Hands On Relay School

Transformer Protection Open Lecture

Open Lecture
Transformer Differential Protection

Introduction:

Transformer differential protection schemes are ubiquitous to almost any power system.

While the basic premise of transformer differential protection is straightforward, numerous features are employed to compensate for challenges presented by the transformer application….

Challenges to Understanding Transformer Differential Protection

- Current Mismatch Caused by the Transformation Ratio and Differing CT Ratios
- Current Mismatch Caused by Differing CT Ratios
- Delta-Wye Transformation of Currents
- Zero Sequence Elimination
- LTC Induced Mismatch, CT Saturation, CT Remanence, and CT Tolerance
- Inrush Phenomena and Harmonic Content Availability
- Over Excitation Phenomena
- Switch Onto Fault concerns

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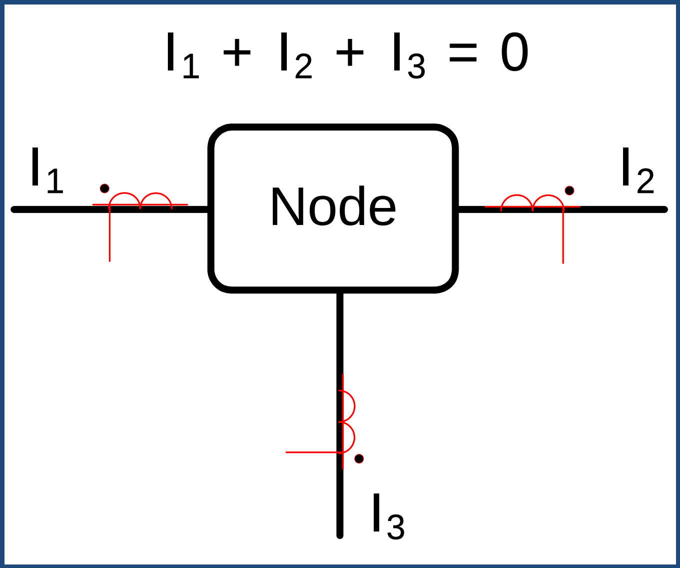
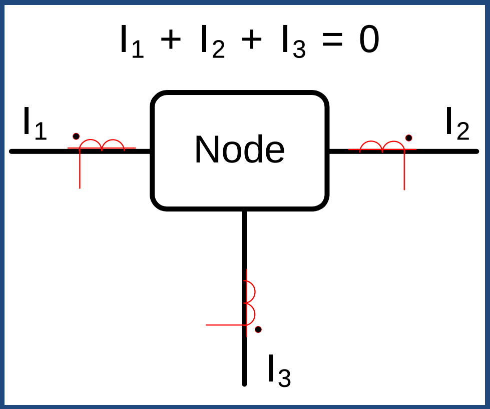
Current Mismatch Caused by the Transformation Ratio and Differing CT Ratios

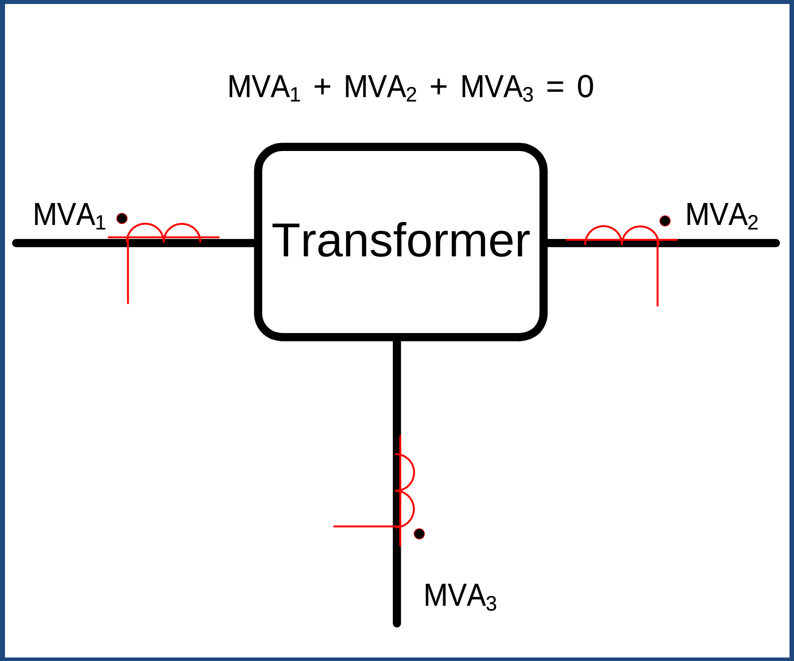
Kirchhoff's Current Law: At any node, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node (fig 1).



Current Mismatch Caused by the Transformation Ratio and Differing CT Ratios

Because of the transformation ratio and probable CT ratio mismatch, transformer winding currents cannot be directly compared, but the MVA on each side can be compared.





