Differential Protection Applied to Motors & Transformers

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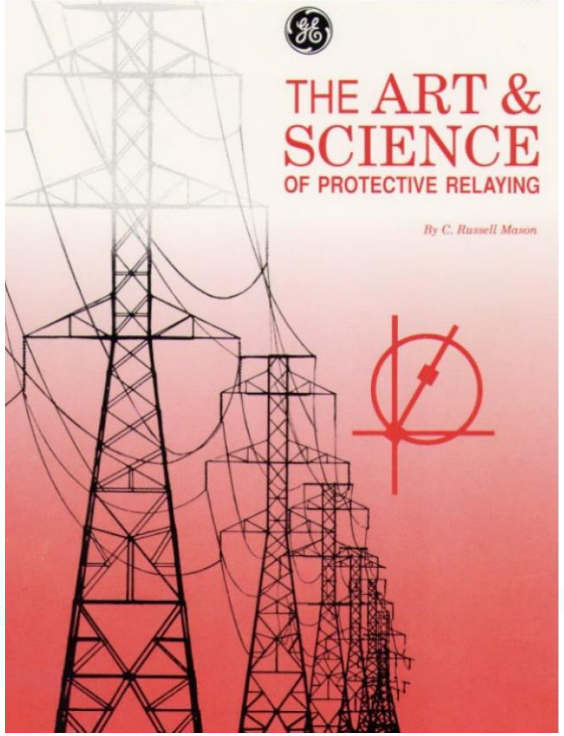
September 18, 2018

The Art & Science of Protective Relaying



C. Russell Mason
Wiley; 1 edition (January 15, 1956)

www.gegridsolutions.com/multilin/notes/artsci/artsci.pdf

Characteristics of Good Protective Relaying

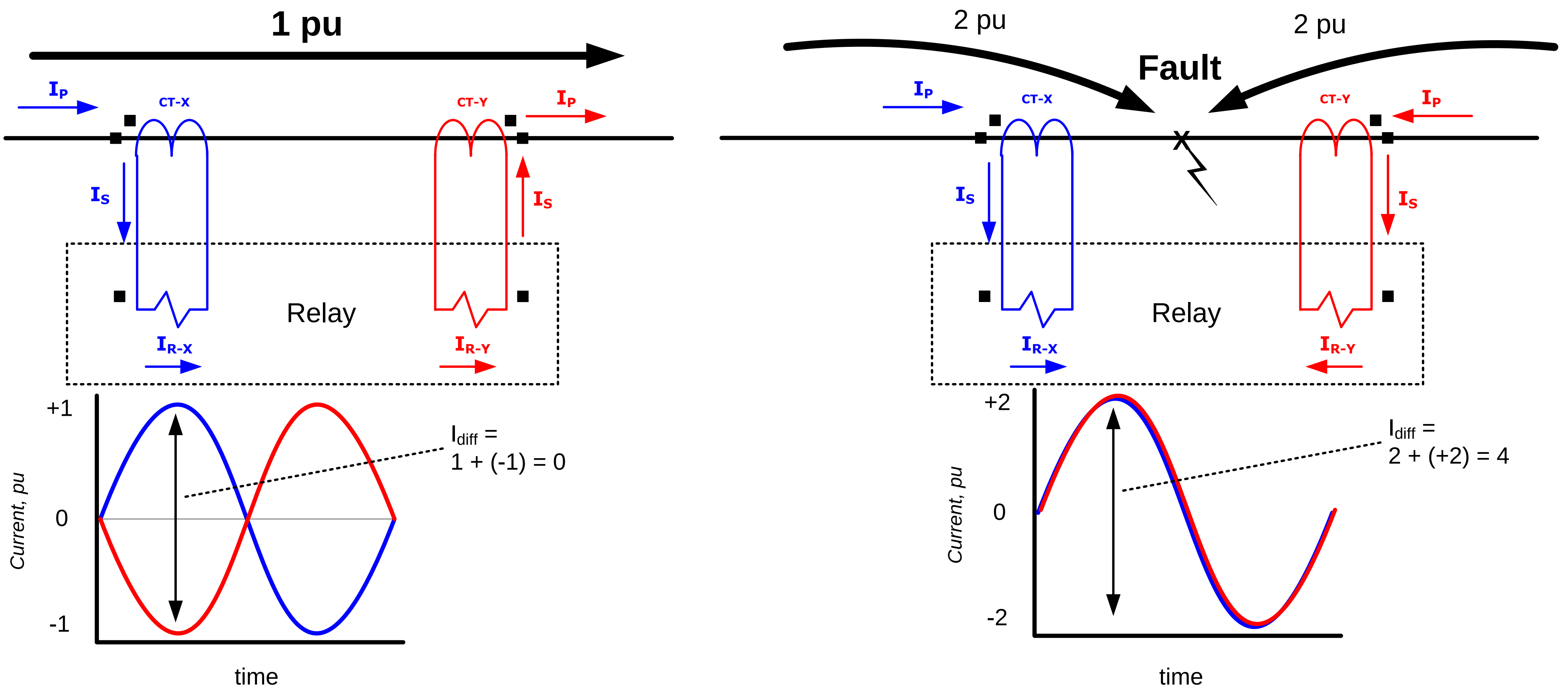
The "5 S's" Mnemonic

- Speed
  When it needs to operate, you want it to operate fast.
- Selectivity
  Ideally, you only de-energize the faulted equipment and nothing more.
- Sensitivity
  The best protection system can detect any fault, large or small.
- Security
  A good protection system trips when you need it to and never trips otherwise.
- Simplicity
  Ideally, no engineering effort is required, and it's very inexpensive.

Basics of Differential Relaying

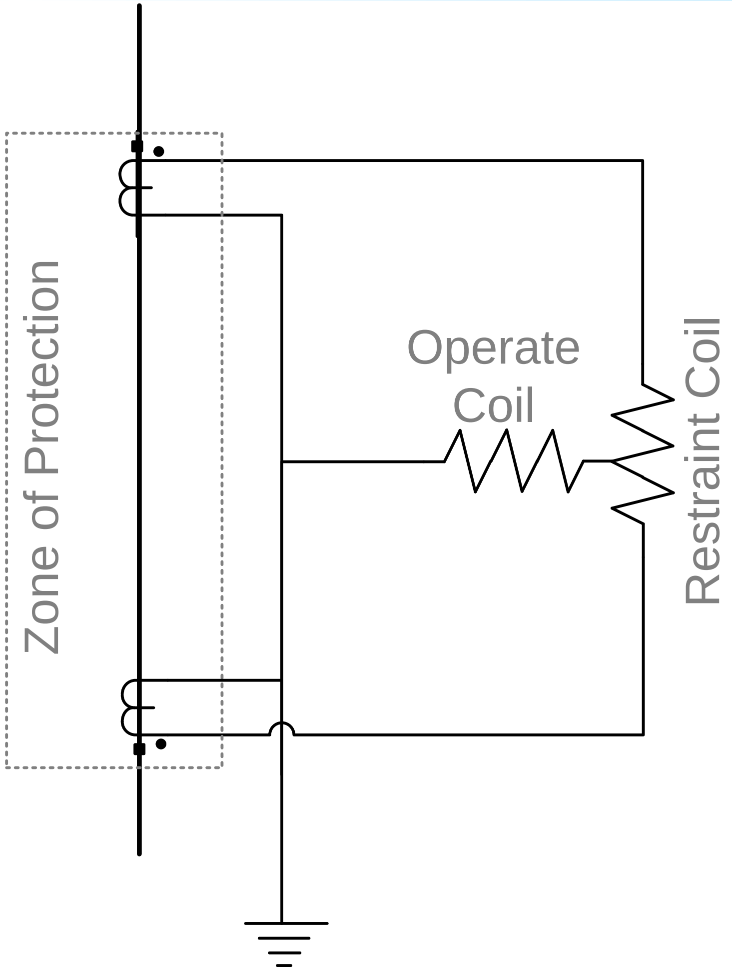
Basic Differential Principle

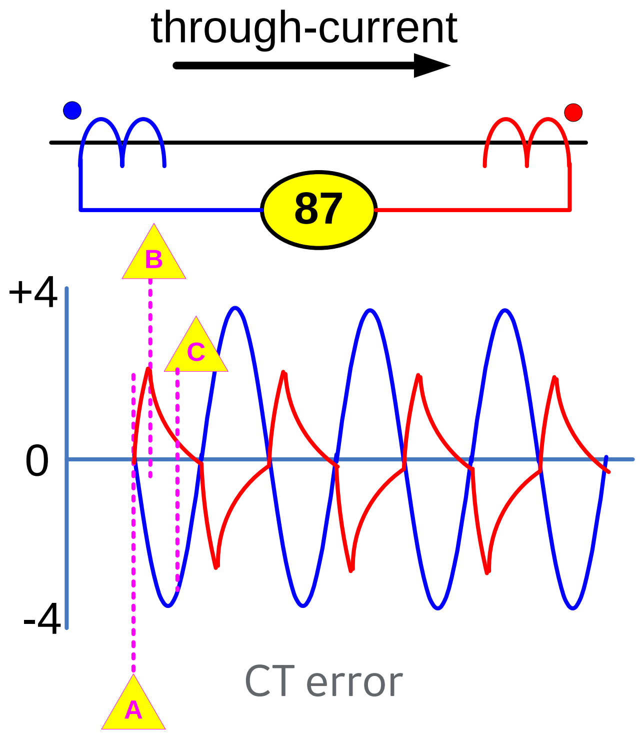
Kirchoff's Current Law: Current in should equal current out. Otherwise, there's a fault.

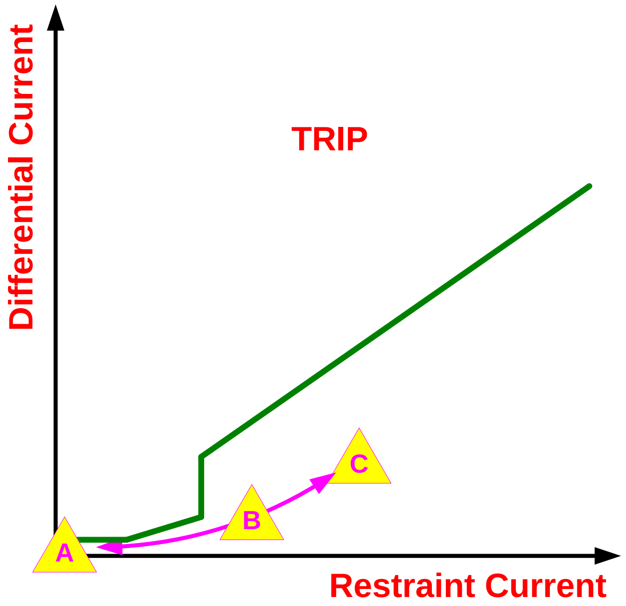


Basic Electromechanical Differential Principle

Relays use restraint to increase security.

