Man-Made Faults – Line Protection Operation for an Unintended Phase Cross-Connect Condition

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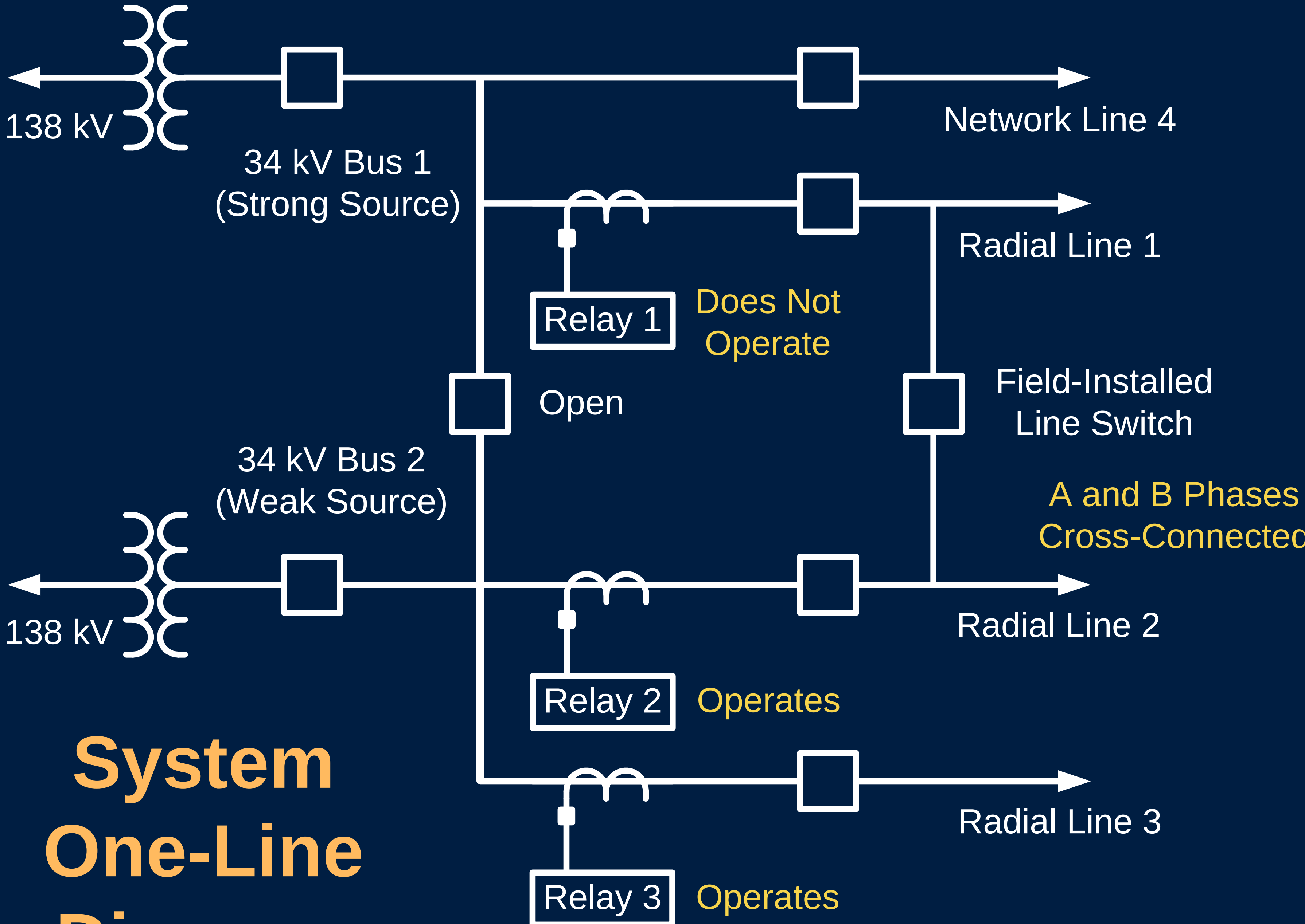
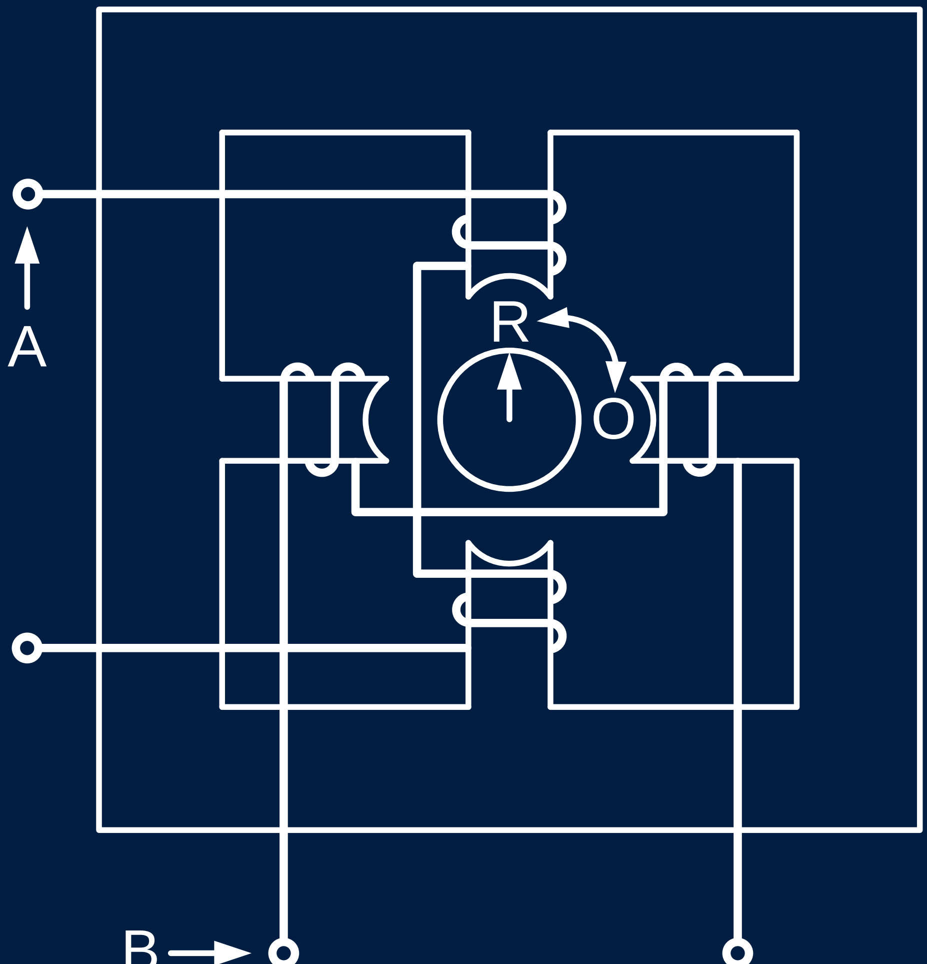
System One-Line Diagram



Compensator Distance Relays

Electromechanical



Digital

$$A = V_{AB} - Z_{1R} \bullet I_{AB}$$

$$B = V_{BC} - Z_{1R} \bullet I_{BC}$$

$$T = \operatorname{Im}\left[A \bullet (B)^{*}\right]$$

$$Z_{1R} = r \bullet Z_1 \angle MTA$$

Negative Torque → Operates

R = Restraint (A Leads B)

O = Operate (B Leads A)

