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Practical Use of Vectors in Electric Metering

TESCO's Meter School

TESCOOL

Tuesday July 11th ,2023

10:00AM -11:00AM

Dan Hollow

The most basic statement of metering:

Watts = Voltage x Current x Power Factor

Mathematically:

$$Watts = V \times I \times \cos\theta$$

What is a Vector?

A measurement that takes two numbers to represent.

BOTH a magnitude (size) and direction

Vectors or Phasors are…

a Symbolic Representation of the relationship of the voltage and current

- **Vectors & Vector Diagrams**
  - SIMPLE. Used to Represent Electrical Quantities.
  - QUICK. Saves time.
  - Vastly more effective
  - Also referred to as "Phasors"

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Representing *Voltage(E)* & Current (*I*) with Lines

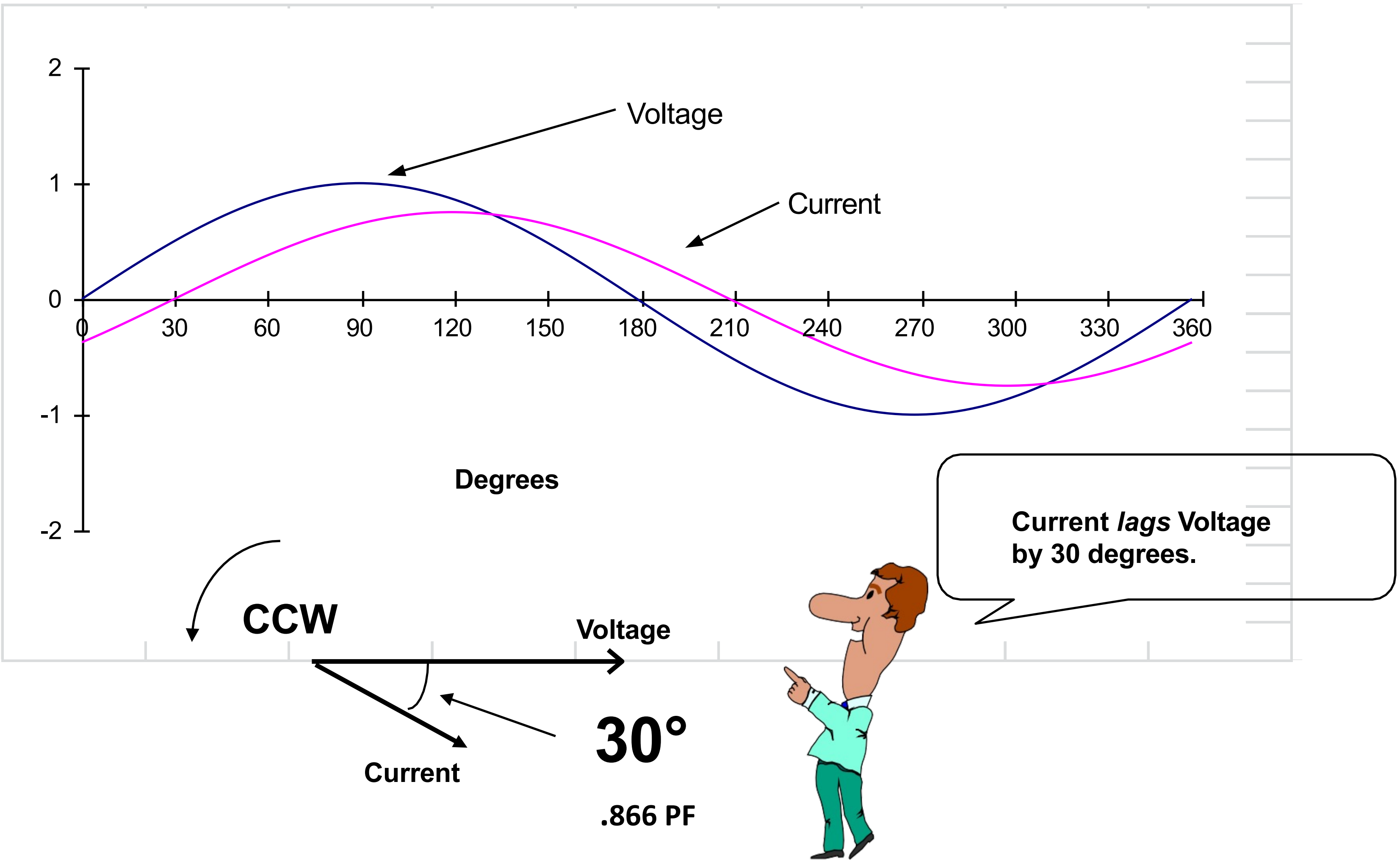
- **Vectors all have MAGNITUDE and DIRECTION**
- **Line length can represent MAGNITUDE.**
- **Line with arrowhead in a given direction indicates that quantity's relationship to any other quantity being represented.**
- **DIRECTION: Angles between lines take on significance. They represent time (shown in degrees instead of seconds).**

Drawing the Phasor

General Guidelines

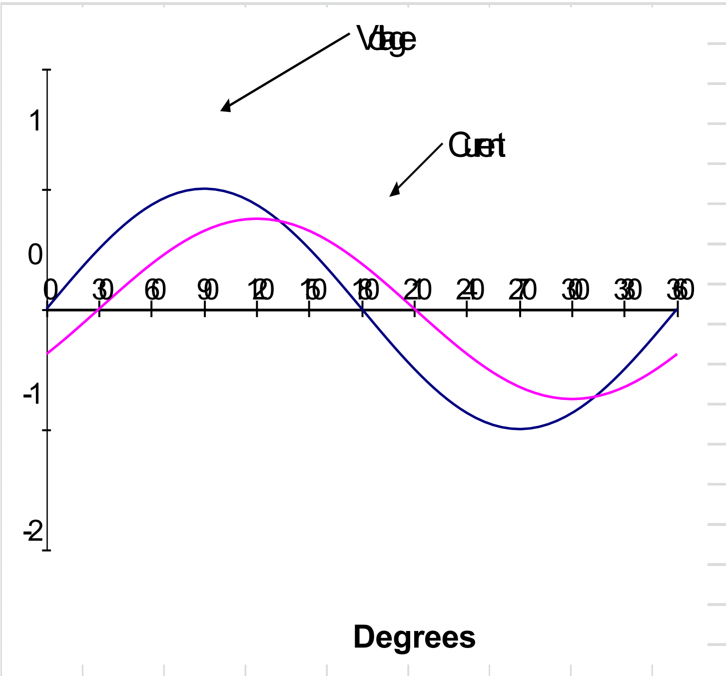
- Complete circle (360 Degrees) equal one cycle of the frequency displayed.
- One component (Usually Phase A voltage) becomes the reference and is placed at zero degrees.
- Use “open” arrowhead on voltage line(s).
- Use “closed” (or filled in) arrowhead on current line(s).
- Label all voltages and currents by phase.
- Indicate Phase Rotation (counter-clockwise assumed if not noted).

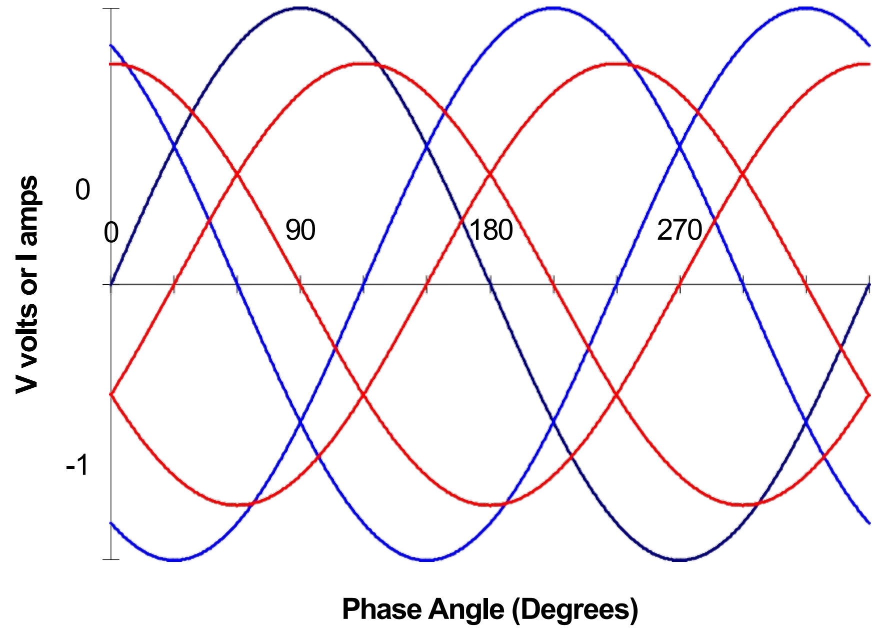
"TIME" IN DEGREES

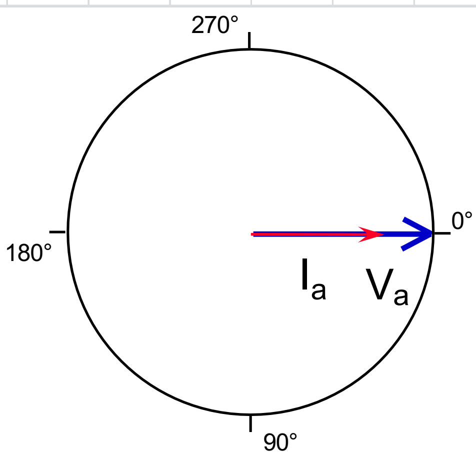


“Time” in Degrees

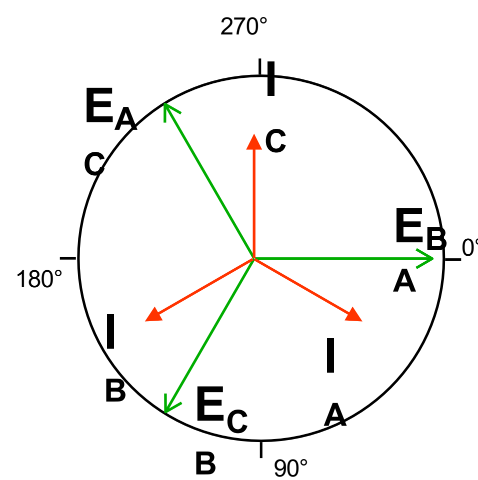
1







1 Element

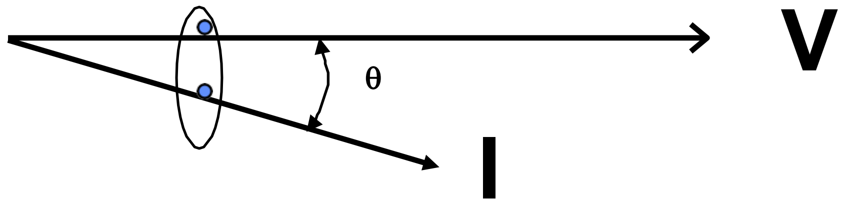


Watthour Metering

- **Watthour meter theory review:**
  - **If we apply "V" volts and "I" amps to a meter, and the phase angle between the voltage and current is some angle θ, the meter speed will be proportional to:**

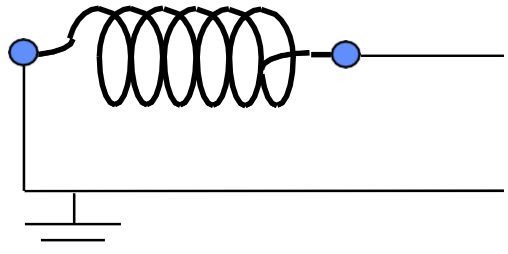
$$Watts = V \times I \times cos\theta$$

VECTORIALLY

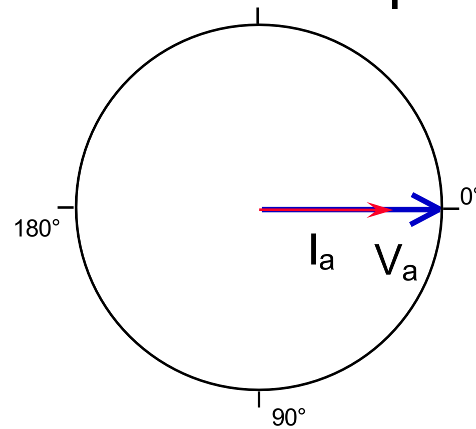


Expected Meter Phasors

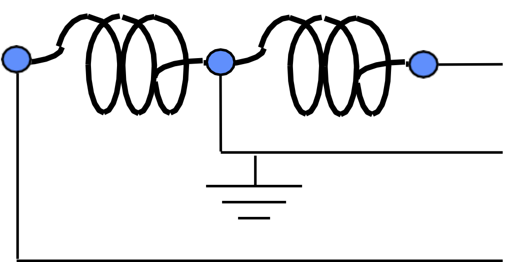
(at Power Factor = 1, ABC Phase Sequence)



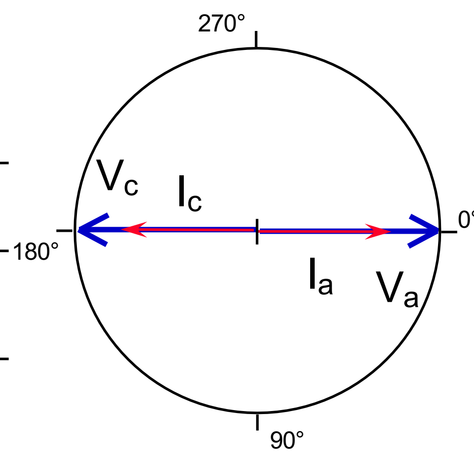
2 wire, 1 φ



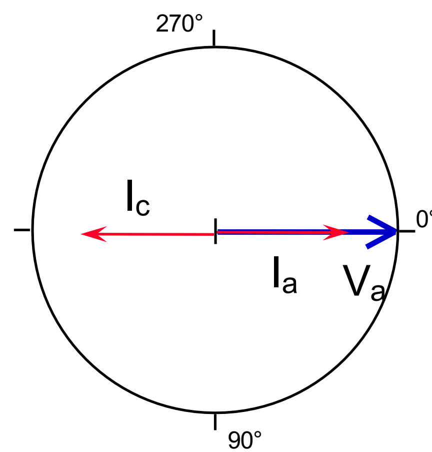
1 Element



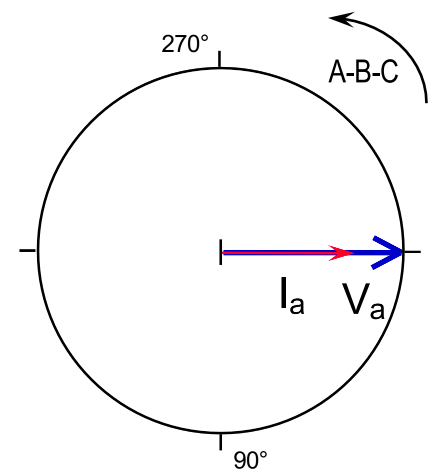
3 wire, 1 φ



2 Element

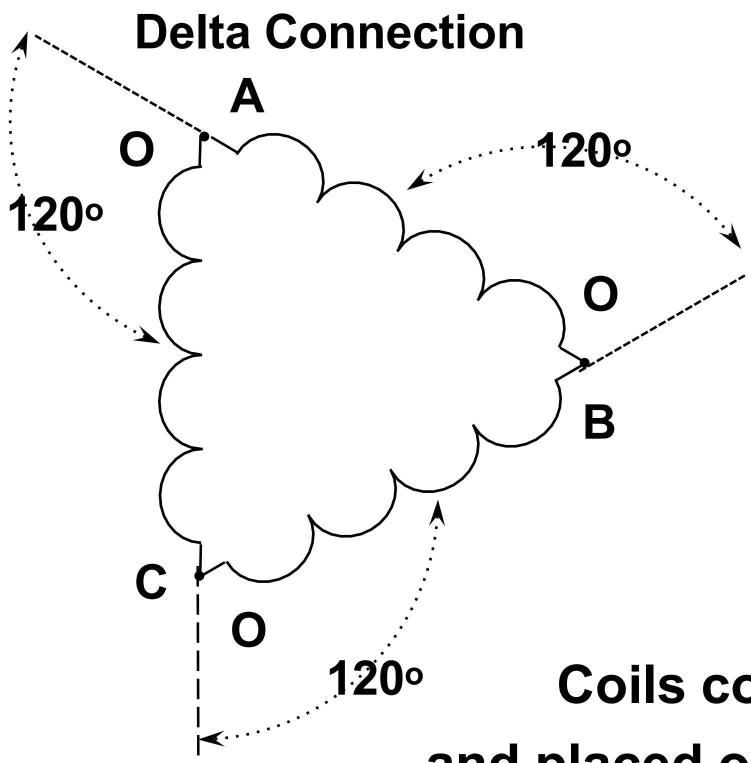


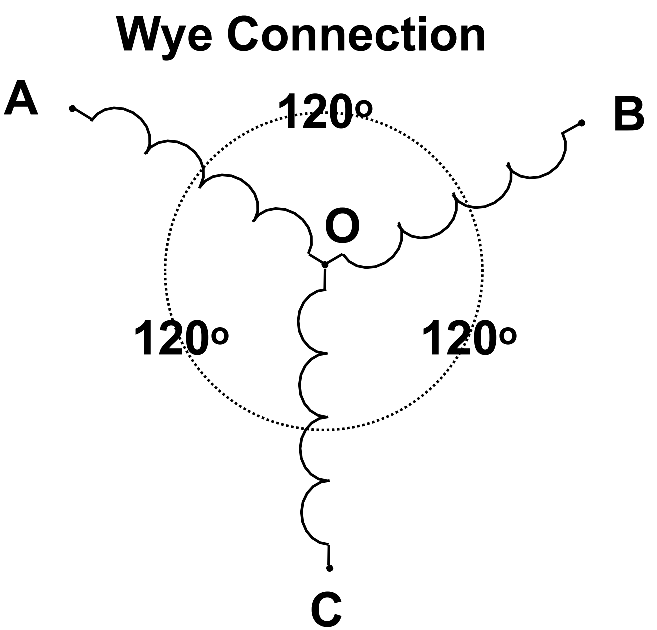
1½ Element



1 Element

PLACING COILS IN ORDER





Coils connected together

and placed on an alternator in order

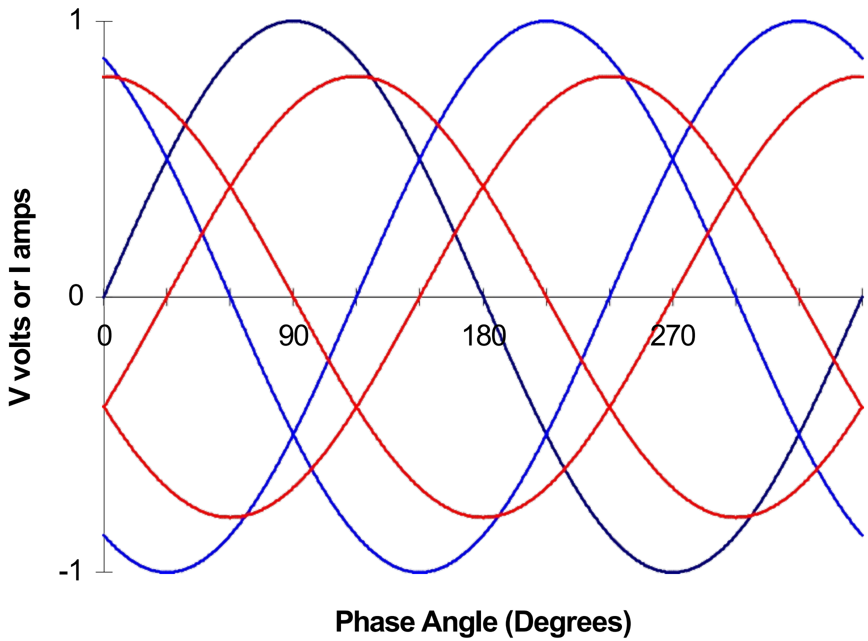
OA, OB, and OC

(Changing Coil order changes *Sequence*)