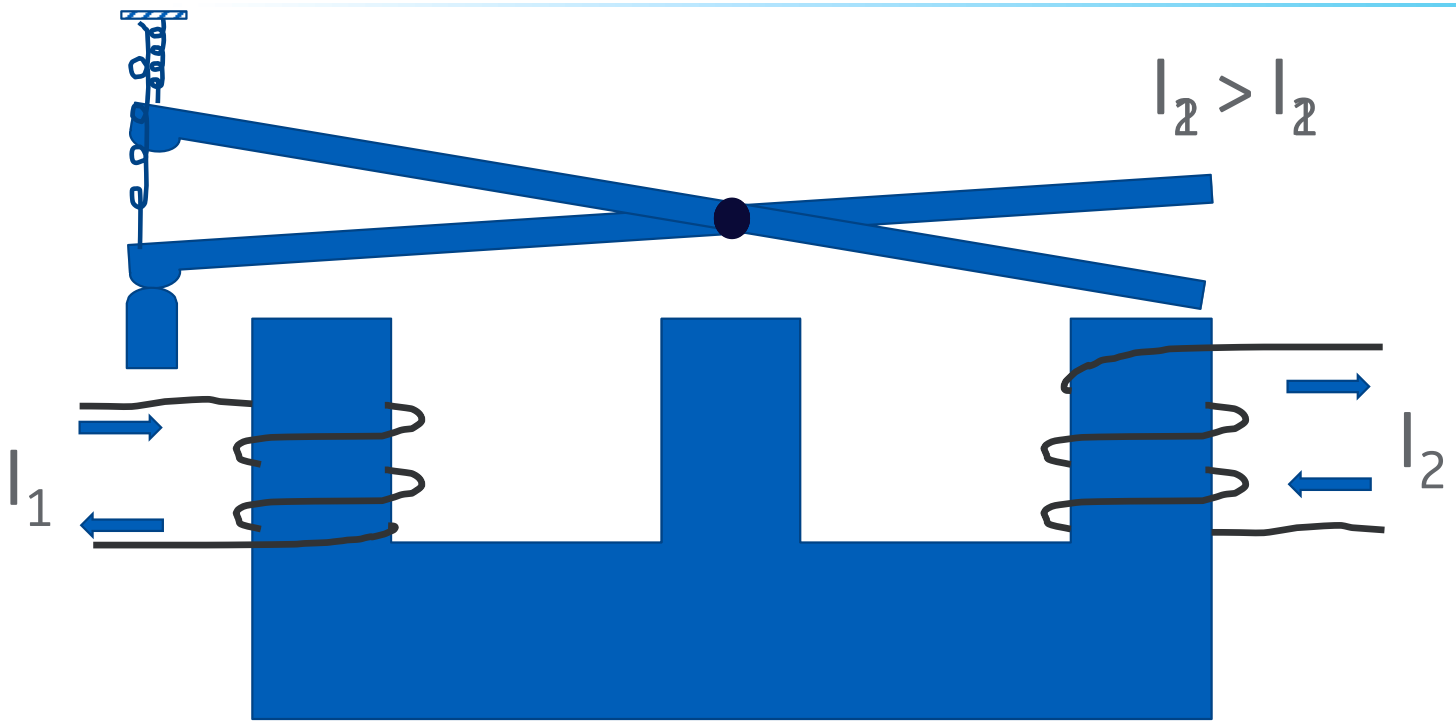




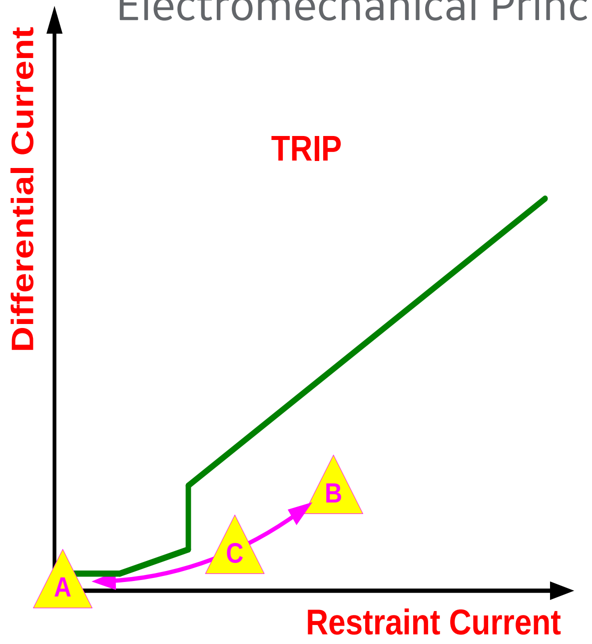


Electromechanical Principle

ANSI Function 60 – Voltage or Current Balance Relay
ANSI Function 87 – Differential Protective Relay



Digital Representation of Electromechanical Principle



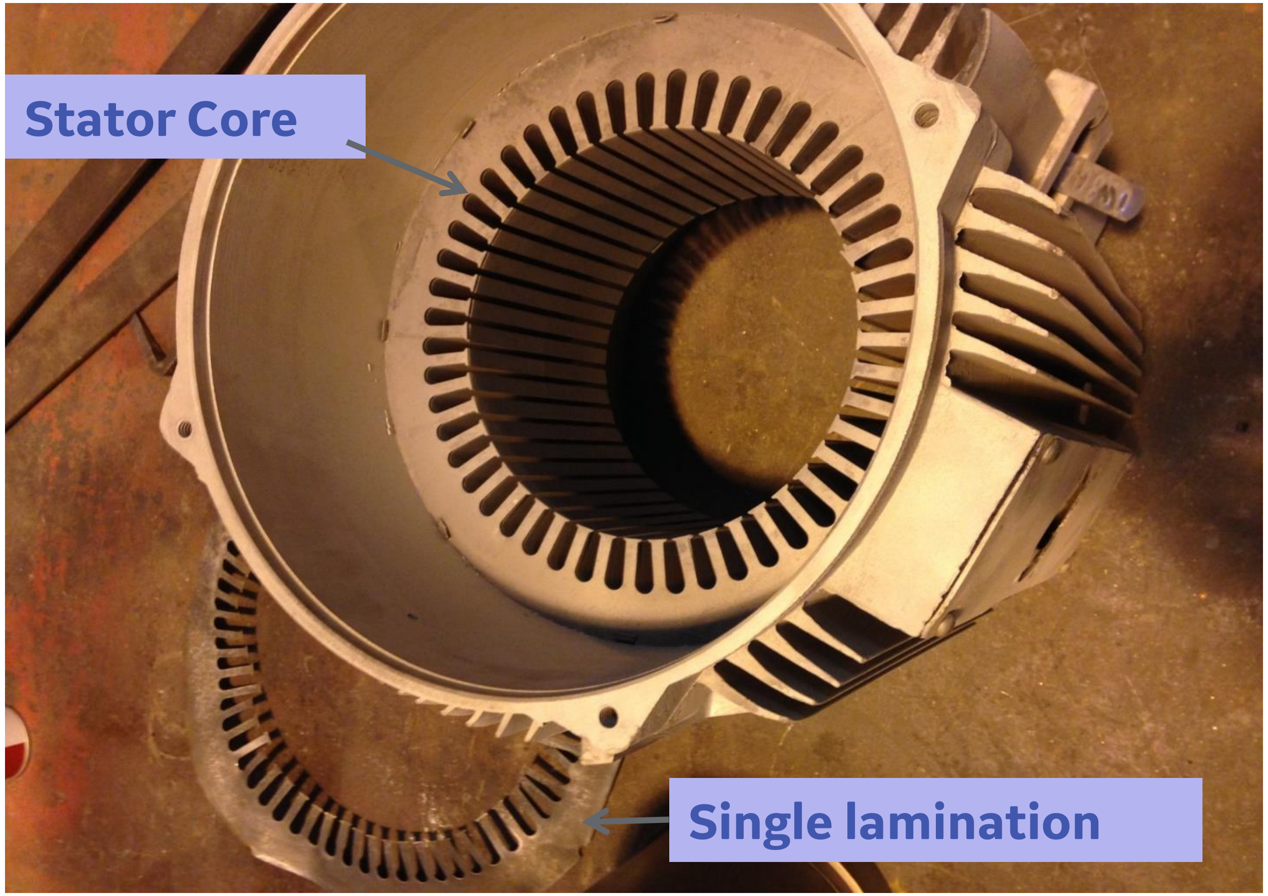
“Operate” current creates a tripping force.

“Restraint” current creates a counter-tripping force.

Differential Relaying Applied to Motors

Why Use Stator Differential?

Limit Damage to Windings. Save the Core.



Why Use Stator Differential?

- Speed

  Limit the destructive energy in a fault by clearing it quickly. No delay required.

- Sensitivity

  Detect a fault at its incipience before it evolves into a lower impedance (higher current) fault.

Why Use Stator Differential?

- IEEE 1068 – IEEE Standard for the Repair and Rewinding of AC Electric Motors in Petroleum, Chemical and Process Industries.

  If the core damage is less than 10% of surface area, the core might be repaired by air hammer and/or grinding.

  Beyond 10% surface area damage of if a hot-spot can't be fixed by aforementioned methods, you may be re-stacking the core.

Is Stator Differential Recommended?

If you have a fused contactor, the answer is most likely, "No."

If the interrupting device includes fuses, let those fuses do their job.

Otherwise, risk damaging a contactor.

Don't assume a fault will be incipient (high impedance/low current)

Is Stator Differential Recommended?

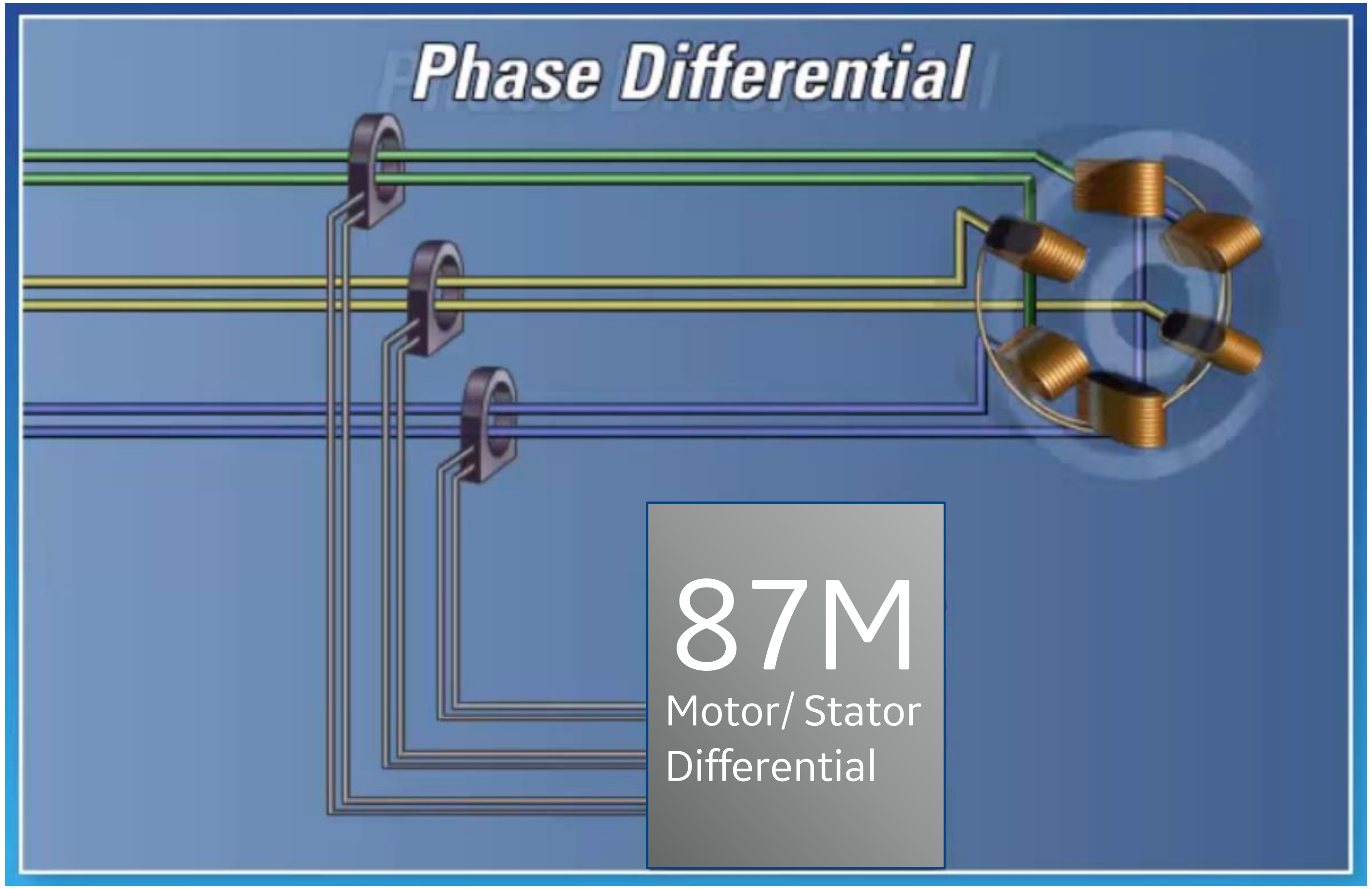
If you have a breaker, the answer is, “Maybe.”

