PHASOR FUNDAMENTALS

HANDS-ON RELAY SCHOOL 2019

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Presentation Information

- This presentation is a revision to *Phasor Diagrams*, presented at the Hands-On Relay School for many years by Ron Alexander.
- Much of the content in this presentation is based on *J. Lewis Blackburn's* fantastic reference: ***Protective Relaying Principles and Applications*** (multiple editions).
- Our Primary Objective for this presentation is to enhance attendee knowledge by:
  - Reviewing Phasor fundamentals
  - Examining In-Service/Load checks
- Our Secondary Objective (time permitting) will add:
  - Reviewing Fault Phasors
  - Using phasors to determine phase shift across three-phase transformer banks

Phasors – Why?

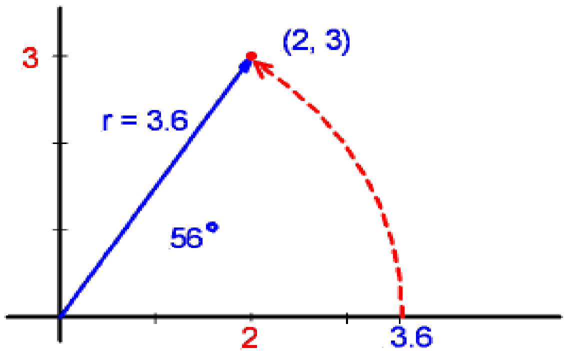
- Tool for understanding the power system during load and fault conditions.
- Assists a person in understanding principles of relay operation for testing and analysis of relay operations.
- Allows technicians to simulate faults that can be used to test relays.
- Common language of power protection engineers and technicians.
- Provides both mathematical and graphical view of System conditions.

Phasor Definitions

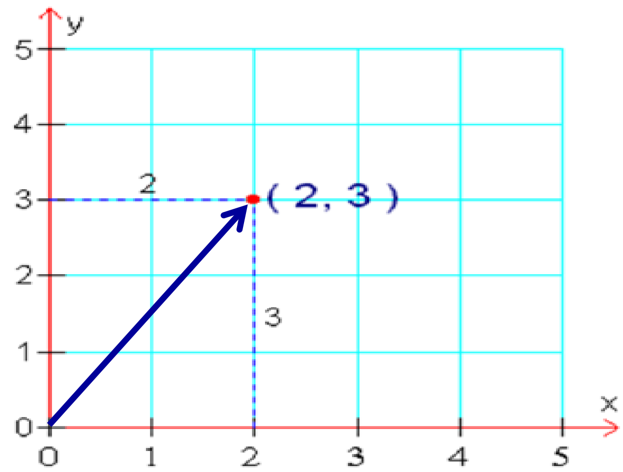
- A line used to represent a complex electrical quantity as a vector. (Google)
- A rotating vector representing a quantity, such as an alternating current or voltage, that varies sinusoidally. (Collins Dictionary)
- A vector that represents a sinusoidally varying quantity, as a current or voltage, by means of a line rotating about a point in a plane, the magnitude of the quantity being proportional to the length of the line and the phase of the quantity being equal to the angle between the line and a reference line. (Dictionary.com)

Phasor Representation

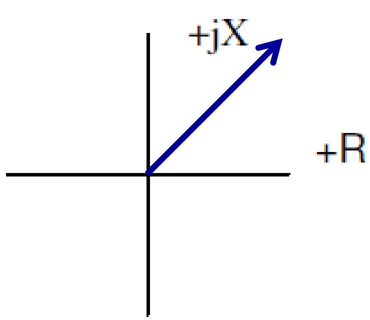
Common pictorial form for representing electrical and magnetic phasor quantities uses the Cartesian coordinates with x (the abscissa) as the axis of the real quantities and y (the ordinate) as the axis of imaginary quantities. (see figures below)



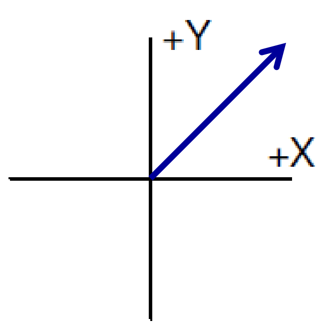
(Polar coordinates)



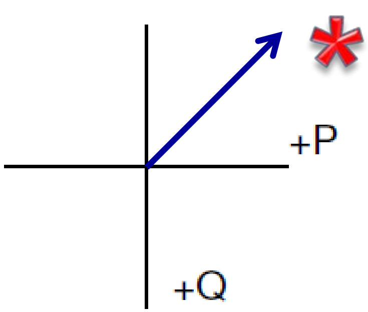
(Rectangular coordinates)



Impedance

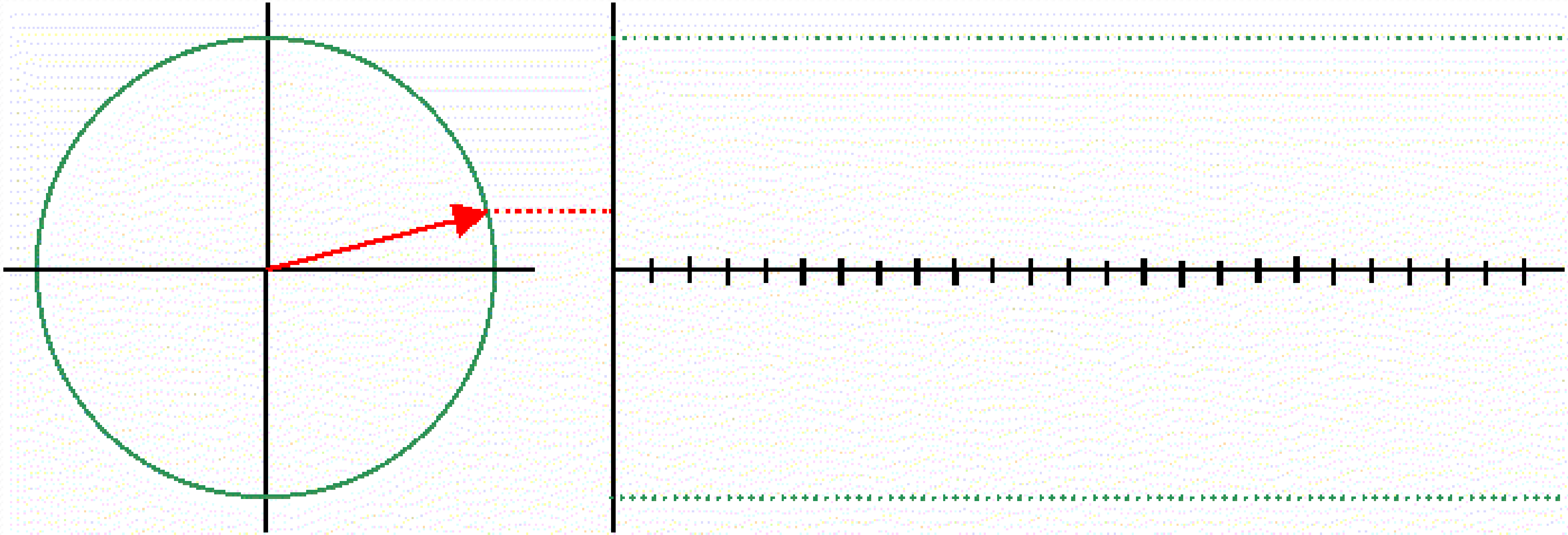


Current & Voltage



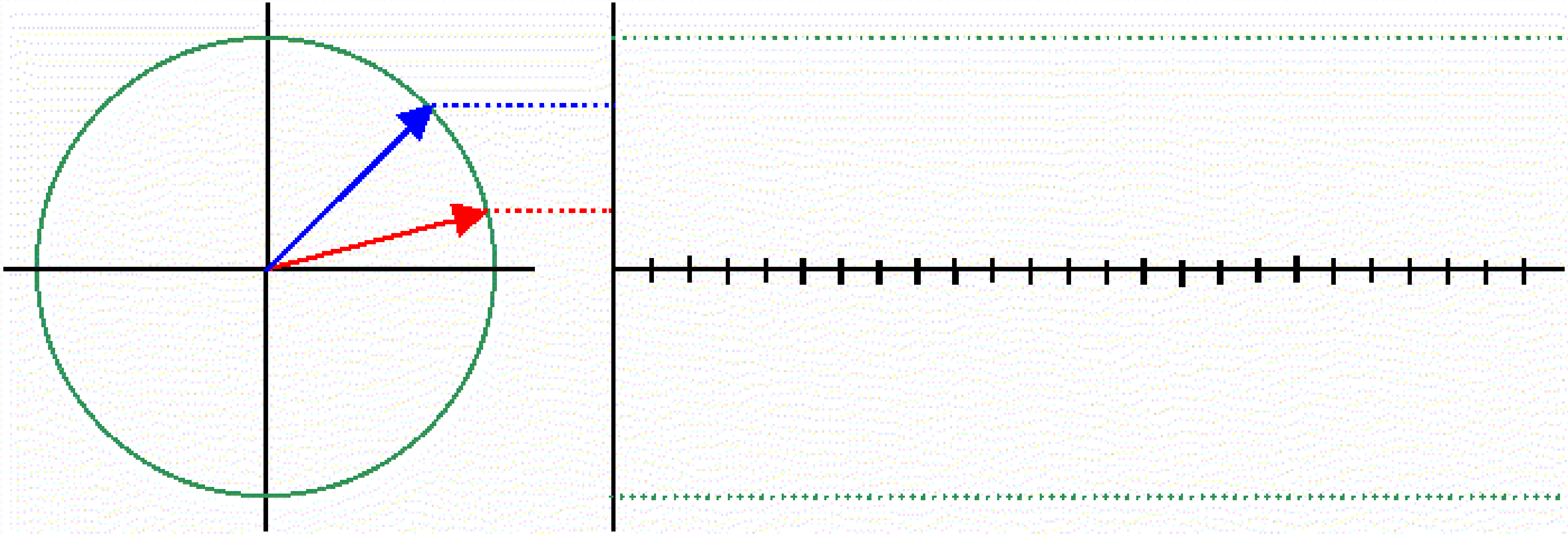
Power

Phasor Rotation



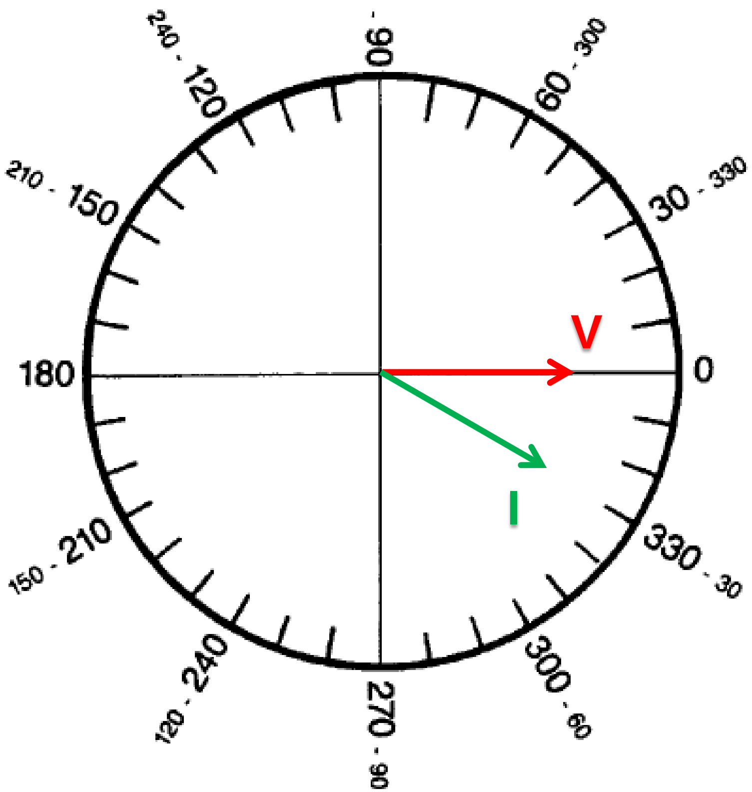
- Here we can see a plot of an electrical quantity and its phasor representation.
- Note the phasor has a constant (usually RMS) magnitude that rotates while the actual electrical quantity varies sinusoidally over time.

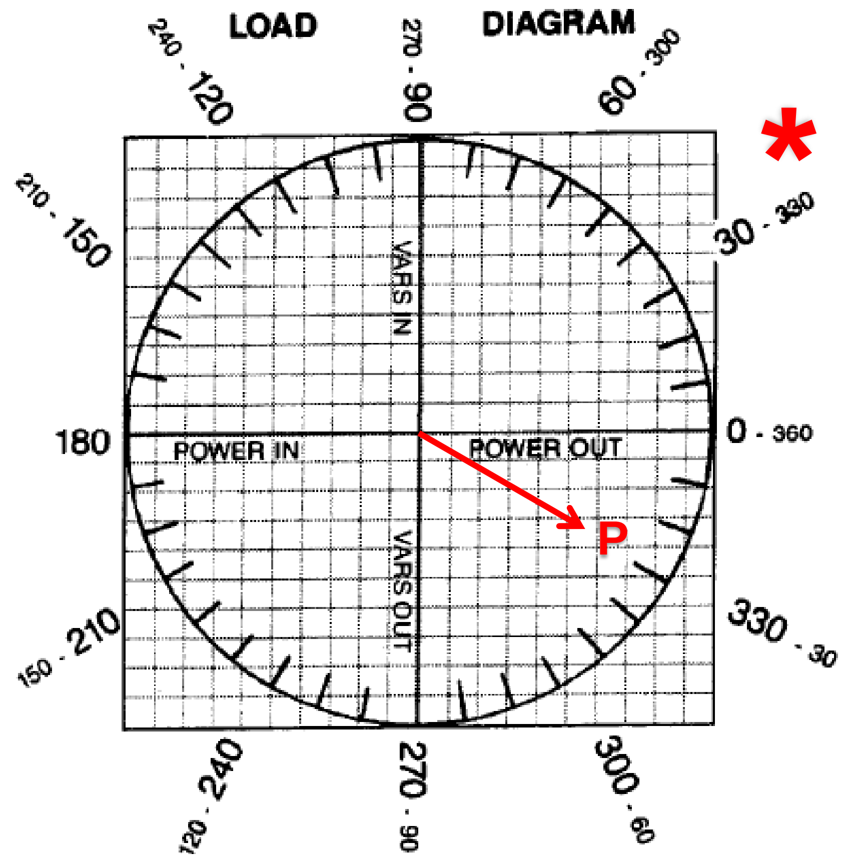
Multiple Phasors



- Here we can see two phasors of the same frequency rotating.
- Note that their phase relationship to each other is constant – in this case, the blue phasor leads the red phasor by some constant angle that does not change.

PLOTTING PHASORS





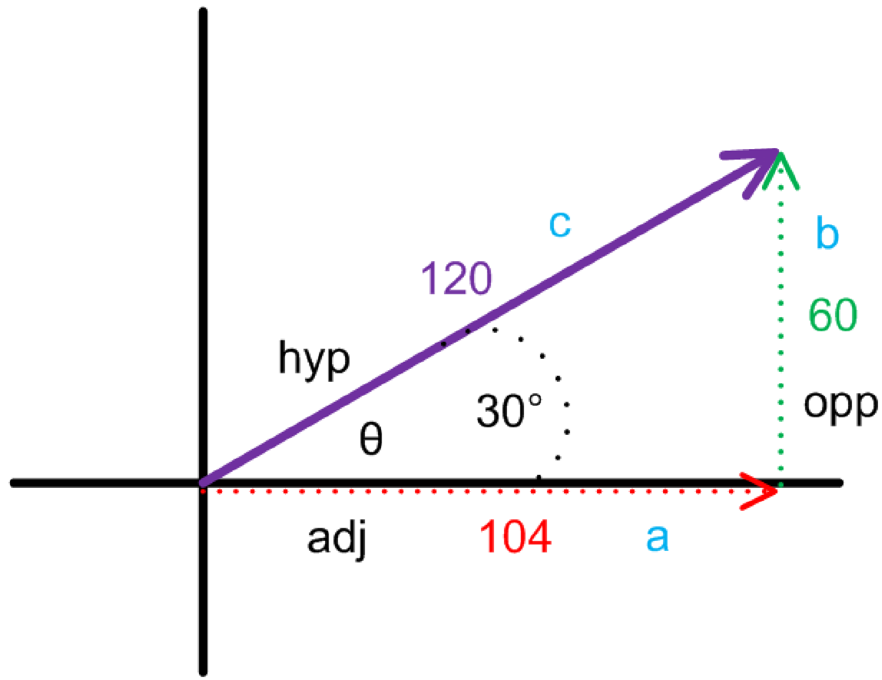
CARTESIAN COORDINATE SYSTEM

Phasor Representation

- Consider an example phasor ‘c’ having a magnitude of $120V_{RMS}$ and a phase angle of 30 degrees:
  - Rectangular Form: $c = x + jy$
    - $c = 104 + j60$ V
  - Polar Form: $c = |c|\angle\theta$
    - $c = 120\angle 30°$ V
  - Complex Form: $c = |c|(\cos\theta + j\sin\theta)$
    - $c = 120(\cos(30) + j\sin(30))$ V
  - Exponential Form: $c = |c|e^{j\theta}$
    - $c = 120e^{j30}\ V$

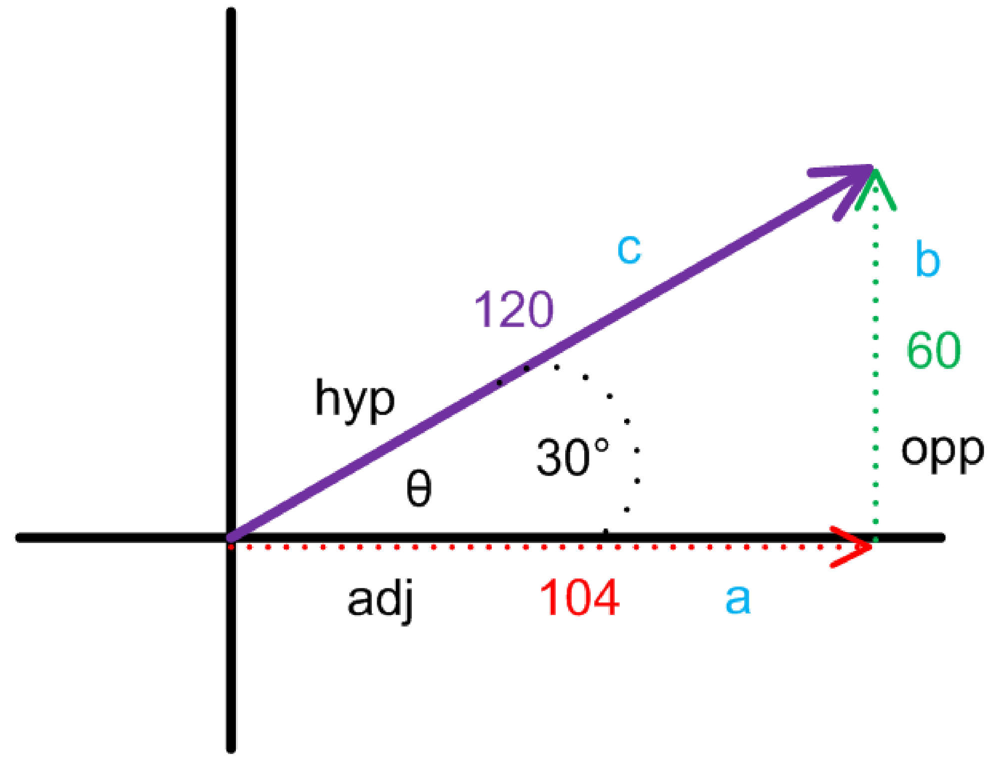
Phasor Conversion

- Rectangular <> Polar Conversion:
  - Rectangular Form: $c = x + jy$
    - $c = 104 + j60$
  - Polar Form: $c = c\angle\theta$
    - $c = 120\angle 30°$
- Trig Functions (right triangles only):
  - $\sin(\theta)$ = opposite / hypotenuse
  - $\cos(\theta)$ = adjacent / hypotenuse
  - $\tan(\theta)$ = opposite / adjacent
- Pythagorean Theorem
  - $c^2 = a^2 + b^2$



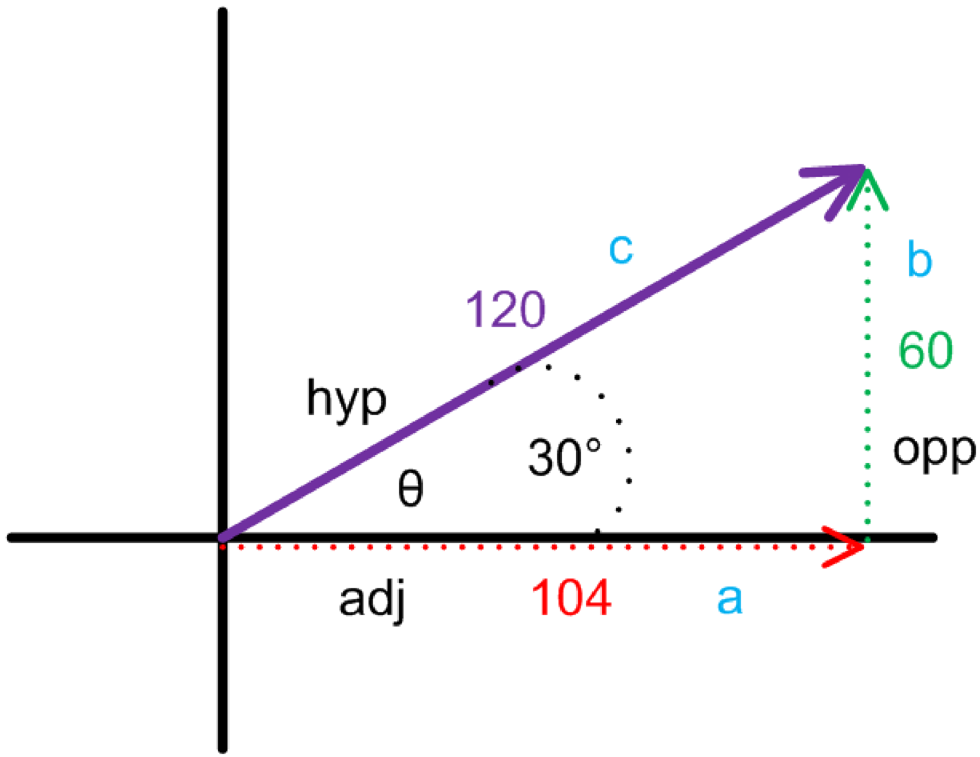
Phasor Conversion

- Rectangular to Polar Conversion:
  - Rectangular Form: c = x + jy
    - c = 104 + j60
    - $c^2 = a^2 + b^2$
    - $c^2 = 104^2 + 60^2$ >> c = 120
    - Tan (θ) = opposite / adjacent
      - Tan (θ) = 60 / 104 >> θ = 30°
  - Converted: $c = 120\angle 30°$



