Testing Numerical Transformer Differential Relays

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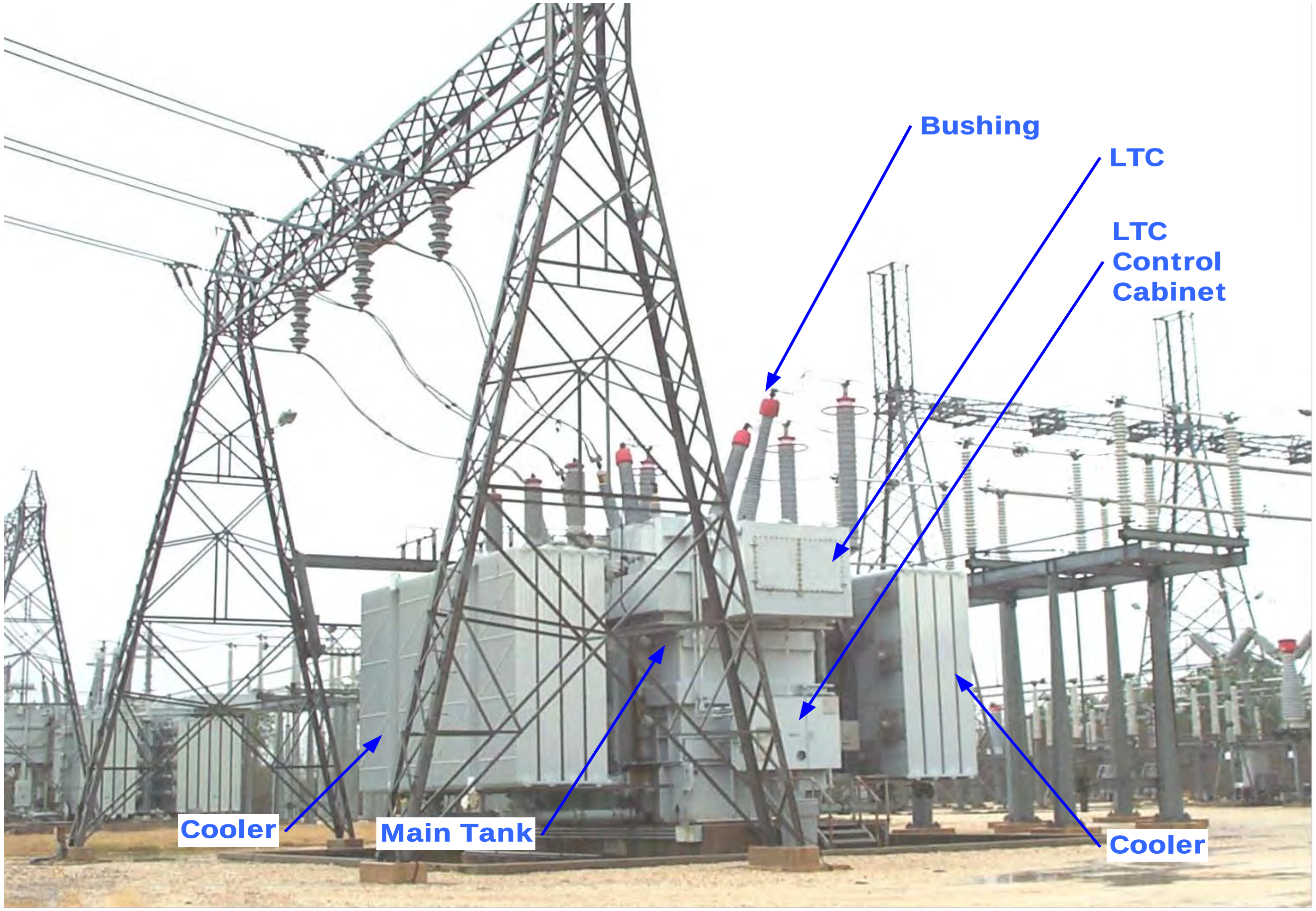
Beckwith Electric Co., Inc.

Power Transformers



INTRODUCTION

Commissioning versus Maintenance Testing

Main Transformer Protection:

- ***Restrained Phase Differential***
- **High Set Phase Differential**
- ***Ground Differential***

INTRODUCTION

Topics:

- ***Transformer Differential Boundary Test*** **(Commissioning)**
- ***Ground Differential Sensitivity Test*** **(Commissioning/Maintenance)**
- **Secondary Transformer Protection**
- ***Harmonic Restraint for Transformer Inrush*** **(Maintenance)**

Failure Statistics of Transformers

Failure Statistics of Transformers

	1955- 1965		1975- 1982		1983- 1988	
	Number	% of Total	Number	% of Total	Number	% of Total
Winding failures	134	51	615	55	144	37
Tap changer failures	49	19	231	21	85	22
Bushing failures	41	15	114	10	42	11
Terminal board failures	19	7	71	6	13	3
Core failures	7	3	24	2	4	1
Miscellaneous	12	4	72	6	101	26
Total	262	100	1127	100	389	100

Source: IEEE C37.91

Commissioning

Common Practice:

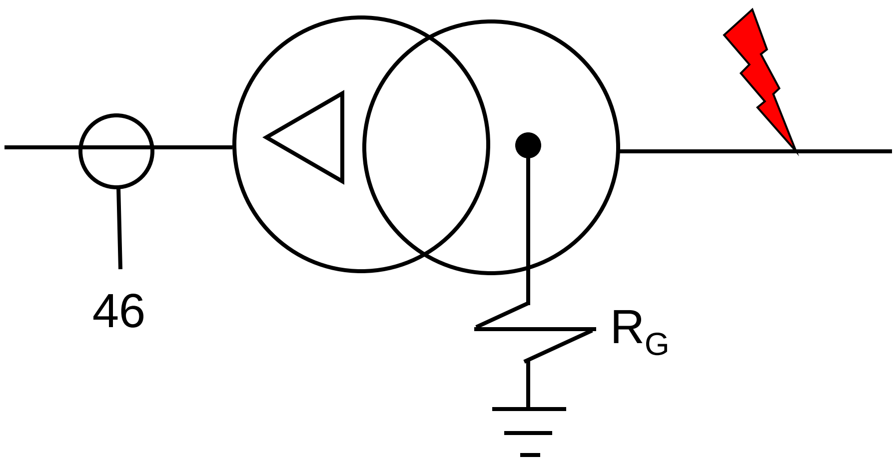
- Test all numerical relay settings –
  verify settings properly entered
- Easily facilitated using computer –
  automate test set & store results
- Hundreds of tests are possible –
  numerical relays have many settings

Commissioning

Final Goal

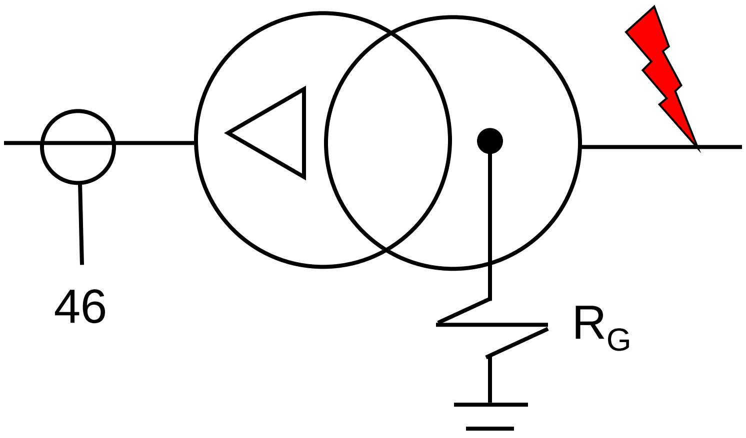
- **Ensure the transformer is properly protected for the *particular* application**

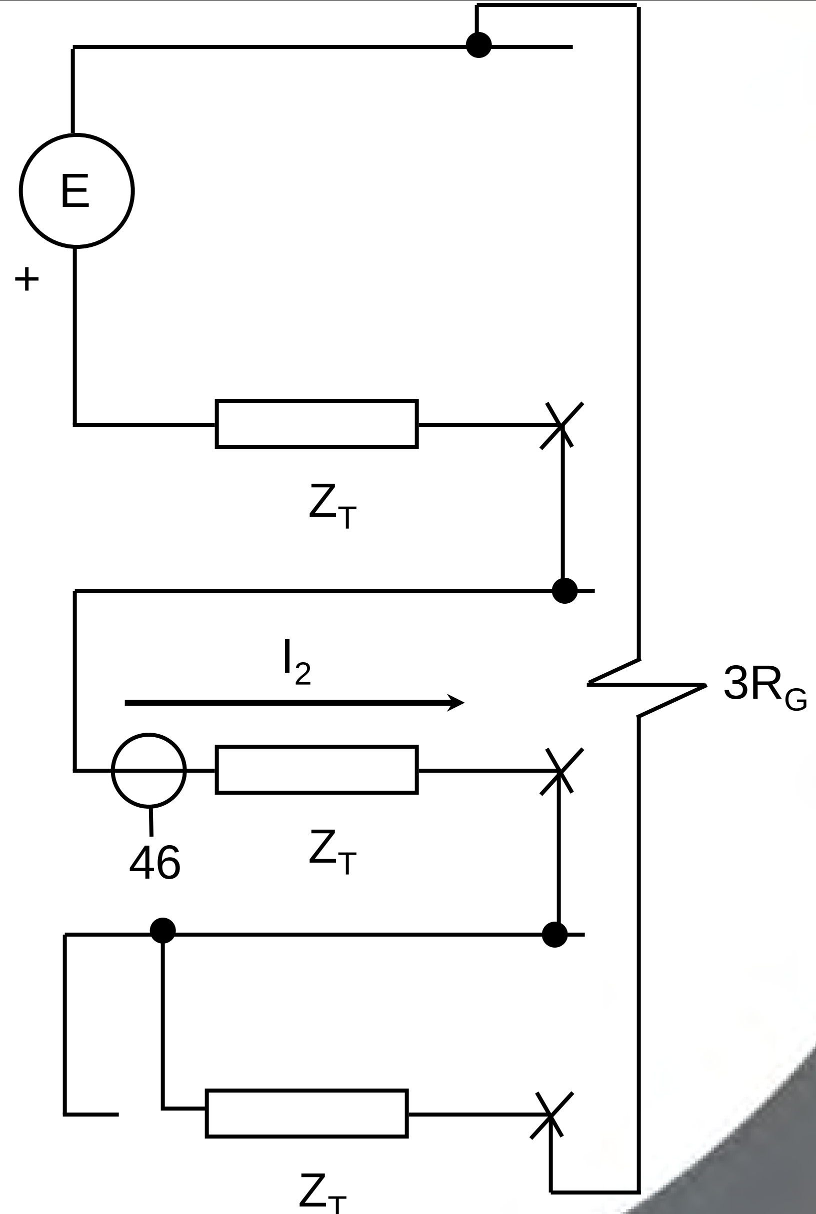
Typical Distribution Transformer



46: Negative-Sequence Overcurrent Element
(*sees ground faults through bank*)

