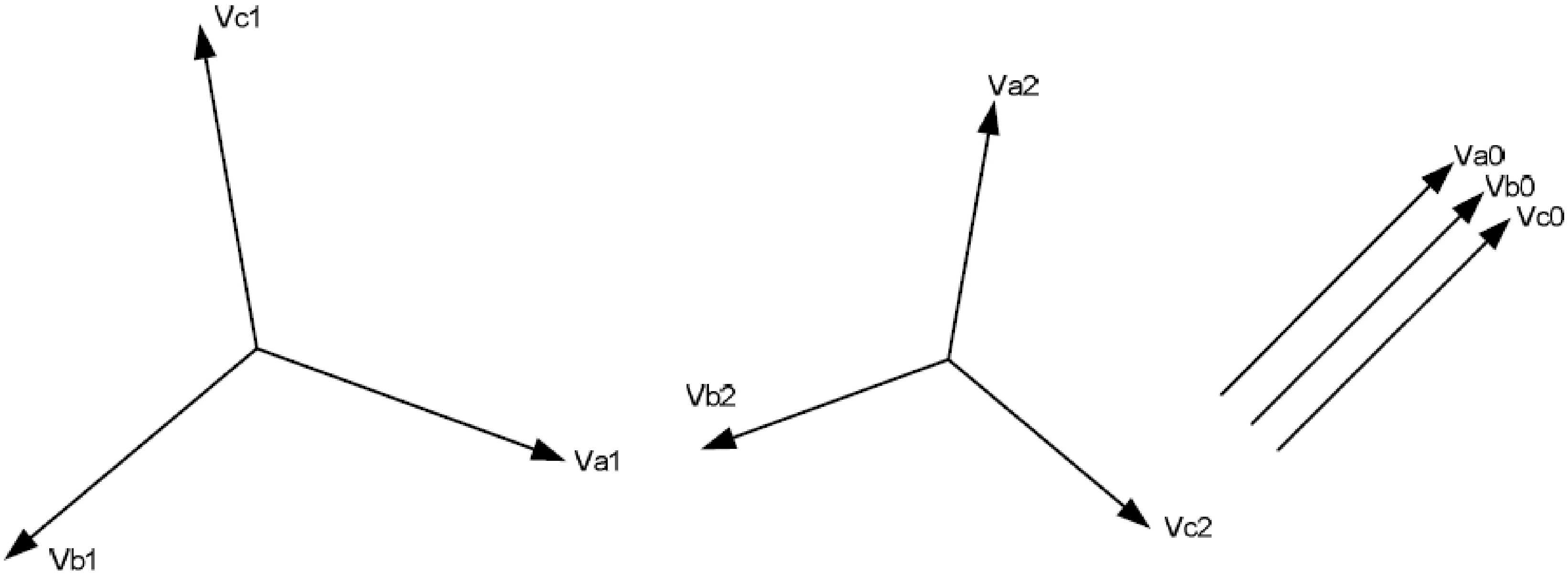
Simulating Real World Conditions for Relay Scheme Testing



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Objective

- Understand the theory of symmetrical components
- See how the theory is applied to selected protective relay examples
- See how to perform tests on protective relays using that theory

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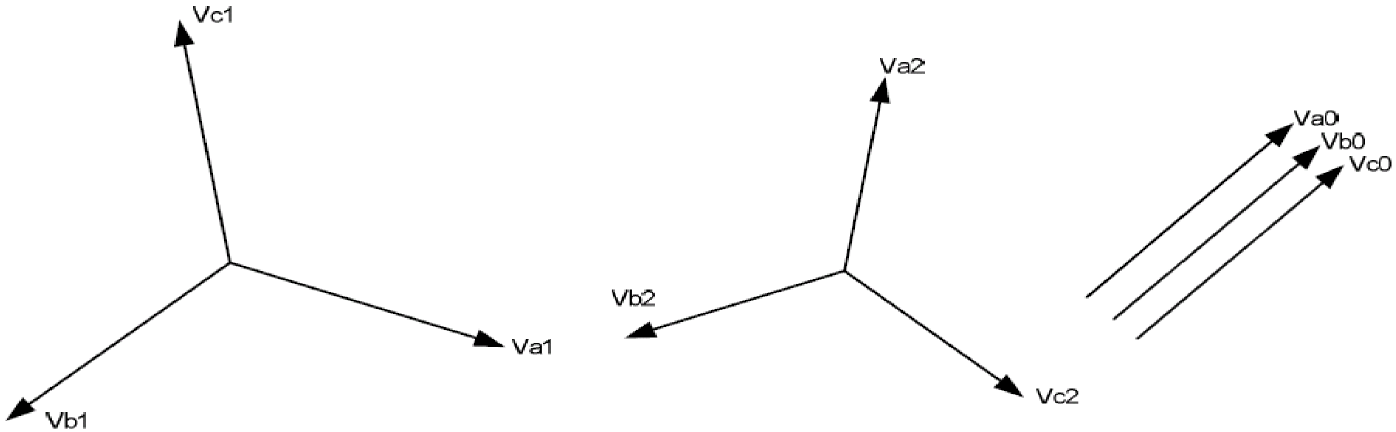
What are Symmetrical Components