Phasor Conversion

- Polar to Rectangular Conversion:
  - Polar Form: $c = |c|\angle\theta$
    - $c = 120\angle 30°$
    - $\mathrm{Sin}(\theta) = o/h$
      - $o = h * \mathrm{Sin}(\theta)$
      - $o = 120 * \mathrm{Sin}(30) = 60$
    - $\mathrm{Cos}(\theta) = a/h$
      - $a = h * \mathrm{Cos}(\theta)$
      - $a = 120 * \mathrm{Cos}(30) = 104$
  - Converted: $c = 104 + j60$



Operators

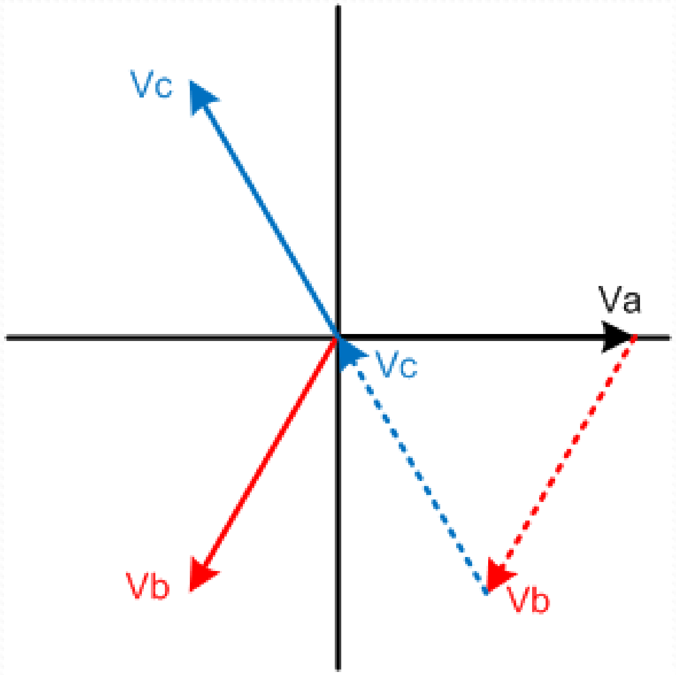
- Two 'Operators' related to phasors are commonly used in the Power world: '***j***' and '***a***'
  - Mathematically '*j*' is an imaginary number representing the imaginary (reactive) portion of a phasor: $j = \sqrt{-1}$
  - Graphically, it is a 'rotator' constant with an angle of 90°
  - It can also be viewed as a 'unit phasor' always having a value of $1\angle 90°$
- The '*a*' Operator, commonly used when working with Symmetrical Components.
  - Graphically it is a 'rotator' constant with an angle of 120°
  - It is also a 'unit phasor' with a value of $1\angle 120°$

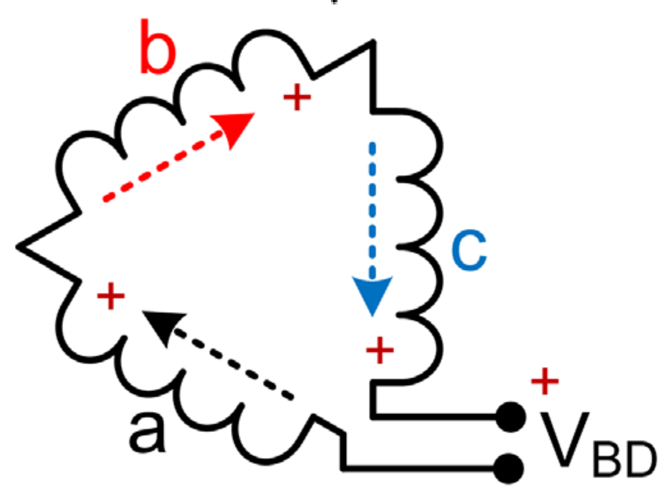
Combining Phasors

- Two common operations are performed with phasors:
  - Adding / Subtracting
  - Multiplying / Dividing
- It's generally easier to add/subtract in rectangular form and easier to multiply/divide in polar form.
- When adding/subtracting in rectangular form, add/subtract the real and reactive components (respectively):
  - Example: $(2+j3) + (3+j4) = (5+j7)$
- When multiplying/dividing in polar form, multiply/divide the magnitude, and add/subtract the angle:
  - Example: $(10\angle 30°) * (5\angle 45°) = 50\angle 75°)$

Adding Phasors Graphically

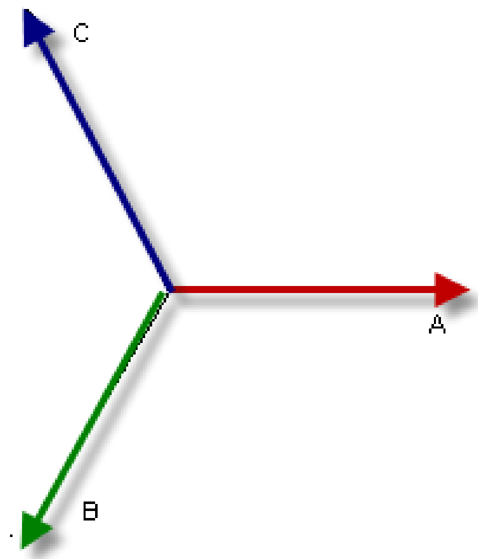
- You can also add vectors graphically by connecting them head to tail.
- The resultant is the phasor originating at the origin of the first arrow and ending at the head of the last arrow.
- Here, if we have the following:
  - Va = 120∠0°V
  - Vb = 120∠-120°V
  - Vc = 120∠120°V
- Va + Vb + Vc = 0

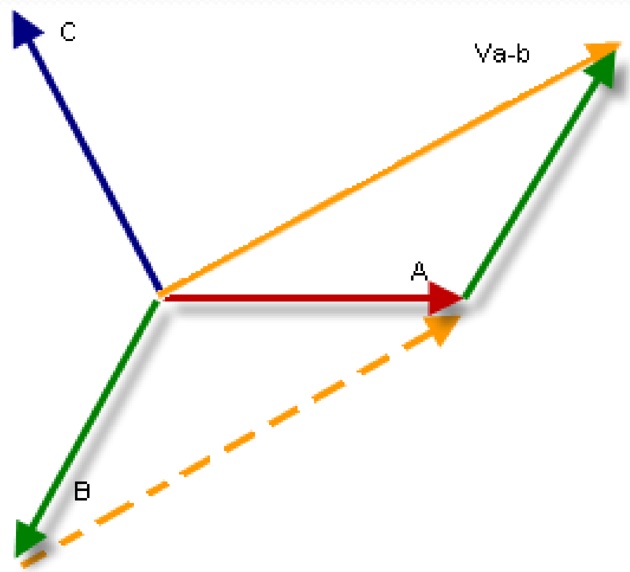


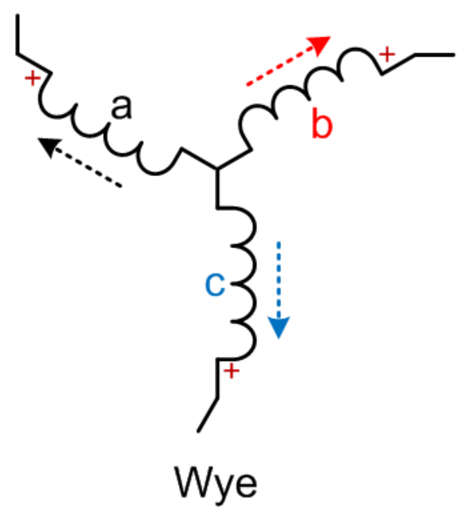


Adding Phasors Graphically

- In this example, the V_{AB} voltage is V_A-V_B. We subtract V_B by reversing the V_B phasor and adding it to V_A.
- $V_{AB} = V_A - V_B = V_A + (-V_B)$

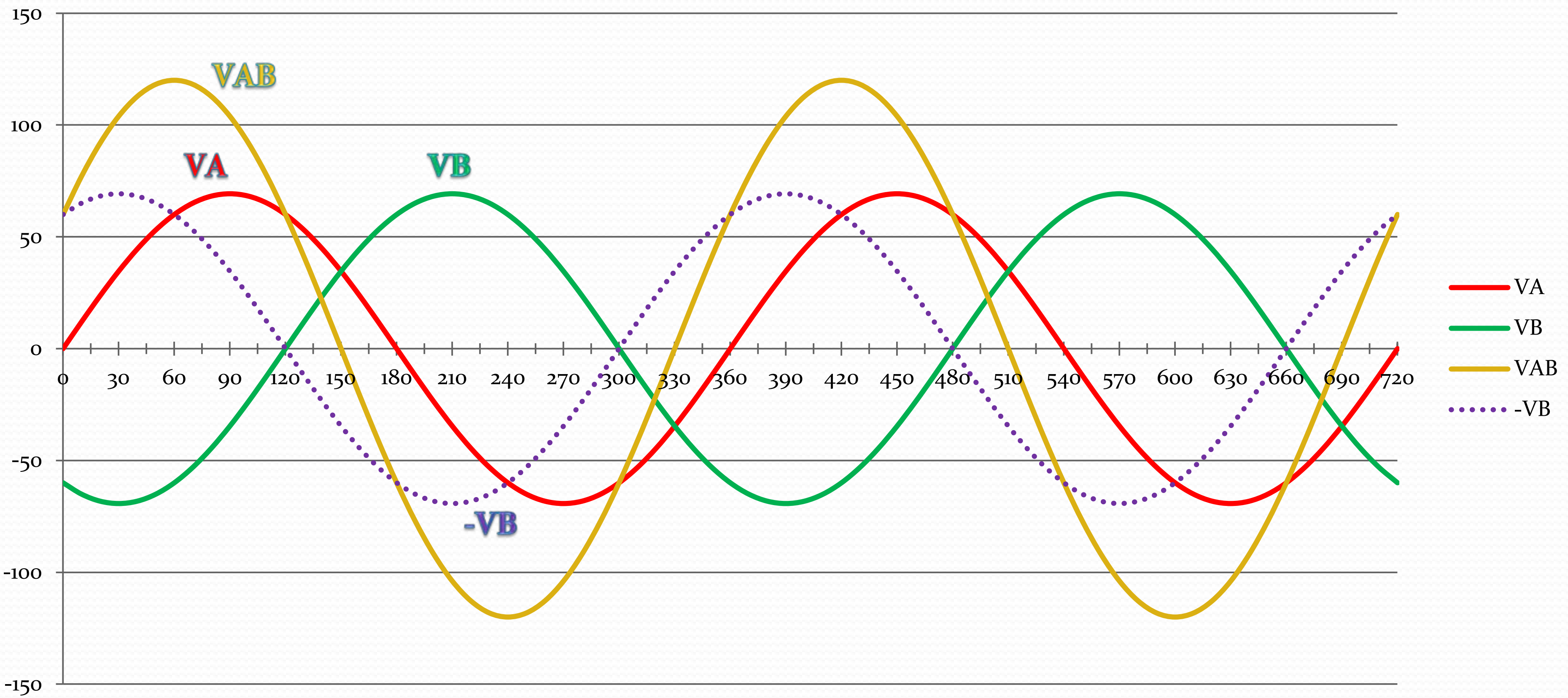




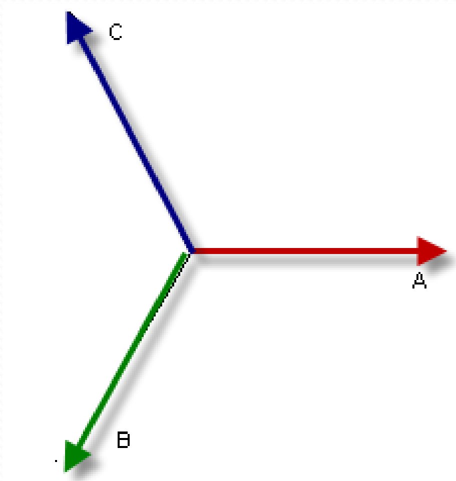


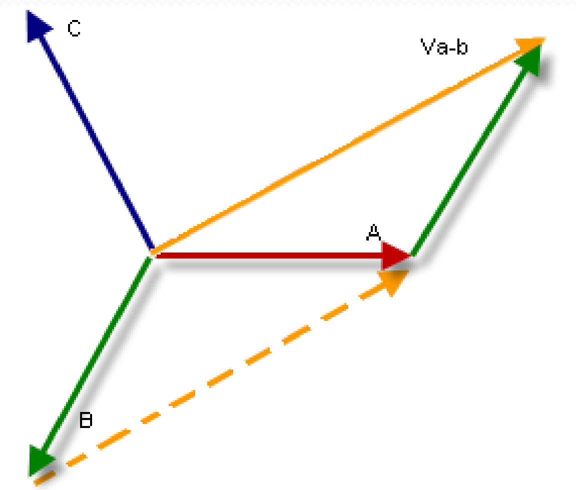
Sinusoidal Waveforms

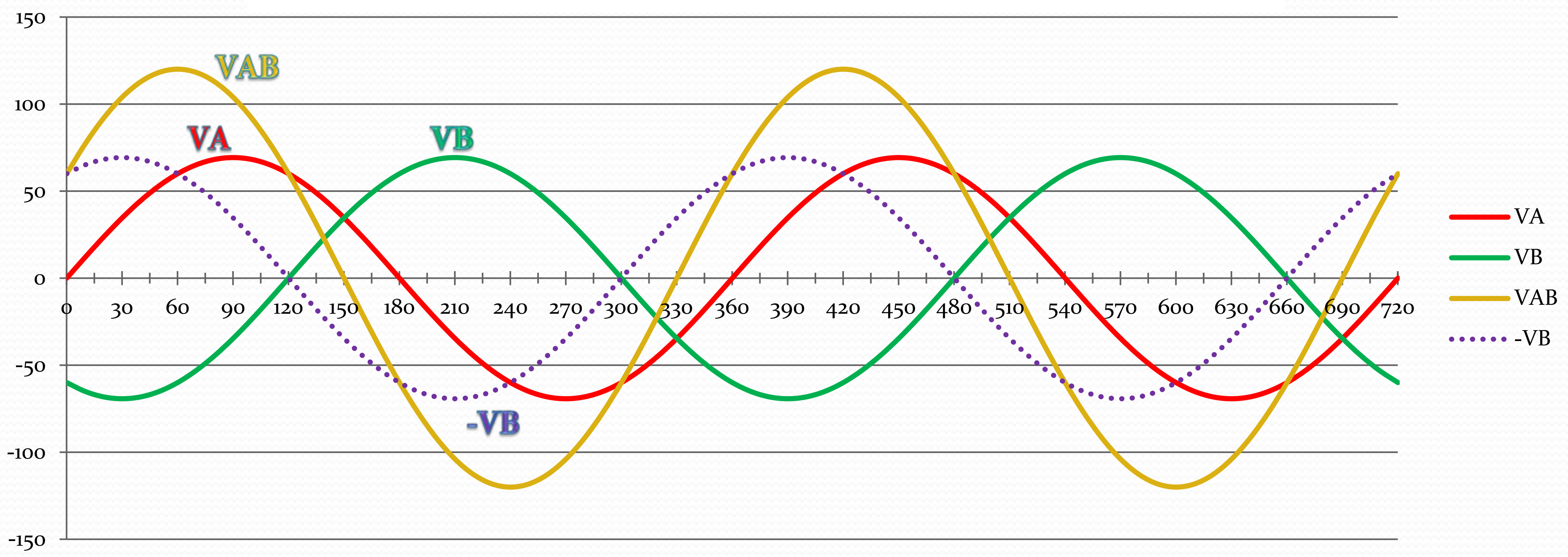
- Note that adding or subtracting sinusoidal waveforms simply produces a resultant sinusoidal waveform of the same frequency.



Which One is Easier?





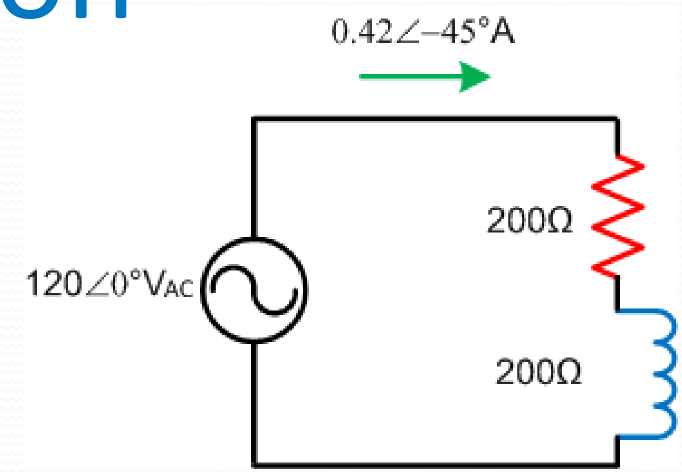


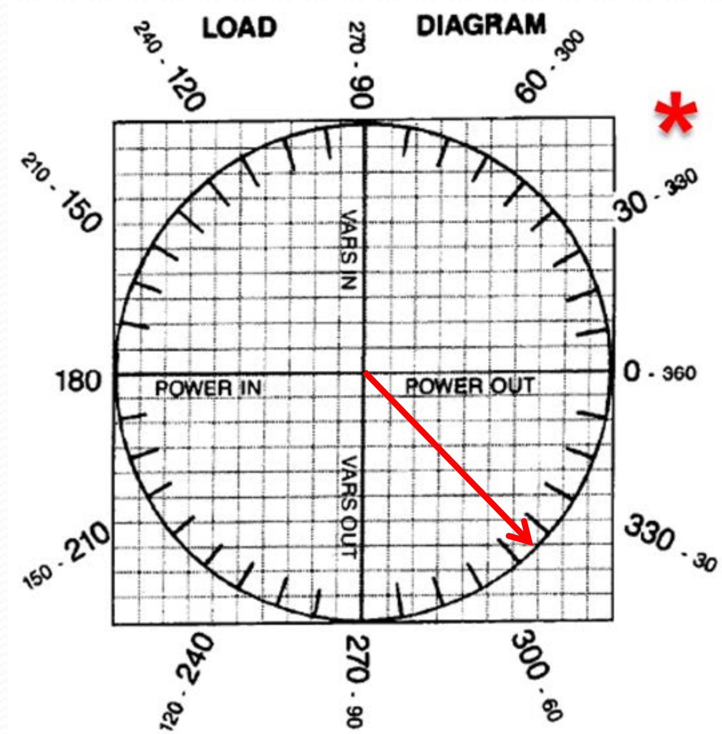
Phasors – Conjugation

- Most commonly used in power calculation: *P=EI* where the conjugate of I is sometimes used and shown as: $P=EI^*$
  - Conjugates:
    - $c = x - jy$
    - $c = c\angle -\Phi$
    - $c = |c|(\cos\Phi - j\sin\Phi)$
    - $c = |c|e^{-j\Phi}$

Phasors – Conjugation

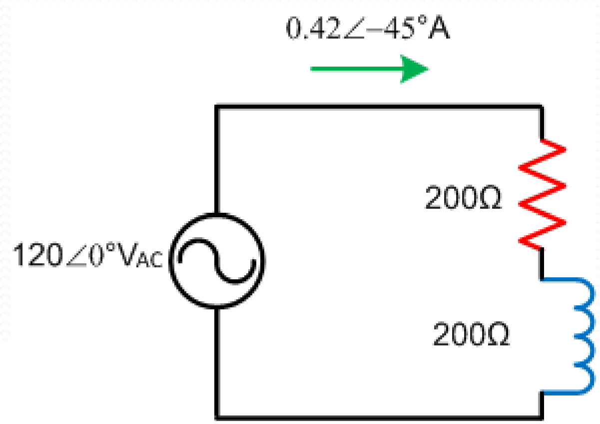
- Calculating: P = E * I we get:
  - P = 120∠0°V * 0.42 ∠-45°A = 50.9∠-45°VA
  - Placing this phasor on one of our previous Power Flow diagrams gives →→→
- But Blackburn and many others use +Q in the 1st Quadrant.
- If we calculate P using the conjugate of the current: P = E * I*
  - P = 120∠0°V * 0.42 ∠+45°A = 50.9∠+45°VA
  - This places P in the 1st Quadrant.

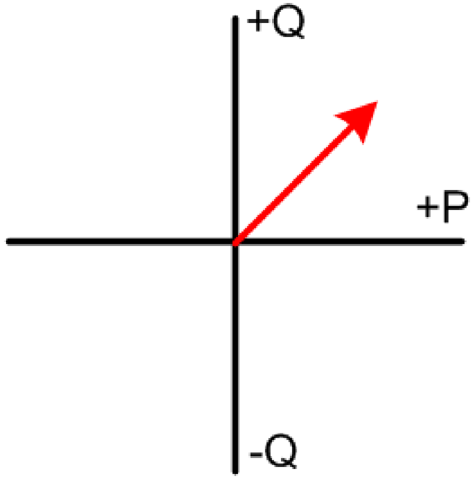


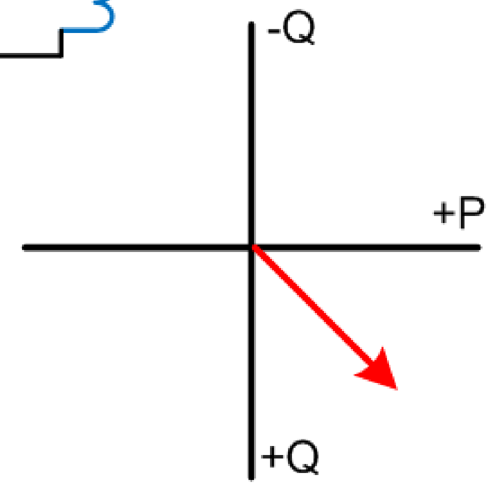


Phasors – Conjugation

- It’s extremely important to remember that phasor diagrams are descriptors of circuit information. How they are placed on a diagram does not change the electrical qualities of a circuit.

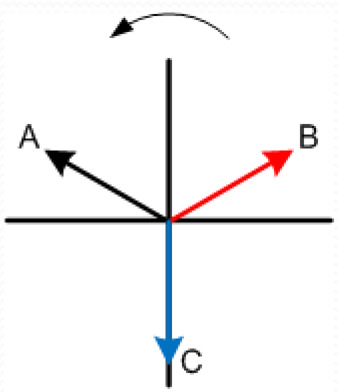




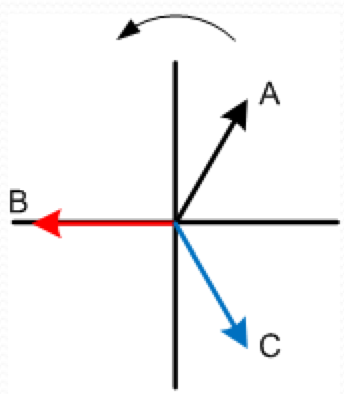


Phase Sequence

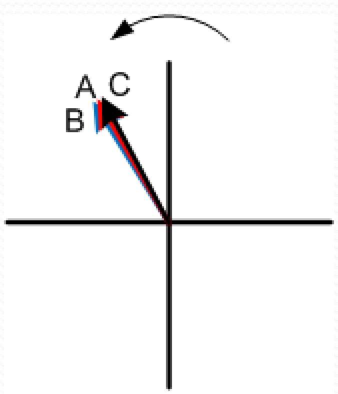
- Phase Sequence is the order in which phasors pass a reference point.
- In Symmetrical Components, you will hear the terms: positive sequence, negative sequence, and zero sequence.
  - Positive Sequence = ABC
  - Negative Sequence = ACB.
  - Zero sequence is all 3 phases rotating together at the same angle.