Symmetrical Component Analysis

Compensated Voltages

$$V_1C = V_{1A} - Z_{1R} \bullet I_{1A}$$

$$V_2C = V_{2A} - Z_{1R} \bullet I_{2A}$$

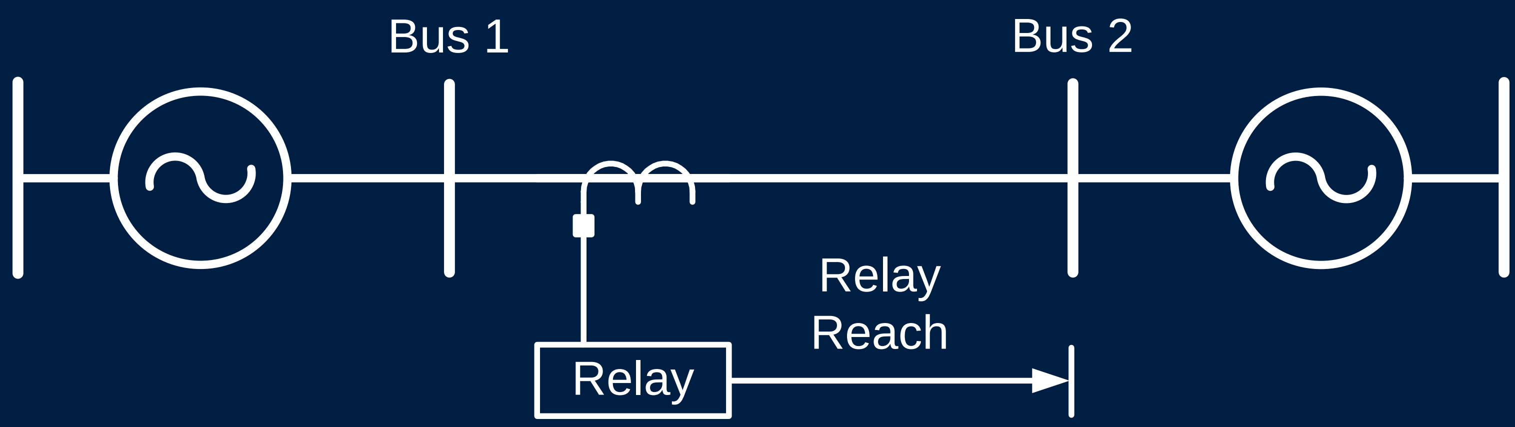
Balance Point

$$\frac{V_2C}{V_1C} = 1\angle\theta$$

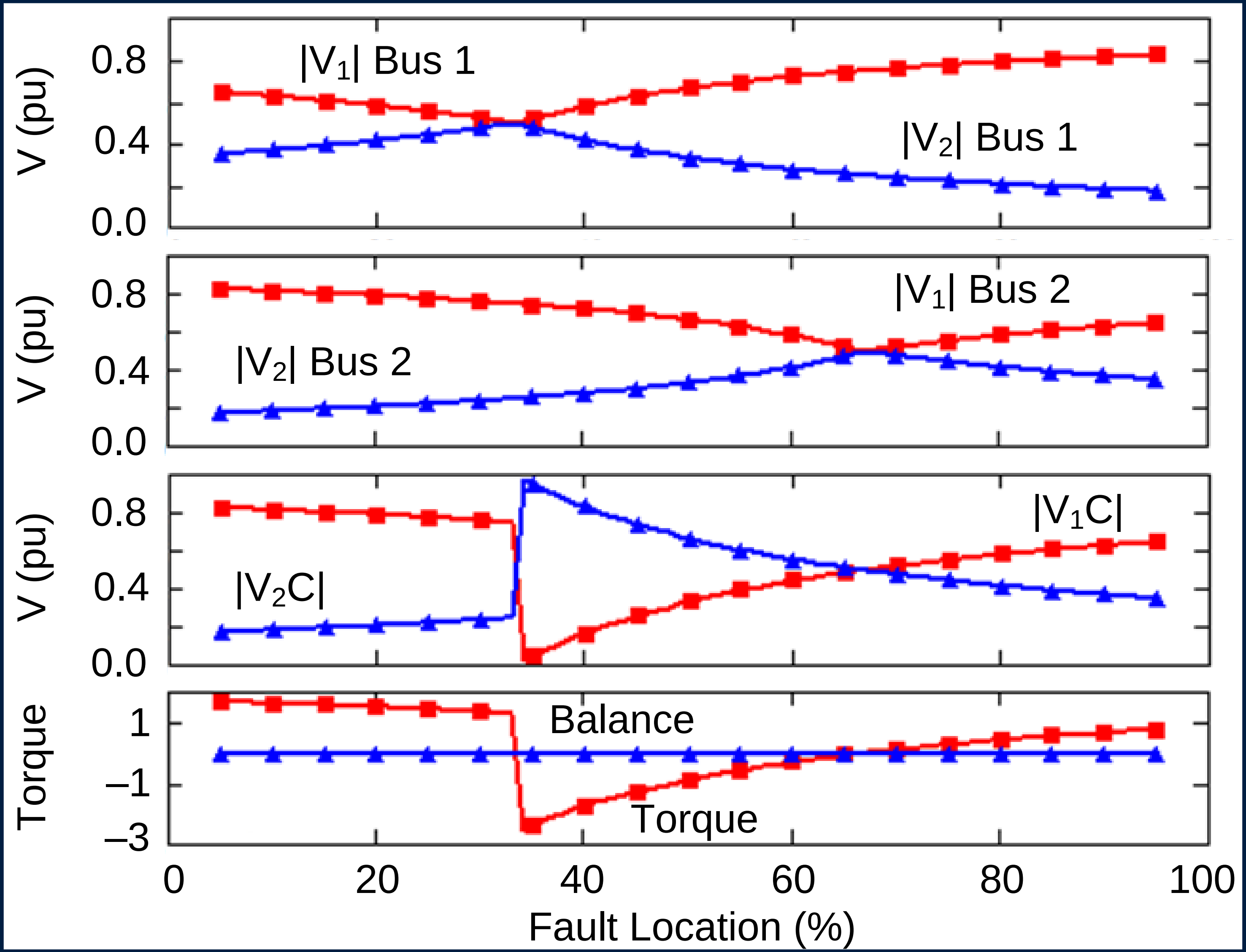
Phase Reversal (Relay Operates)