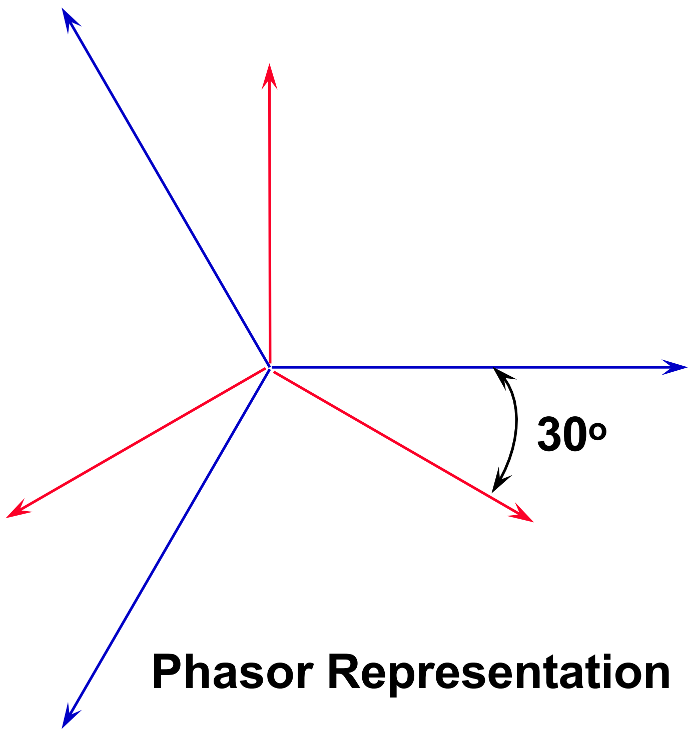
The Phasor Diagram

- **A phasor diagram is a method of expressing the magnitudes and time relationships (or phase angle relationships) between two or more sinusoidal quantities of the *same frequency*.**
- **Each alternating quantity having the same frequency can be represented on the same diagram by additional lines. Their time relationship will determine the angle between the lines.**
- **The phasor diagram is a "snap-shot" of the set of lines at an instant in time. The instant is generally chosen to be the time at which the voltage passes through zero in the positive direction. If there is more than one voltage, the instant at which phase A voltage passes through zero is chosen.**

Representing Polyphase V & I



Time Domain Representation



Phasor Representation

Representing *E* & *I* with Lines

- **Line length can represent MAGNITUDE.**
- **Line with arrowhead in a given direction indicates that quantity's relationship to any other quantity being represented.**
- **Angles between lines take on significance. They represent time (shown in degrees instead of seconds).**

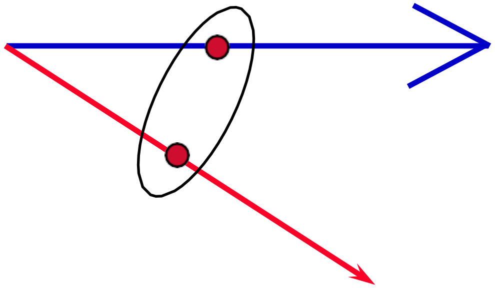
Developing the Phasor Drawing

General Guidelines

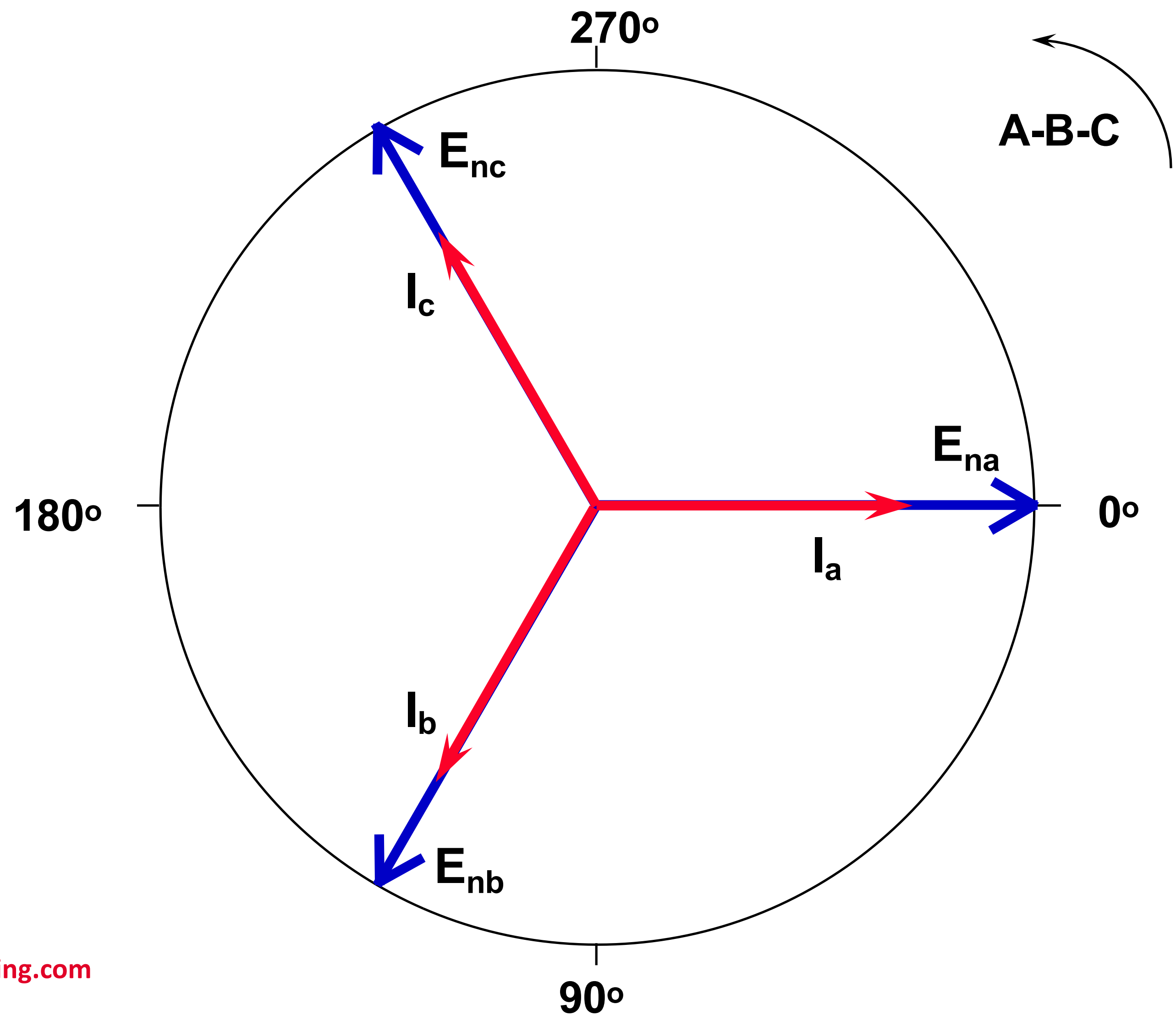
- Complete circle (360 Degrees) equal one cycle of the frequency displayed.
- One component (Usually Phase A voltage) becomes the reference and is placed at zero degrees.
- Use “open” arrowhead on voltage line(s).
- Use “closed” (or filled in) arrowhead on current line(s).
- Label all voltages and currents by phase.
- Indicate Phase Rotation (counter-clockwise assumed if not noted).

Analyzing the Phasor Picture

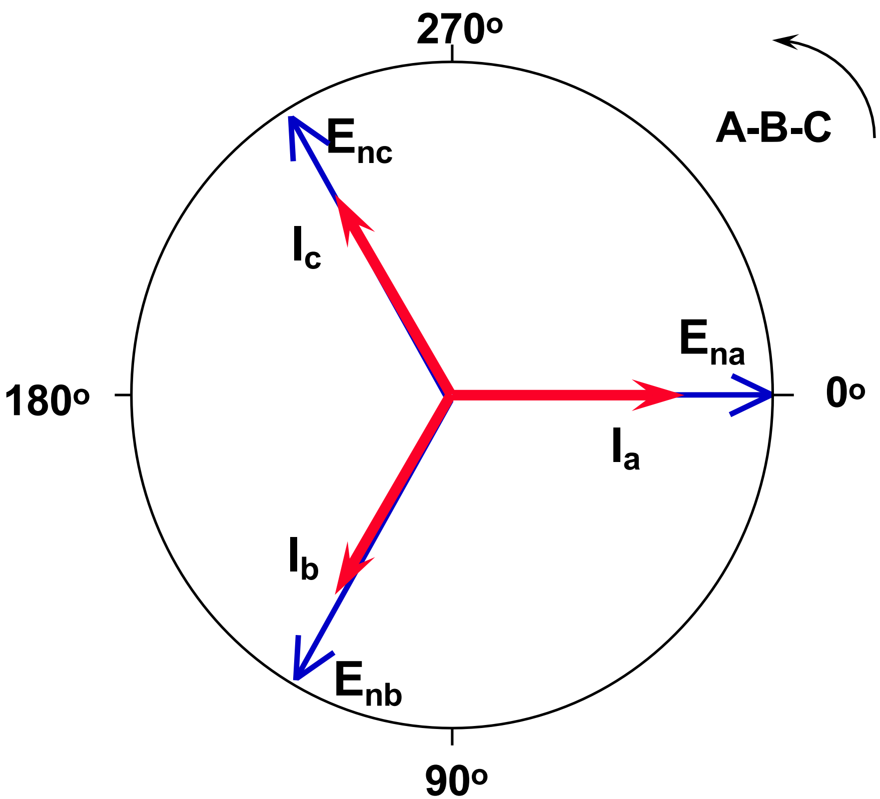
- **Both voltage & current are required in each meter element (stator) for that element to have an effect on registration.**
- **Time relationship (degrees separation) between voltage & current acting together on each element will determine that element's effect.**
- **Only angles of less than 90 Degrees between the current and voltage on any meter element will cause positive watthour registration.**



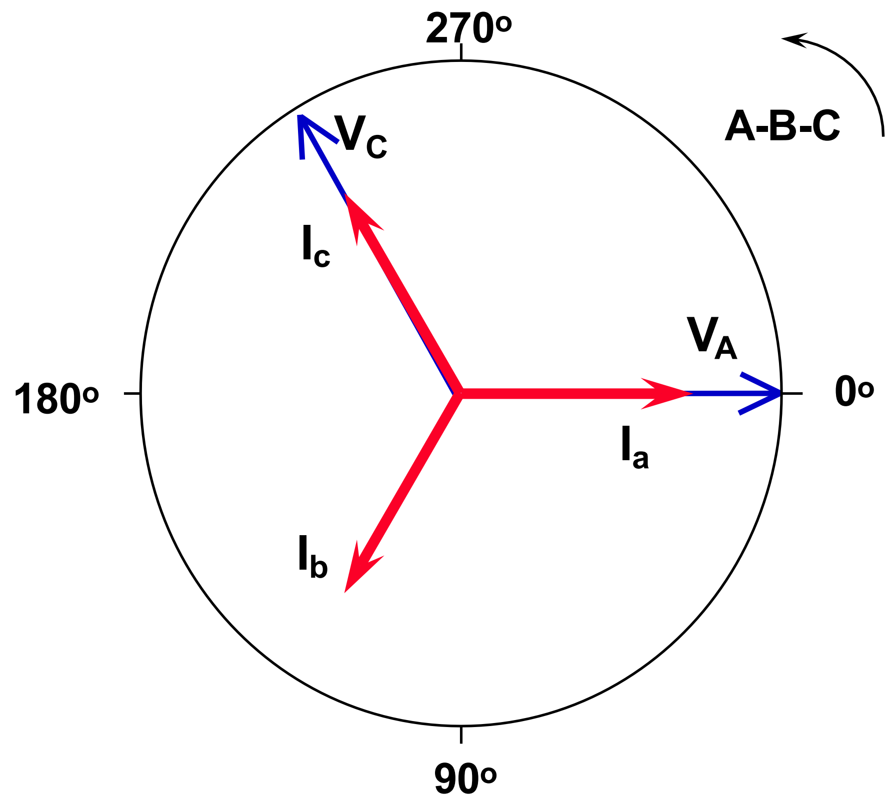
The Phasor Diagram



SERVICE & METER PHASORS



Service Phasors



Meter Phasors

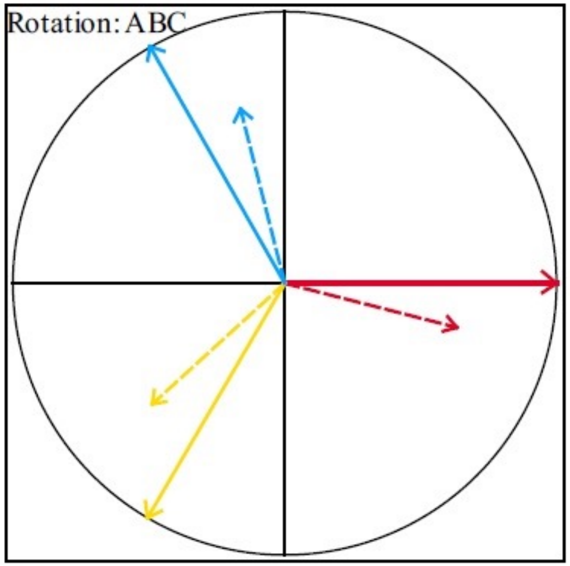
2 ½ Element

Phase Rotation & Site Measurements

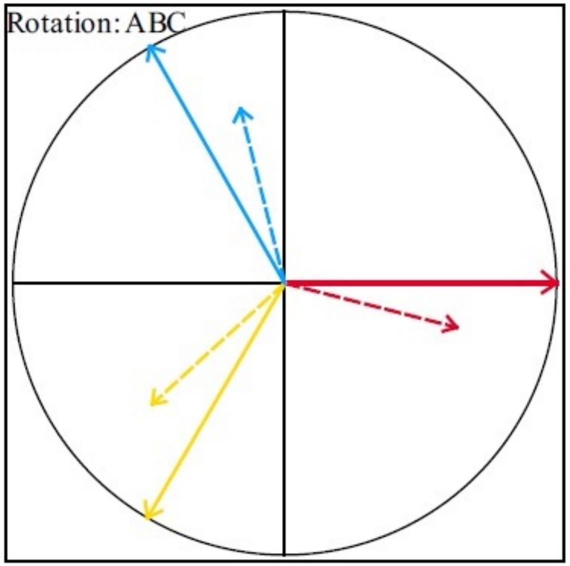
Site Measurements

Phase	Voltage	Voltage Phase	Current	Current Phase	Probe Current	Probe Phase
A	113.605	0.000°	2.901	14.345°	578.355	14.45°
B	114.364	120.147°	3.002	136.931°	599.459	137.140°
C	113.611	240.312°	2.864	256.188°	570.920	256.198°

Secondary Phasor



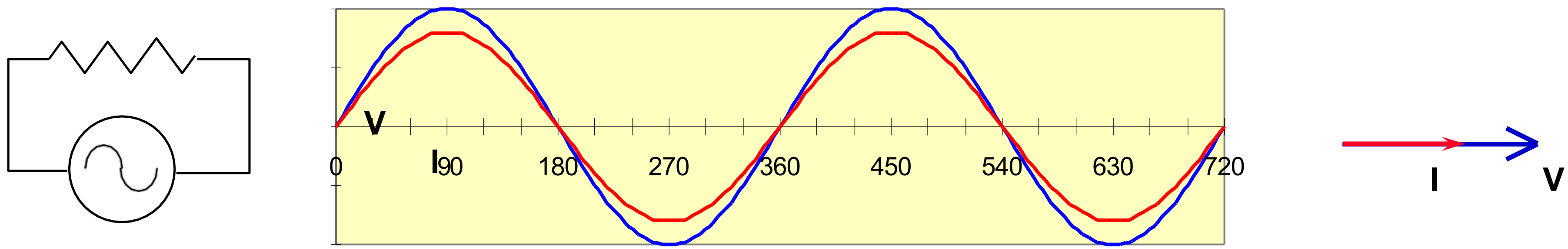
Primary Phasor

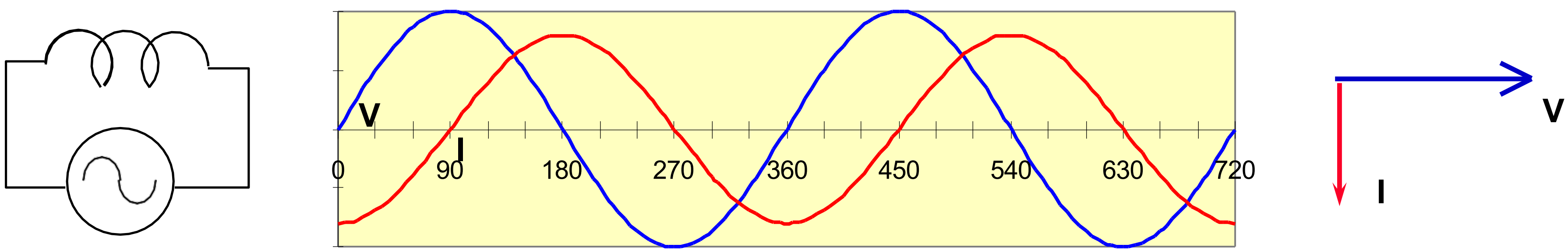


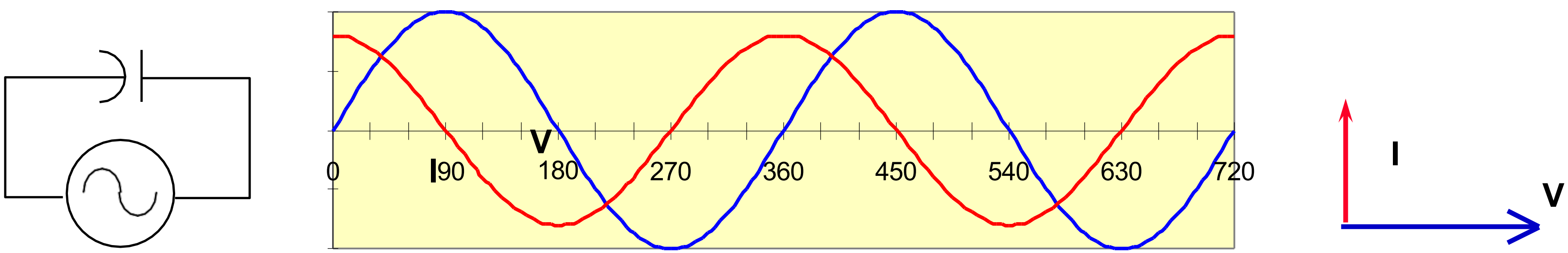
Power

Phase	Watts	VA	VAR	Voltage THD	Current THD	Power Factor	CT Ratio
A	0.354	1.464	0.360	0.016	0.075	0.966	996.98:5
B	1.456	1.525	0.438	0.016	0.073	0.955	998.58:5
C	1.387	1.445	0.393	0.016	0.075	0.959	996.57:5

