Negative Sequence: How to Use It

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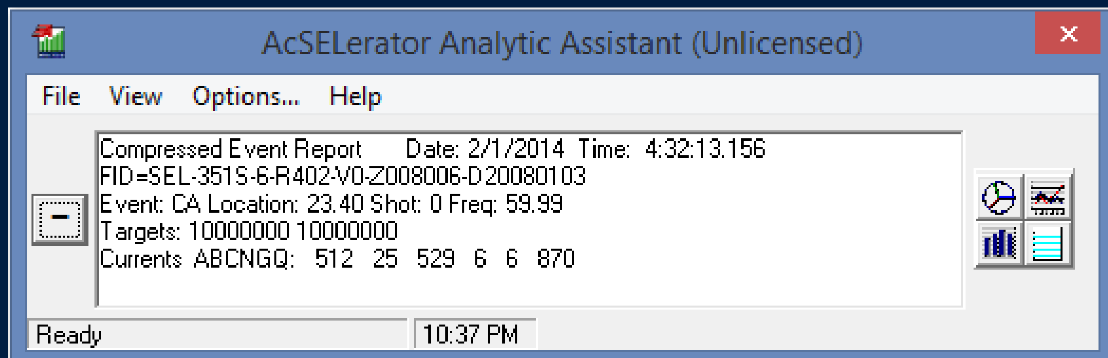
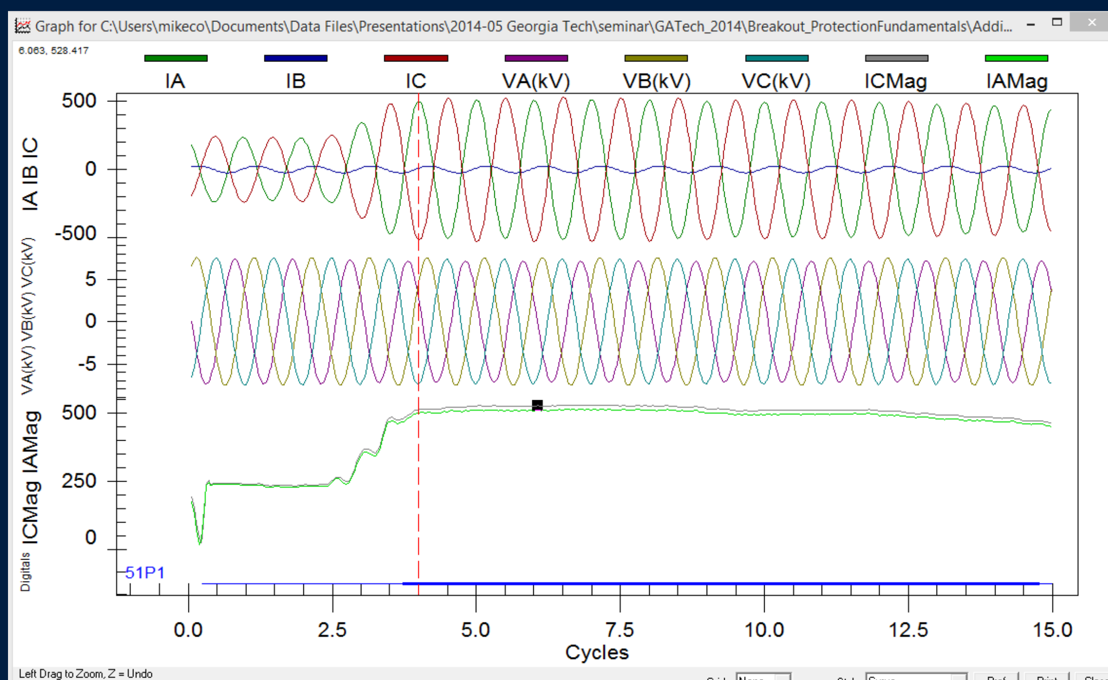
Negative-Sequence Quantities

- Include voltage, current, and impedance
- Can be used for overcurrent, differential, directional, and fault location elements

Negative-Sequence Overcurrent Element

Long Clearing Time
February 2014





Long Clearing Time

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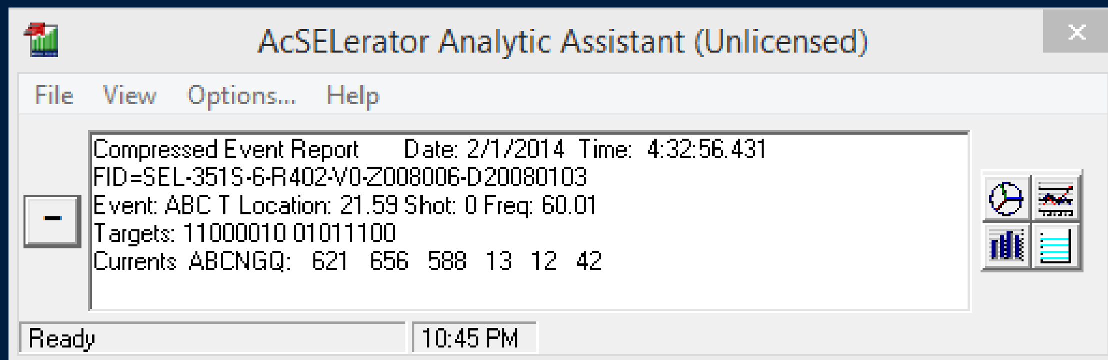
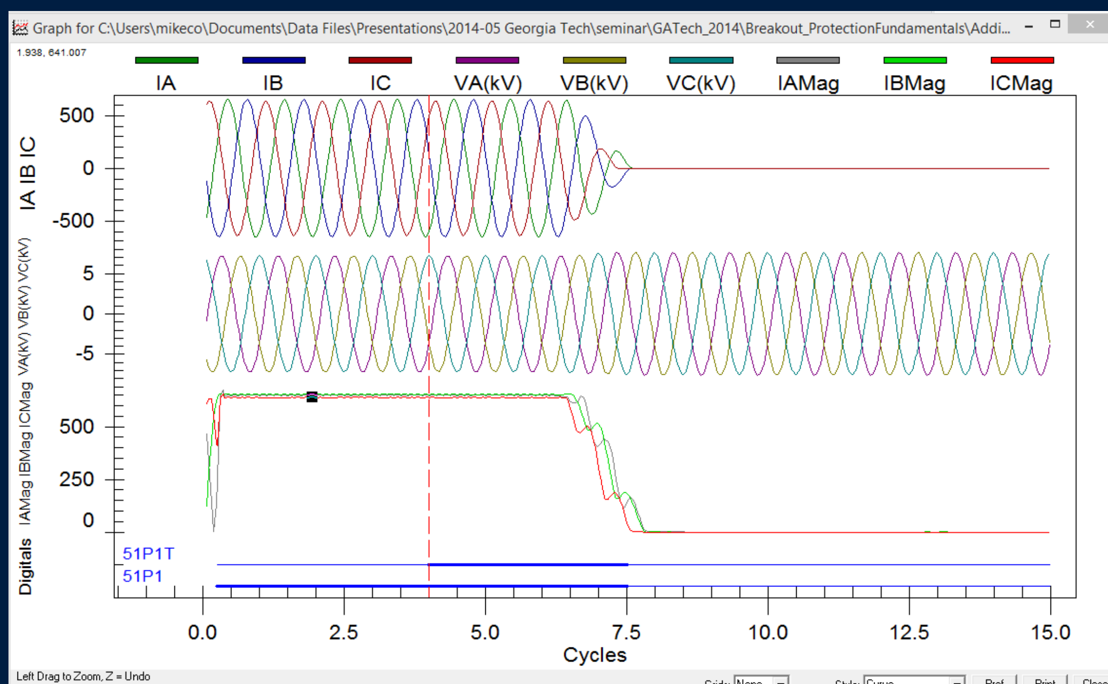
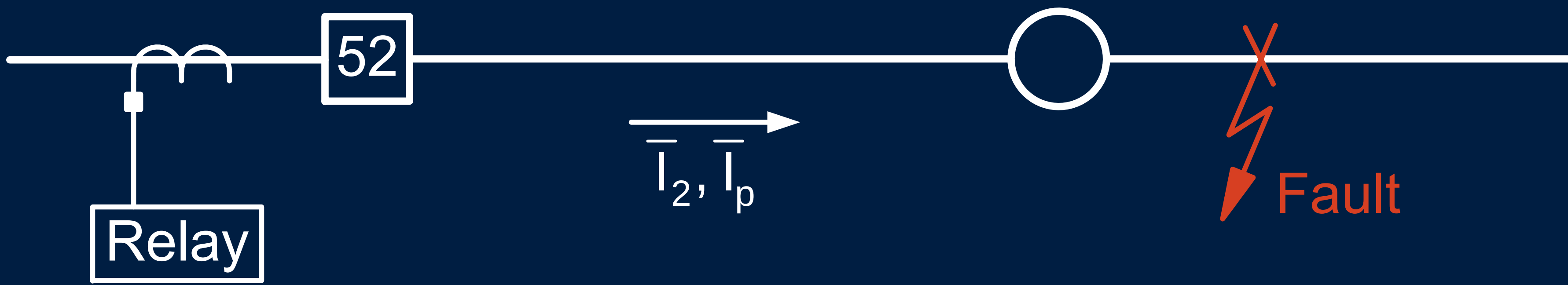


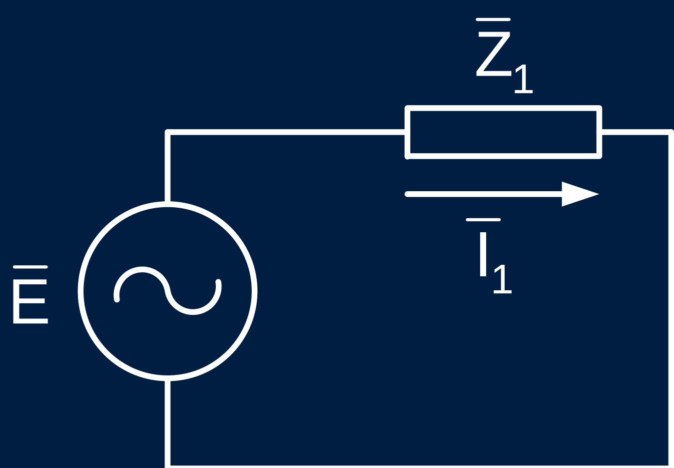


The Perfect Storm

- Phase-to-phase fault was right at pickup of phase time-overcurrent element (512 A)
- Fault time was long enough to burn line down (43 seconds)
- Phase-to-phase fault current was approximately 0.86 pu of three-phase fault