Positive Sequence



Negative Sequence

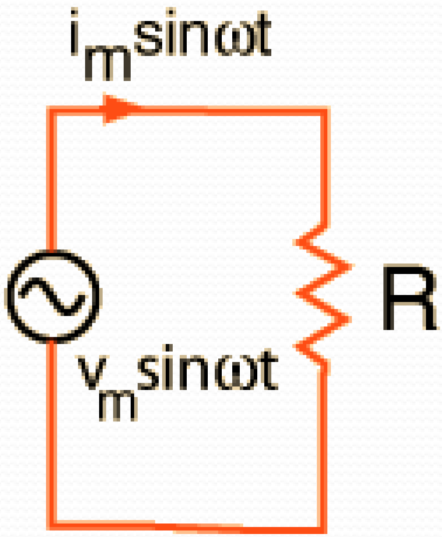


Zero Sequence

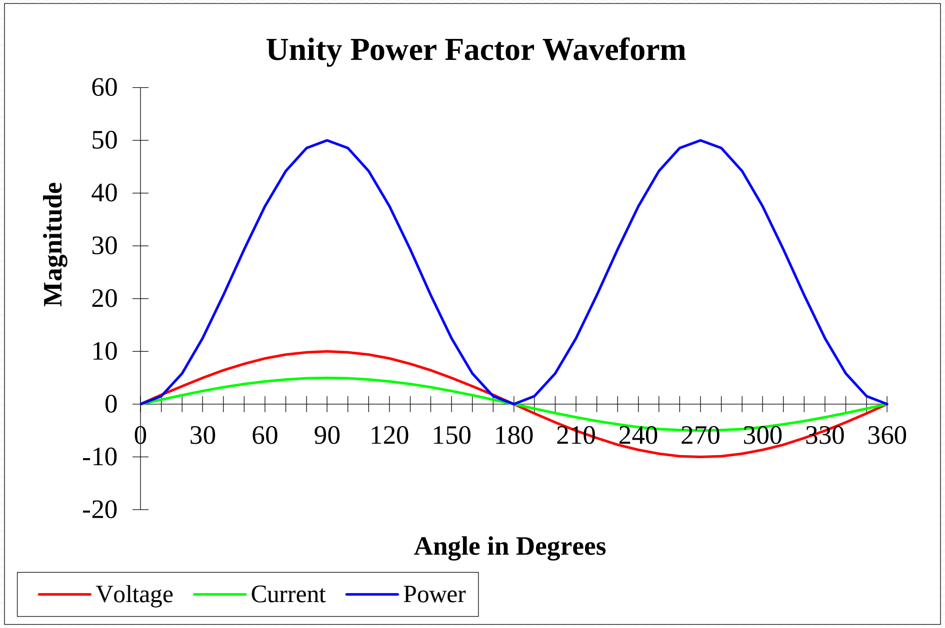
Resistor AC Response

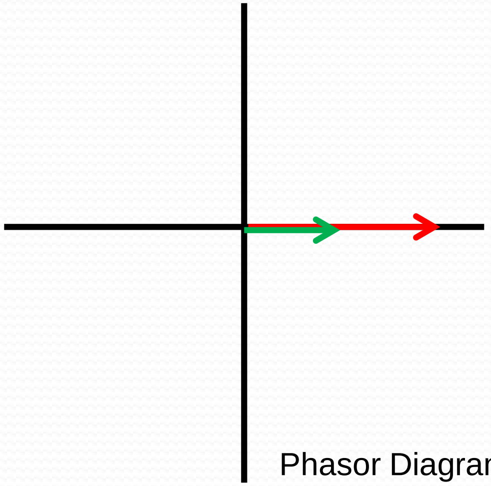
$$I = \frac{V}{R}$$

$$Z = R$$



$$I = \frac{I_m}{\sqrt{2}}, \quad V = \frac{V_m}{\sqrt{2}}$$





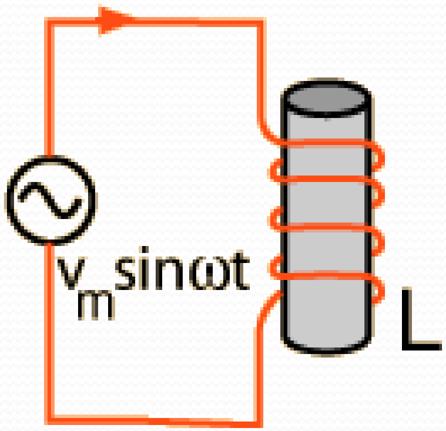
Phasor Diagram

Inductor AC Response

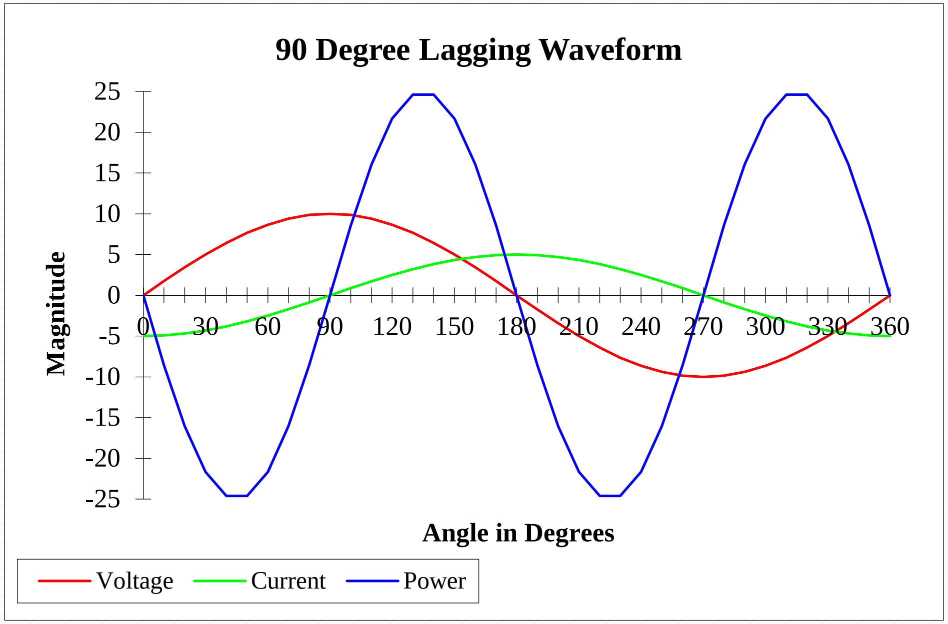
$$I = \frac{V}{X_L}$$

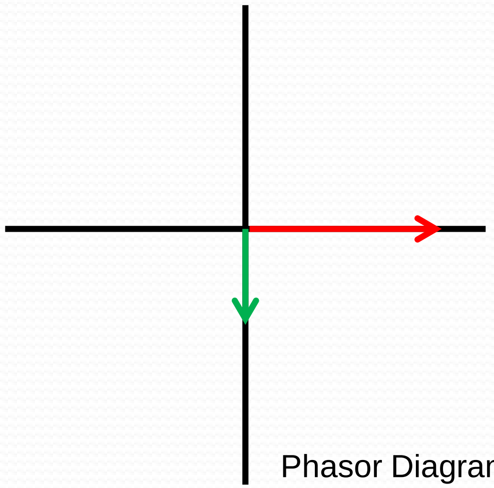
$$X_L = \omega L$$

$$i_m \sin(\omega t - 90°)$$



$$I = \frac{I_m}{\sqrt{2}}, \quad V = \frac{V_m}{\sqrt{2}}$$





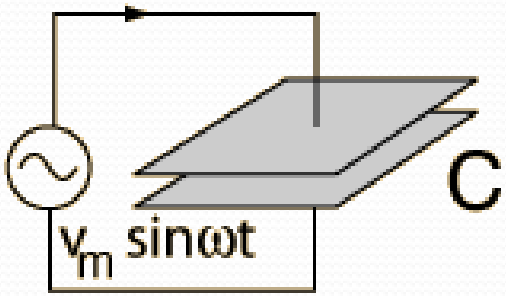
Phasor Diagram

Capacitor AC Response

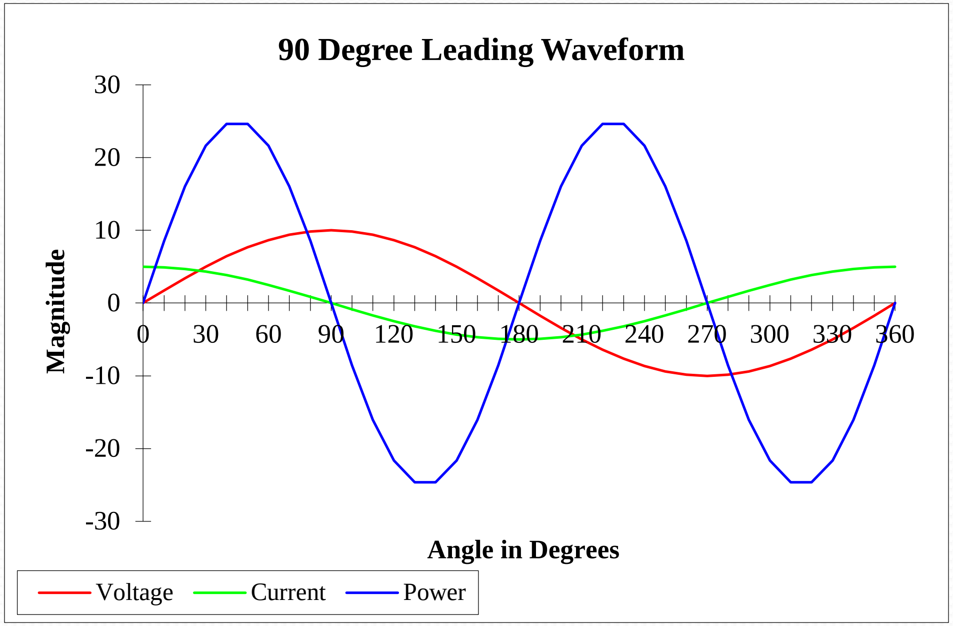
$$I = \frac{V}{X_C}$$

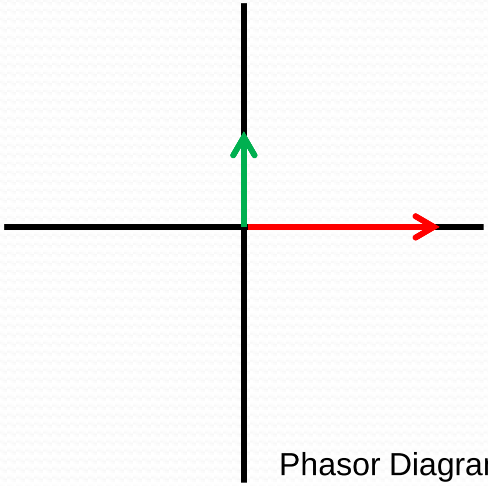
$$X_C = \frac{1}{\omega C}$$

$$i_m \sin(\omega t + 90°)$$



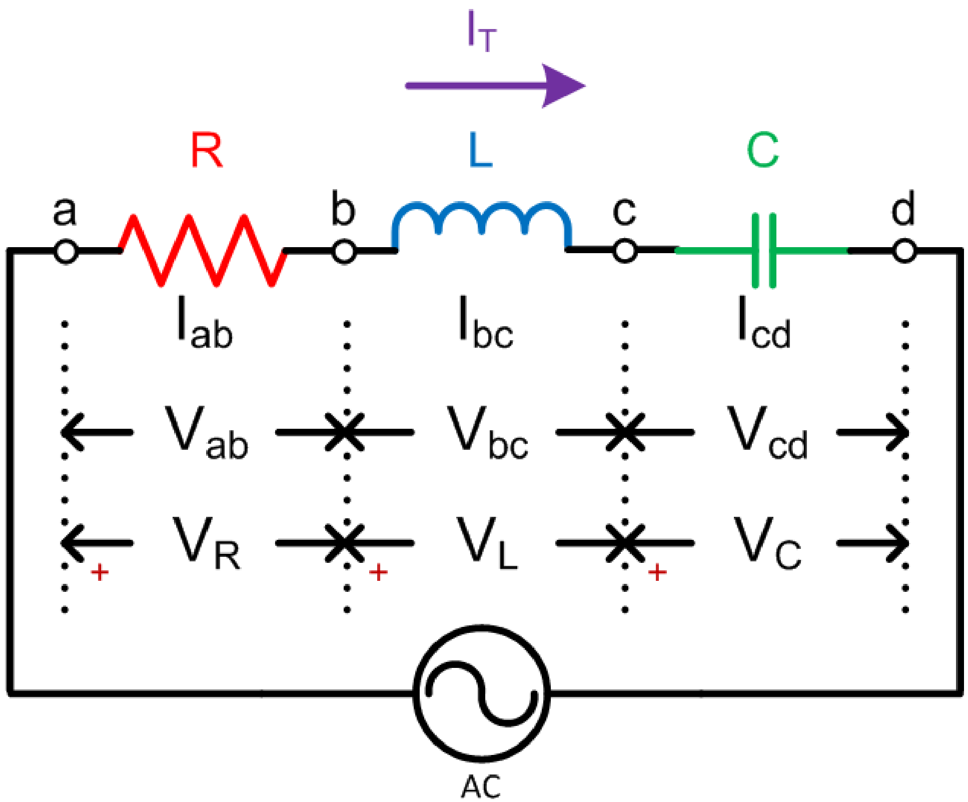
$$I = \frac{I_m}{\sqrt{2}}, \quad V = \frac{V_m}{\sqrt{2}}$$



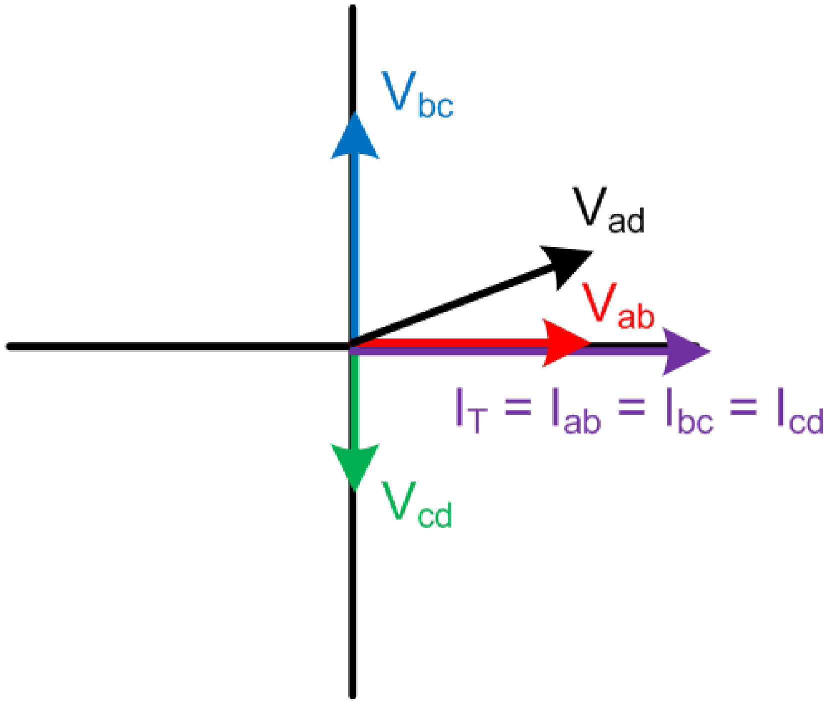


Phasor Diagram

Phasor Nomenclature

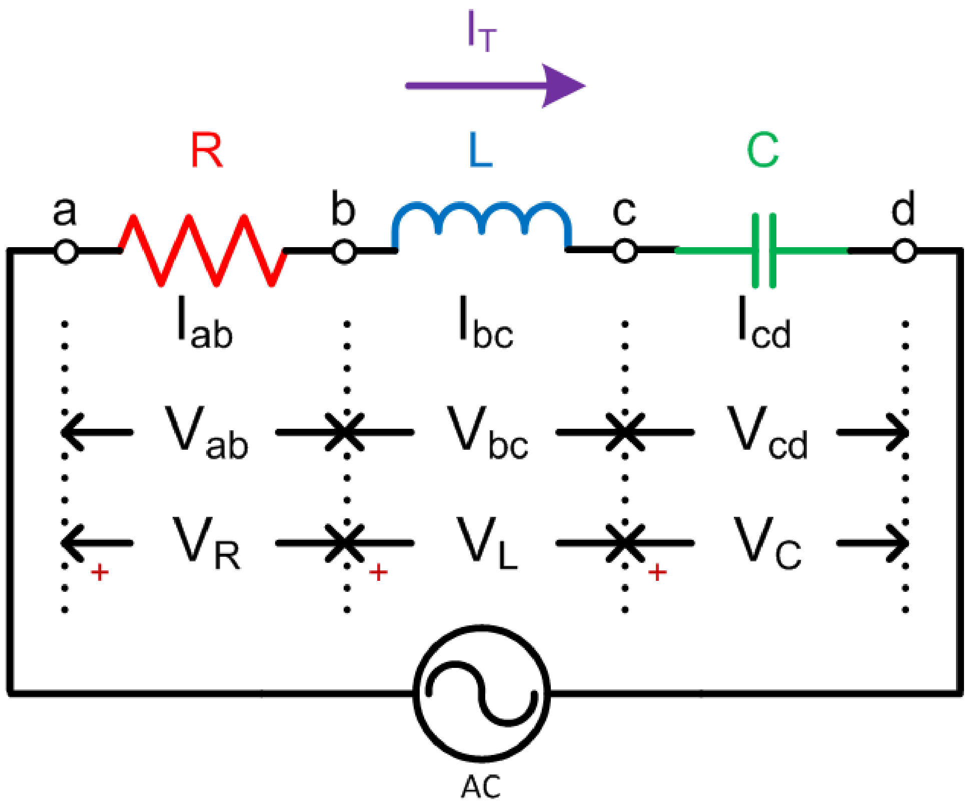


Circuit Diagram

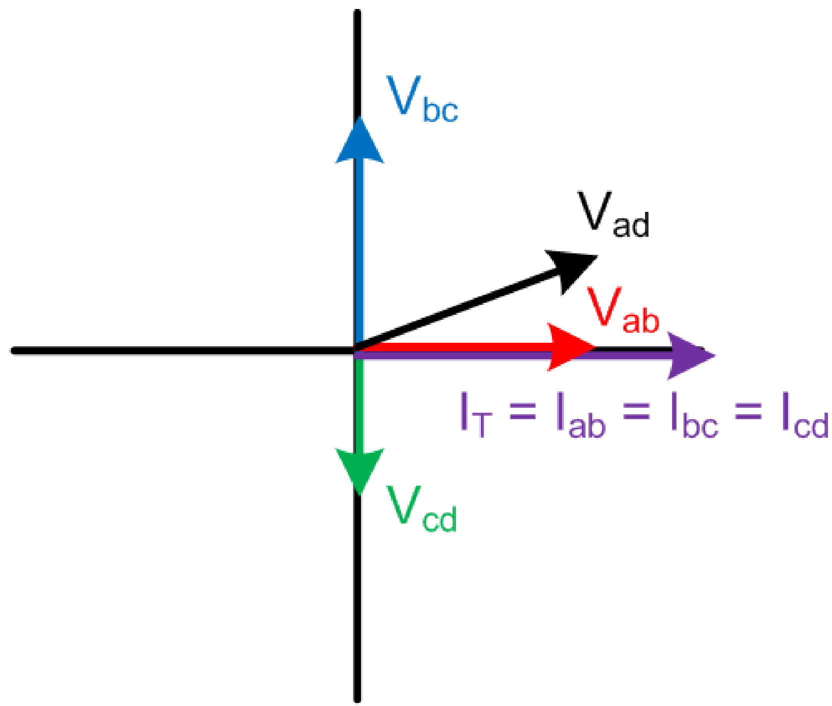


Open Phasor Diagram

Phasor Nomenclature



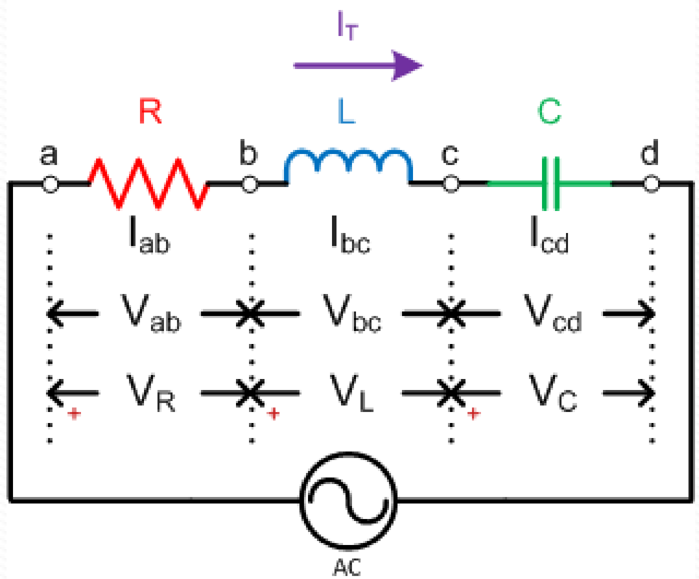
Circuit Diagram



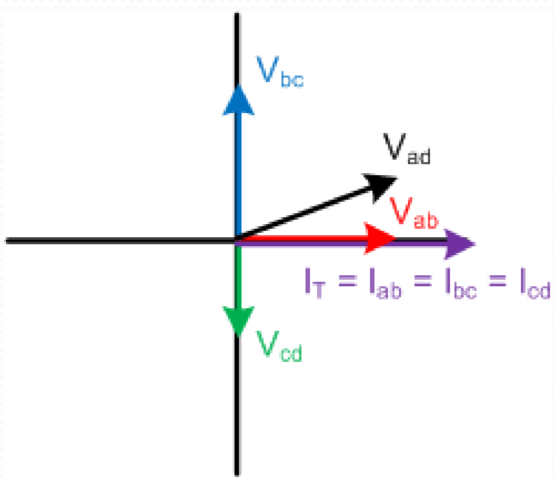
Open Phasor Diagram

Phasor Nomenclature

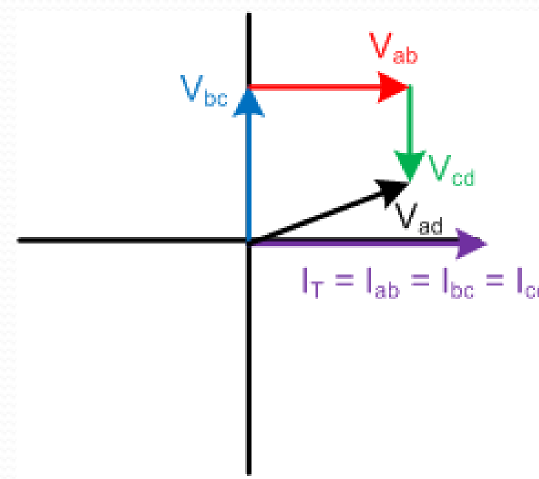
- Phasor diagrams can be drawn ‘open’ or ‘closed’.