LOAD CAUSED PHASE ANGLES



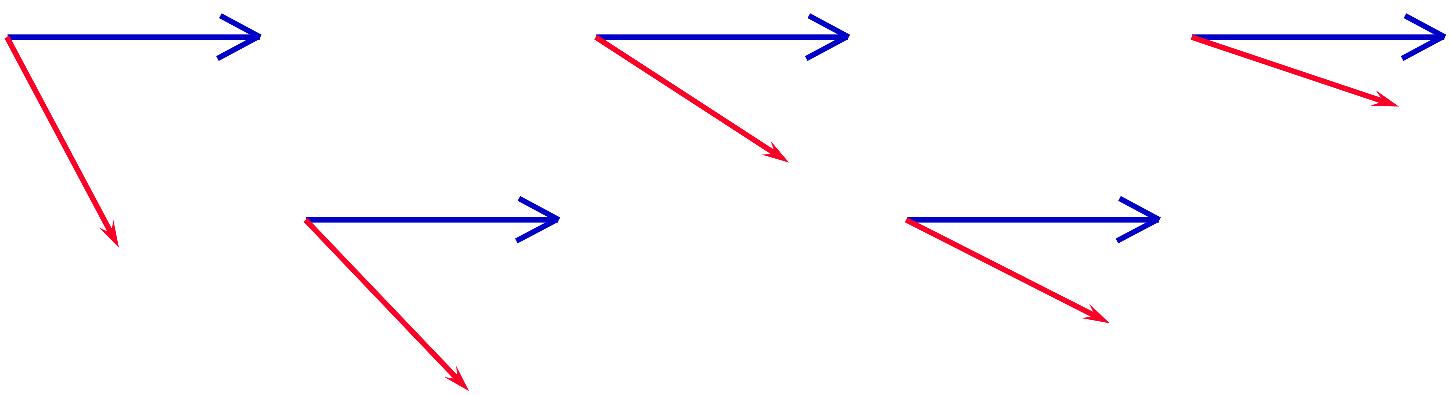




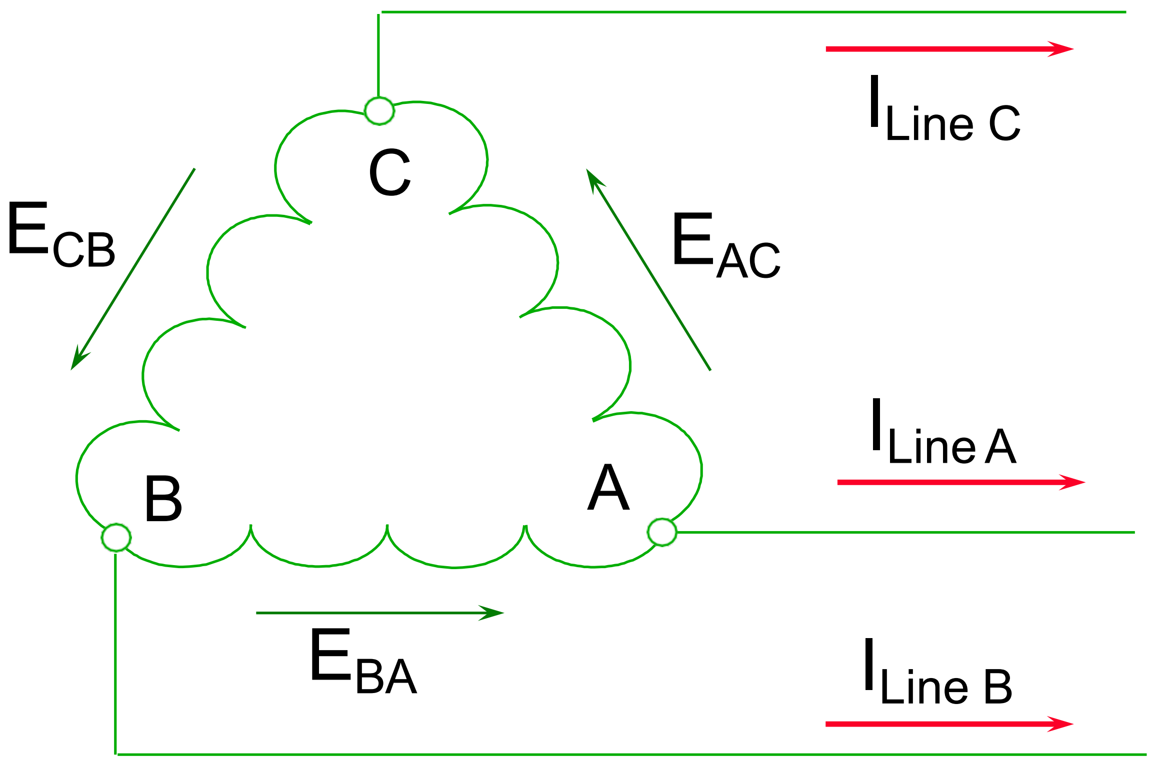
Effect of Power Factor

- **We represent energy as:** $Energy = E \times I \times \cos\theta \times t$
  - **θ is the angle between V and I**
  - **Cos θ is also known as Power Factor**
- **What θ values give with these lagging Power Factors?**

Power Factor	**0.50**	**0.70**	**0.85**	**0.90**	**0.95**
Phase Angle	**60°**	**45.6°**	**31.8°**	**25.8°**	**18.2°**



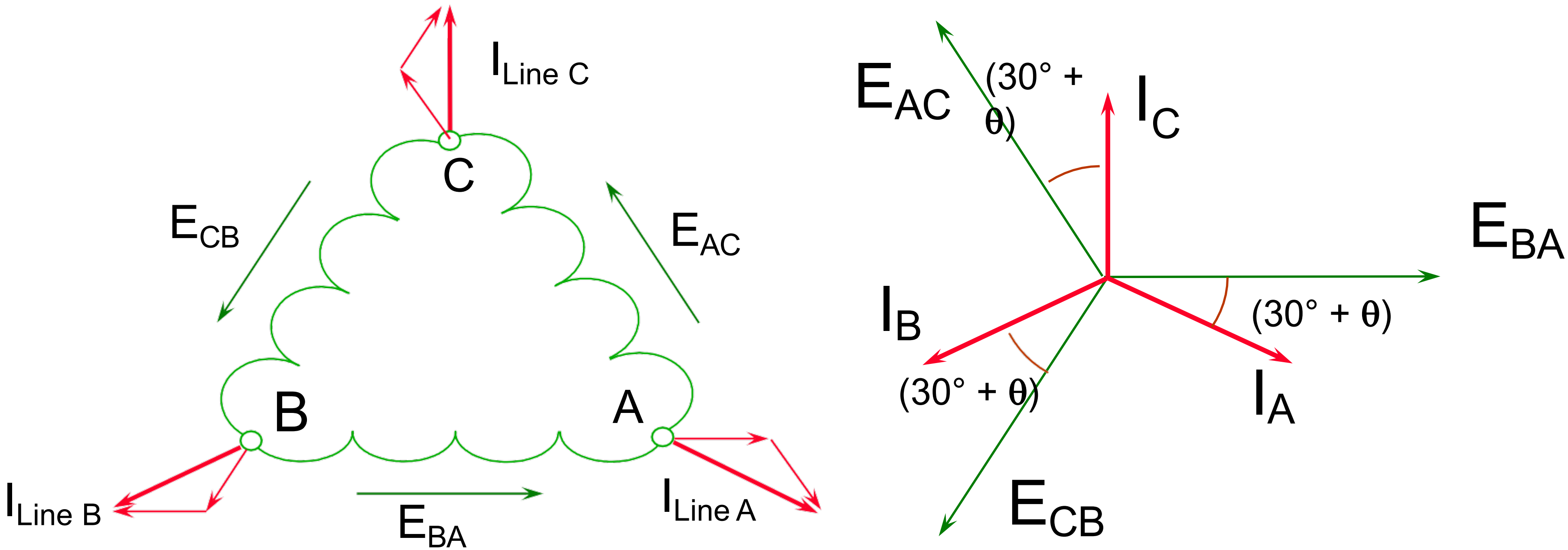
Three Wire Delta Source



With pure resistance balanced three-phase load, the current in each supply transformer is in phase with the voltage across each transformer.

Drawing Source Phasors

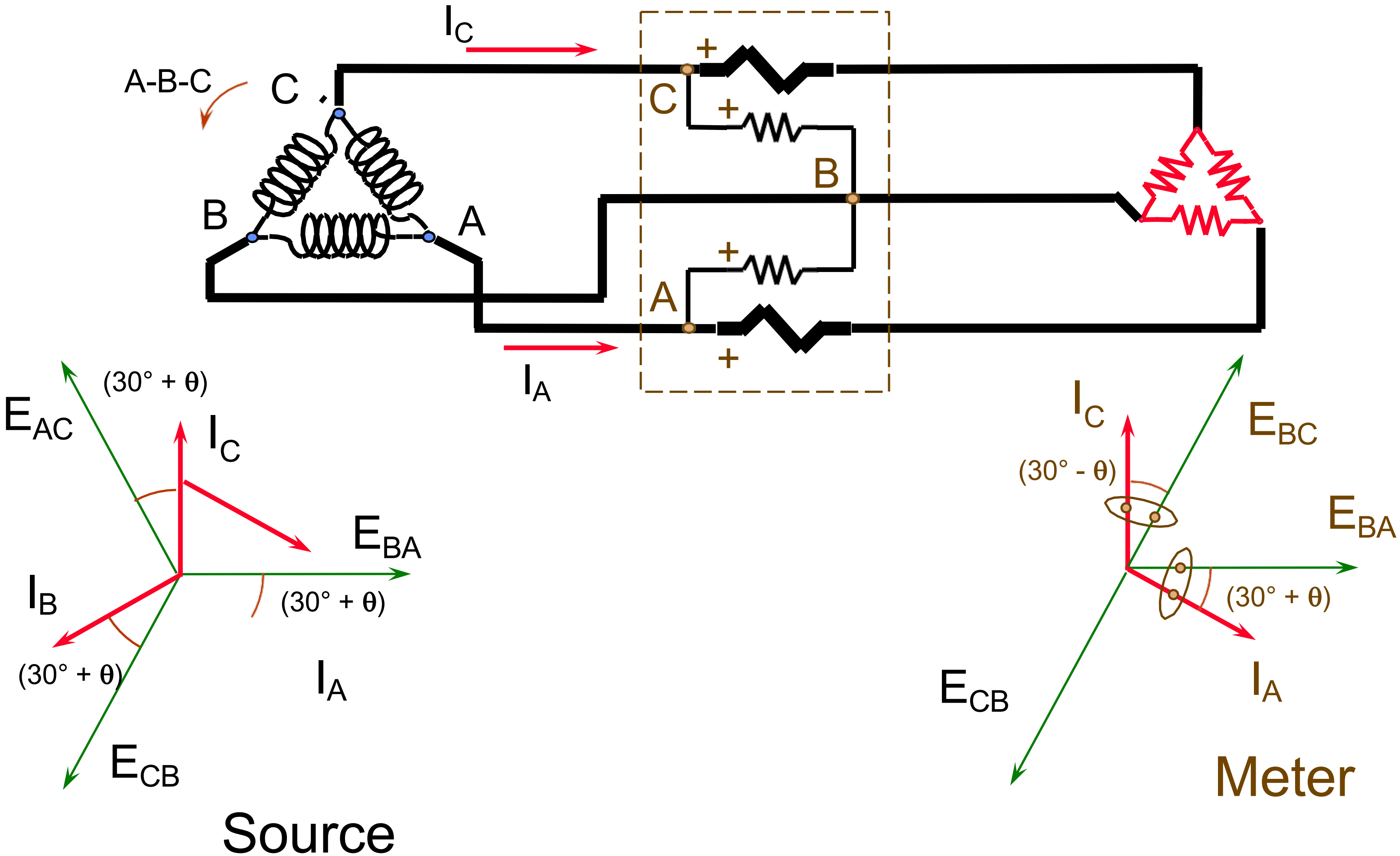
Phasor diagram for delta-connected three-phase system with three-phase delta-connected resistance load



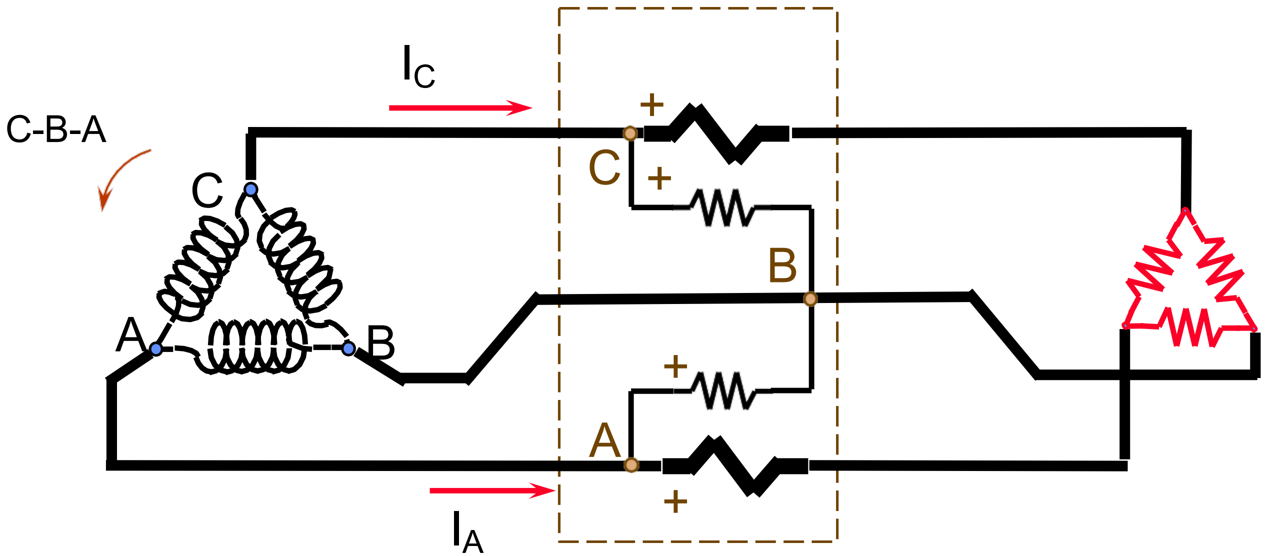
Phase voltages = E_{BA}, E_{CB}, & E_{AC}

Line currents = I_A, I_B, & I_C

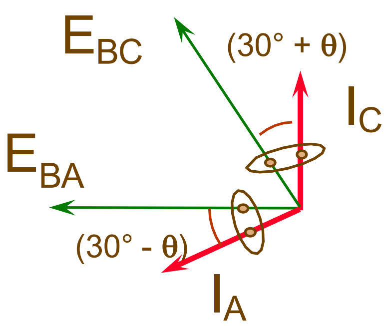
Phasors for Source & Meter



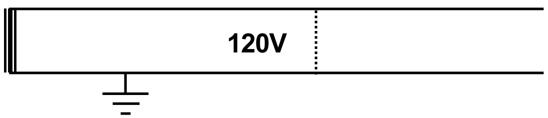
Phase Sequence CBA



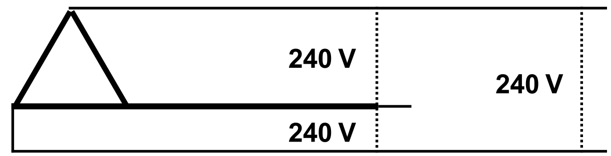
C-B-A
Meter
Phasors



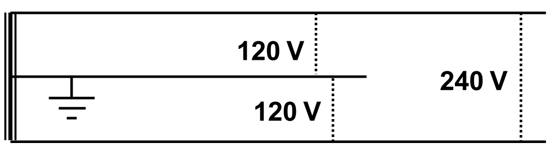
Common Distribution Circuits



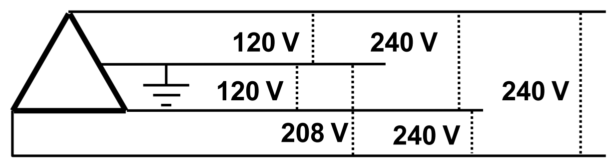
Two-Wire
Single Phase



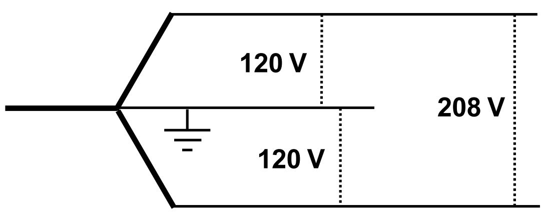
Three-Wire
Three Phase
Delta



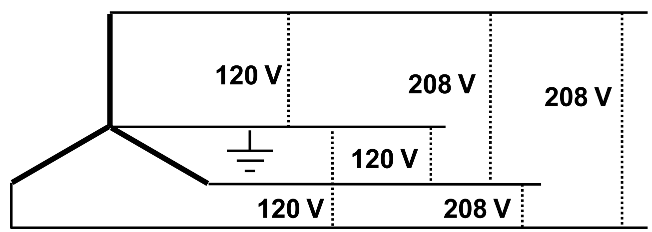
Three-Wire
Single Phase



Four-Wire
Three Phase
Delta



Three-Wire
Network



Four-Wire
Three Phase
Wye

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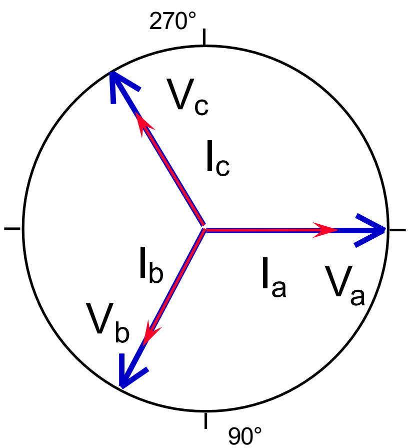
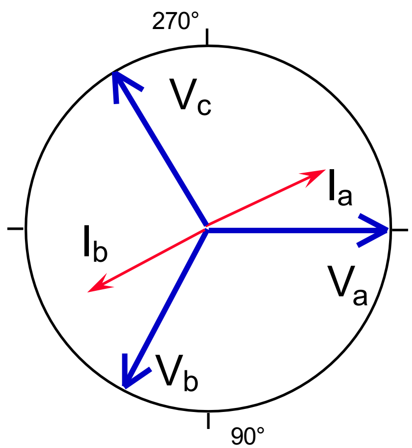
3 Element Expected Meter Phasors

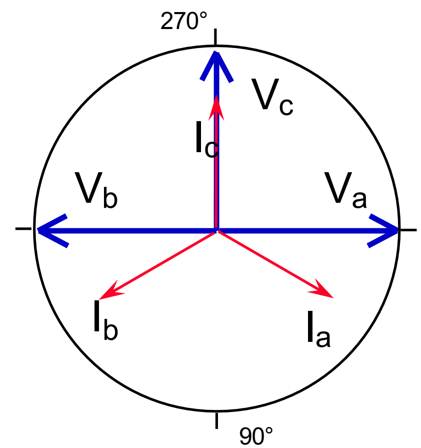
(at Power Factor = 1, ABC Phase Sequence)