Current Mismatch Caused by the Transformation Ratio and Differing CT Ratios

To calculate the secondary current equal to one per unit, the following calculations are used on each side of the transformer:

For wye-connected CT's:

$$WindingTap = \frac{TransformerVA}{V_{L-L} * CTR * \sqrt{3}}$$

For delta-connected CT's:

$$WindingTap = \frac{TransformerVA}{V_{L-L} * CTR * \sqrt{3}} \times \sqrt{3}$$

Current Mismatch Caused by the Transformation Ratio and Differing CT Ratios

During testing, the desired starting current values is determined by multiplying the desired per unit current by the tap to find the equivalent secondary current for each side.

$$PU_{Desired} \times WindingTap = I_{Test}$$

To convert a measured trip current to a per unit current, divide the current by the tap for that winding.

$$PU_{measured} = \frac{I_{measured}}{WindingTap}$$

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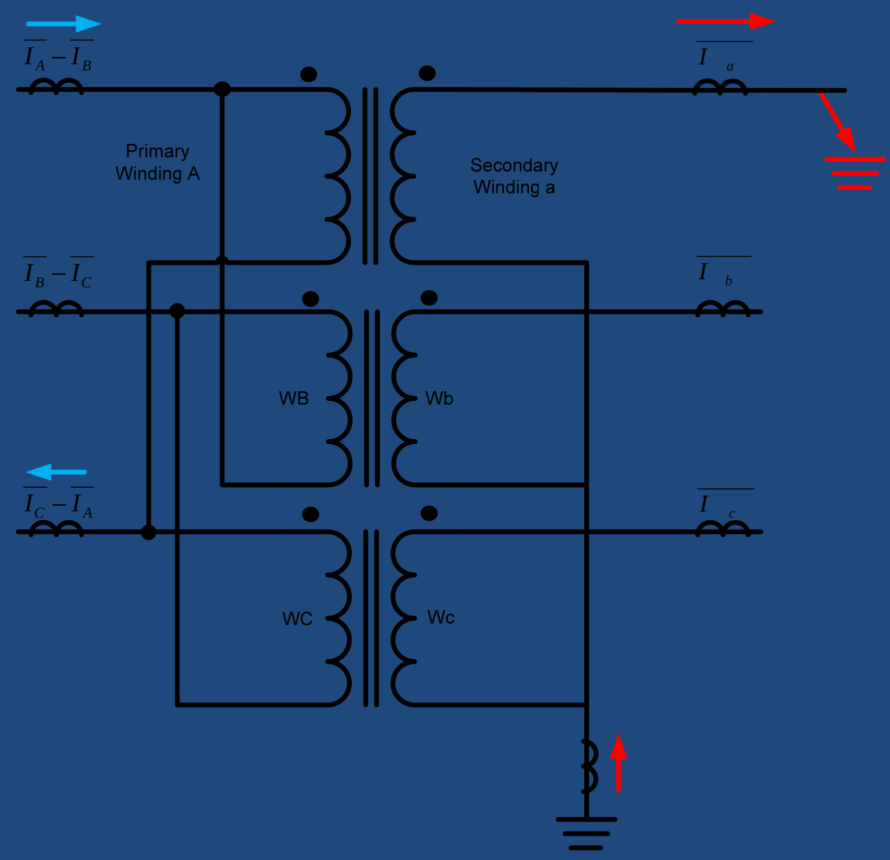
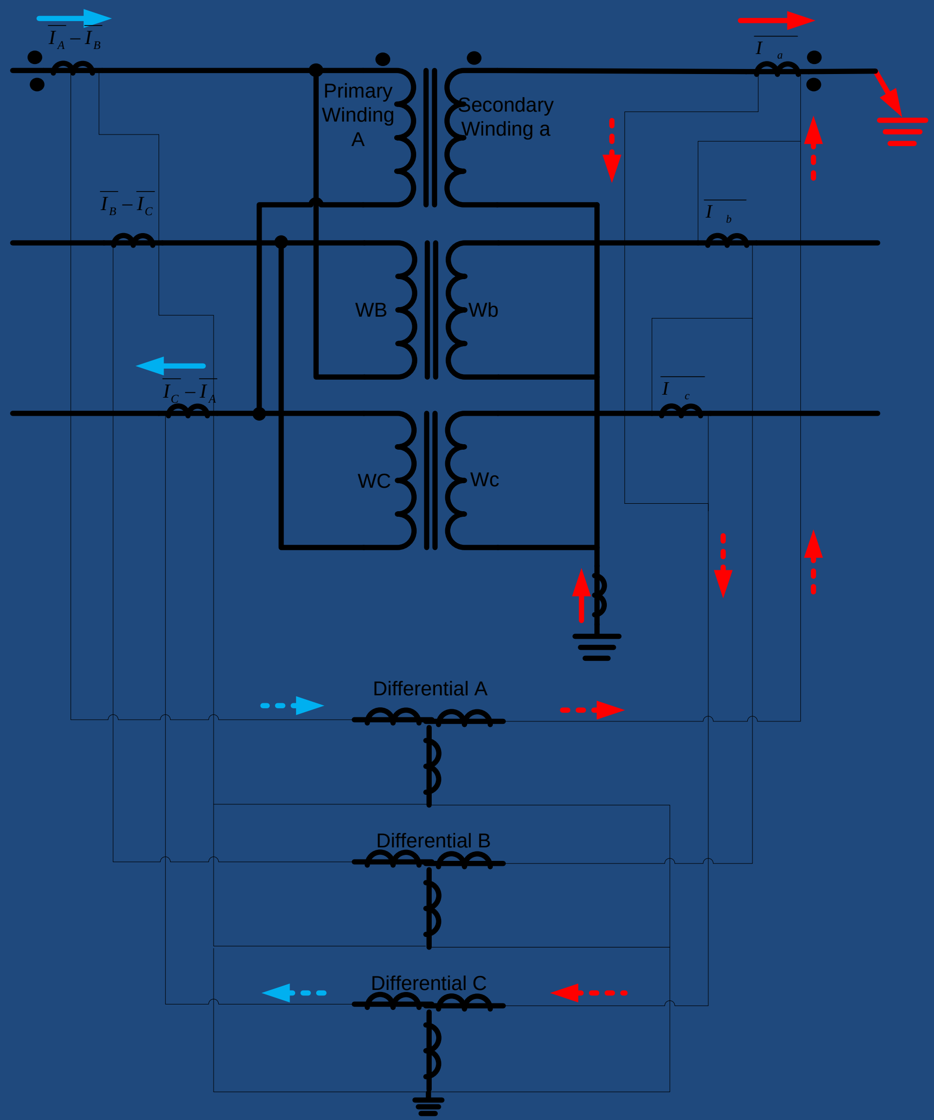
Delta-Wye Transformation of Currents