Circuit Diagram



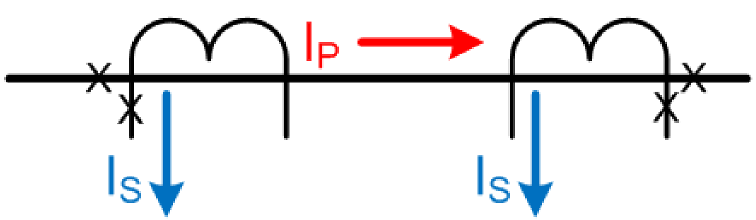
Open Phasor Diagram



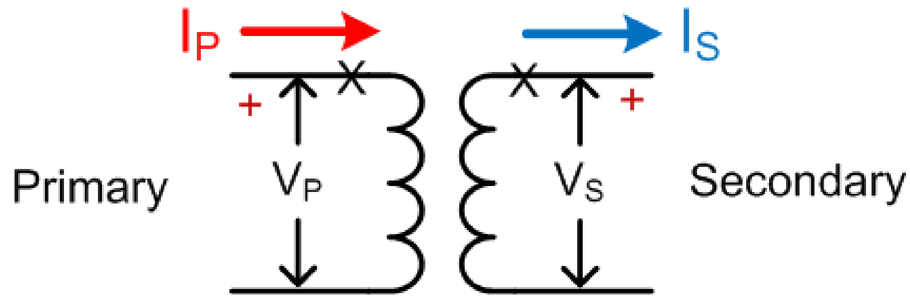
Closed Phasor Diagram

Polarity

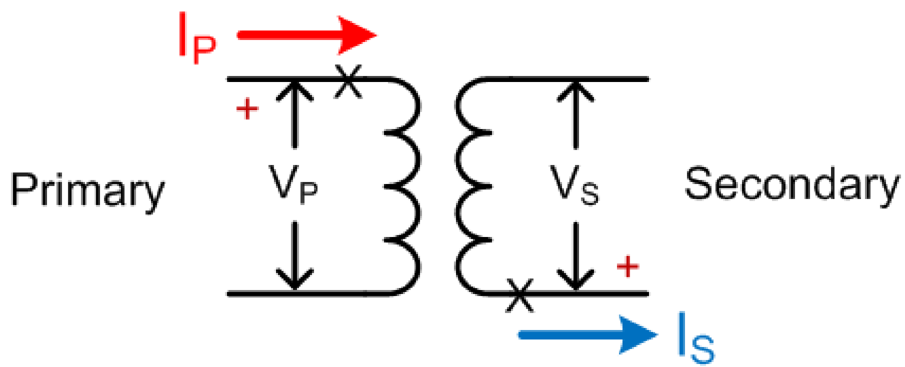
- Current into the primary polarity and out of the secondary polarity are (essentially) in-phase.
- Voltage drop from polarity to non-polarity on both windings are (essentially) in-phase.



Current Transformer Polarity



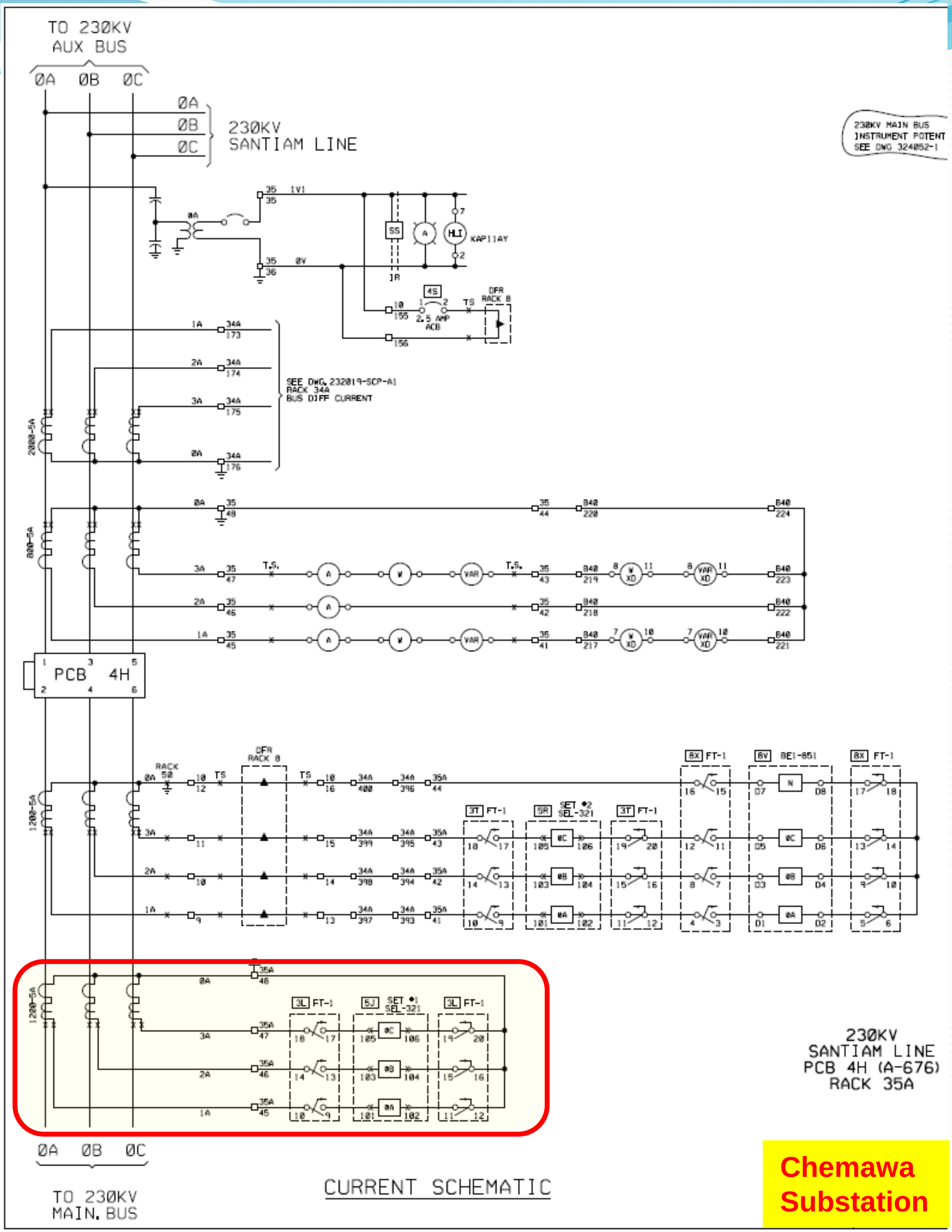
Subtractive Polarity



Additive Polarity

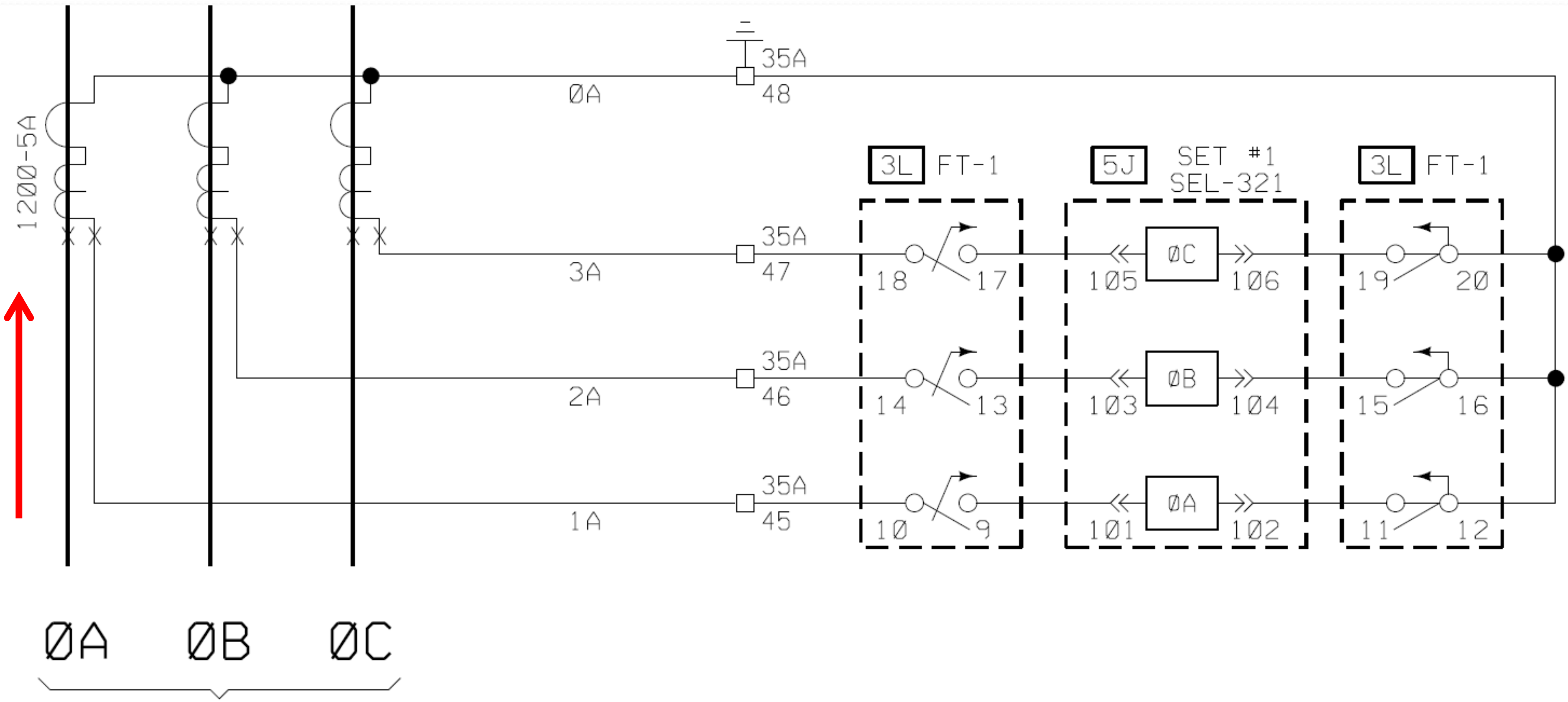
Polarity and Phasors

- When dealing with Phasors, we make assumptions about current and voltage polarity on our circuit diagram so polarity is also extremely important.
- Consider the following circuit: we'll do 'in-service' checks of the relays in the bottom current circuit.



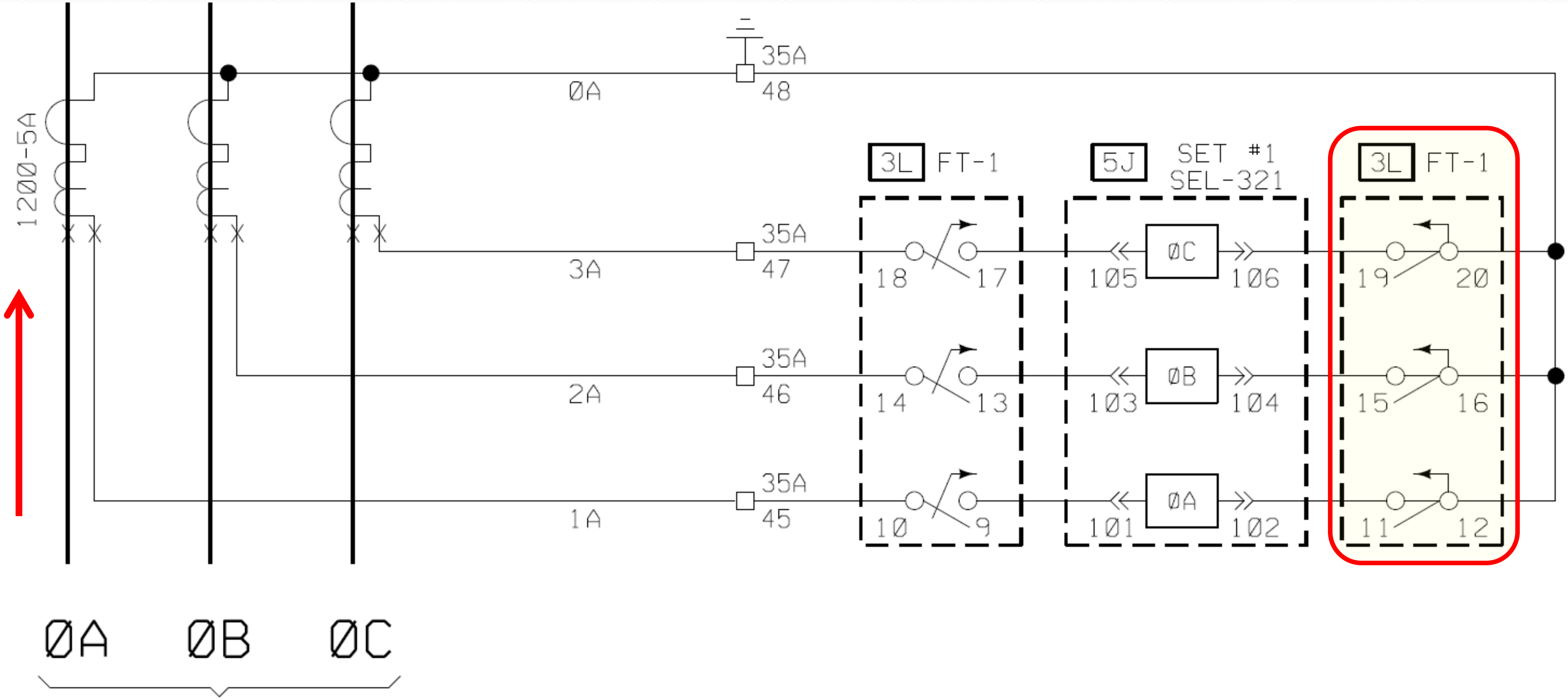
Phasors in Practice

- Here we've zoomed in on the current circuit we are interested in:
- We'll assume for convenience that the normal load flow for this circuit is from the Main Bus out into the line – the 'up' direction on this print.



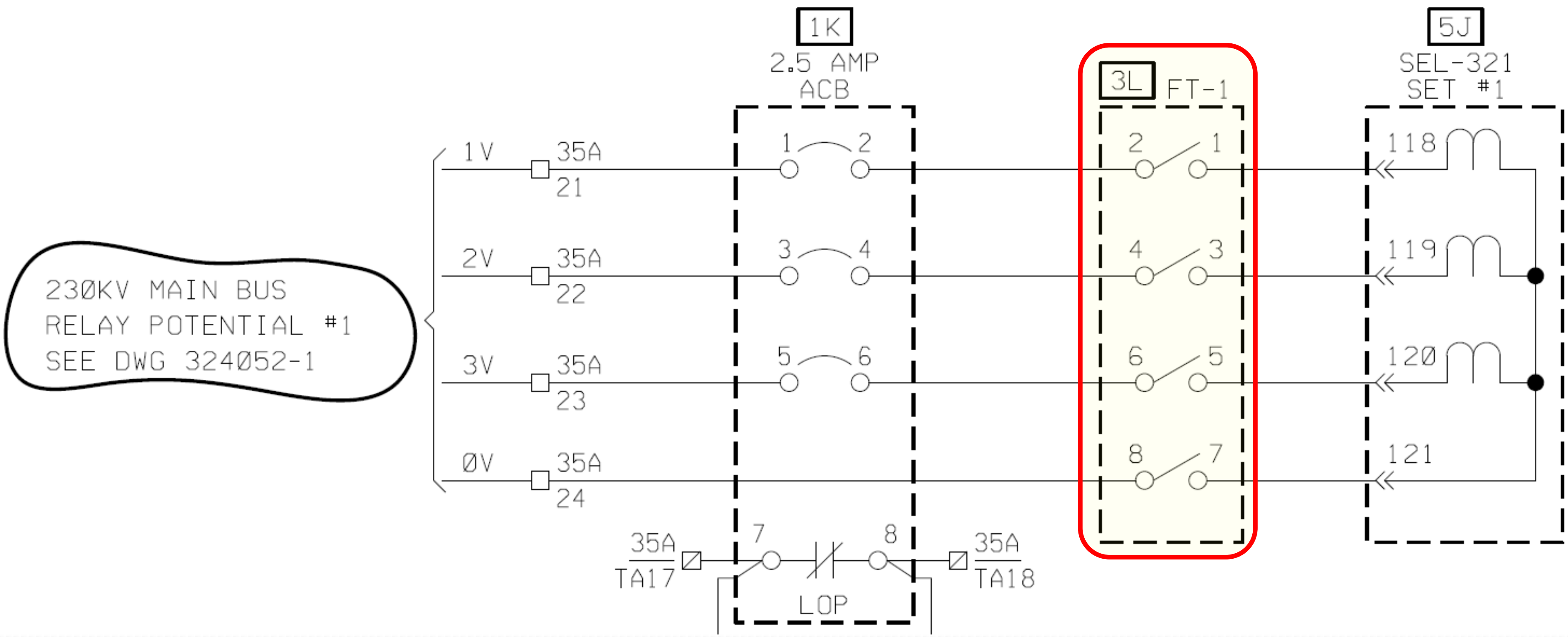
Phasors in Practice

- Now we'll plan on where we will take secondary current readings. The test switches are made for this so we'll use terminals *11/12*, *15/16*, and *19/20* on test switch *3L*.



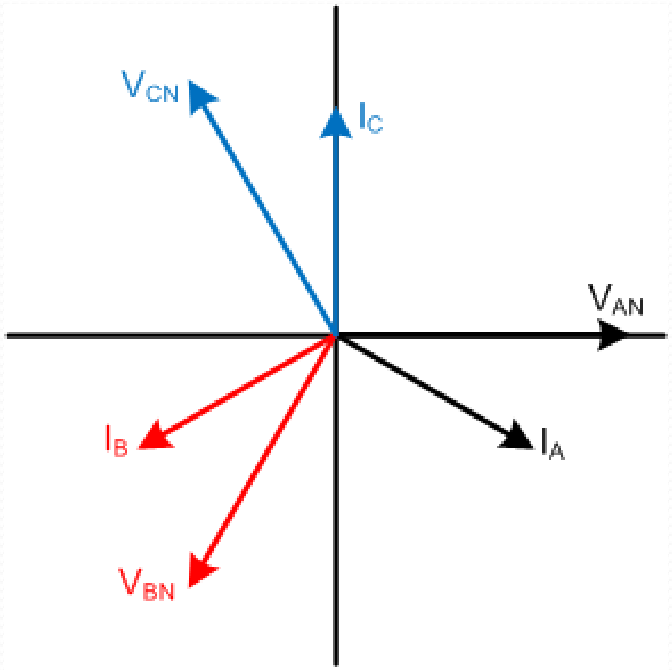
Phasors in Practice

- We'll also plan on checking the voltages to the relays for proper magnitude and polarity.
- We'll use the same *3L* test switch, terminals *1-8*.

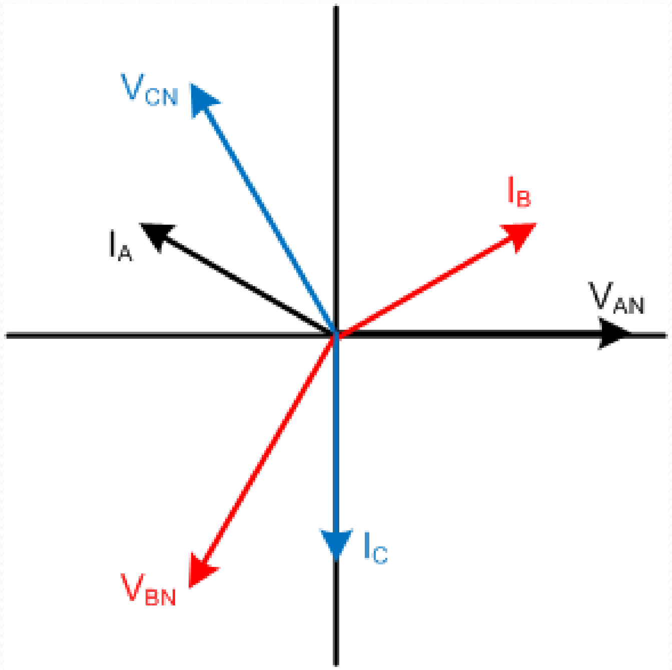


Phasors in Practice

- Which of the following phasor diagrams is correct for the circuit we are doing in-service on?
  - It is indeterminate / uncertain; both could be correct, or wrong…
- Why?
  - We haven't completed our circuit diagram (which we know should accompany our phasor diagram).