Three-Phase Fault

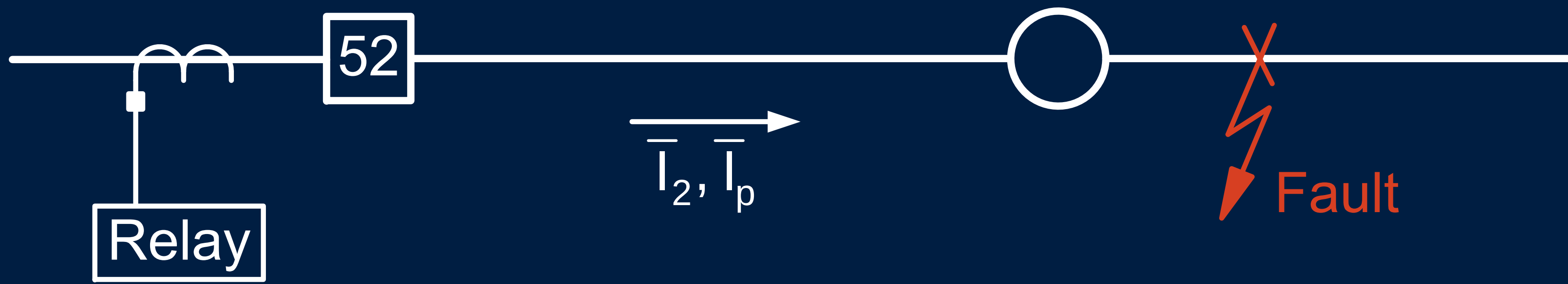


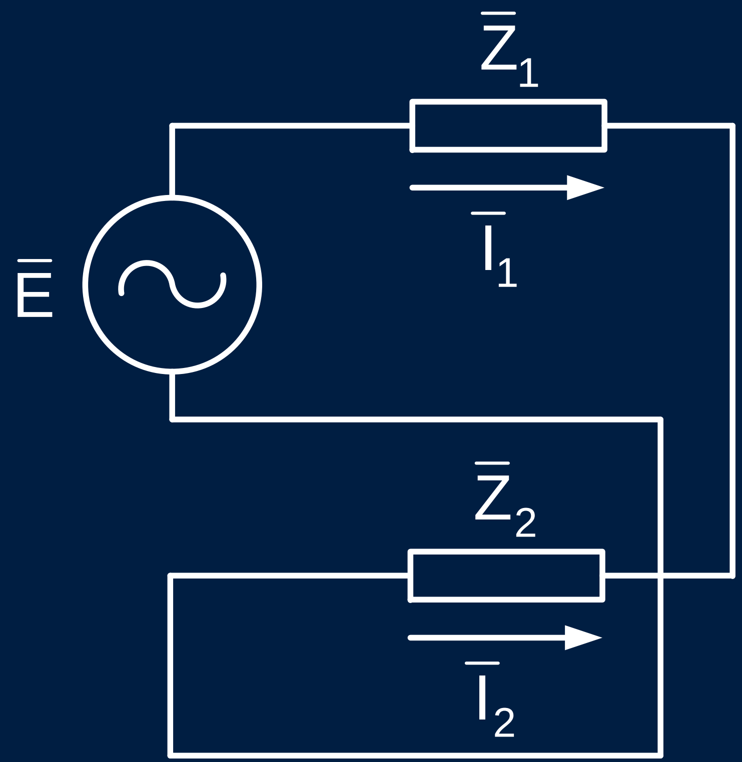


$$\bar{I}_p = \bar{I}_1 = \bar{E} / \bar{Z}_1$$

$$\bar{I}_2 = 0$$

Phase-to-Phase Fault





$$\bar{Z}_1 = \bar{Z}_2$$

$$\bar{I}_1 = -\bar{I}_2 = \bar{E} / \left(2\bar{Z}_1\right)$$

$$\bar{I}_p = \left(a - a^2\right) \bullet \bar{I}_2 = j1.732 \bullet \bar{I}_2$$

$$\bar{I}_p = 1.732 \bullet \bar{I}_1 = \bar{E} \bullet 1.732 / 2 \bullet \bar{Z}_1$$

$$\bar{I}_p = 1.732 / 2 \bullet \bar{E} / Z_1$$

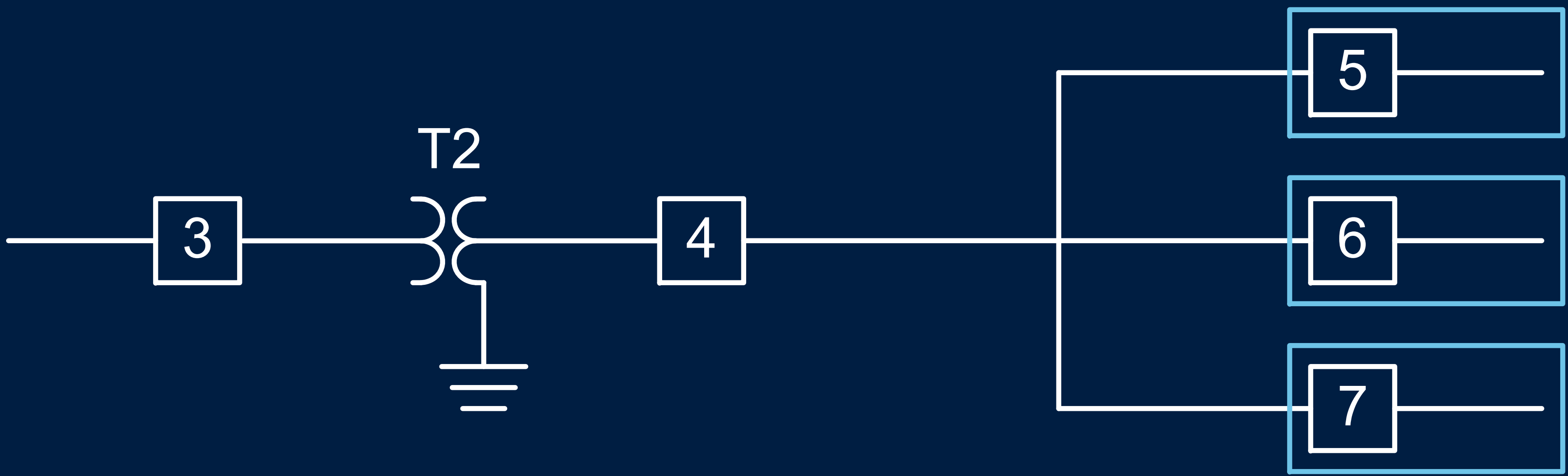
$$\bar{I}_p = 0.866 \bullet \bar{E} / \bar{Z}_1$$

$$I_{\text{phase-to-phase}} = 0.866 \bullet I_{\text{three-phase}}$$

Traditional Versus Enhanced Distribution Protection

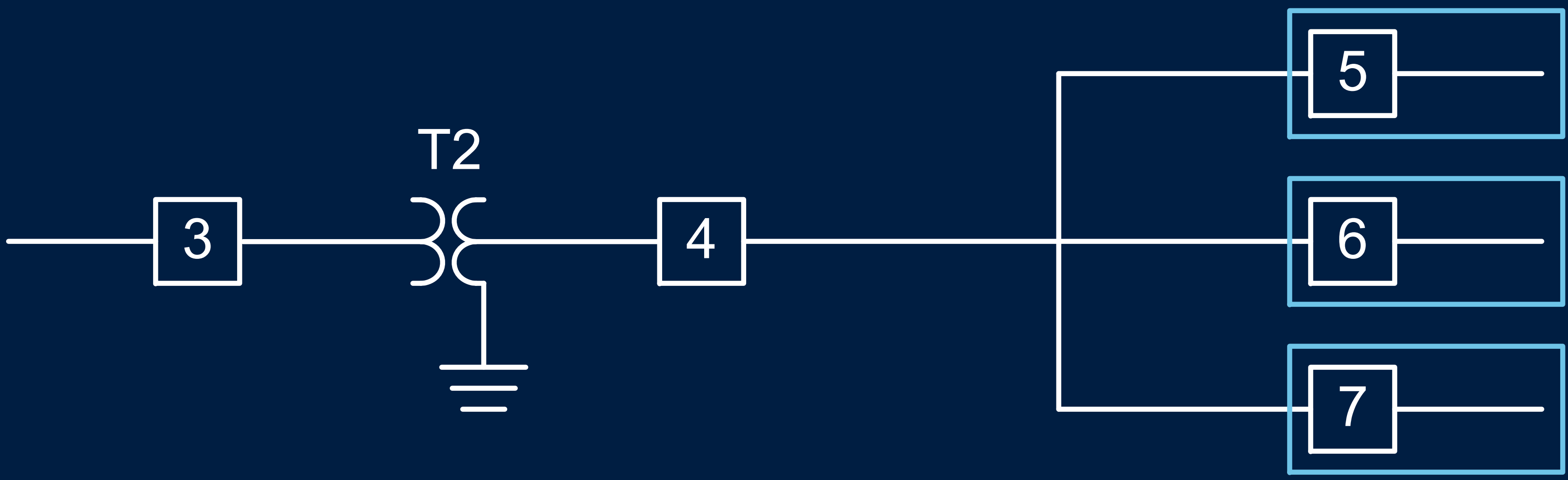
- Traditional protection
  - Time-delayed backup
  - Limited protection features
- Enhanced protection
  - High-speed backup
  - High-speed bus protection
  - No additional relays

Traditional Distribution Protection



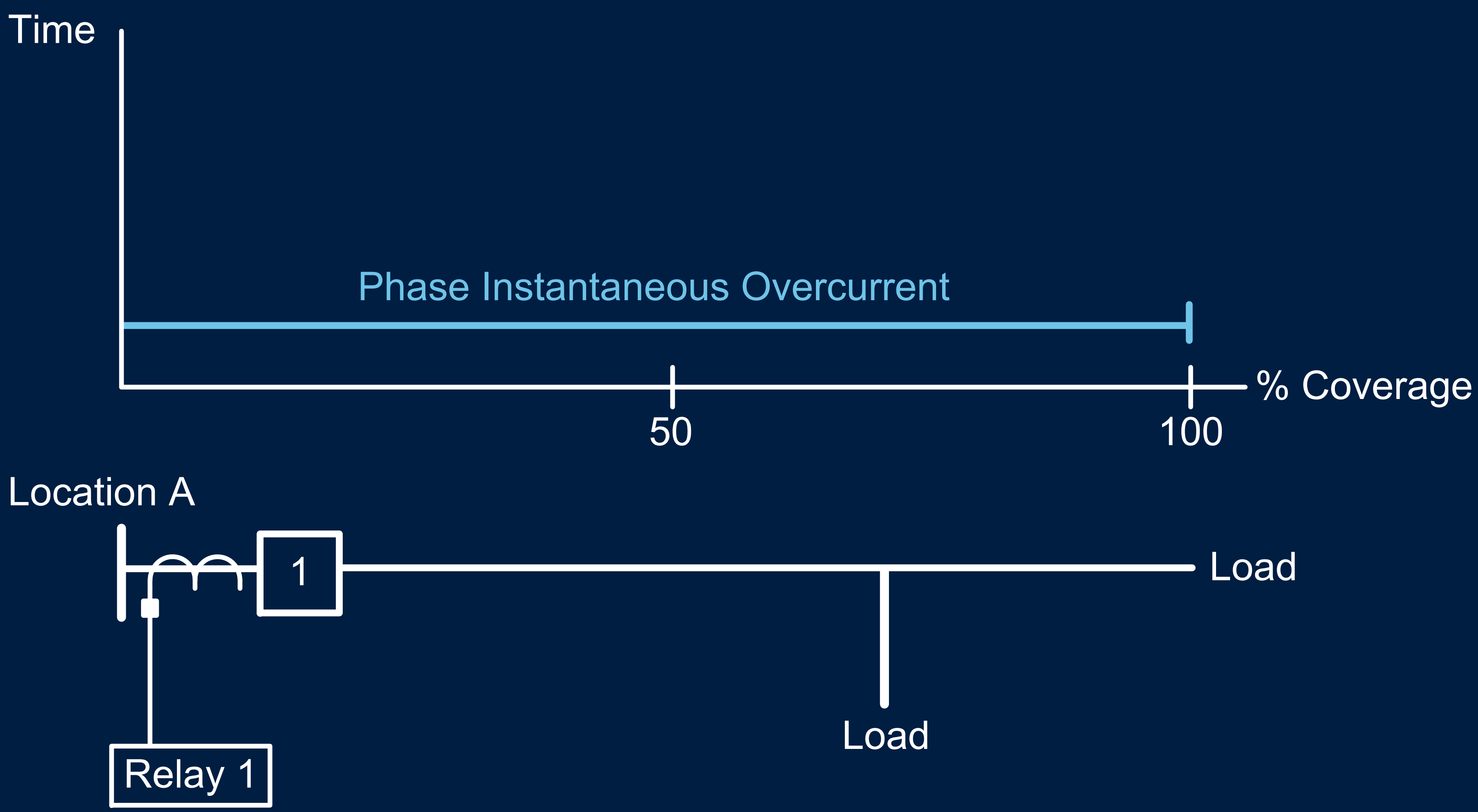
Feeder protection zone 50P, 51P, 50G, 51G, 79