Transformers frequently employ Delta-Wye connections. Not only do these connections introduce a 30 degree phase shift, but they also change the makeup of the currents measured by the CT's. For differential schemes, the current $\overline{I_A}$-$\overline{I_B}$ cannot be directly compared to current $\overline{I_a}$.



Delta-Wye Transformation of Currents

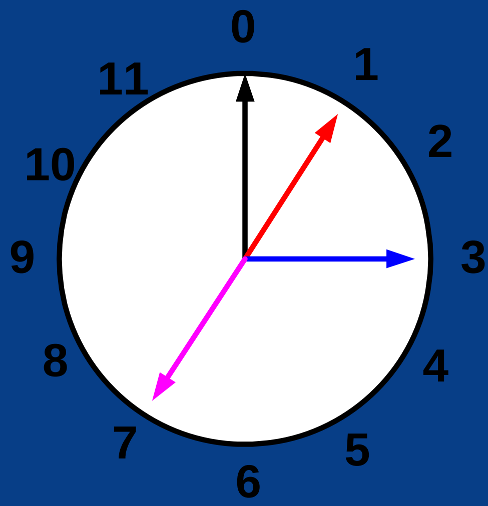
For electromechanical differential relays like the HU, BDD, and CA, the solution for delta-wye transformers is to simply connect the Winding 2 CT secondary circuits in a delta to match the primary main windings.



Delta-Wye Transformation of Currents

Angular Displacement Conventions:

- ANSI Y-Y, Δ-Δ @ 0°; Y-Δ , Δ-Y @ X1 lags H1 by 30°
  - ANSI makes life easy
- Euro-designations use 30° increments of LAG from the X1 bushing to the H1 bushings
  - Dy11=X1 lags H1 by 11*30°=330°
    or, H1 leads X1 by 30°
  - Think of a clock – each hour is 30 degrees



Dy1 = X1 lags H1 by 1*30 = 30, or
H1 leads X1 by 30 (ANSI std.)

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Delta-Wye Transformation of Currents

There are also several transformer relay manufacturer conventions commonly used for defining the transformer connections. The following are examples for ABC rotation except where noted:

- SEL 387 Method: In this convention each winding is given a number 0-11, which corresponds to the number of 30 degree *leading* angle increments.

- Beckwith 3311 Custom Method: In this convention each winding is given a number 0-11, which corresponds to the number of 30 degree lagging angle increments relative of a hypothetical wye winding.

- GE T60 Method: In this convention each winding is given an angle which corresponds to the *lagging* angle relative to the designated reference winding.

Delta-Wye Transformation of Currents

So what does all this mean while testing?

Here is a list of common relays, common connections, and test angles (assuming set to positive angles lead):

W1	W2	IEC	Beckwith Custom		GE (Ref W1)	SEL		Test Angles (ABC Rotation)					
			W1	W2		W1	W2	W1-A	W1-B	W1-C	W2-A	W2-B	W2-C
Y	Y	Yy0	0	0	Yy0	12	12	0	-120	120	180	-60	60
DAB	Y	Dy1	11	1	Dy30	1	12	30	-90	150	180	-60	60
Y	DAB	Yd11	0	11	Yd330	12	1	0	-120	120	-150	-30	90
DAC	Y	Dy11	1	0	Dy330	11	12	-30	-150	90	180	-60	60
Y	DAC	Yd1	0	1	YD30	12	11	0	-120	120	150	30	-90
DAC	DAC	Dd0	1	1	Dd0	11	11	-30	-150	90	150	30	-90
DAB	DAB	Dd0	11	11	Dd0	1	1	30	-90	150	-150	-30	90
DAC	DAB	Dd10	1	11	Dd300	11	1	-30	-150	90	-150	-30	90
DAB	DAC	Dd2	11	1	Dd60	1	11	30	-90	150	150	30	-90