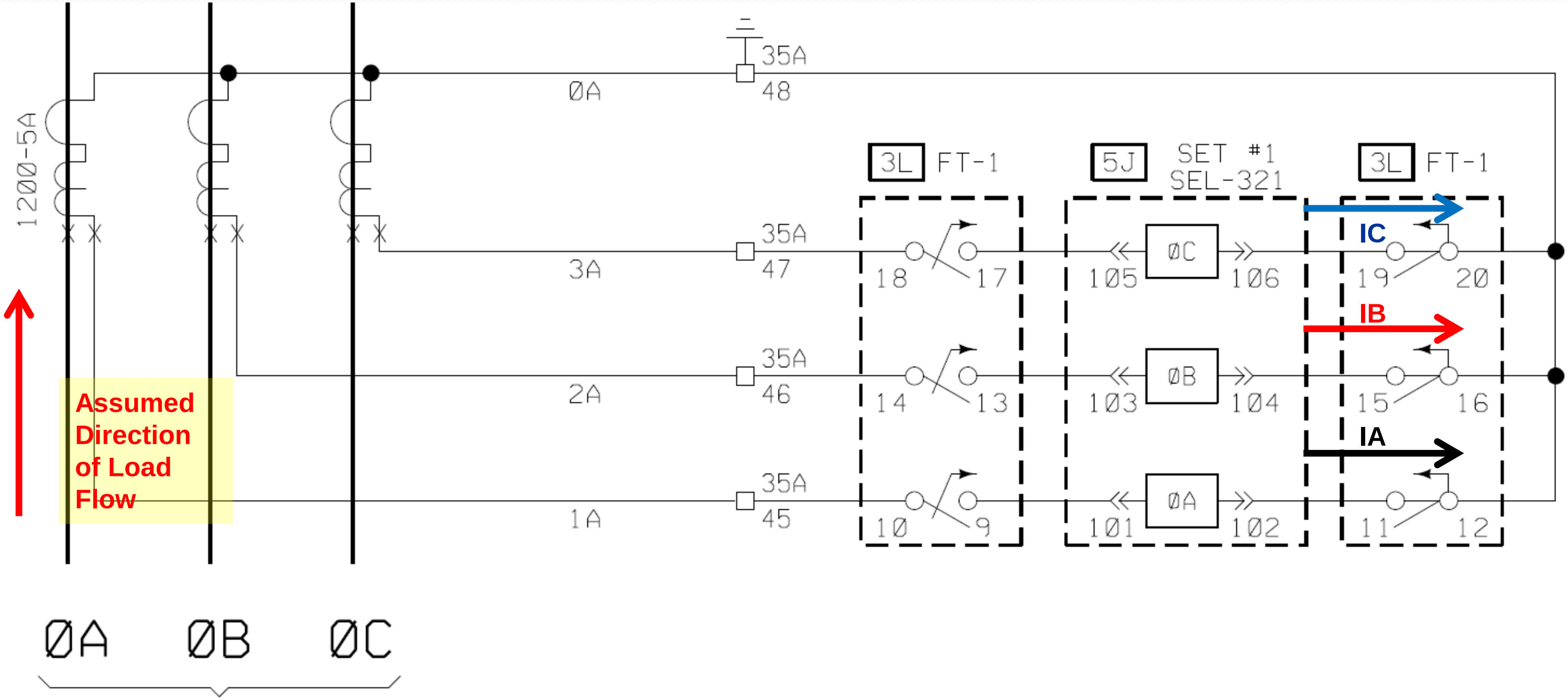
Phasor Diagram #1



Phasor Diagram #2

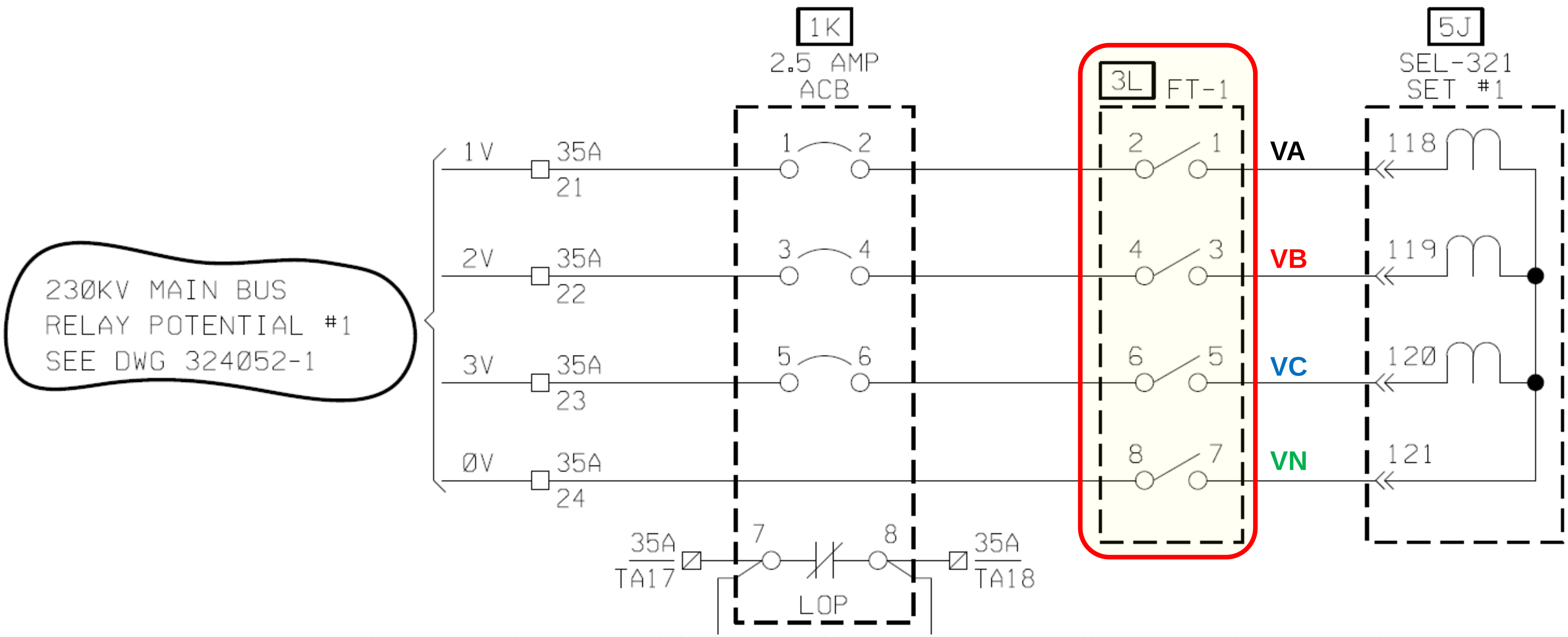
Phasors in Practice

- Since we already assumed a load flow direction, now we just need to show on our circuit diagram our assumed polarity at our measurement point.
- This determines how we 'jack in' to the current circuit using a phase-angle meter. In this diagram we will insert test equipment with assumed current 'in' on terminals 11, 15, and 19.



Phasors in Practice

- Let's show/document our measurement points for the voltages too.
- V_{AN} = (3L) 1-7, V_{BN} = (3L) 3-7, V_{CN} = (3L) 5-7



In-Service Sheet

- Here is a in-service sheet based on our work and our measurements based on our circuit diagram.
- What does it tell us?
- It tells us our ‘assumed’ current direction was correct, and load is flowing from Chemawa to Santiam. It also tells us the load at Santiam is moderately Inductive.

IN SERVICE METER AND RELAY LOAD DATA

REFERENCE POTENTIAL

SOURCE **VAN**

PANEL **123**

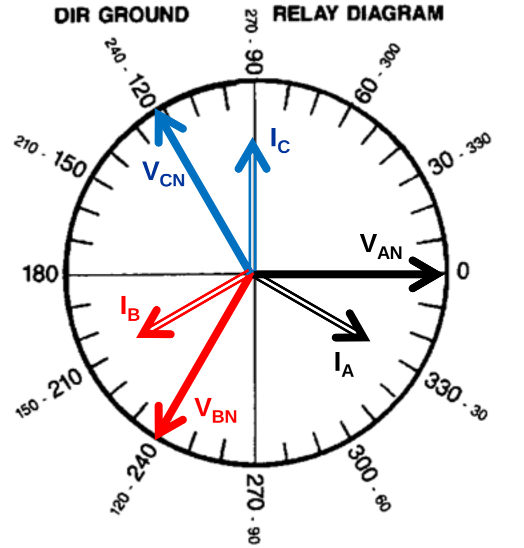
DESIG **Relay Potential**

RATIO **2000:1**

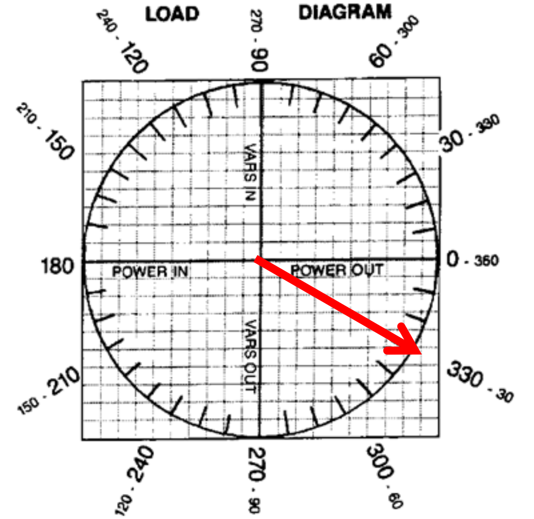
RDG: **68.7** VOLTS

On all directional ground relays route AΦ load current thru relay. On pot polar type, collapse or remove AΦ pot from broken delta pts. On diagram plot cur, pot and relay closing torque area. NOTE if relay closes or opens.

DIR GROUND RELAY DIAGRAM



LOAD DIAGRAM



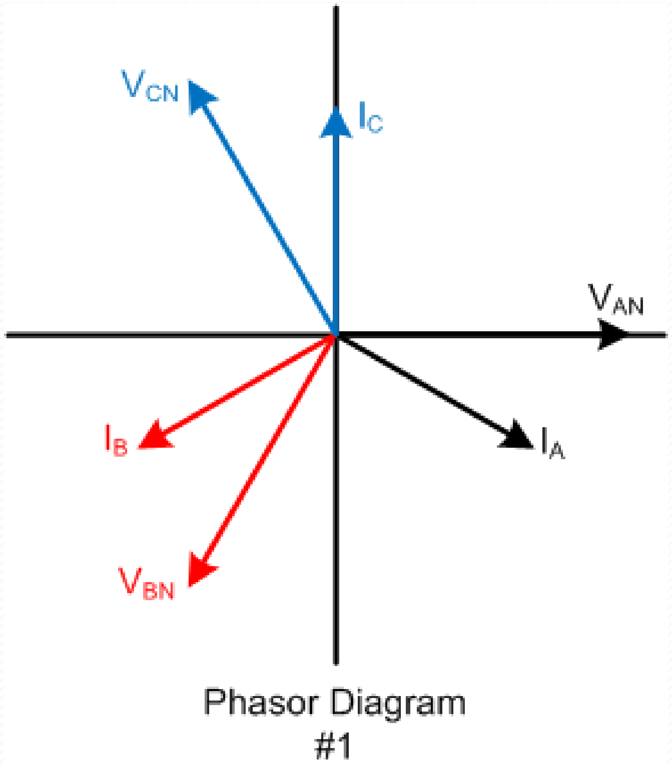
☐ REFERENCE ON CIRCUIT 2 OR CURRENT COIL PLOT ANGLE CLOCKWISE

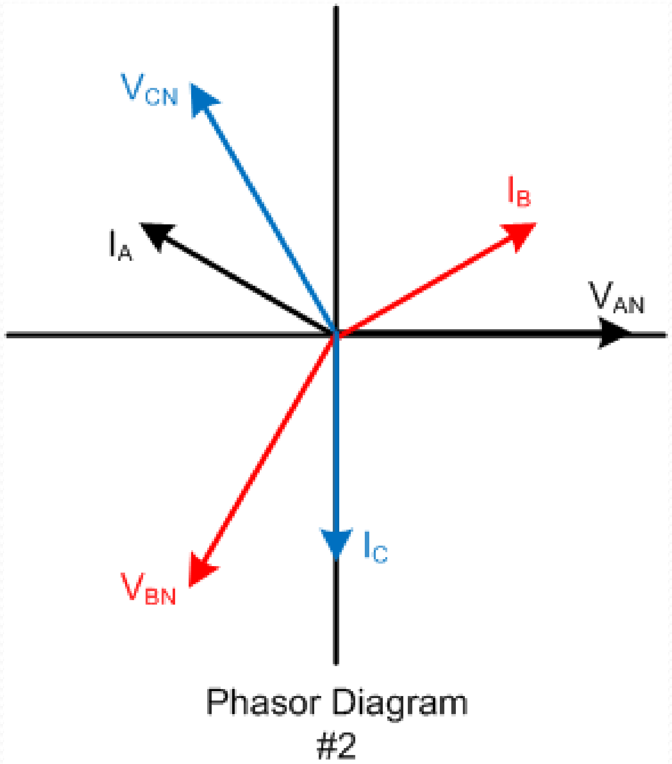
☒ REFERENCE ON CIRCUIT 1 OR POTENTIAL COIL PLOT ANGLE COUNTER-CLOCKWISE

REFERENCE CONNECTED TO ☒	☐	☒	☐	EQUIPMENT TYPE OR POSITION	Φ	TEST MEASUREMENTS Terminal Connec	Designa	Test Reading	Phase Angle	OVERALL CT OR PT RATIO	LOAD DATA Line Voltage KV	Line Current Amps	Mega-kilo Watts	Mega kilo Vars
1	2	PC	CC	Santiam 230kV	A	3L/1-7	VAN	68.5	0	2000	238	500	173 IN OUT	100 IN OUT
1	2	PC	CC	Santiam 230kV	B	3L/3-7	VBN	68.7	240	2000	238	500	IN OUT	IN OUT
1	2	PC	CC	Santiam 230kV	C	3L/5-7	VCN	68.6	120	2000	238	500	IN OUT	IN OUT
1	2	PC	CC										IN OUT	IN OUT
1	2	PC	CC	Santiam 230kV	A	3L/11-12	IA	2.1	330	240	238	500	IN OUT	IN OUT
1	2	PC	CC	Santiam 230kV	B	3L/15-16	IB	2.0	210	240	238	500	IN OUT	IN OUT
1	2	PC	CC	Santiam 230kV	C	3L/19-20	IC	2.1	90	240	238	500	IN OUT	IN PUT

Phasors in Practice

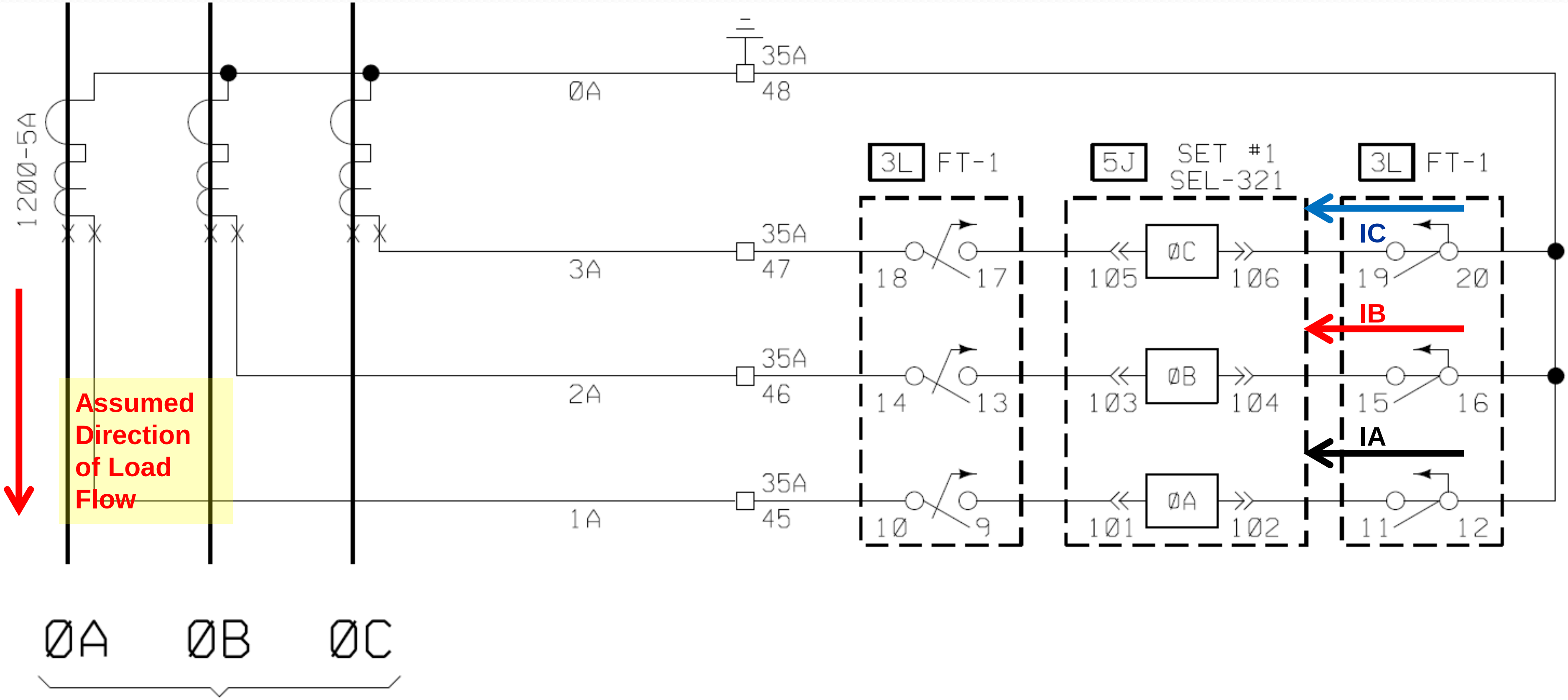
- Revisiting this slide, it appears Phasor Diagram #1 is correct – at least when it is paired with the circuit diagrams we've previously looked at.
- But is Phasor Diagram #2 right or wrong?
- Let's consider that a 2nd Relay Technician took the phasor readings for diagram #2 and let's consider that they used the following circuit diagrams.





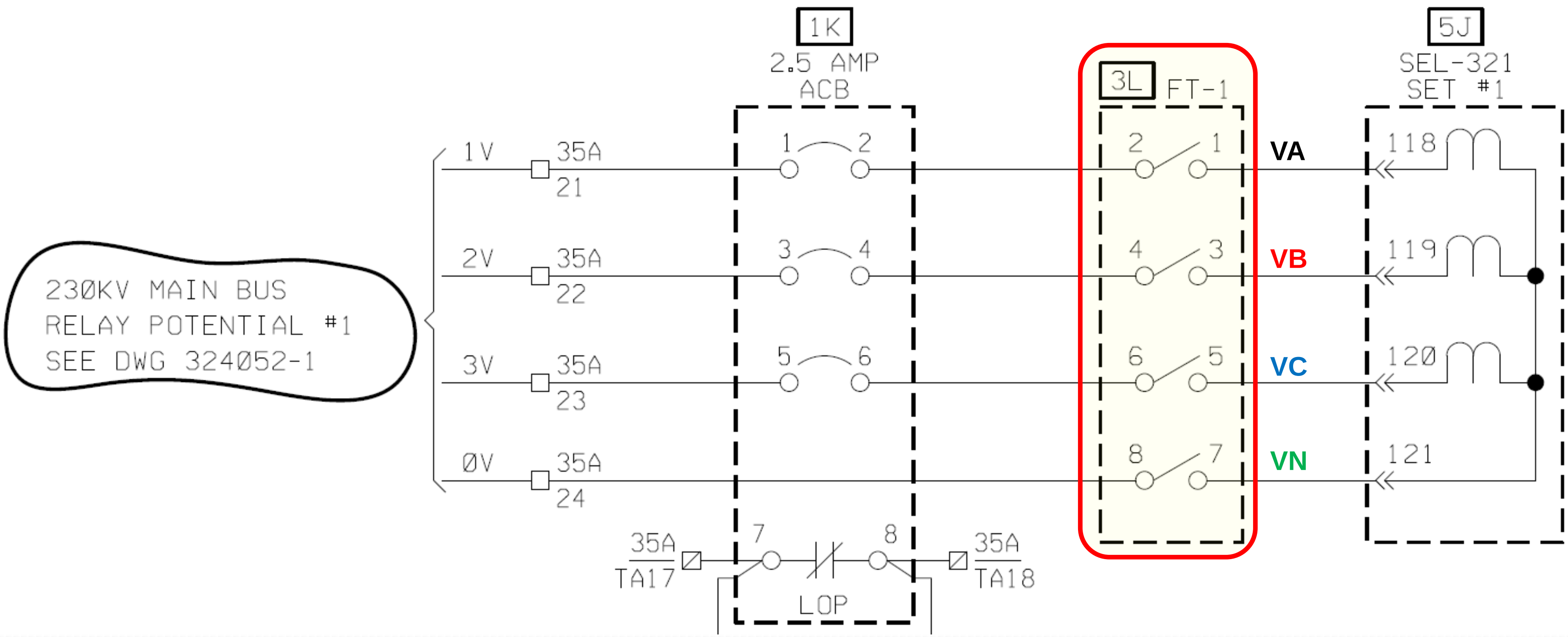
Phasors in Practice

- For Relay Technician #2 they assumed the direction of load flow was from Santiam to Chemawa – reverse to Technician #1.
- Based on assumed current direction, Tech #2 ‘jacked in’ to the current circuit using a phase-angle meter with assumed current ‘in’ on terminals 12, 16, and 20.



Phasors in Practice

- Tech #2 used the same ‘across’ process for the voltages.
- V_{AN} = (3L) 1-7, V_{BN} = (3L) 3-7, V_{CN} = (3L) 5-7



In-Service Sheet

- Here is the in-service sheet for Tech #2.
- What does it tell us?
- It tells us our ‘assumed’ current direction was incorrect, and load is actually flowing from Chemawa to Santiam. It also tells us the load at Santiam is moderately Inductive.

IN SERVICE METER AND RELAY LOAD DATA

REFERENCE POTENTIAL

SOURCE VAN

PANEL 123

DESIG Relay Potential

RATIO 2000:1

RDG: 68.7 VOLTS

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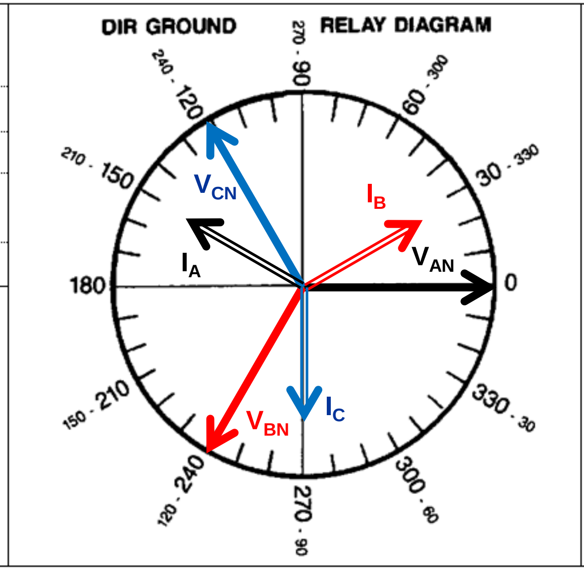

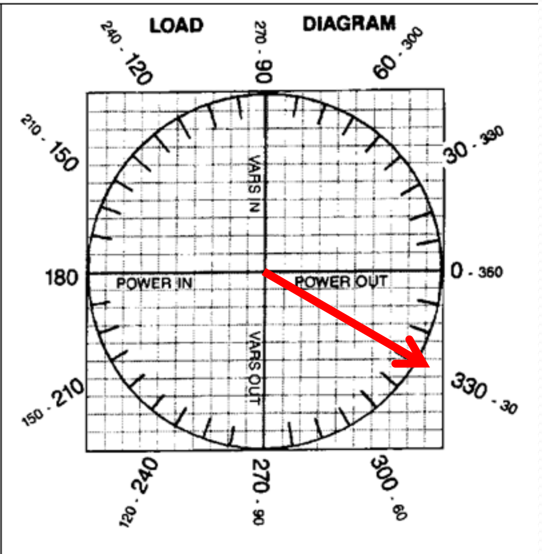

☐ REFERENCE ON CIRCUIT 2 OR CURRENT COIL PLOT ANGLE CLOCKWISE

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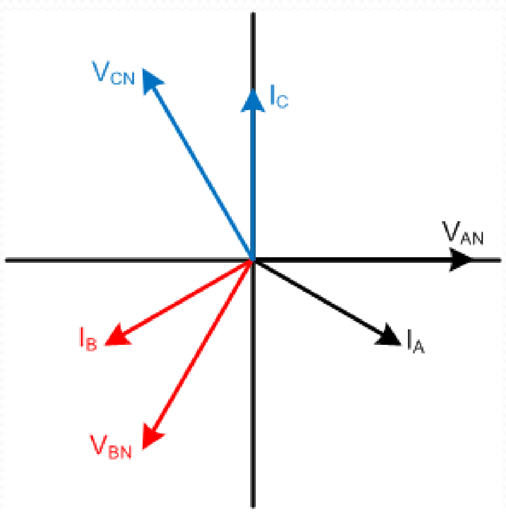
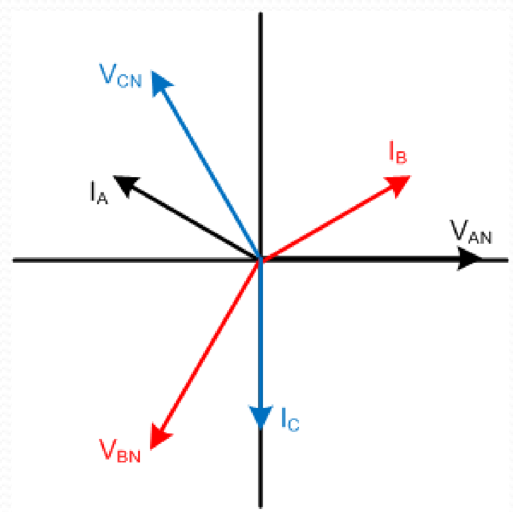
1	2	PC	CC	Santiam 230kV	A	3L/12-11	IA	2.1	150	240	238	500	IN OUT	IN OUT
1	2	PC	CC	Santiam 230kV	B	3L/16-15	IB	2.0	30	240	238	500	IN OUT	IN OUT
1	2	PC	CC	Santiam 230kV	C	3L/20-19	IC	2.1	270	240	238	500	IN OUT	IN PUT

Phasors in Practice

- Now we can see why the circuit diagram is vital in making a determination of whether phasors are correct… or not…
  - In this case, interpretation of the phasors proved both to be correct, when each is properly tied to its circuit diagram.
- Phasors without an associated circuit diagram are essentially unprovable and of questionable value…



Phasor Diagram
#1



Phasor Diagram
#2

Phasor Fundamentals Review

- Important Phasor fundamentals:
  - Phasor Representation
  - Phasor Nomenclature
  - Combining Phasors
  - Circuit Diagrams
  - Phase Rotation and Phase Sequence
  - Polarity
- As Blackburn notes in his book:
  - Phasor fundamentals are essential aids in selection, connection, operation, performance, and testing of protection for power systems.