$$\frac{|V_2C|}{|V_1C|} > 1$$

Example System for Compensator Relay Evaluation



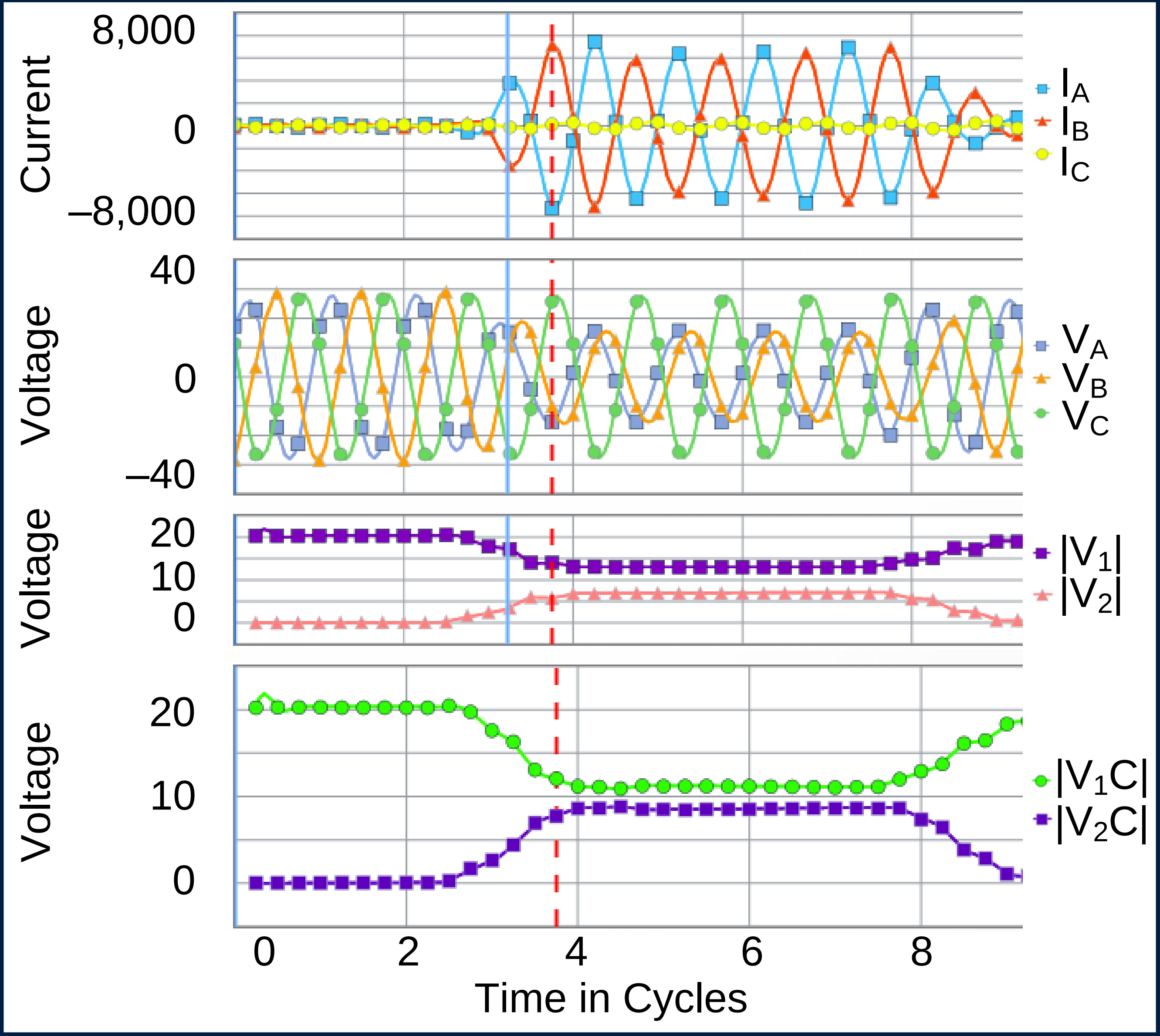
Compensator Relay Evaluation



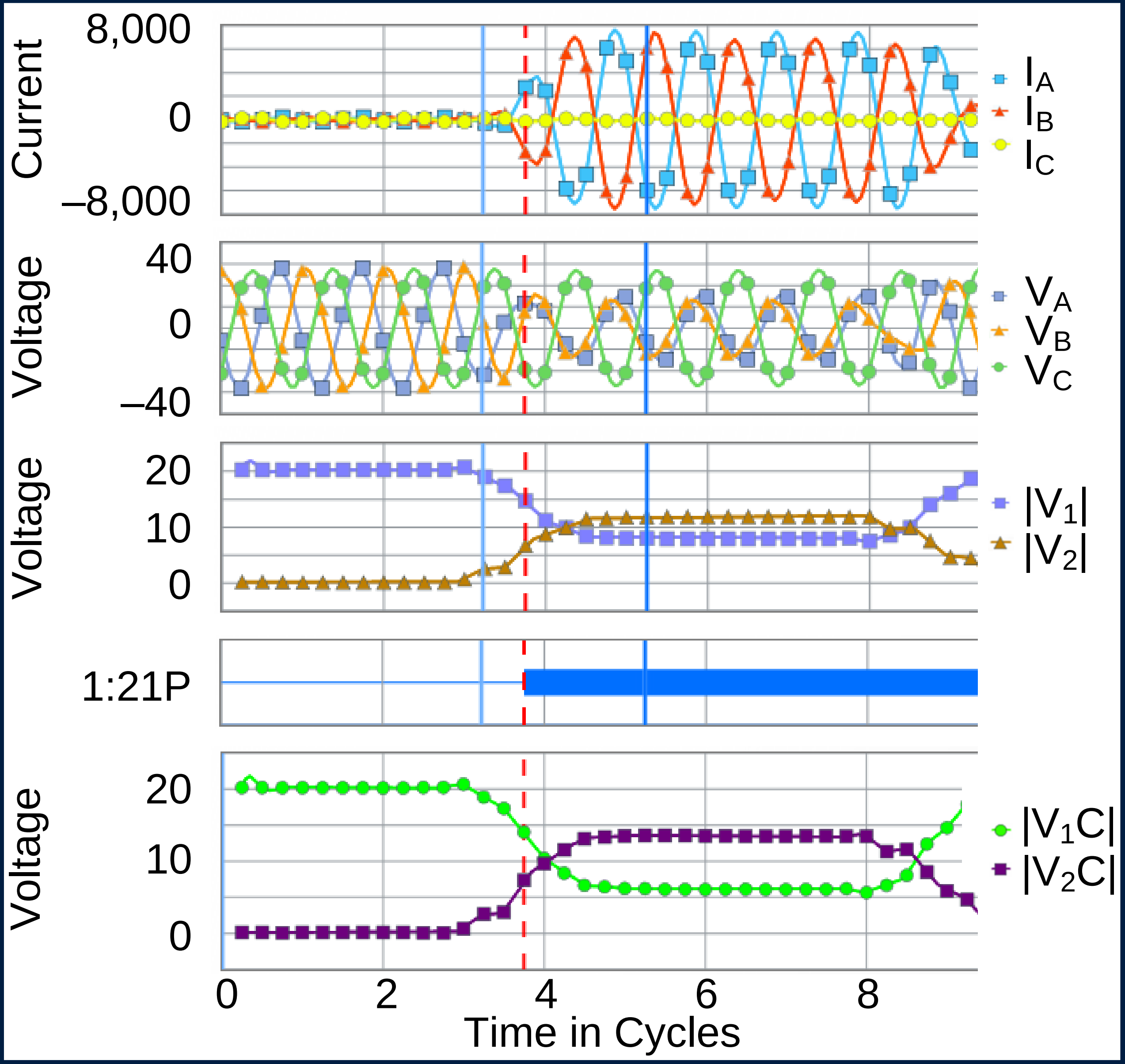
Why Use Compensator Elements?

- Different operating principle
- Delta-wye transformer
- Reclosing blocked for three-phase faults
- Open-delta VTs