R_G: Grounding Resistor
(Industrial Load)

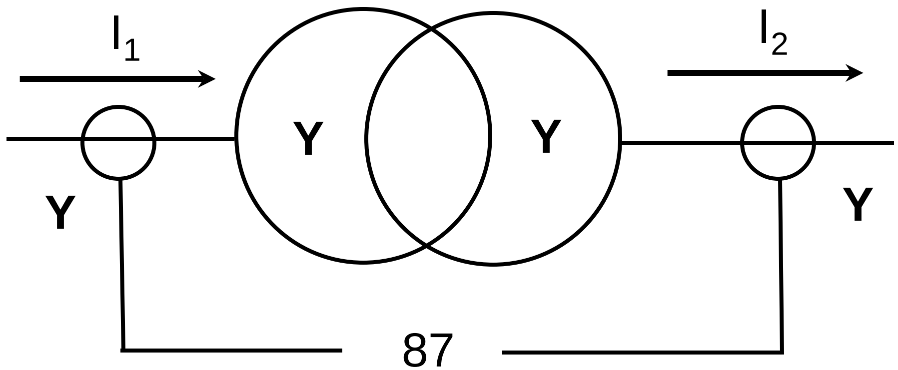




Sensitive setting for ground fault - *overreach for phase-to-phase fault*

Transformer Differential Characteristic

Boundary Test



**** Simulate Through Current***

I_1 = Winding 1 per unit current (A, B or C-phase)

I_2 = Winding 2 per unit current (A, B or C-phase)

3 elements per function (A, B & C-phase)

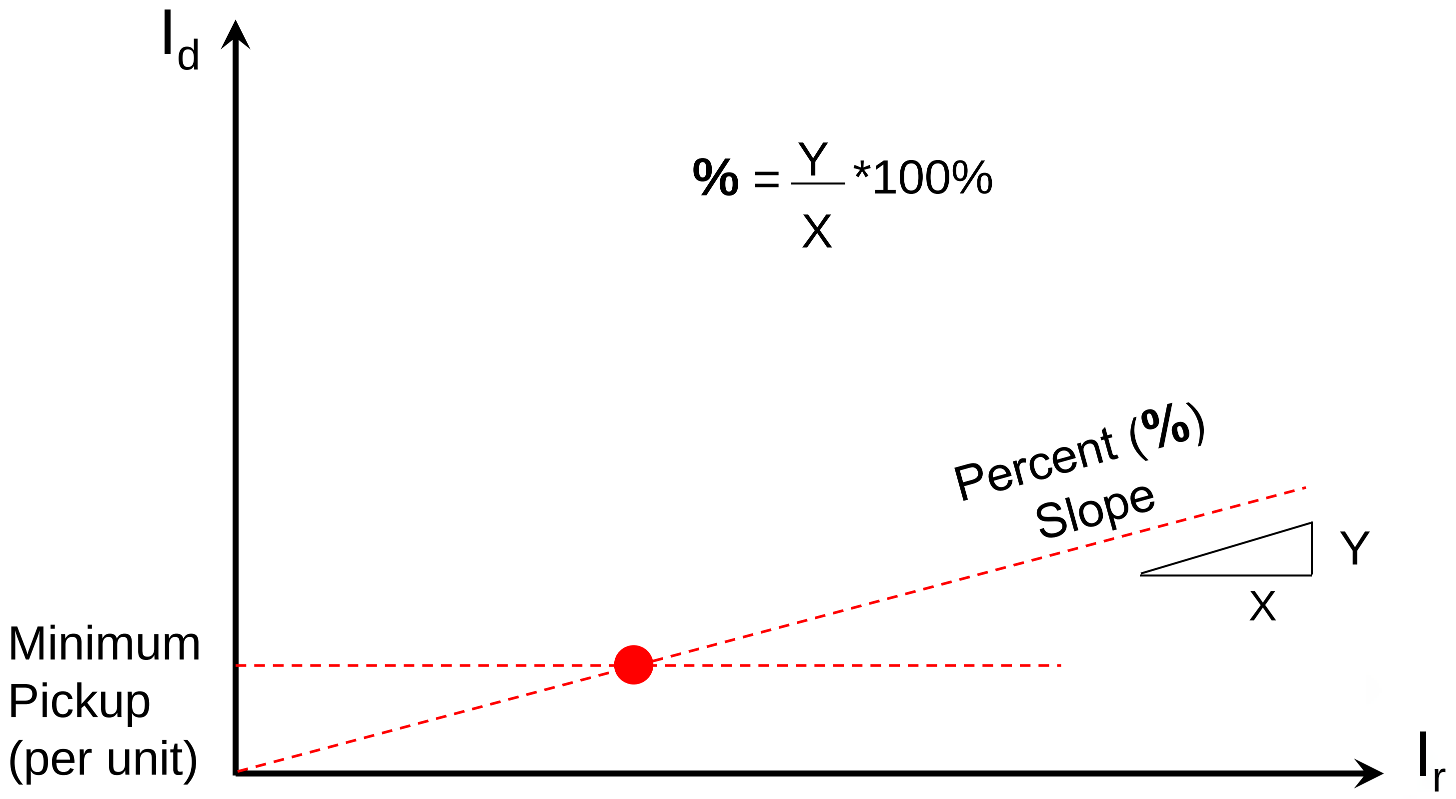
Differential Characteristic

Operating Equations

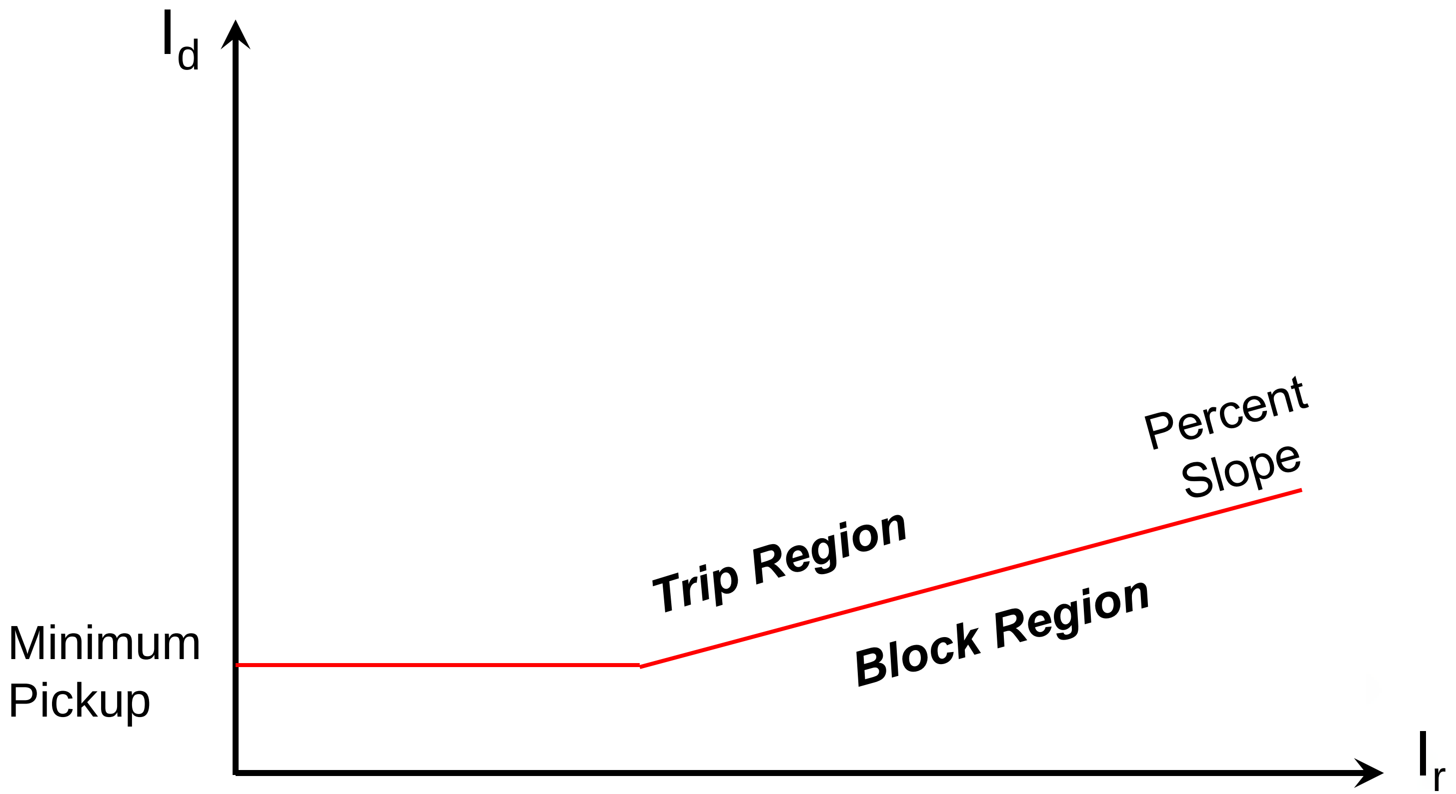
$I_d = |I_1 - I_2|$, Differential Current

$$I_r = \frac{|I_1| + |I_2|}{2}, \quad \text{Restraint Current}$$

Differential Characteristic



Differential Characteristic



Matrix

$$\begin{bmatrix} I_d \\ I_r \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ ½ & ½ \end{bmatrix} * \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

Inverted Matrix

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} \tfrac{1}{2} & 1 \\ -\tfrac{1}{2} & 1 \end{bmatrix} * \begin{bmatrix} I_d \\ I_r \end{bmatrix}$$

Differential Characteristic

Test Current Equations

$I_1 = 0.5*I_d + I_r$, Winding 1 Test Current (per unit)