Enhanced Feeder Protection

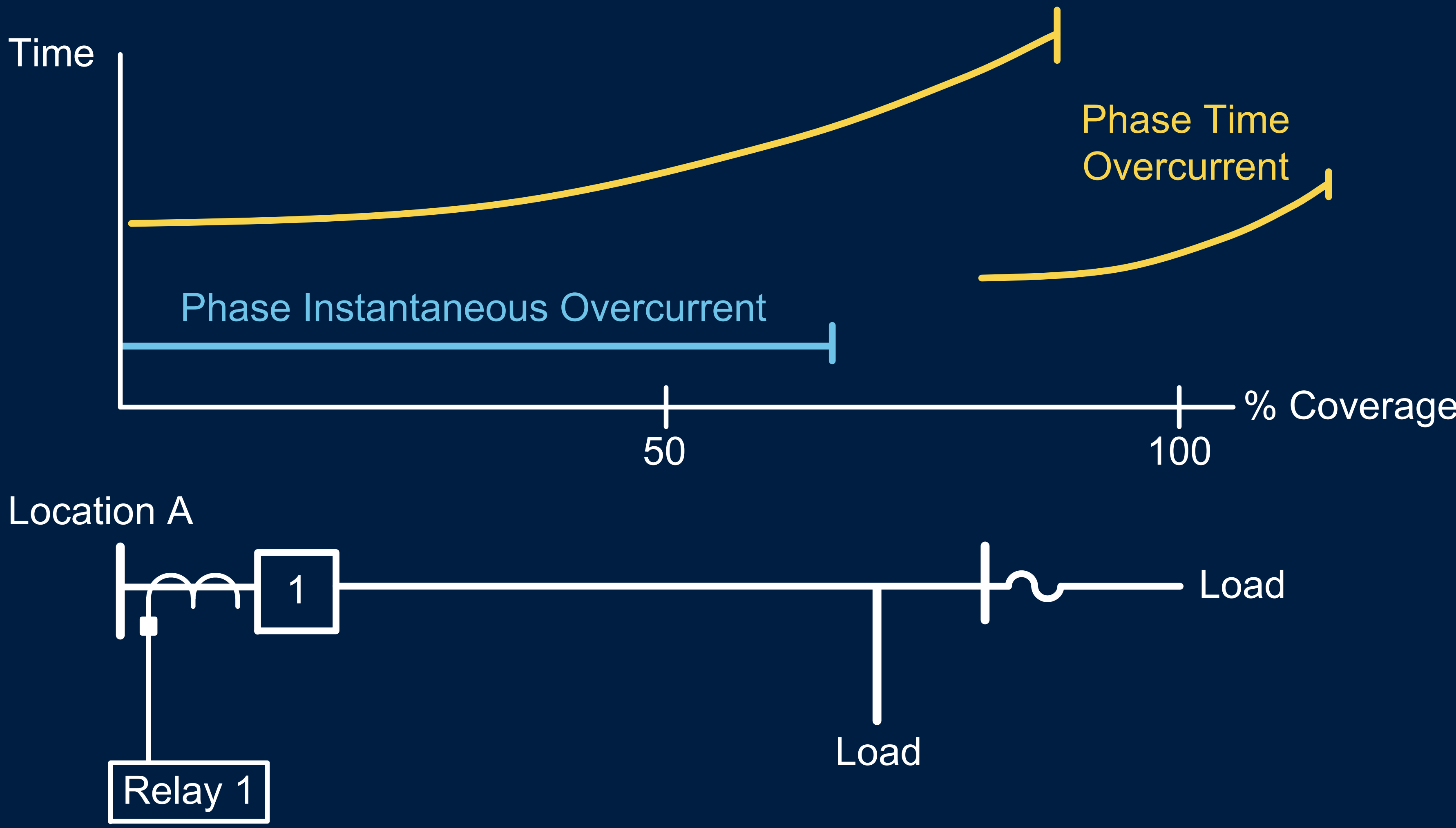


Feeder protection zone 50P, 51P, 50G, 51G, 79, trip coil monitoring, dc trip voltage monitoring, 50BF, 51QT