Relay 1 Event Analysis

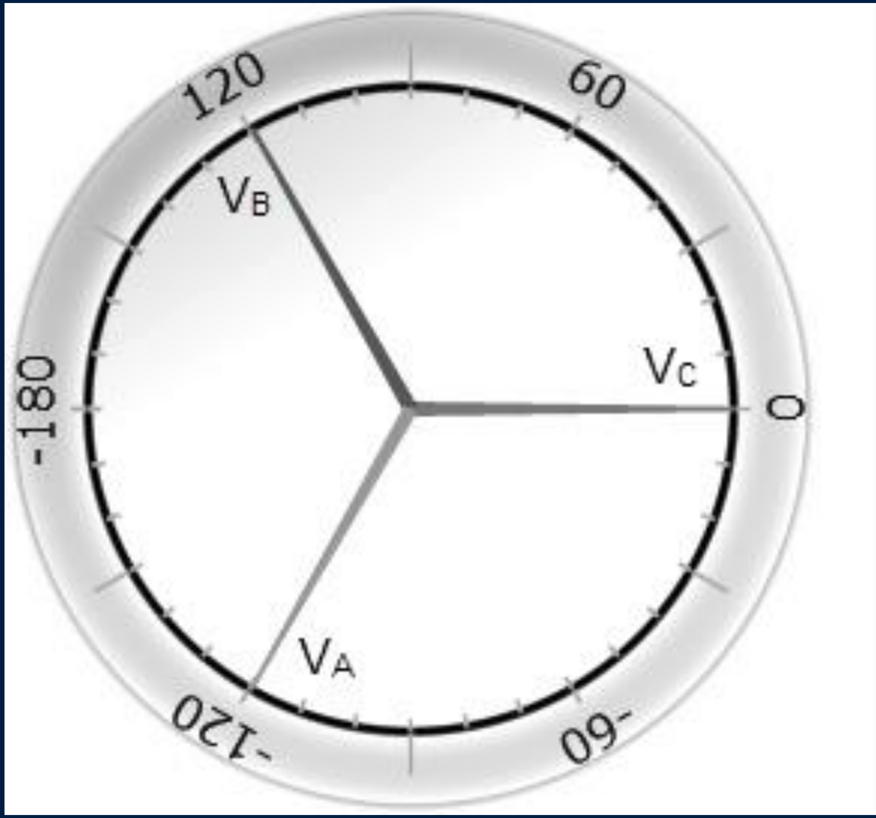


Relay 2 Event Analysis

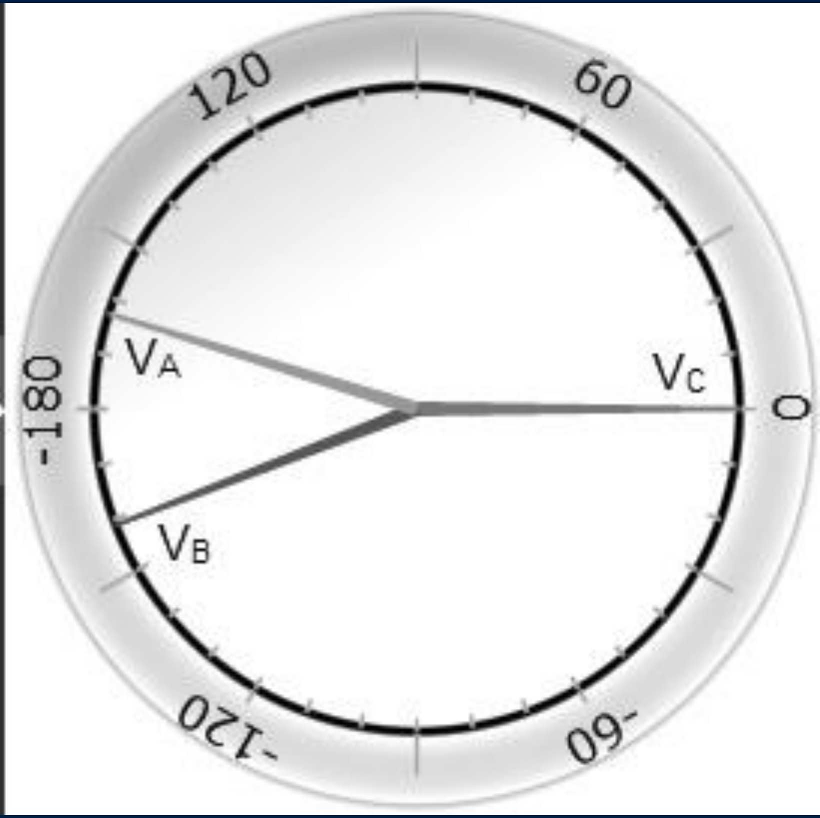


Relay 2 Phasor Analysis

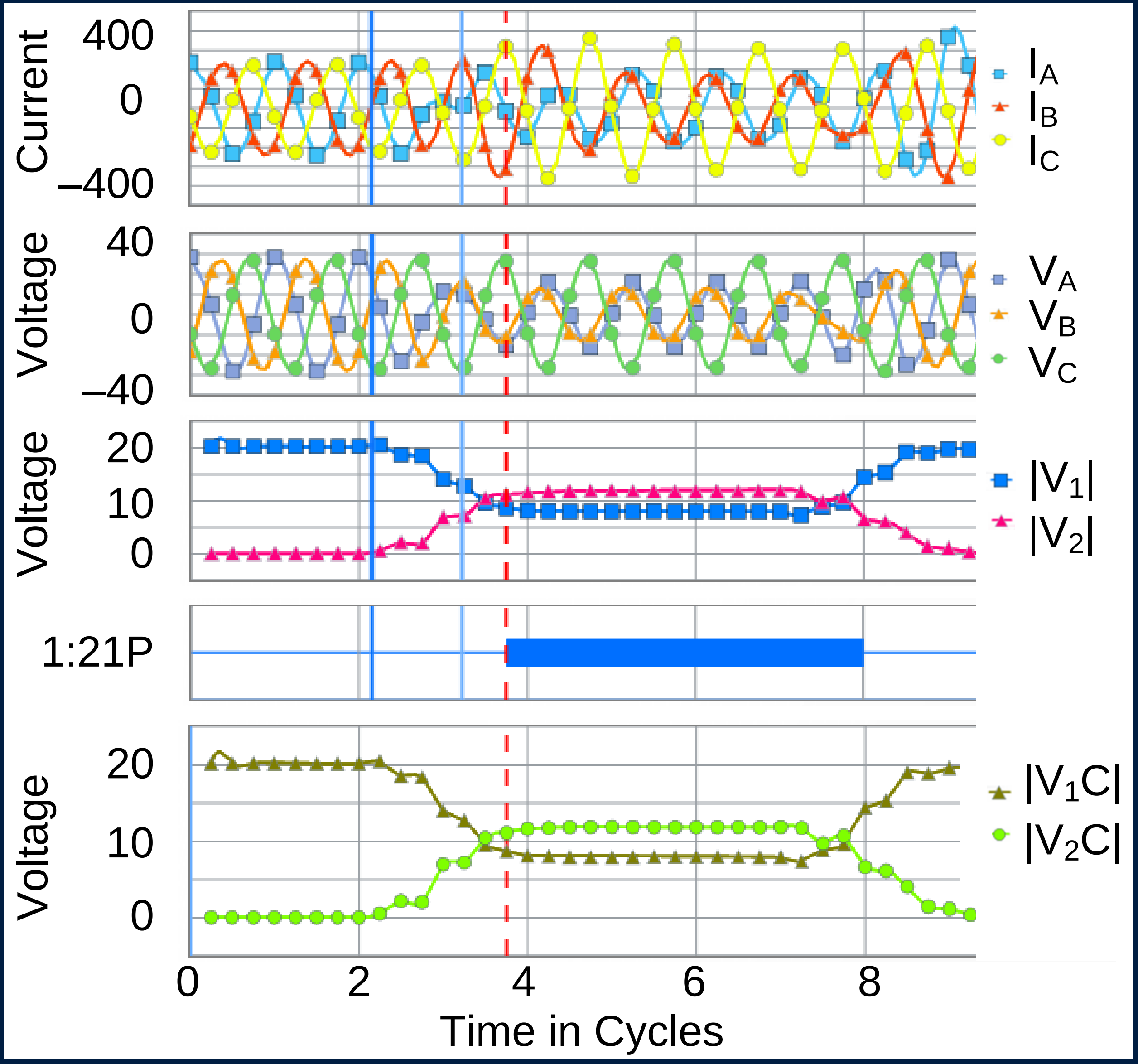
Prefault Voltages



Fault Voltages

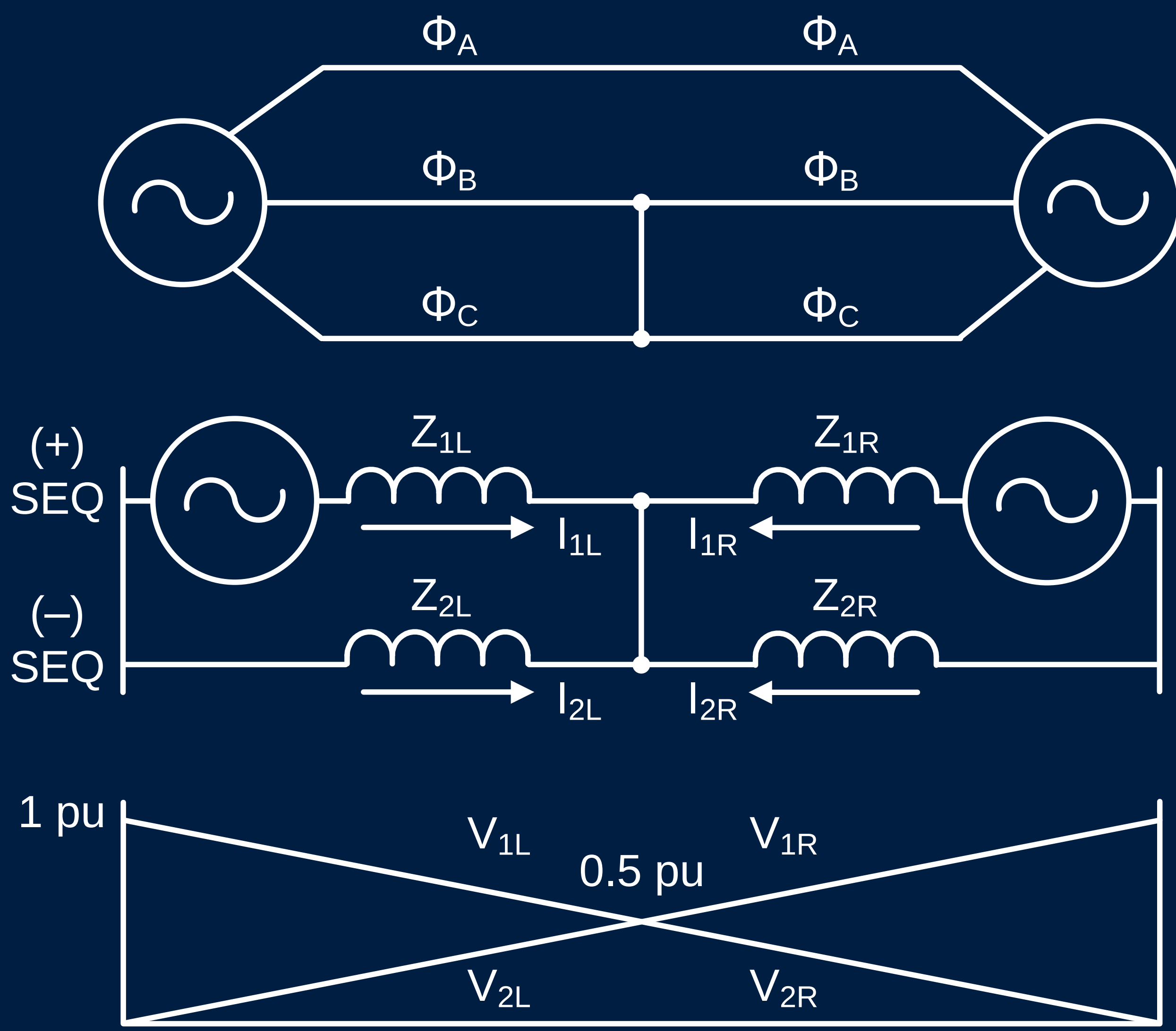