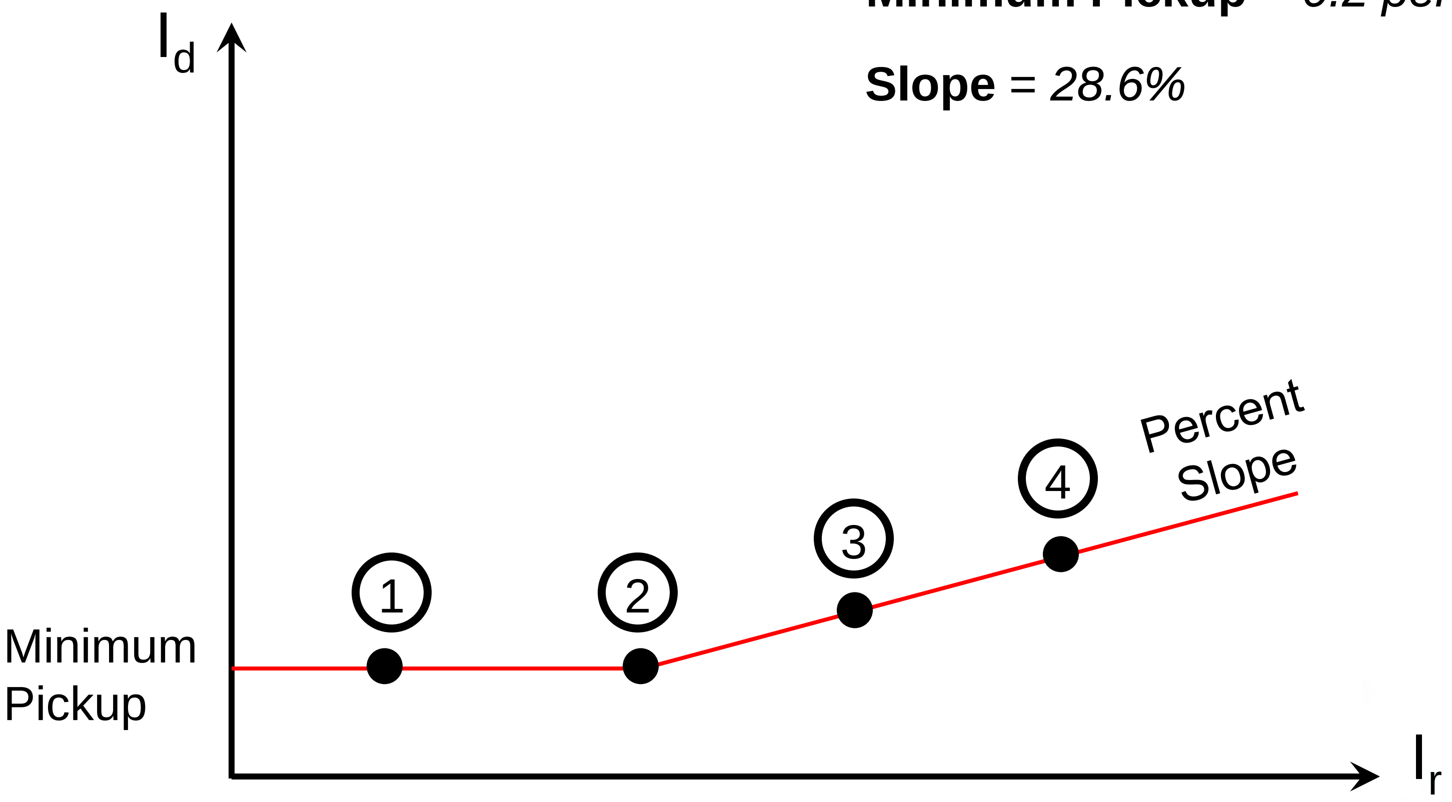
$I_2 = -0.5*I_d + I_r$, Winding 2 Test Current (per unit)

Differential Characteristic

Test Points

Minimum Pickup = *0.2 per unit*

Slope = *28.6%*



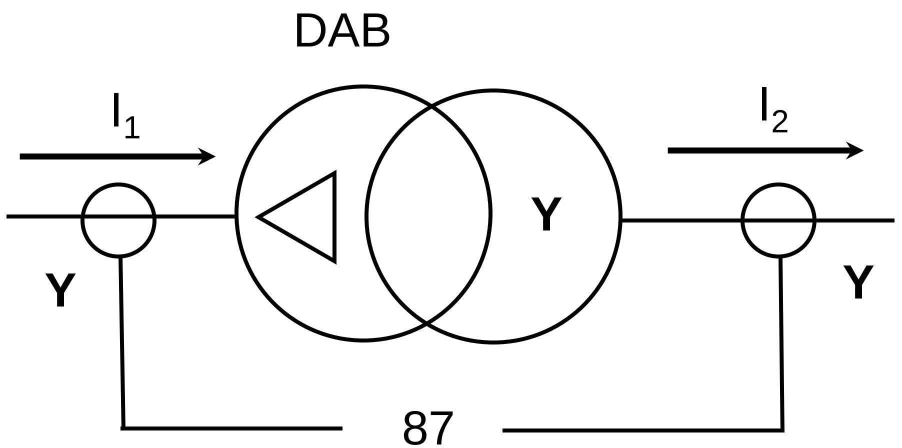
Differential Characteristic

Test Points (Per Unit)

	I_d	I_r	I_1	I_2
1	0.2	0.3	0.4	0.2
2	0.2	0.7	0.8	0.6
3	0.4	1.4	1.6	1.2
4	0.6	2.0	2.3	1.7

TABLE 1

Delta-Wye Differential Characteristic



***** *Simulate Through Current***

I_1 = Winding 1 per unit current (A, B or C-phase)

I_2 = Winding 2 per unit current (A, B or C-phase)

3 elements per relay (A, B & C-phase)

Delta-Wye Differential Characteristic

(Relay Internally Compensates Test Currents)

DAB WINDING	WYE WINDING
$I_{A1}^{relay} = I_{A1}/TAP1$	$I_{A2}^{relay} = (I_{A2} - I_{B2})/(TAP2*SQRT(3))$
$I_{B1}^{relay} = I_{B1}/TAP1$	$I_{B2}^{relay} = (I_{B2} - I_{C2})/(TAP2*SQRT(3))$
$I_{C1}^{relay} = I_{B1}/TAP1$	$I_{C2}^{relay} = (I_{C2} - I_{A2})/(TAP2*SQRT(3))$

$$TAP\# = \frac{MVA\#}{kV\#_{LL}*CTR\#*SQRT(3)}$$

Delta-Wye Differential Characteristic
(*Single-Phase* Test for *A-Phase Element*)

$I_{A1} = I_1*TAP1$

$I_{A2} = I_2*TAP2*SQRT(3)$

From TABLE 1:

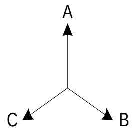
	I_d	I_r	I_1	I_2
2	0.2	0.7	***0.8***	***0.6***

$\mathbf{I_{A1}^{test} = 0.8*TAP1}$

$\mathbf{I_{A2}^{test} = 0.6*TAP2*SQRT(3)}$

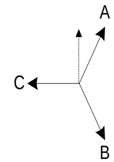
As an example, if we have a two winding transformer with Y/Delta-AC connection (or YD1) with Y-Y cts. This will be equivalent to case 2 with a 30° phase shift.

1: 0°



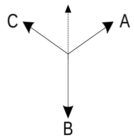
$$I'_{ABC} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} I_{ABC}$$

2: 30°



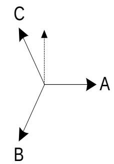
$$I'_{ABC} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} I_{ABC}$$

3: 60°



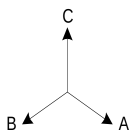
$$I'_{ABC} = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & -1 \\ -1 & 0 & 0 \end{bmatrix} I_{ABC}$$

4: 90°



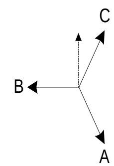
$$I'_{ABC} = \frac{1}{\sqrt{3}} \begin{bmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{bmatrix} I_{ABC}$$

5: 120°



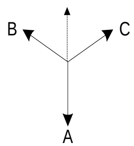
$$I'_{ABC} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} I_{ABC}$$

6: 150°



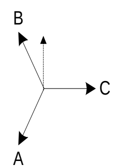
$$I'_{ABC} = \frac{1}{\sqrt{3}} \begin{bmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} I_{ABC}$$

7: 180°



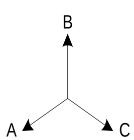
$$I'_{ABC} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} I_{ABC}$$

8: 210°



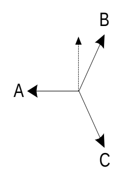
$$I'_{ABC} = \frac{1}{\sqrt{3}} \begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 1 & 0 & -1 \end{bmatrix} I_{ABC}$$

9: 240°



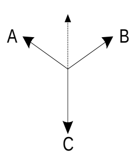
$$I'_{ABC} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} I_{ABC}$$

10: 270°



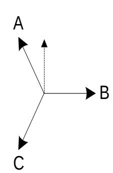
$$I'_{ABC} = \frac{1}{\sqrt{3}} \begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix} I_{ABC}$$

11: 300°



$$I'_{ABC} = \begin{bmatrix} 0 & 0 & -1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} I_{ABC}$$