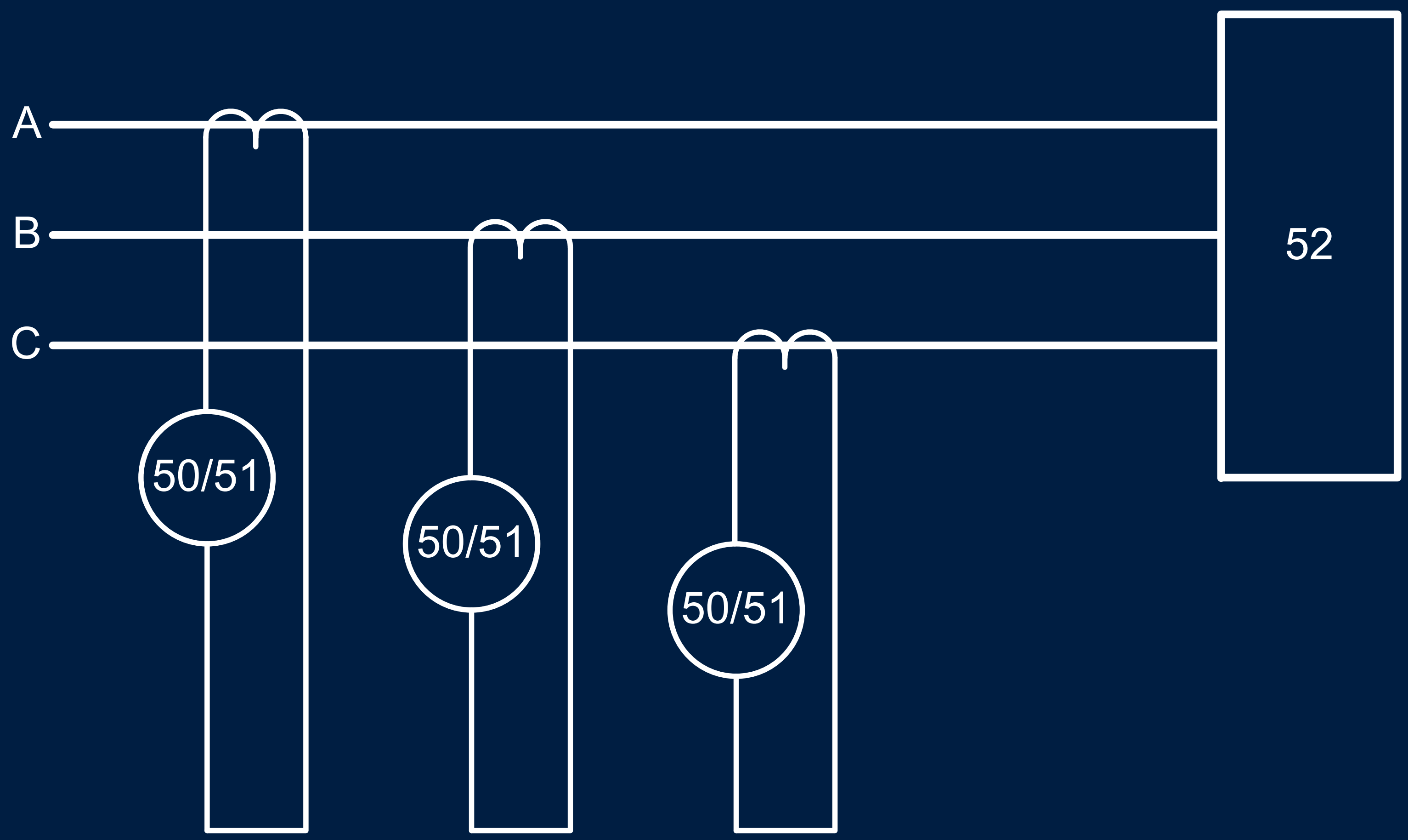
Traditional Overcurrent Protection



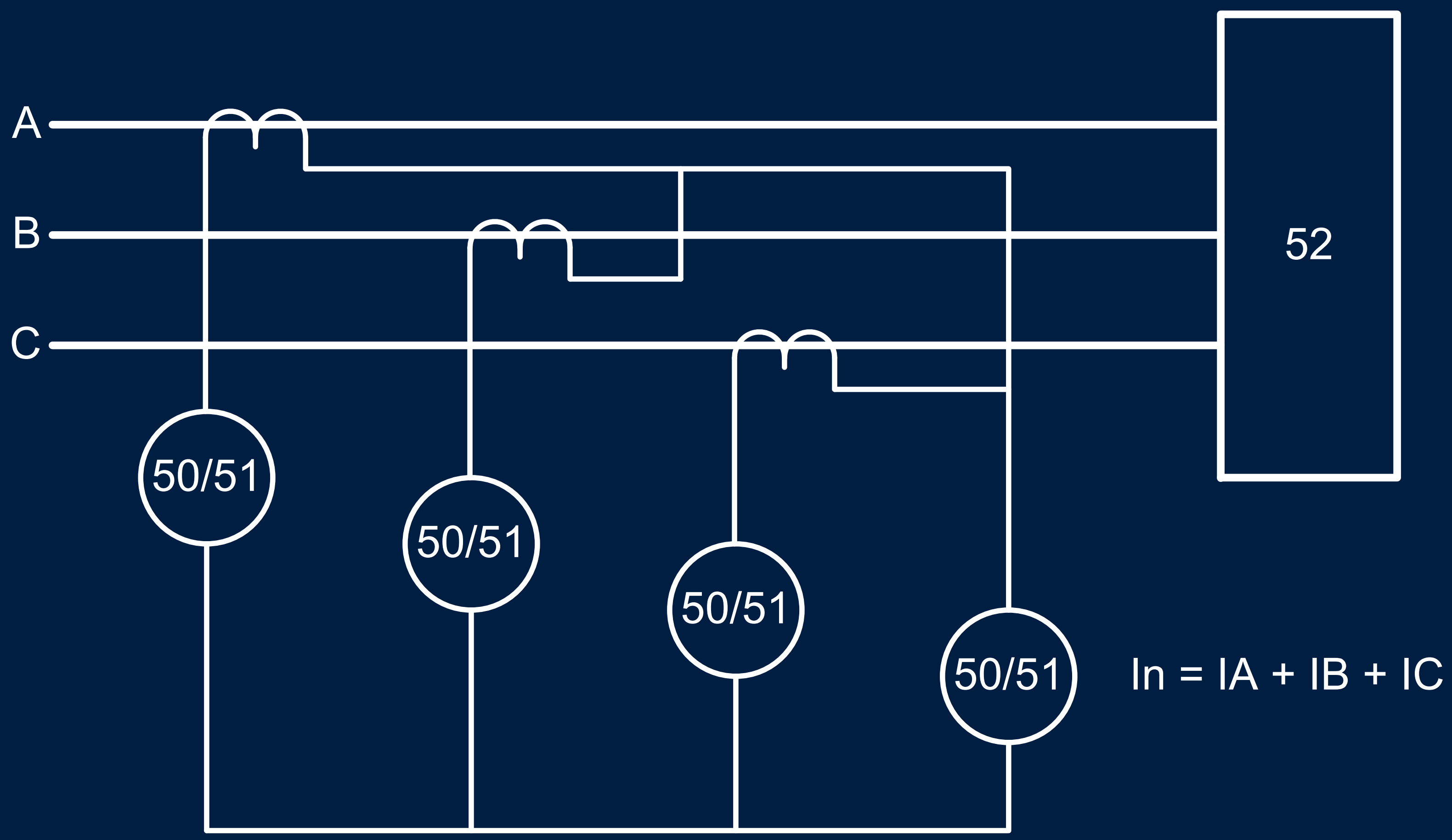
Traditional Overcurrent Protection



Phase Overcurrent Protection



Phase and Ground Overcurrent Protection Three-Line Diagram

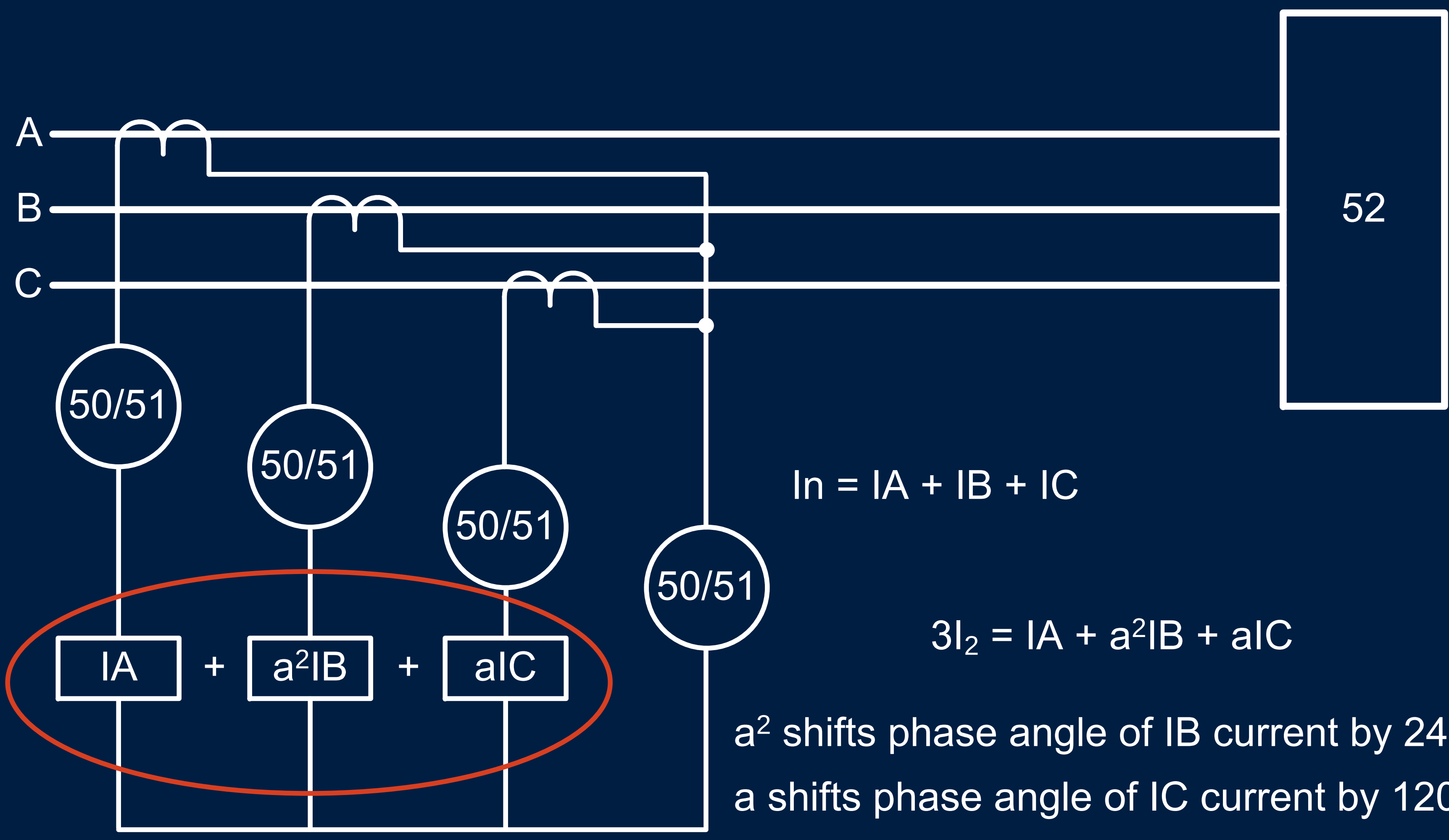


Ground Overcurrent Protection
Not a Complete Solution

- Advantages
  - Is more sensitive than phase overcurrent protection for ground faults
  - Is easy to make connection to detect ground current
  - Improves protection for most common fault type
- Disadvantage – no protection for phase-to-phase or three-phase faults

Introduction to Negative-Sequence Overcurrent Elements

Phase, Ground, Negative-Sequence Overcurrent Protection



In = IA + IB + IC

$3I_2$ = IA + a^2IB + aIC

a^2 shifts phase angle of IB current by 240°

a shifts phase angle of IC current by 120°

Phase-to-Phase Fault Detector
Negative-Sequence Overcurrent Element

- Advantages
  - Is more sensitive than phase overcurrent protection for phase-to-phase faults
  - Is easy to calculate negative sequence in relay
  - Improves protection for second most common fault type
- Disadvantage – not sensitive to three-phase faults

Setting Negative-Sequence Overcurrent Elements

Step 1: Find Downstream Phase Overcurrent Device of Greatest Coordination Concern

- Usually next downstream overcurrent device
- Typically no downstream negative-sequence overcurrent device

Step 2: Think of Negative-Sequence Element

- As equivalent phase time-overcurrent element backup
- As being located at downstream device

Step 3: Perform Typical Phase Coordination With Downstream Phase Overcurrent Device

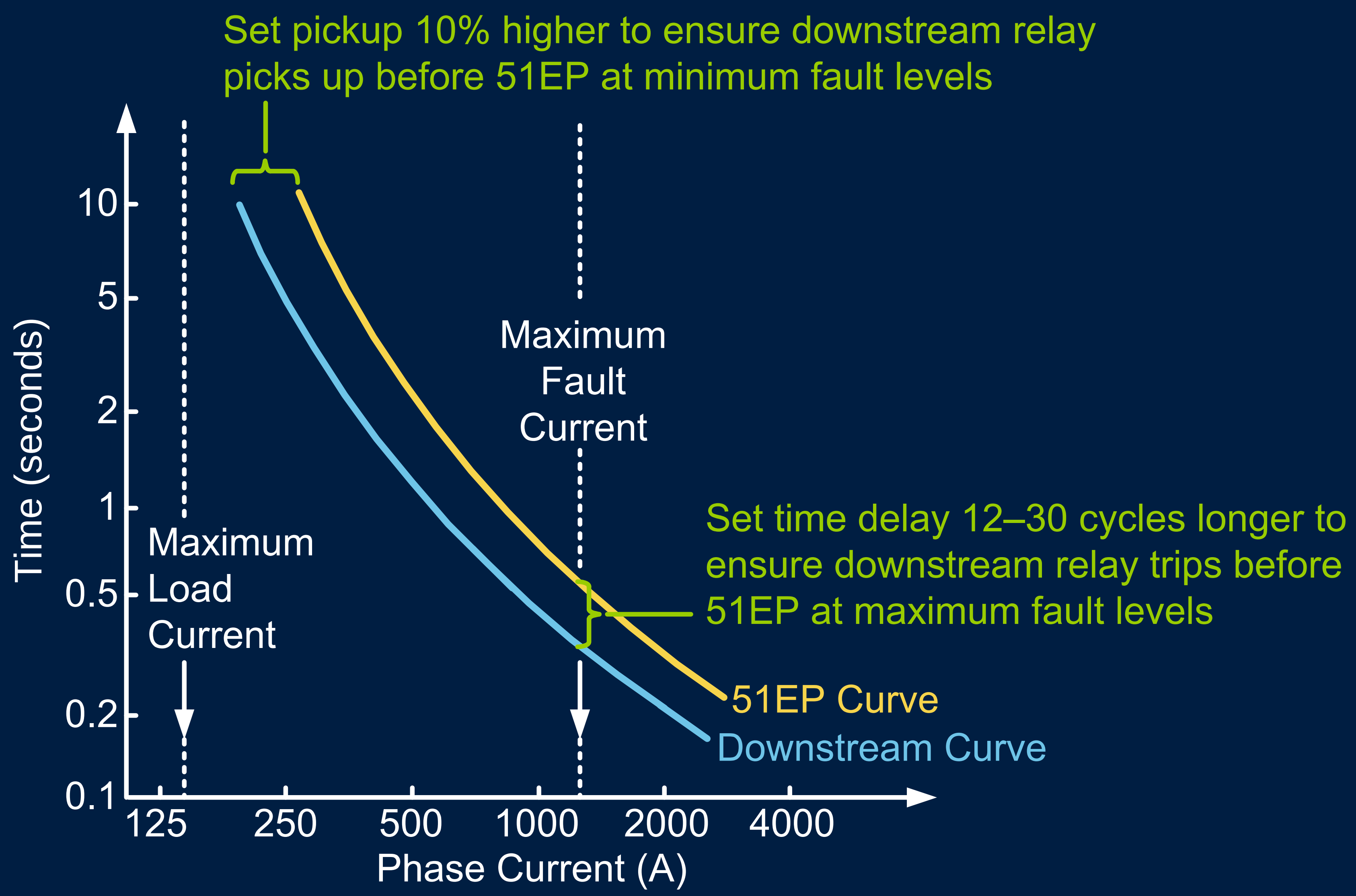
- Same curve shape
- Coordination margin of 12 to 30 cycles
- Same pickup plus 10%

Step 4: Transform Equivalent Element Settings to Negative-Sequence Overcurrent Settings

