA

Reference | Show Wiring | Interval | Sec V/Pri I | Stop

Phase A CT reversed.

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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!

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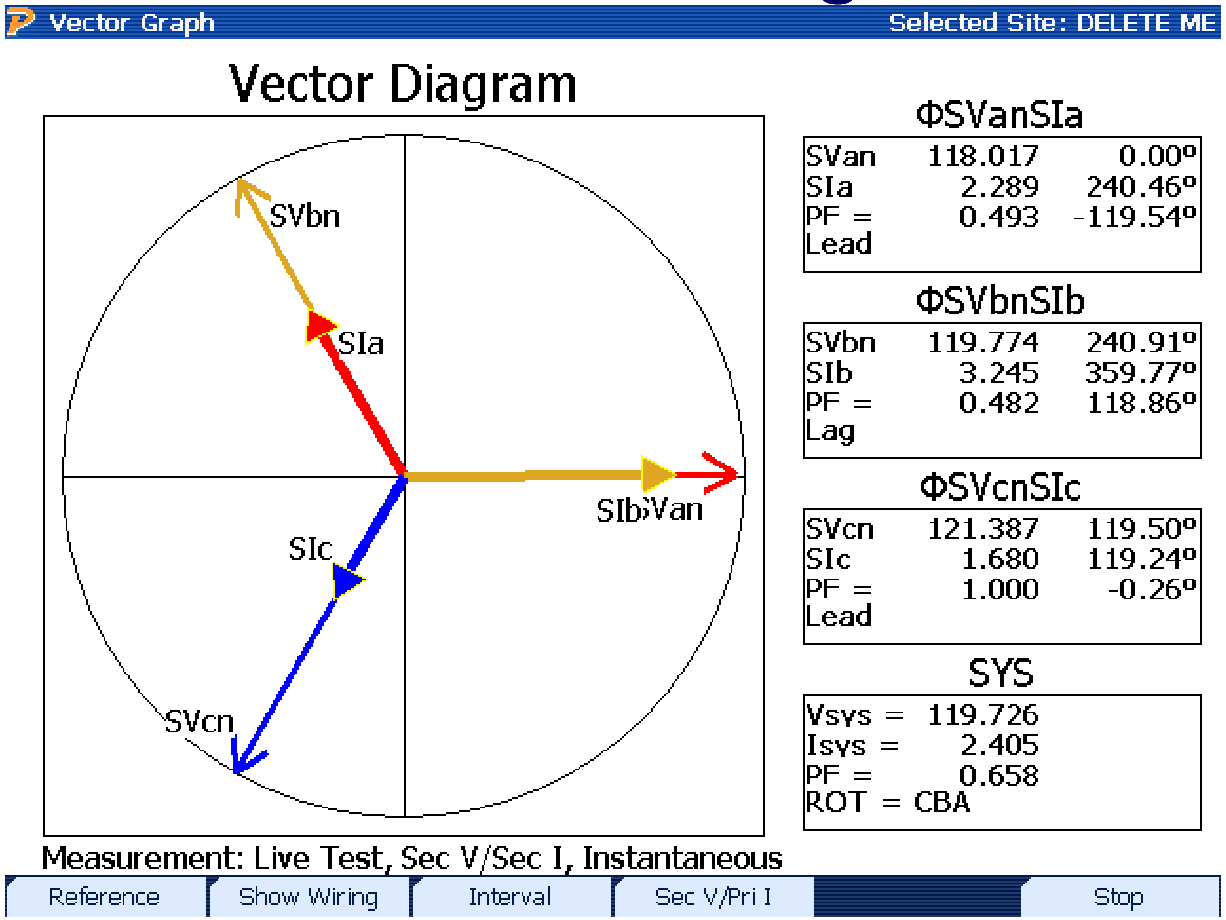
Troubleshooting with Vectors

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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Summary – Vector Diagrams

- Vectors show the relationship between voltage and current amplitude and phase
- There are different vectors for each meter form and service type combination
- Vectors can quickly help find problems in your system

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Summary – Power Factor

- 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

Questions? Comments?

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Thank you for your time!

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