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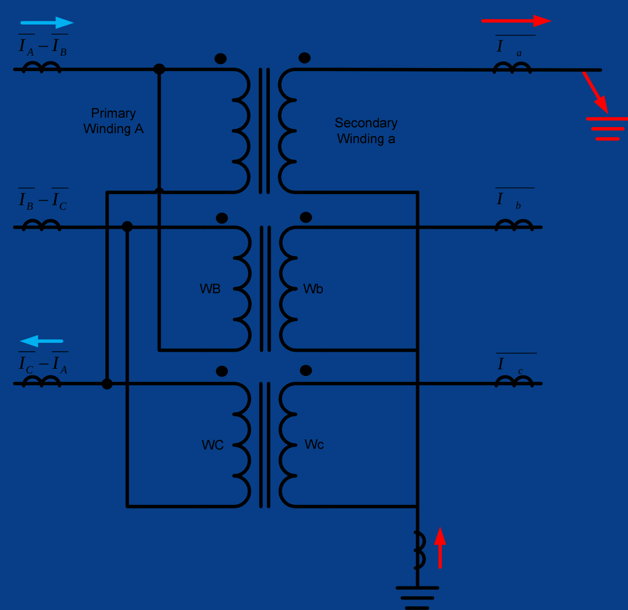
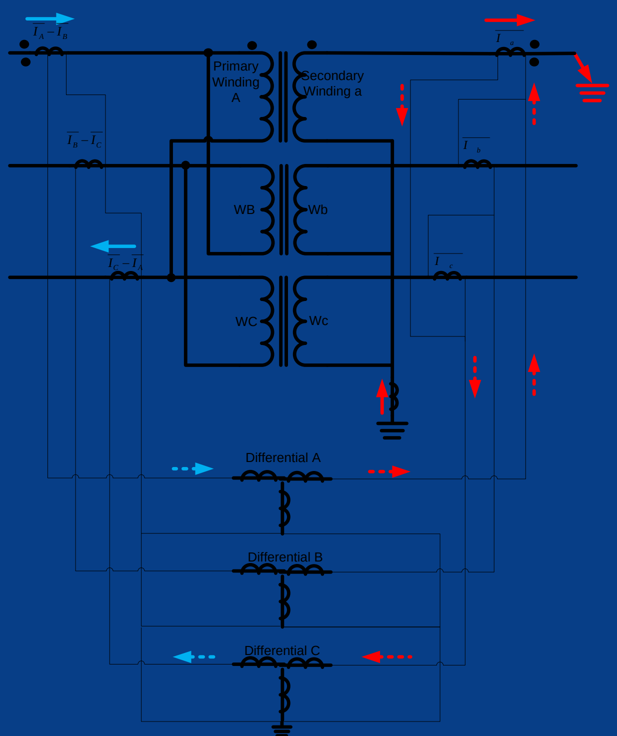
Zero Sequence Elimination

In all wye connected windings, the ground provides a way for current to enter the differential zone without being measured by a phase differential CT. This can unbalance the differential during external phase to neutral faults. If the differential protection is to resist improperly tripping for external faults, this current has to be removed from differential calculations.



Zero Sequence Elimination

The first removal method is to simply connect the CT secondary circuit in delta. This straightforward method is used in electromechanical and in some digital relay retrofit differential applications.



Zero Sequence Elimination

In digital applications with wye connected CT secondary circuits, the ground current has to be removed numerically. This is done by either converting the currents to delta quantities or by directly subtracting calculated zero sequence current from the differential quantity.

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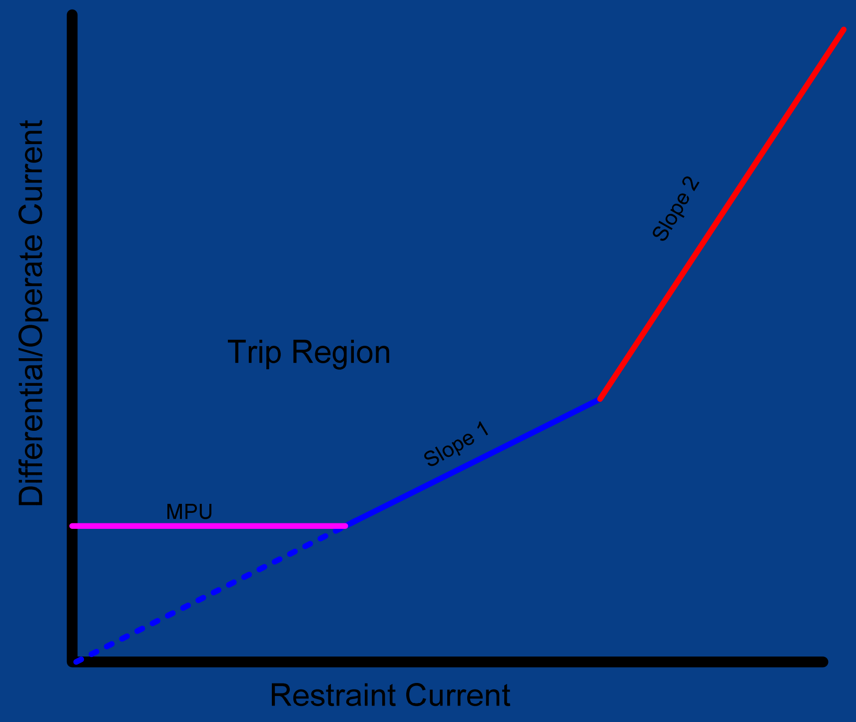
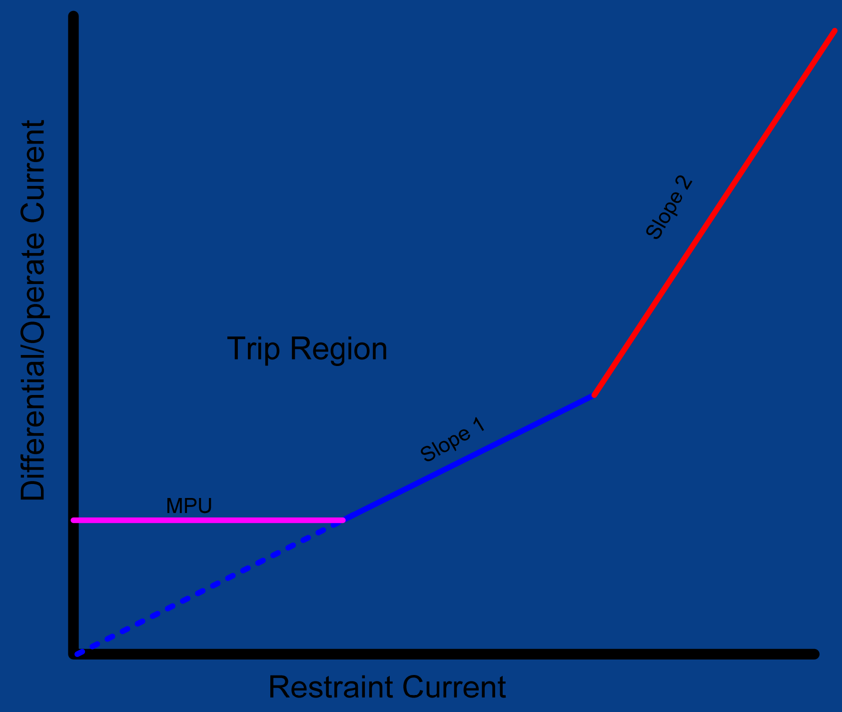
LTC Induced Mismatch, CT Saturation, CT Remanence, and CT Tolerance