- IEEE C37.96 – IEEE Guide for AC Motor Protection
  Rule of thumb: If the motor kVA rating is less than half the transformer, use overcurrent (50) in lieu of differential (87).

- IEEE Standard 242 – Buff Book
  - All motors 750 kVA and above on ungrounded systems.
  - All motors 750 kVA and above on grounded systems where ground fault protection won’t detect phase-phase faults.
  - Smaller MV motors (although 1900 kVA is easy to justify).

How is Stator Differential Implemented?

“Core Balance” or “Flux-balance” method



- Preferred method

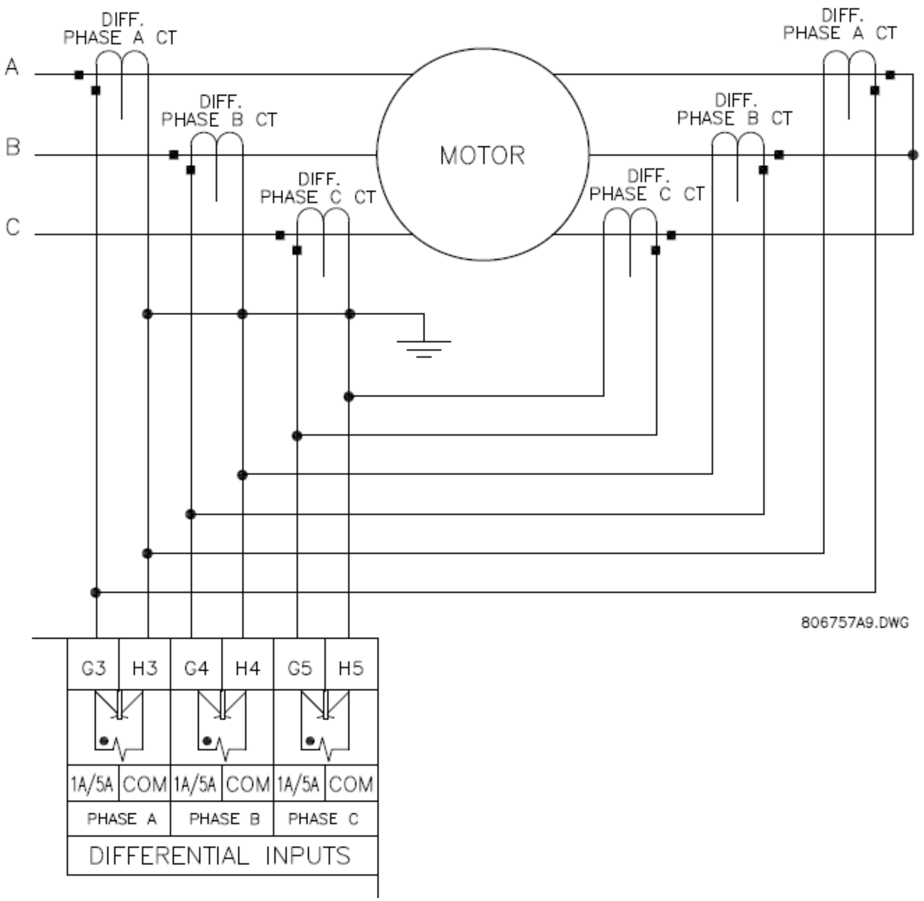
  Most secure because flux inherently cancels for non-fault conditions.

  Almost any protection class CT can be used. Digital relays are very good at responding within spec (fast) for an IOC (or DIFF) element despite severe saturation. Unbelievably enough, 60kA through a 100/5 C10 CT would probably still work for an 87M. Check with your relay manufacturer.

  Be aware of proximity effects. Currents can be induced on the secondary circuit and cause nuisance trips if the pickup is too sensitive.

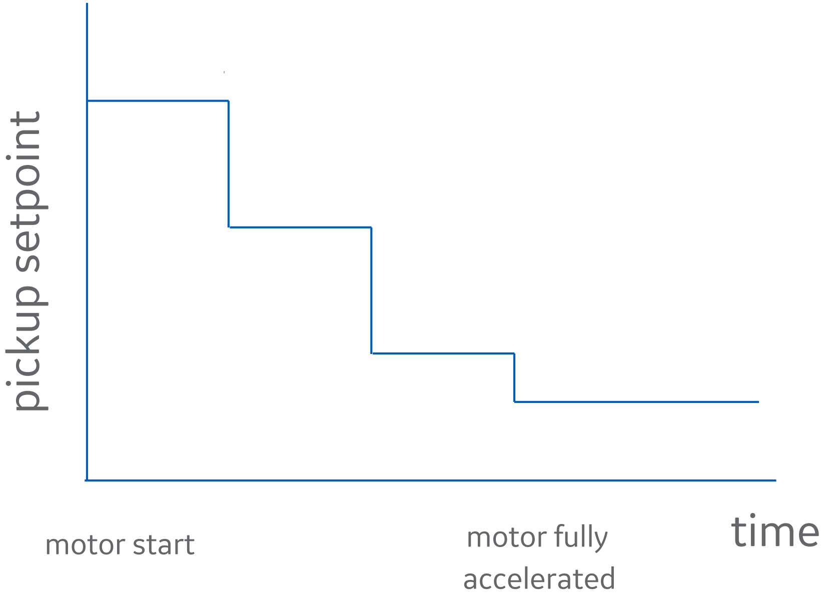
How is Stator Differential Implemented?

“External Summation” method



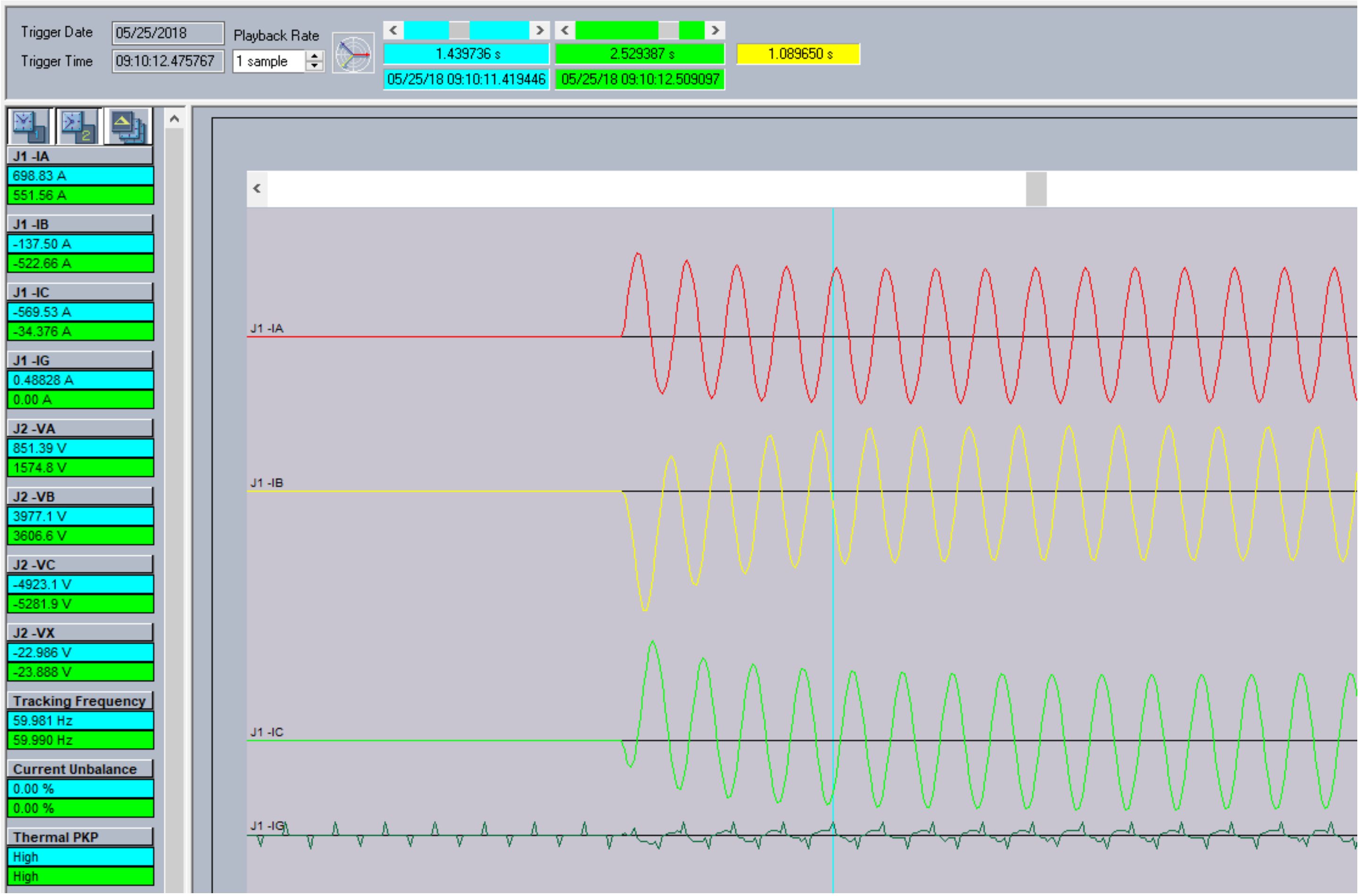
- Not Optimal

  Poor (and unequal) CT performance because of asymmetry causes false differential currents on startup.
  Can be addressed by adding a start delay to the protective function, or gradually increasing sensitivity as motor starts, but this is not ideal.



How is Stator Differential Implemented?

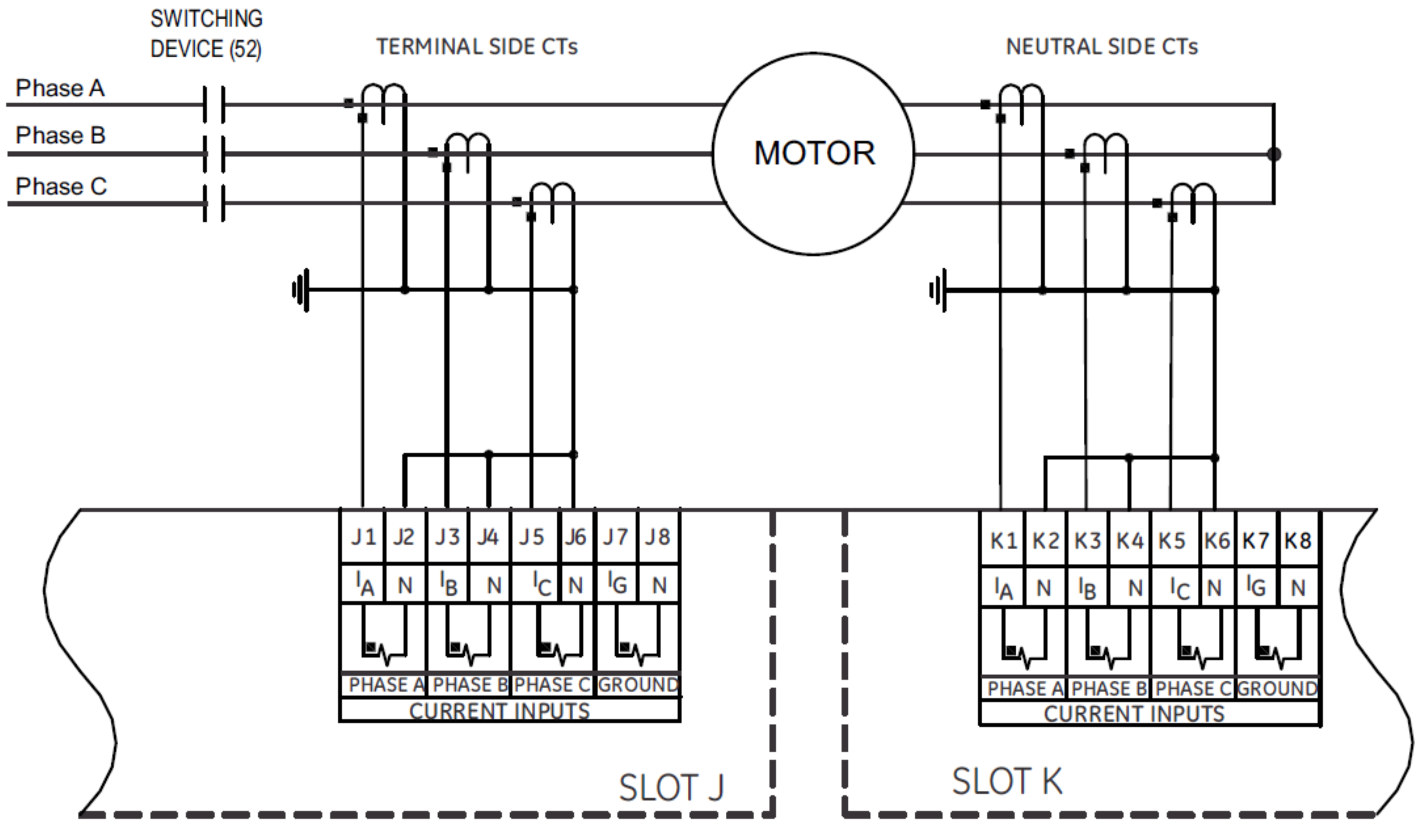
“External Summation” method



Notice the asymmetrical nature of this induction motor start. CT’s perform poorly under asymmetrical currents.