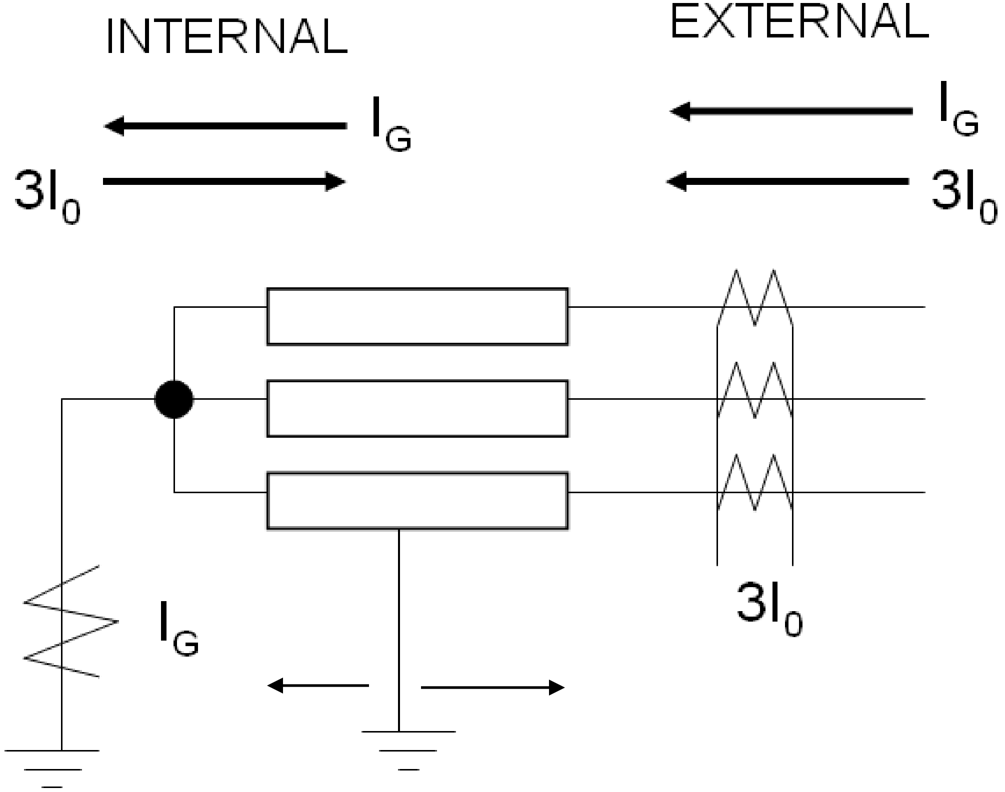
12: 330°



$$I'_{ABC} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} I_{ABC}$$

Ground Differential Element

Sensitivity Test



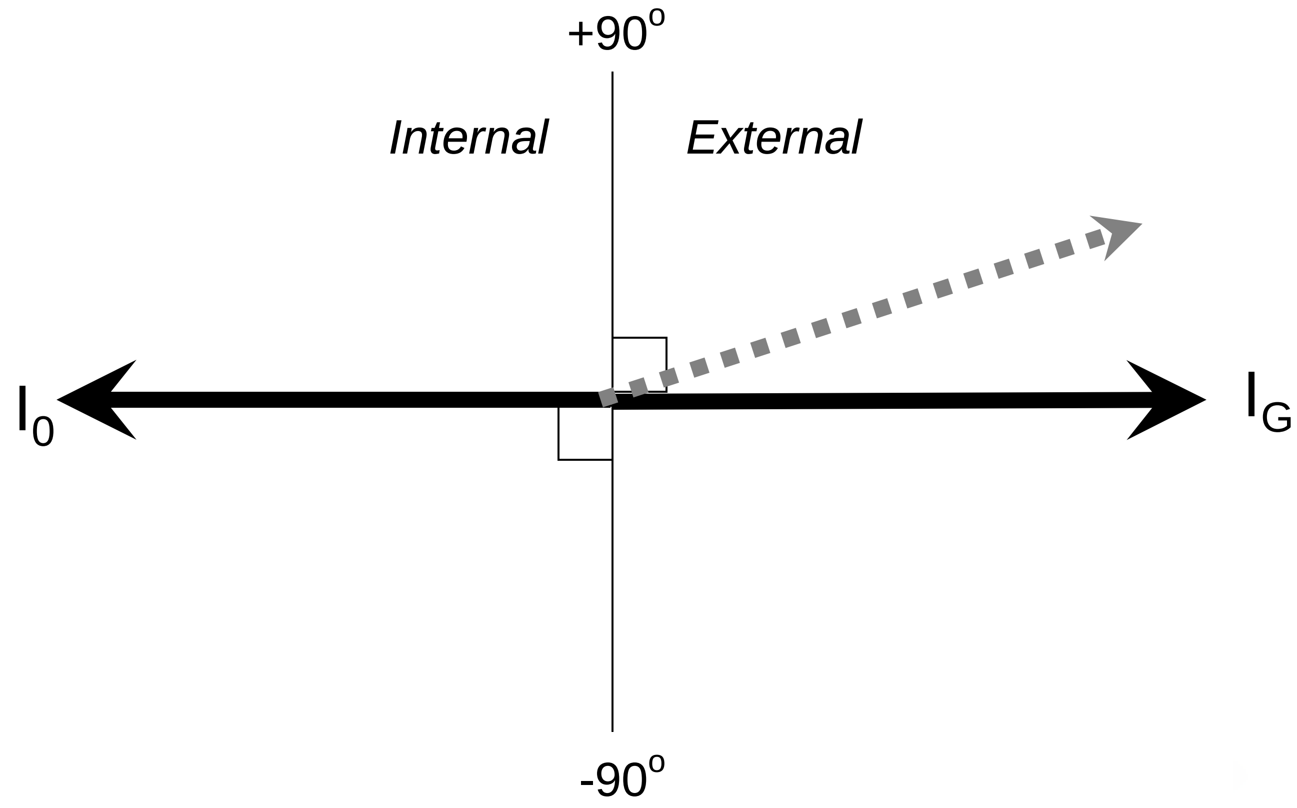
Ground Fault Location along Windings

Directionality

(I_0 vs. I_G)

Ground Differential Element

Directional Element



Disabled if $|3I_0|$ less than 140 mA

(Improves Security for CT saturation during external faults)

Ground Differential Element

Pickup

Operate When:

$$|3I_0 - I_G| > \text{Pickup}$$

Ground Differential Element

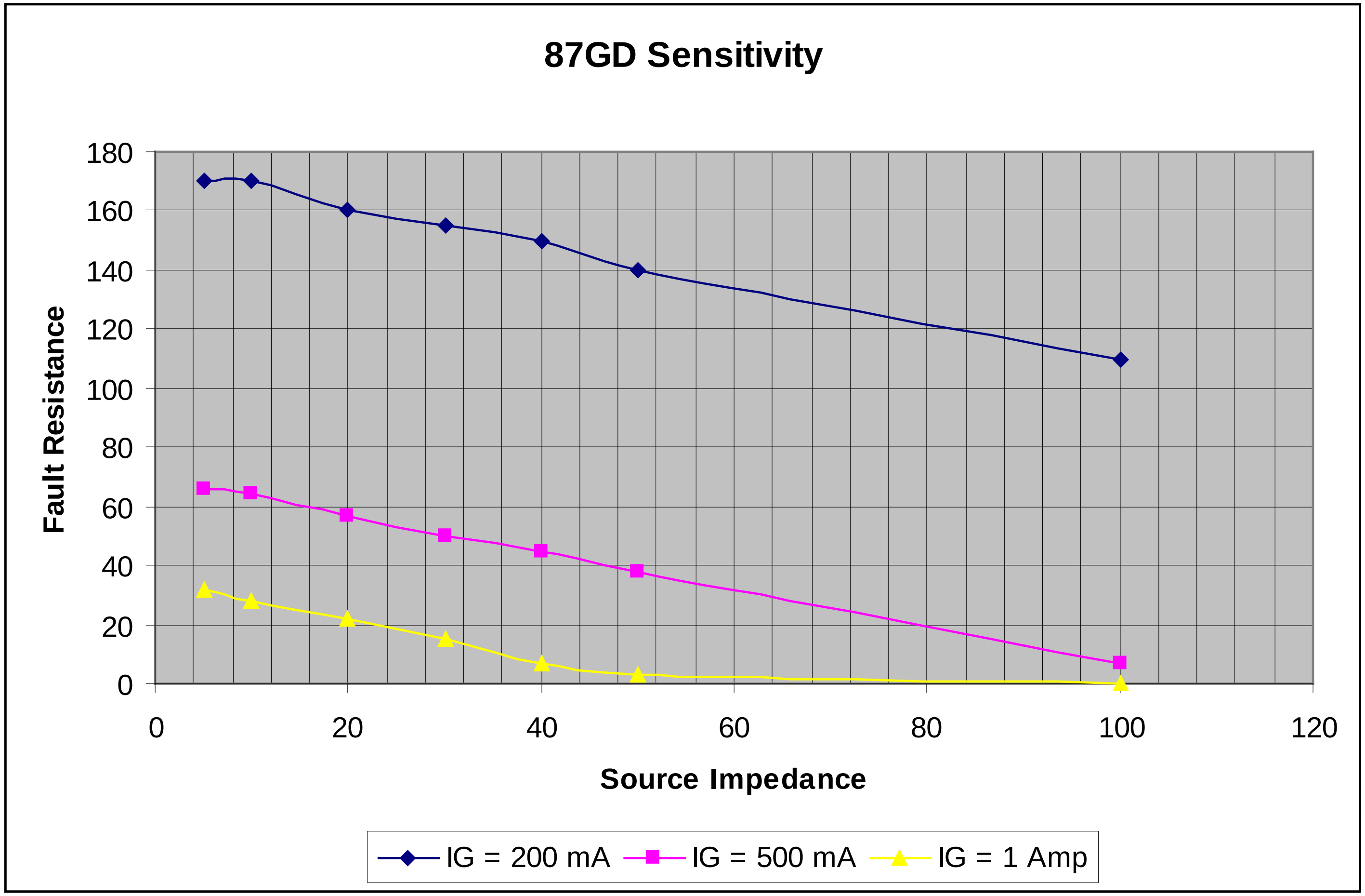
Sensitivity Test

Power System Parameters:

- **Source Impedance (*Varies*)**
- **X_T = 10%**
- **R_F (*Varies*)**
- **Ground Fault Location (5% from Transformer Neutral)**