- They are a mathematical method that breaks down voltages and currents in a power system into sets of balanced components.
- In a three phase system, each phase voltage or current is broken into 3 components
- Components are referred to as Positive, Negative, and Zero Sequence Components



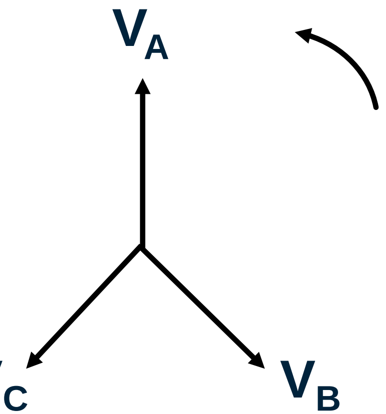
Positive Sequence　　Negative Sequence　　Zero Sequence

THE “a” OPERATOR

The “a” operator rotates a vector counterclockwise by 120°, e.g. balanced 3-phase system :

Note :

$$1 + a + a^2 = 0$$



$V_C = a^2.V_A = V_A \underline{/240°}$

$V_B = a.V_A = V_A \underline{/120°}$

“a” operator is used to derive general equations for symmetrical components, by referring all quantities to a reference phase

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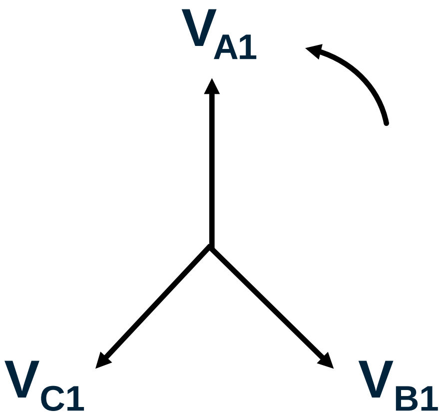
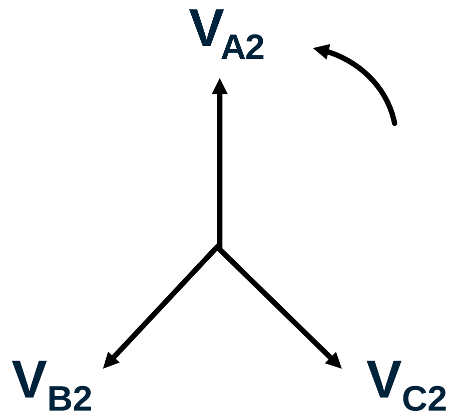
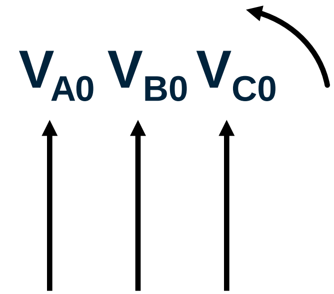
SYMMETRICAL COMPONENTS



Positive Sequence Component (Normal Rotation)



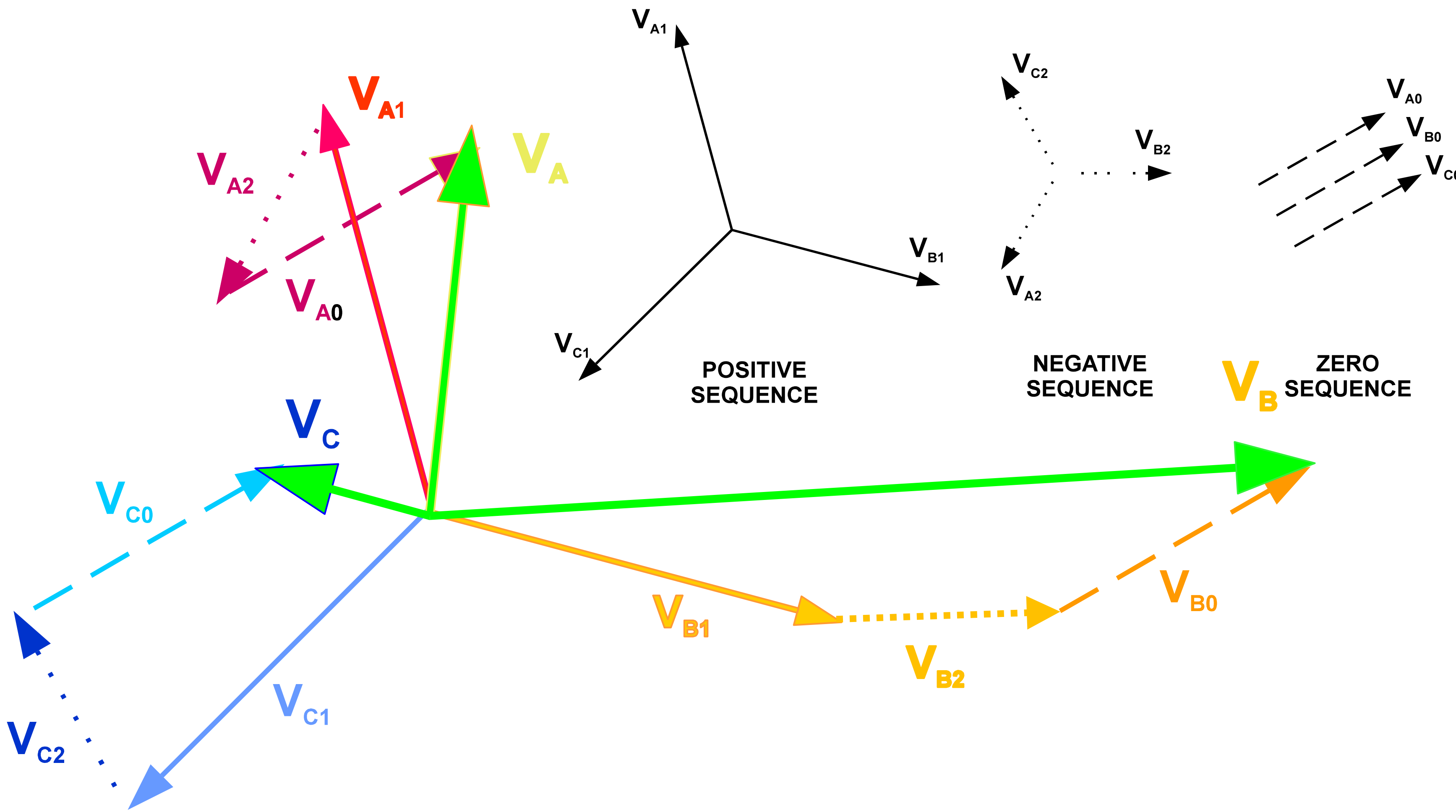
Negative Sequence Component (Reverse Rotation)



