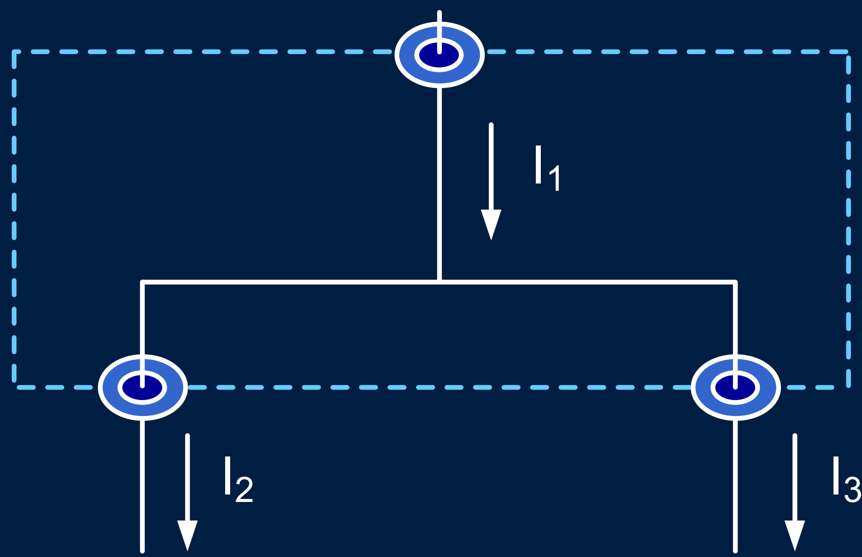
Applying SEL Differential Relays

Introduction to Transformer Differential Protection

Transformer Differential Protection Presentation Objectives

- Explain challenges of transformer differential protection
- Understand need for tap, phase, and zero-sequence compensation and how they work
- Understand how transformer differential relays are made secure for inrush and overexcitation

Differential Protection is Easy in Theory

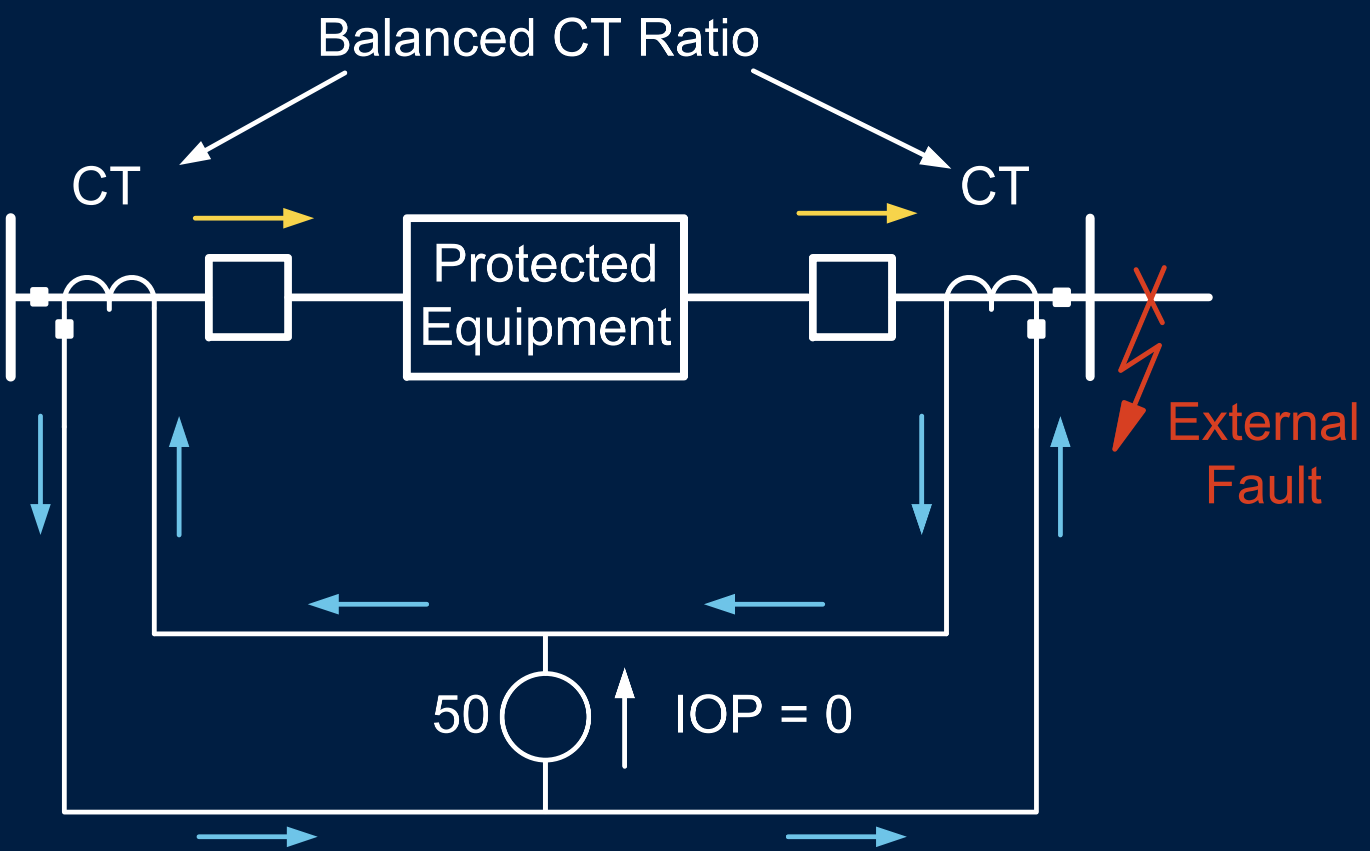


Kirchhoff's Current Law (KCL): $\sum_{k=1}^{n} I_k = 0$

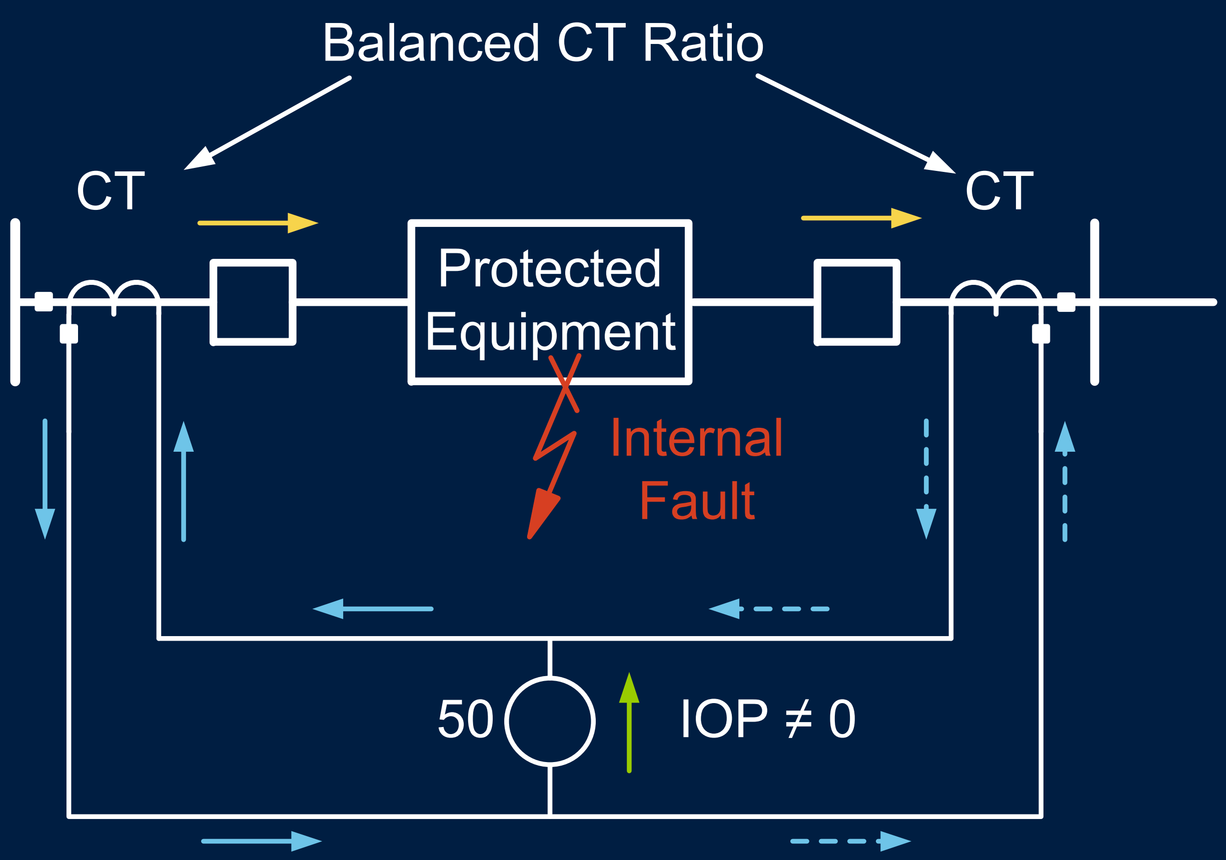
Challenges to Transformer Differential Protection

- Current magnitude mismatch
- Phase shift across transformer
- Zero-sequence sources
- Energization inrush
- Overexcitation
- Unequal CT performance