Relay 3 Event Analysis



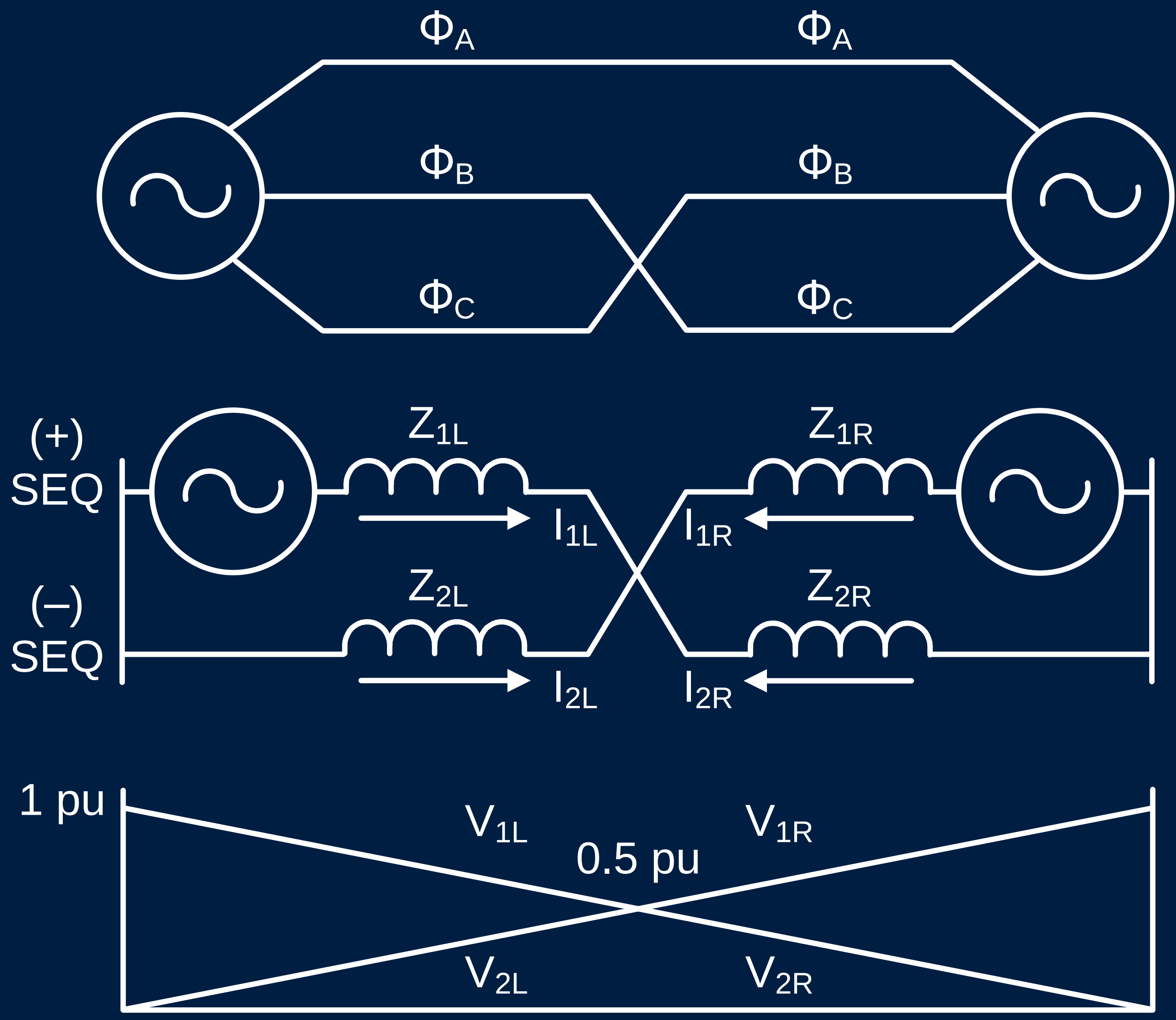
Symmetrical Component Analysis

Phase-to-Phase Fault at Electrical Center



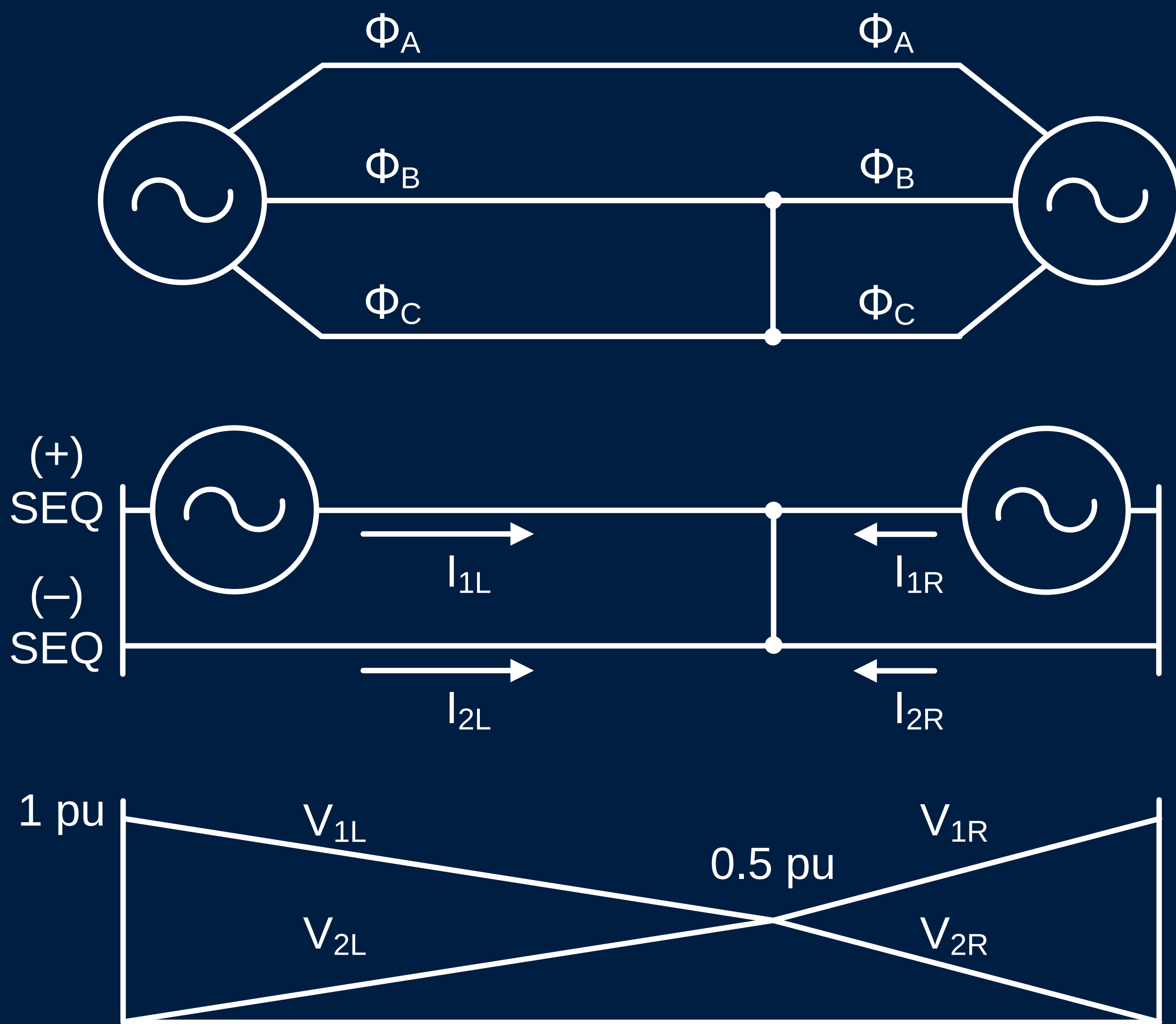
Symmetrical Component Analysis

Cross-Connect Fault at Electrical Center