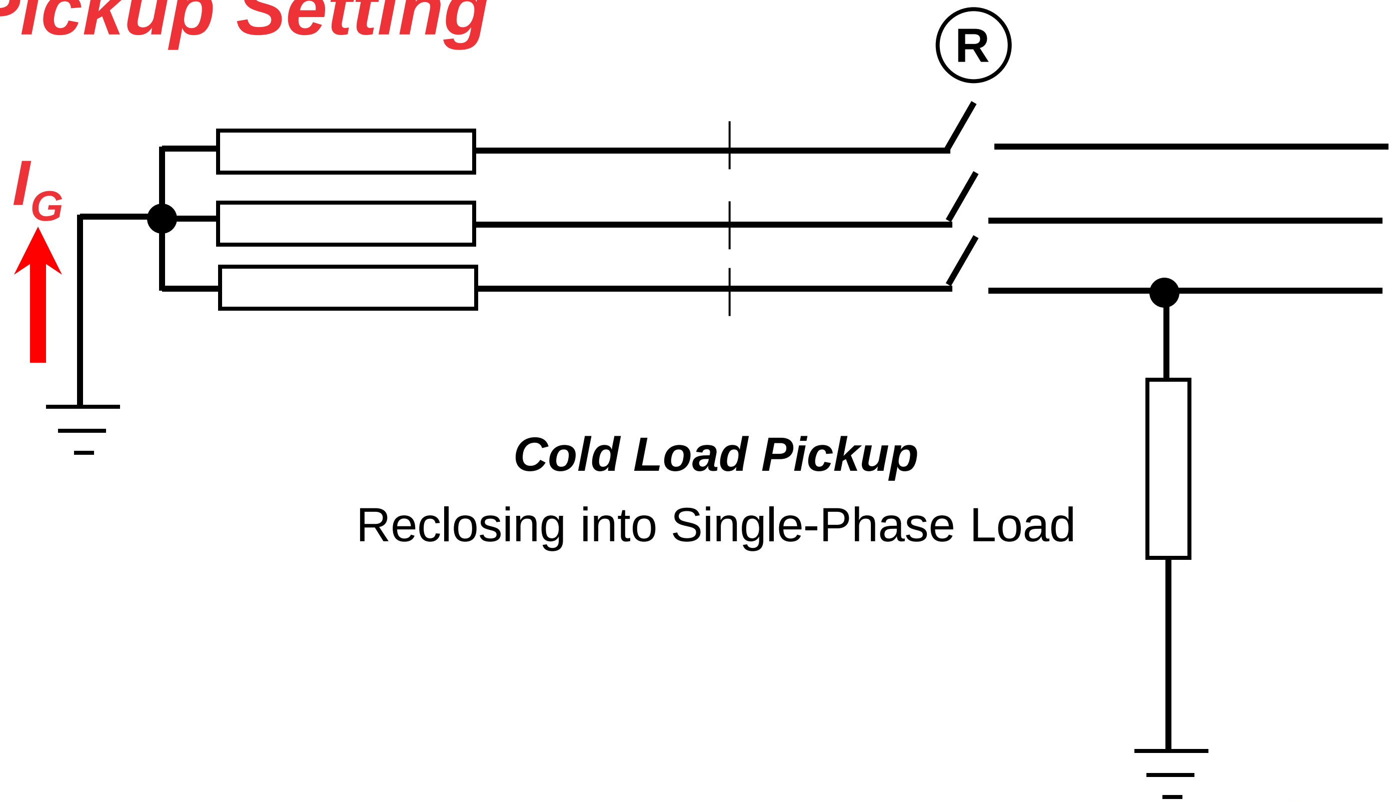
Ground Differential Element

R_F Coverage vs. Source Strength



Ground Differential Element

Pickup Setting

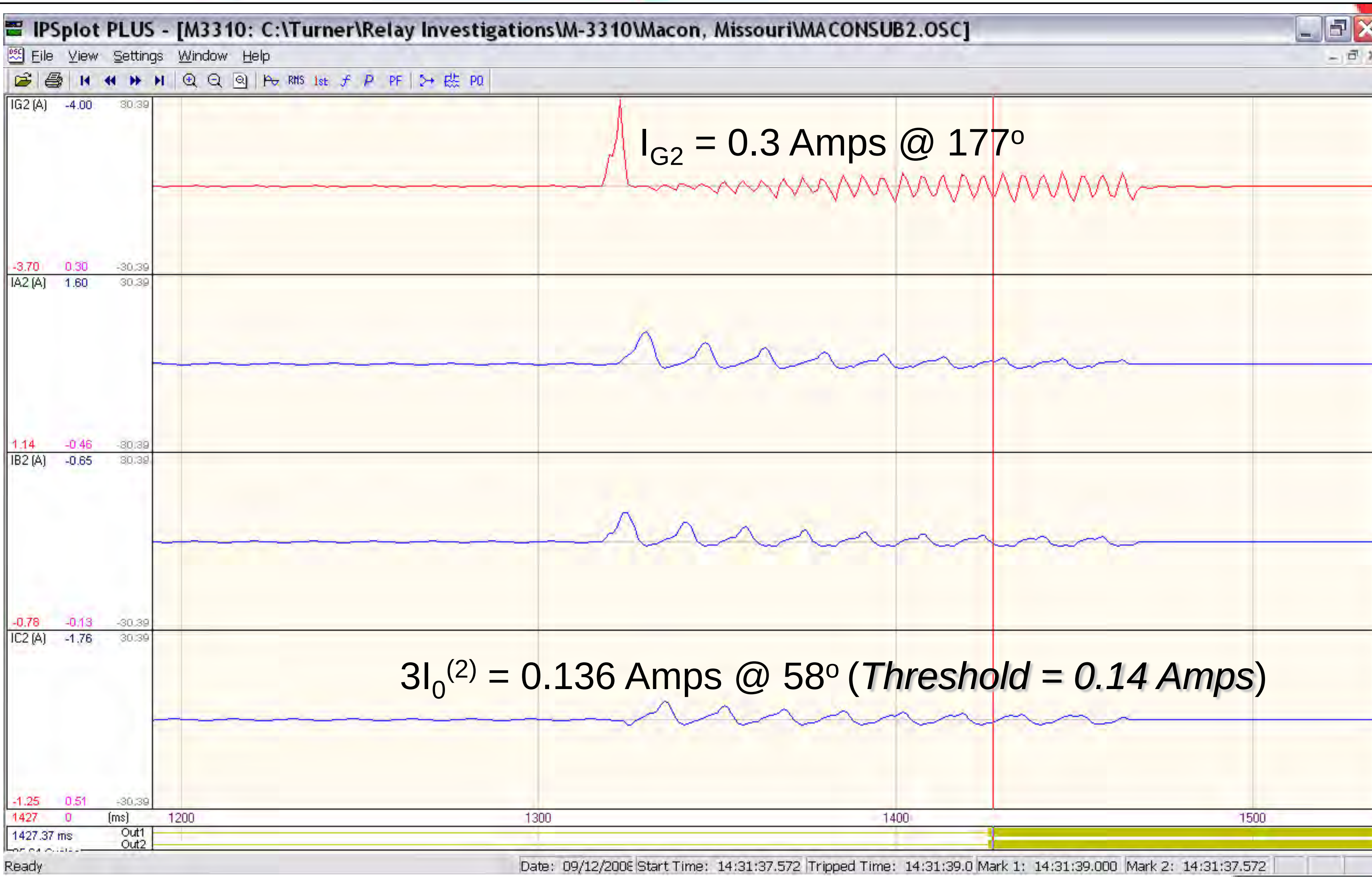


Cold Load Pickup

Reclosing into Single-Phase Load

Pickup > Unbalance

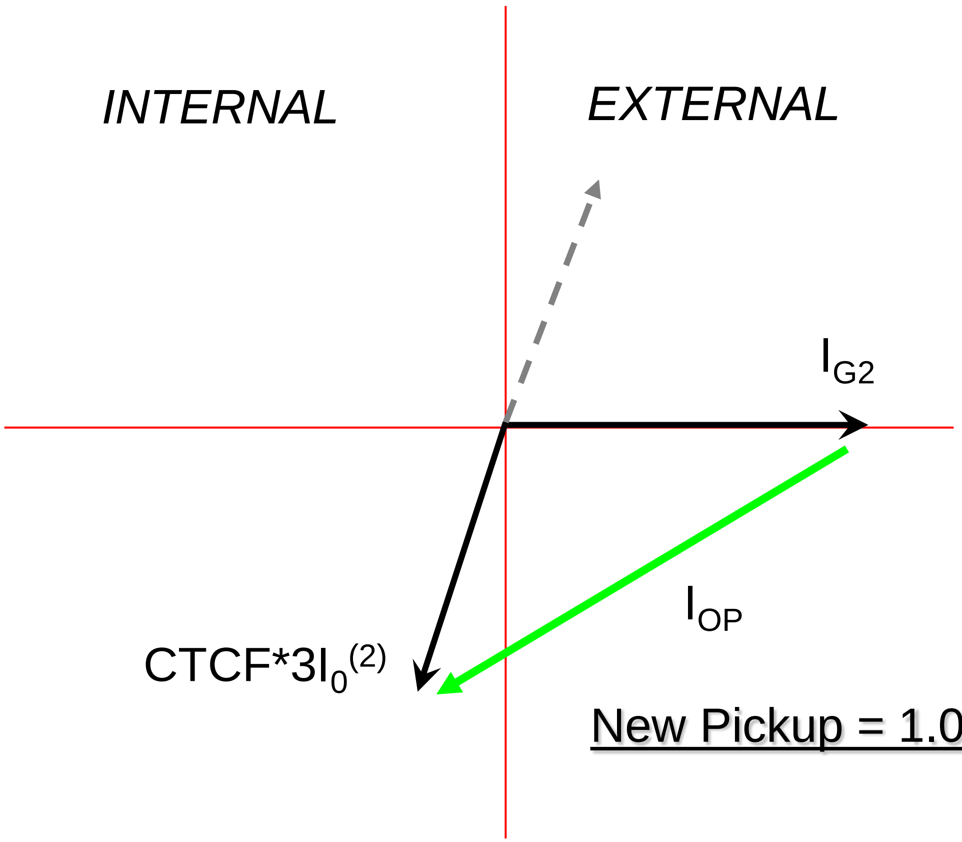
Directional Element Disabled if $3I_0$ Low



$|CTCF*3I_0^{(2)} - I_{G2}| = 0.75$ Amps

Original Pickup = 0.3 Amps

Directional Element



New Pickup = 1.0 Amps

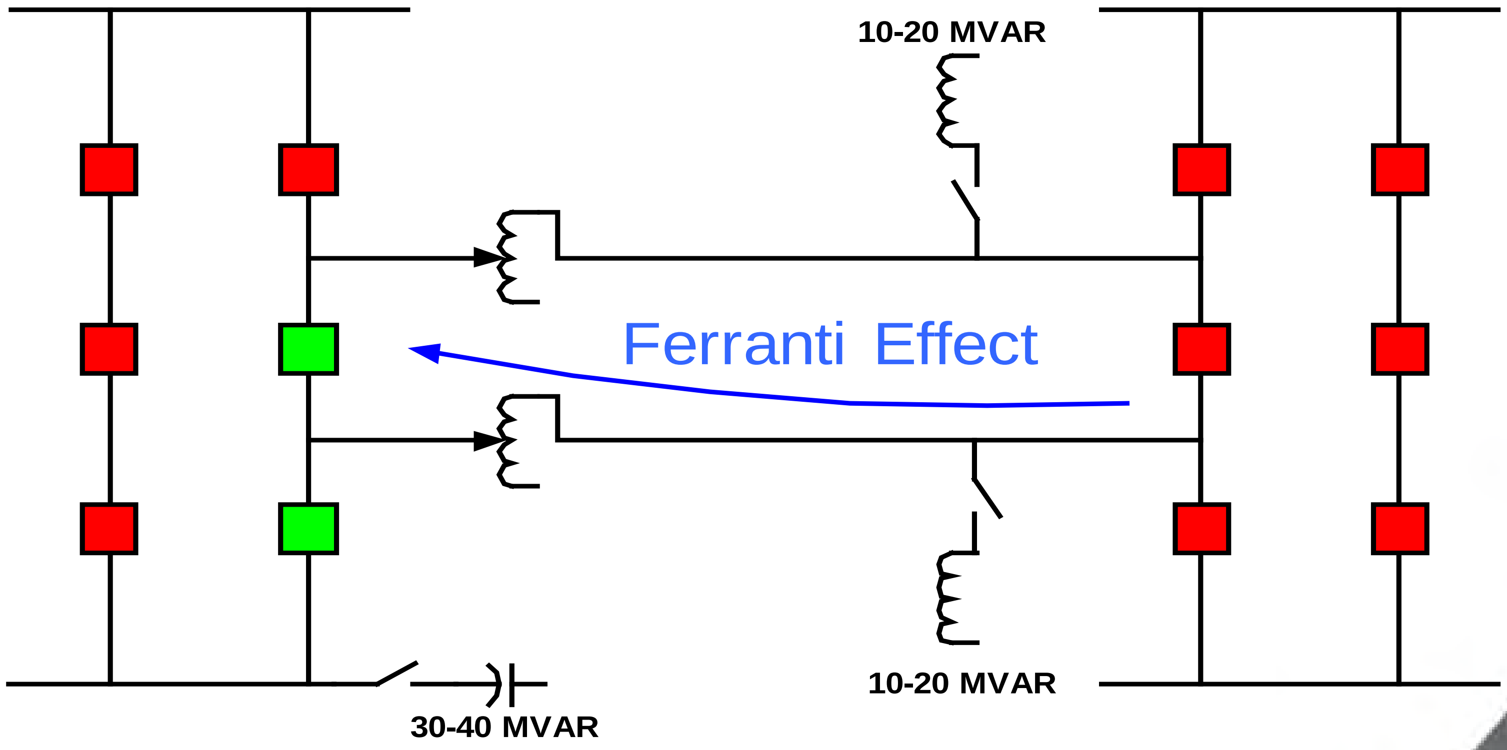
Other Transformer Protection

- **24** – Overexcitation (V/Hz)
- **46** – Negative-Sequence Overcurrent
- **49** – Winding Overload
- **50** – Instantaneous Phase Overcurrent (per winding)
- **50G** – Instantaneous Ground Overcurrent (per winding)
- **50N** – Instantaneous Neutral Overcurrent (per winding)
- **51** – Inverse Time Phase Overcurrent (per winding)
- **51G** – Inverse Time Ground Overcurrent (per winding)
- **51N** – Inverse Time Neutral Overcurrent (per winding)
- **59G** – Ground Overvoltage (Ungrounded Windings)
- **63** – Sudden Pressure