Differential Protection Principle



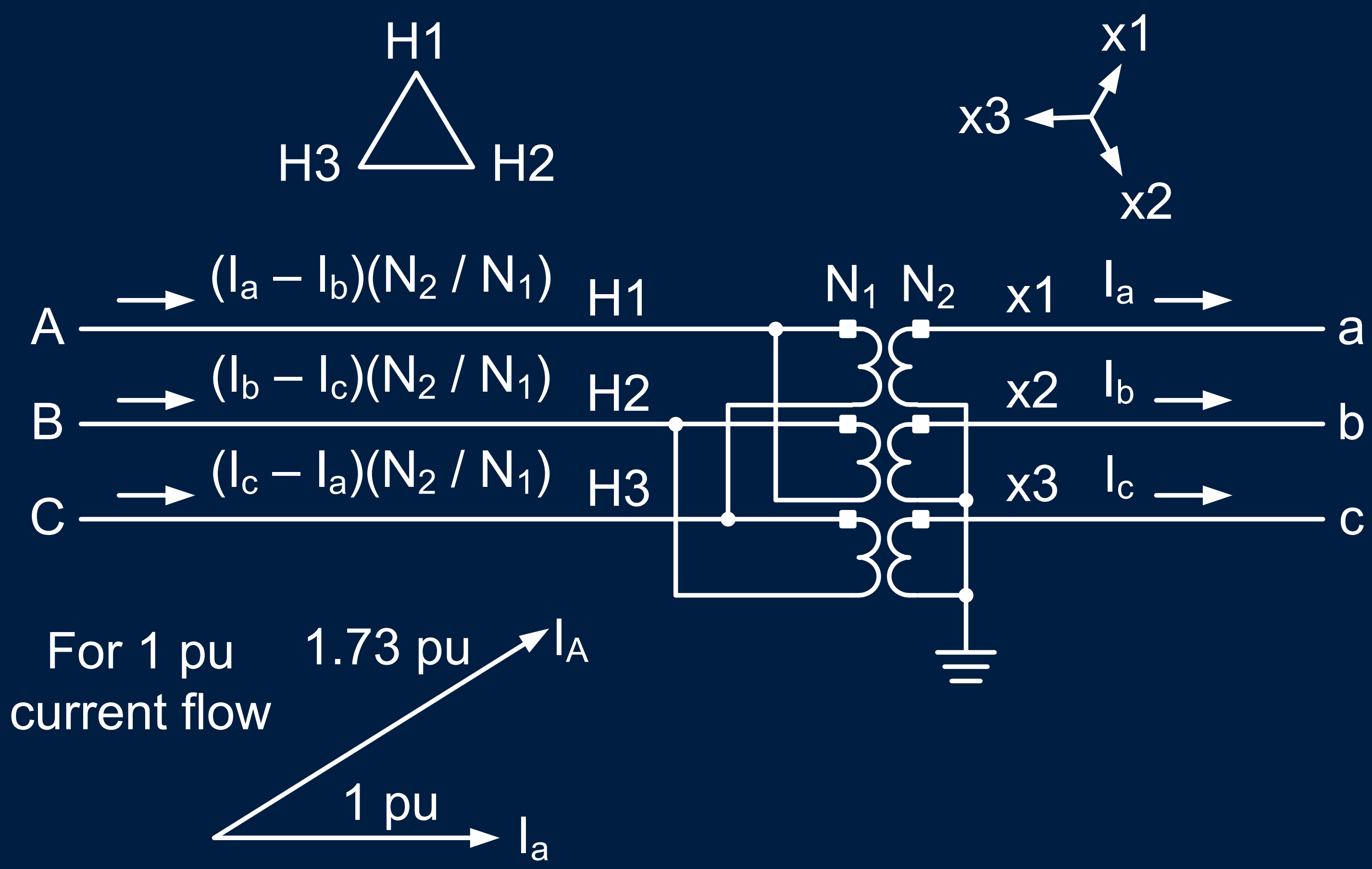
Differential Protection Principle



Current Magnitude and Phase Angle Difference Compensation

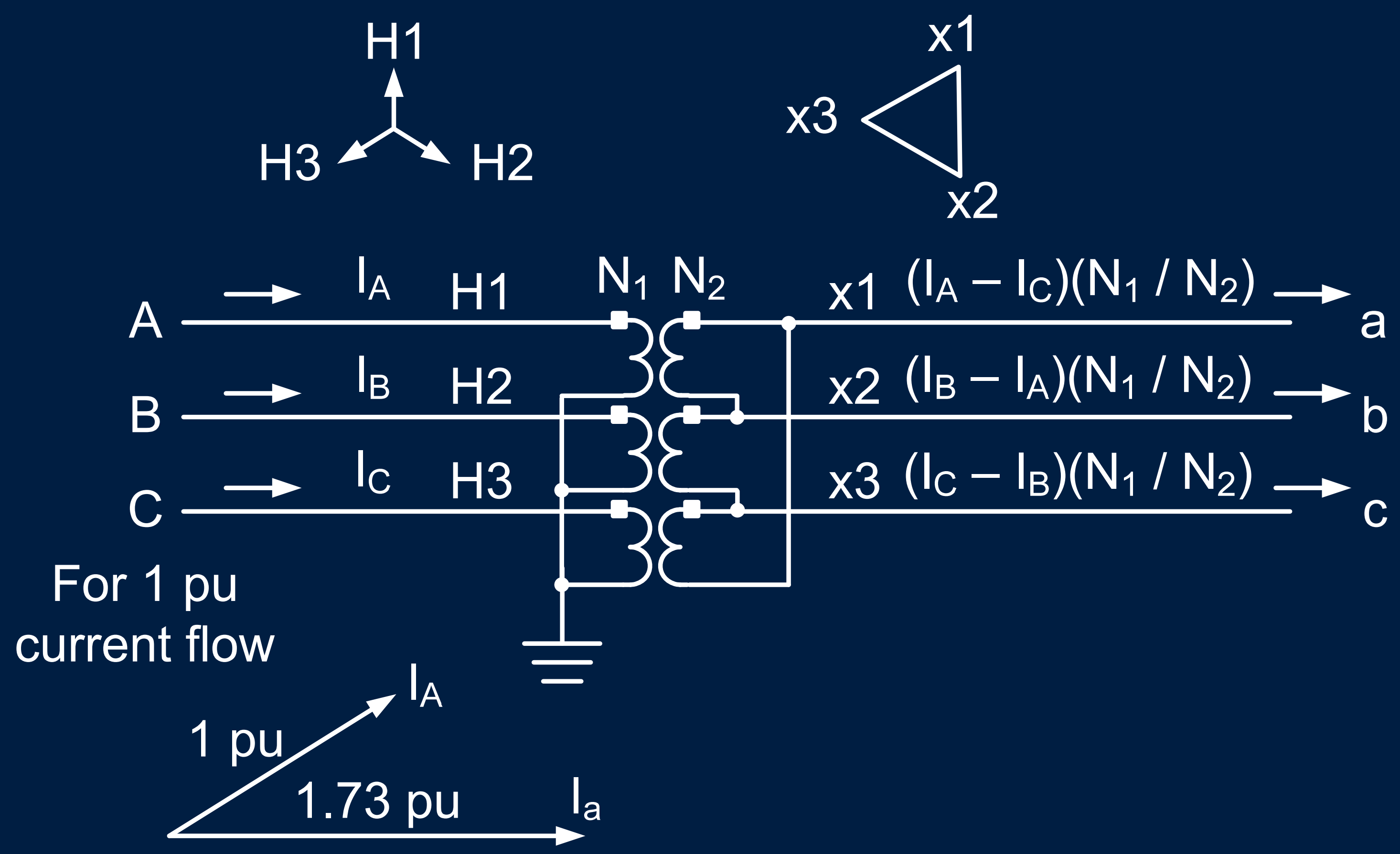
ANSI Transformer Connections

DABY or Dy1

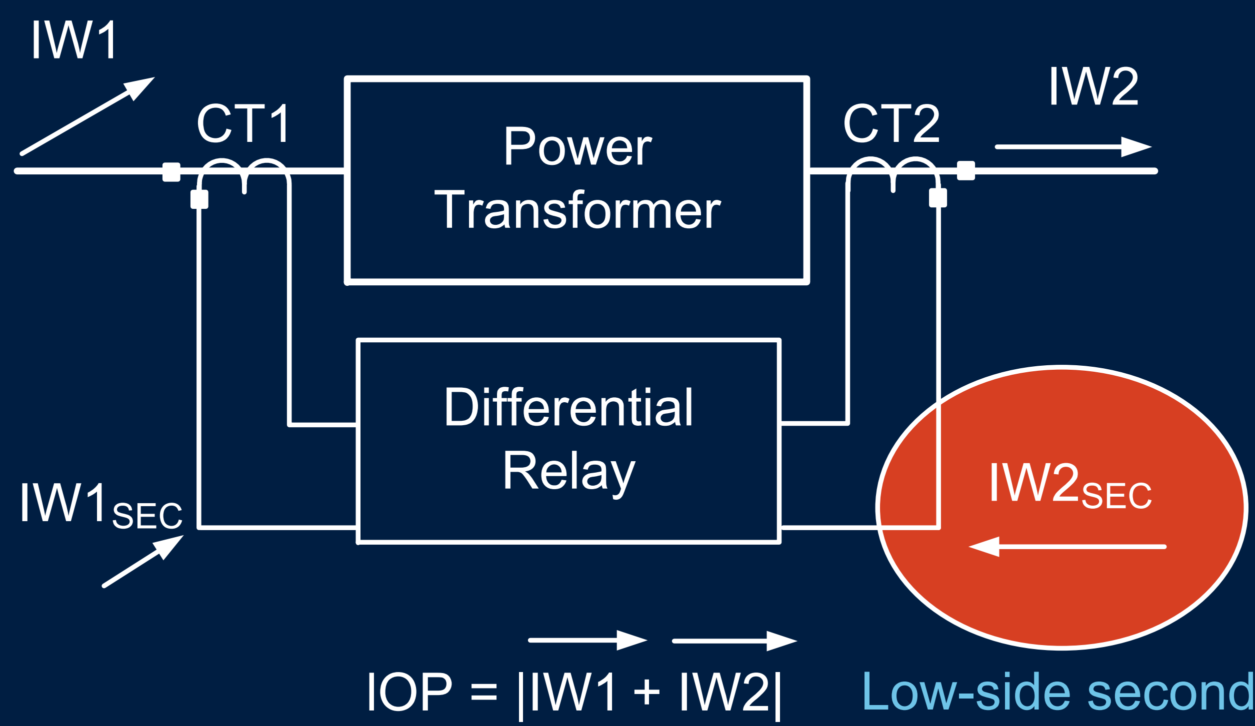


ANSI Transformer Connections

YDAC or Yd1

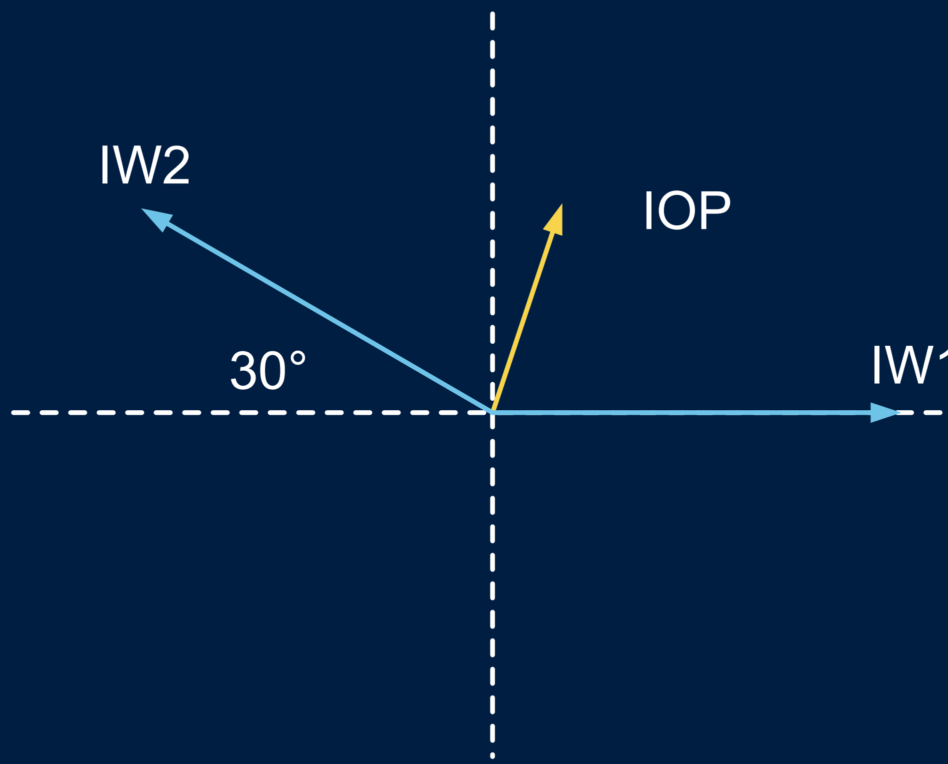


Secondary Currents

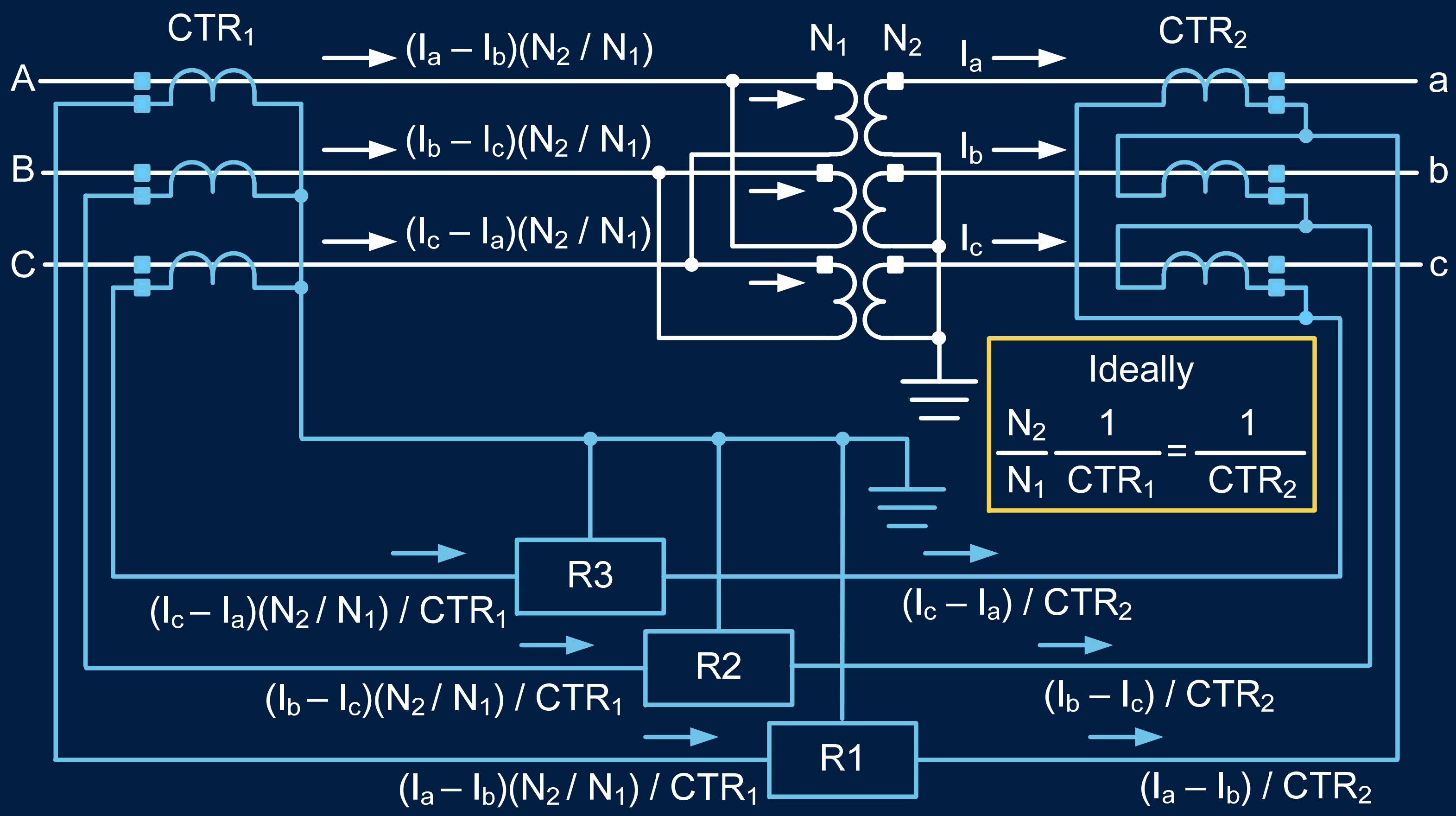


Low-side secondary current **leads** by 150 degrees!

Result of Uncompensated Phase Shift



Traditional Compensation



CTR_1 and CTR_2 Ideal Relationship

$$\frac{N_2}{N_1}\frac{1}{CTR_1} = \frac{1}{CTR_2} \Rightarrow$$

$$\frac{N_1}{N_2} CTR_1 = CTR_2 \Rightarrow$$

$$CTR_2 = \sqrt{3}\frac{kV_1}{kV_2} CTR_1$$

Not always possible with standard CT ratios

Compensation With Relays

- EM relays provide limited magnitude compensation
- SEL relays provide magnitude and phase-shift compensation (SEL-387 considers not only ANSI / IEEE standard connections, but all possible connections)

Current Magnitude Mismatch

- Current magnitude is transformed (transformer is constant KVA device)
  - $kV_H \cdot I_{high\text{-}side} = kV_L \cdot I_{low\text{-}side}$
  - $I_{high\text{-}side} \neq I_{low\text{-}side}$
- Load tap changer dynamically changes transformation ratio

Tap Compensation

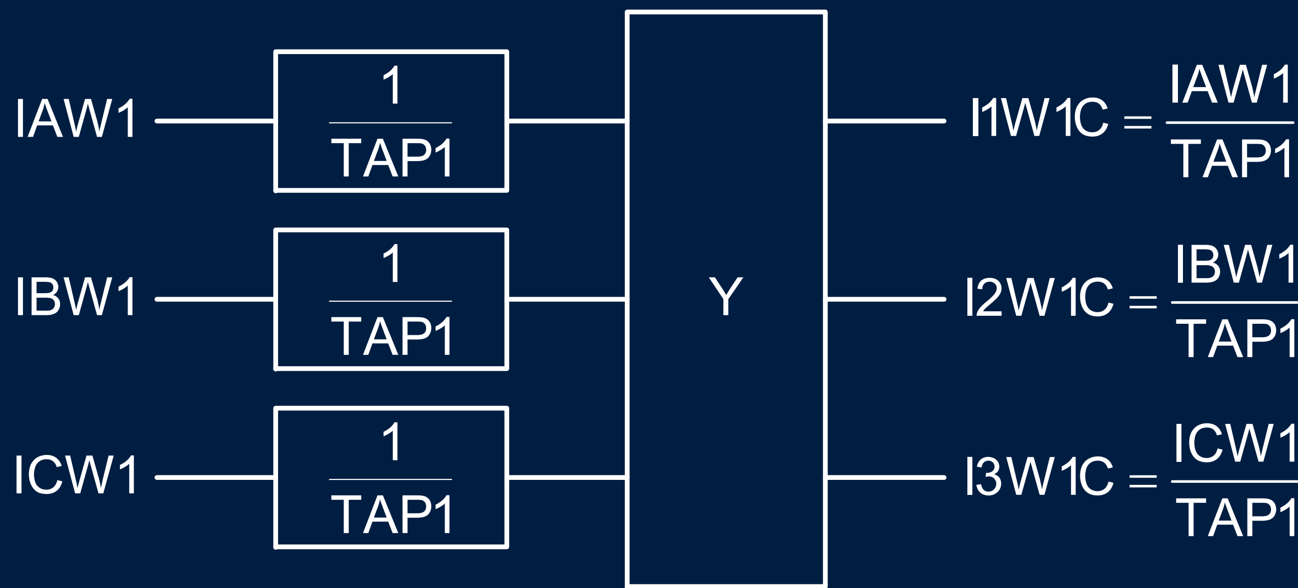
$$TAP = \frac{MVA \bullet 1000 \bullet C}{\sqrt{3} \bullet kV_{WDG} \bullet CTR}$$

where:

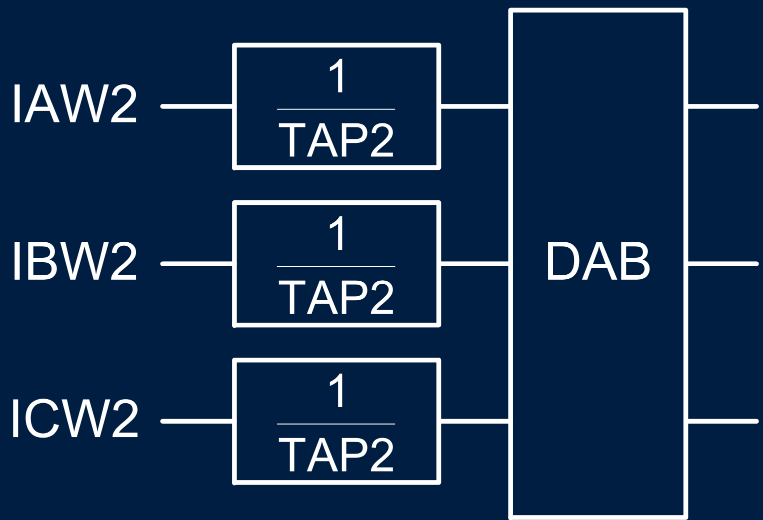
C = 1 for wye-connected CTs

C = $\sqrt{3}$ for delta-connected CTs

Wye Connection Compensation



DAB Connection Compensation

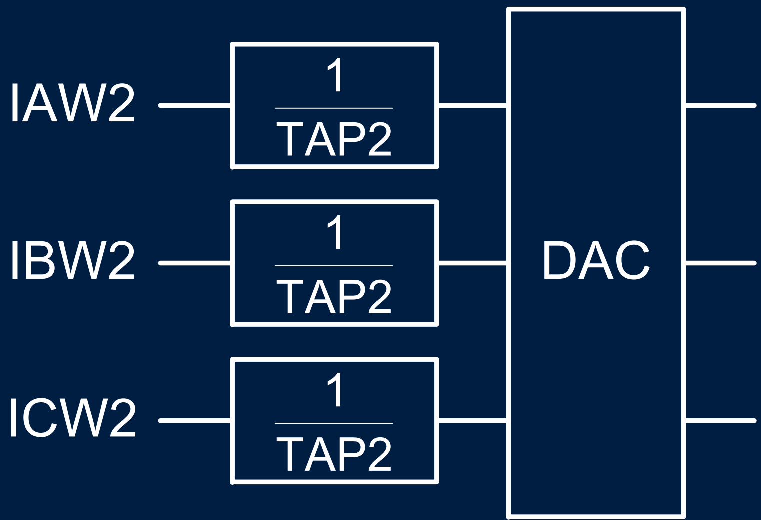


$$I1W2C = \frac{1}{TAP2} \bullet \frac{(IAW2 - IBW2)}{\sqrt{3}}$$

$$I2W2C = \frac{1}{TAP2} \bullet \frac{(IBW2 - ICW2)}{\sqrt{3}}$$

$$I3W2C = \frac{1}{TAP2} \bullet \frac{(ICW2 - IAW2)}{\sqrt{3}}$$

DAC Connection Compensation



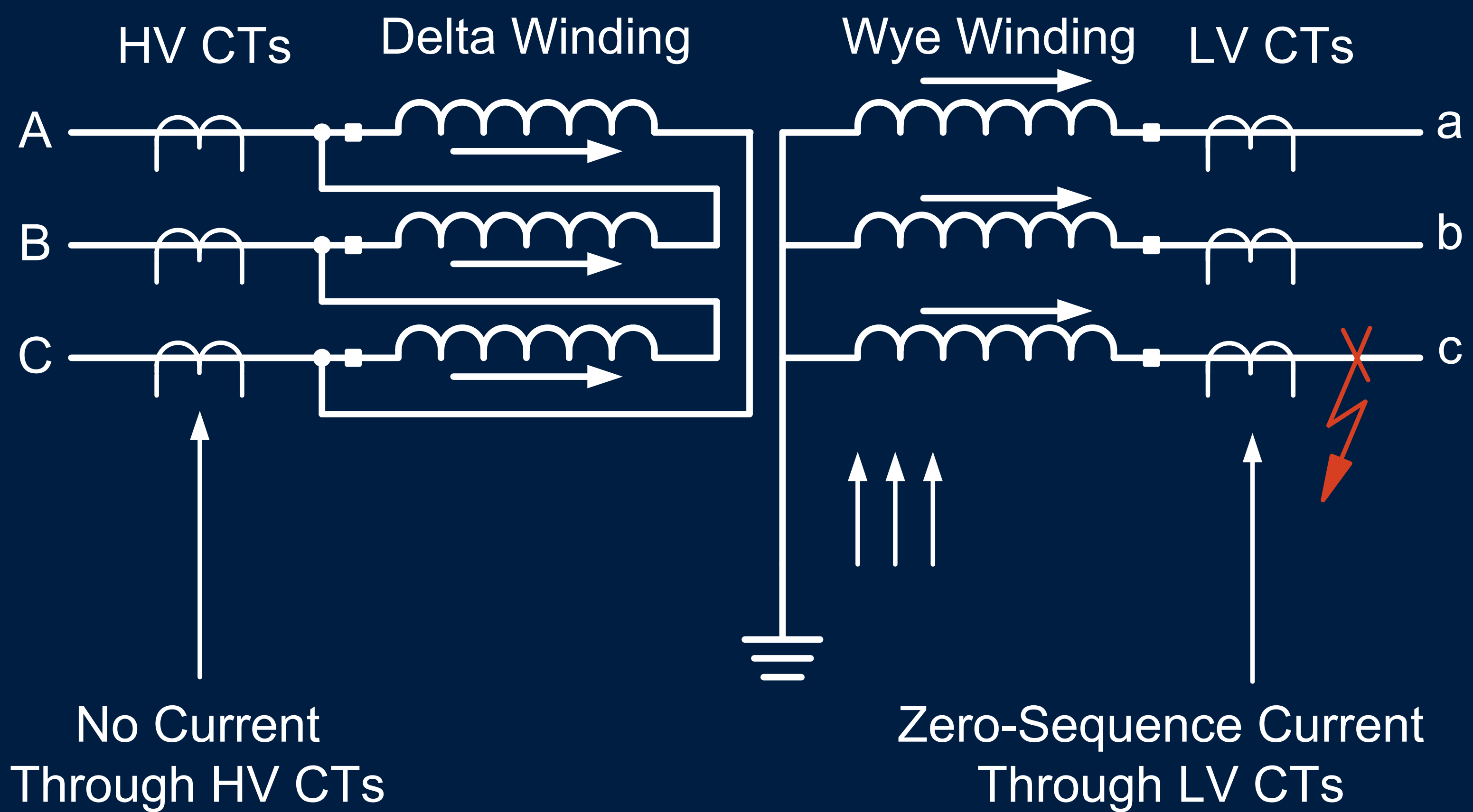
$$I1W2C = \frac{1}{TAP2} \bullet \frac{(IAW2 - ICW2)}{\sqrt{3}}$$

$$I2W2C = \frac{1}{TAP2} \bullet \frac{(IBW2 - IAW2)}{\sqrt{3}}$$

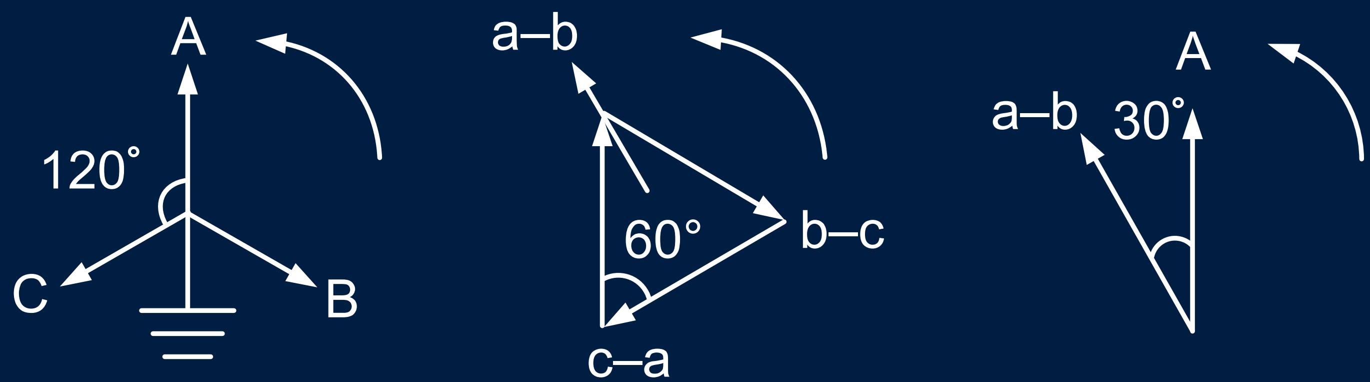
$$I3W2C = \frac{1}{TAP2} \bullet \frac{(ICW2 - IBW2)}{\sqrt{3}}$$

Compensation for Zero-Sequence Currents

Why Eliminate Zero-Sequence Current?



Removal Via Delta Connection



$$I_a = I_1 + I_2 + I_0$$

$$I_b = a^2 I_1 + a I_2 + I_0$$

$$I_a - I_b = I_1 + I_2 + I_0 - (a^2 I_1 + a I_2 + I_0)$$

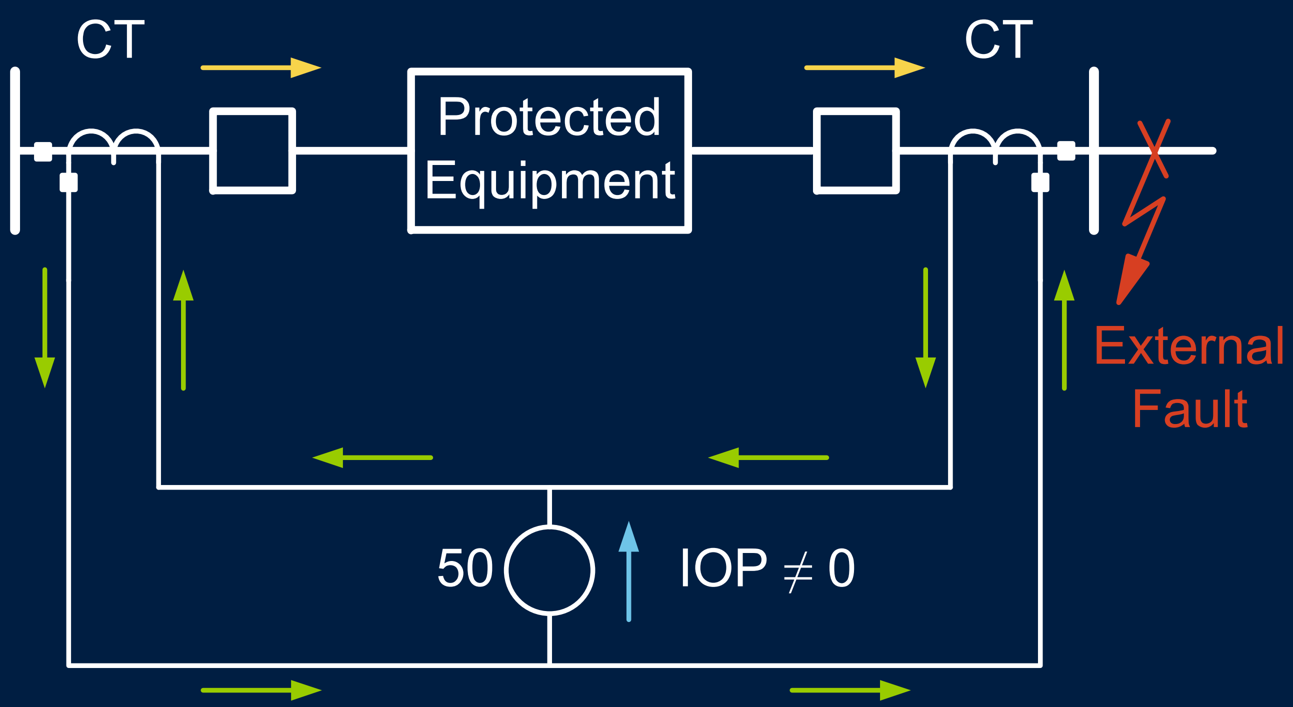
$$= I_1(1 - a^2) + I_2(1 - a) + (I_0 - I_0)$$