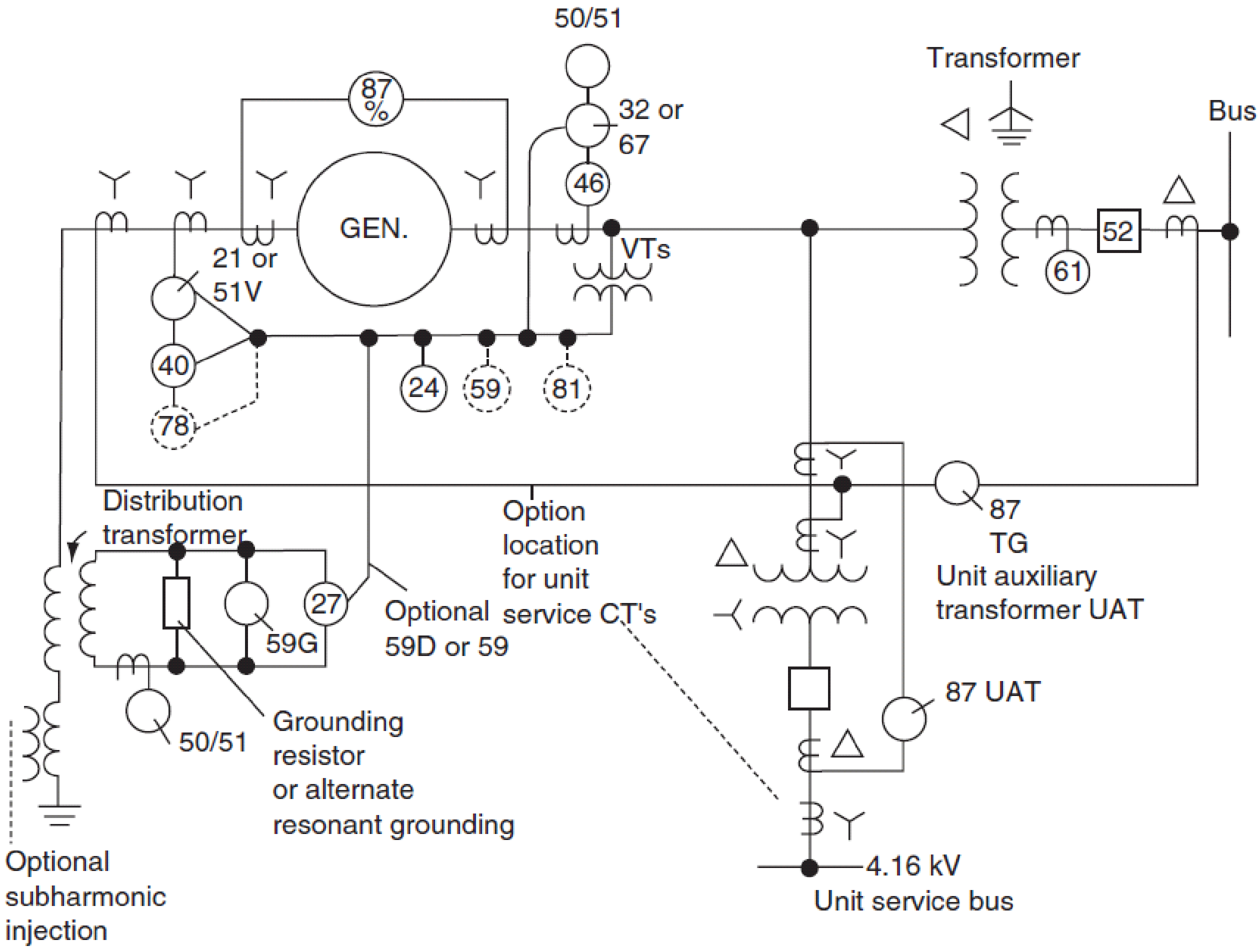
Zero Sequence Component (In-phase)