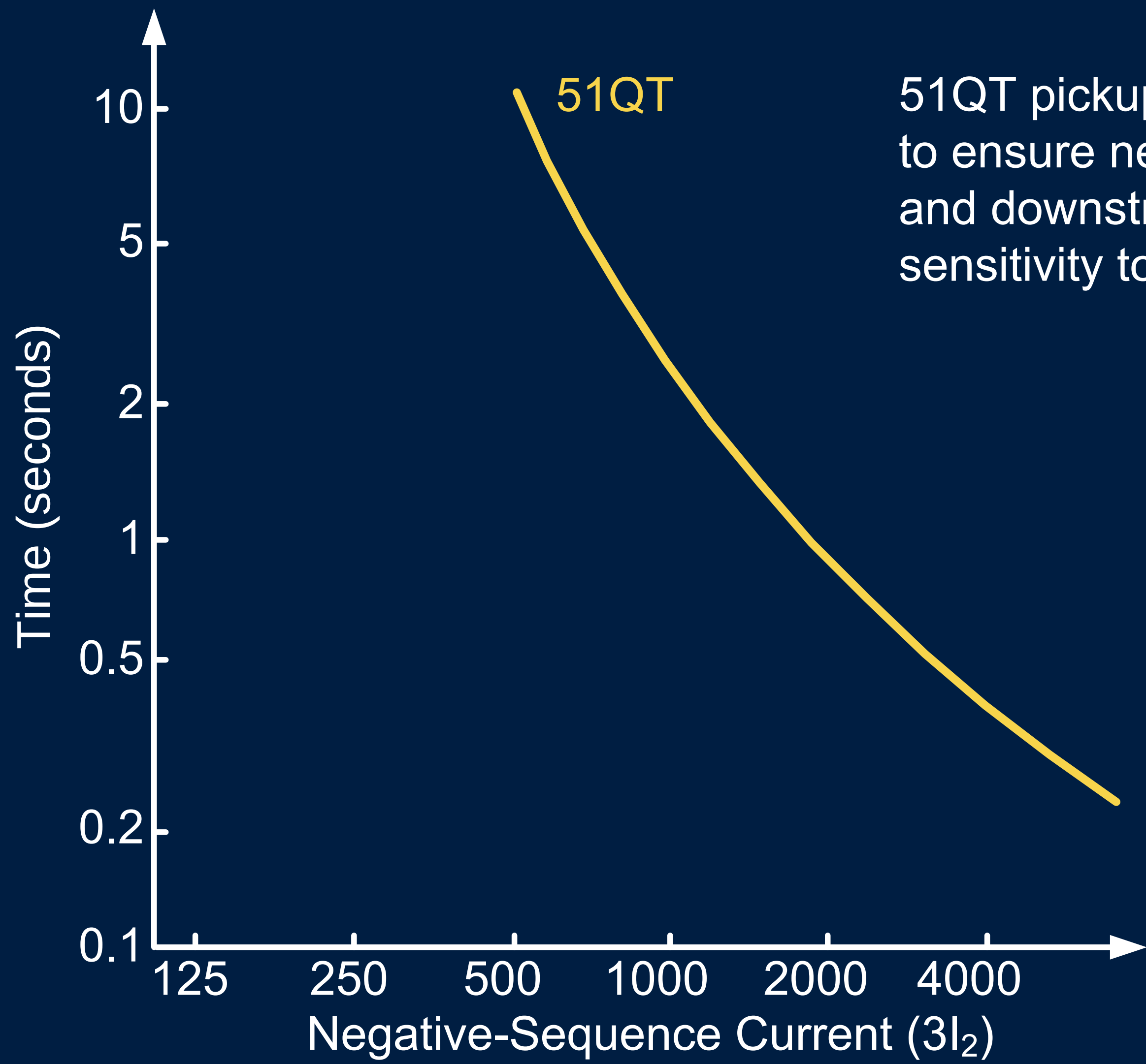
$$\text{Negative-sequence element pickup} = \sqrt{3} \bullet (\text{equivalent element pickup})$$

Time dial and curve type are unchanged

Equivalent Phase Overcurrent Element

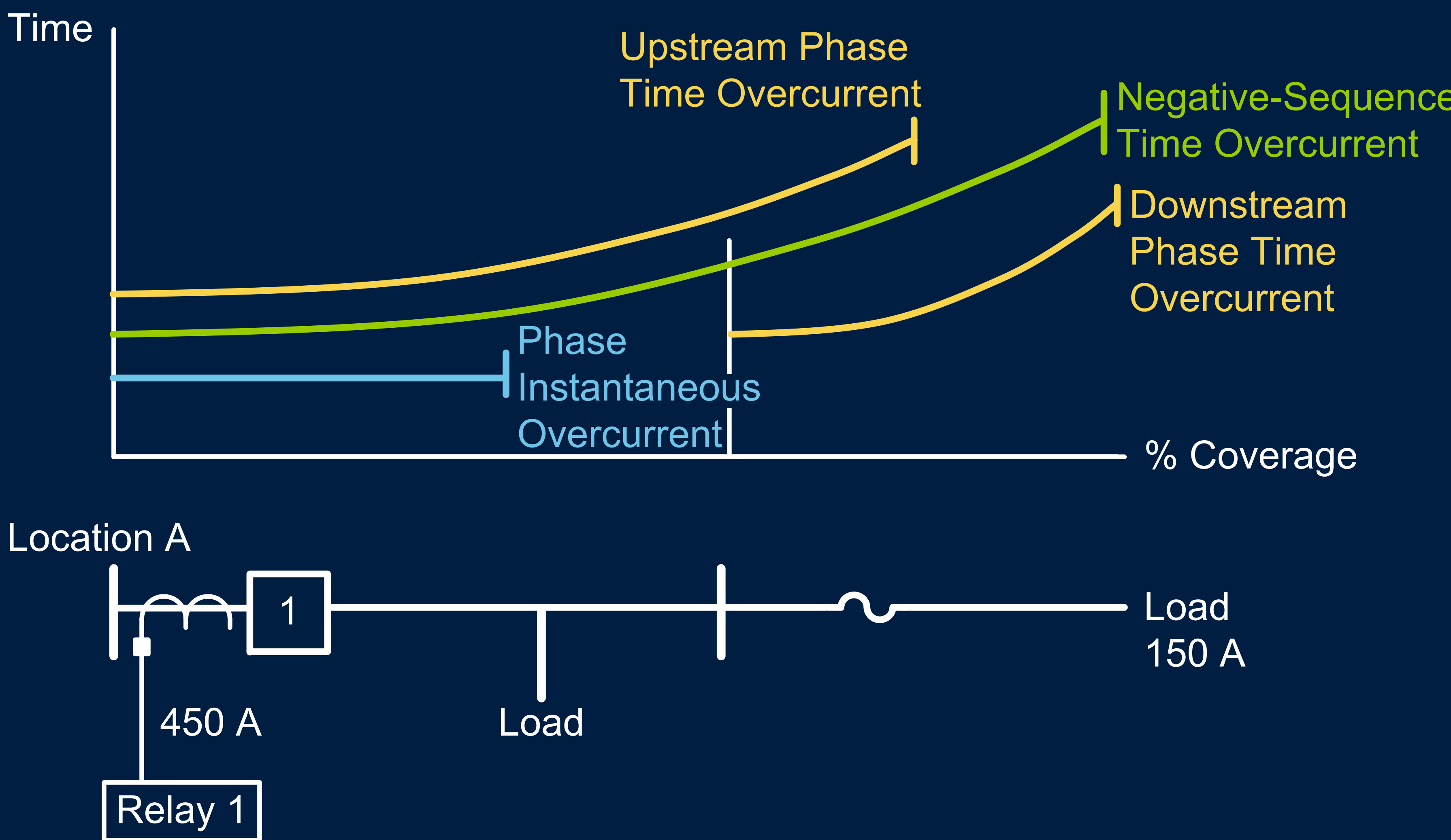


Negative-Sequence Overcurrent Element



51QT pickup is 51EP pickup • 1.732 to ensure negative-sequence element and downstream relay have equal sensitivity to phase-to-phase faults

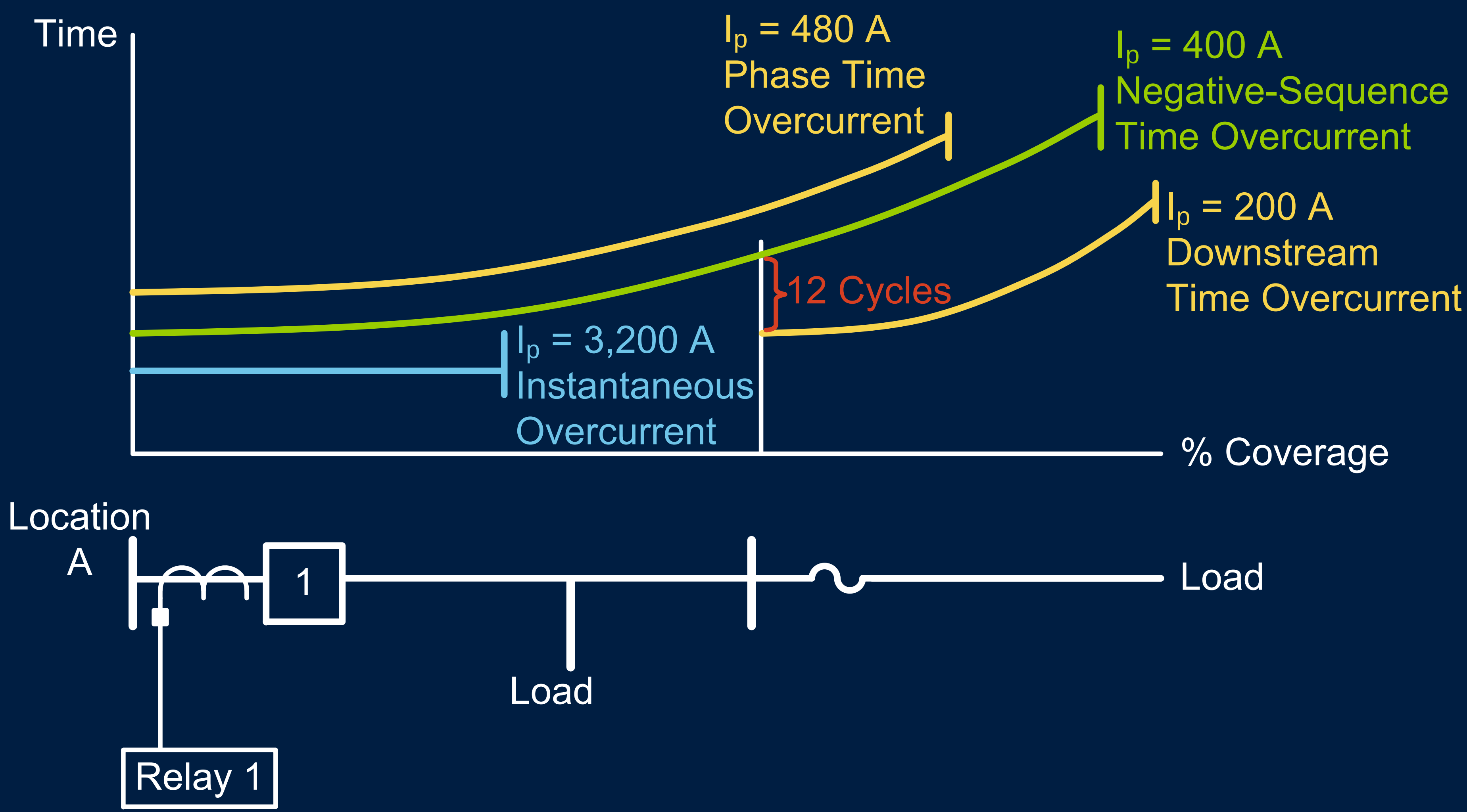
Enhanced Overcurrent Protection



Negative-Sequence Elements

- Are immune to balanced load conditions
- Improve sensitivity to phase-to-phase faults
- Can be easily implemented in microprocessor-based relays
- Are easy to set