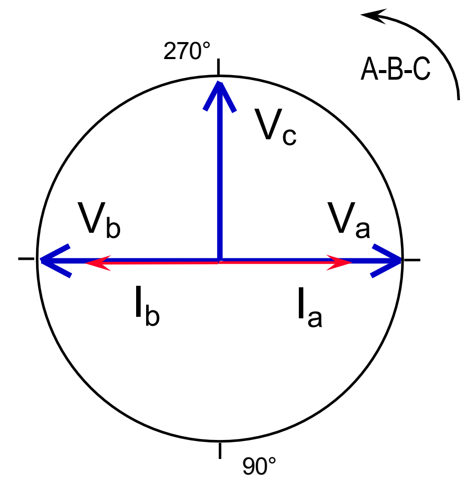
Balanced Polyphase Load



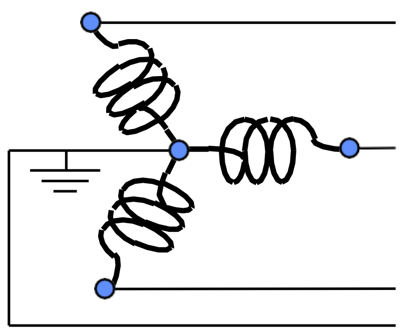
Single phase Load Connected A to B



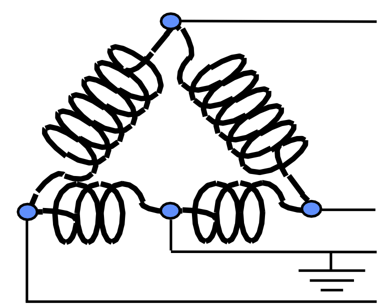
Balanced Polyphase Load



Single phase Load Connected A to B



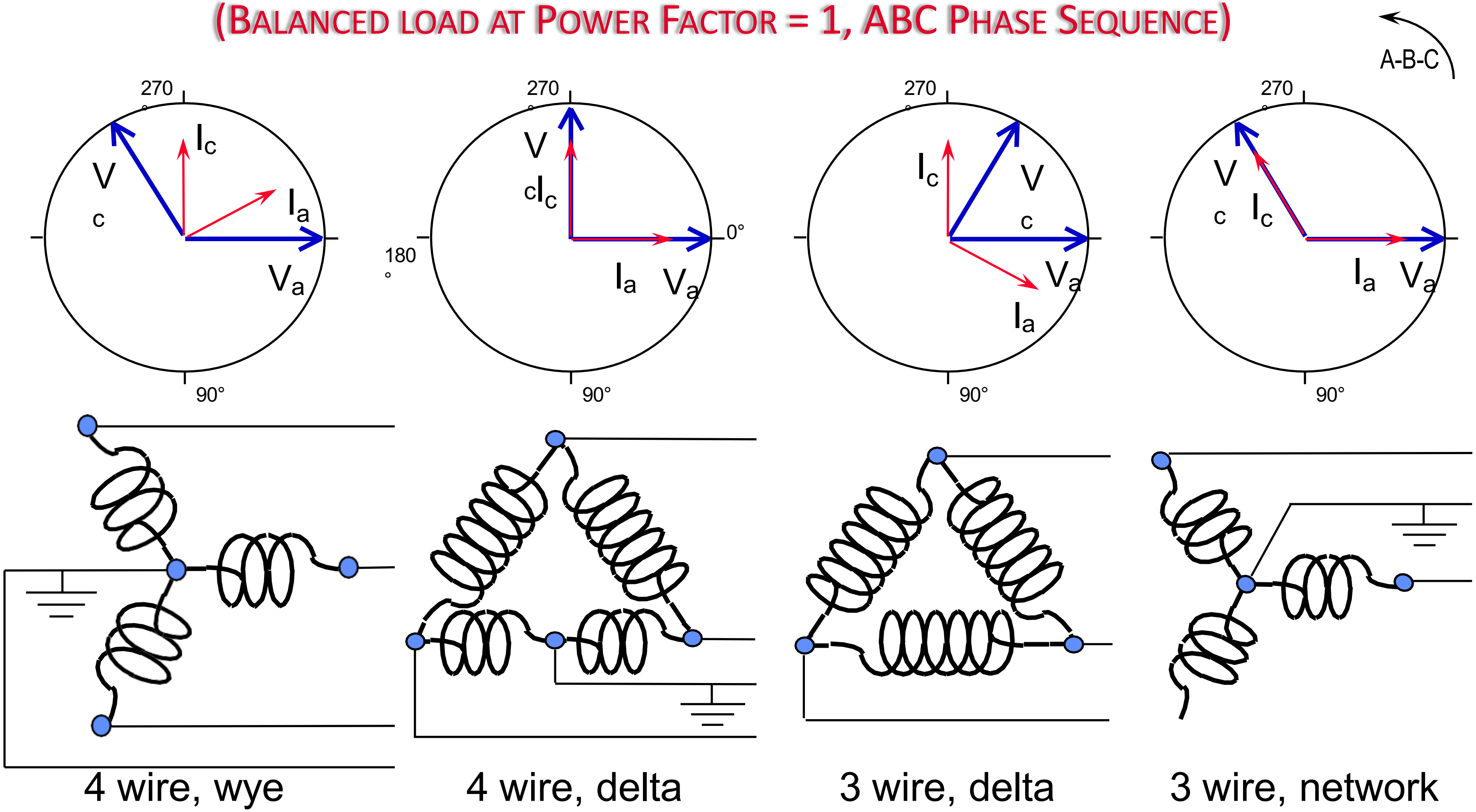
4 wire, wye



4 wire, delta

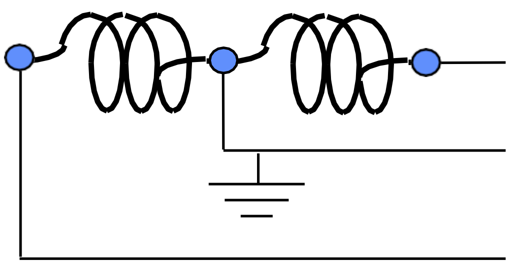
2 Element Expected Meter Phasors

(Balanced load at Power Factor = 1, ABC Phase Sequence)

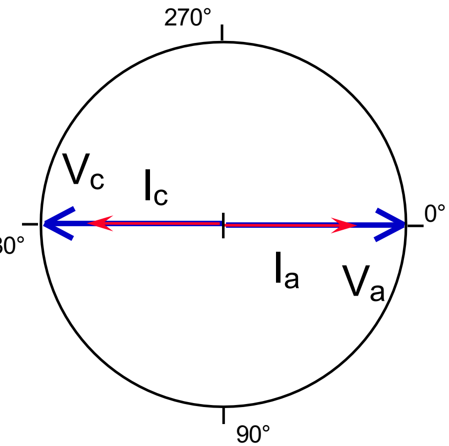


1φ Expected Meter Phasors

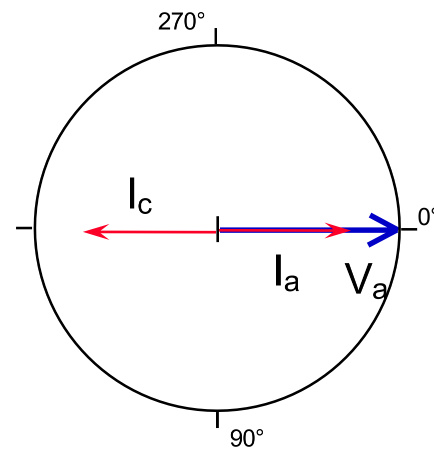
(Balanced Load at Power Factor = 1, ABC Phase Sequence)



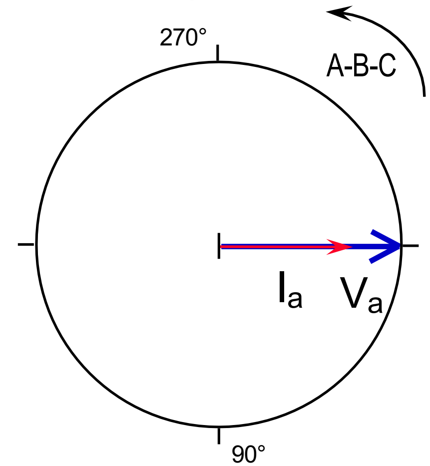
3 wire, 1 φ



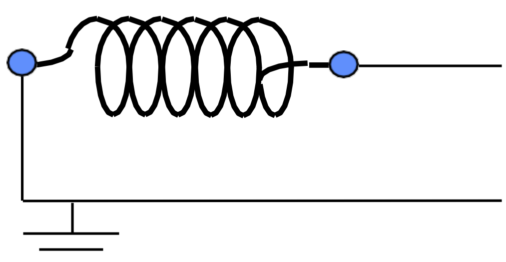
2 Element



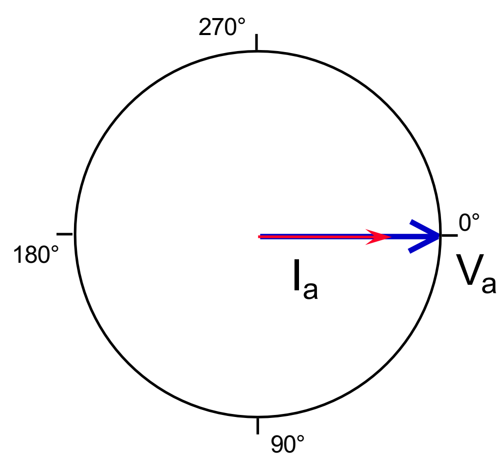
1½ Element



1 Element



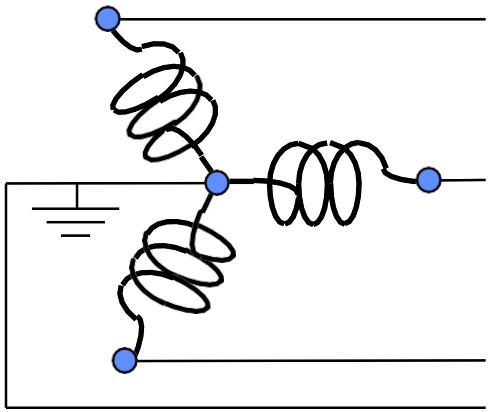
2 wire, 1 φ



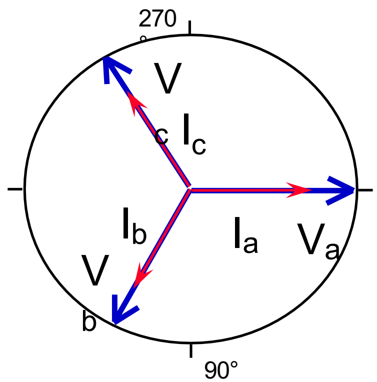
1 Element

Expected Meter Phasors

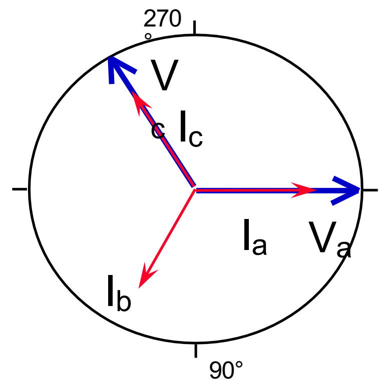
(AT POWER FACTOR = 1, ABC PHASE SEQUENCE)



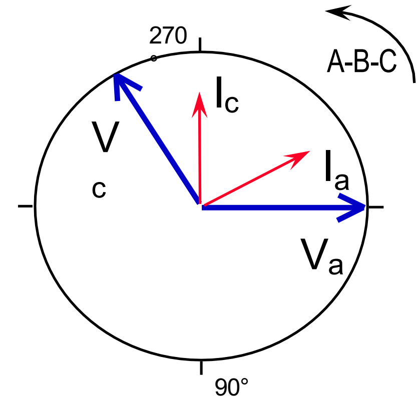
4 wire, wye



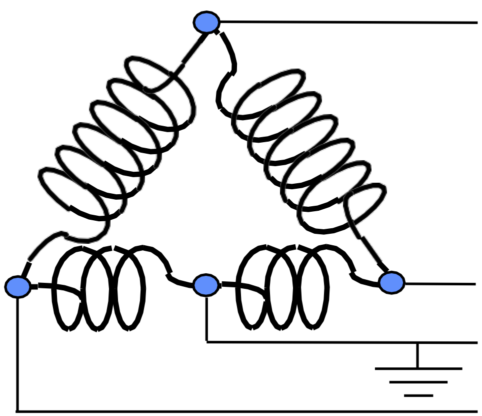
3 Element



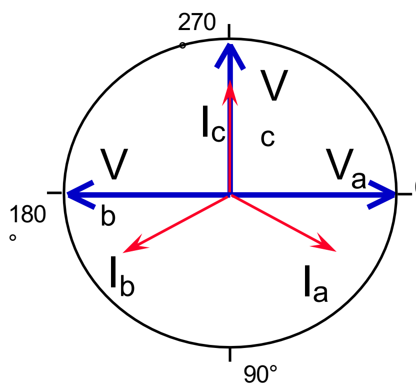
2½ Element



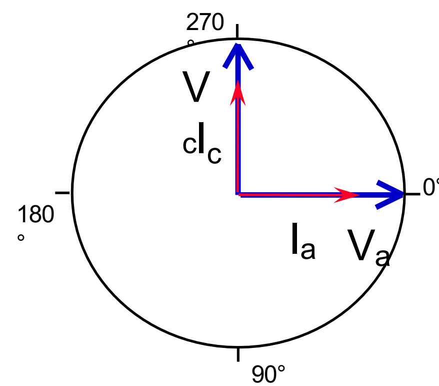
2 Element



4 wire, delta



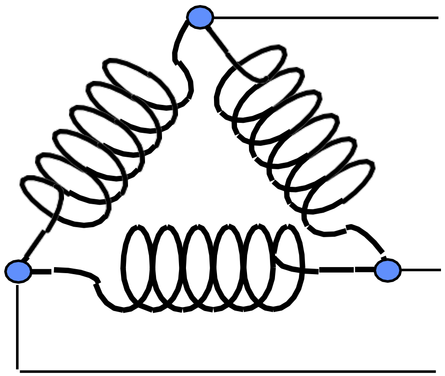
3 Element



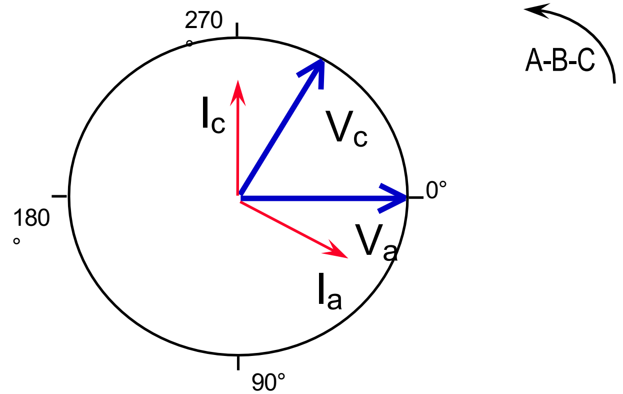
2 Element

Expected Meter Phasors

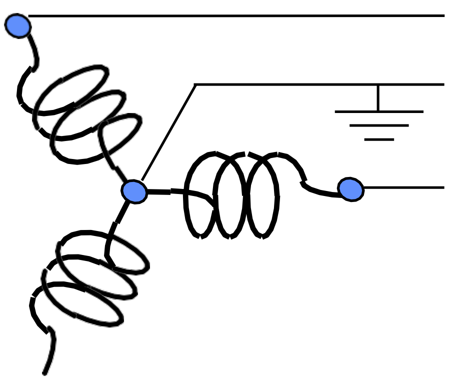
(AT POWER FACTOR = 1, ABC PHASE SEQUENCE)



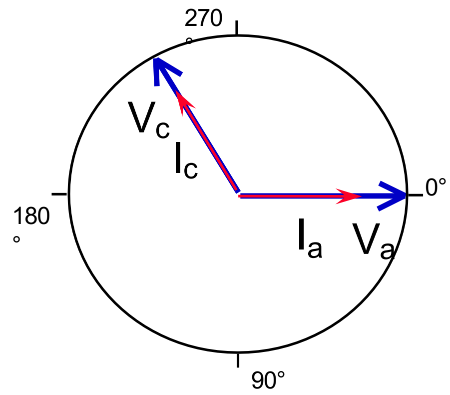
3 wire, delta



2 Element



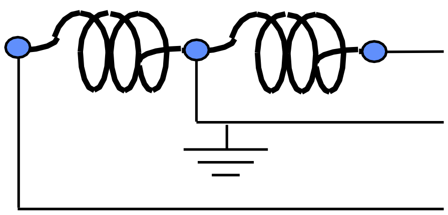
3 wire, network



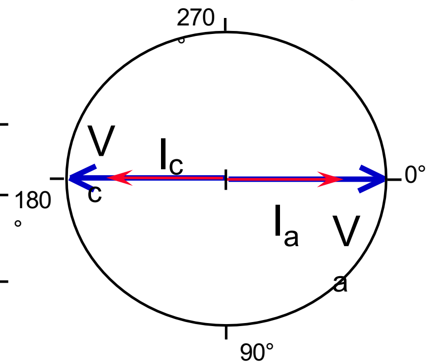
2 Element

Expected Meter Phasors

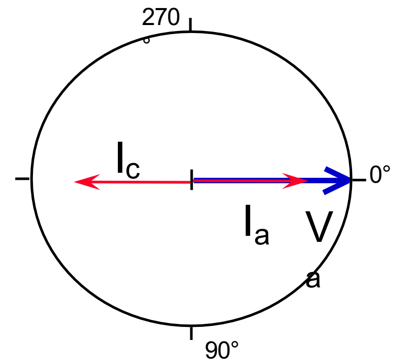
(At Power Factor = 1, ABC Phase Sequence)



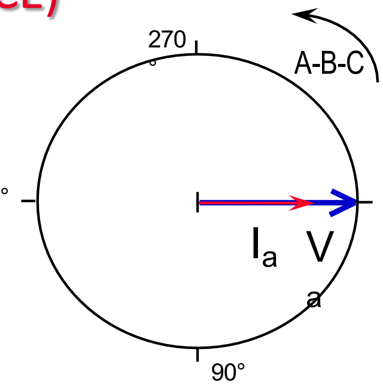
3 wire, 1 φ



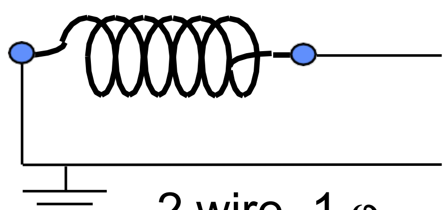
2 Element



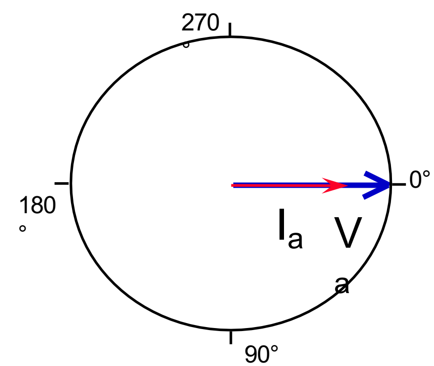
1½ Element



1 Element



2 wire, 1 φ



1 Element

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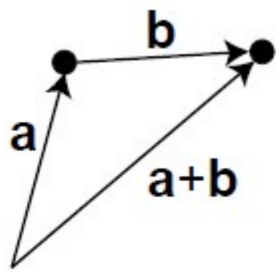
Let's Talk about Why We Need to Understand Vectors.