Zero-Sequence
Current Eliminated

Restrained Differential Element

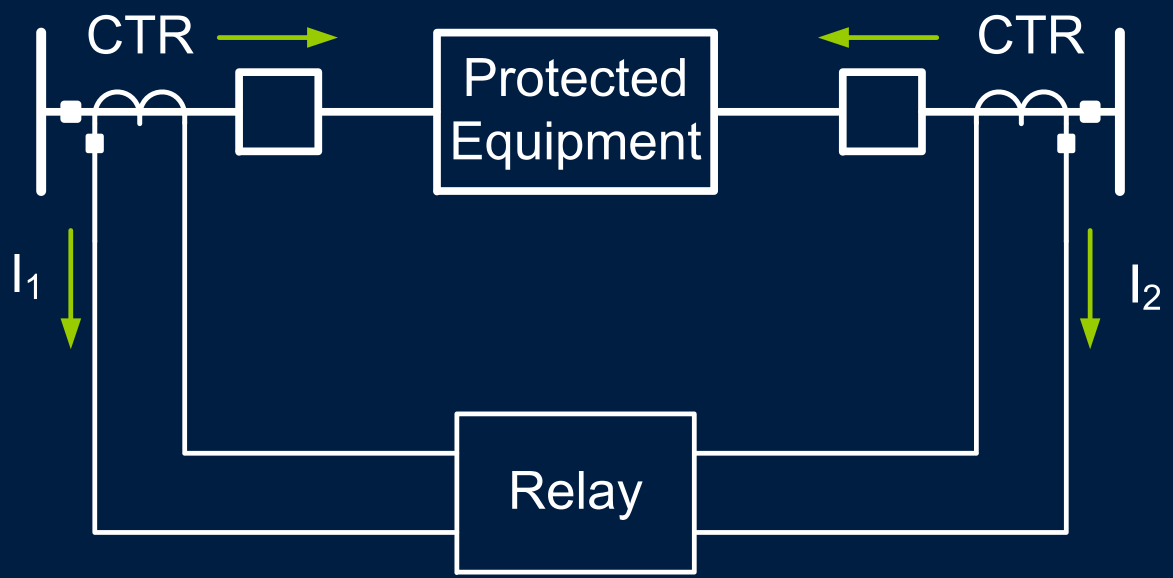
Differential Protection Principle

Unequal CT Performance



CT saturation and CT ratio error

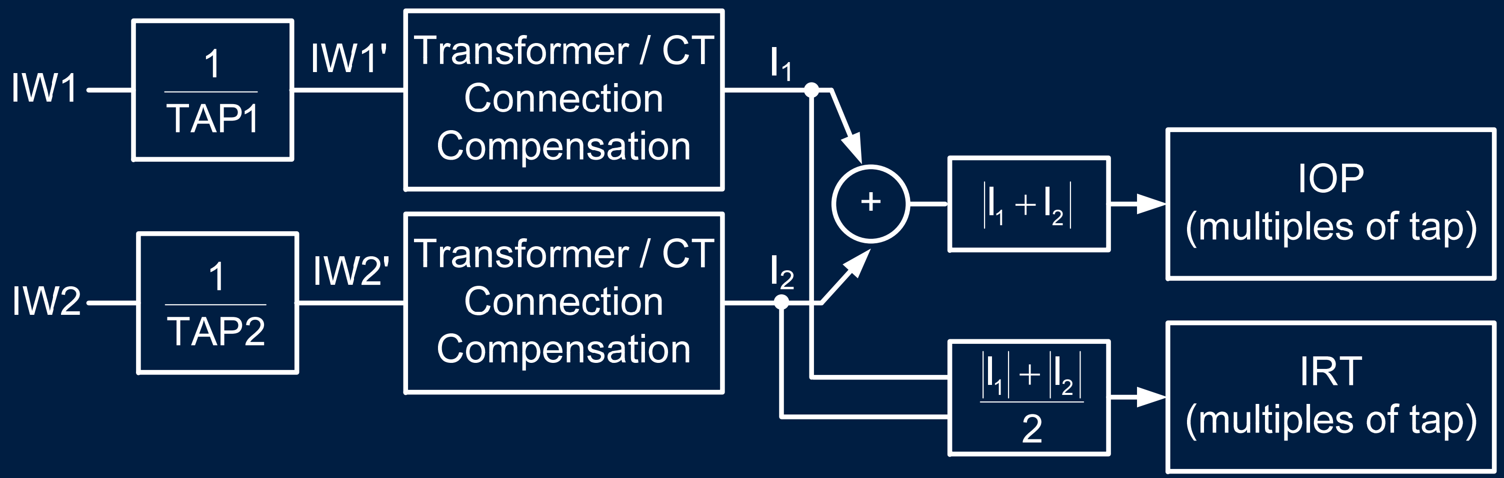
Percentage Differential Protection Principle



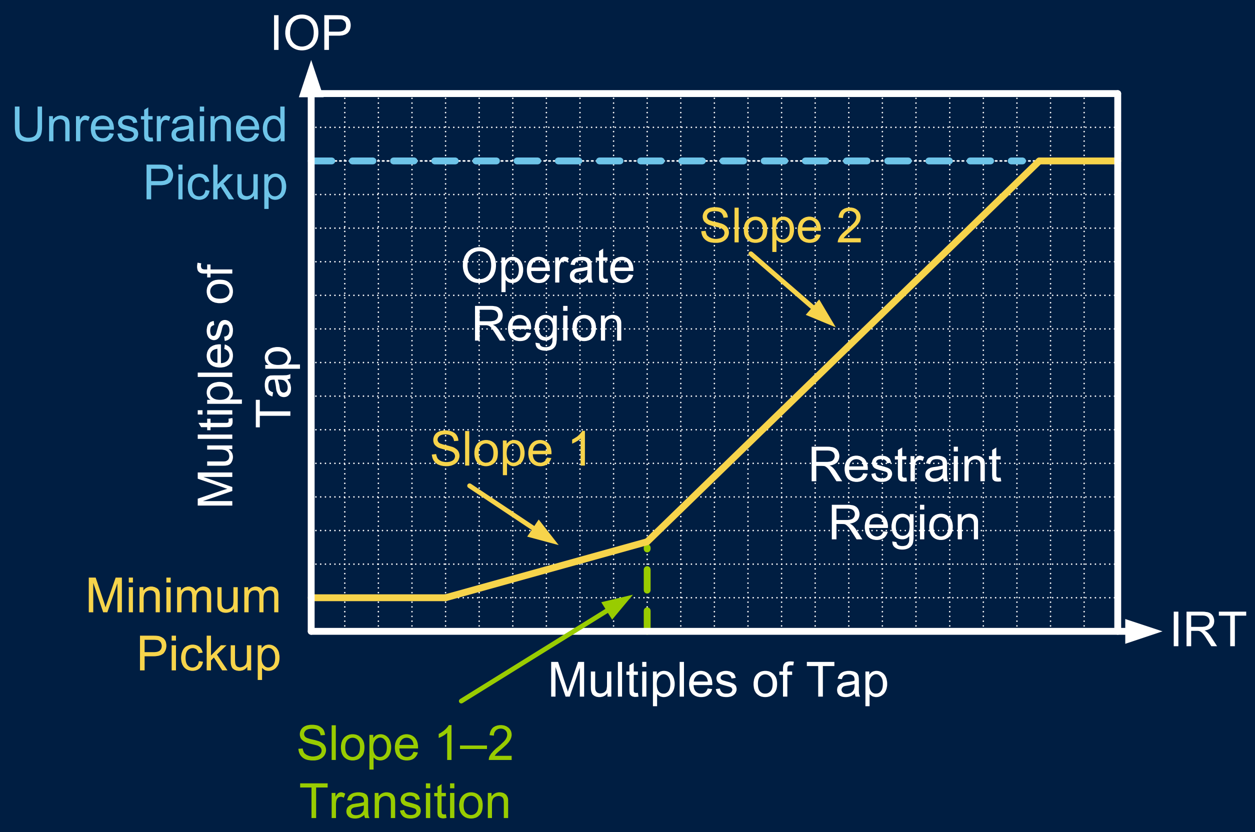
$$IOP = \left| \bar{I}_1 + \bar{I}_2 \right|$$

$$IRT = 0.5 \cdot \left(\left| \bar{I}_1 \right| + \left| \bar{I}_2 \right| \right)$$

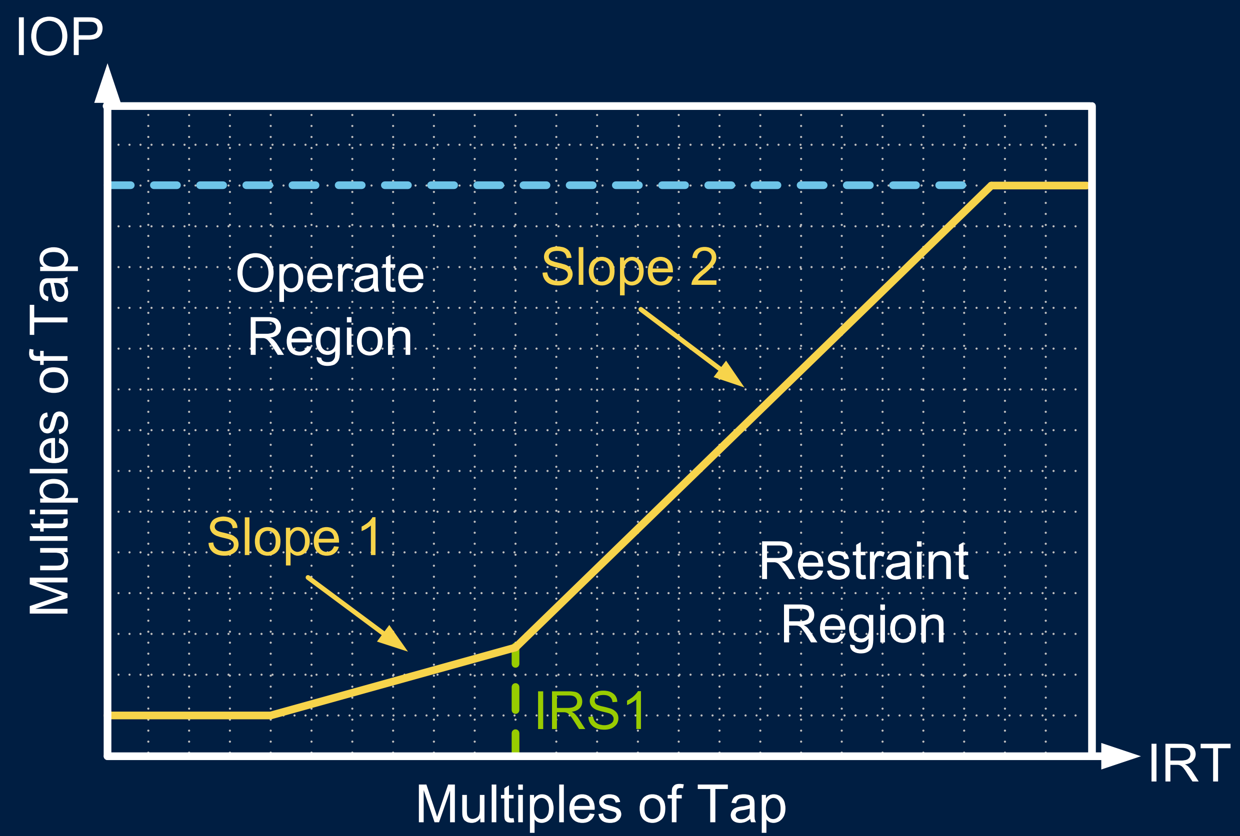
Differential Element Operate and Restraint Quantities