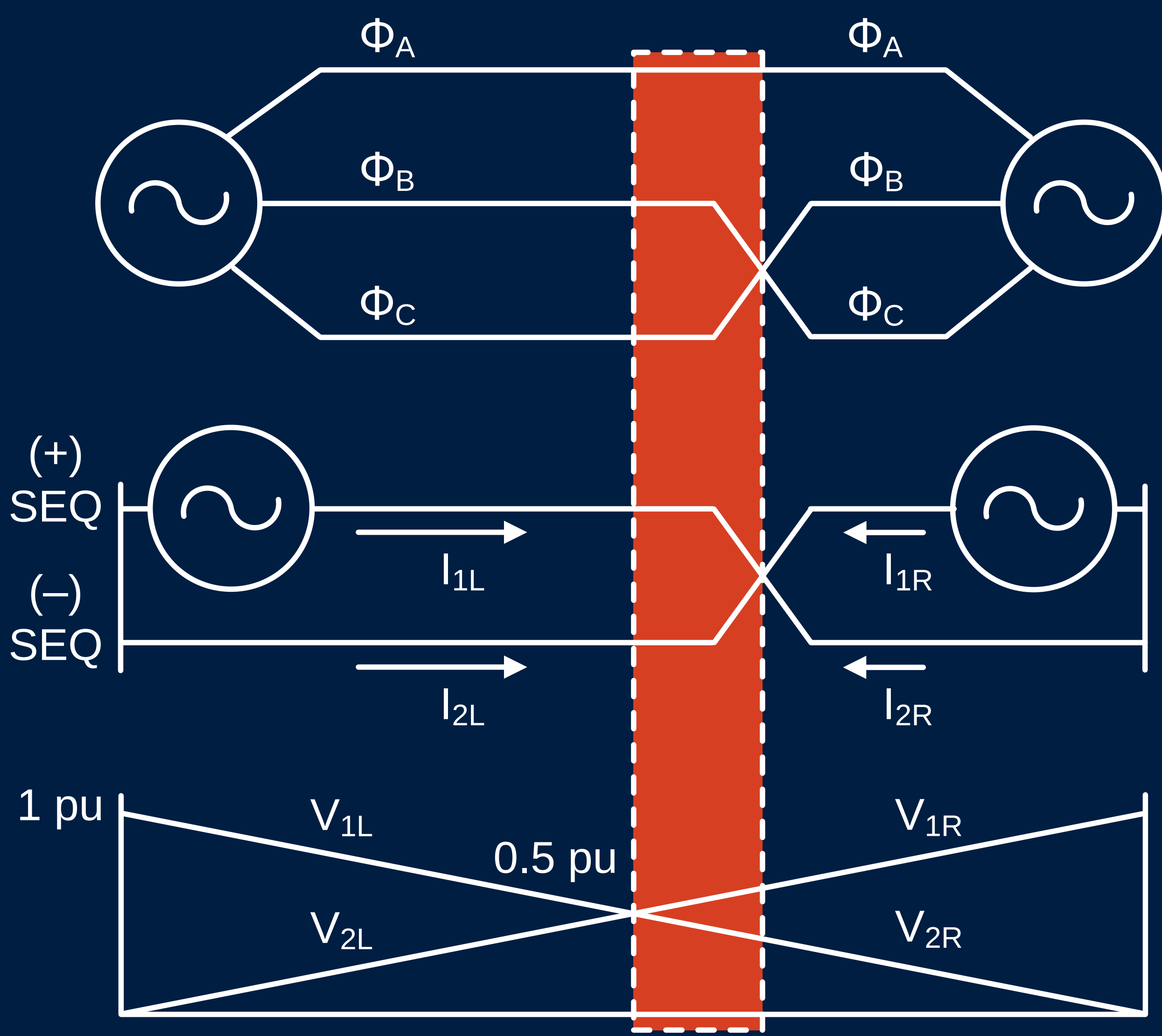
Symmetrical Component Analysis

Phase-to-Phase Fault Not at Electrical Center



Symmetrical Component Analysis

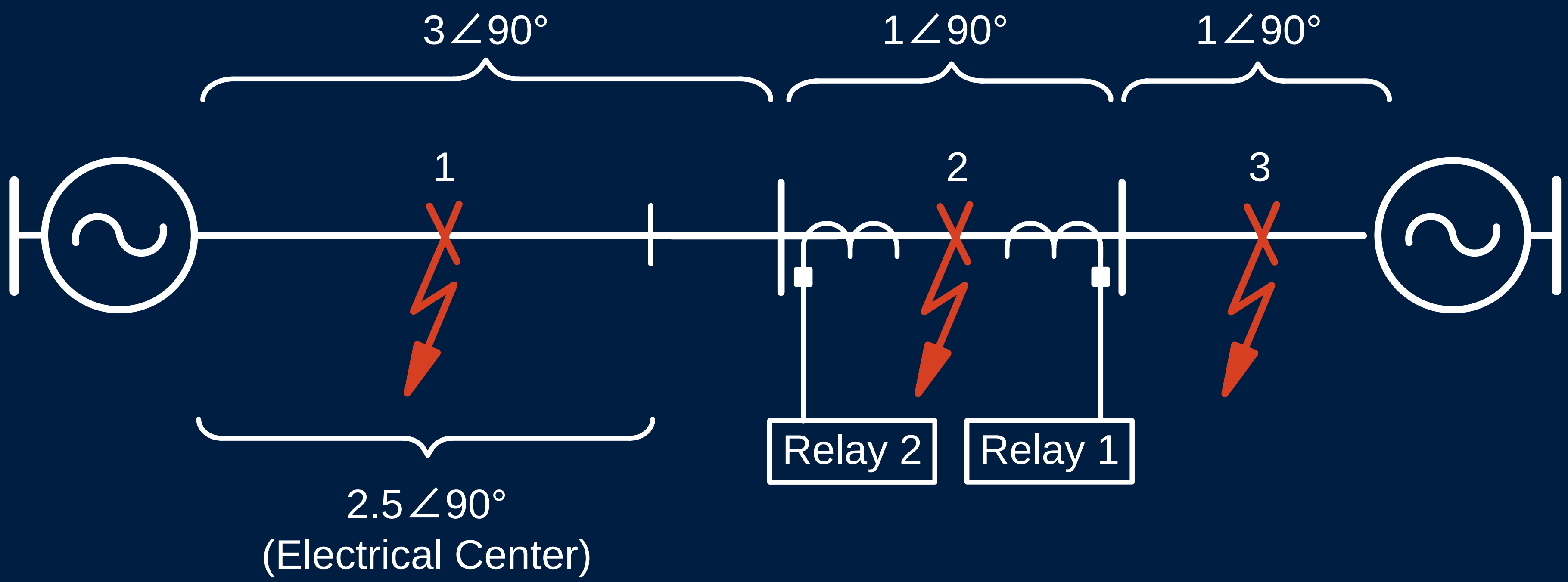
Cross-Connect Fault Not at Electrical Center