Vector Addition

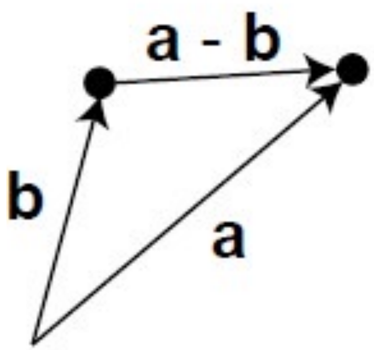


Addition of vectors can be expressed by a diagram. Placing the vectors end to end, the vector from the start of the first vector to the end of the second vector is the sum of the vectors. One way to think of this is that we start at the beginning of the first vector, travel along that vector to its end, and then travel from the start of the second vector to its end. An arrow constructed between the starting and ending points defines a new vector, which is the sum of the original vectors. Algebraically, this is equivalent to adding corresponding terms of the two vectors:

$$\mathbf{a} + \mathbf{b} = \begin{bmatrix} a_x \\ a_y \end{bmatrix} + \begin{bmatrix} b_x \\ b_y \end{bmatrix} = \begin{bmatrix} a_x + b_x \\ a_y + b_y \end{bmatrix}.$$

We can think of this as again making a trip from the start of the first vector to the end of the second vector, but this time traveling first horizontally the distance $a_x + b_x$ and then vertically the distance $a_y + b_y$.

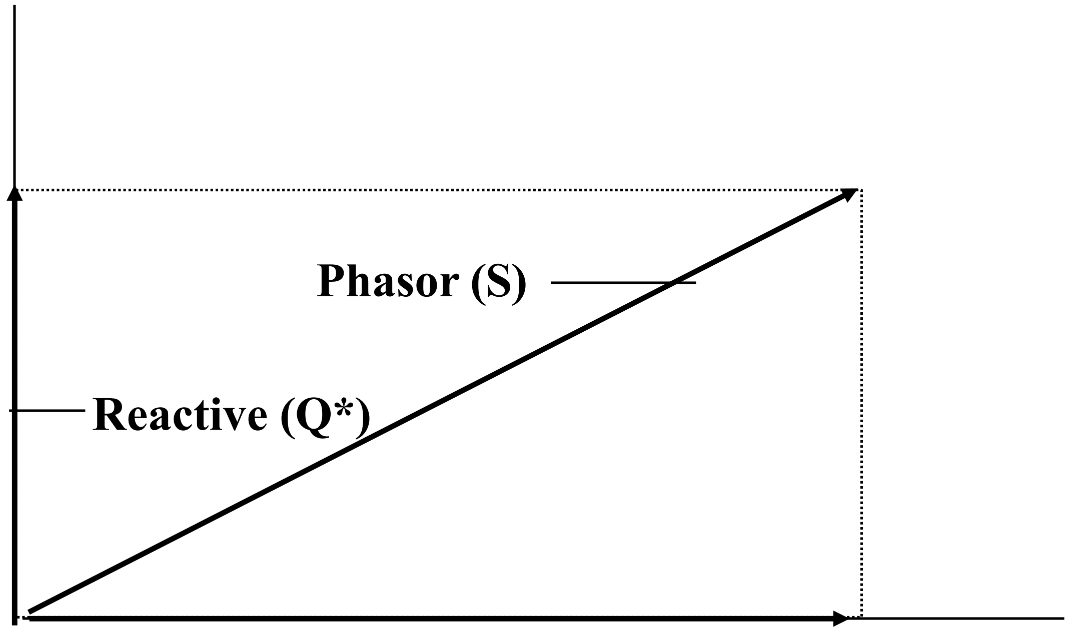
Vector Subtraction



Subtraction of vectors can be shown in diagram form by placing the starting points of the two vectors together, and then constructing an arrow from the head of the second vector in the subtraction to the head of the first vector. Algebraically, we subtract corresponding terms:

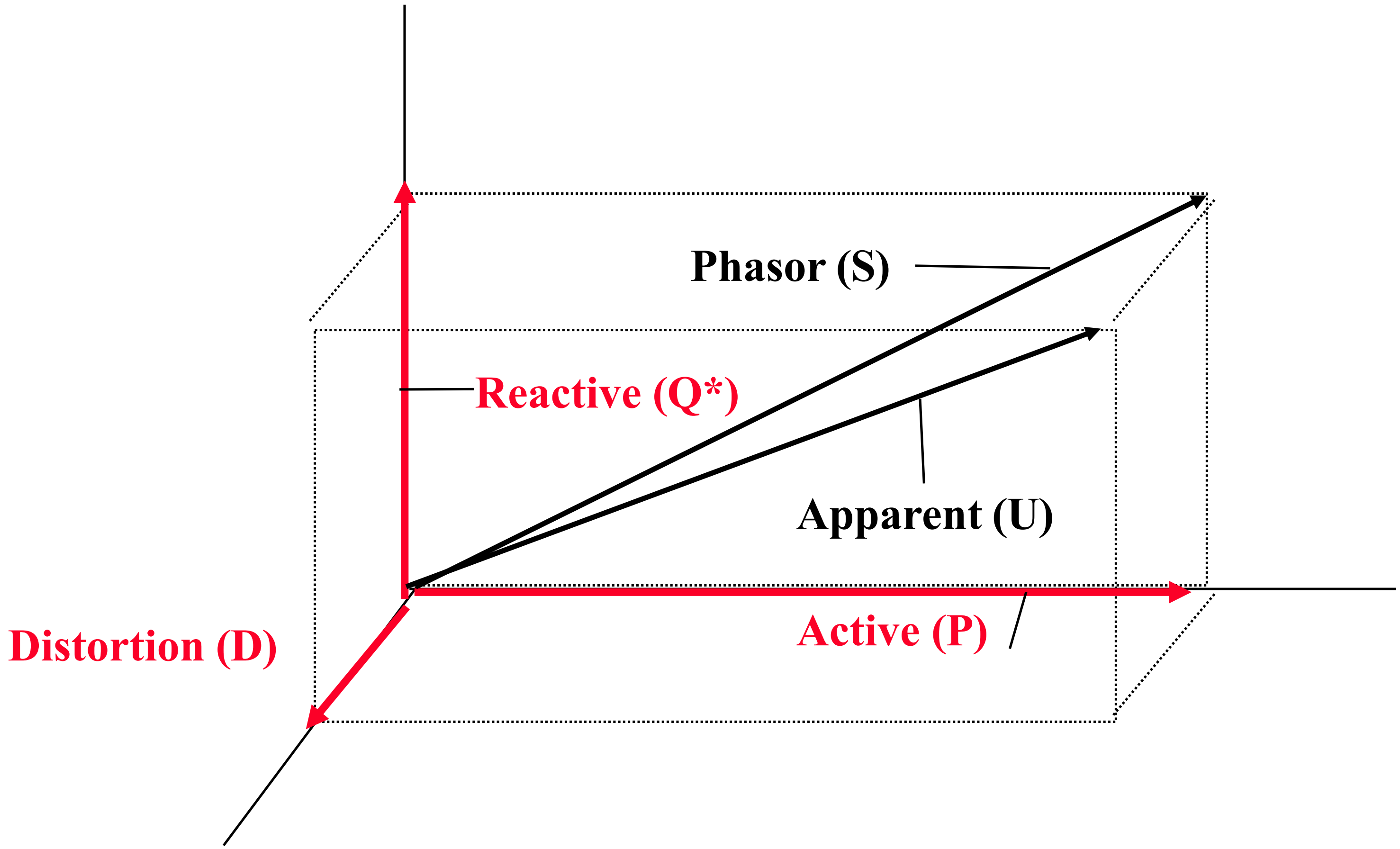
$$\mathbf{a} - \mathbf{b} = \begin{bmatrix} a_x \\ a_y \end{bmatrix} - \begin{bmatrix} b_x \\ b_y \end{bmatrix} = \begin{bmatrix} a_x - b_x \\ a_y - b_y \end{bmatrix}.$$

AC POWERS



*Not the “Q” of Q-hour metering

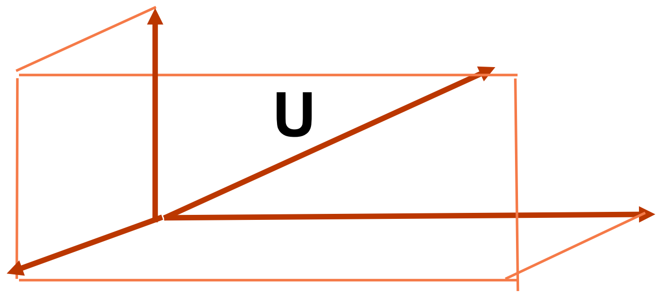
AC Powers



*Not the “Q” of Q-hour metering

How is 3φ Apparent Power calculated?

- **To calculate Apparent power (U), first add the components for the phases together,**



How is 3φ Apparent Power calculated?

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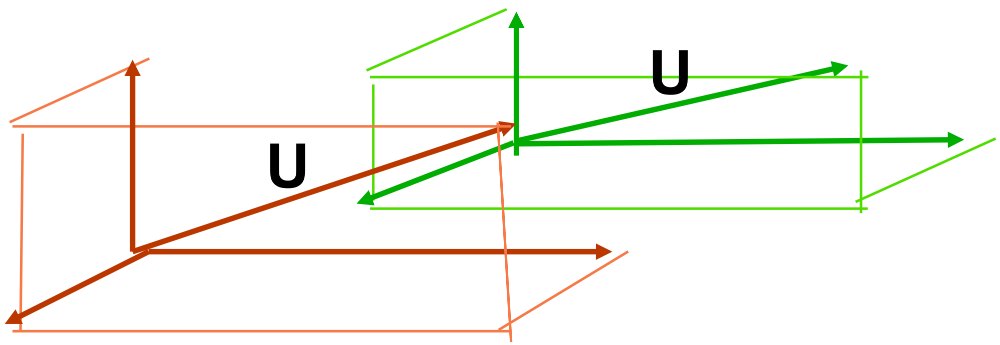
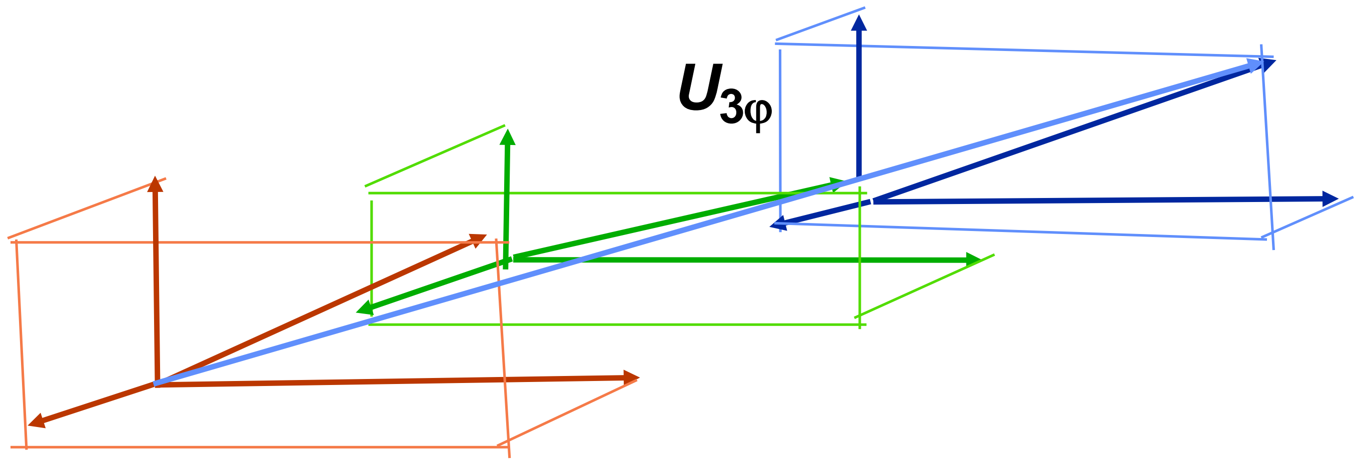


How is 3φ Apparent Power calculated?

- **To calculate Apparent power (U), first add the components for the phases together, then solve for U.**



$$U_{3\varphi} = \sqrt{\left(P_A + P_B + P_C\right)^2 + \left(Q_A + Q_B + Q_C\right)^2 + \left(D_A + D_B + D_C\right)^2}$$

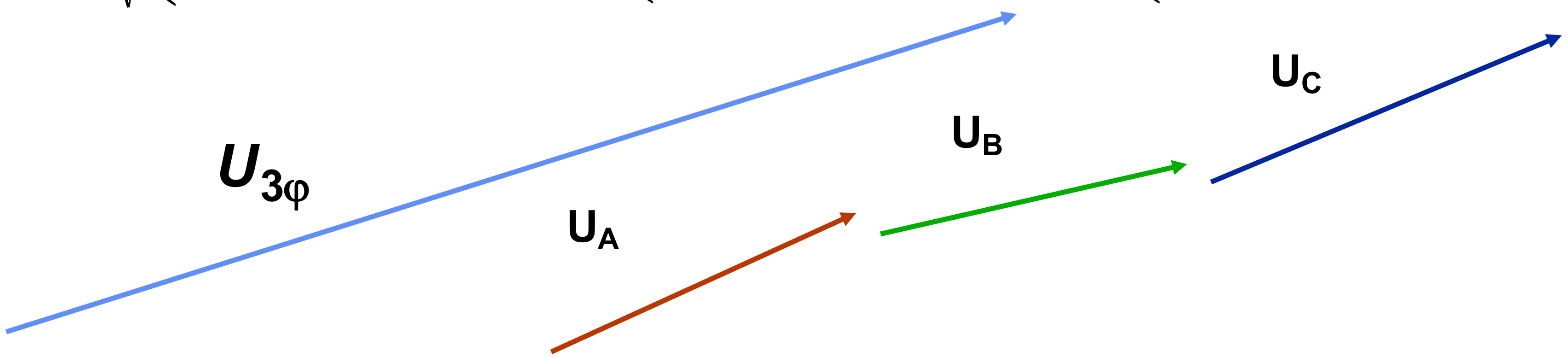
$$S = \sqrt{\left(P_A + P_B + P_C\right)^2 + \left(Q_A + Q_B + Q_C\right)^2}$$

$$U_{(arith)} = U_A + U_B + U_C$$

Apparent Power vs. Arithmetic Apparent Power

- **To calculate Apparent power (U), first add the components for the phases together, then solve for U.**

$$U_{3\varphi} = \sqrt{\left(P_A + P_B + P_C\right)^2 + \left(Q_A + Q_B + Q_C\right)^2 + \left(D_A + D_B + D_C\right)^2}$$



- **To calculate *Arithmetic* Apparent power, add the Apparent power magnitudes of the three individual phases.**

$$U_{Arithmetic} = U_A + U_B + U_C$$

ALL KVAS ARE NOT CREATED EQUAL

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Power Calculations

POWERS		Phase A	Phase B	Phase C	Total
Active	(P)	3626.4	2880.0	2833.0	9339.4
Reactive	(Q)	317.3	2146.0	2112.0	4575.3
Distortion	(D)	0.0	1102.6	1784.5	2887.1
Apparent	(U)	3640	3757	3959	

PHASOR	(S)	$(VA)_{Total}$ =	10,400	PF = 89.8
APPARENT	(U)	$(VA)_{Total}$ =	10,793	PF = 86.5
ARITH.	(U_{arth})	$(VA)_{Total}$ =	11,356	PF = 82.2

Modern Reactive Metering

- Which "kVA" calculation method is correct?
  - They all are "correct", by definition.
  - Each utility needs to decide which value is appropriate for their own needs.
  - Phasor Power is what results from calculations based on traditional kWh and kvarh meter readings, using a Phase-Shifting Transformer.
  - Apparent Power provides more complete picture of "cost of service", expected answers under all conditions.
  - Arithmetic Apparent Power may provide unexpected results (low PF, high kVA) for asymmetrical or unbalanced conditions.

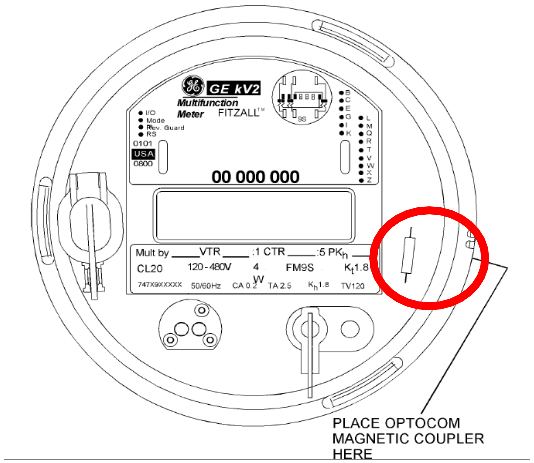
PHASE "X" FORMULAE

RMS Potential,	$E_X = \sqrt{\sum_{h=1}^{H} E_{Xh}^2}$	$(Volts)$
RMS Current,	$I_X = \sqrt{\sum_{h=1}^{H} I_{Xh}^2}$	$(Amperes)$
Apparent Power,	$U_X = E_X I_X$	(kVA)
Active Power,	$P_X = \sum_{h=1}^{H} E_{Xh} I_{Xh} \cos(\alpha_{Xh} - \beta_{Xh})$	(kW)
Re*active Power,*	$Q_X = \sum_{h=1}^{H} E_{Xh} I_{Xh} \sin(\alpha_{Xh} - \beta_{Xh})$	$(k\,\mathrm{var})$
Distortion Power,	$D_X = \pm\sqrt{U_X^2 - P_X^2 - Q_X^2}$	(kVA)
Phasor Power,	$S_X = +\sqrt{P_X^2 + Q_X^2}$	(kVA)
Fictitious Power,	$F_X = +\sqrt{U_X^2 - P_X^2}$	(kVA) $(a.k.a.\text{"}Fuzzy\ \mathrm{var}\,s\text{"})$
Nonreactive Power,	$N_X = +\sqrt{U_X^2 - Q_X^2}$	(kVA)

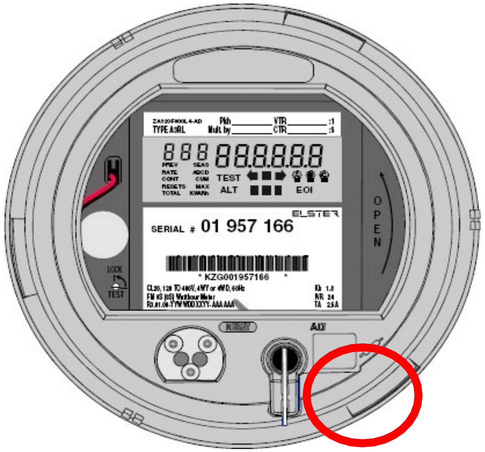
E_{xh} and I_{xh} are the RMS voltage and amperage of harmonic h. α_{xh} and β_{xh} are the phase angles of the voltage and current of harmonic h with respect to the reference time-frame. H is the highest harmonic ordinal.