Percentage Restraint Differential Characteristic

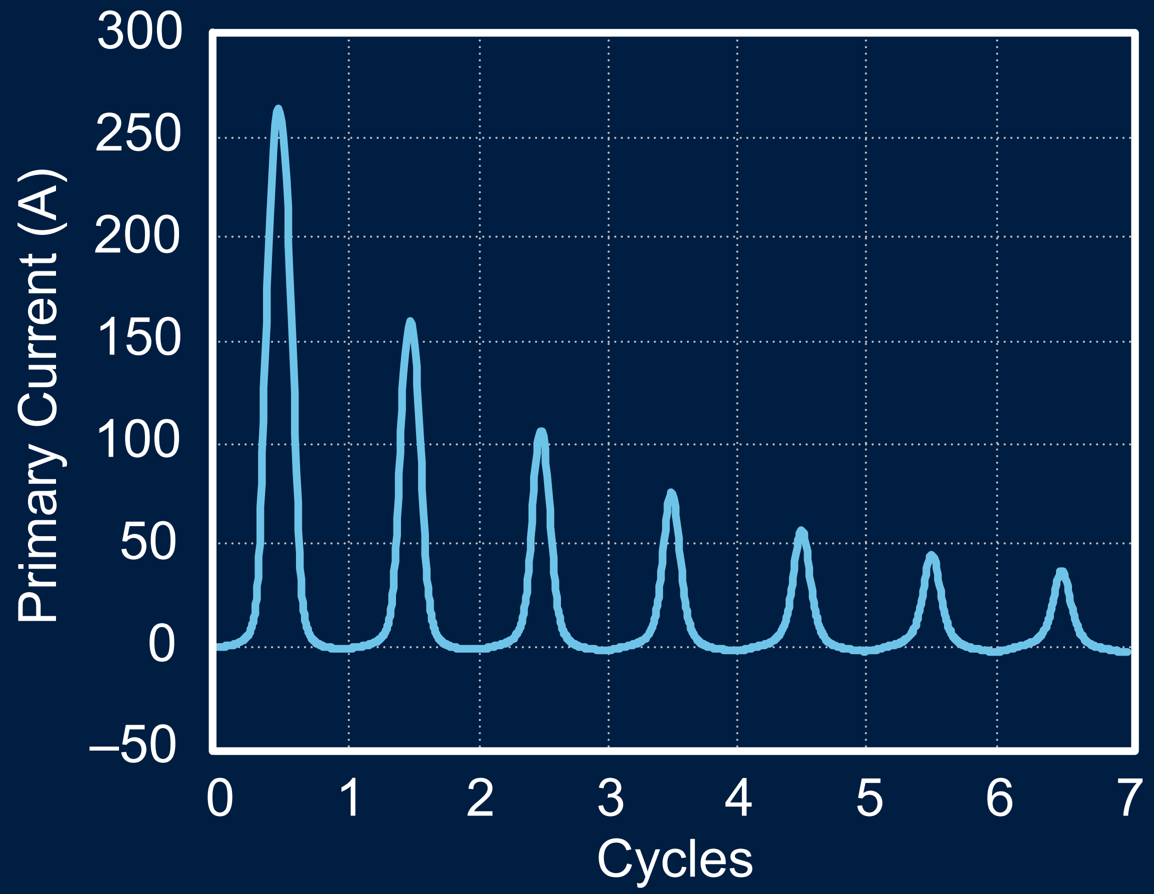


Percentage Restraint Differential Characteristic

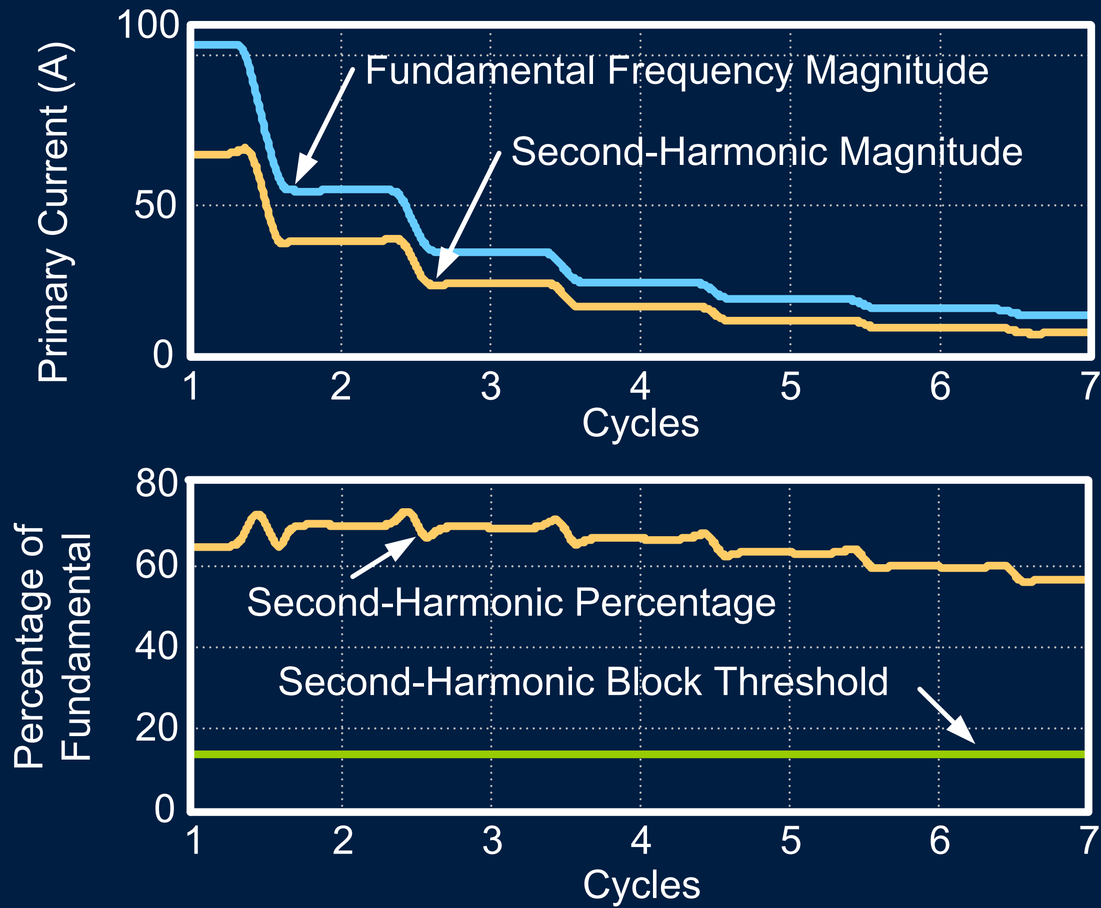


Transformer Energization

C-Phase Inrush Current



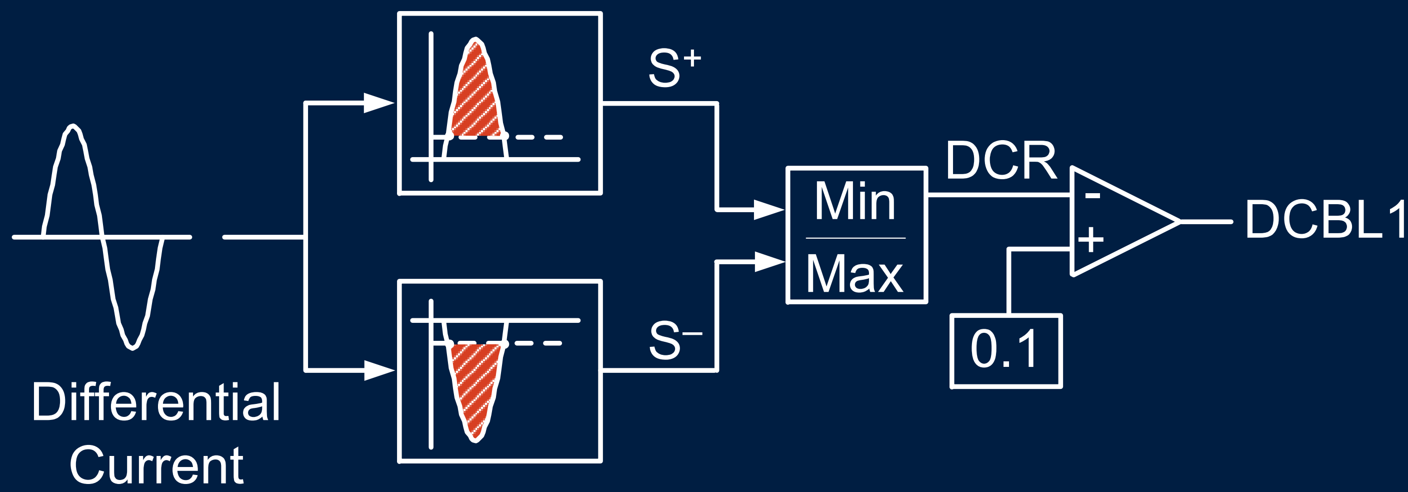
Inrush Current



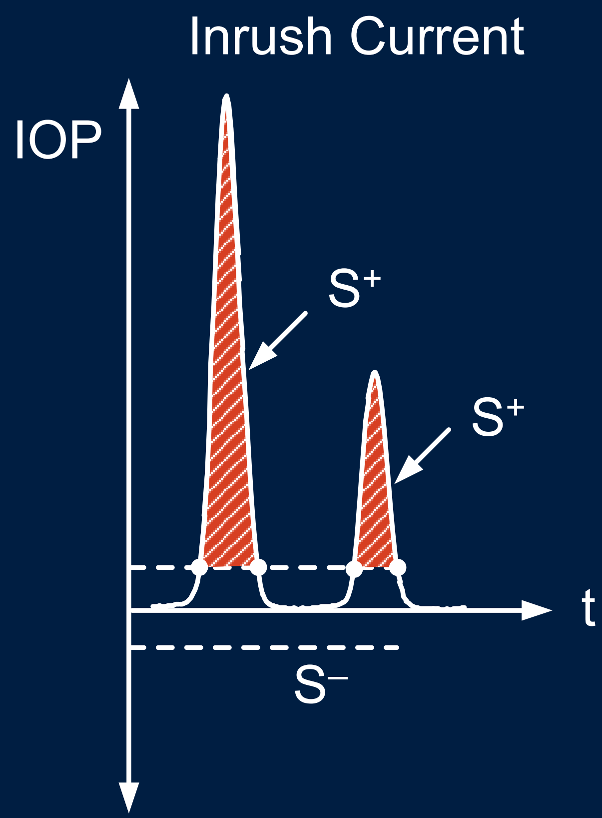
Discriminating Internal Faults Versus Inrush Conditions

- Harmonic blocking
- Harmonic restraint
- DC blocking

DC Blocking

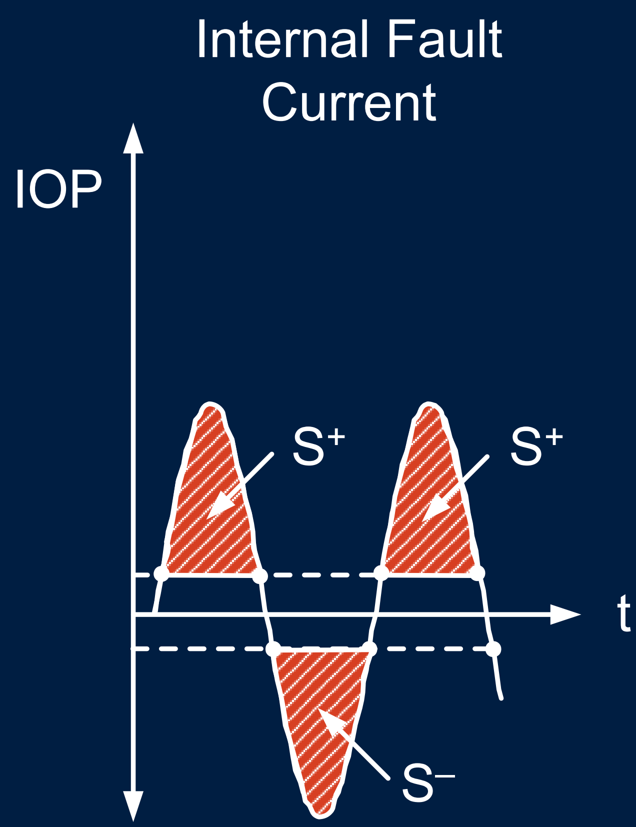


DC Blocking



$S^+ = 1$
$S^- = 0$
$0/1 = 0$
$0<0.1$
DCBL1 is asserted

DC Blocking



$S^{+} = 1$

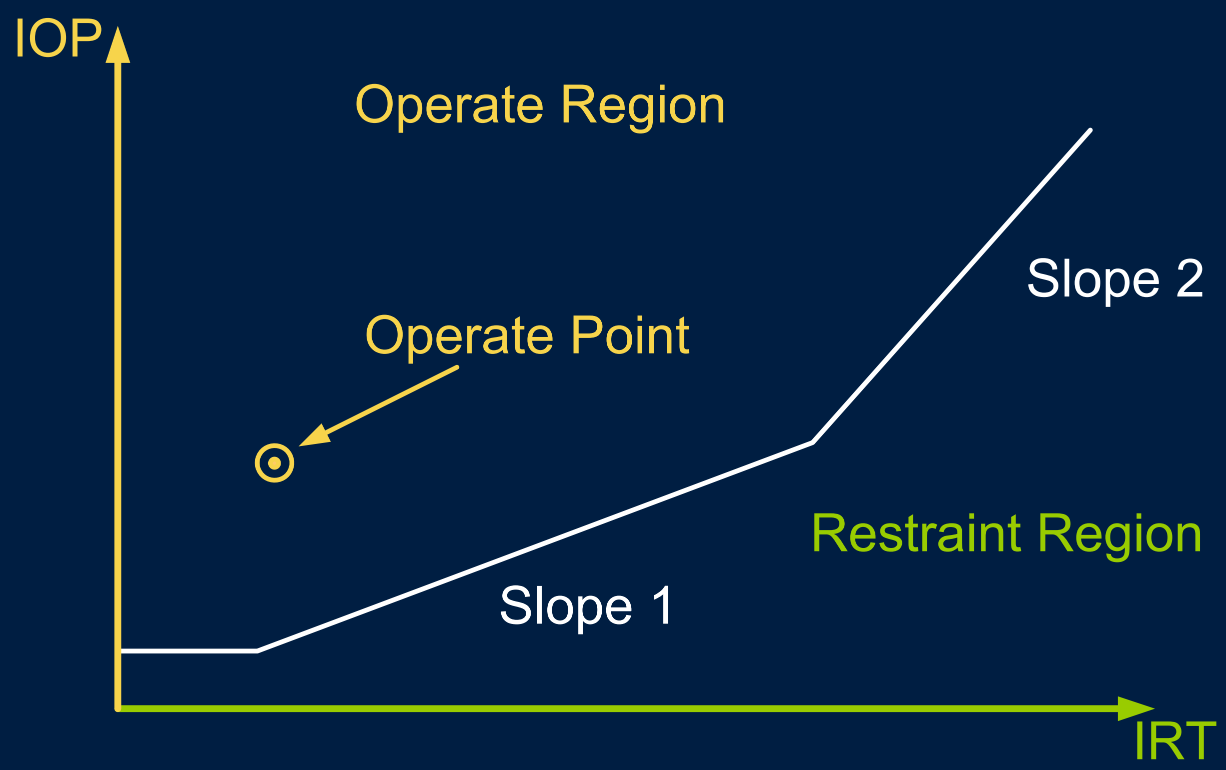
$S^{-} = 1$

$1/1 = 1$

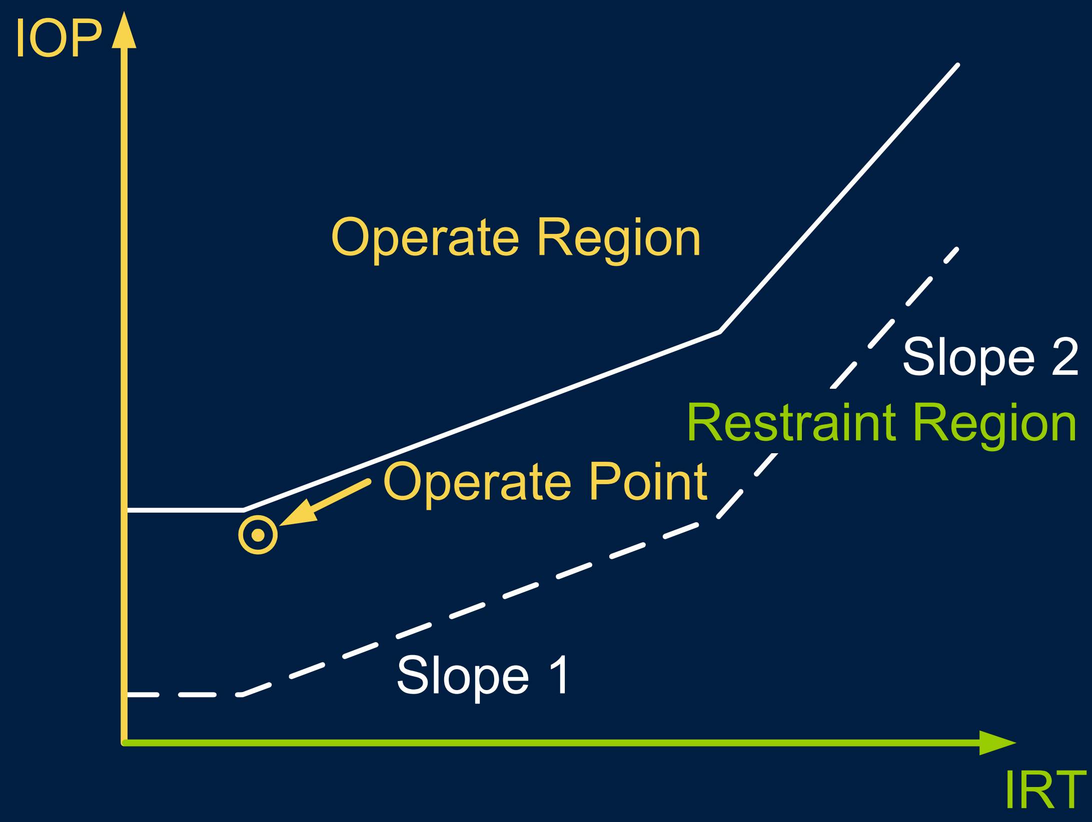
$1 > 0.1$

DCBL1 is not asserted

Inrush Conditions (Blocking)