$$V_A = V_{A1} + V_{A2} + V_{A0}$$
$$V_B = V_{B1} + V_{B2} + V_{B0} = a^2.V_{A1} + a.V_{A2} + V_{A0}$$
$$V_C = V_{C1} + V_{C2} + V_{C0} = a.V_{A1} + a^2.V_{A2} + V_{A0}$$

SYMMETRICAL COMPONENTS



Application Example 1: Motor/Generator



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Motor/Generator Current Unbalance

- **Current Unbalance**
  - Looks at percent of negative sequence current to positive sequence current
- **Remember**
  - Positive Sequence Current = Balanced
  - Negative Sequence Current = Unbalanced
- **How Traditionally Tested**
  - Apply current to only one phase, and ramp current until pickup.
  - This is inaccurate. (Positive, Negative, and Zero)

Current Unbalance

- Traditional Method of Test:
  - Ramp only one current until pickup
- Secondary FLA: 5 A
- % Unbalance = 20%
  - Misconception for this element: 20% of 5 = 1A
- However, relay won't pickup until 3 A applied
- Why?
- Positive, Negative and Zero Sequence values all present and evenly distributed.
  - (1 A Positive, 1 A Negative, 1 A Zero)

Current Unbalance Calculations

- Proper Method:
  - Compute Symmetrical Component Quantities
- Secondary FLA: 5 A
- % Unbalance Pickup: 20% of FLA
  - This equals 1 A of negative sequence current
- So, 5 A of positive sequence to be applied along with 1 A of negative sequence current.
- This will require all 3 phases of the relay in order to be applied properly.

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Current Unbalance Calcs cont'd

Where :

$$a = -120$$

$$a^2 = -240$$

$$Ia = I_a^0 + I_a^+ + I_a^-$$

$$I_a^+ = 5\angle 0°, I_a^- = 1\angle 180°$$

Separate into Real and Imaginary Values :

$$Ia_{\mathrm{Real}} = 5\cos(0°) + 1\cos(180°) = 4$$

$$Ia_{\mathrm{Imaginary}} = 5\sin(0°) + 1\sin(180°) = 0$$

$$Ia_{Magnitude} = \sqrt{(Ia_{\mathrm{Real}})^2 + (Ia_{\mathrm{Imaginary}})^2} = 4\text{A}$$

$$Ia_{Angle} = \tan^{-1}\left(\frac{Ia_{\mathrm{Imaginary}}}{Ia_{\mathrm{Real}}}\right) = \tan^{-1}\left(\frac{0}{4}\right) = 0°\ \text{Leading} \rightarrow 0°\ \text{Lagging}$$

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Current Unbalance Calcs cont'd

$$Ib_{\mathrm{Re}al} = 5\cos(0-240) + 1\cos(180-120) = -2$$

$$Ib_{\mathrm{Im}aginary} = 5\sin(0-240) + 1\sin(180-120) = 5.196$$

$$Ib_{Magnitude} = \sqrt{(5.196)^2 + (-2)^2} = 5.568\text{ A}$$

$$Ib_{Angle} = \tan^{-1}\frac{Ib_{\mathrm{Im}aginary}}{Ib_{\mathrm{Re}al}} = -68.95^\circ\text{ Leading} \rightarrow 111.05^\circ\text{ Lagging}$$

$$Ic_{\mathrm{Re}al} = 5\cos(0-120) + 1\cos(180-240) = -2$$

$$Ic_{\mathrm{Im}aginary} = 5\sin(0-120) + 1\sin(180-240) = -5.196$$

$$Ic_{Magnitude} = \sqrt{(-5.196)^2 + (-2)^2} = 5.568\text{ A}$$

$$Ic_{Angle} = \tan^{-1}\frac{Ic_{\mathrm{Im}aginary}}{Ic_{\mathrm{Re}al}} = 68.95^\circ\text{ Leading} \rightarrow 248.95^\circ\text{ Lagging}$$