- The X-axis is the Restraint Current is the measure of current in the transformer. Differential relay sensitivity is inversely proportional to restraint current. Relay manufacturers use a variety of calculations like the maximum of the winding currents or the average of the currents.
- The Y-axis is the Differential/Operate current is the sum of all winding currents after amplitude and angle compensation.



LTC Induced Mismatch, CT Saturation, CT Remanence, and CT Tolerance

- The **Minimum Pickup region** is used between zero and approximately 0.5 per unit restraint current. It provides security against CT remanence and accuracy errors and is usually set between 0.3 and 0.5pu.
- The **Slope 1** region is used between the minimum pickup region and the slope 2 breakpoint. Slope 1 provides security against false tripping due to CT accuracy. Class C CT accuracy is +/-10%, therefore 20% should be the absolute minimum setting with greater than 30% preferred. For LTC applications, another +/-10% is added.
- The **Slope 2** region is used above the slope 2 breakpoint, which is normally set at 2pu. Slope 2 provides security against false tripping during through fault events where CT saturation is likely. Above 2pu current, a significant DC current component will be present and therefore saturation is likely. Slope 2 is normally set at 60-80%.



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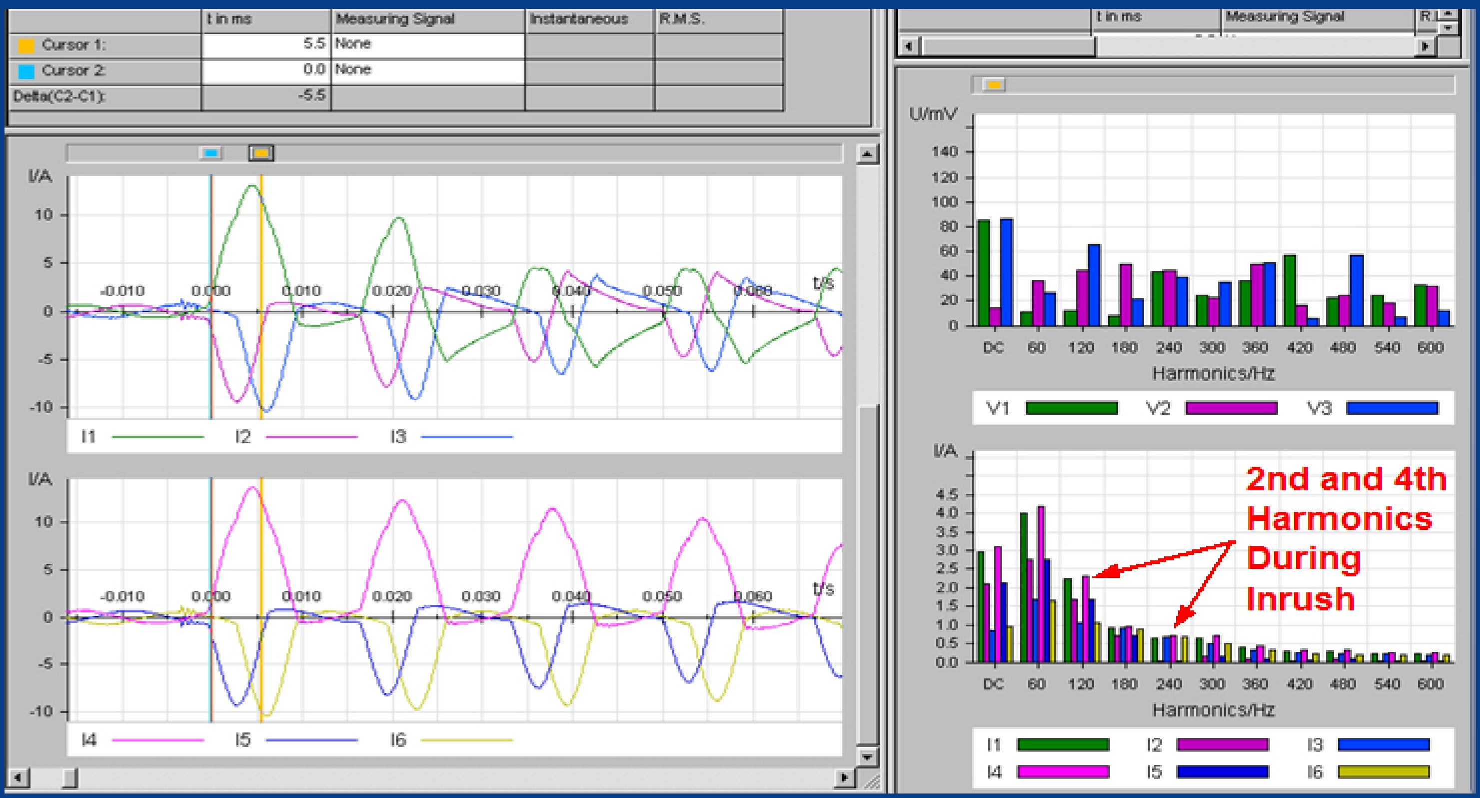
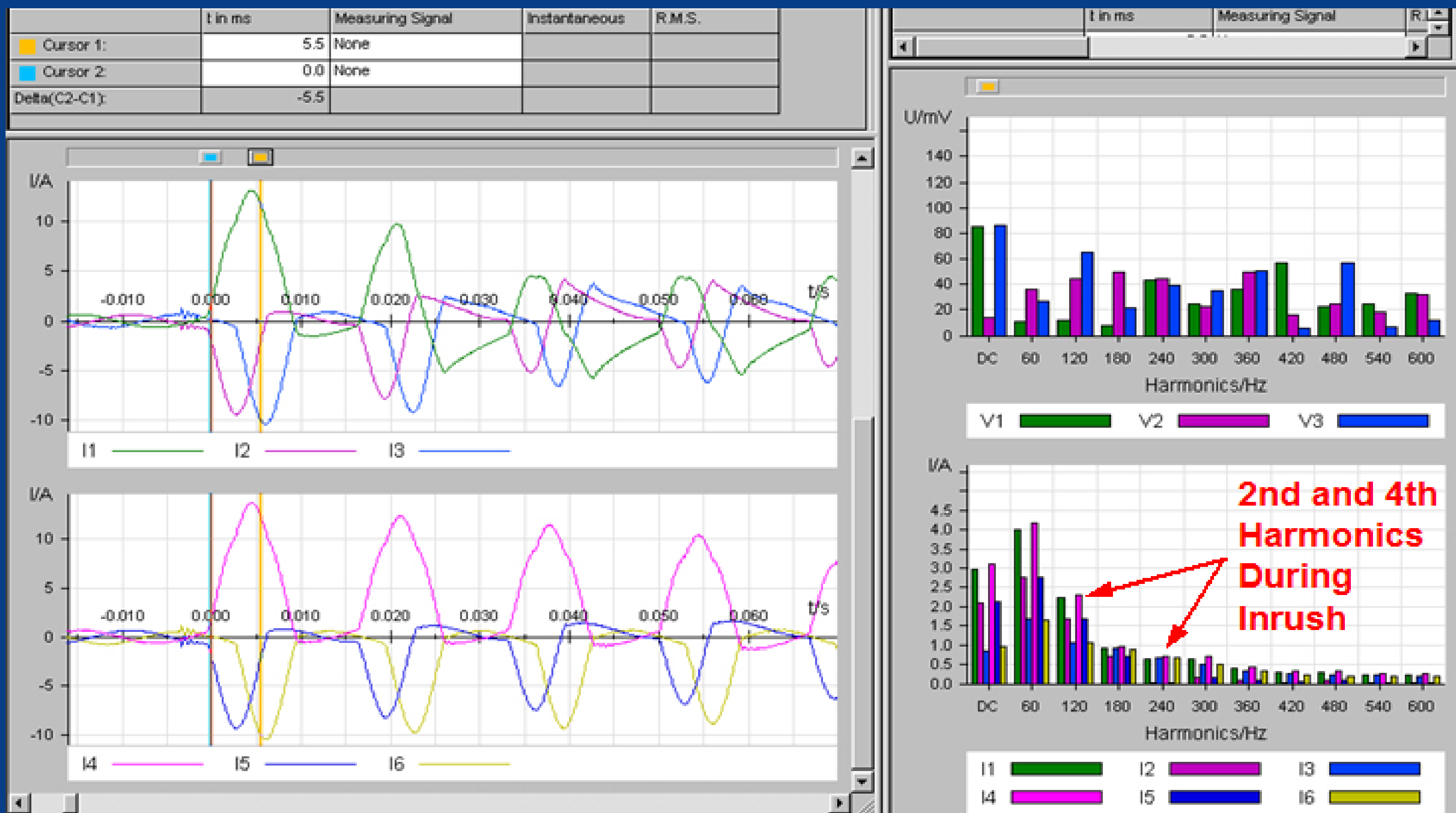
Inrush Phenomena and Harmonic Content Availability

When a transformer is energized, a step change in magnetizing voltage occurs. This step change in magnetizing voltage results in over fluxing the transformer core, causing magnetizing currents of up to 10pu.