Fault Phasors

Faults are unavoidable in the operation of a power system. Faults are caused by:

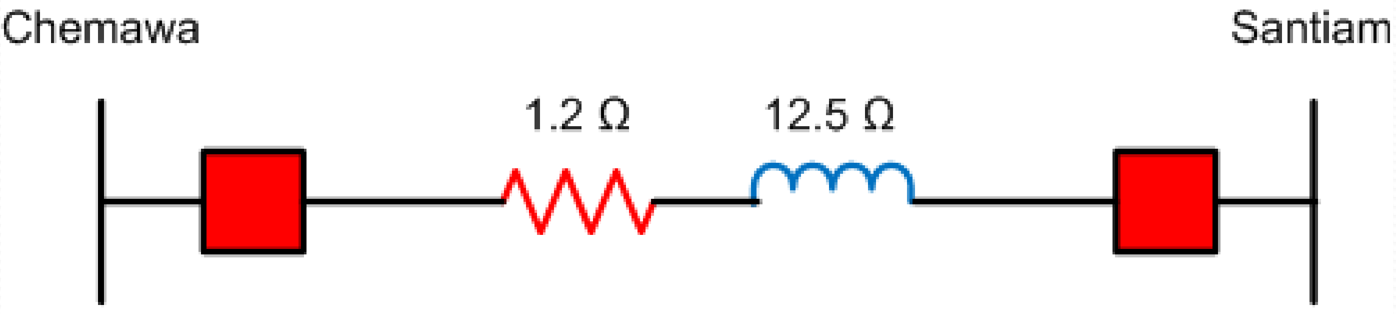
- Lightning
- Insulator failure
- Equipment failure
- Trees
- Accidents
- Vandalism such as gunshots
- Fires
- Foreign material

Faults are essentially short circuits on the power system and can occur between phases and ground in virtually any combination:

- One phase to ground
- Two phases to ground
- Three phase to ground
- Phase to phase

- These fault types are (relatively) easy to understand; only one requires some consideration (Phase-to-Phase Fault) but even it is not hard once you consider some fault Fundamentals.

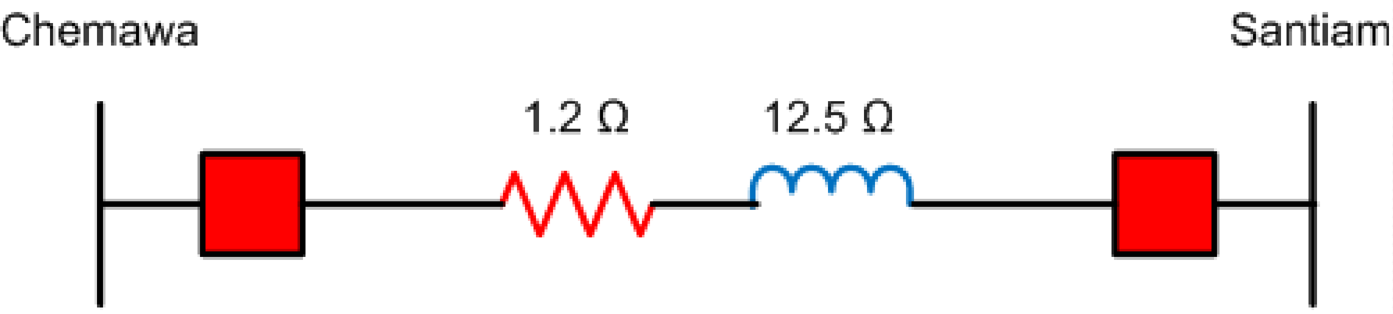
Fault Phasors



Chemawa – Santiam 230kV Line

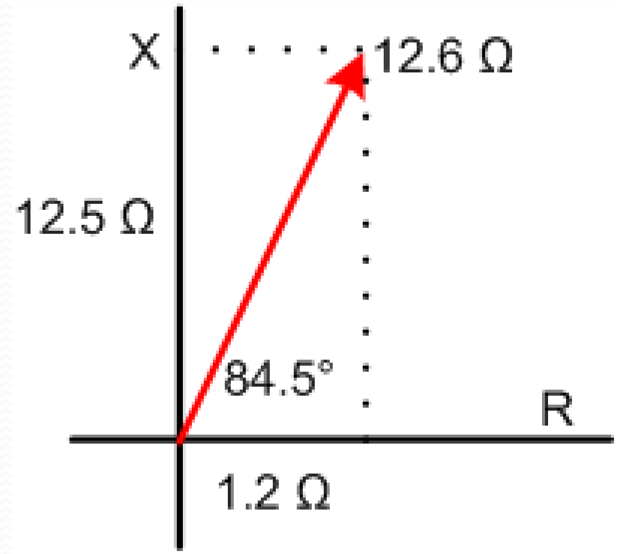
- Transmission line faults are almost always inductive; let's examine why:
  - Transmission line impedance is based on the length of line, the type of conductor, and the type and spacing of the structures the line is installed on.
  - When the line is loaded with normal shunt loads, the transmission line impedance is (for the most part) negligible and the loading and phase angle is determined by the load impedance; thus the load angles can be inductive/resistive/capacitive.
  - When a line faults, the load impedance is bypassed (shunted) and the fault current is limited by the source voltage and the impedance of the transmission line itself.

Fault Phasors



Chemawa – Santiam 230kV Line

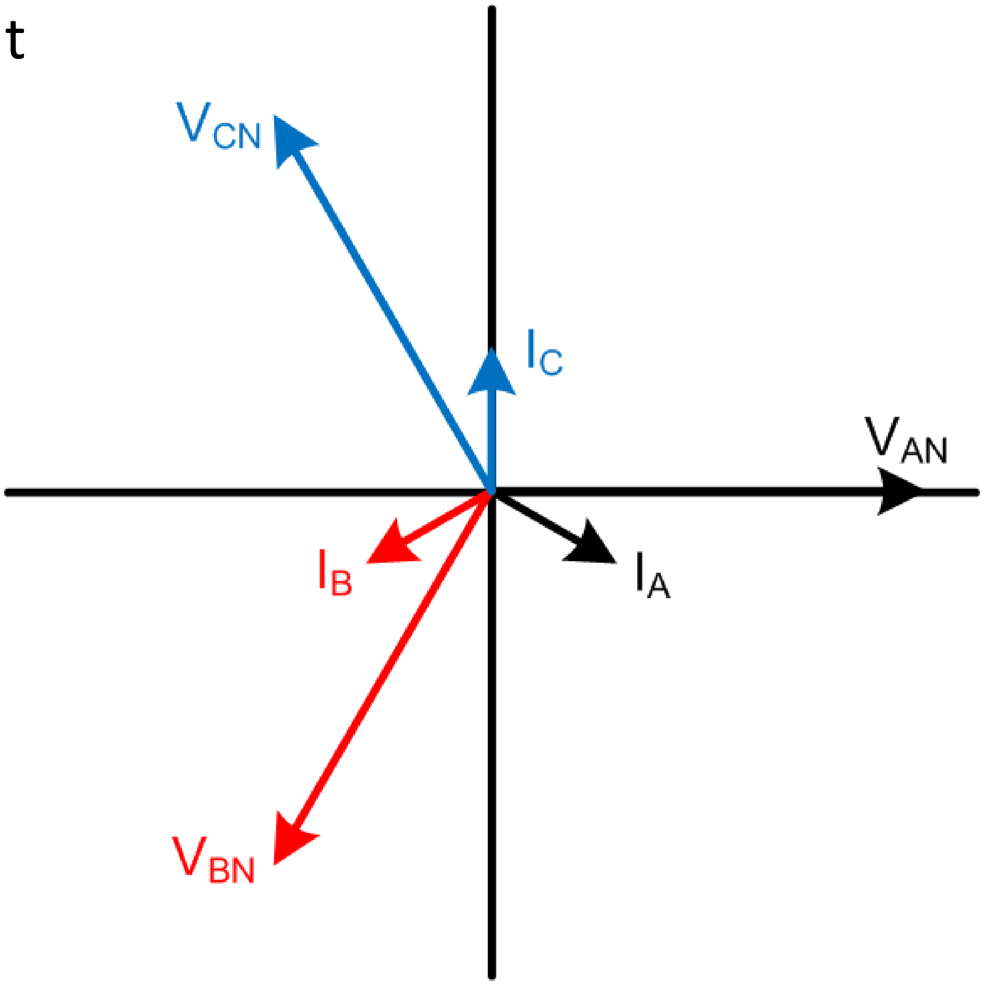
- It's important to note that given a uniform transmission line the fault angle will not vary for a fault anywhere on the transmission line.



Transmission Line Impedance (Not to Scale)

Fault Phasors

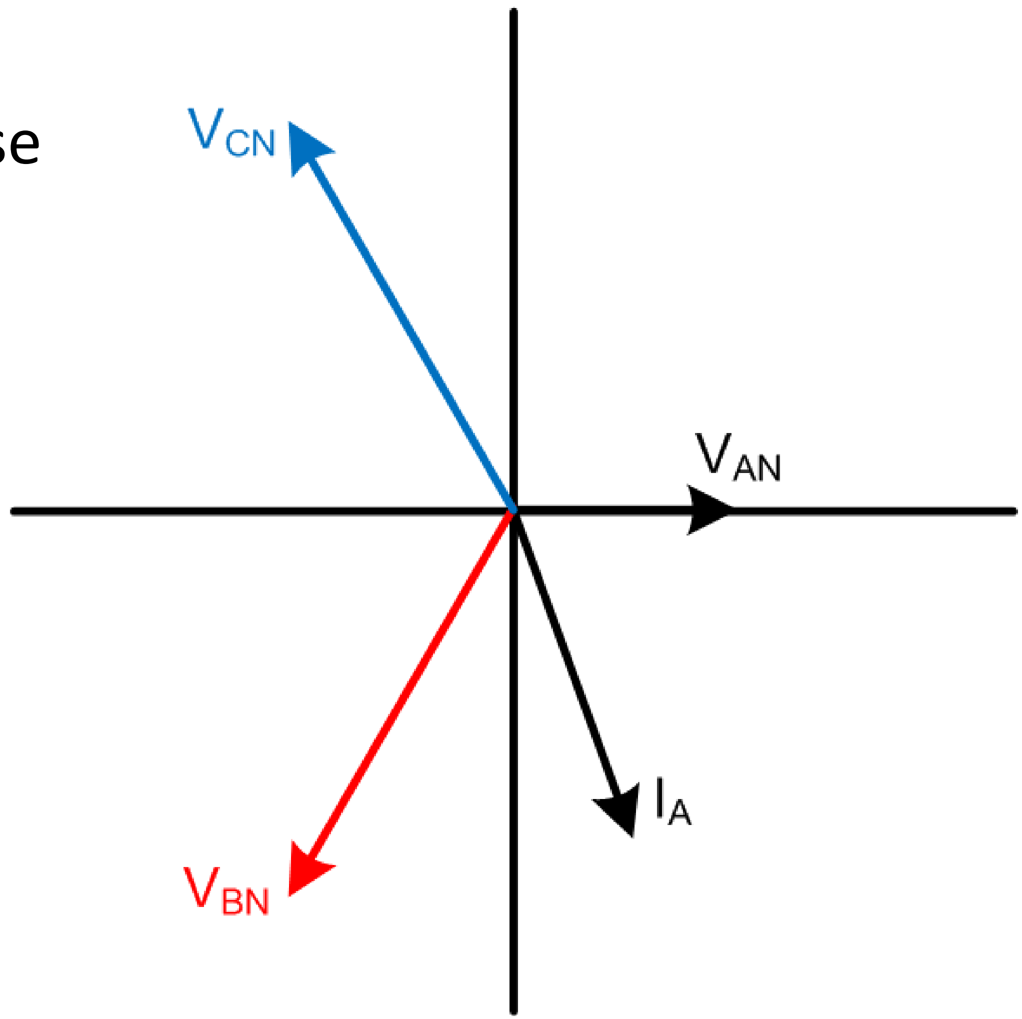
- Let's look at some standard fault phasors.
- To begin with, we'll examine an ideal unfaulted system:
  - We'll use V_{AN} as our reference.



Unfaulted System with Load Current

1LG Fault – AG

- Assume a fault angle of 70°
- Assume 50% voltage collapse



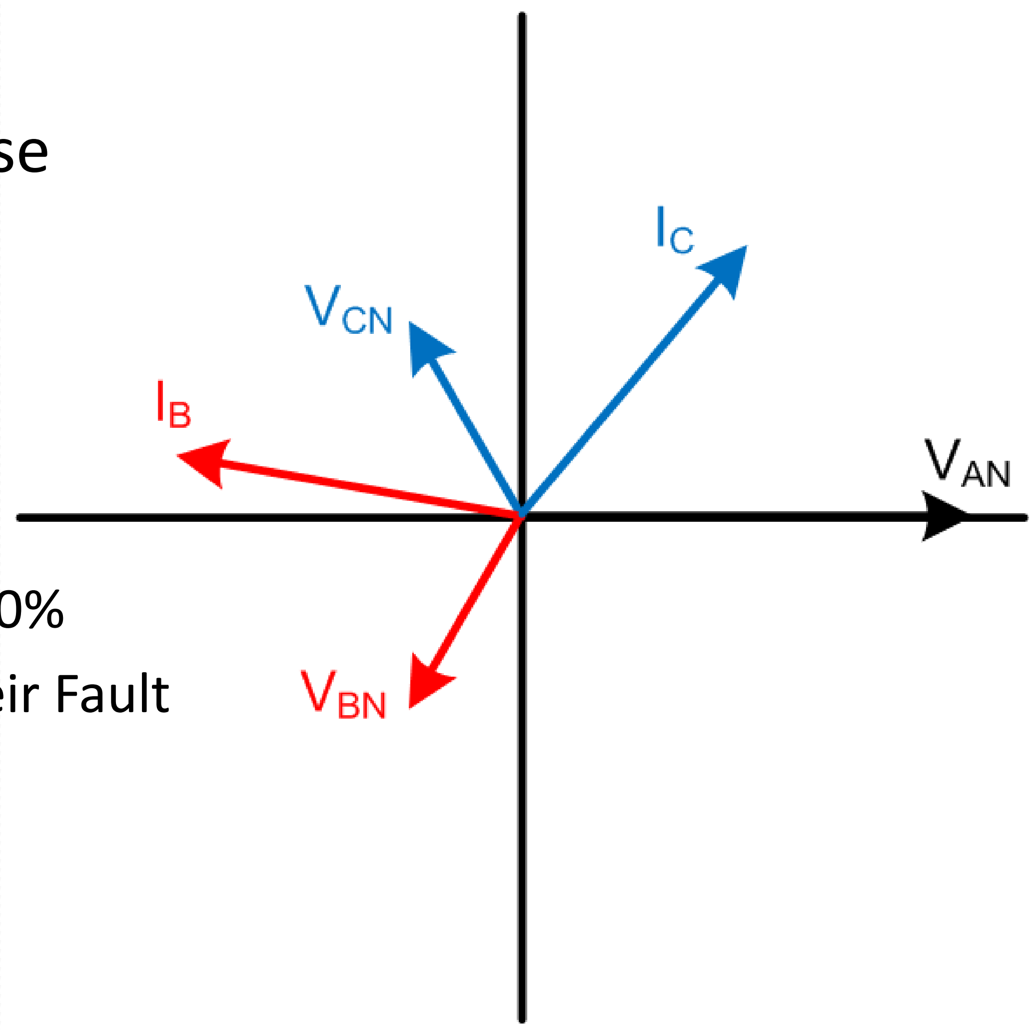
A-Ground Fault

- Key points:
  - V_{AN} is reduced by 50%
  - I_A increases and lags the Fault Voltage by the line angle, 70°

2LG Fault - BCG

- Assume a fault angle of 70°
- Assume 50% voltage collapse

- Key points:
  - V_{BN} and V_{CN} are reduced by 50%
  - I_B and I_C increase and lags their Fault Voltage by the line angle, 70°

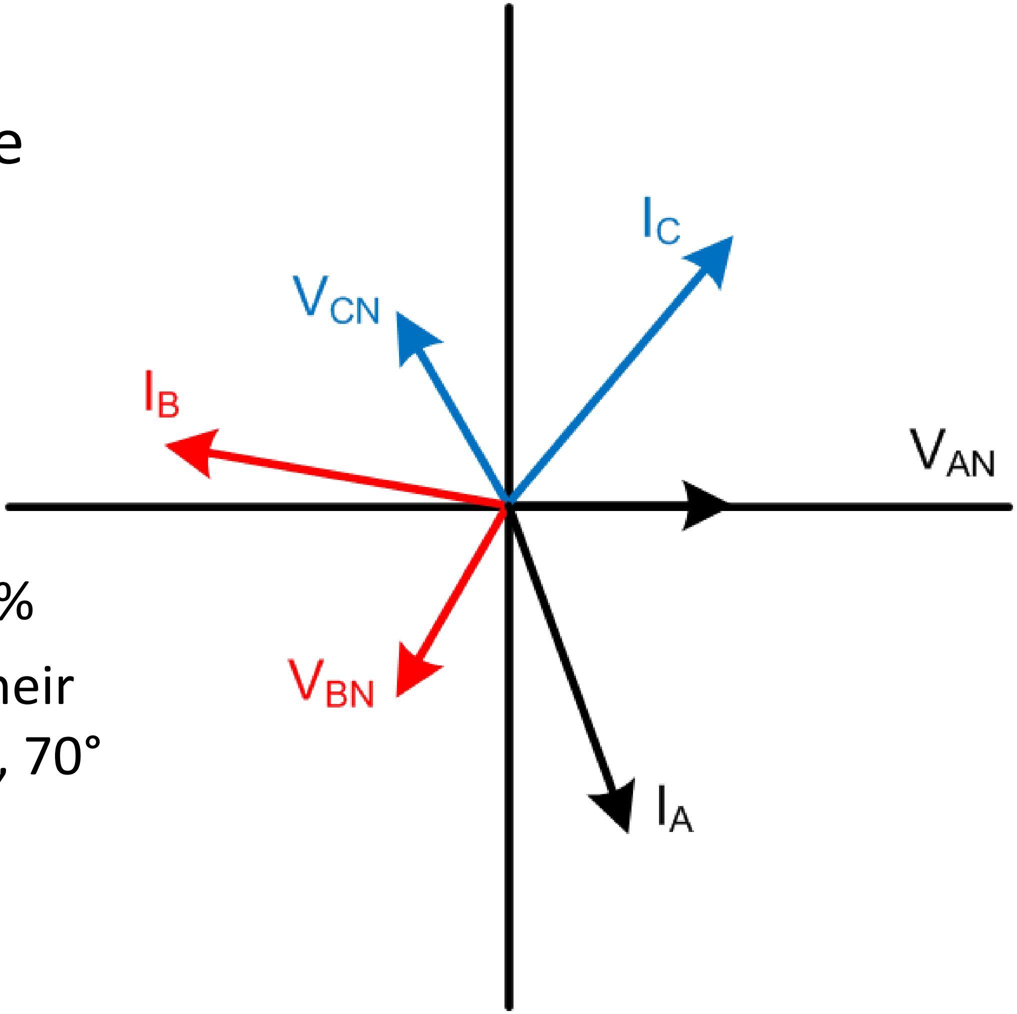


B-C-Ground Fault

3LG Fault - ABCG

- Assume a fault angle of 70°
- Assume 50% voltage collapse

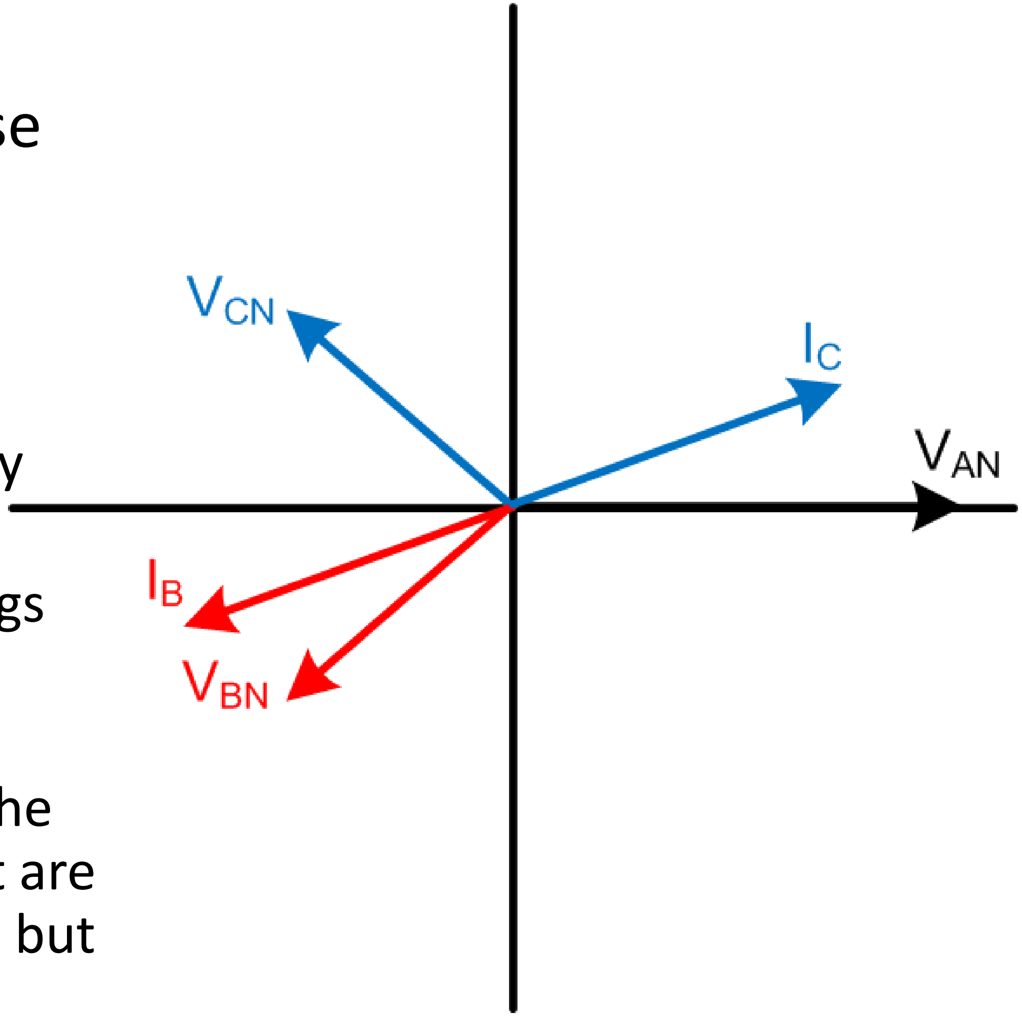
- Key points:
  - All voltages are reduced by 50%
  - All currents increase and lag their Fault Voltage by the line angle, 70°