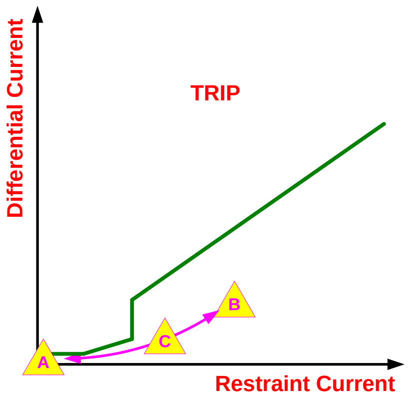
How is Stator Differential Implemented?

“Internal Summation” method



Note the CT polarity. This can vary by manufacturer.

- Preferred method if core balance is not practical.
  - Percent Slope Differential can be applied.
  - Addresses CT inaccuracy issues without introducing time delay or decreasing sensitivity.
  - Addresses CT inaccuracy for both motor starting and fault-circuit contribution.



Differential Relaying Applied to Transformers

Transformer Protection Basics

Art & Science Confirmed by IEEE Standard.

- "There is no one standard way to protect all transformers, or even identical transformers that are applied differently."
  - IEEE C37.91 Protection of Power Transformers

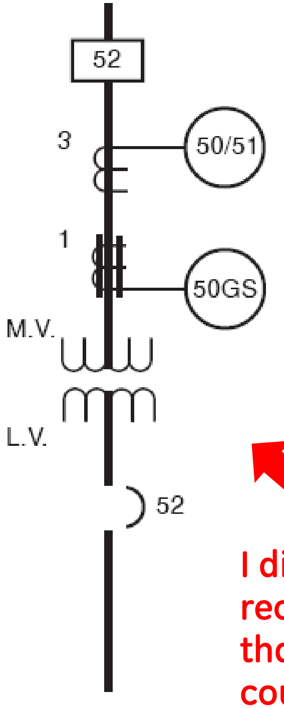
  Consider these factors when developing a protection scheme:

- Repair damage
- Cost of lost production
- Adverse effects on the rest of the system
- Collateral damage to other equipment
- Time that damaged equipment will be out of service.

Is Transformer Differential Recommended?

It depends. See list of factors to consider on previous slide.

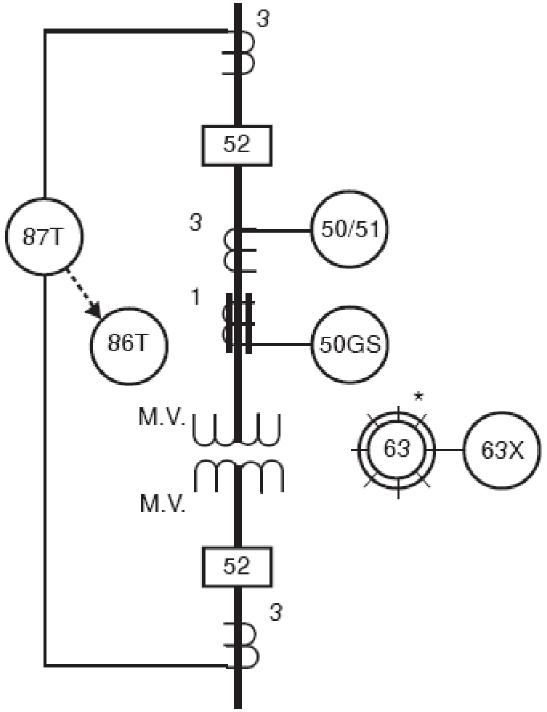
For transformers 2500KVA and below, medium and low voltage windings



Source: GE Relay Selection Guide, GET-8048A circa 2002

I disagree with this recommendation on grounds that arc-flash incident energy could be greatly reduced with 87T.

For transformers 750KVA and above, medium voltage windings



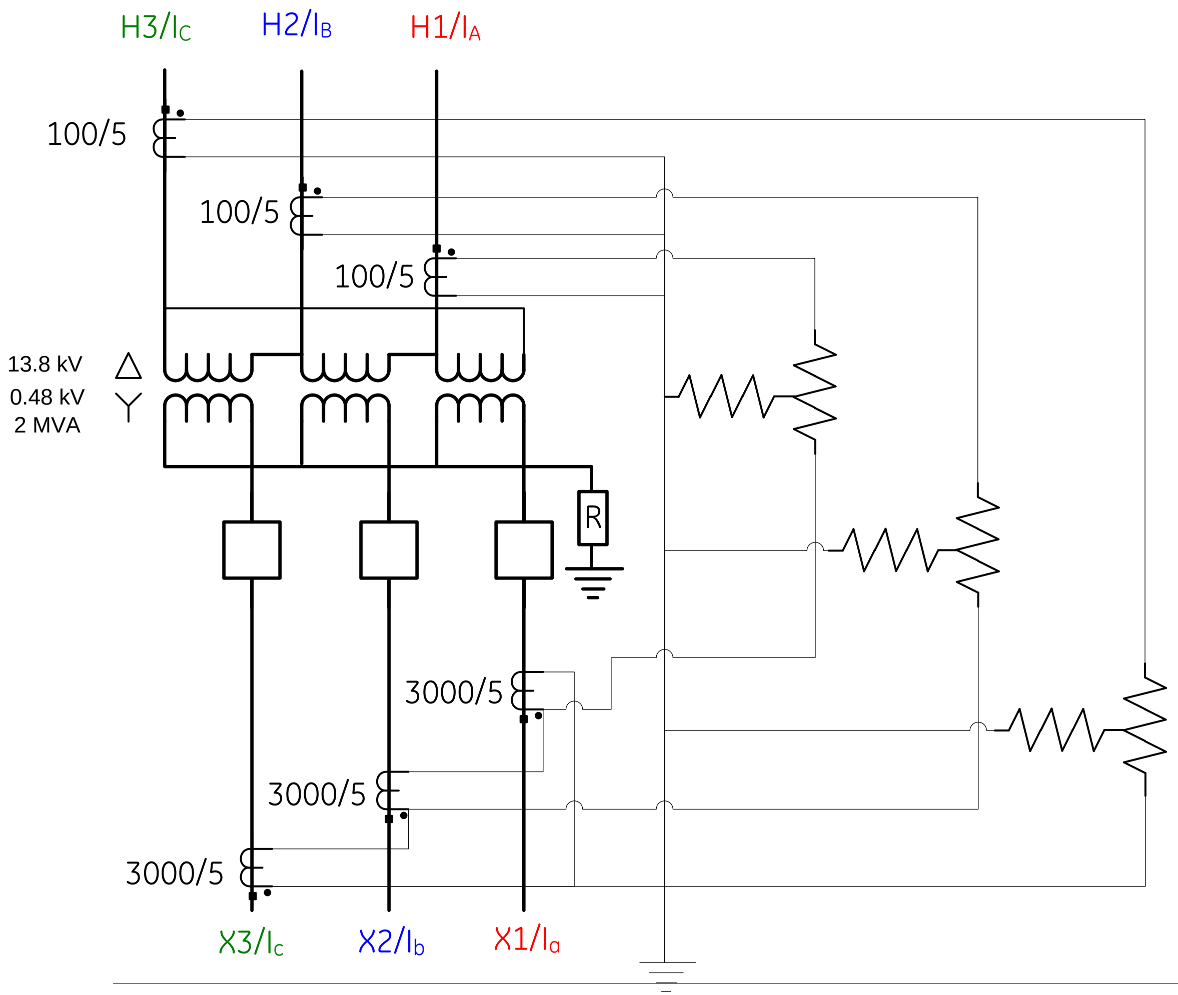
Challenges of Transformer Differential

It's usually not as simple as stator differential.

- **CT mismatch**
- **Transformer winding phase shift**
- **Zero-sequence current compensation**
- **Ground fault sensitivity in impedance grounded systems**
- **Magnetizing current inrush**
- **CT performance**

Challenges of Transformer Differential

CT mismatch.



In the days before digital relays, CT ratios would need to be sized to “normalize” secondary currents as closely as possible.

In this example 2MVA Dy30 transformer, CT ratios of 100/5 and 3000/5 might be chosen to “normalize” the full load secondary amps at approx. 4.

2 MVA/13.8kV(SQRT(3) = 83.6 Pri = 4.18 secondary.

2 MVA/0.48kV(SQRT(3) = 2405 Pri = 4.00 secondary.

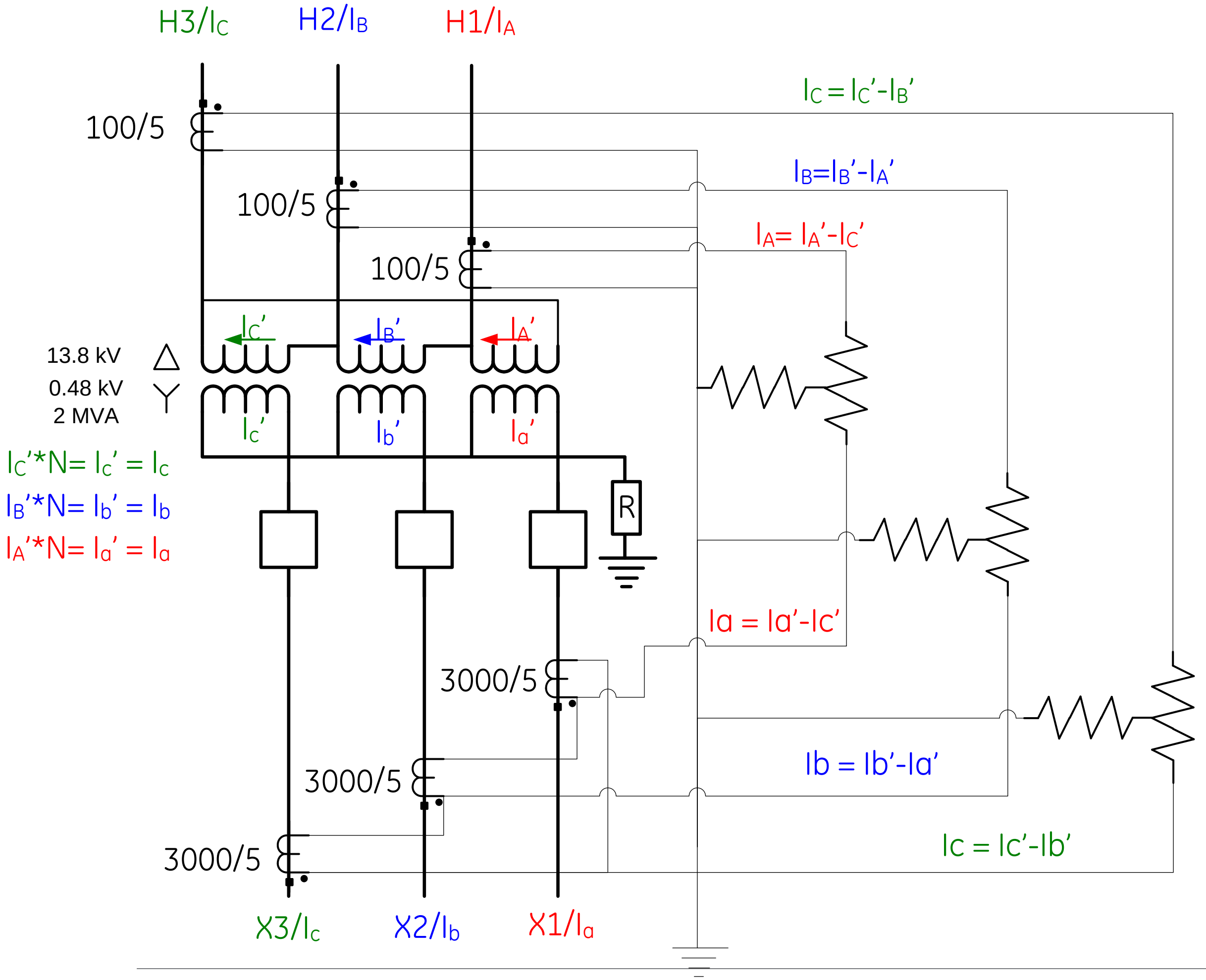
In digital relays, the currents are mathematically normalized to a reference winding. If the 13.8kV winding is used as the reference, a relay would scale the 480V winding currents using this factor:

(3000/5) x 480V / (100/5)/13800 V = 1.04.

In other words, a digital relay would scale the 4 secondary amps of measured current at 480V by 1.04 to make it equal the 4.18 amps measured at 13.8kV.

Challenges of Transformer Differential

Transformer Winding Phase Shift.



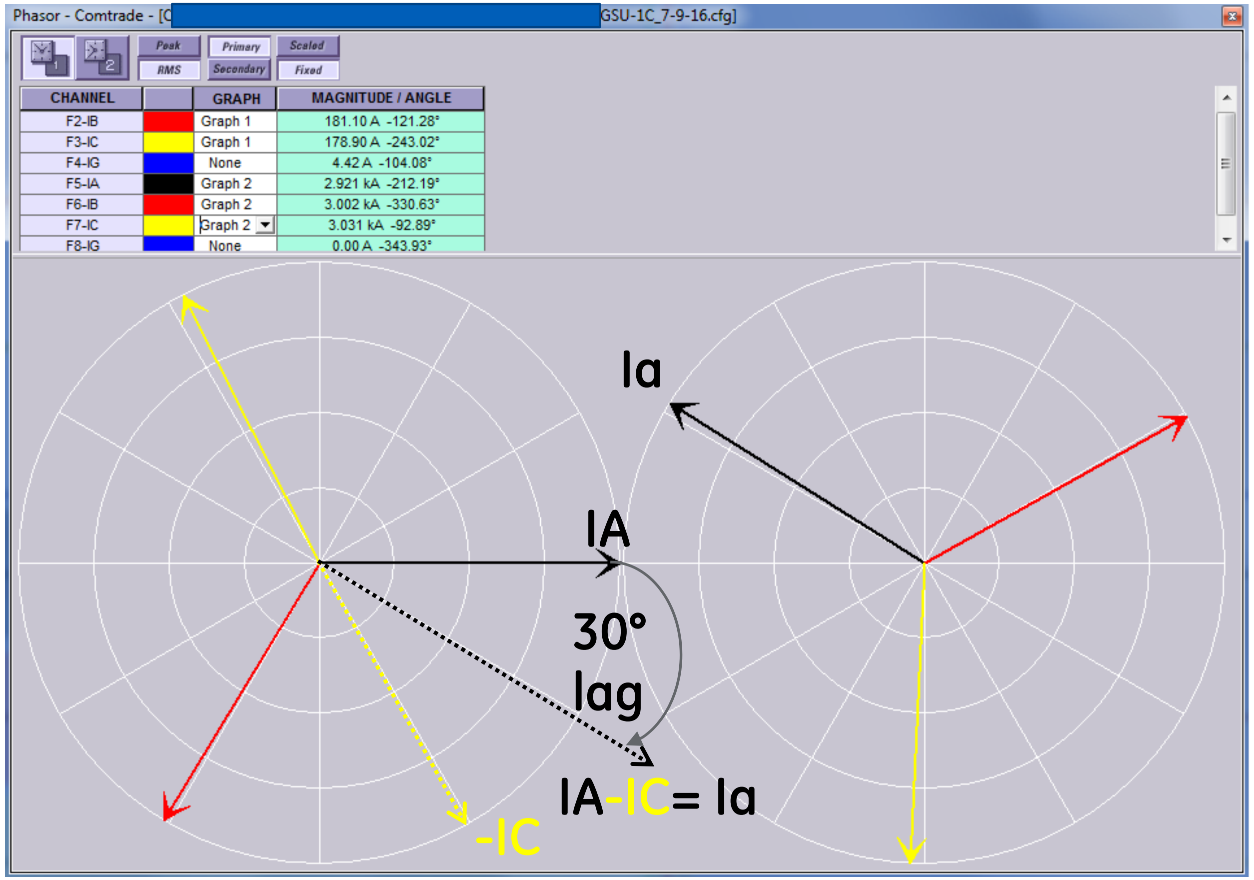
Transformer nameplates will identify the phase shift. MOST of the time, we deal with standard ANSI transformers whose secondary windings lag the primary by 30 degrees.

Electromechanical relays accounted for that phase shift with CT wiring. Notice the delta-wired CT's on the secondary winding in this example.

Ignore the turns ratio and the CT ratios, and it is easy to see how these current summations elegantly sum to zero for normal load or through-faults.

Challenges of Transformer Differential

Transformer Winding Phase Shift.



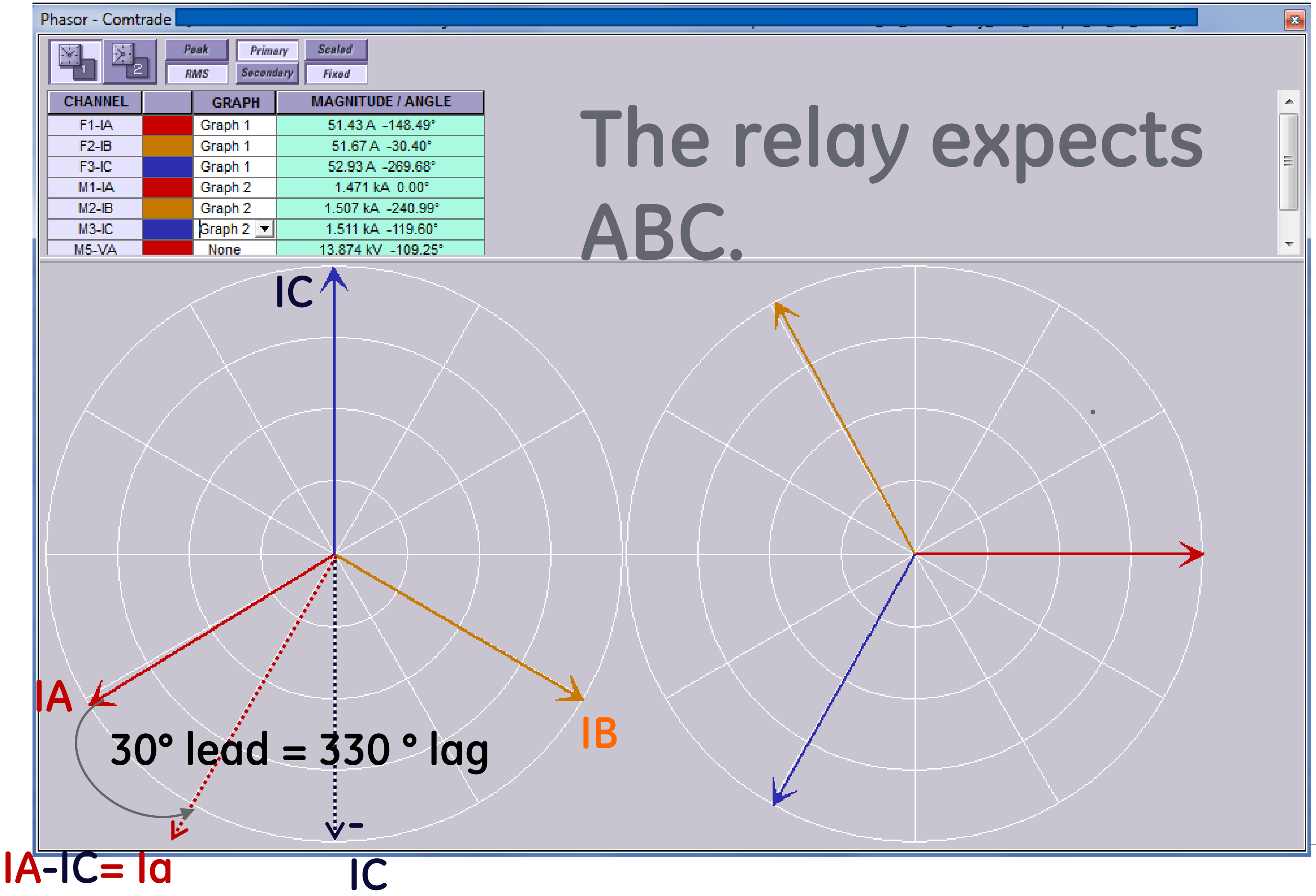
This is an example of the phasors that one would expect to see for a Dy30 transformer with ABC rotation.

Notice Ia, when flipped 180 degrees to account for CT polarity (both winding CT polarities are AWAY from the transformer), it lags IA by 30 degrees.

It's important to understand that a microprocessor relay is not just "shifting" phasors to account for phase angle shift. It is applying the same complex algebra that an electromechanical system accomplished with physical summation by connecting wires

Challenges of Transformer Differential

Transformer Winding Phase Shift - Example.