Inrush Conditions (Restraint)



Unrestrained Differential Element

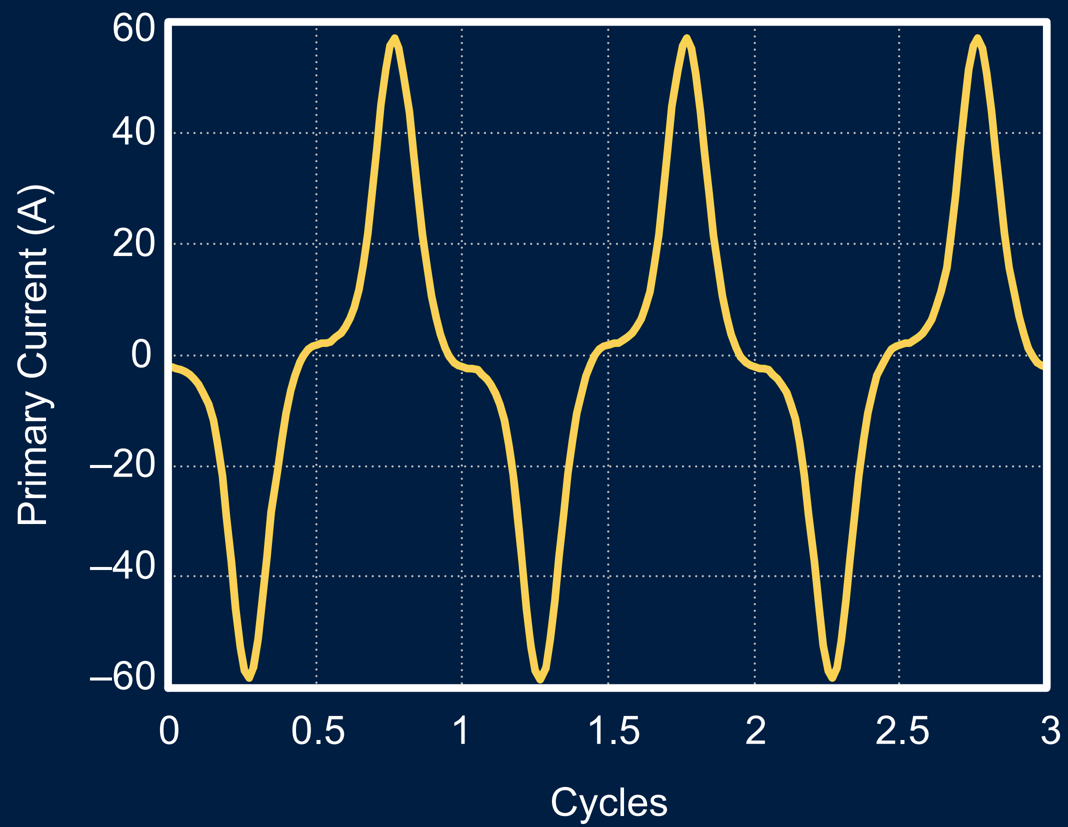
Unrestrained Element

- Element instantaneously trips on magnitude of differential current
  - No percentage restraint
  - No harmonic block
- CT saturation includes harmonics

Transformer Overexcitation

Excitation Current From Testing

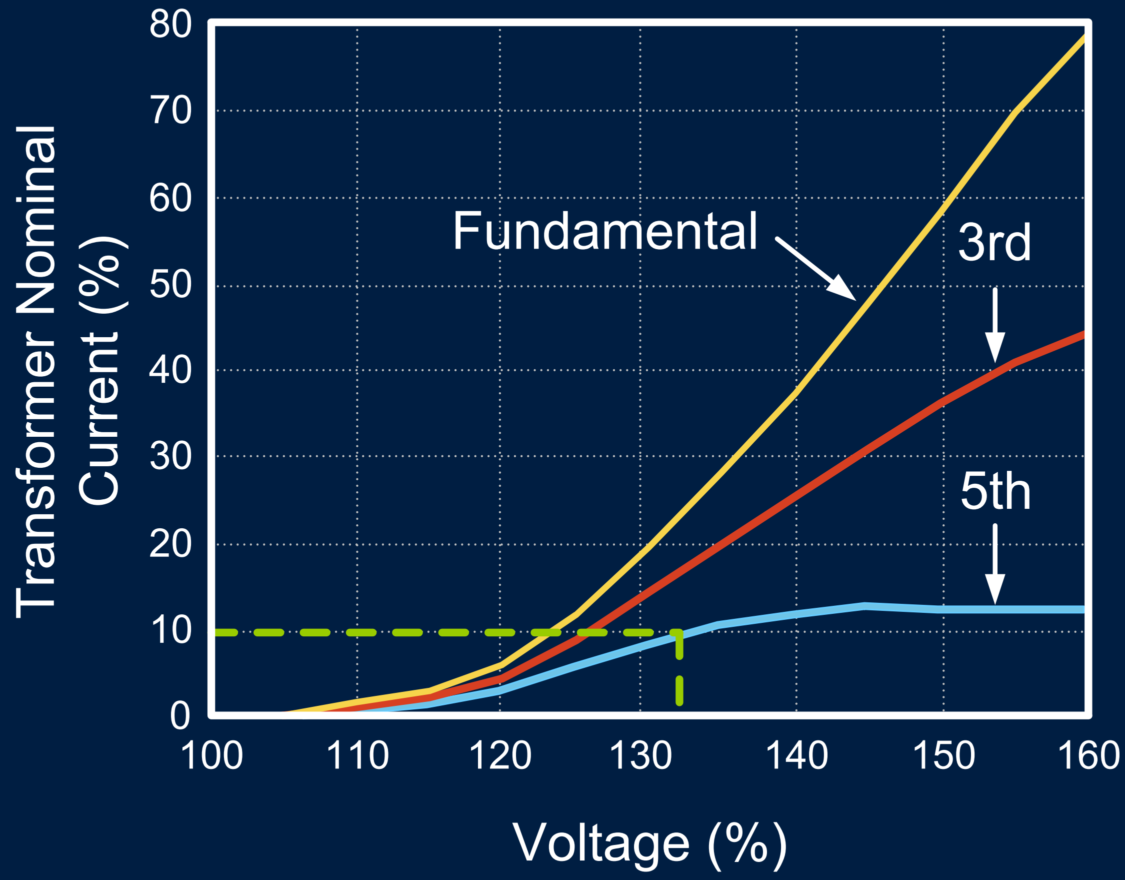
150 Percent Overvoltage



Fifth-Harmonic Content in Excitation Current

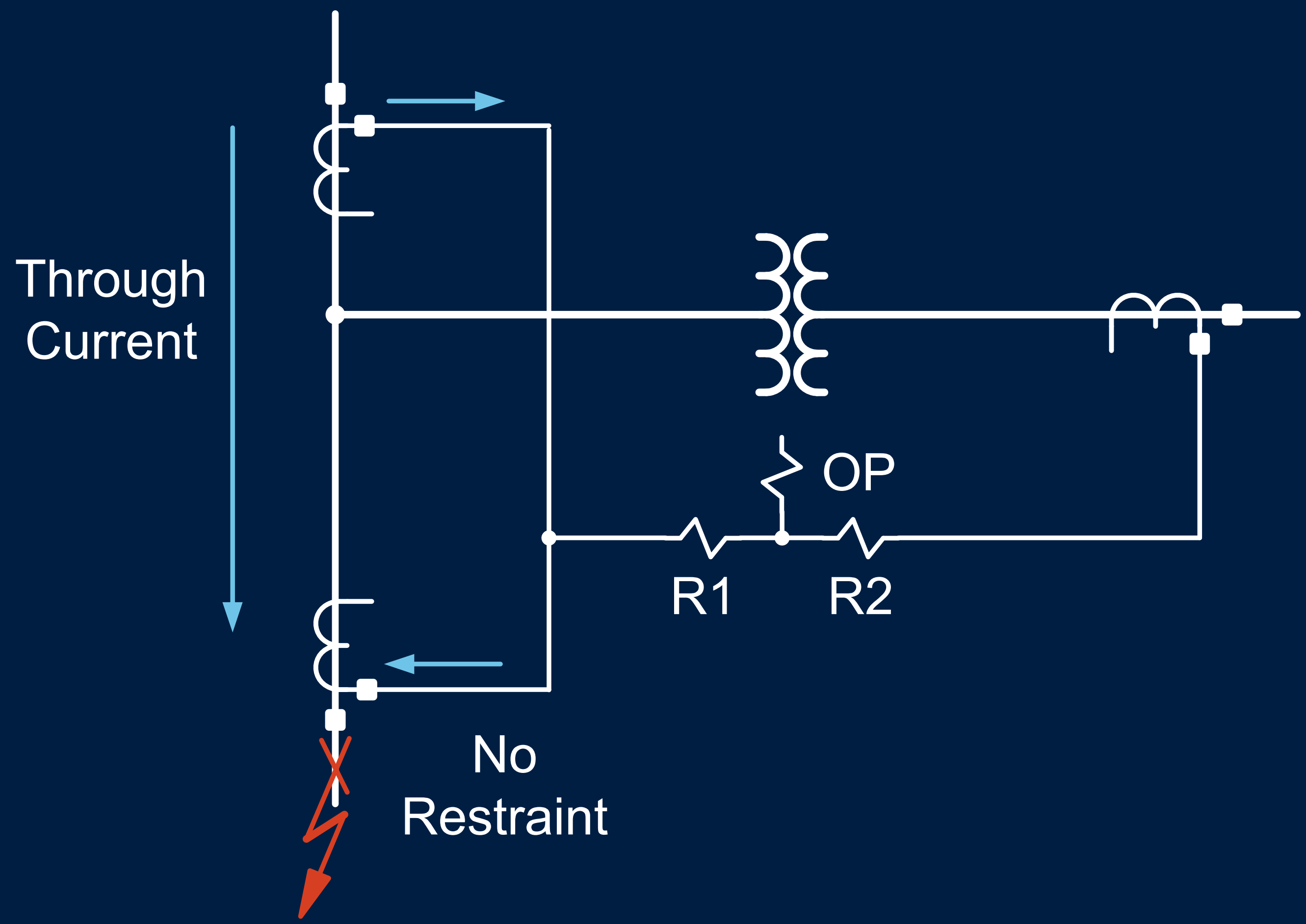
Frequency Component	Magnitude (primary A)	Percent of Nominal
Fundamental	22.5	52.0
3rd	11.1	26.0
5th	4.9	11.0
7th	1.8	4.0