Causes of Overexcitation

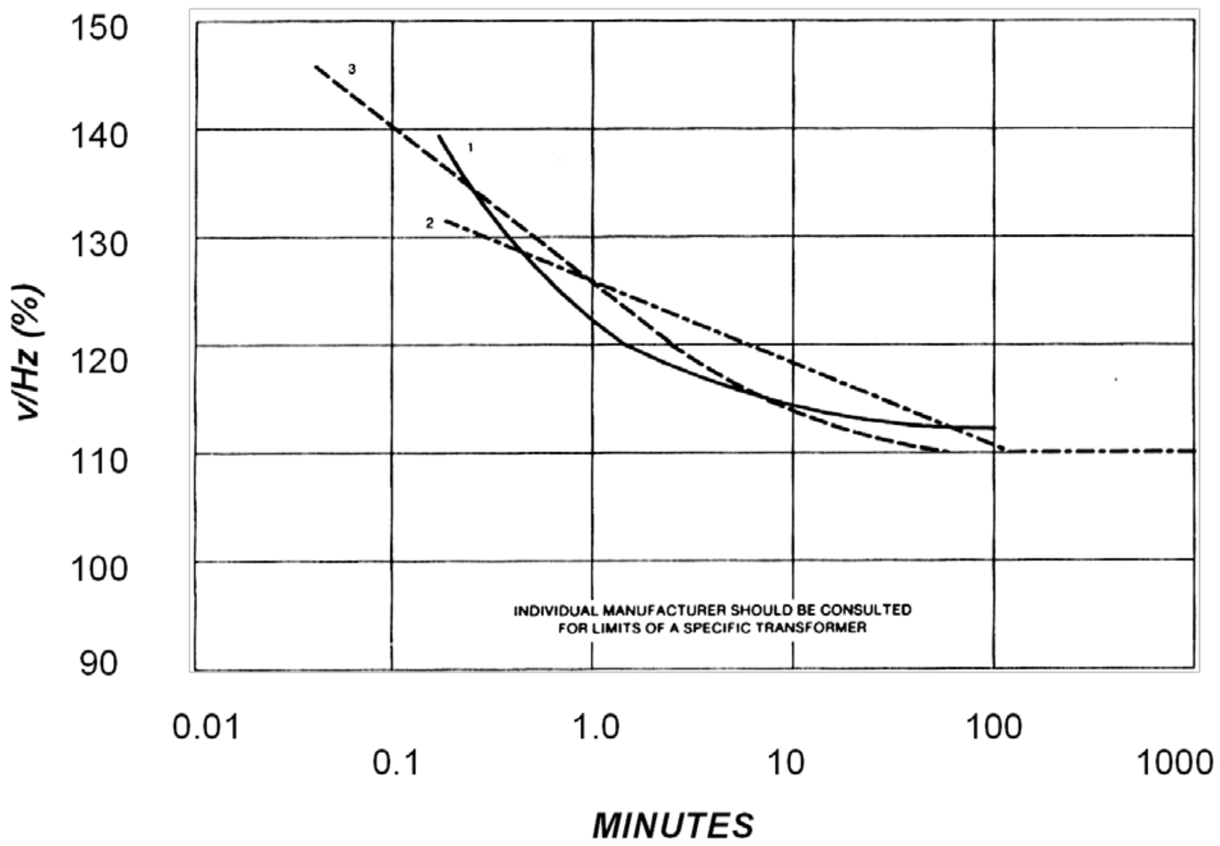
- **Generating Plants**
  - Excitation system runaway
  - Sudden loss of load
  - Operational issues (reduced frequency)
    - Static starts
    - Pumped hydro starting
    - Rotor warming
- **Transmission Systems**
  - Voltage and Reactive Support Control Failures
    - Capacitor banks ON when they should be OFF
    - Shunt reactors OFF when they should be ON
    - Near-end breaker failures resulting in voltage
    - rise on line (Ferranti effect)
    - Runaway LTCs

System Control Issues: Overvoltage and Overexcitation

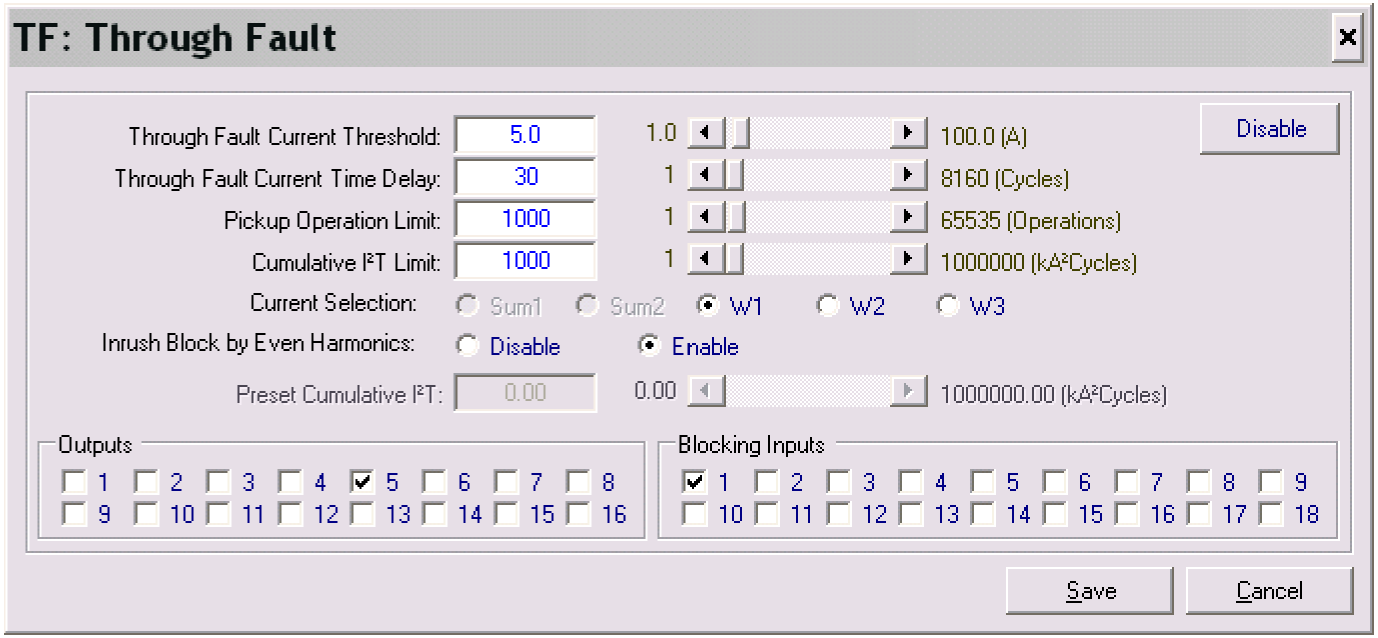


Reactors are off but should be on

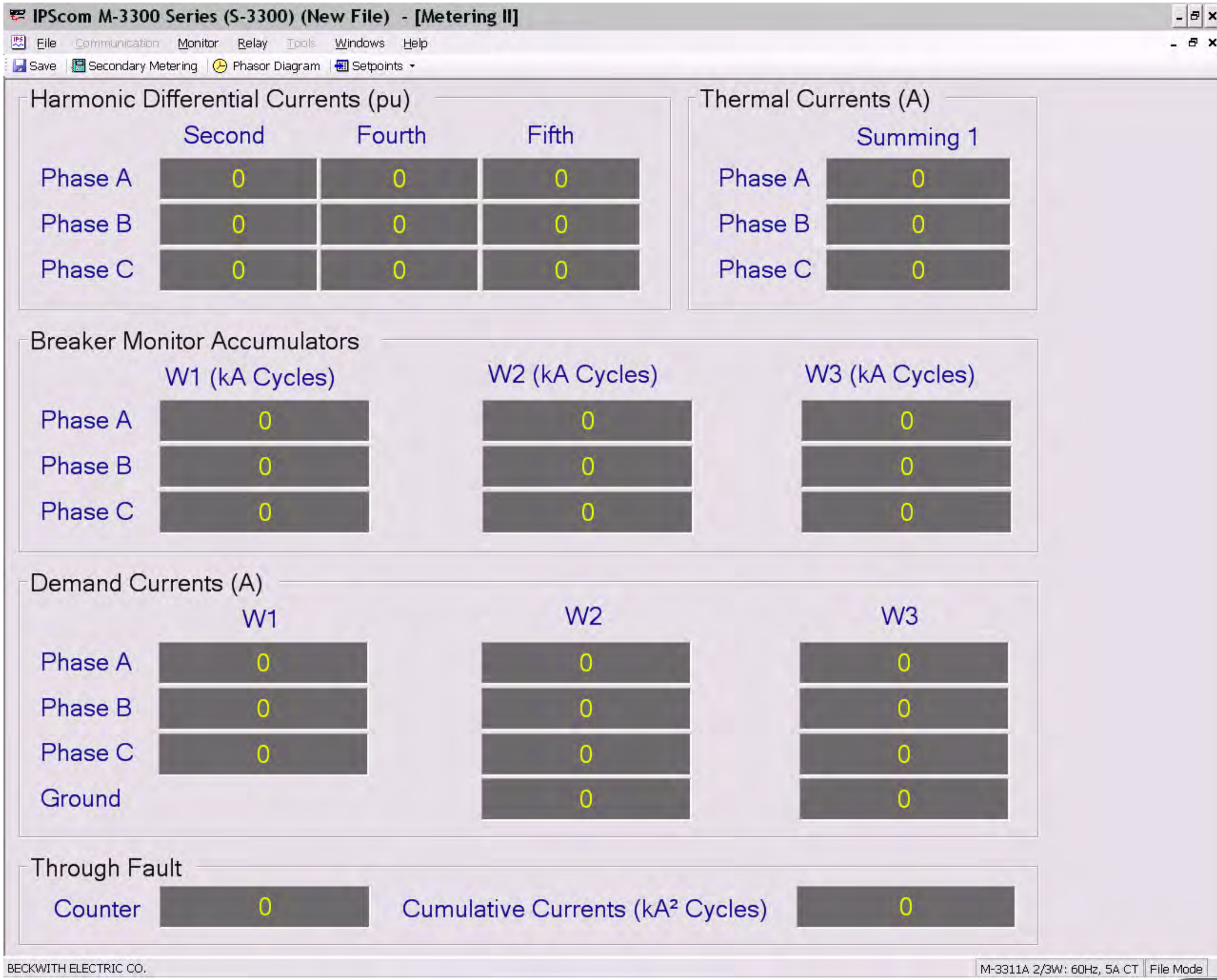
Overexcitation Curves



Through Fault Monitoring



Through Fault Monitoring



Even Harmonic Restraint during Inrush

COMTRADE PLAYBACK

Waveform Sources:

- Events from Numerical Relays
- Events from Digital Fault Recorders
- Simulate using Transient Software

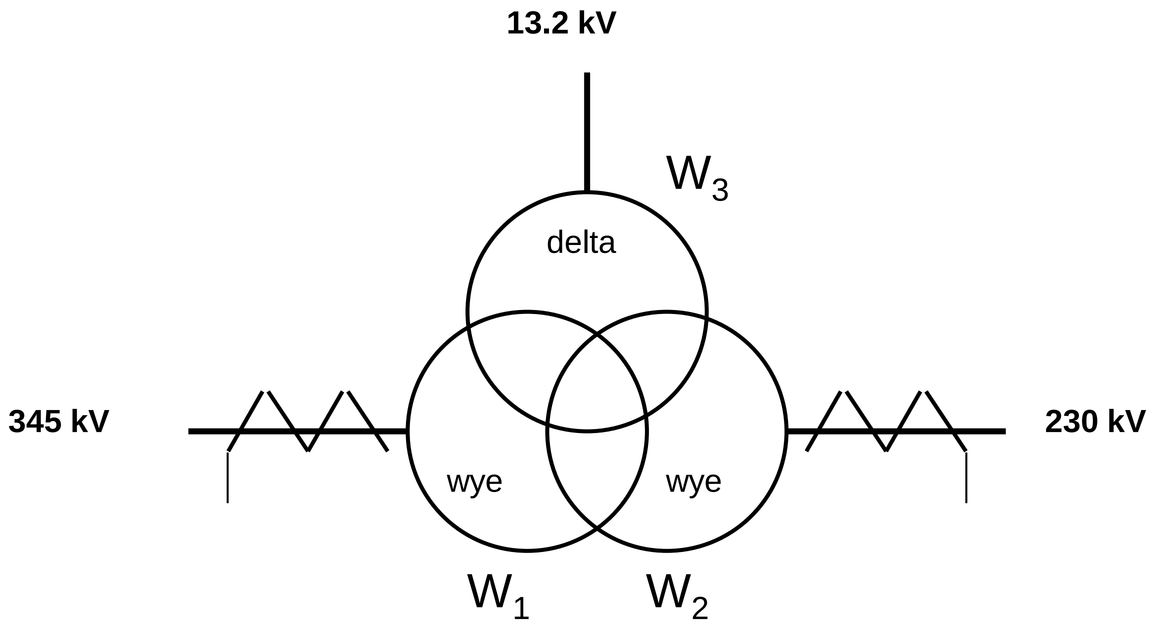
Even Harmonic Restraint during Inrush

Traditional Approach

- 2^{nd} Harmonic Restraint
- Cross Phase Blocking

Even Harmonic Restraint during Inrush

Auto-Transformer Model



600 MVA Auto-Transformer (Tertiary Winding DAC)

Even Harmonic Restraint during Inrush

Auto-Transformer Model

Auto-transformer Characteristics

Z_{HM} = 0.01073 per unit
Z_{HL} = 0.04777 per unit
Z_{ML} = 0.03123 per unit

$$Z_H = \frac{Z_{HM} + Z_{HL} - Z_{ML}}{2} = 0.0140 \text{ per unit}$$

$$Z_M = \frac{Z_{HM} + Z_{ML} - Z_{HL}}{2} = -0.0029 \text{ per unit}$$

$$Z_L = \frac{Z_{HL} + Z_{ML} - Z_{HM}}{2} = 0.0340 \text{ per unit}$$

CTR_{W1} = 1200:5 (wye connected)
CTR_{W2} = 2000:5 (wye connected)