Applied Test Values

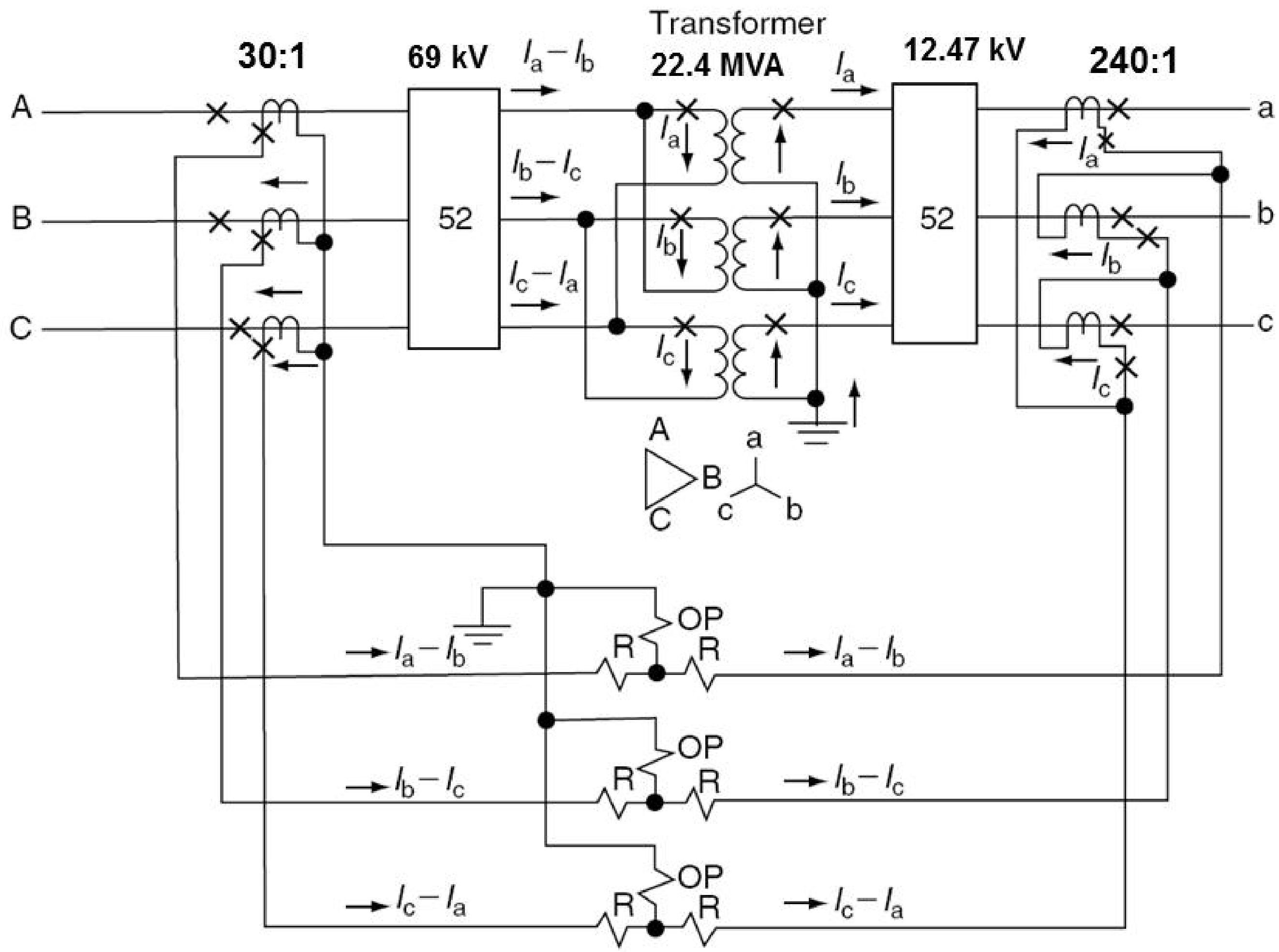
- Here are the Calculated pickup values:

	Ia	Ib	Ic
Magnitude	4 A	5.568 A	5.568 A
Angle (Lagging)	0°	111.05°	248.95°

- These values are equivalent to applying 5 A of Positive Sequence Current and 1 A of Negative Sequence Current
- Will provide a more accurate pickup test than other methods.

Application Example 2: Transformer Zero Sequence Current Removal

Why is Zero Sequence Current a Problem?



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Internal Corrections

Eliminating Zero Sequence Current

- Performed Internally
- Dependent Upon Following:
  - CT Connections
  - Compensation: Internal or External
  - Winding Compensation:
    - Vector Groups

$$[CTC(1)] = \frac{1}{\sqrt{3}} \times \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

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Elimination of Zero Sequence

- The matrix for vector group one will provide a positive 30 degree shift to the secondary current. This will also include the 1.73 factor.
- These matrix will also eliminate the zero sequence current mathematically. This is shown below.

Symmetrical Components:

$$Ia = I1 + I2 + I0$$
$$Ib = a^2 I1 + aI2 + I0$$
$$Ic = aI1 + a^2 I2 + I0$$

- Using these values with matrix one will yield the following results shown on next slide.

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Proof That It's Gone

$$[CTC(1)] = \frac{1}{\sqrt{3}} \times \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} = \begin{matrix} \frac{1}{\sqrt{3}}(Ia - Ib) \\ \frac{1}{\sqrt{3}}(Ib - Ic) \\ \frac{1}{\sqrt{3}}(Ic - Ia) \end{matrix} = \begin{matrix} \frac{1}{\sqrt{3}}\left(I1 + I2 + I0 - a^2 I1 - aI2 - I0\right) \\ \frac{1}{\sqrt{3}}\left(a^2 I1 + aI2 + I0 - aI1 - a^2 I2 - I0\right) \\ \frac{1}{\sqrt{3}}\left(aI1 + a^2 I2 + I0 - I1 - I2 - I0\right) \end{matrix}$$

- The I_0 terms cancel out in each equation.
- This is equivalent to a delta connection that acts as a zero sequence trap or shunt.