Excitation Current Harmonics

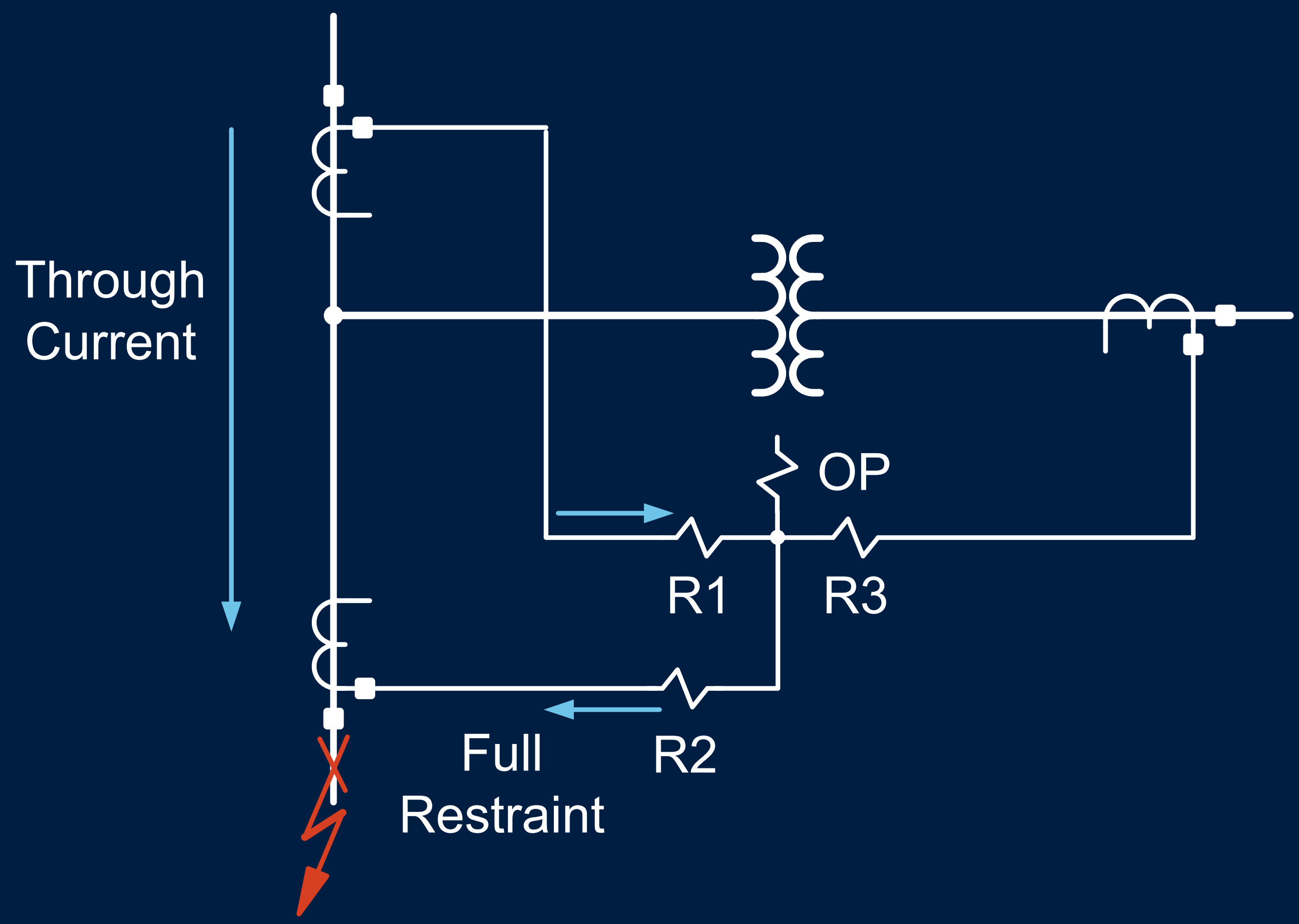


Application Considerations

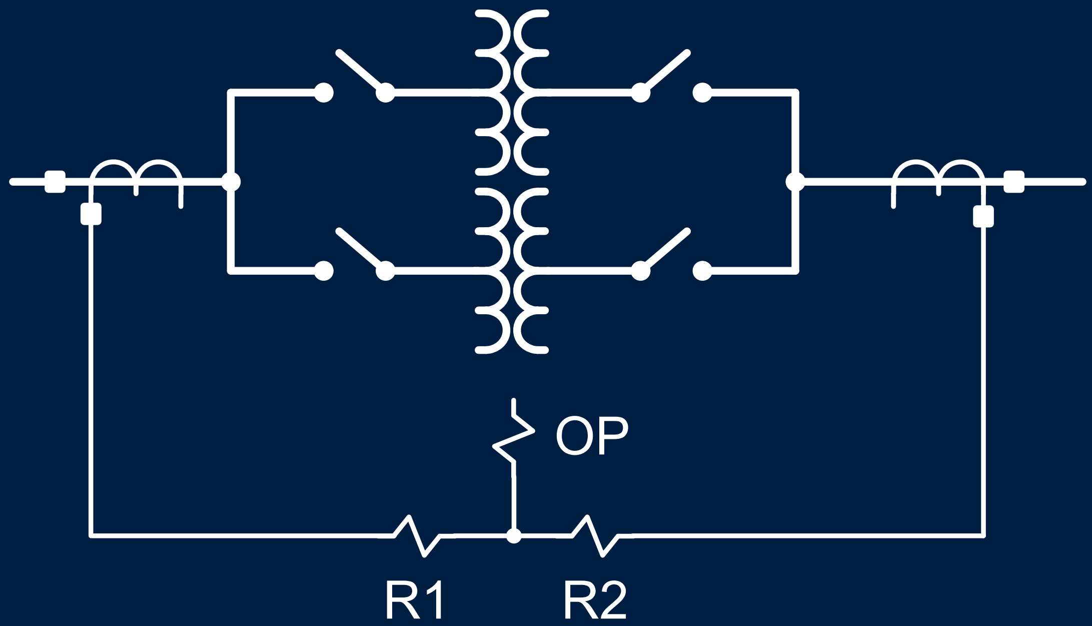
Paralleling CTs on Restraint Input



Paralleling CTs on Restraint Input



Paralleling Transformers
Sympathetic Inrush

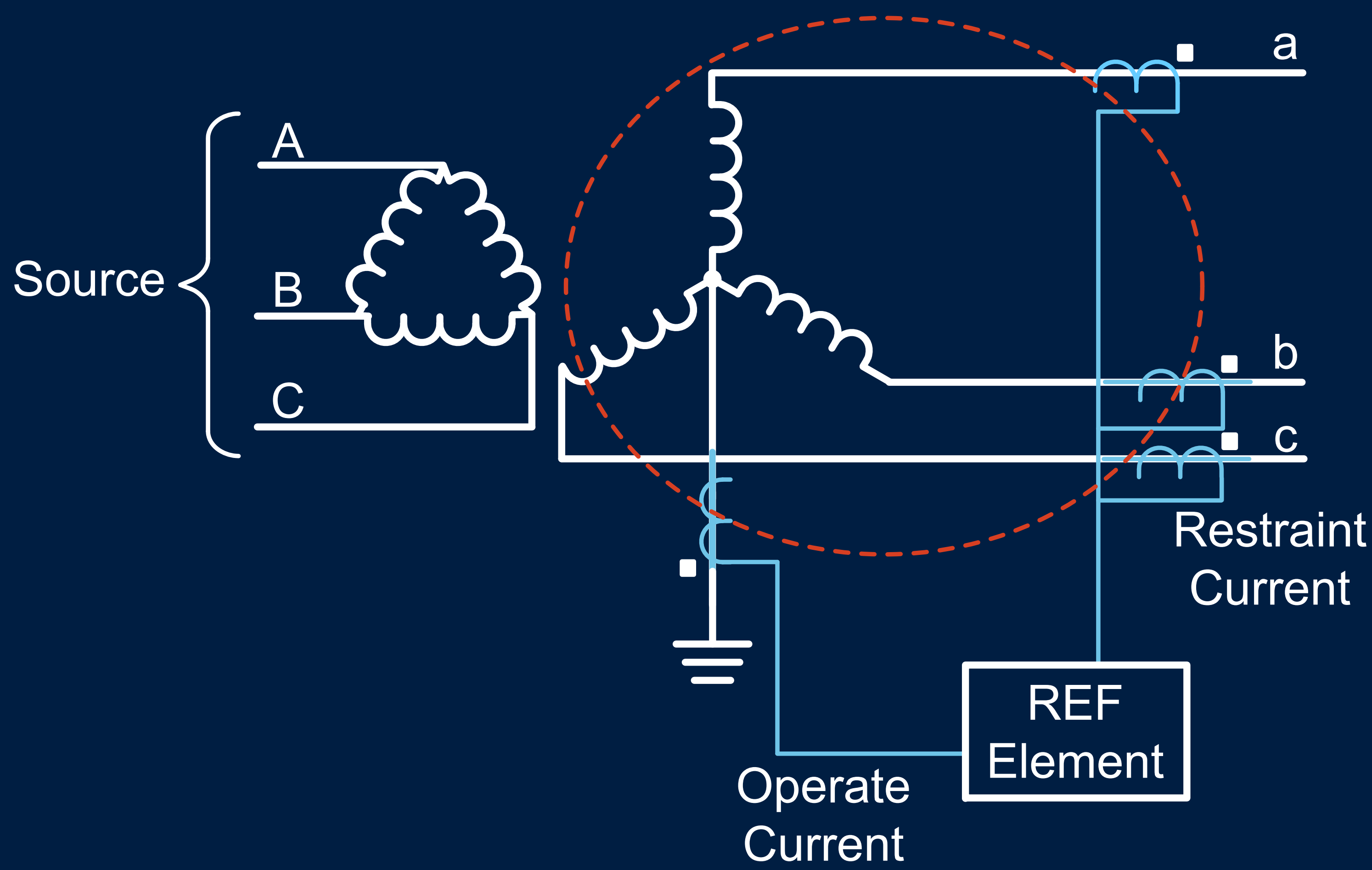


Setting Taps for Three-Winding Transformers

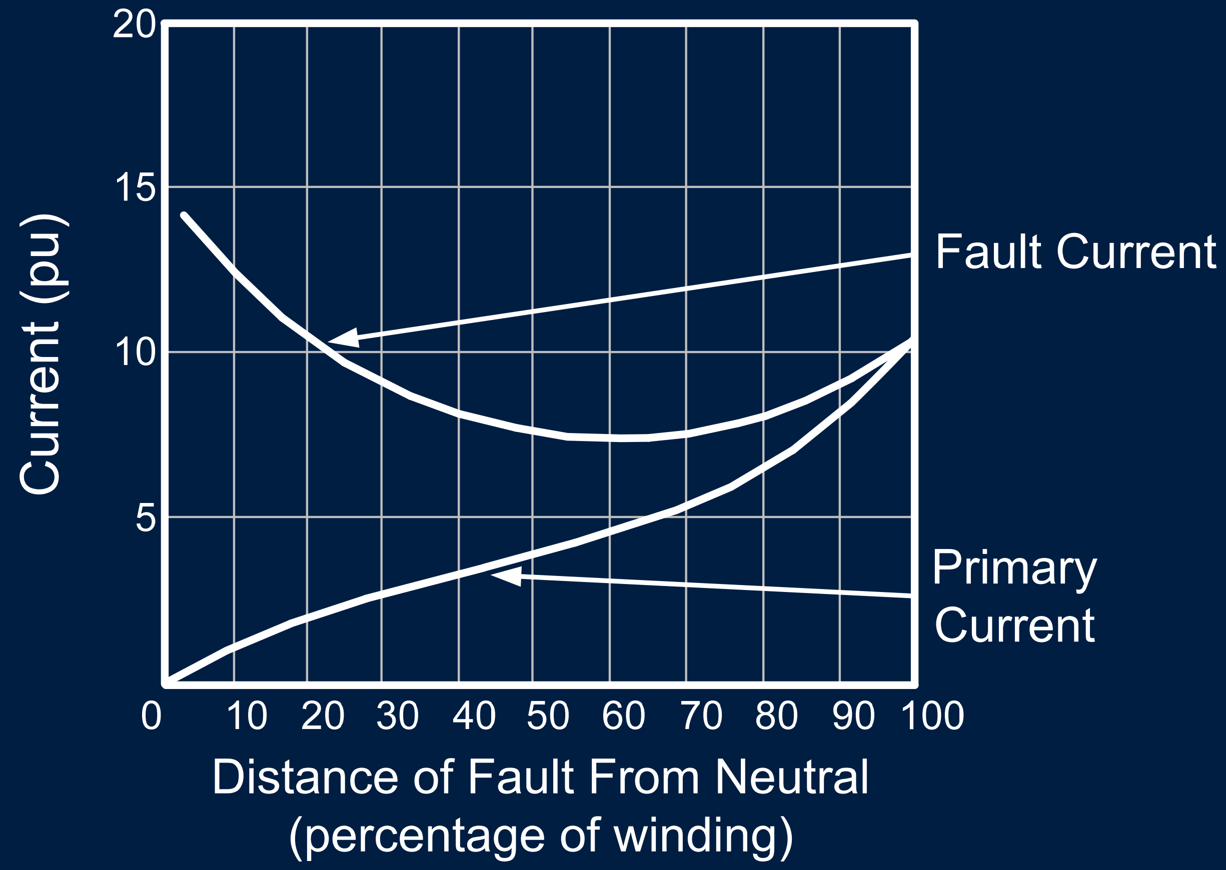
- Know that third winding may not be rated at same MVA as main windings
- Set taps on multirestraint relay
  - Work through matching taps in pairs
  - Be sure to use same MVA base for each tap calculation

Restricted Earth Fault (REF) Protection

Protect Windings Close to Neutral



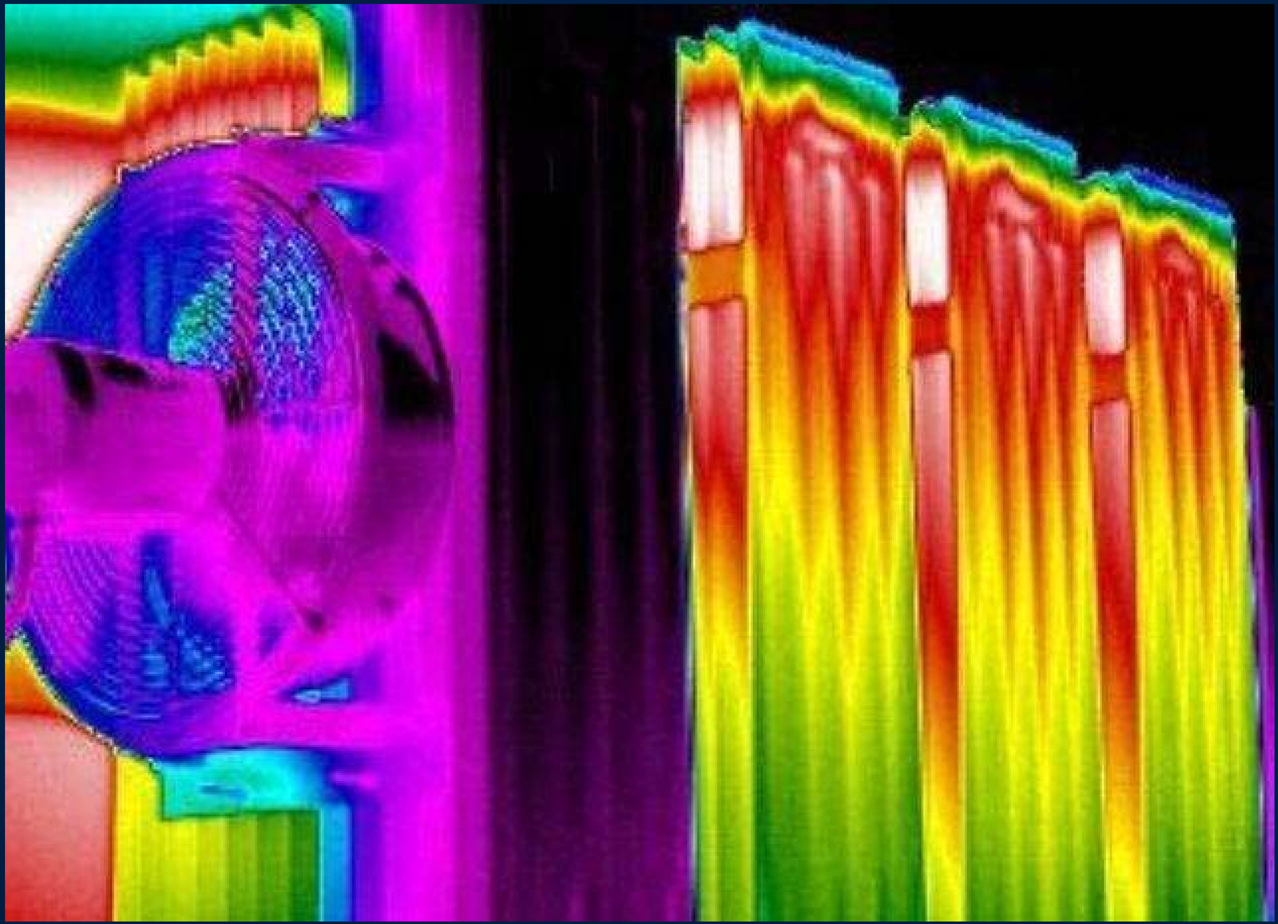
Protection Basics – Why Use REF Protection?