Different Meters

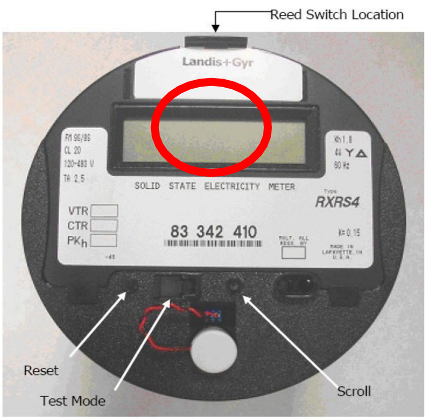
Aclara kV2c Meter



Honeywell A3

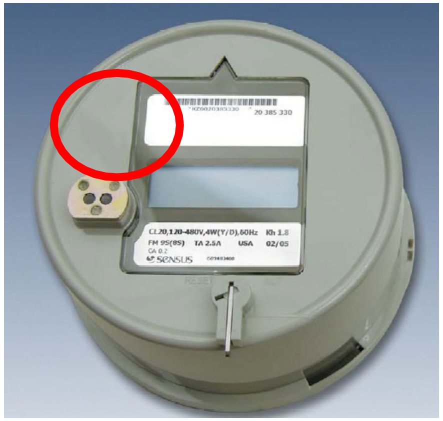


Landis + Gyr S4e



Itron Sentinel

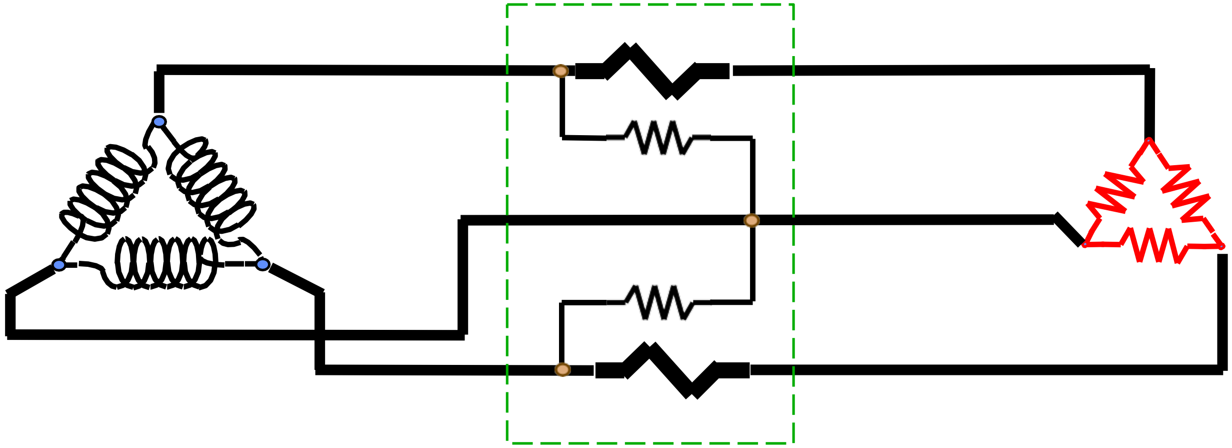
Sensus Icon APX



Step 1: Draw Diagram for…

Power **Meter** **Load**

Transformer

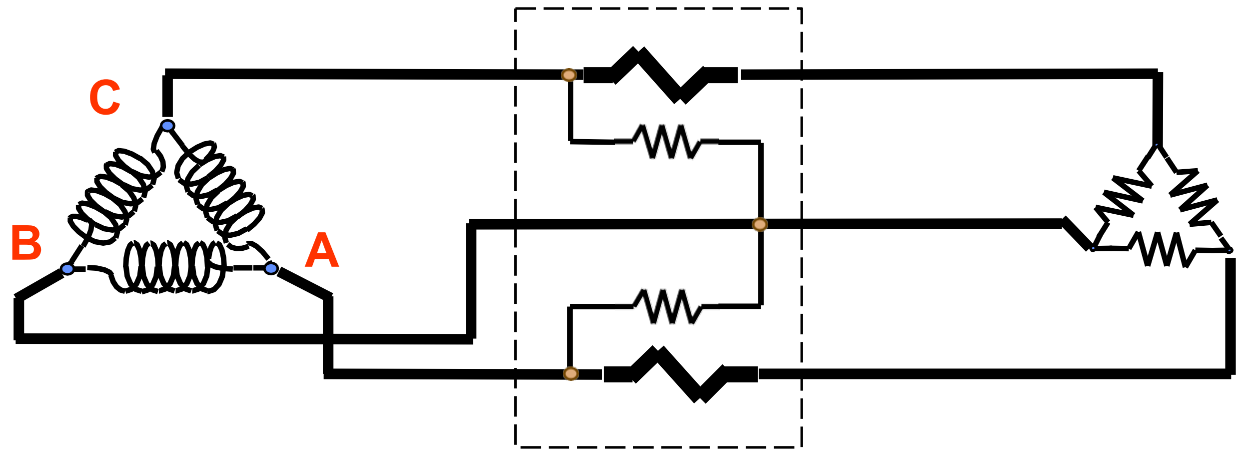


Phasor Construction

Step 2: Draw Diagram for…

Power **Meter** **Load**

Transformer



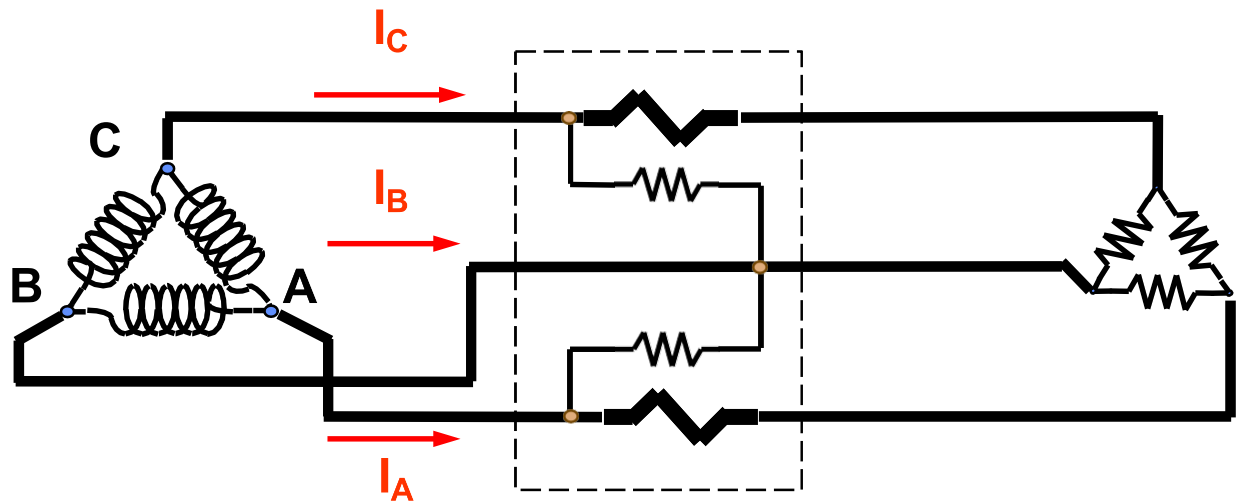
Step 2: Label points of Power Transformer

Phasor Construction

STEP 3: DRAW AND LABEL ALL LINE CURRENTS

Power **Meter** **Load**

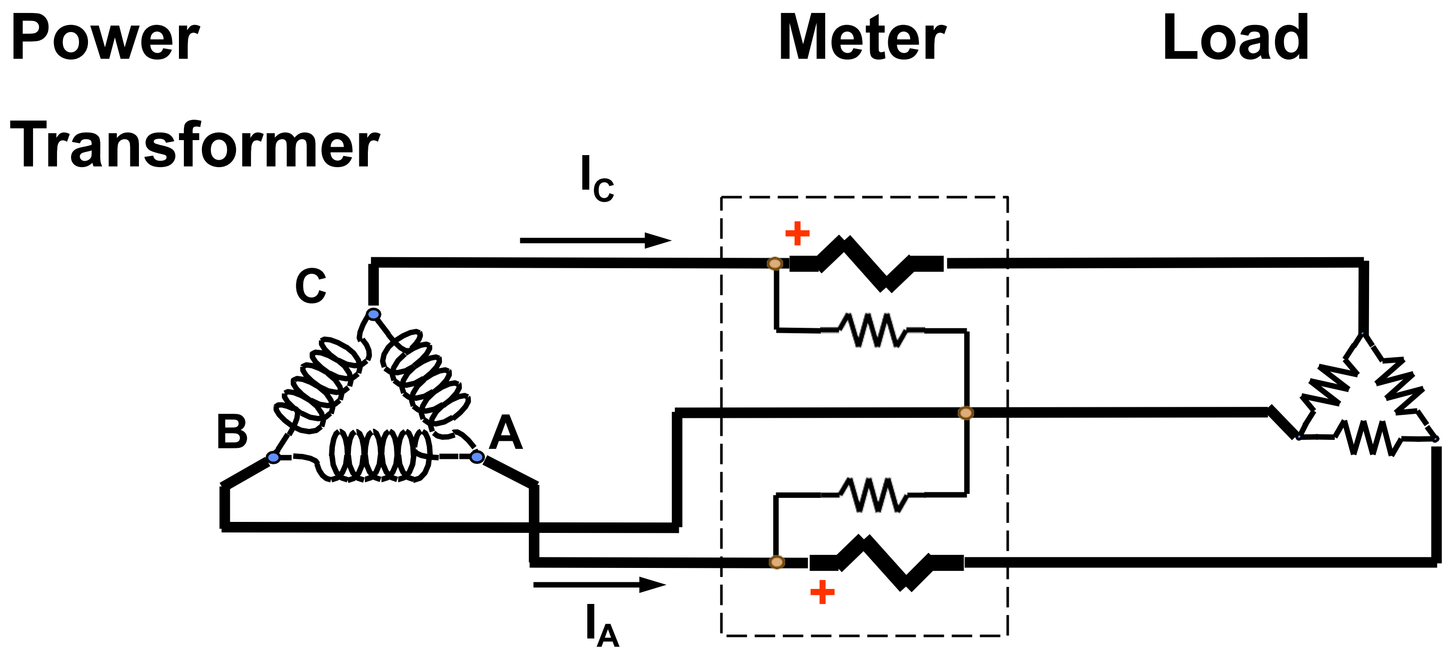
Transformer



Draw line currents between power transformer and meter. Use arrows with closed points (⟶). Assume all currents flow from transformer to load. Where necessary, draw power transformer coil currents and label with double subscript notation (I_{BA}, I_{AC}, etc.

Phasor Construction

Step 4: Mark Polarity on all Current Coils

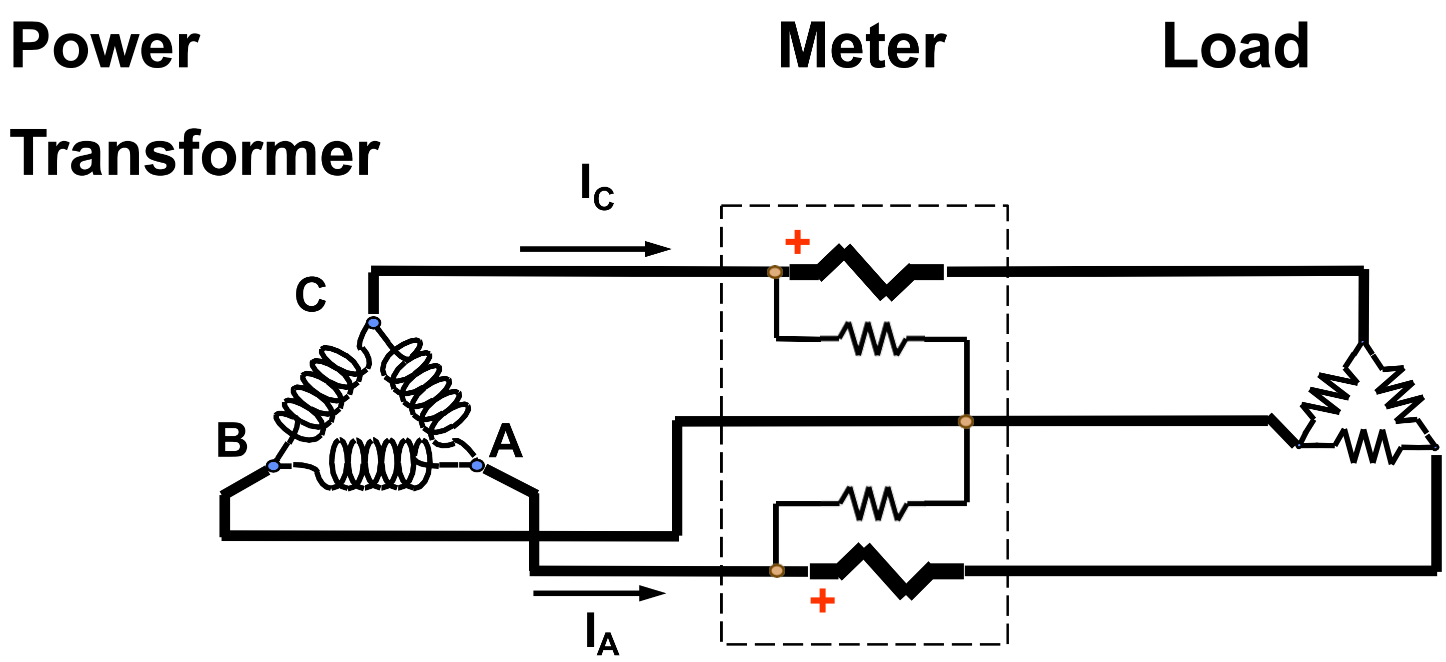


The polarity mark (+) goes on the line side of all current coils except:

(a): For 2 1/2 stator Z-coil meters. The polarity "+" goes on the load side of the Z-coil.

(b): For 3-wire, 1-phase meters and the 3-wire stator on the left side of a 4-wire delta meter, the "+" goes on the load side of the right hand coil of the single stator meter, and the "inside" coil of the left hand stator in the 4-wire delta meter.

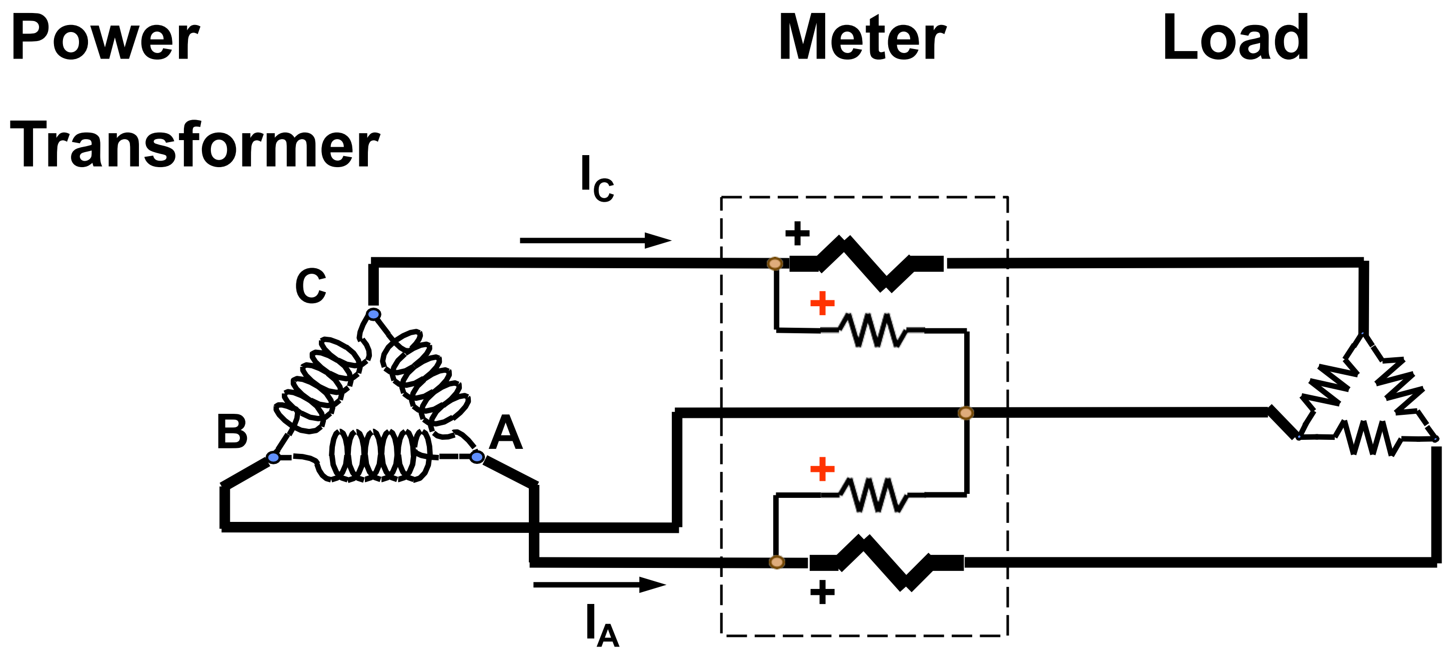
Step 4: Polarity of Current Coils (cont.)



If line current enters the "+" end of a current coil, the coil current is assumed to be in phase with the line current. If, however, the current enters the unmarked end of the coil, the current is assumed to be 180° out of phase with the line current.

Phasor Construction

Step 5: Mark Polarity on all Voltage Coils



The polarity mark (+) goes on the end of the voltage coil that connects to the "+" end of the current coil.