A-B-C-Ground Fault

2L Fault – BC

- Assume a fault angle of 70°
- Assume 50% voltage collapse

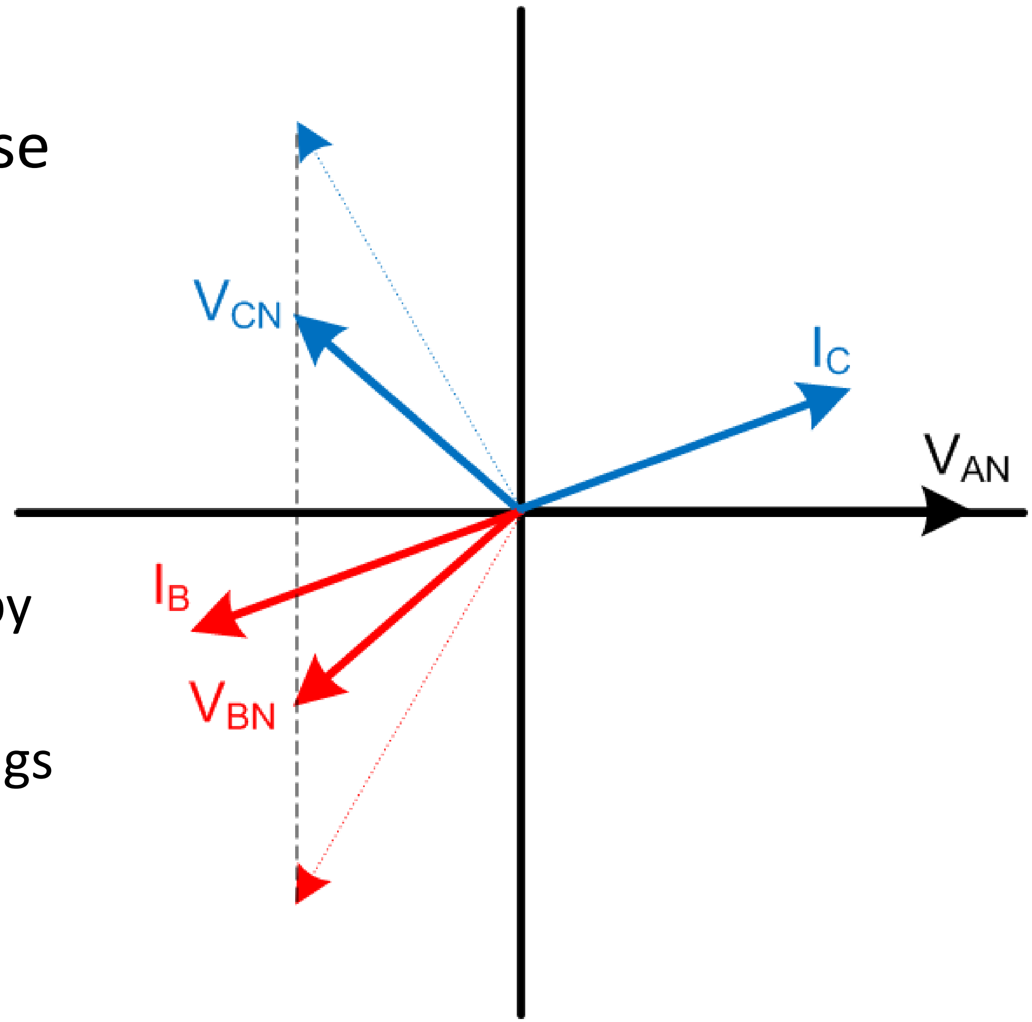


B-C Fault

- Key points:
  - The fault voltage is reduced by 50%
  - Fault current increases and lags the Fault Voltage by the line angle, 70°
  - It should be recognized that the fault voltage and fault current are not line-to-ground quantities, but phase-to-phase.

2L Fault – BC

- Assume a fault angle of 70°
- Assume 50% voltage collapse



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2L Fault – BC

- Assume a fault angle of 70°
- Assume 50% voltage collapse

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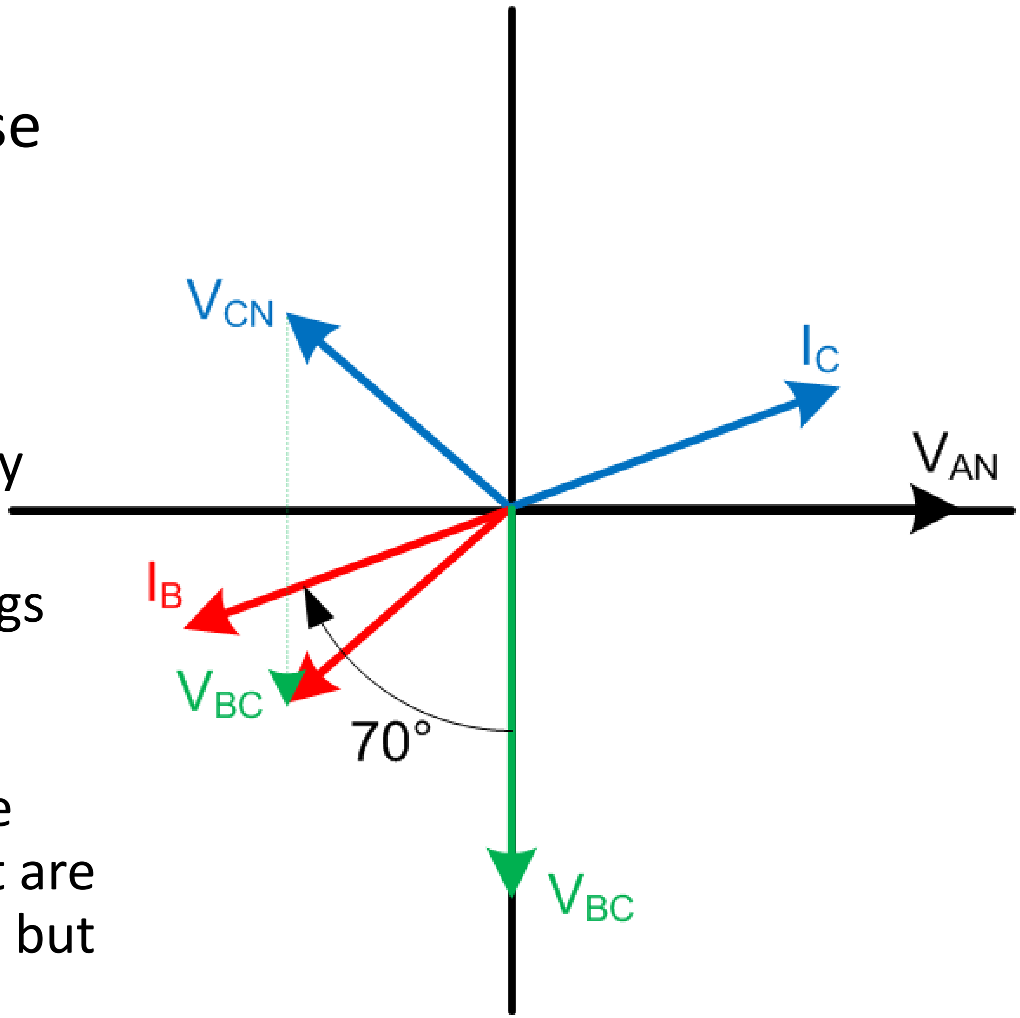
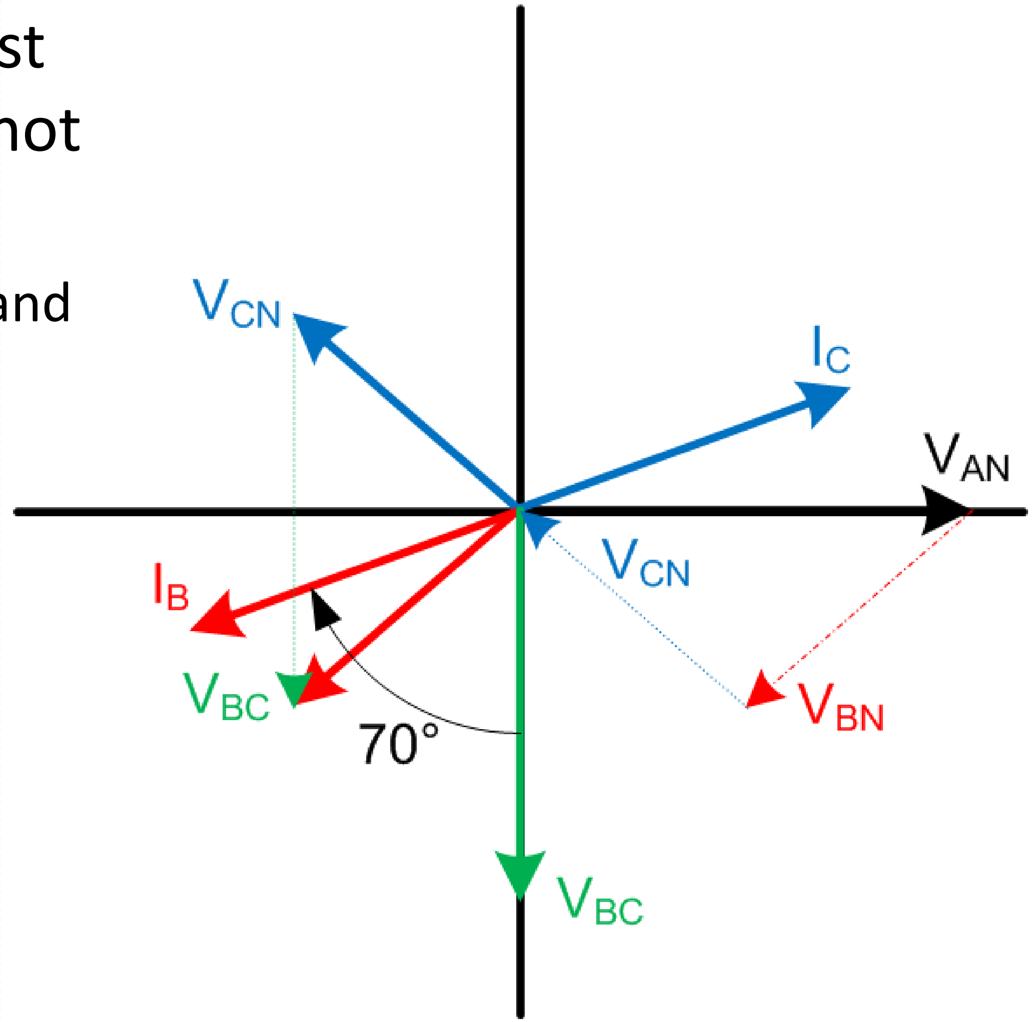


B-C Fault

2L Fault – BC

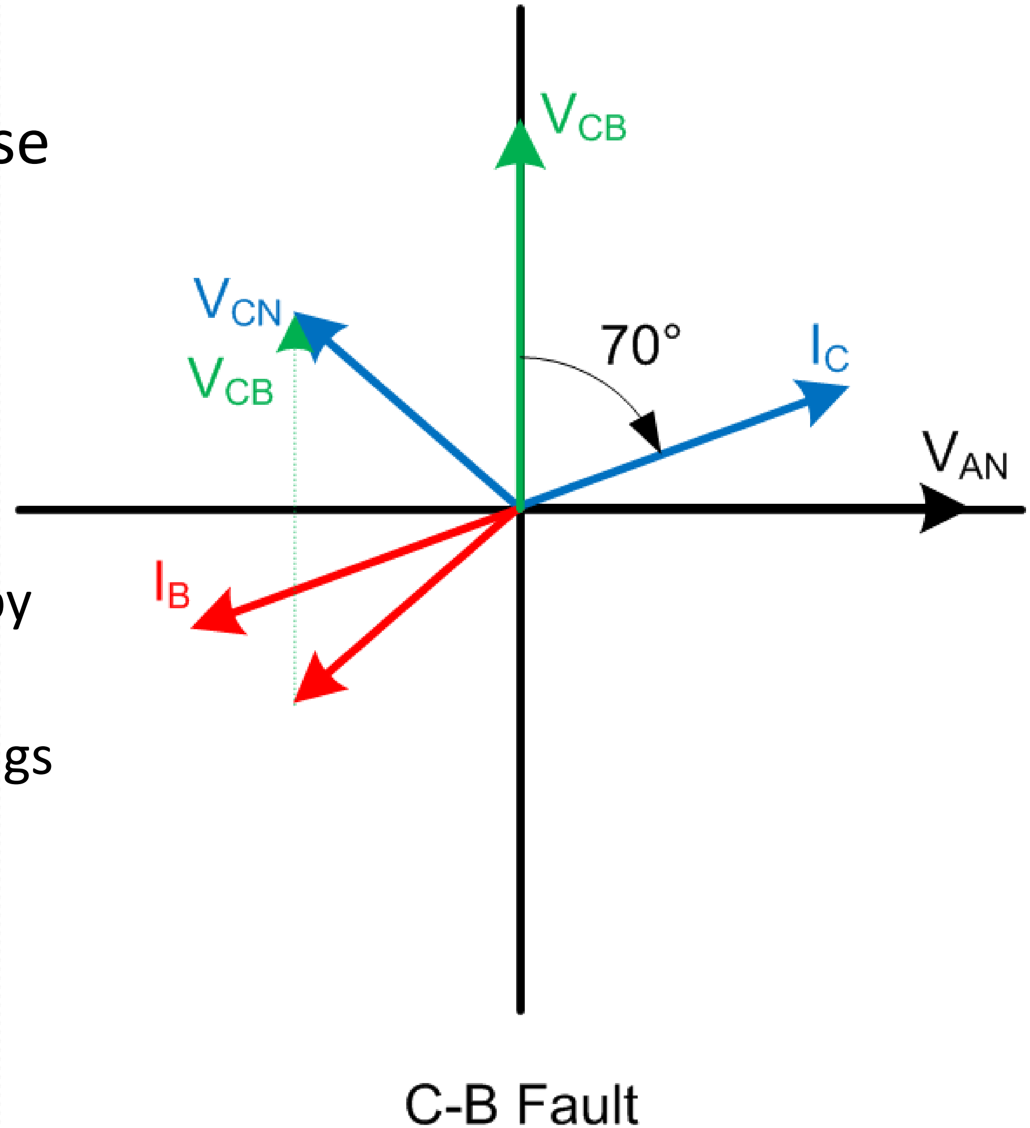
- Sum of Voltage Phasors must equal zero when ground is not involved.
- This can only happen when V_{BN} and V_{CN} rotate.



B-C Fault

2L Fault – CB

- Assume a fault angle of 70°
- Assume 50% voltage collapse



- Key points:
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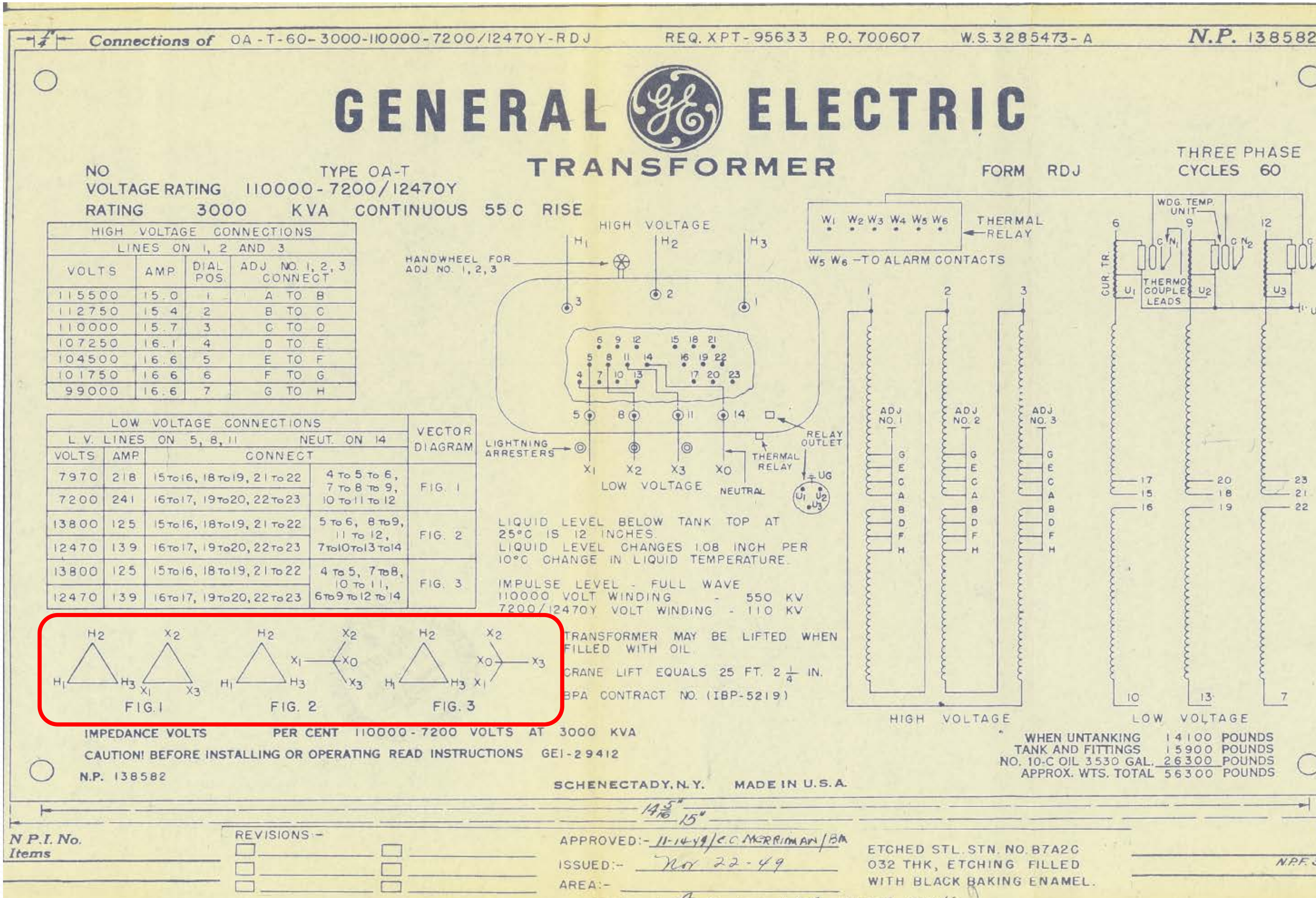
Phasors and Transformers



HIGH VOLTAGE CONNECTIONS			
LINES ON 1, 2 AND 3			
VOLTS	AMP.	DIAL POS.	ADJ NO. 1, 2, 3 CONNECT
115500	15.0	1	A TO B
112750	15.4	2	B TO C
110000	15.7	3	C TO D
107250	16.1	4	D TO E
104500	16.6	5	E TO F
101750	16.6	6	F TO G
99000	16.6	7	G TO H

LOW VOLTAGE CONNECTIONS				VECTOR DIAGRAM
L.V. LINES ON 5, 8, 11 NEUT. ON 14				
VOLTS	AMP.	CONNECT		
7970	218	15 TO 16, 18 TO 19, 21 TO 22	4 TO 5 TO 6, 7 TO 8 TO 9, 10 TO 11 TO 12	FIG. 1
7200	241	16 TO 17, 19 TO 20, 22 TO 23		
13800	125	15 TO 16, 18 TO 19, 21 TO 22	5 TO 6, 8 TO 9, 11 TO 12, 7 TO 10 TO 13 TO 14	FIG. 2
12470	139	16 TO 17, 19 TO 20, 22 TO 23		
13800	125	15 TO 16, 18 TO 19, 21 TO 22	4 TO 5, 7 TO 8, 10 TO 11, 6 TO 9 TO 12 TO 14	FIG. 3
12470	139	16 TO 17, 19 TO 20, 22 TO 23		

Phasors and Transformers

LOW VOLTAGE CONNECTIONS				VECTOR DIAGRAM
L.V. LINES ON 5, 8, 11			NEUT. ON 14	
VOLTS	AMP	CONNECT		
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12470	139	16 To 17, 19 To 20, 22 To 23		