Inrush Phenomena and Harmonic Content Availability

During inrush, transformers also generate significant amounts of even harmonics. These even harmonics can be used to prevent undesired differential relay operation by restraining the differential if the even harmonic content is above a preset level.



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Over Excitation Phenomena

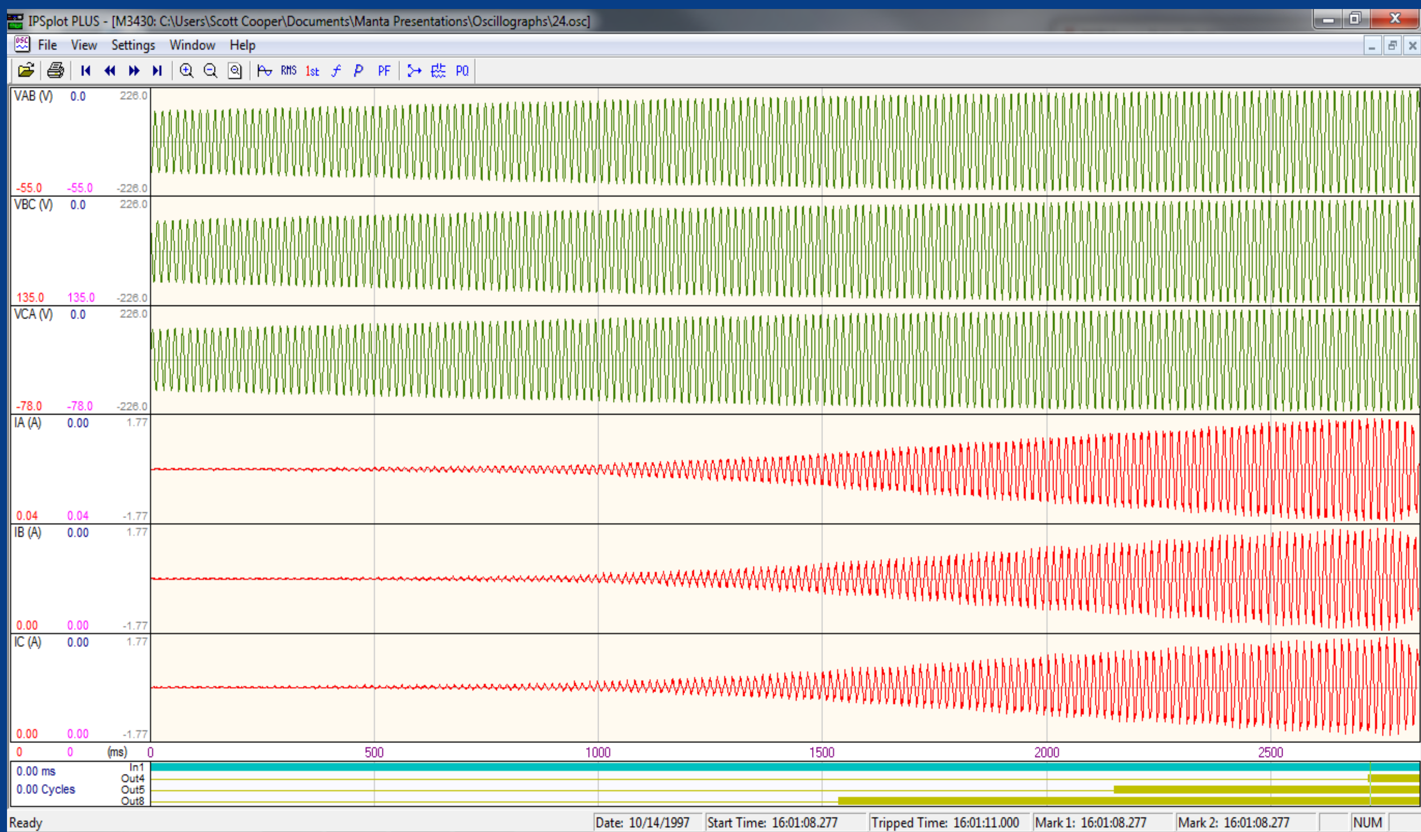
Over excitation occurs whenever the transformer voltage is too high for the frequency. Over excitation is expressed as a percentage:

$$\frac{V_{transformer}}{V_{nominal}} \Big/ \frac{F_{transformer}}{F_{nominal}} \times 100 = Percent\ Over\ Excitation$$

Transformers are normally rated for at least 105% over excitation. Levels above this can damage the transformer.