Phasor Construction

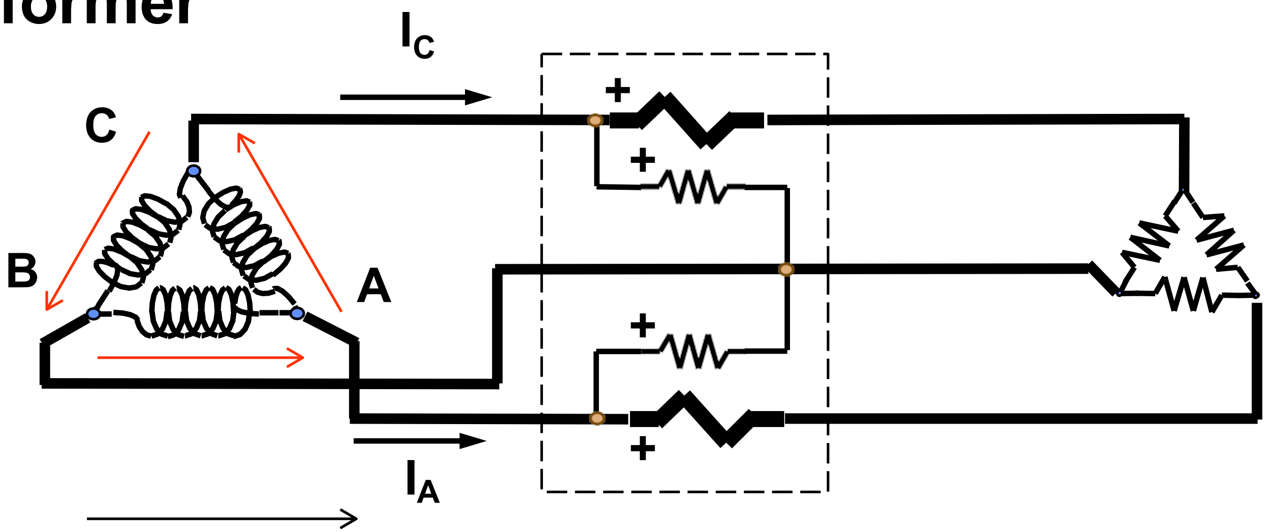
STEP 6: DRAW VOLTAGE ARROWS AT POWER TRANSFORMER

Power

Transformer

Meter

Load

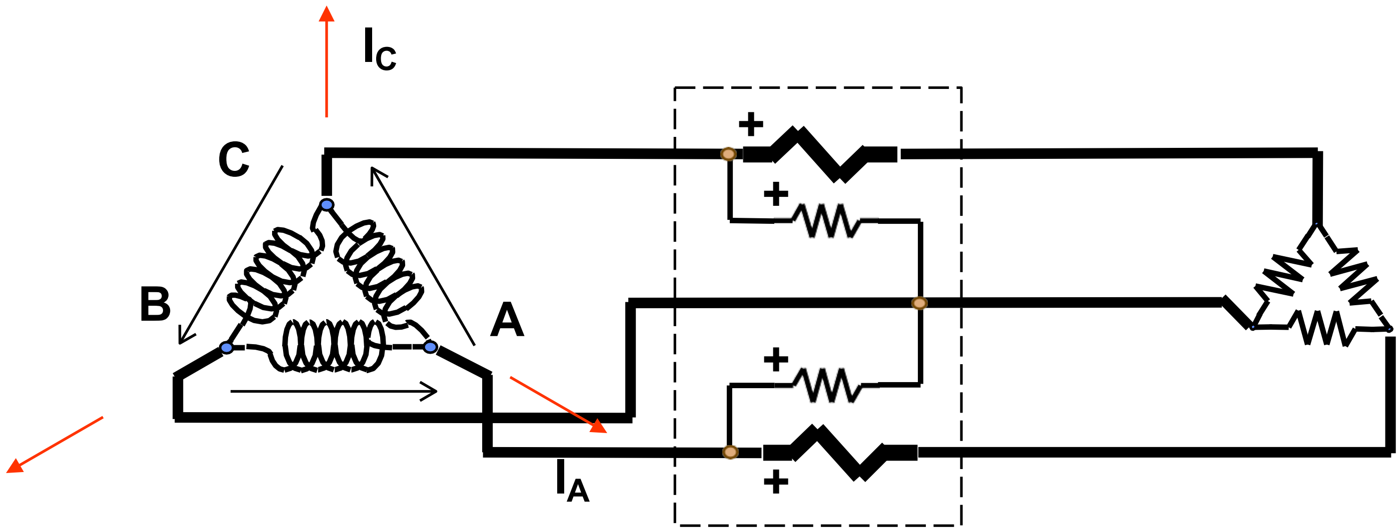


Draw open ended arrows to represent voltage at the power transformer.

- **Wye-connected: point away from the neutral.**
- **Delta-connected: tracing tail-to-head-to-tail, etc., around the delta following a counter-clockwise direction.**

Phasor Construction

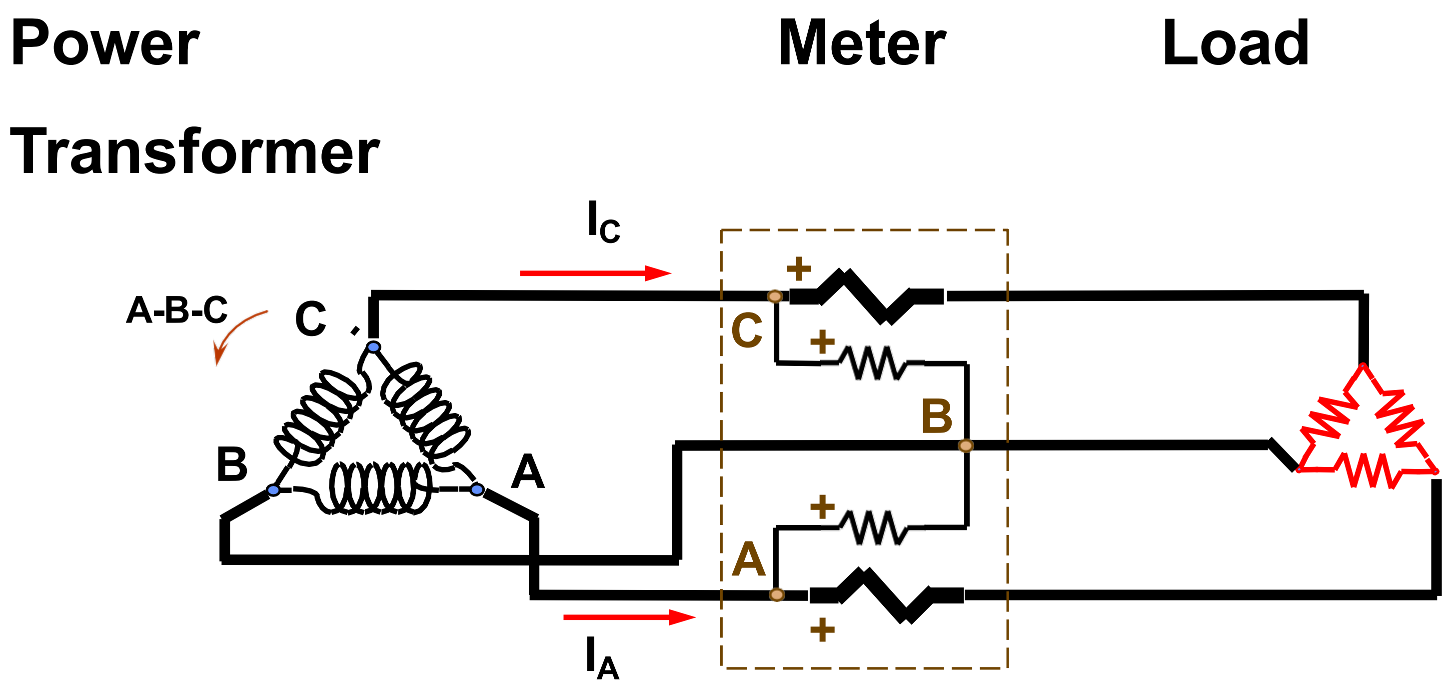
Step 7: Establish Voltage & Current Relationships



Use Kirchoff's Laws to establish the needed relationships between voltages and currents at the power transformer.

Phasor Construction

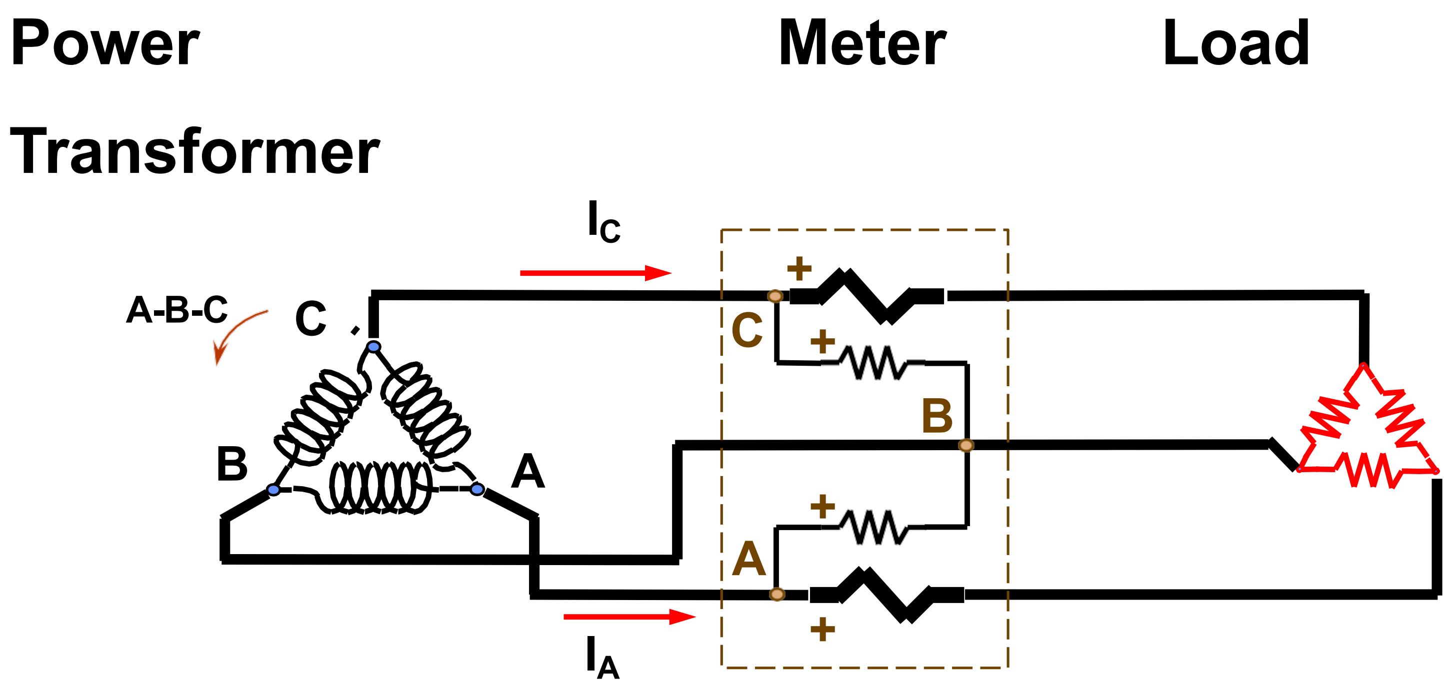
STEP 8: COMPLETE THE "SOURCE" PHASORS



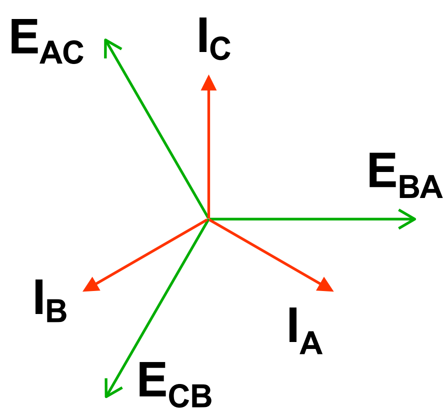
Complete the phasor diagram for the power transformer (source).

Phasor Construction

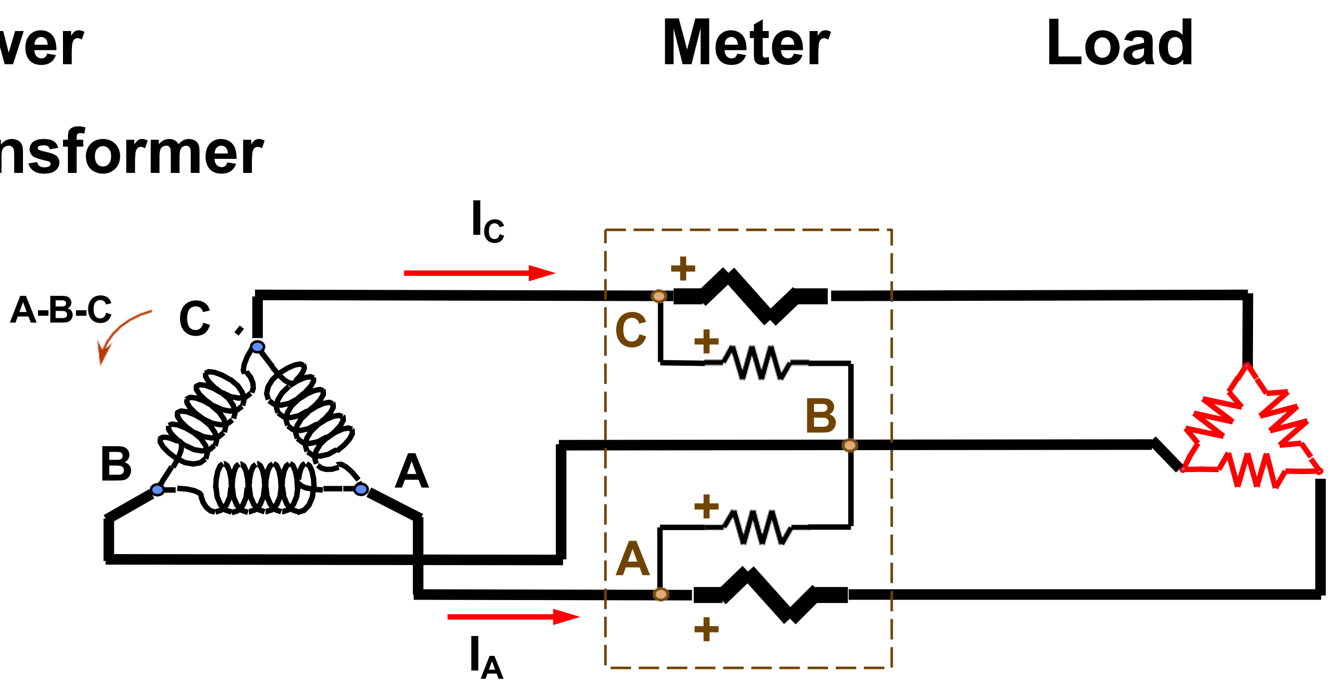
STEP 8: COMPLETE THE "SOURCE" PHASORS



Phasor Construction



Step 9: Construct Meter Voltage Phasors



Draw the voltage phasors for the meter, using the <u>tracing method</u>.
Starting at the polarity end of the voltage coil, trace through the voltage coil, back through the source, and return to the polarity end of the voltage coil.
The direction of the METER phasor is the direction traveled through the source transformer.

Step 9: Construct Meter Voltage Phasors

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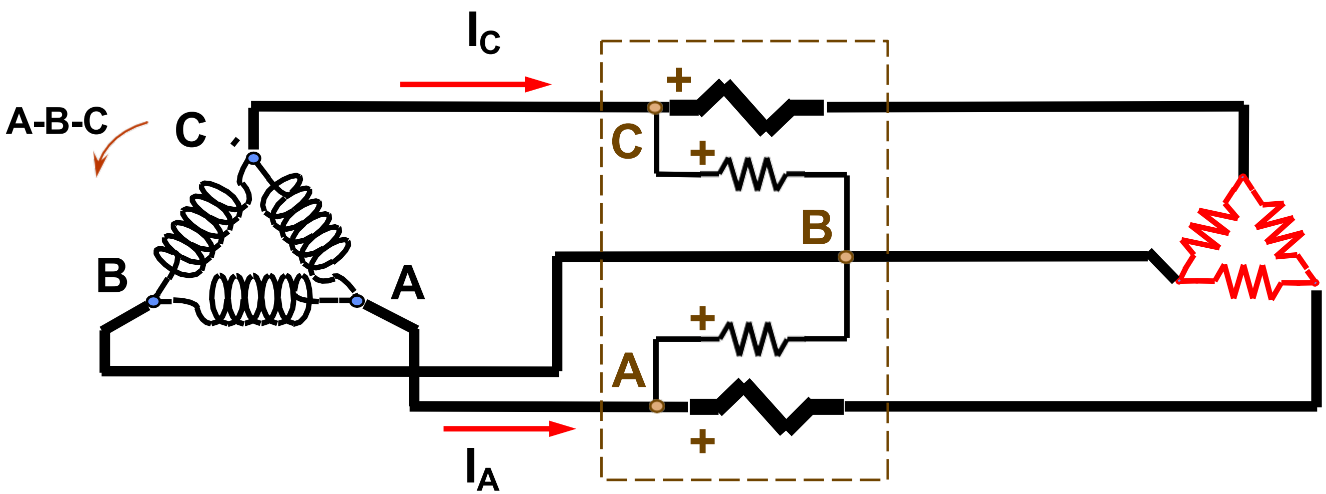
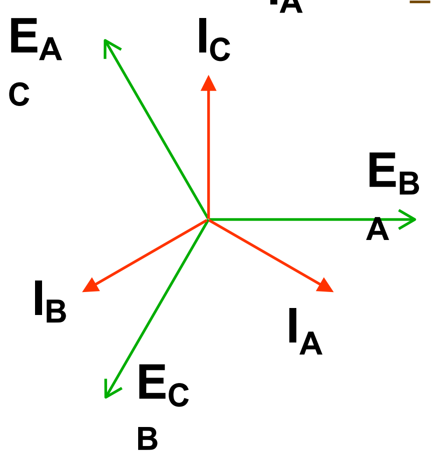
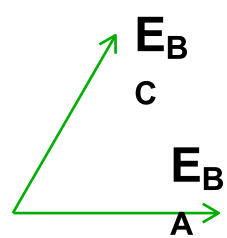
Power Transformer **Meter** **Load**

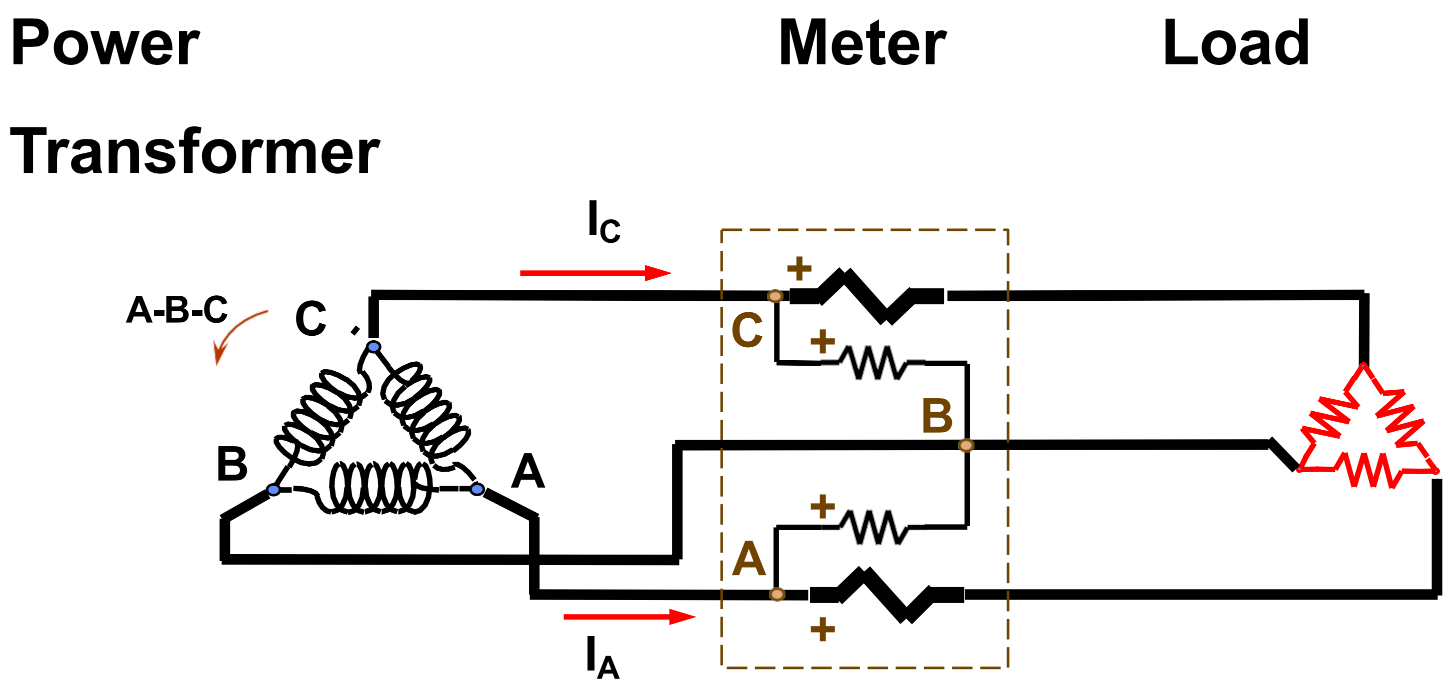


Phasor Construction





STEP 10: CONSTRUCT METER CURRENT PHASORS



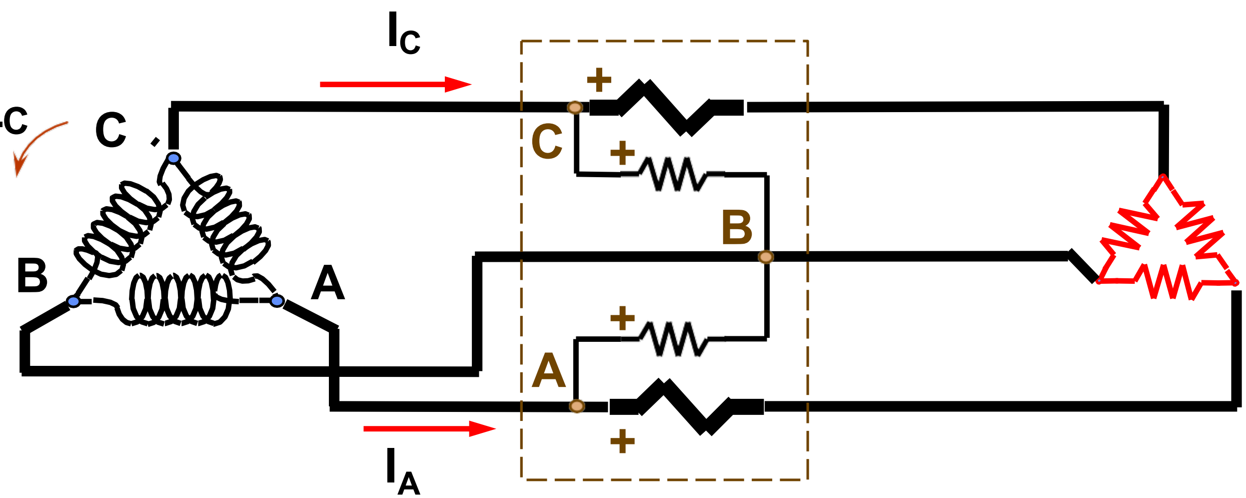
Add meter current phasors by using the relationships developed in step 8, and observing the polarity marks of the current coils. Make sure all voltage and current phasors are labeled, and show the interactions between voltages and currents in the meter stators by connecting the appropriate phasors with elongated ellipses.