Customer Negative-Sequence Settings Coordination



Customer Solution

Add Negative-Sequence Protection

51QP = 5.00

51QTD = 3.00

51QCT = 0.00

51QC = U3

51QRS = N

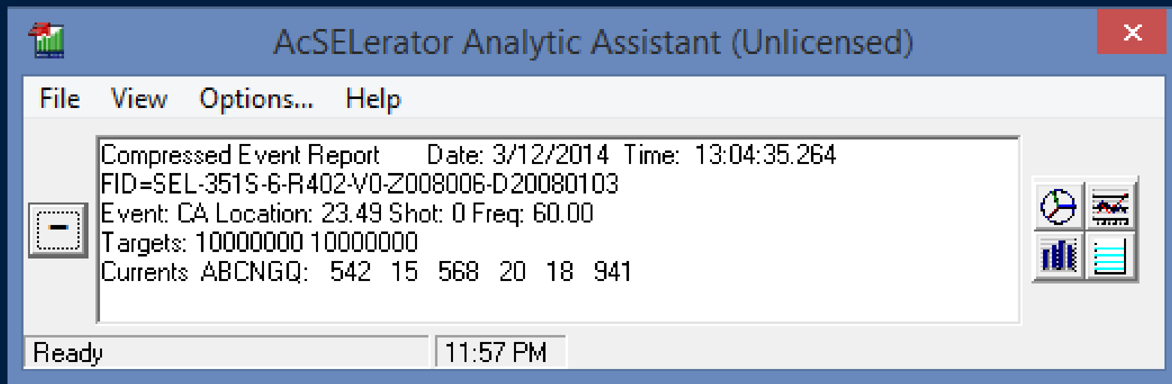
51QMR = 0.00

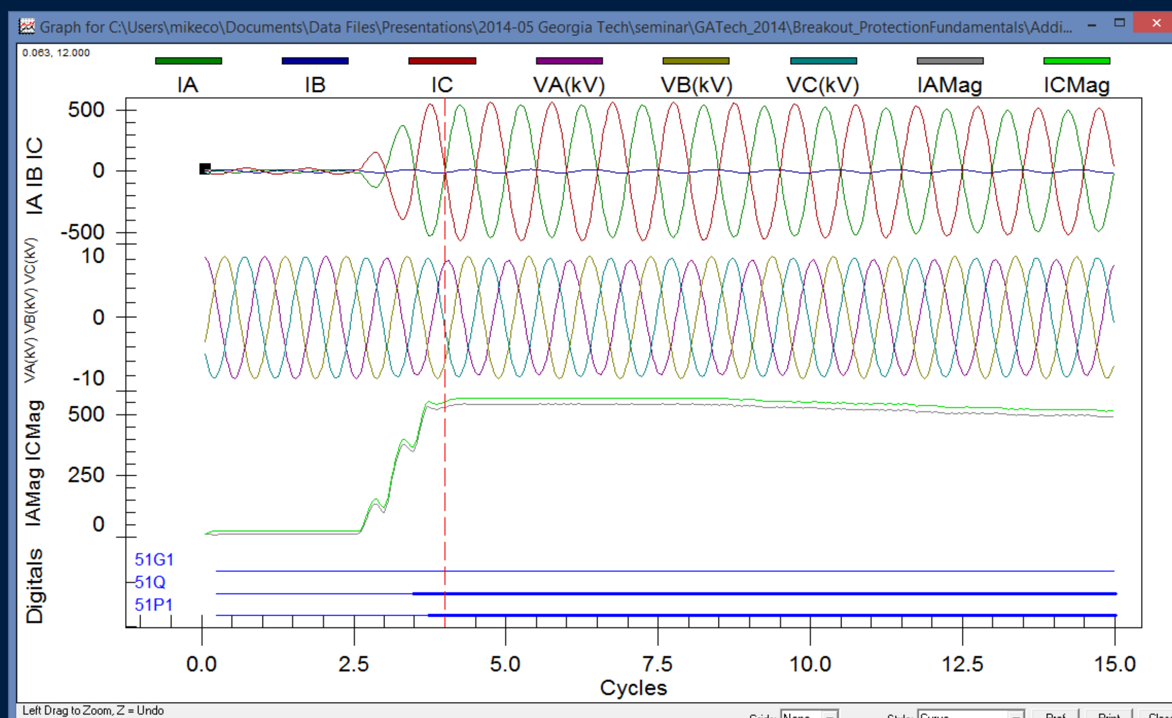
Customer Solution

Add Negative-Sequence Protection

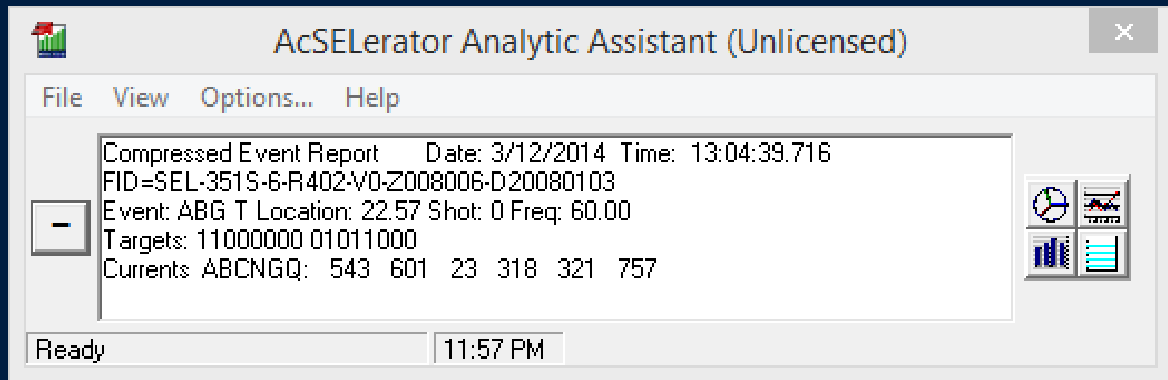
- Old TR = 50P1 + 51P1T + (51G1T + 50G1) * LT1 + OC + 81D2T + (51P1 + 51G1) * !LT5 + (PB8 * SV2T)
- New TR = 50P1 + 51P1T + (51G1T + 50G1 + 51QT) * LT1 + OC * LT3 + (51P1+ 51G1) * !LT5 + (PB8 * SV2T)

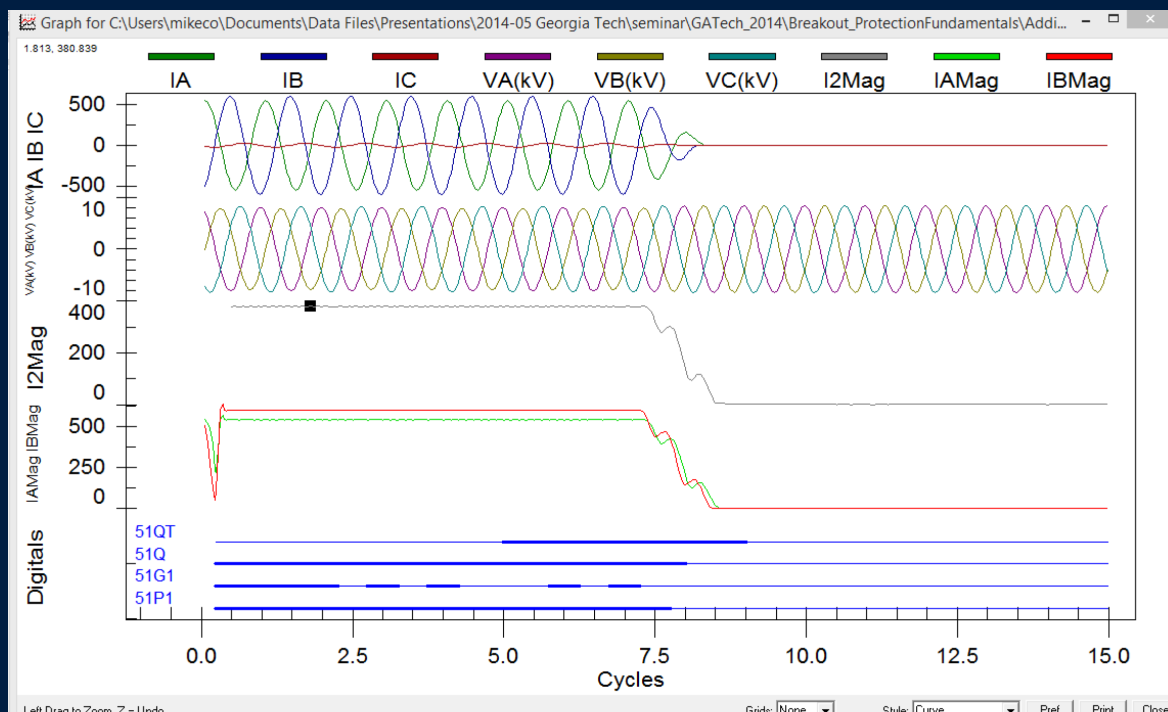
Déjà Vu in March 2014





Déjà Vu in March 2014





Noticeable Improvement

- 51QT clearing time of 4 seconds

  Line was not damaged

- Phase fault current

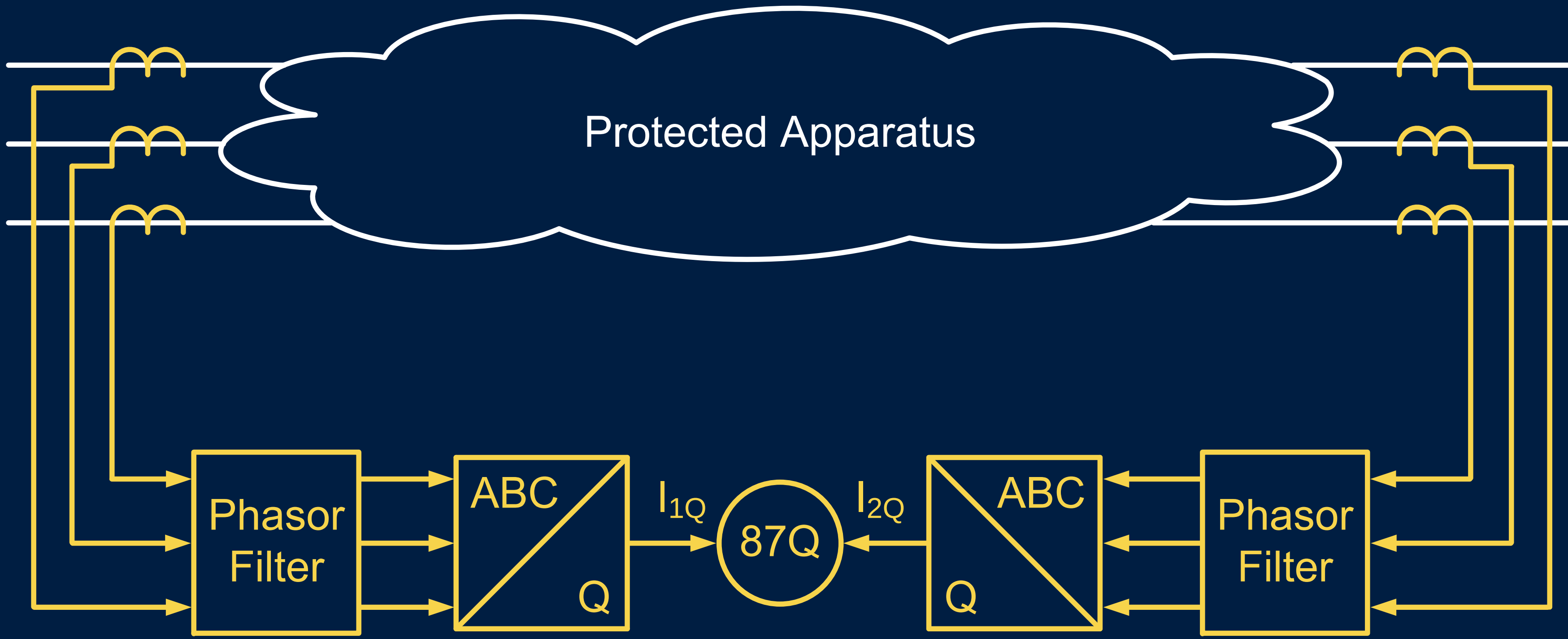
  540 A (1.125 multiples of pickup)