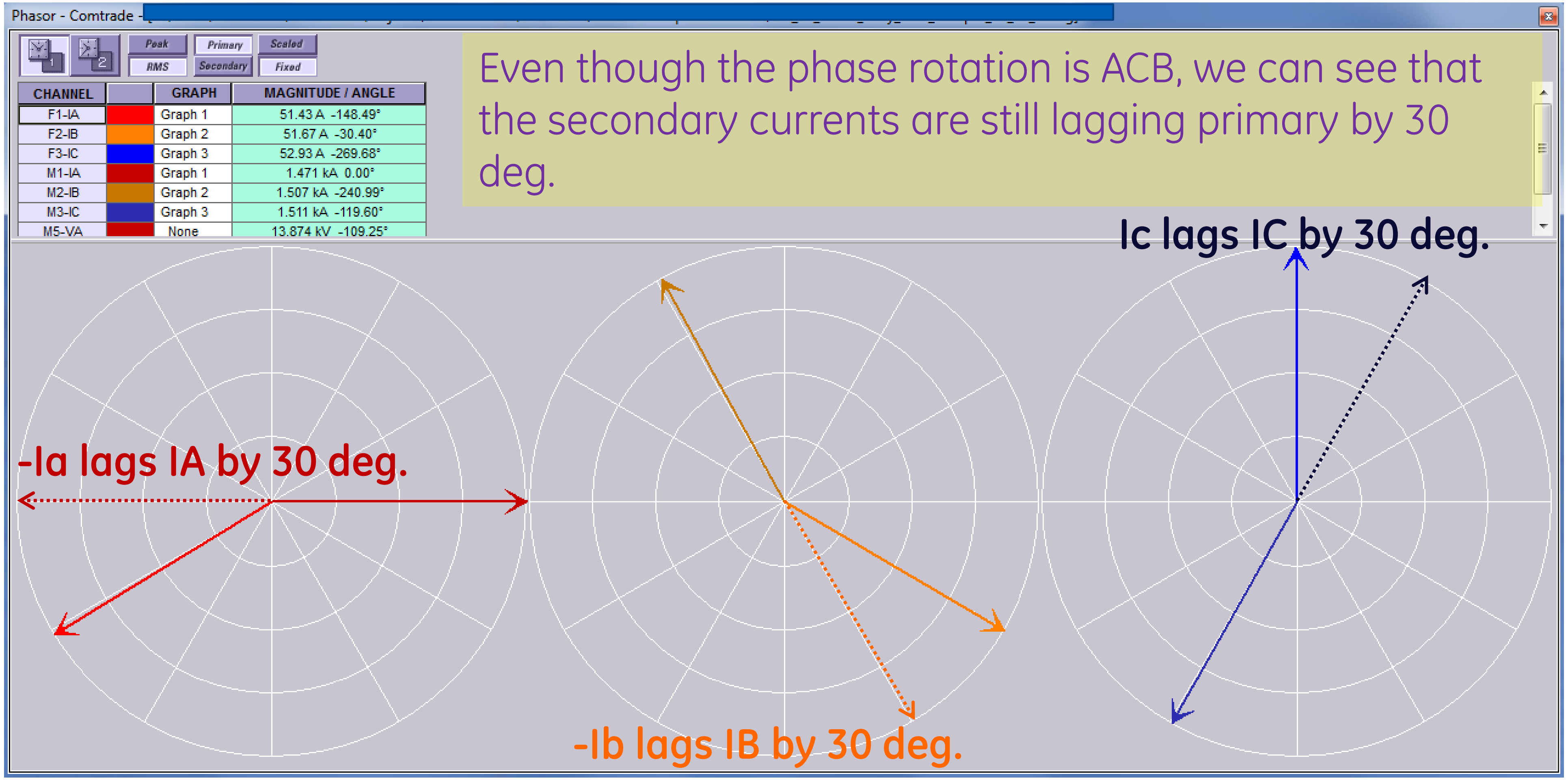


This Dy30 transformer's relay has been programmed to expect ABC rotation, but it has been wired as ACB.

The dashed line shows the calculated angle-compensated value of Ia. It should be 180 degrees out-of-phase with the measured Ia on the right.

Challenges of Transformer Differential

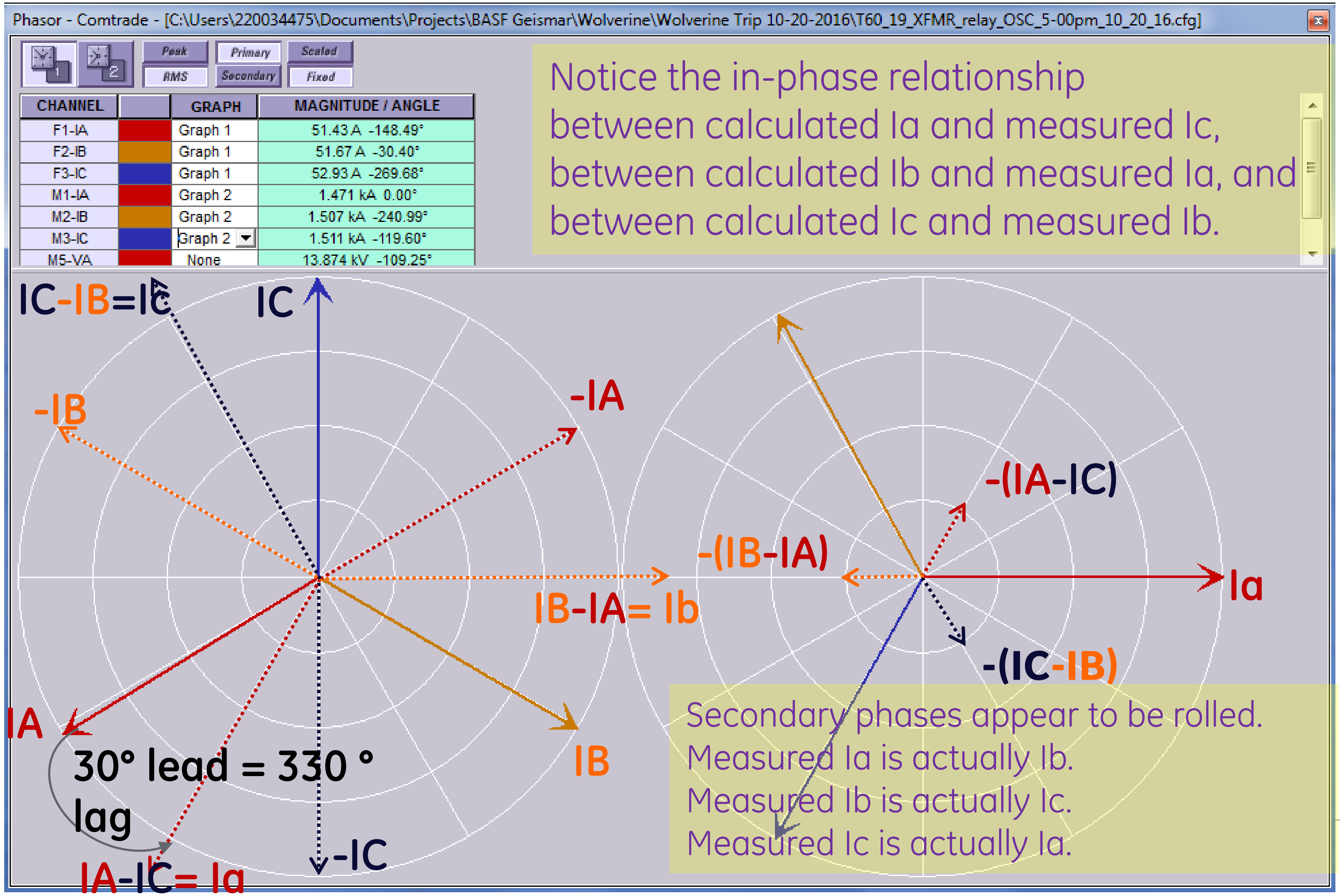
Transformer Winding Phase Shift - Example.



If we misunderstand what the relay is doing and assume that the relay simply shifts Ia, Ib & Ic forward by 30 degrees, it's hard to understand why this does not work.

Challenges of Transformer Differential

Transformer Winding Phase Shift - Example.

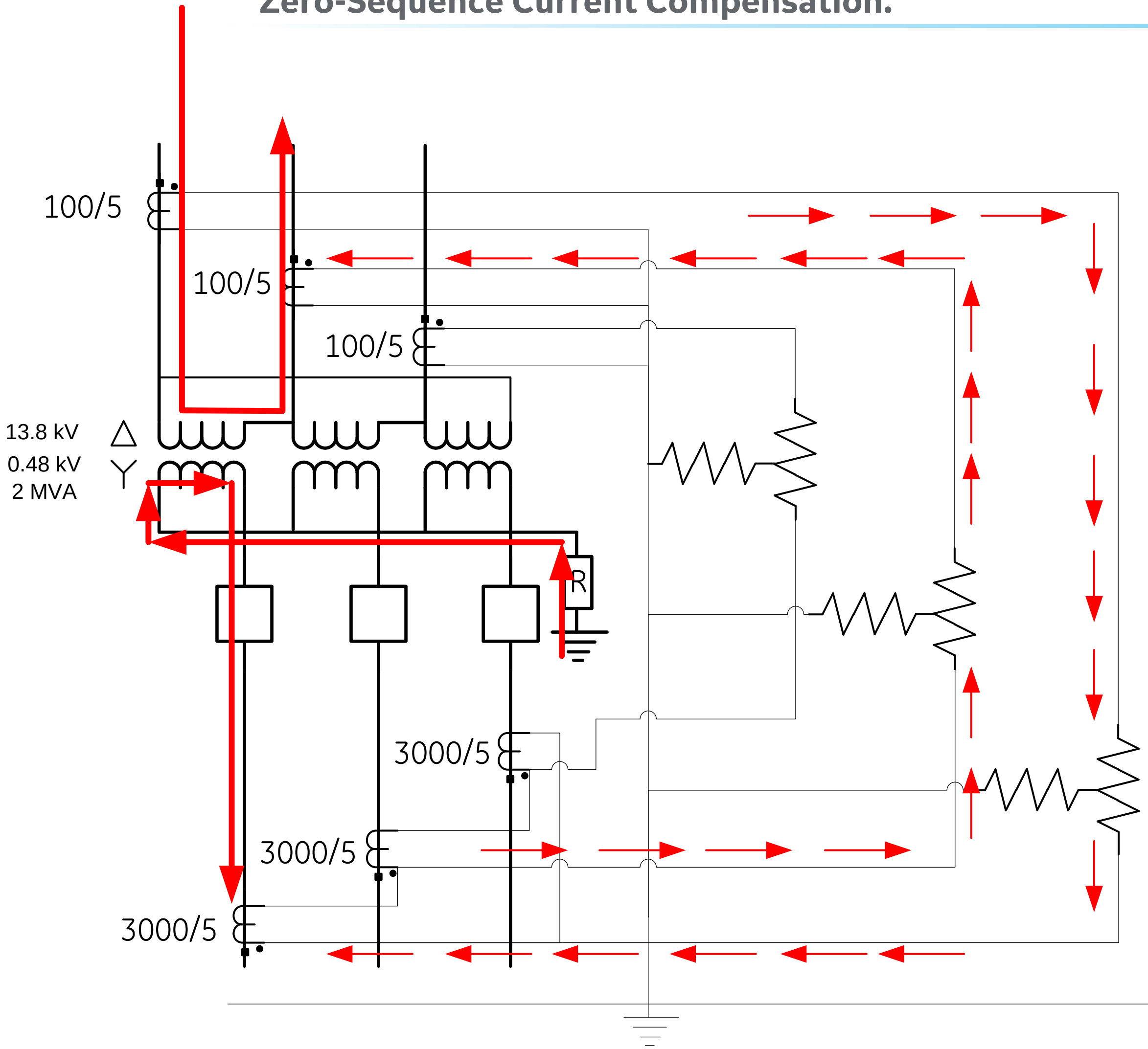


If we know the math that the relay is applying for phase angle compensation for a Dy30 with ABC, we can see that the secondary phases are all wired into the wrong spot. They have all been rolled.

For example, the mathematical outcome of Ia would sum to zero if it were summed with measured Ic.

Challenges of Transformer Differential

Zero-Sequence Current Compensation.



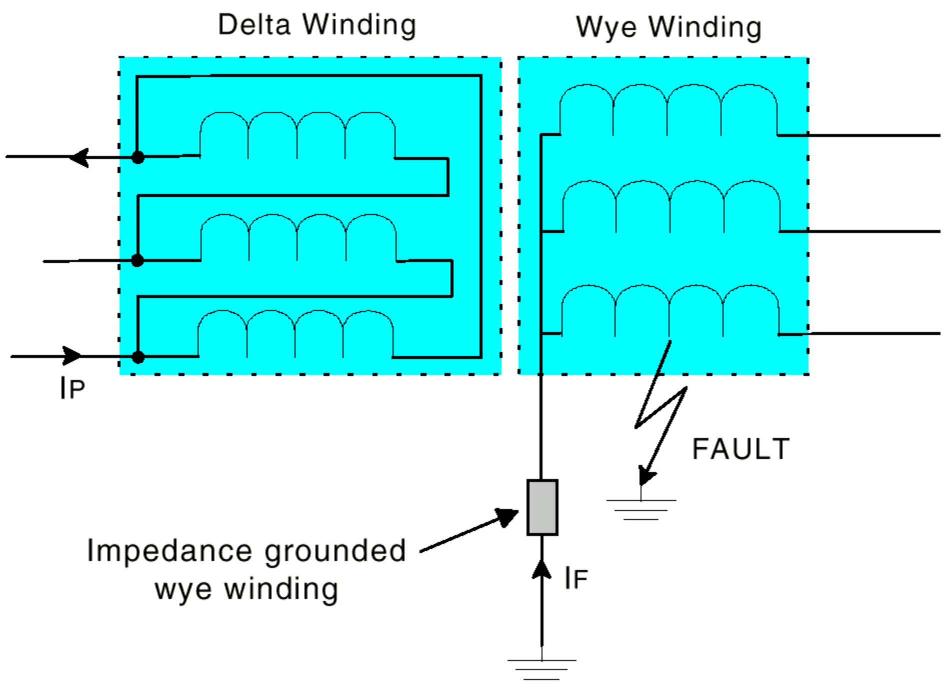
When 1LG faults occur outside the zone of protection on the wye side, the differential must not operate.