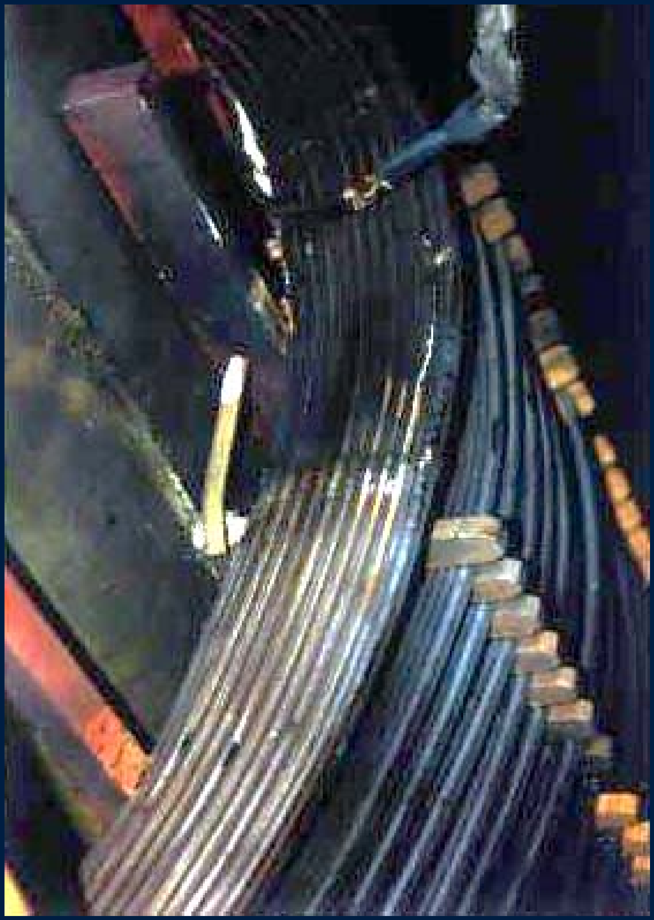
Prevention Before Protection

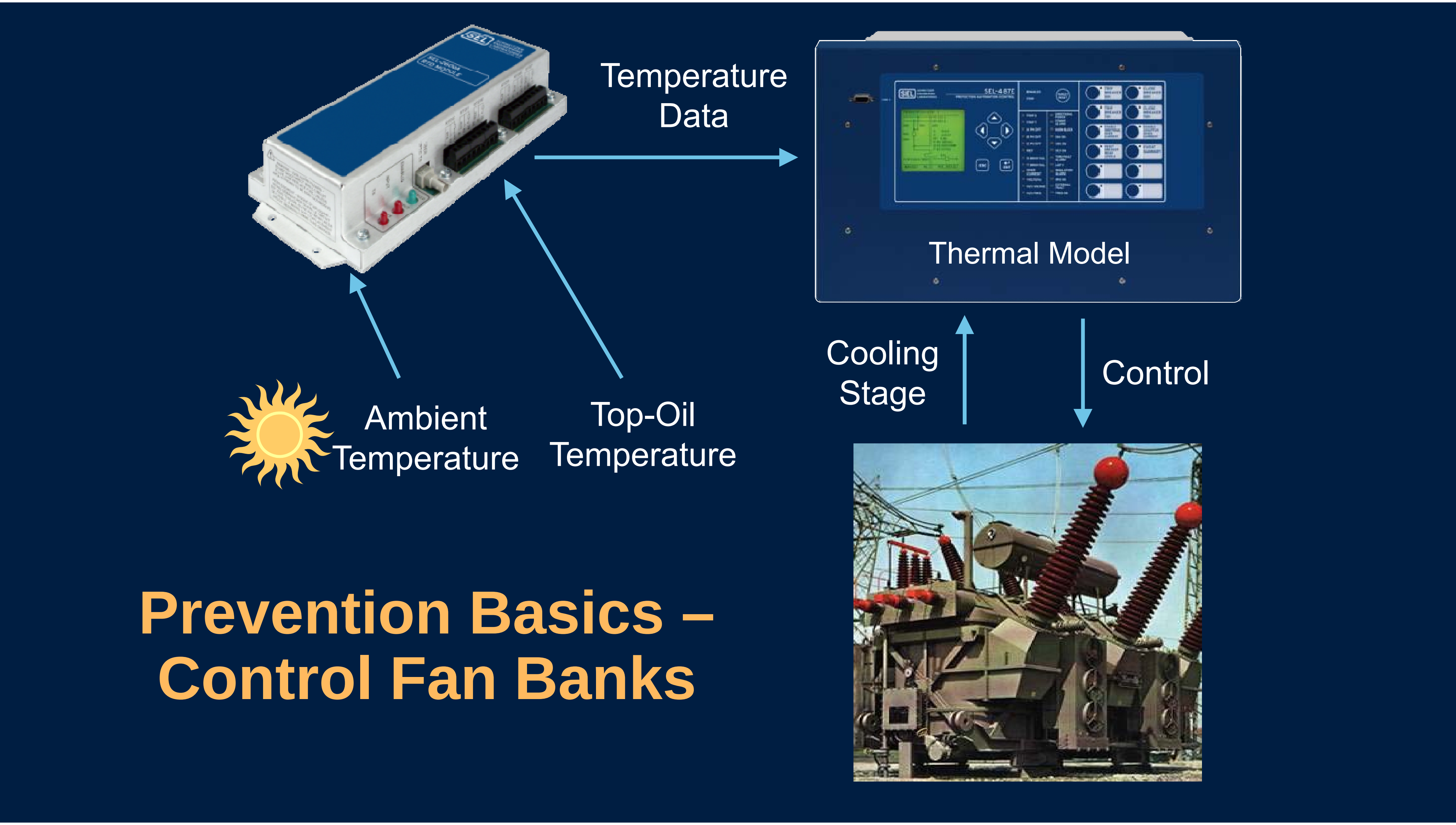
- Thermal model
- Through-fault monitoring

What Causes Transformer Overheating?

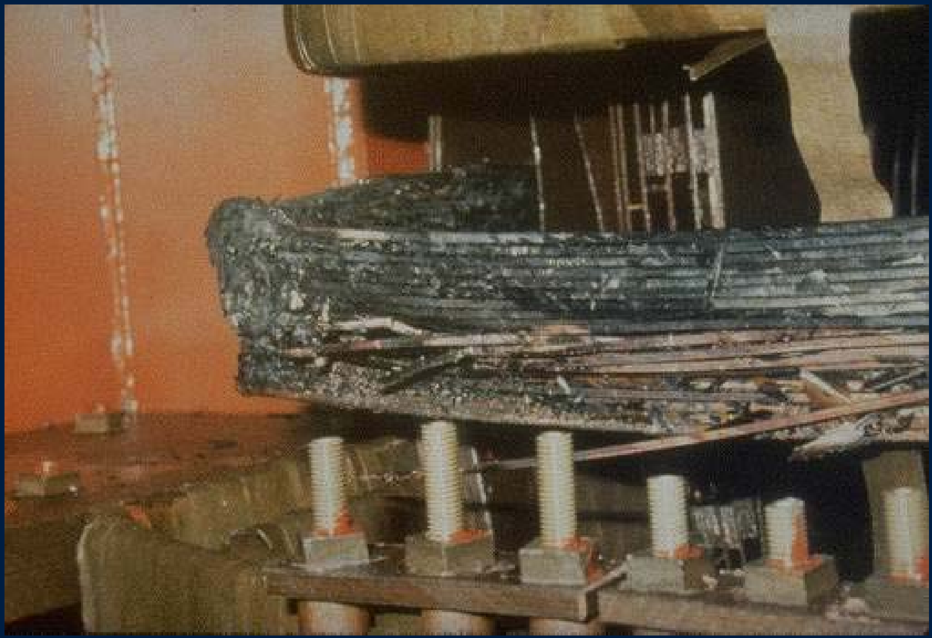


What Does Overheating Do?

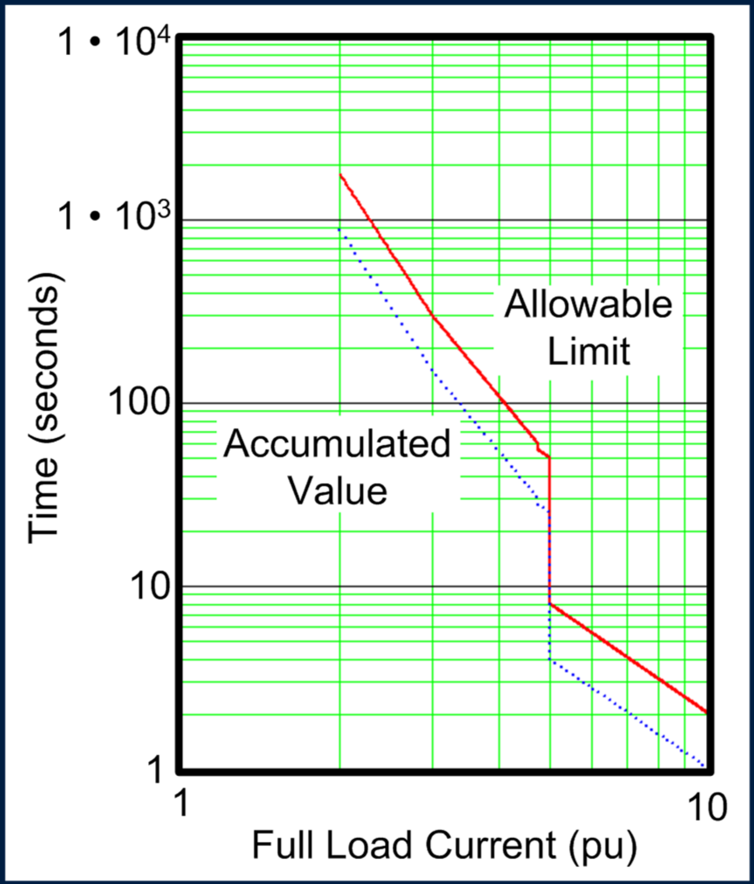



Temperature
Data
Thermal Model
Cooling
Stage
Control
Ambient
Temperature
Top-Oil
Temperature
Prevention Basics –
Control Fan Banks

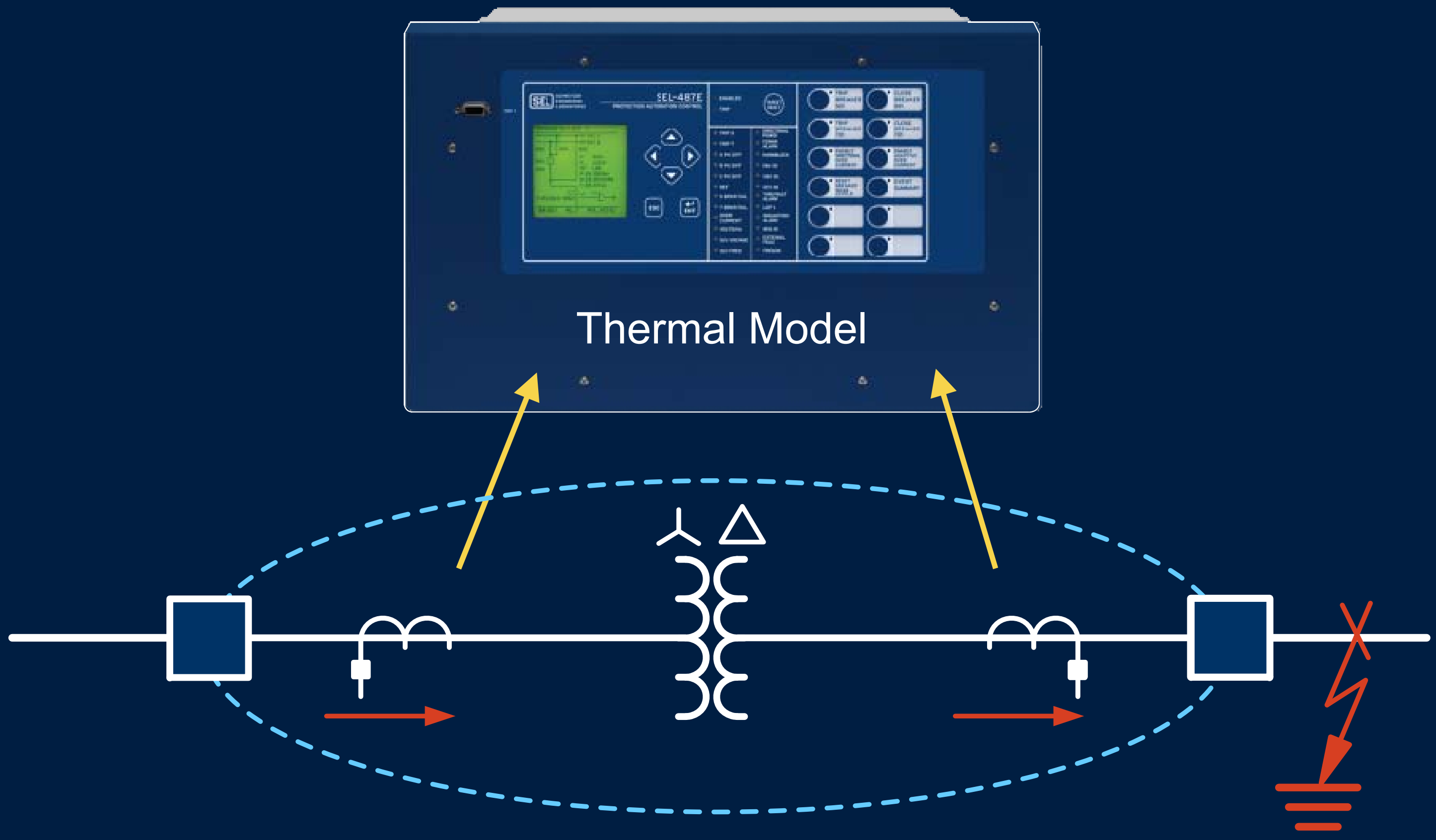
Why Enable Through-Fault Monitoring?



Track Through Faults Transformer Has Experienced



Prevention Basics –
Enable Through-Fault Monitoring



Questions?