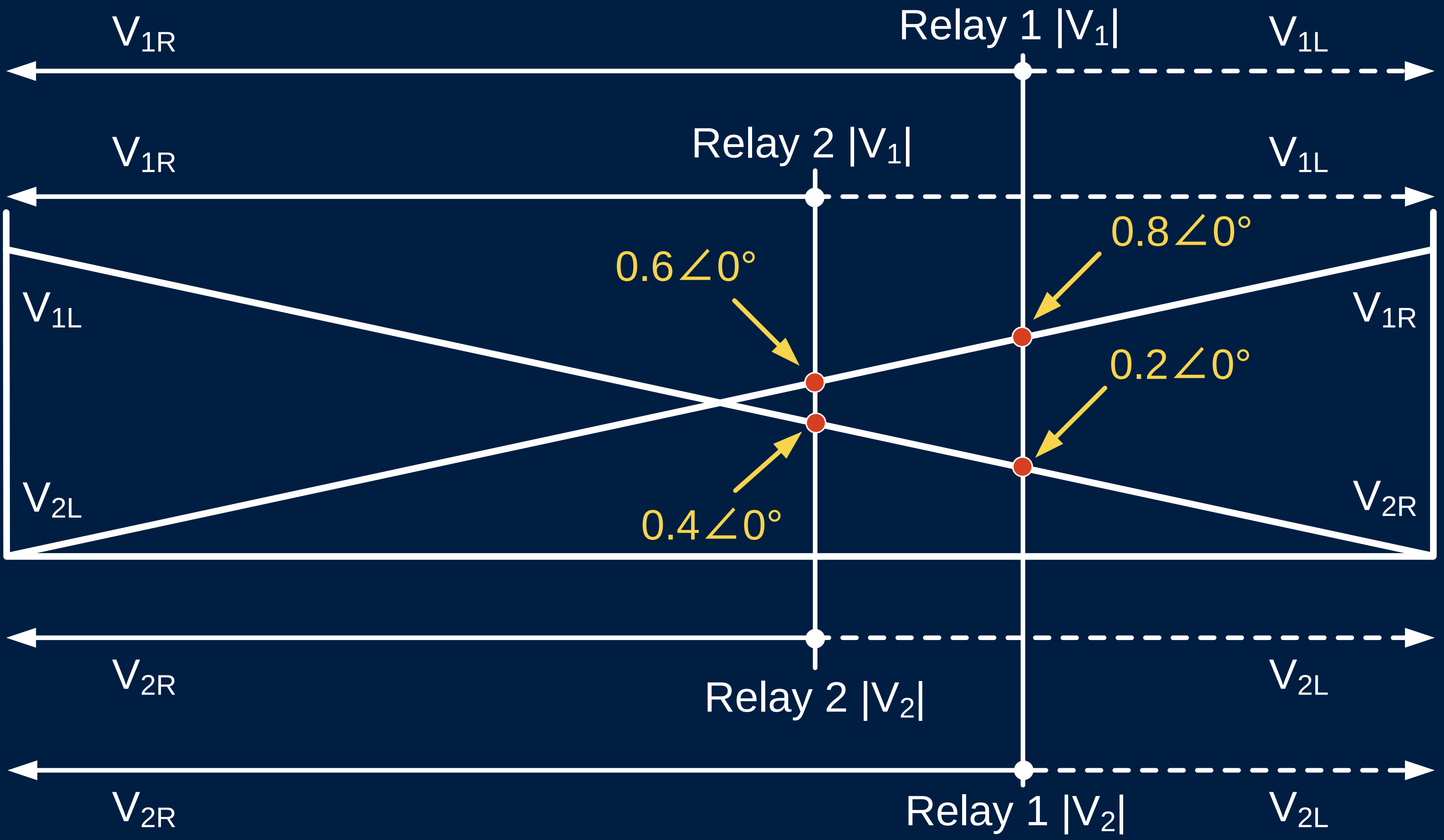
Symmetrical Components Summary

- For all cross-connect locations, fault current is calculated with fault at electrical center
- Relay voltage depends on relay location relative to electrical center and cross-connect fault
- $|V_2|$ exceeds $|V_1|$ when relay is located between electrical center and cross-connect fault

Relay Performance During Cross-Connect Fault

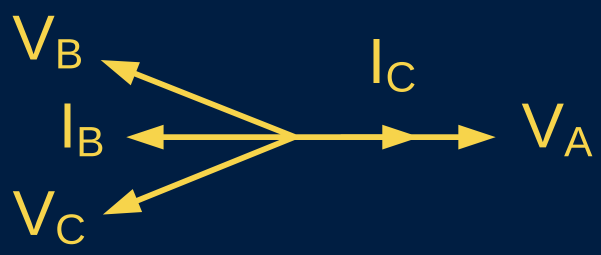


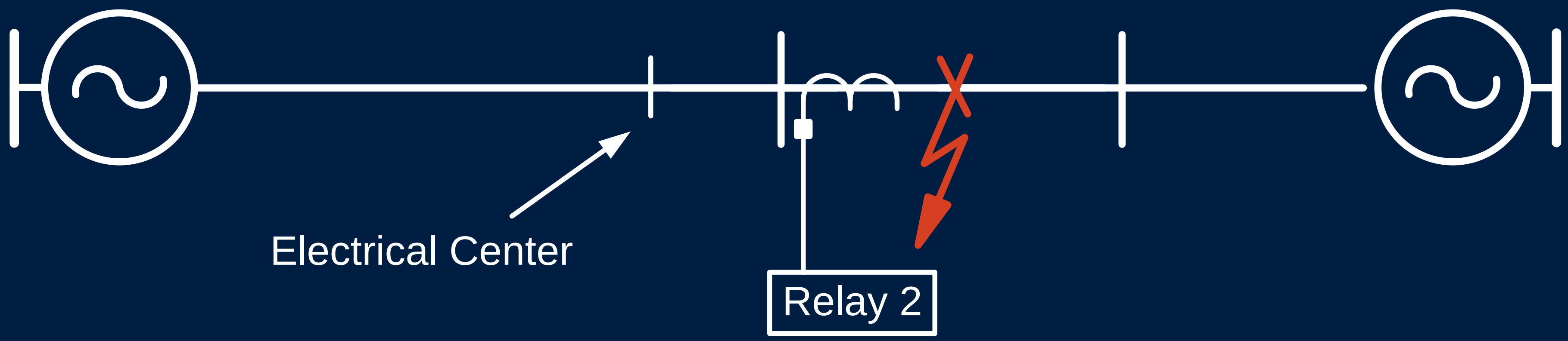
Relay Performance During Cross-Connect Fault