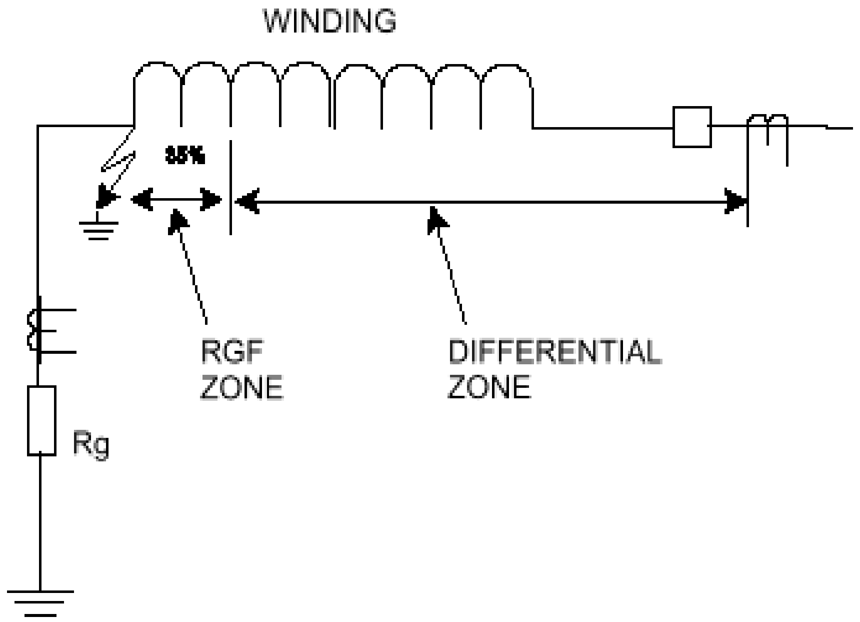
A review of the current flow in the relay's CT circuits shows how the delta-wired CT's in an electromechanical system negate the currents that flow in two phases on the delta side.

Digital relays perform this zero-sequence current compensation mathematically, using the aforementioned equations used in phase angle compensation, so there is no need for delta-wired CT's.

Challenges of Transformer Differential

Ground fault sensitivity in impedance grounded systems



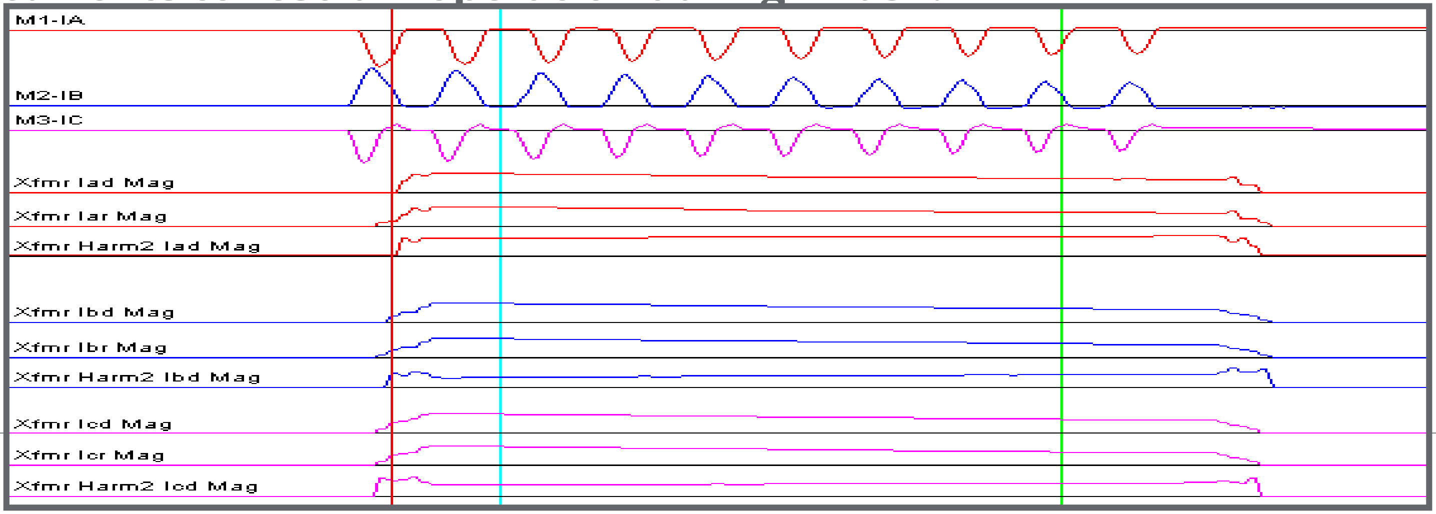


Relay compares measured Ig to calculated 3I0. This is one reason that delta-connected CT's are not recommended. Delta-connected CT's negate the relay's ability to calculate 3I0.

Challenges of Transformer Differential

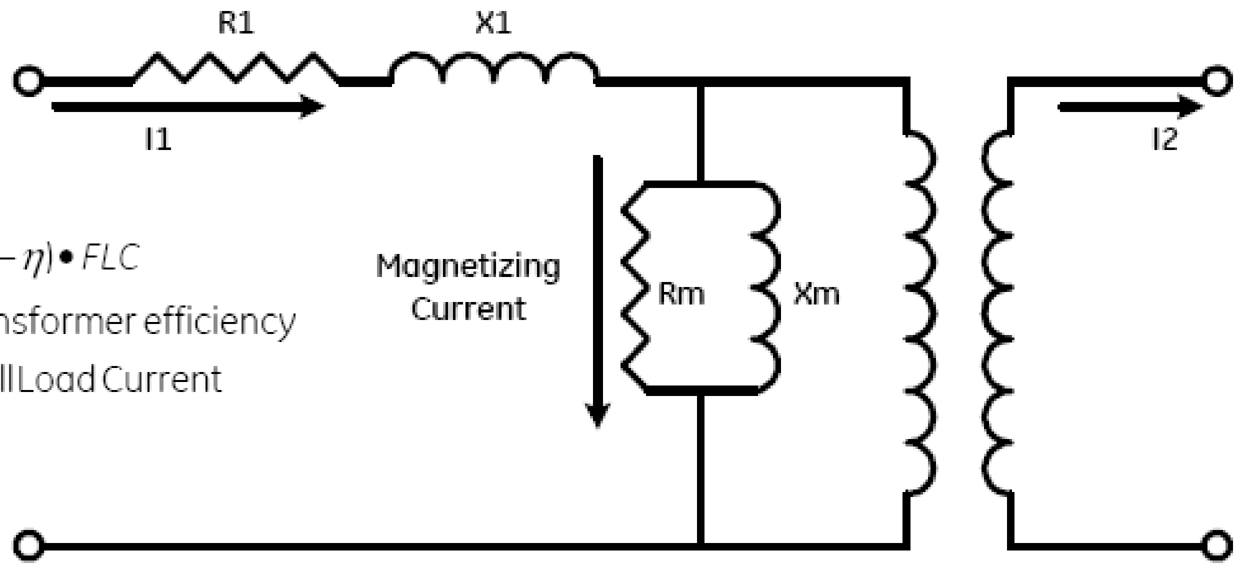
Magnetizing Current Inrush

- **When a transformer is energized, inrush current can be as high as 10 x FLC of the transformer.**
- **Inrush lasts for only a few cycles but can cause the differential element to operate because it has the appearance of an internal fault (current flows into but not out of the unloaded transformer).**
- **Predominantly 2nd harmonic.**
- **Digital relay filters can eliminate the 2nd harmonic component from "restraint coil" currents to restrain operation during inrush.**



Challenges of Transformer Differential

Magnetizing Current Inrush



$$I_{magnetizing} = (1-\eta) \bullet FLC$$

where η = transformer efficiency

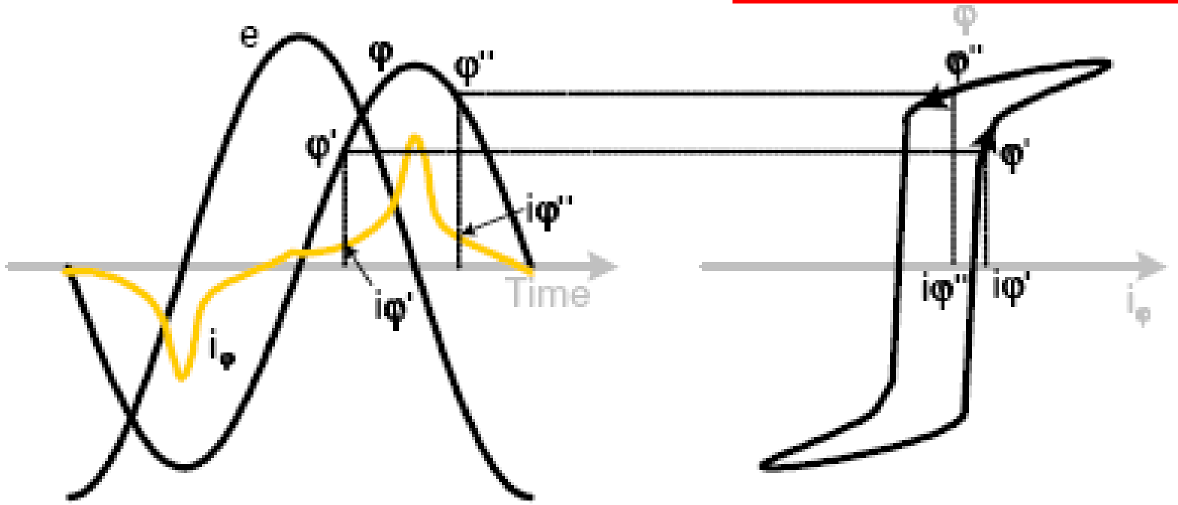
FLC = Full Load Current

- All transformers must establish flux in the transformer core
- This flux causes a current to flow known as the magnetizing current
- Magnetizing current appears as differential current