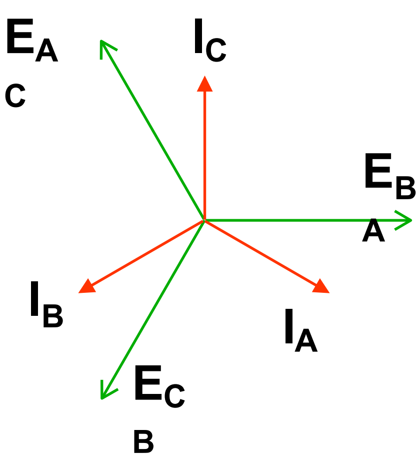
Phasor Construction

Step 10: Construct Meter Current Phasors

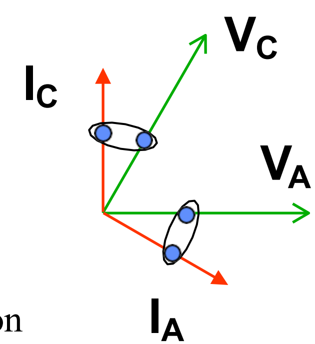
Power | **Meter** | **Load**

Transformer



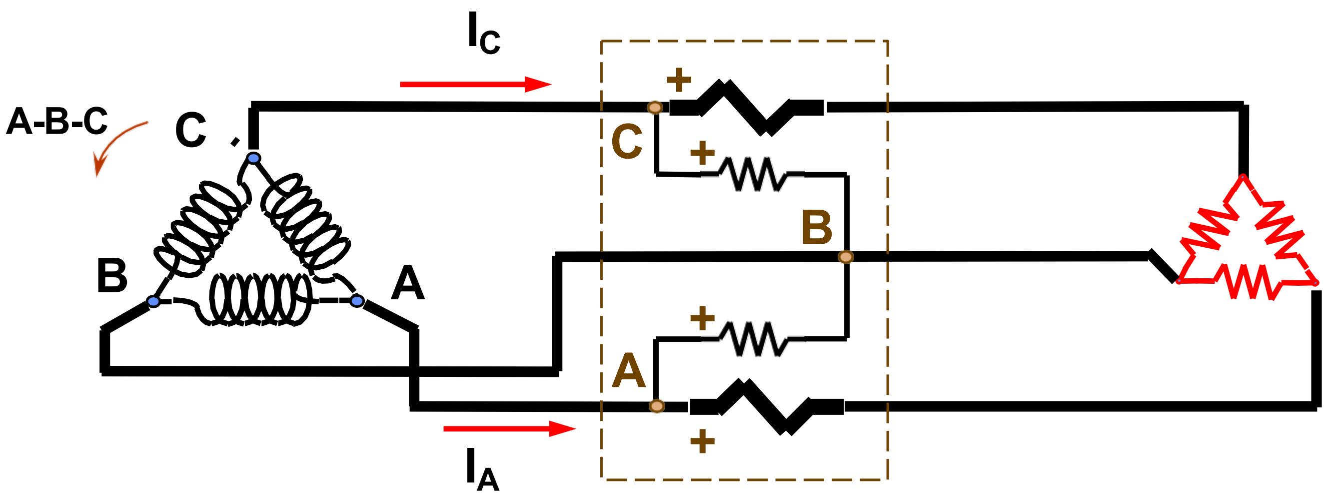


Phasor Construction



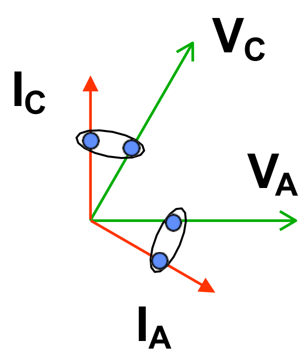
STEP 11: WRITE EQUATION FOR METER WATTS

Power Transformer **Meter** **Load**



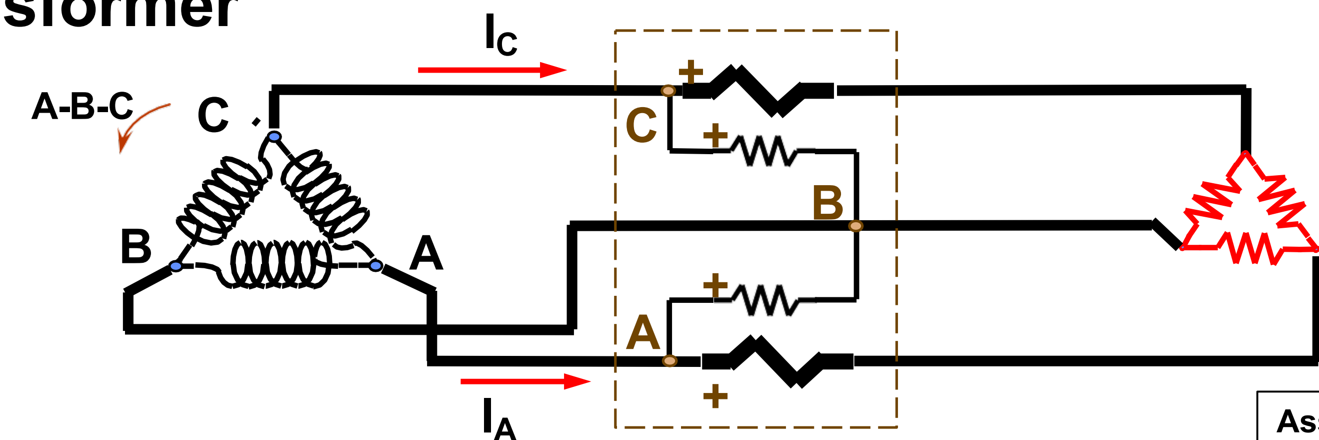
Show the expression for the Meter Watts.

Phasor Construction



Step 11: Write Equation for Meter Watts

Power Transformer **Meter** **Load**



Show the expression for the Meter Watts.

Assuming balanced 3-phase load and balanced voltages

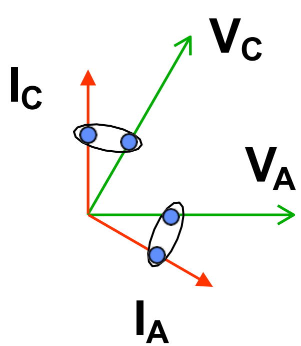
$$MeterWatts = V_A I_A \cos(30+\theta_A) + V_C I_C \cos(30-\theta_C)$$

$$= V_{LL} I_L \cos(30+\theta) + V_{LL} I_L \cos(30-\theta)$$

$$= V_{LL} I_L \left[(\cos 30 \cos\theta - \sin 30 \sin\theta) + (\cos 30 \cos\theta + \sin 30 \sin\theta) \right]$$

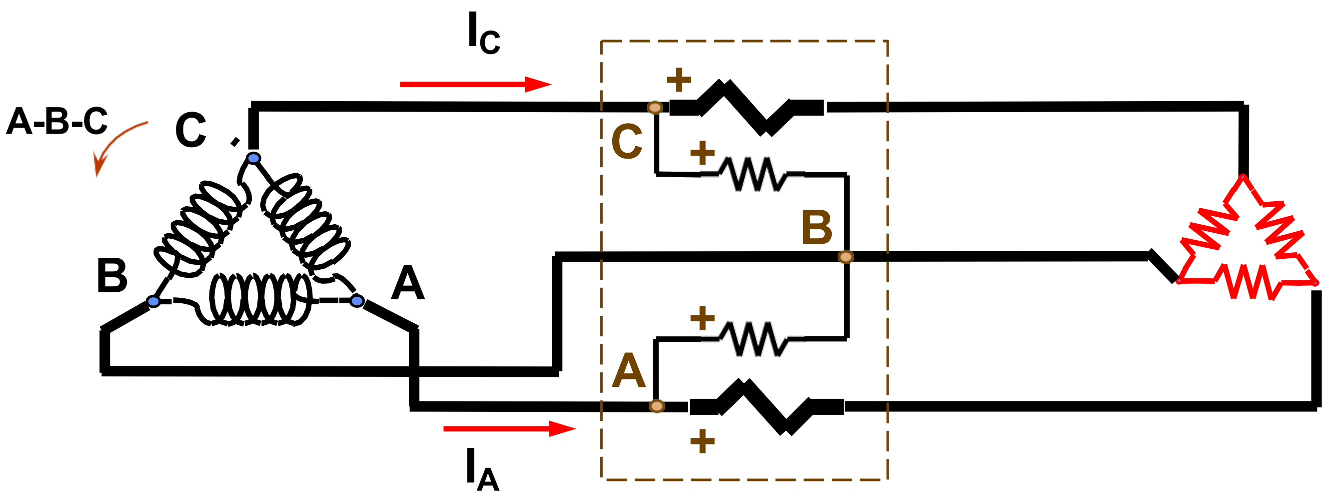
$$= V_{LL} I_L \left[\left(\frac{\sqrt{3}}{2}\cos\theta \right) + \left(\frac{\sqrt{3}}{2}\cos\theta \right) \right]$$

$$= \sqrt{3} V_{LL} I_L \cos\theta$$



STEP 12: WRITE EQUATION FOR LOAD WATTS

Power Transformer | Meter | Load

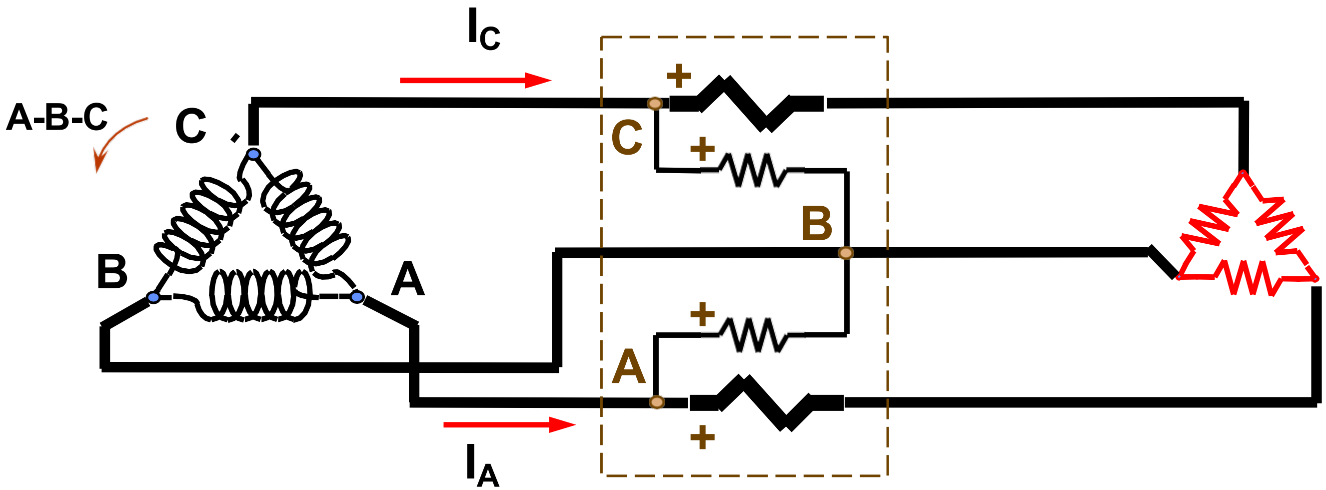


Show the expression for the Delivered Watts, or Load Watts.

Phasor Construction

STEP 12: WRITE EQUATION FOR LOAD WATTS

Power Transformer **Meter** **Load**



Show the expression for the Delivered Watts, or Load Watts.

For a balanced 3-phase load:

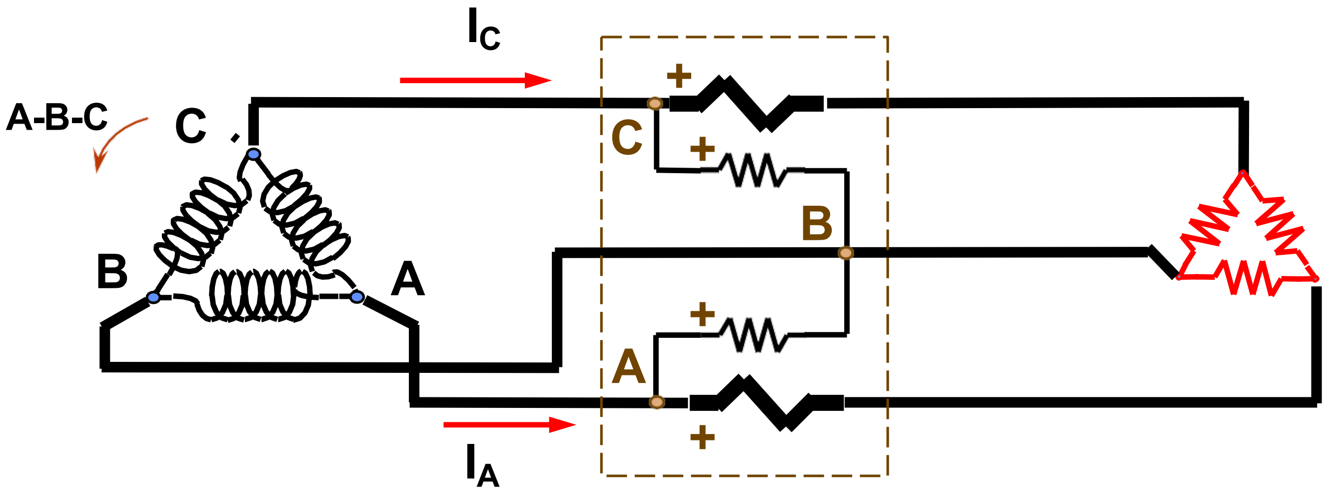
$$Load\ Watts = \sqrt{3}V_{LL}I_L\cos(\theta)$$

Phasor Construction

Step 13: Calculate "Percent Registration"

Power **Meter** **Load**

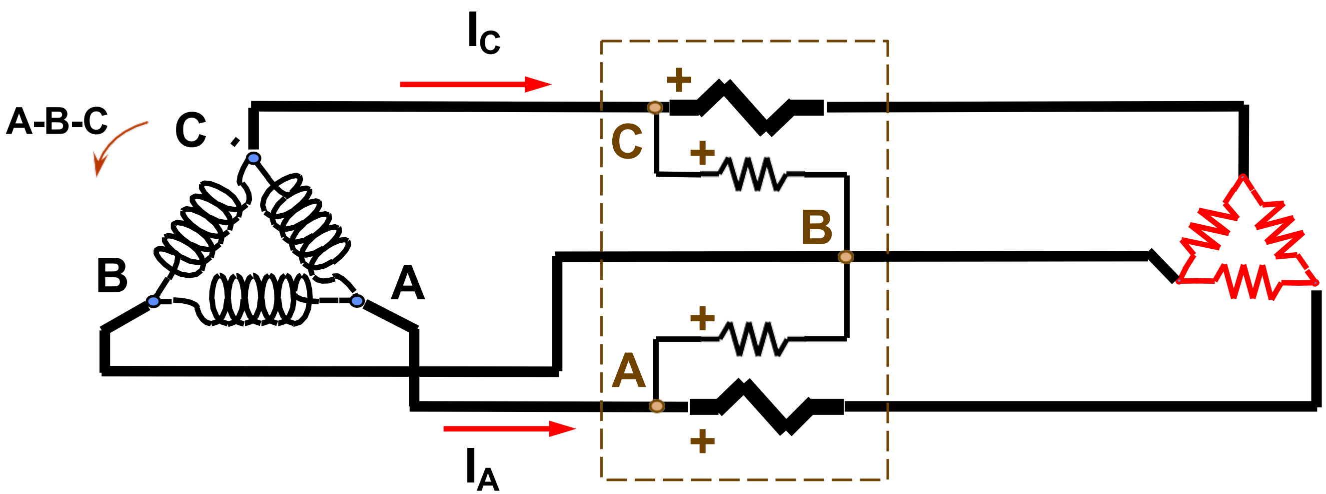
Transformer



Calculate the percent registration of the meter by dividing the Meter Watts by the Load Watts, then multiplying the result by 100%.

Step 13: Calculate "Percent Registration"

Power Transformer **Meter** **Load**



Calculate the percent registration of the meter by dividing the Meter Watts by the Load Watts, then multiplying the result by 100%.

$$\text{Percent Registration} = \frac{\text{Meter Watts}}{\text{Load Watts}} \times 100\%$$

Phasor Construction

$$= \frac{\sqrt{3}V_{LL}I_L\cos\theta}{\sqrt{3}V_{LL}I_L\cos\theta} \times 100\%$$

$$= 100\%$$

QUESTIONS?

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