- Negative-sequence fault current

  $3I_2$ = 981 A (2.45 multiples of pickup)

Negative-Sequence Differential Element

87Q Principle

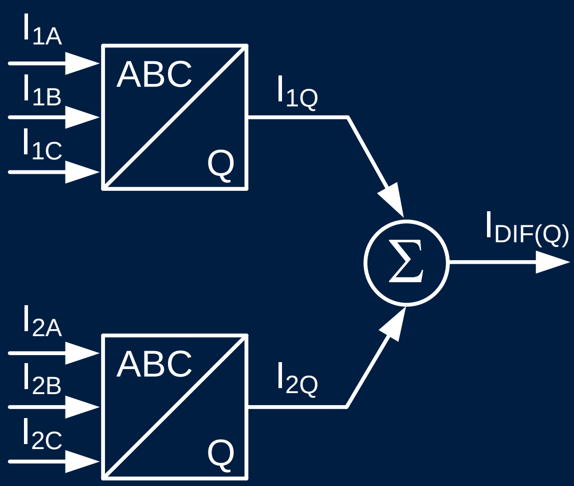


- Sensitive
- Fast
- Inherently secure

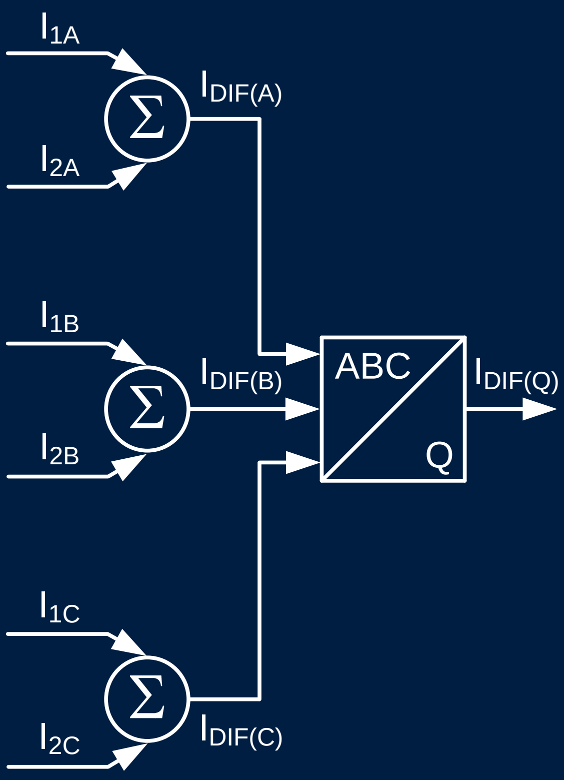
The Secret to Sensitivity

Differential Current?

$$I_{DIF(Q)} = \left| I_{1(Q)} + I_{2(Q)} + \ldots + I_{N(Q)} \right|$$



Mathematically Equivalent



No 87P differential = no 87Q differential

The Secret to Sensitivity

Restraining Current?

$$I_{RST(Q)} = \left|I_{1(Q)}\right| + \left|I_{2(Q)}\right| + \ldots + \left|I_{N(Q)}\right|$$

Lower restraint provides sensitivity but challenges security

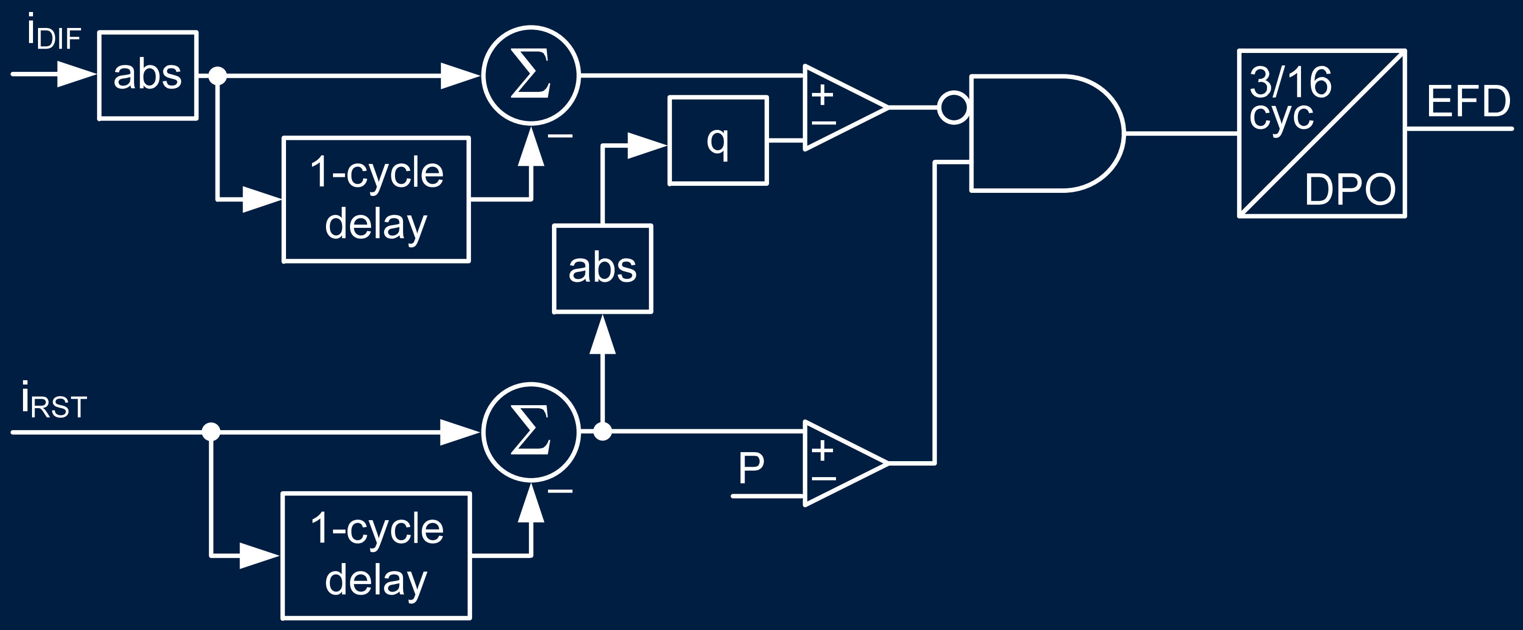
Restraining Current Purpose

Reflect the stress on protection system components, CTs in particular, that can cause spurious differential current

Negative-sequence restraining current does not meet this requirement for balanced faults / events

The Secret to Sensitivity
Addressing CT Saturation

- Security problems under CT saturation
- Need for external fault detection logic



Negative-Sequence Differential

- Is excellent for protecting lines and transformers
- Needs security for CT saturation

Negative-Sequence Directional Element

Negative-Sequence Equations

Voltage and Current

$$3V_2 = V_A + a^2 V_B + aV_C$$

$$3I_2 = I_A + a^2 I_B + aI_C$$

where $a = 1\angle 120°$

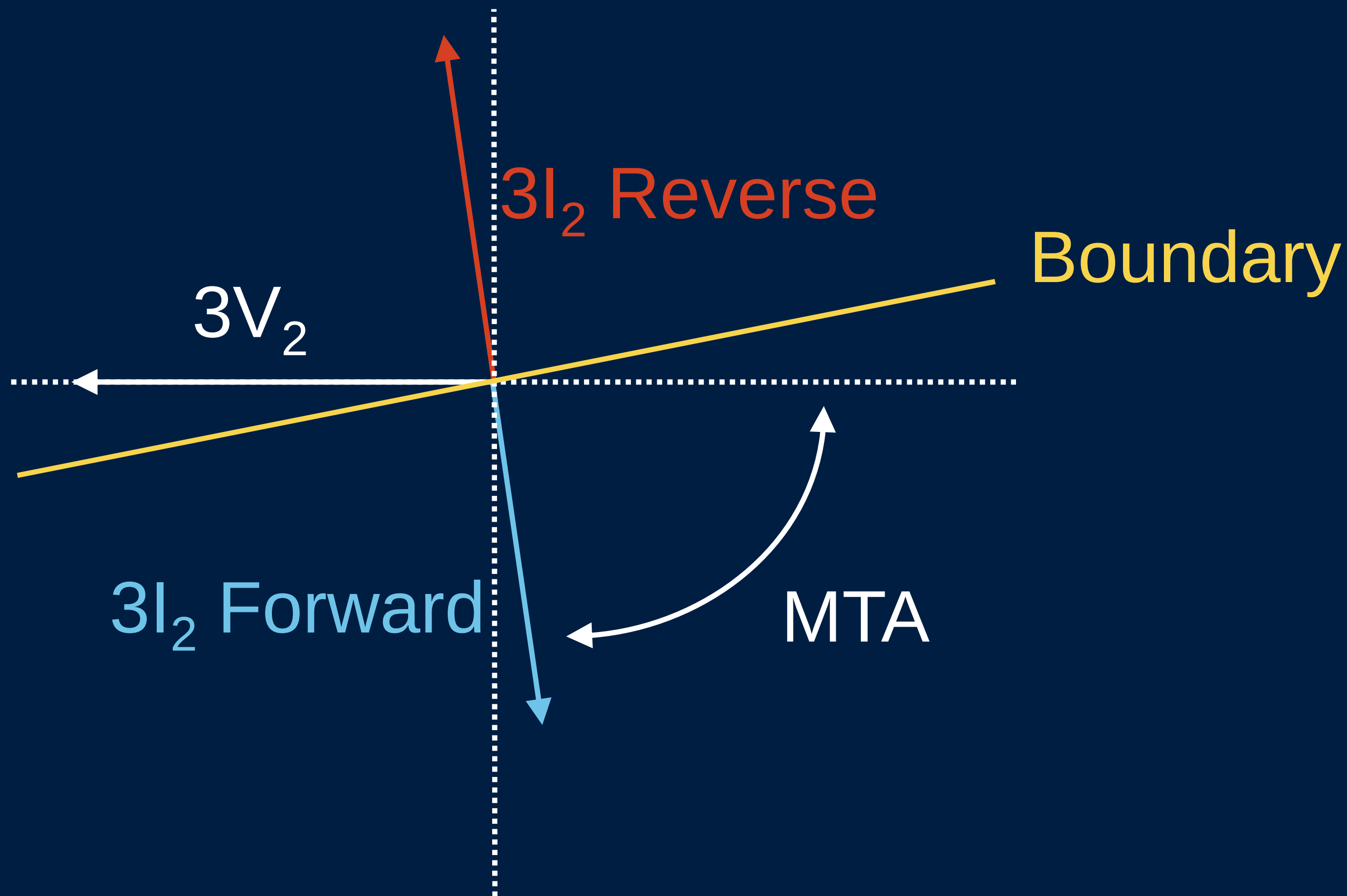
and $a^2 = 1\angle 240°$

Traditional Negative-Sequence Directional Element

$$T32Q = |V_2||I_2|\cos\left(\angle -V_2 - \left(\angle I_2 + MTA\right)\right)$$

- Positive torque indicates forward direction
- Negative torque indicates reverse direction

Phasor Diagram Shows Maximum Torque Angles for Traditional Negative-Sequence Directional Element



Traditional Negative-Sequence Directional Element Limitations

$$T32Q = |V_2||I_2|\cos\left(\angle -V_2 - \left(\angle I_2 + MTA\right)\right)$$