Procedure to Prove It's Removal

- Calculate secondary current values
  - Values for Winding 1 and Winding 2 should be just below pickup point of Differential Trip
- Calculate the phase angles needed for compensation based on transformers vector group
  - Check your test equipment to see if its angle reference is lead or lag
- Apply test current values with appropriate angles
  - Relay should be at threshold of trip
- Apply Zero Sequence Current to relay
  - Applied to winding with internal compensation active
  - If phase angles are correct, relay should not trip
  - If phase angles are incorrect, relay will trip

Slope Calculation (Three Phase)

- Tap1: 6.24 Tap2: 4.32
- Inject 4.50 amps into winding 1 and 3.97 amps into winding 2 will give a slope of:

$$I_{OPERATE(PU)} = \frac{I_{Winding1}\angle\theta_{Winding1}}{Tap1} + \frac{I_{Winding2}\angle\theta_{Winding2}}{Tap2}$$

$$I_{OPERATE(PU)} = \frac{4.50\angle 0}{6.25} + \frac{3.97\angle 180}{4.32} = 0.721\angle 0 + 0.919\angle 180 = \left|-0.199\right|$$

$$I_{RESTRAINT(PU)} = \frac{\frac{\left|4.50\angle 0\right|}{6.25} + \frac{\left|3.97\angle 180\right|}{4.32}}{2} = \frac{0.720 + 0.919}{2} = 0.82$$

$$Slope = \frac{0.199}{0.820} \times 100 = 24.26\%$$

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Applied Test Values

- Here are the Calculated pickup values:

	Magnitude (A)	Angle (Lagging)
I_A (Winding 1)	4.50 A	0°
I_B (Winding 1)	4.50 A	120°
I_C (Winding 1)	4.50 A	240°
I_a (Winding 2)	3.97 A	210°
I_b (Winding 2)	3.97 A	330°
I_c (Winding 2)	3.97 A	90°

- These Values will be just below the threshold for tripping on Slope 1
- Applying additional zero sequence current should not trip the relay

Adding Zero Sequence Current

- Going through the same sequence calculations as before we find the new values:

	Magnitude (A)	Angle (Lagging)
I_A (Winding 1)	4.50 A	0°
I_B (Winding 1)	4.50 A	120°
I_C (Winding 1)	4.50 A	240°
I_a (Winding 2)	3.144 A	219.15°
I_b (Winding 2)	4.862 A	335.90°
I_c (Winding 2)	4.094 A	75.86°

- The relay should not trip with these values.

Application Example 3: Phase Time Overcurrent and Residual Time Overcurrent on the Same Trip Contact

Testing with One Contact (Distribution)

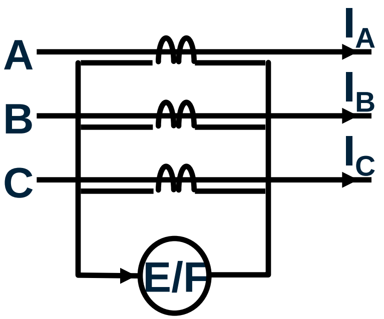
- Trip Contact May Have Many Elements:
  - Trip1 = 27+50+51+51N+59+81

- Most elements are easy to prevent from false tripping while testing something else

- Problem arises with 51+51N
  - Traditionally, both elements are tested the same way
  - 51N normally set lower than 51 and will trip first

The Residual Connection

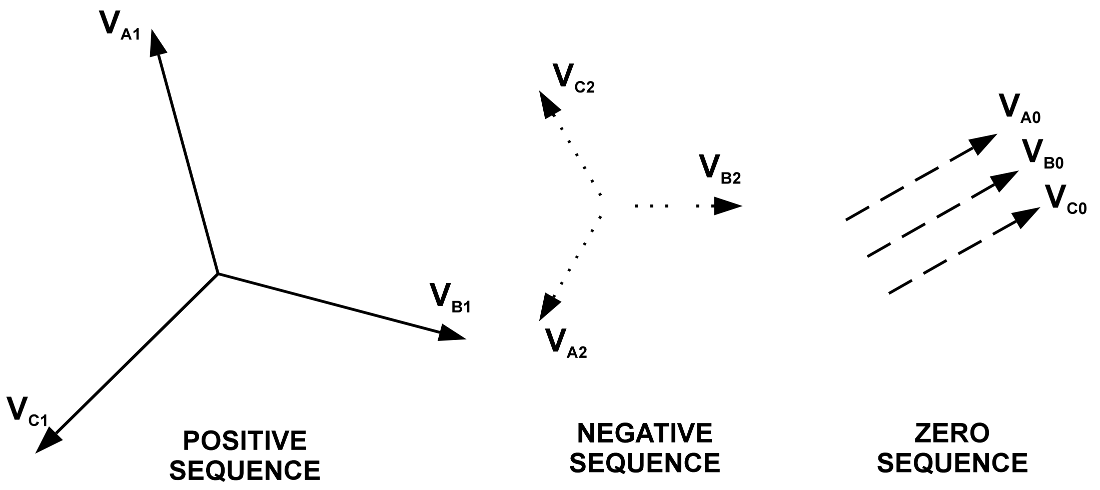
Residual CT Connection :



$$I_a + I_b + I_c = 3I_0$$

- Sums zero sequence current from each of the phases
- Fairly straight forward to isolate using knowledge of symmetrical components