LIGHTNING ARRESTERS

LIQUID
25°C
LIQUID
10°C

IMPULS
110000
7200/

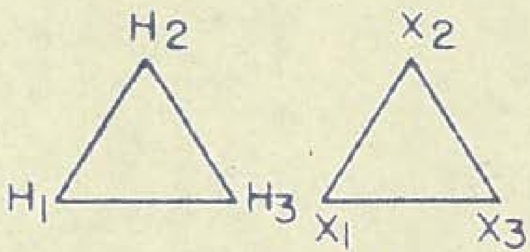


FIG. 1

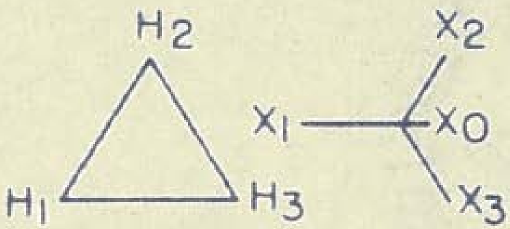


FIG. 2

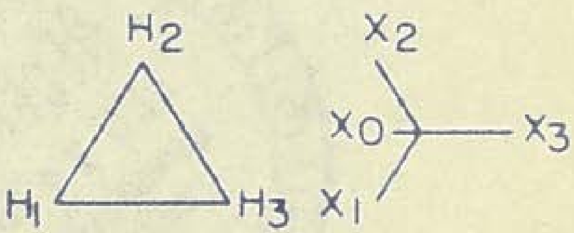
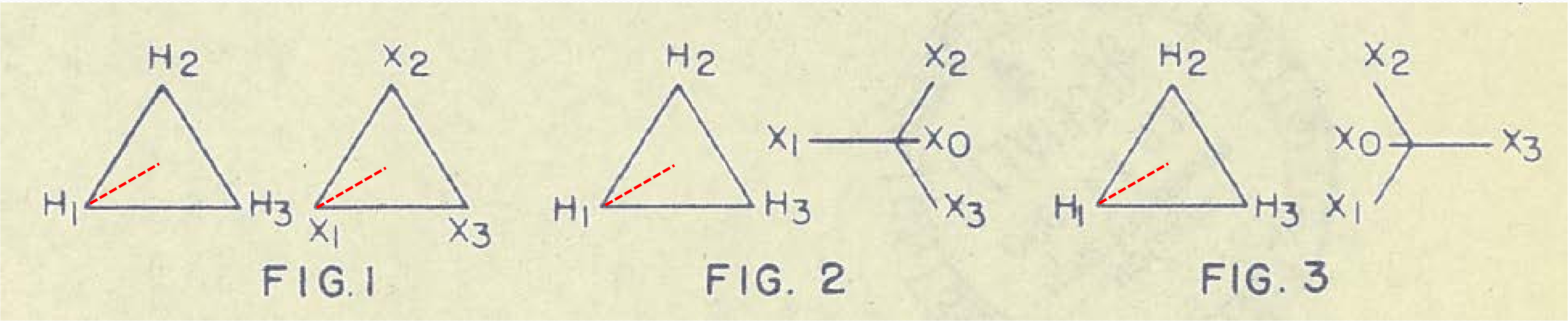


FIG. 3

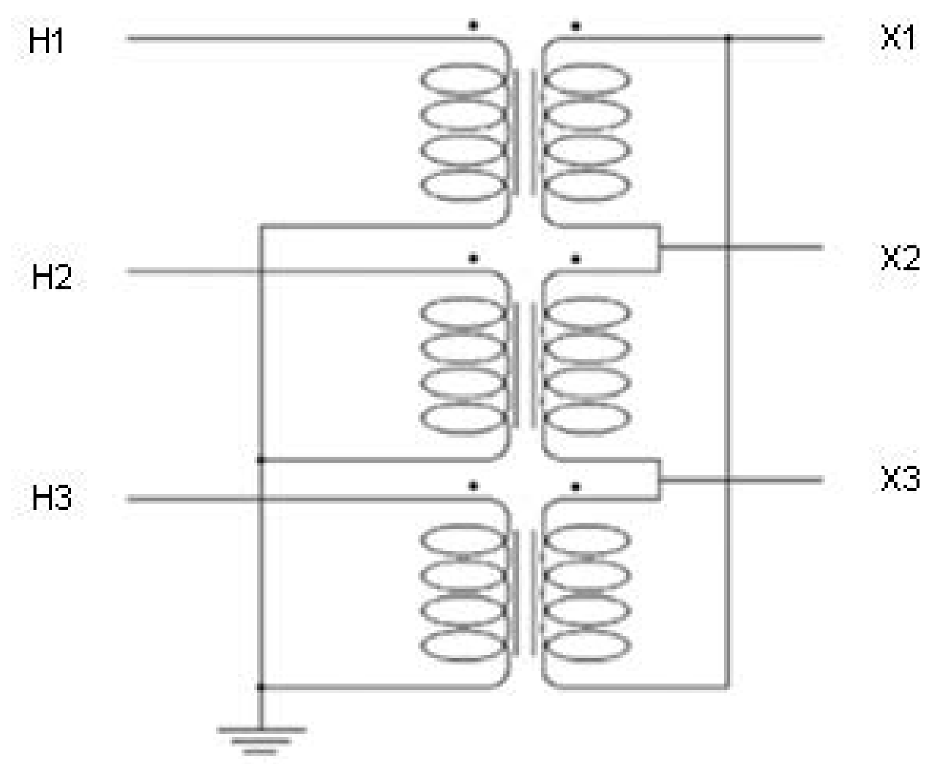
Phasors and Transformers



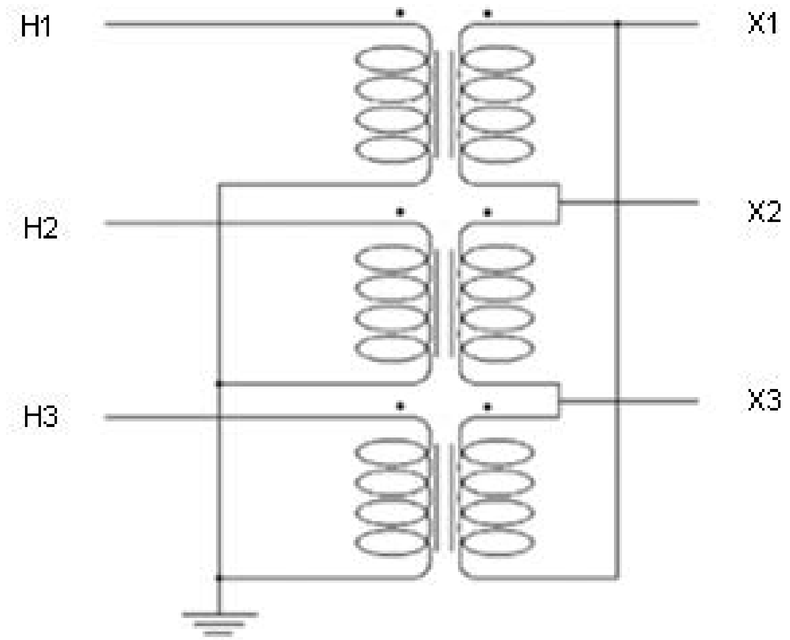
Dd0 Dyn1 Dyn11

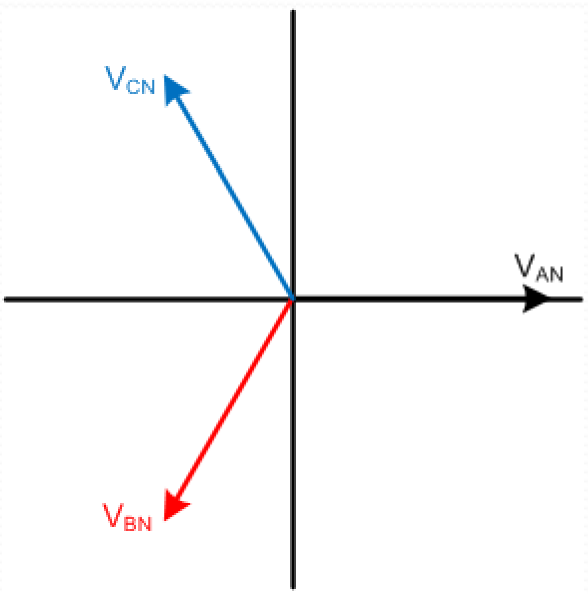
- Note use of upper case for high voltage winding and lower case for lower voltage winding.
- ‘Clock number’ is a multiple of 30° in the lagging direction.
  - 1 = 30 degree lag
  - 11 = 330 degree lag (30 degree lead)

Phasors and Transformer Phase Shift

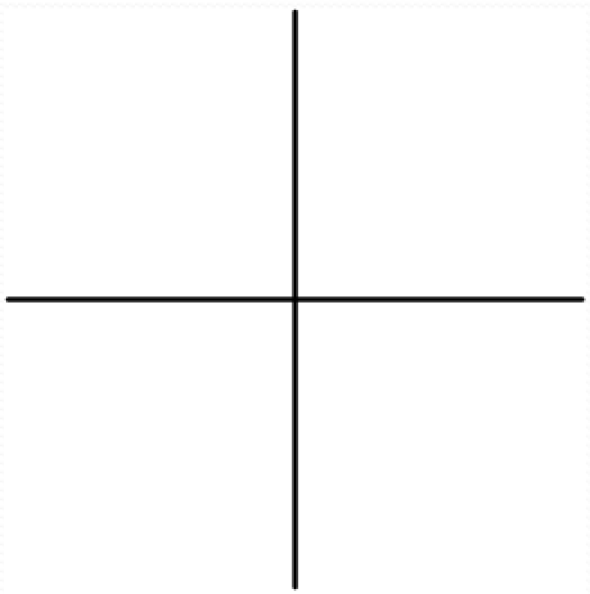


- Let’s try to plot some phase shifts through a sample transformer connection.

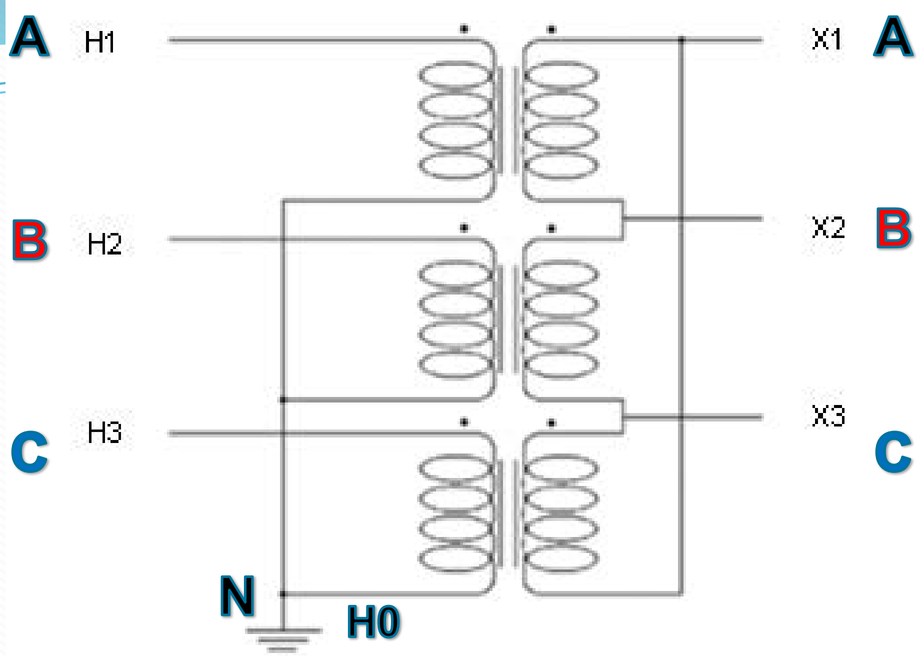


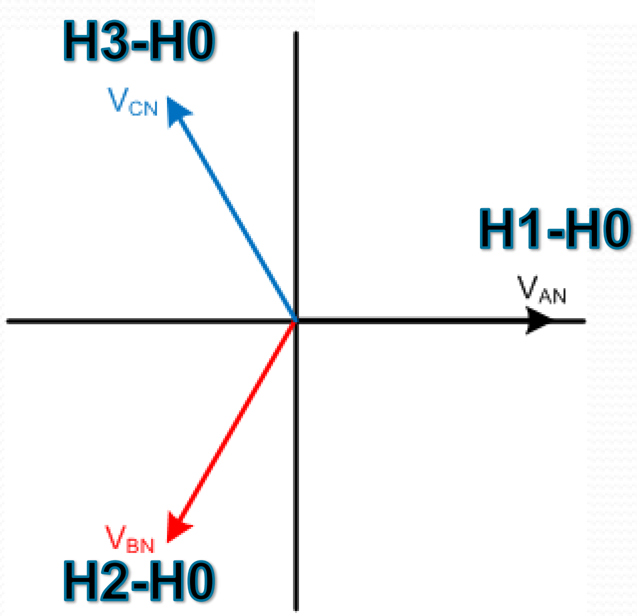


Primary Voltages



Secondary Voltages





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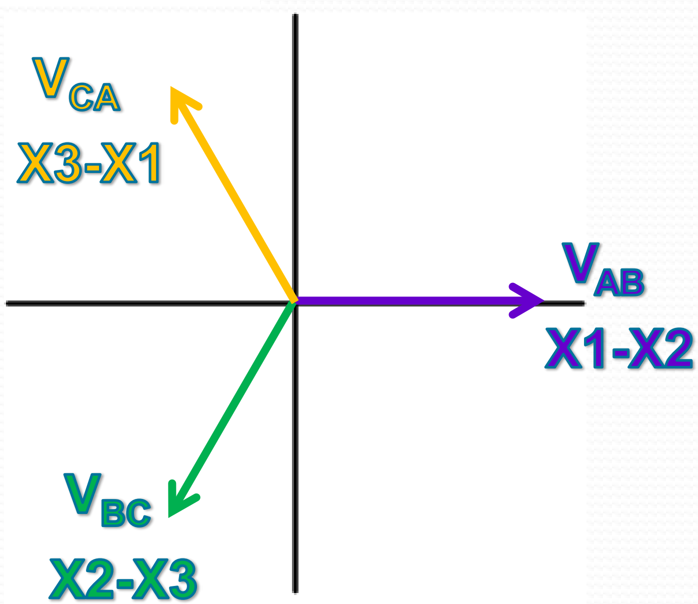
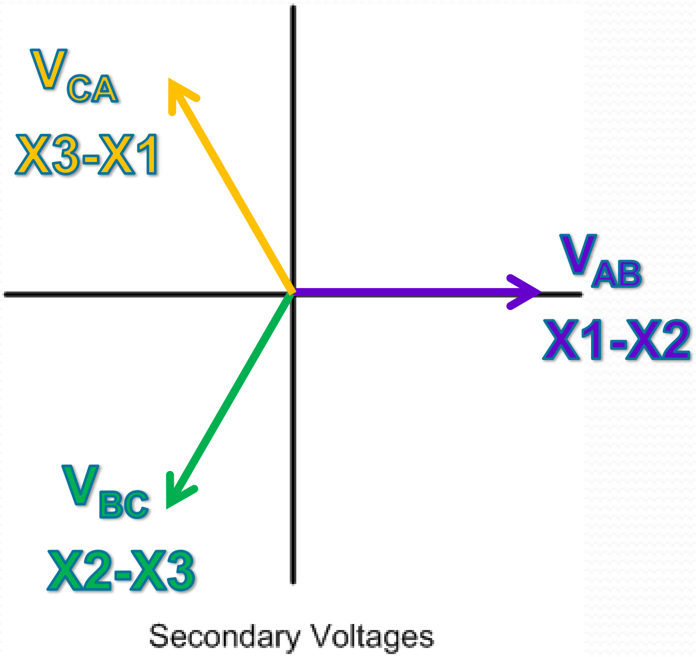
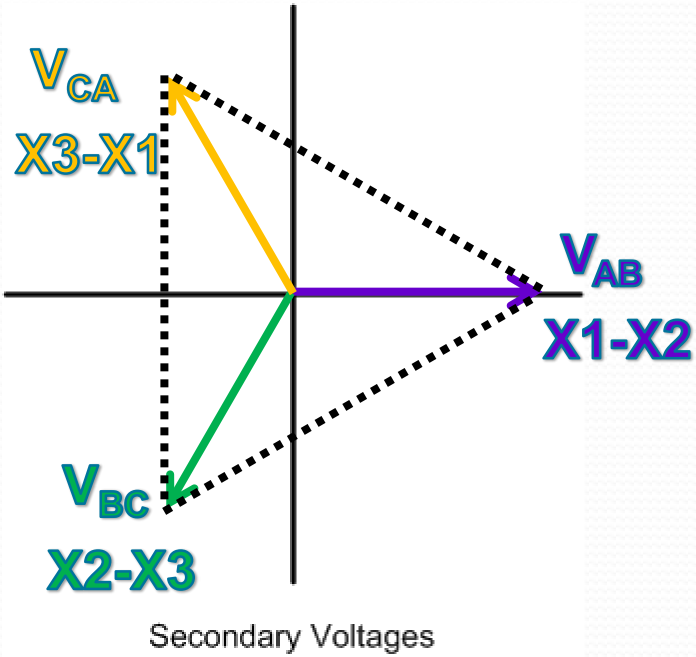


Secondary Voltages

Closing our Phasor Diagram

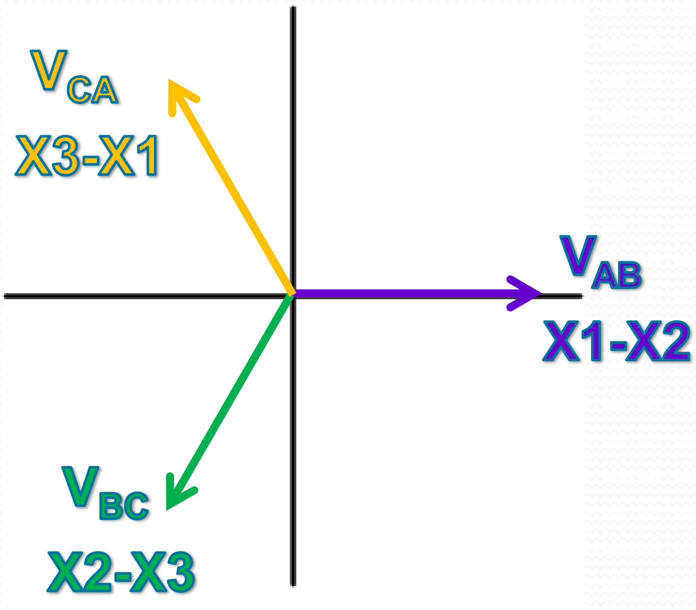
- Is this correct?
  - No. There is no VAN / X1-X0 to use for our comparison to the primary to determine phase shift.
  - You can sometimes 'close' a phasor diagram this way but you have to know when it is ok.



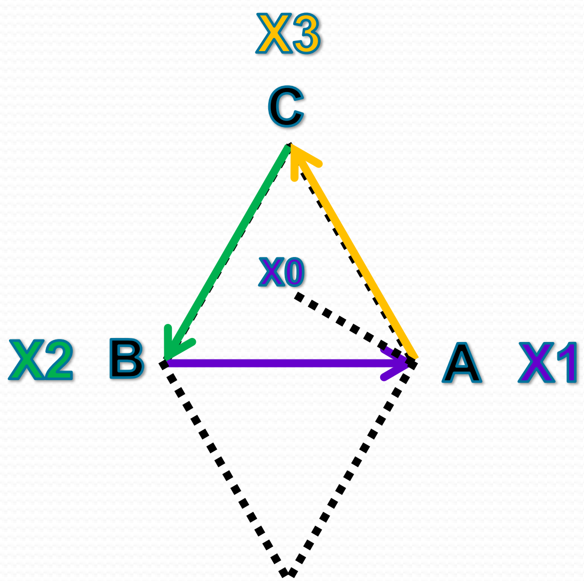


Closing our Phasor Diagram

- How to close a Delta Connection:
- Now we can see that the secondary reference voltage lags the primary voltage by 30°
- What is our connection type then?
  - Yd1



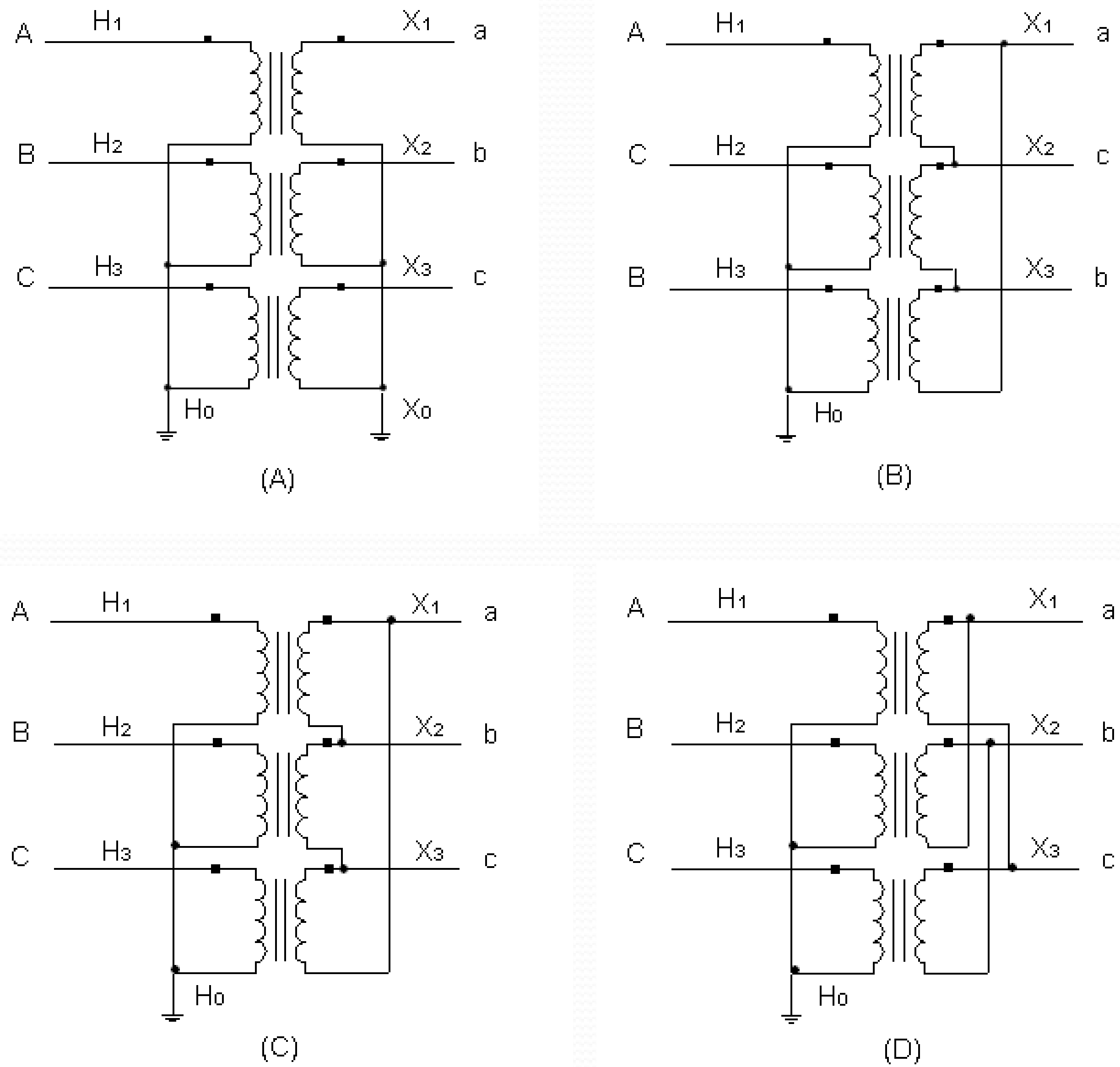
Secondary Voltages



Closed Diagram

Practice Connections

- Here are some practice connections for you to try on your own.
- Phase Shift answers are listed in the notes.



Phasors: Faults and Transformers

- Our Secondary Objective:
  - Reviewing Fault Phasors
  - Using phasors to determine phase shift across three-phase transformer banks
- As Blackburn notes in his book:
  - Phasor fundamentals are essential aids in selection, connection, operation, performance, and testing of protection for power systems.
- Thanks for your time and participation!