Compensator Distance Element

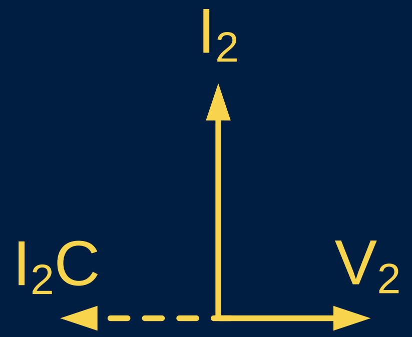
- Element operates when relay experiences phase reversal
- Phase reversal occurs when relay is located between electrical center and cross-connect fault





Negative-Sequence Impedance Directional Element

$$Z_2 = \frac{\mathrm{Re}\left[V_2 \cdot \overline{\left(I_2 \cdot 1\angle \mathrm{MTA} \right)} \right]}{|\, I_2 \,|^2}$$

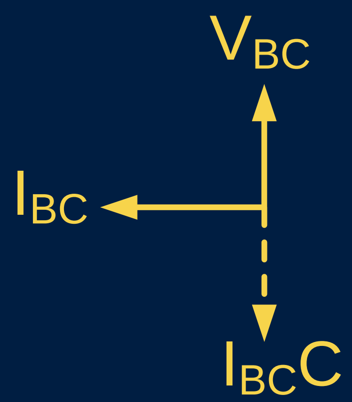


Directional element correctly identifies location of cross-connect fault

Self-Polarized Mho Element

Measures Impedance to Electrical Center

$$MBC = \frac{\mathrm{Re}(V_{BC} \cdot \overline{V_{BC}})}{\mathrm{Re}(1\angle MTA \cdot I_{BC} \cdot \overline{V_{BC}})}$$

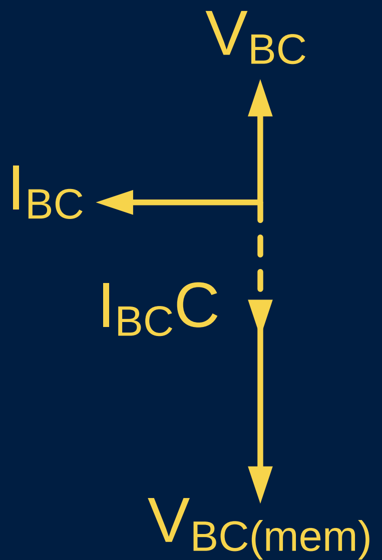


- Element is not applied in modern digital relays
- Denominator determines direction
  (+ → Forward)

Memory-Polarized Mho Element

Measures Impedance to Electrical Center

$$MBC_{(mem)} = \frac{\mathrm{Re}\left(V_{BC} \cdot \overline{V_{BC(mem)}}\right)}{\mathrm{Re}\left(1\angle MTA \cdot I_{BC} \cdot \overline{V_{BC(mem)}}\right)}$$



Electrical center → Relay → Cross-connect fault

Always operates

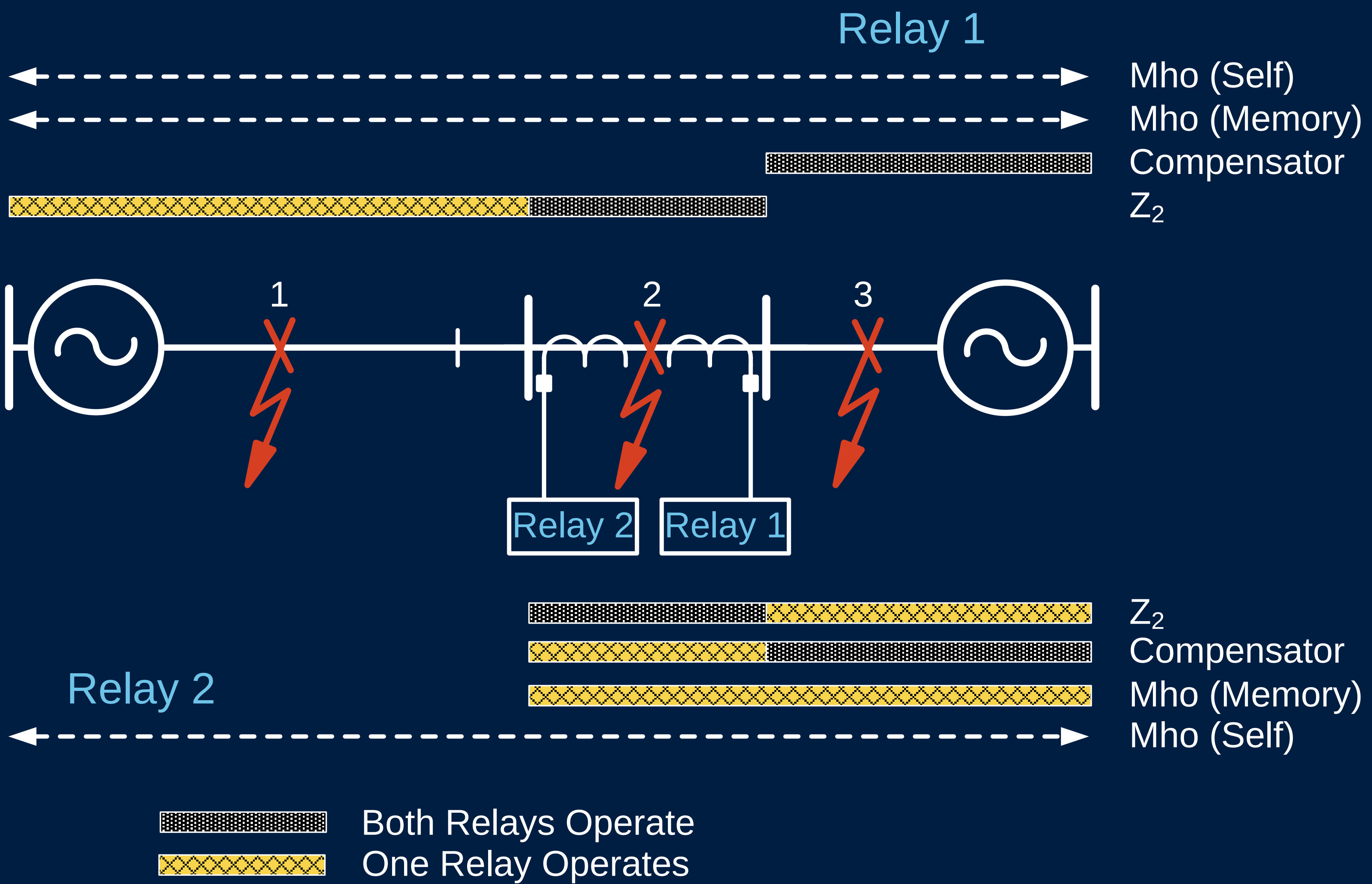
Relay → Cross-connect fault → Electrical center

May operate

Cross-connect fault → Relay

Will not operate

Summary for Example System



Relay 1 and 2 Element Performance

Actual Event

Z_2		Mho		Compensator	
Relay 2	Relay 1	Relay 2	Relay 1	Relay 2	Relay 1
Forward	Forward	–0.36 ohms secondary	0.448 ohms secondary	NA	0.448 ohms secondary
Fault on line		Fault behind Relay 2		Fault behind Relay 2	

Conclusion

- Cross-connect faults are similar to phase-to-phase faults, but different
- $|V_2|$ can exceed $|V_1|$, which leads to voltage phase reversal
- Compensator distance elements operate for voltage phase reversal regardless of setting

Conclusion

- Compensator distance elements are dependable for a cross-connect fault, but not secure
- Security can be improved by applying fault detectors or by supervising with negative-impedance-based directional elements
- Line current differential schemes are secure and dependable for cross-connect faults

Conclusion

- Good engineering judgment is required to limit exposure to problems caused by cross-connect faults
- Proper operating procedures must also be followed to limit exposure to these faults

Questions?