How to Test Phase TOC (51)



- Only apply positive sequence current
- Negative and zero sequence current is equal to zero

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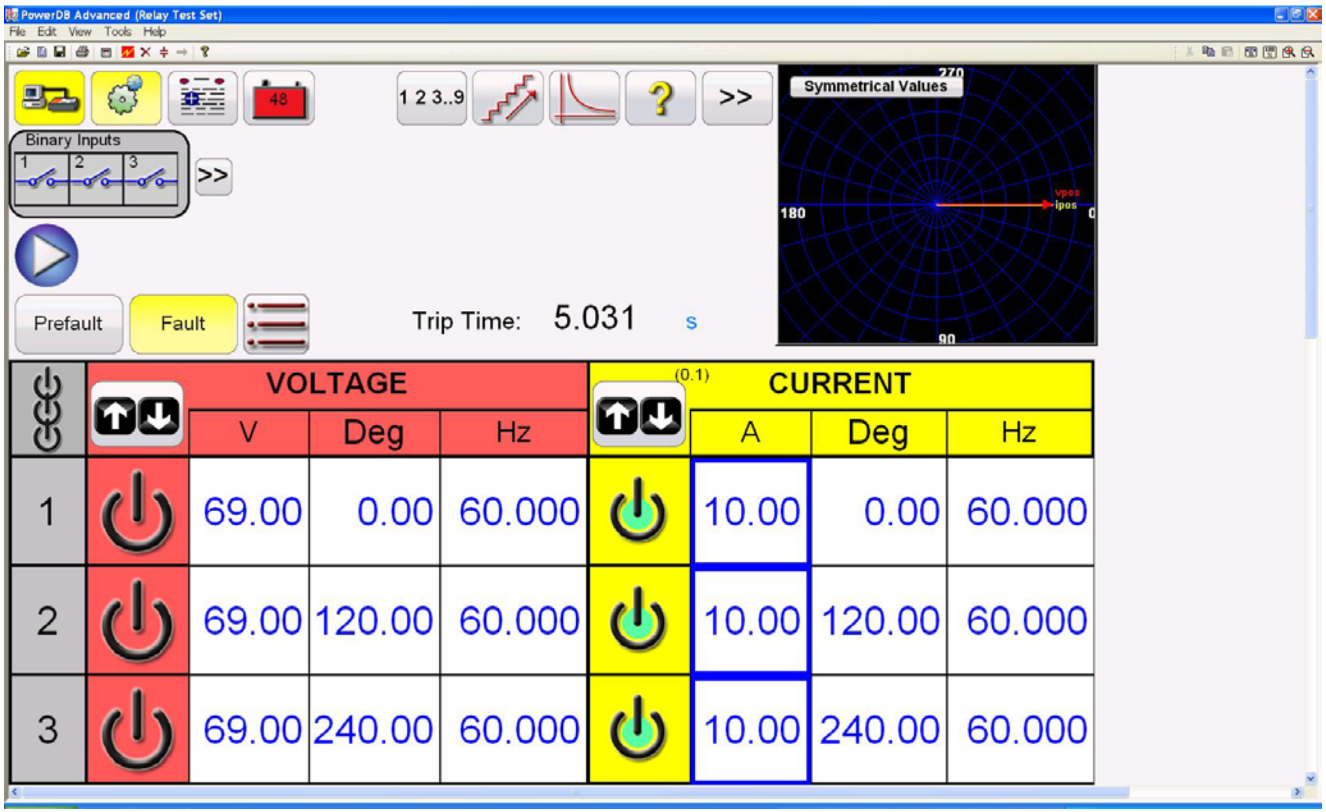
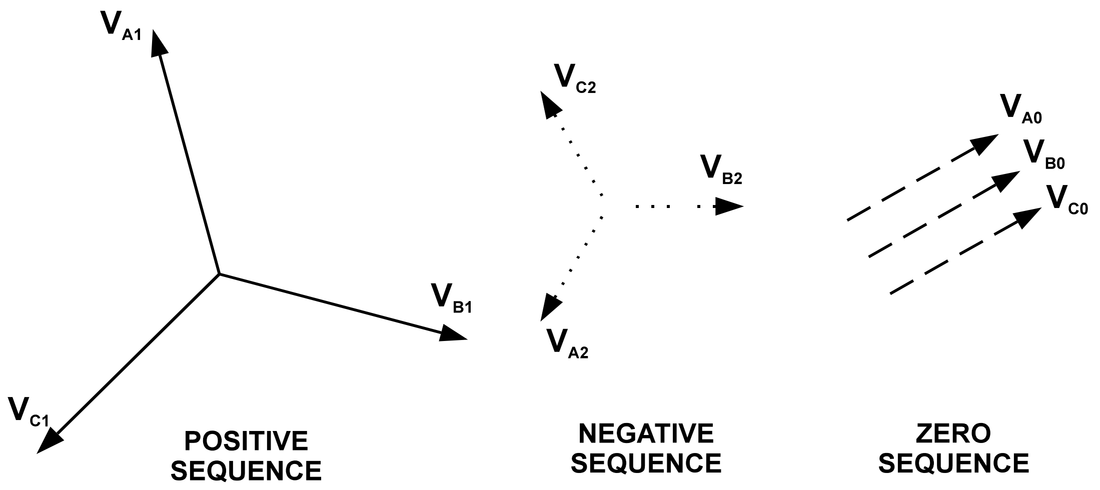
How to Test Phase TOC (51)