Even Harmonic Restraint during Inrush

Auto-Transformer Model

$$TAP1 = \frac{600\ MVA}{345\ kV * 240 * SQRT(3)} = 4.18$$

$$TAP2 = \frac{600\ MVA}{230\ kV * 400 * SQRT(3)} = 3.77$$

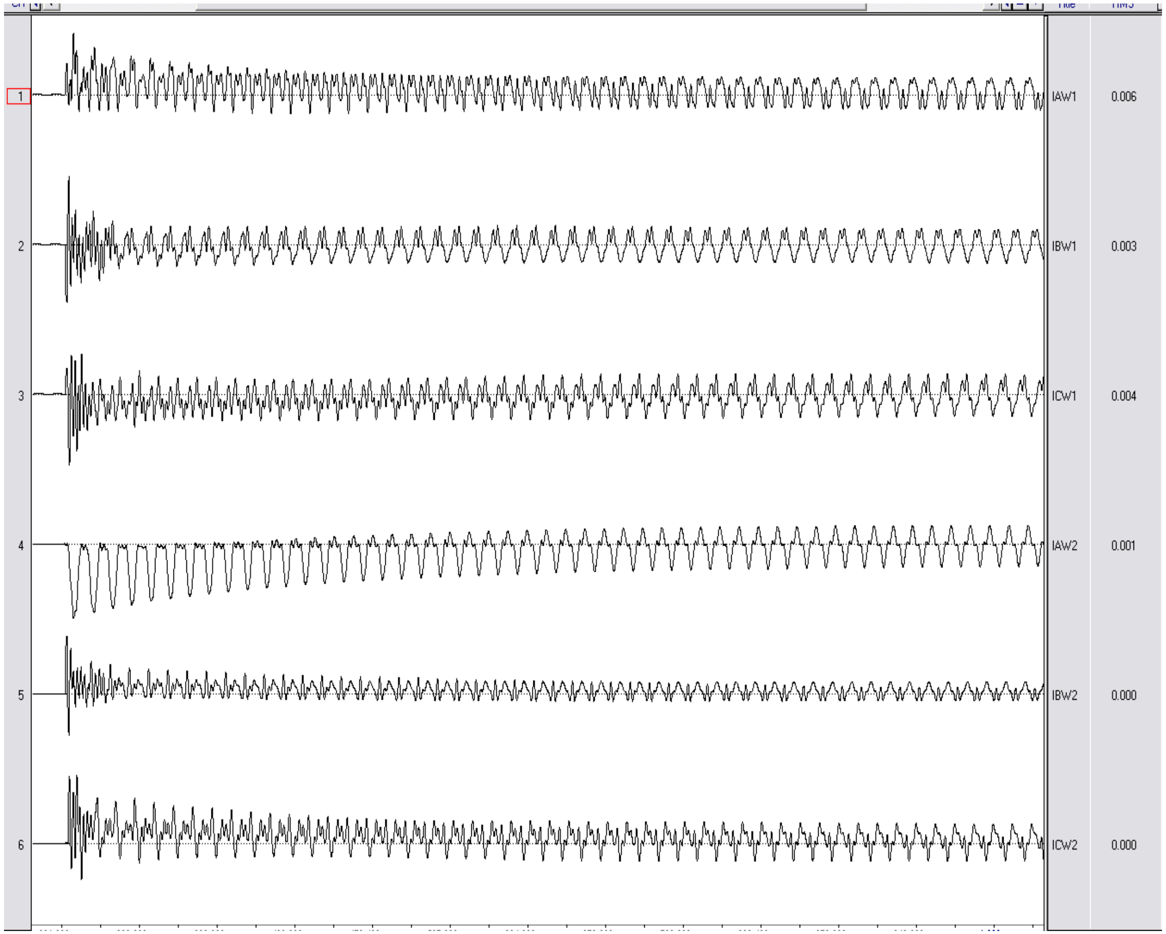
Minimum Pickup* = 0.5 per unit

Slope = 25%

*__*Original Pickup = 0.45 per unit*__

Even Harmonic Restraint during Inrush

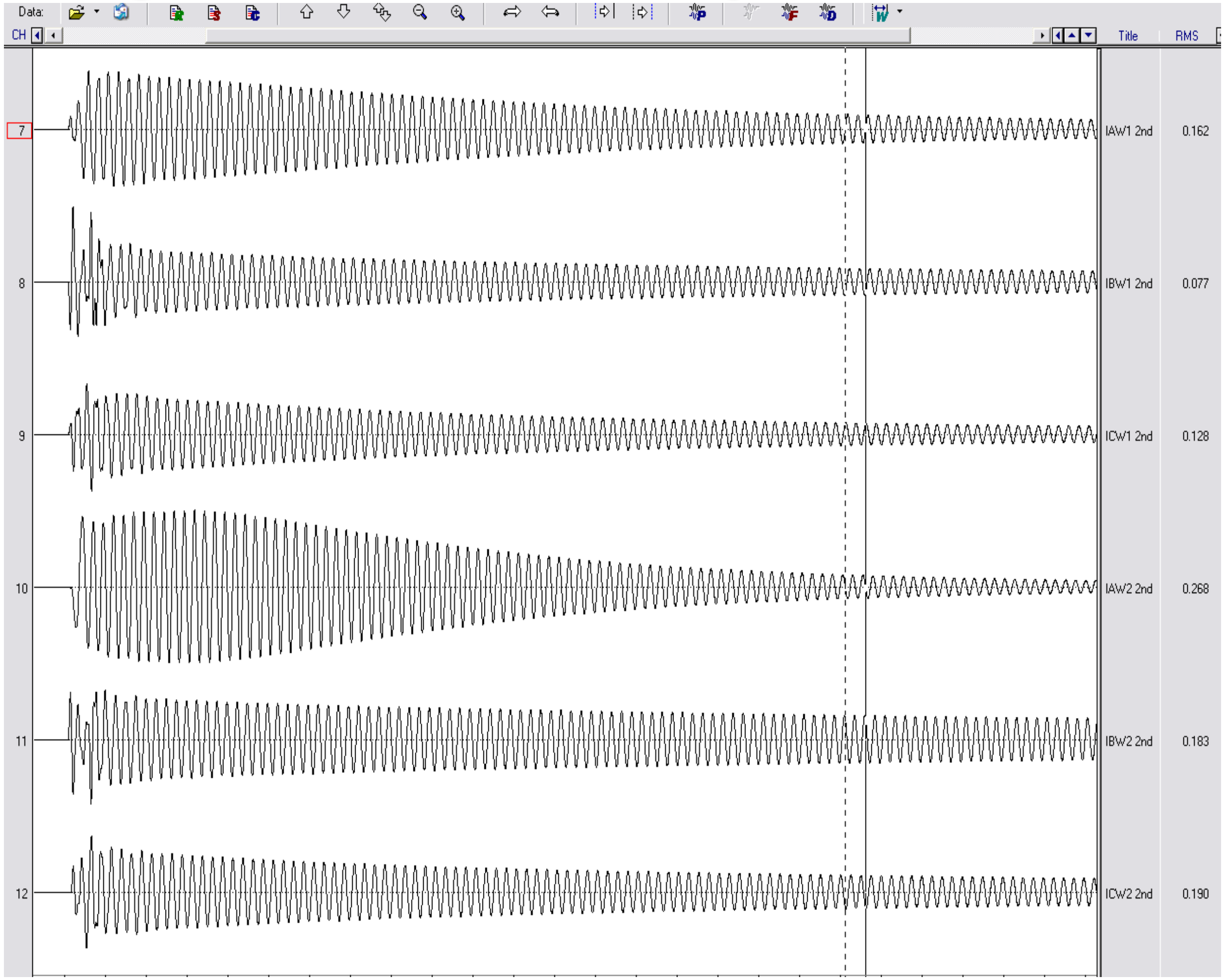
Energize Bank with Heavy A-Phase Residual Flux



Total Phase Current

Even Harmonic Restraint during Inrush

Energize Bank with Heavy A-Phase Residual Flux



2^{nd} Harmonic Phase Current

Even Harmonic Restraint

$$I_{even} = (I_2{}^2 + I_4{}^2)^{1/2}$$

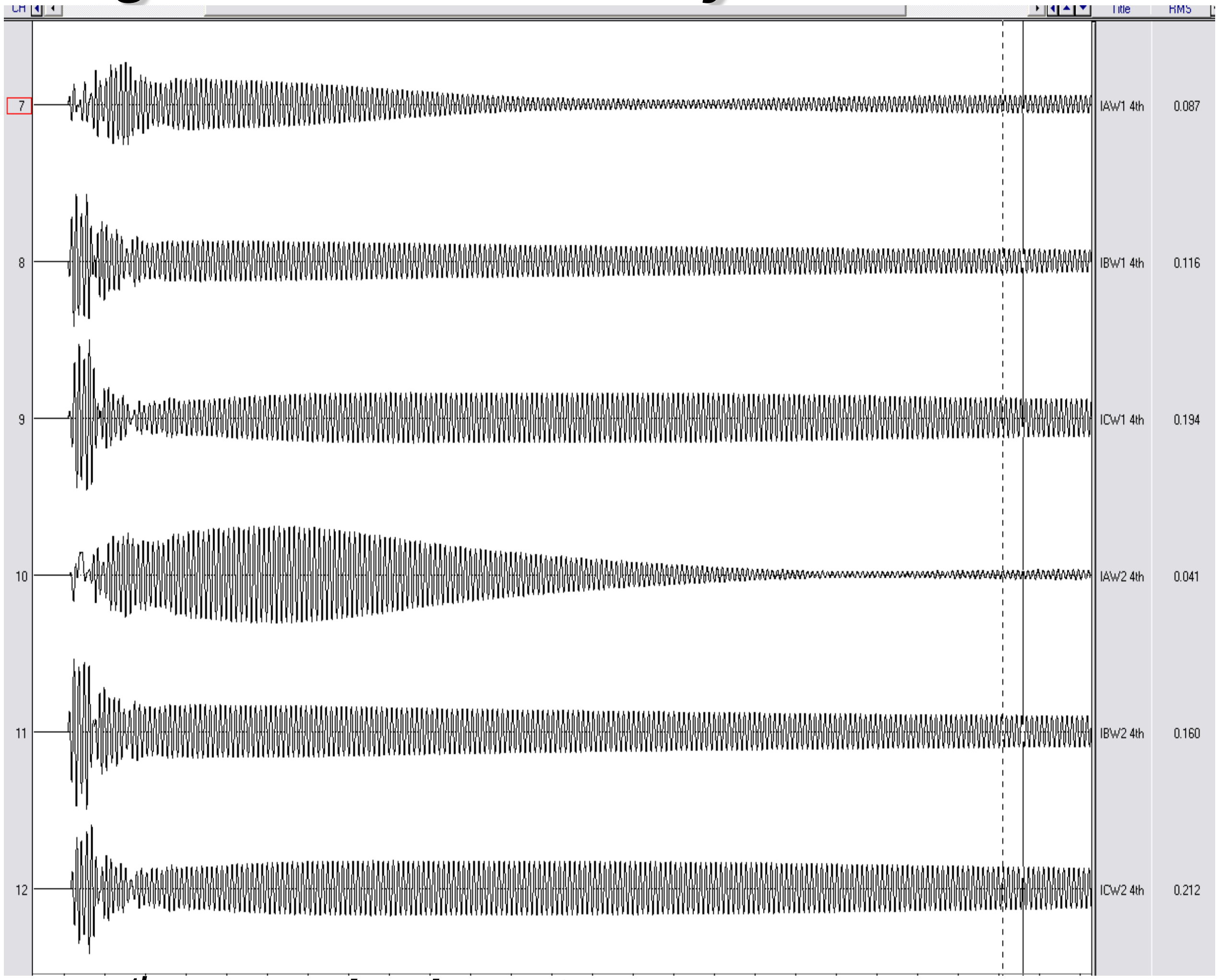
Cross Phase Averaging

- Provides security if any phase has low harmonic content during inrush
- Cross phase averaging uses the sum of harmonics on all three phases as the restraint value

$$Id_{CPA24} = \sqrt{IAd_{24}^{2} + IBd_{24}^{2} + ICd_{24}^{2}}$$

Even Harmonic Restraint during Inrush

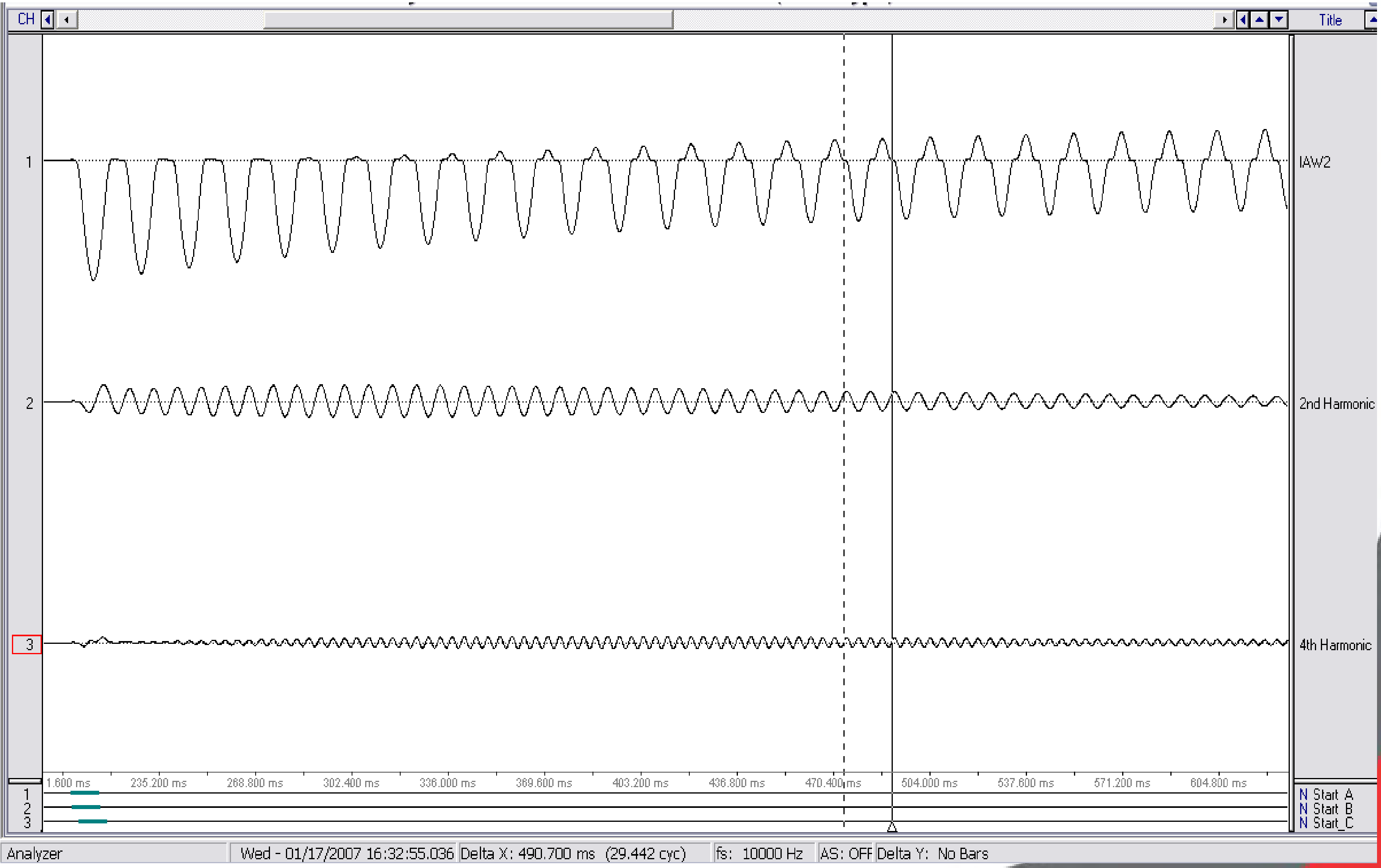
Energize Bank with Heavy A-Phase Residual Flux



4th Harmonic Phase Current

Even Harmonic Restraint during Inrush

A-Phase Current (Winding 2)



CONCLUSIONS

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- ***Transformer Differential Boundary Test (Commissioning)***
- ***Ground Differential Sensitivity Test (Commissioning/Maintenance)***
- ***Harmonic Restraint for Transformer Inrush (Maintenance)***

QUESTIONS