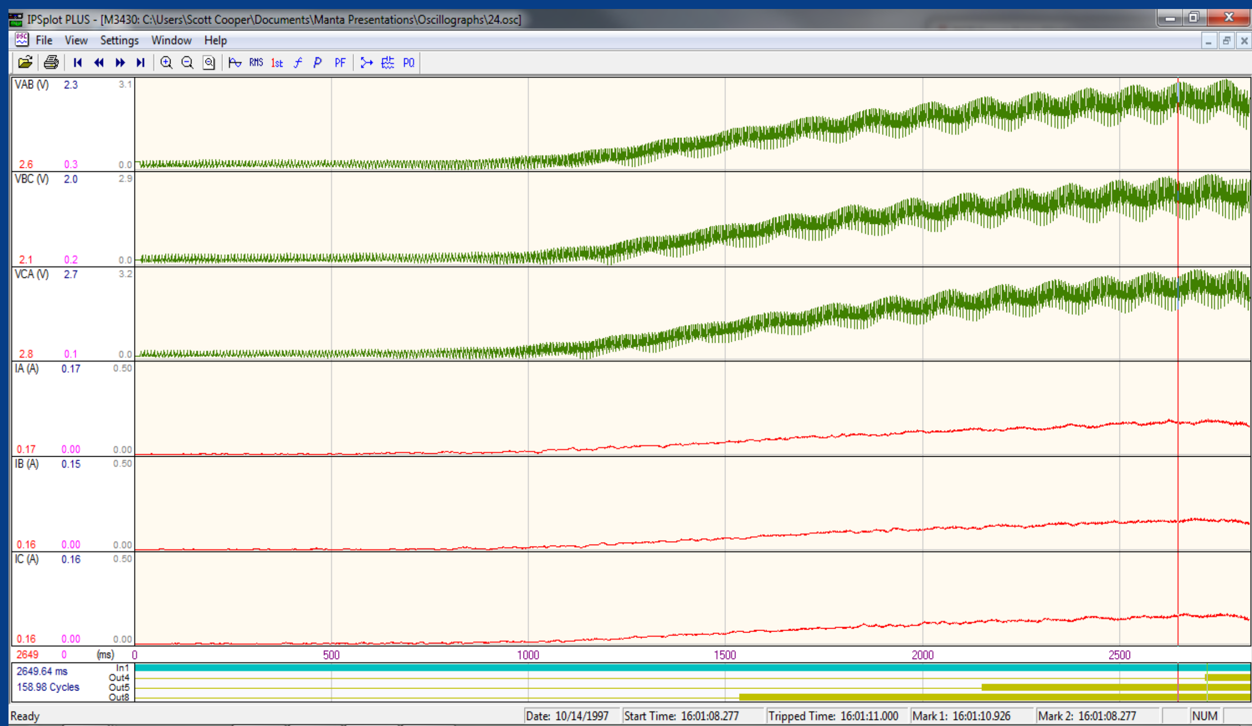
Over Excitation Phenomena

As percent over excitation increases, magnetizing current will increase. Without appropriate logic, this can lead misoperation of the differential scheme ahead of dedicated V/Hz relays.



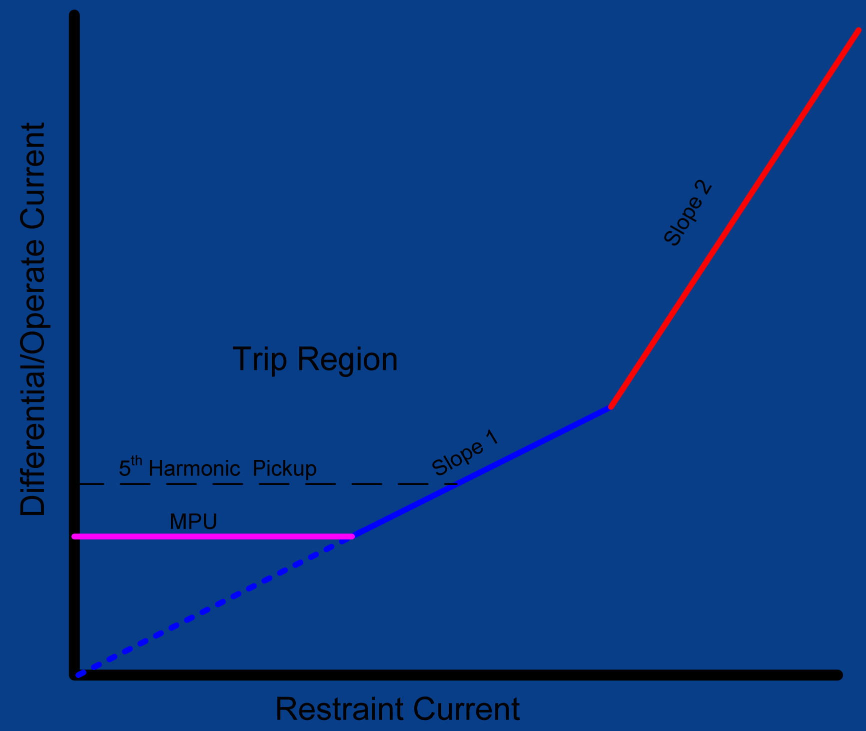
Over Excitation Phenomena

This additional magnetizing current is rich in 5th harmonic current.
This plot shows the same fault record filtered for 5th harmonic content.



Over Excitation Phenomena

Modern digital relays have logic that increases the differential elements minimum pickup setting if significant 5th harmonic current is detected



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Switch Onto Fault concerns

If a transformer experiences an internal fault on energization, the harmonic restraint feature on a restrained differential could delay tripping.

Therefore relays commonly employ a secondary, unrestrained differential element. Of course this element must be set above the maximum expected inrush current, normally 8-12pu.

Switch Onto Fault concerns

In GE BDD and or Westinghouse HU types, an instantaneous overcurrent unit in series with the differential provides this feature.

In digital relays, a separate setpoint is provided. To test these elements, parallel current channels as necessary and apply currents to one side of the differential.

Understanding Transformer Differential Protection

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