- With these values, the 51 element will pickup and 51N will not be asserted



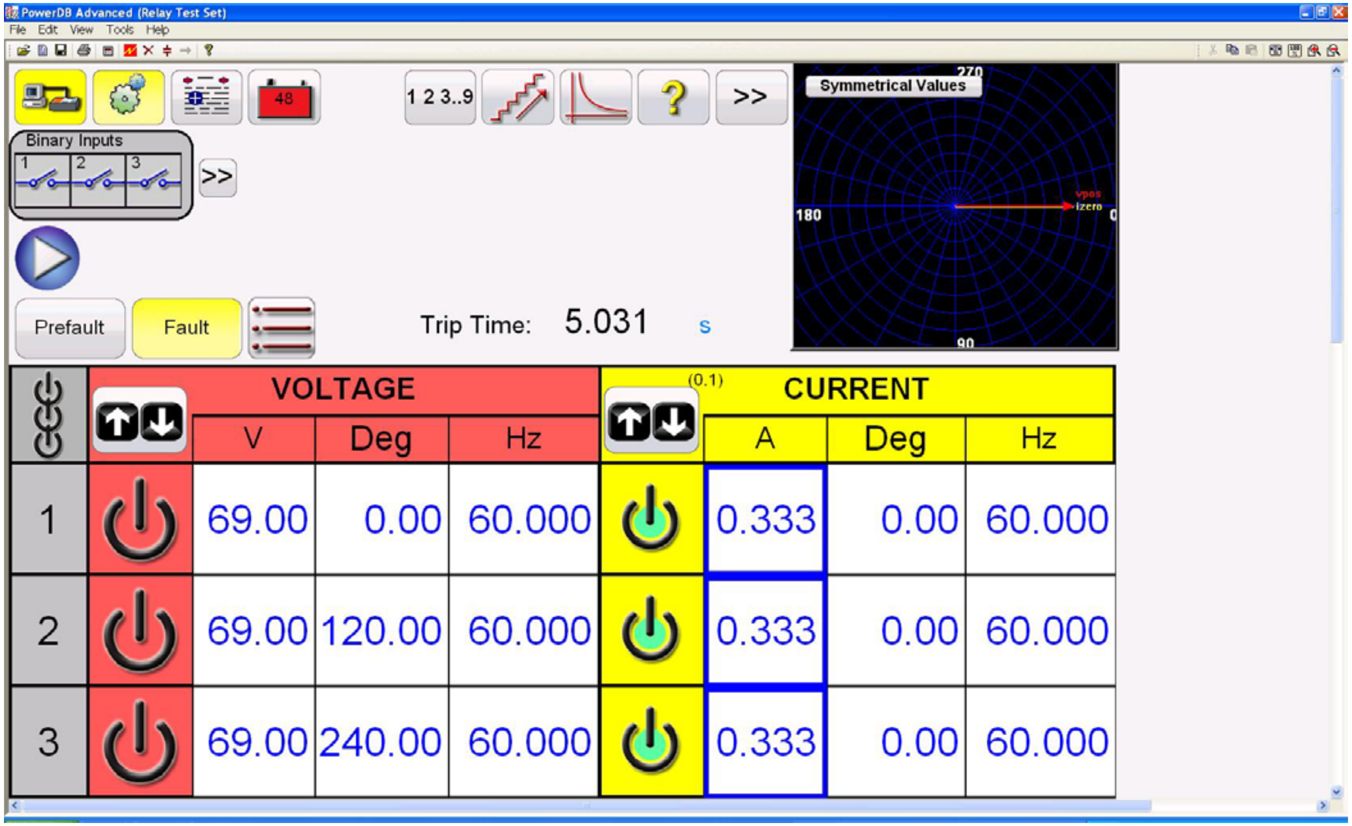
How to Test Phase Neutral TOC (51N)

- Assuming Neutral TOC Pickup = 1 A
- We can apply zero sequence current
  - Zero sequence = 3I0, so applied current to each phase will equal 1/3 of pickup value



How to Test Neutral TOC (51N)

- Now Neutral TOC will Assert and Phase TOC will not



Symmetrical Components Conclusions

- Testing of many elements can be simplified by understanding of symmetrical components

- Methods will work across various manufacturers of relays

- Symmetrical components help construct more realistic fault conditions for relay operation

- Rigorous calculations are not always necessary

Questions?