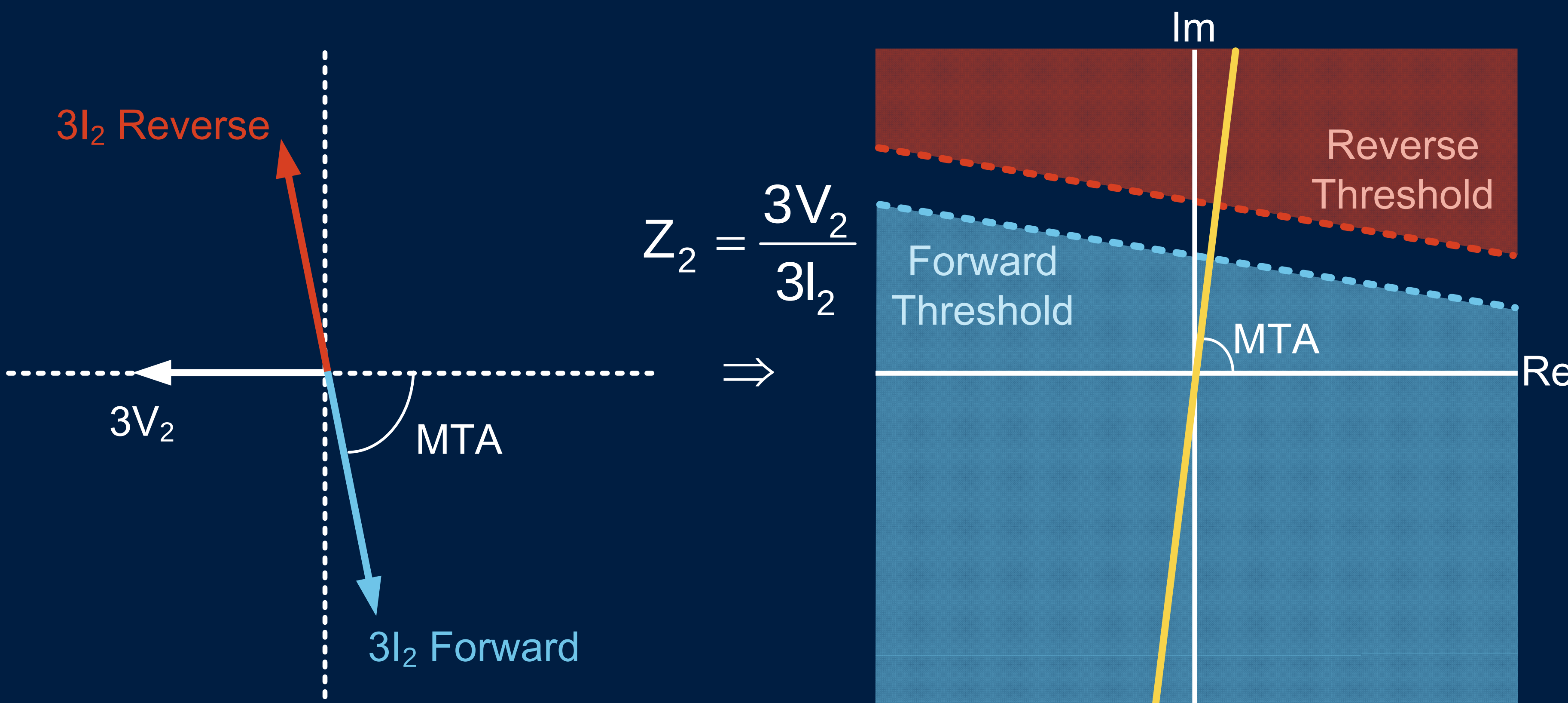
- Torque produced is proportional to magnitude of V_2 and I_2, limits sensitivity of directional element
- Direction of very short phasor is difficult to determine, incorrect directional declarations may result

Negative-Sequence Impedance Directional Element

$$Z_2 = \frac{V_2}{I_2} = \frac{3V_2}{3I_2}$$

- Negative impedance indicates *forward* direction
- Positive impedance indicates *reverse* direction
- Forward and reverse thresholds can be applied for security

Negative-Sequence Impedance Directional Element



$$Z_2 = \frac{3V_2}{3I_2}$$

Negative-Sequence Impedance Directional Element

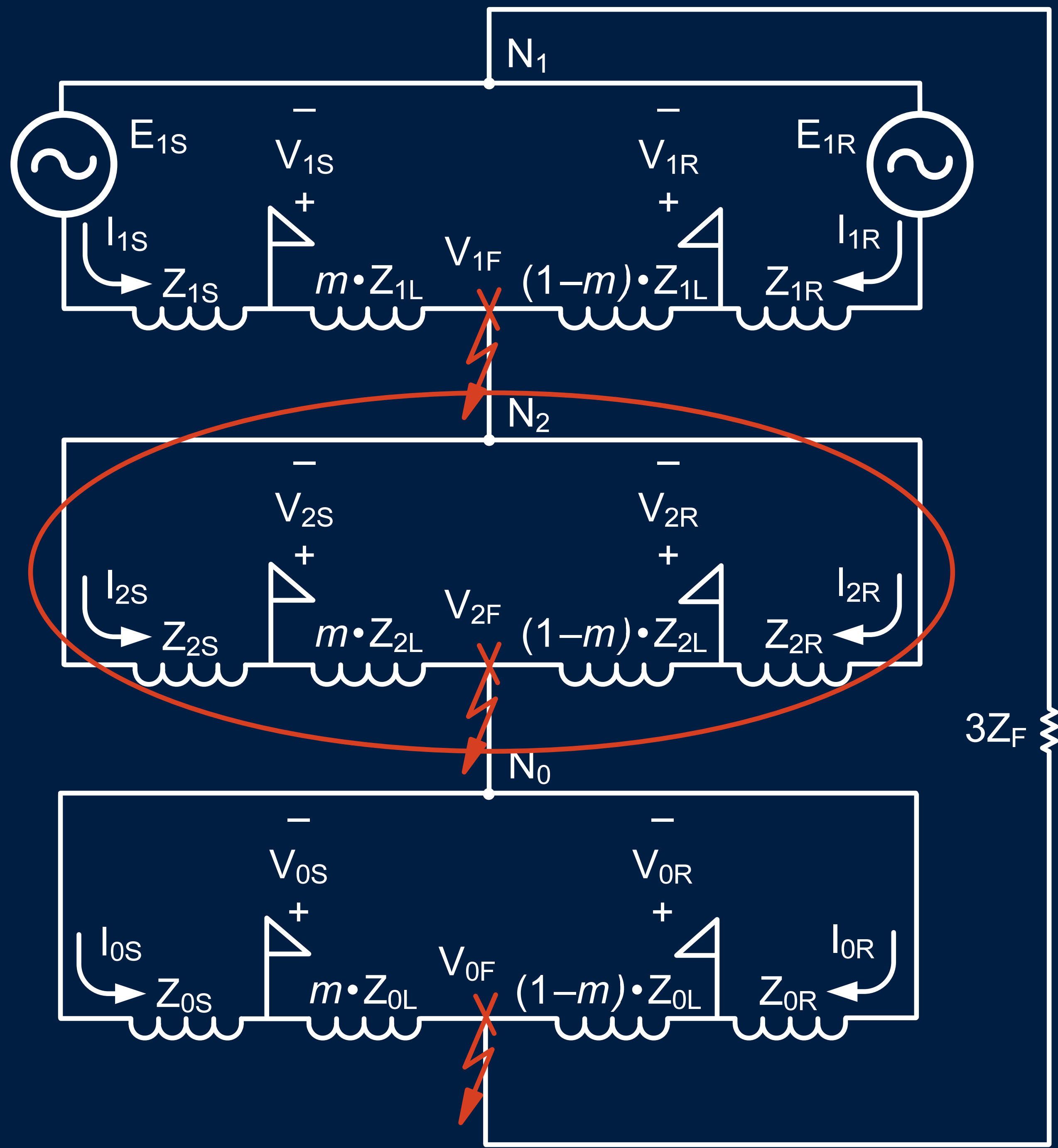
$$Z_2 = \frac{V_2}{I_2} = \frac{3V_2}{3I_2}$$

- Direction can be determined for faults with essentially zero negative-sequence voltage
- Directional element has greater sensitivity

Negative Sequence for Fault Location

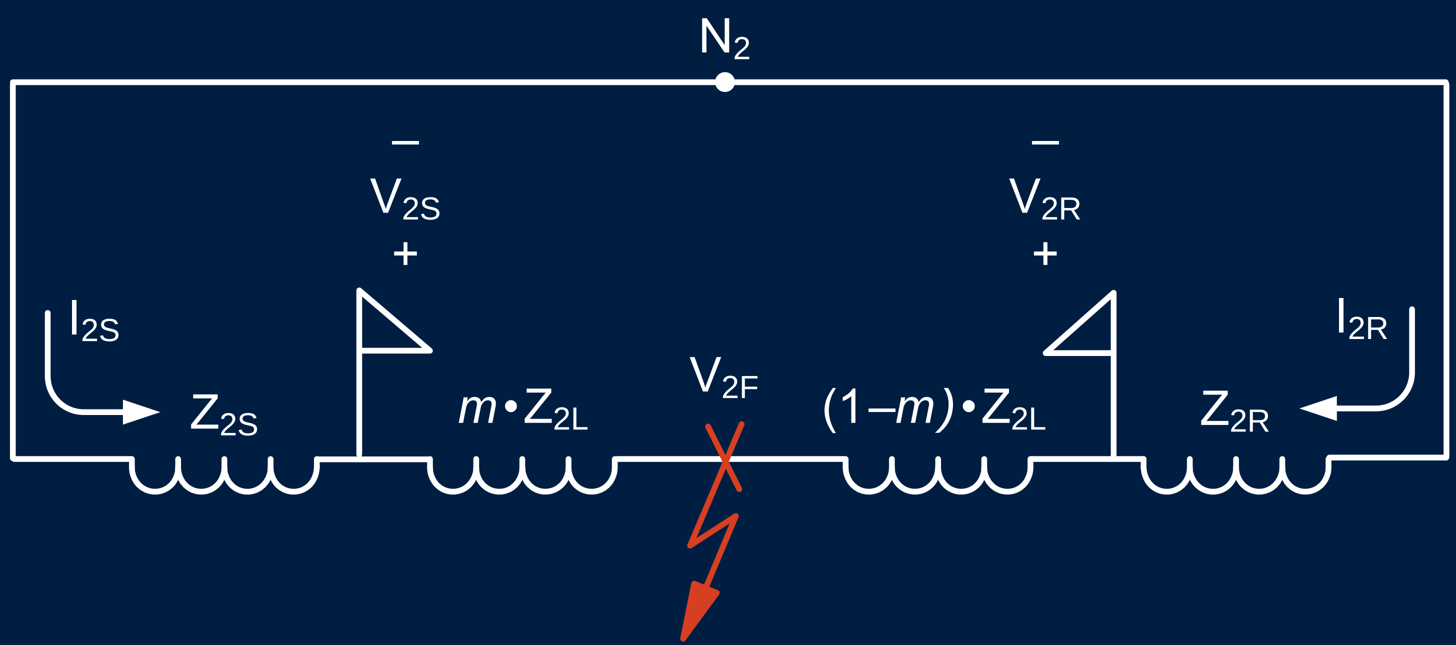
Negative Sequence for Fault Location

Double-Ended



Negative Sequence for Fault Location

Double-Ended



$$m = \frac{V_{2S} - V_{2R} + I_{2R} \bullet Z_{2L}}{Z_{2L}(I_{2S} + I_{2R})}$$

Negative-Sequence Quantities

- Include voltage, current, and impedance
- Can be used for overcurrent, differential, directional, and fault location elements
- Are already built in to many digital relays; just need to be enabled

Understand elements and associated settings before applying

Questions?