Challenges of Transformer Differential

Magnetizing Current Inrush

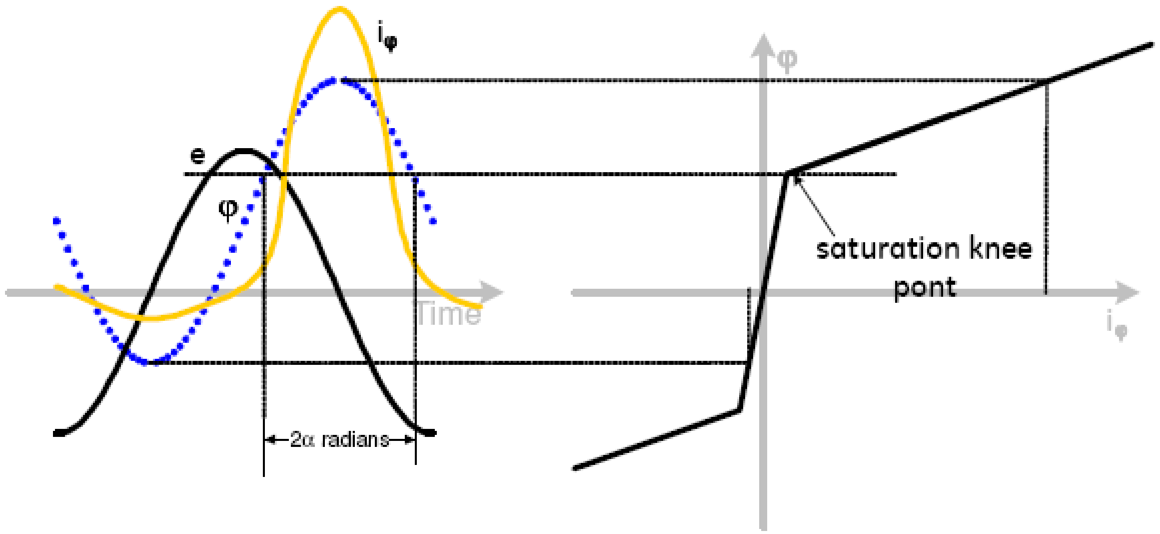
Magnetic Hysteresis Loop



- Non-Linearity of the core results in a non-linear magnetizing current waveform
- Notice flux lags excitation voltage by 90 degrees
- Steady State Magnetizing current is in the range of 1-3% of XFMR Full Load Amps

Challenges of Transformer Differential

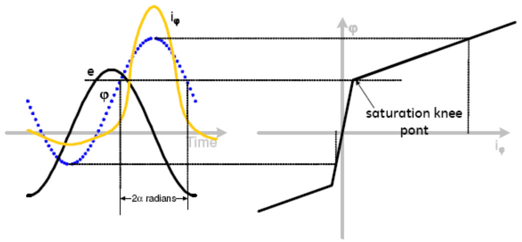
Magnetizing Current Inrush

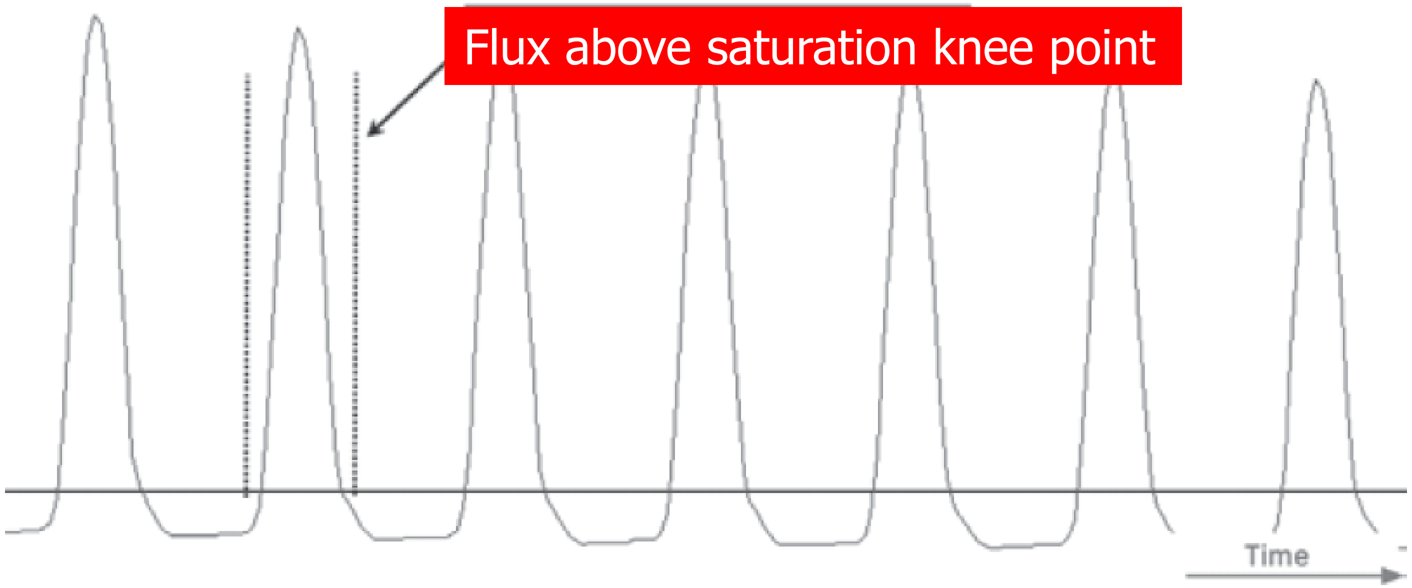


- When an abrupt change in excitation voltage occurs, as when transformer is en energized, a large magnetizing current can flow. Magnetic hysteresis loop becomes negligible.
- The Magnetizing Inrush Current is dependent on several factors, which will be discussed on the following slides

Challenges of Transformer Differential

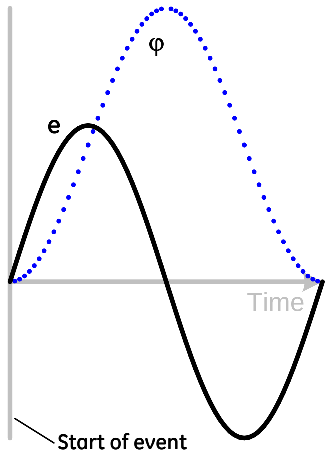
Magnetizing Current Inrush

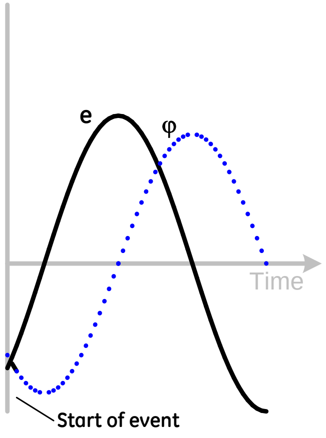




Challenges of Transformer Differential

Magnetizing Current Inrush – Point on Wave Switching

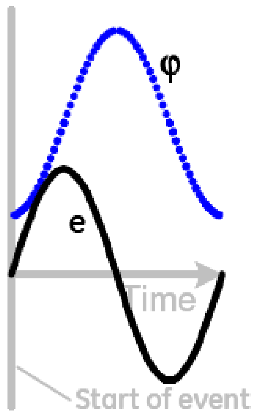




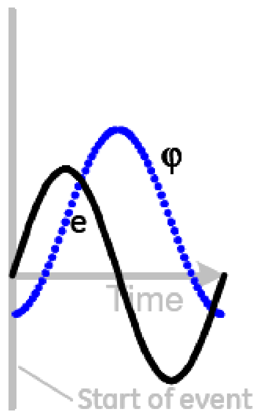
- Highest magnitude inrush occurs when excitation voltage is applied at zero crossing
- Lowest magnitude inrush occurs when excitation voltage is applied at –90 degrees
- Switching point is not controlled thus magnitude of inrush unpredictable

Challenges of Transformer Differential

Magnetizing Current Inrush – Remanent Flux



Positive remanent flux



Negative remanent flux

- Remanent Flux can be 30-80% of maximum core flux
- Remanent Flux can be positive or negative
- This can lead to increased or decreased magnetizing inrush current
- Amount of remanent flux present is unpredictable

Challenges of Transformer Differential

Magnetizing Current Inrush – Core Design

- Saturation flux density and peak flux density of a transformer core is primarily affected by core design
- Steel quality has remained constant over the years
- Laminated core designs have become more common
- Laminations provide an air gap between each lamination – resulting in lower steady state and inrush magnetization currents

Challenges of Transformer Differential

Magnetizing Current Inrush – Core Design

- Laminated core designs lead to lower reluctance cores
- Lower reluctance cores are more efficient leading to lower magnetizing current

Challenges of Transformer Differential

Magnetizing Current Inrush – Impact of Power System

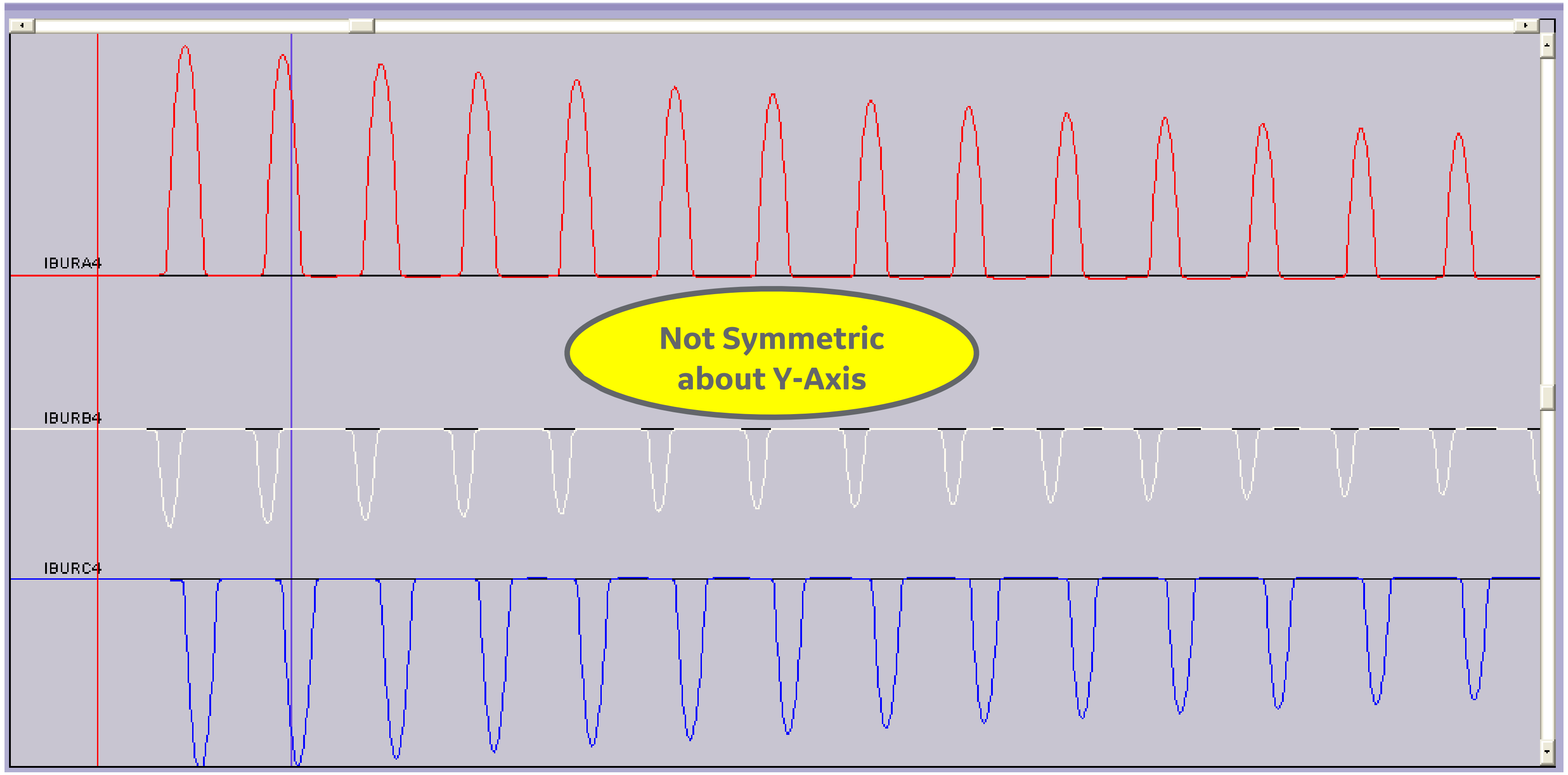
- The peak magnitude of the inrush current is dictated by the strength of the power system source
- The duration of an inrush event is dictated by the resistive losses in the circuit
- The change in flux over time is defined by:

$$\Delta\varphi = \int_{t}^{t+T} (R \times i)\,dt$$

where $\Delta\varphi$ = flux change per cycle,
R = total series resistance including transformer winding resistance
T = period of one cycle.

Challenges of Transformer Differential

Magnetizing Current Inrush – Naturally non-linear

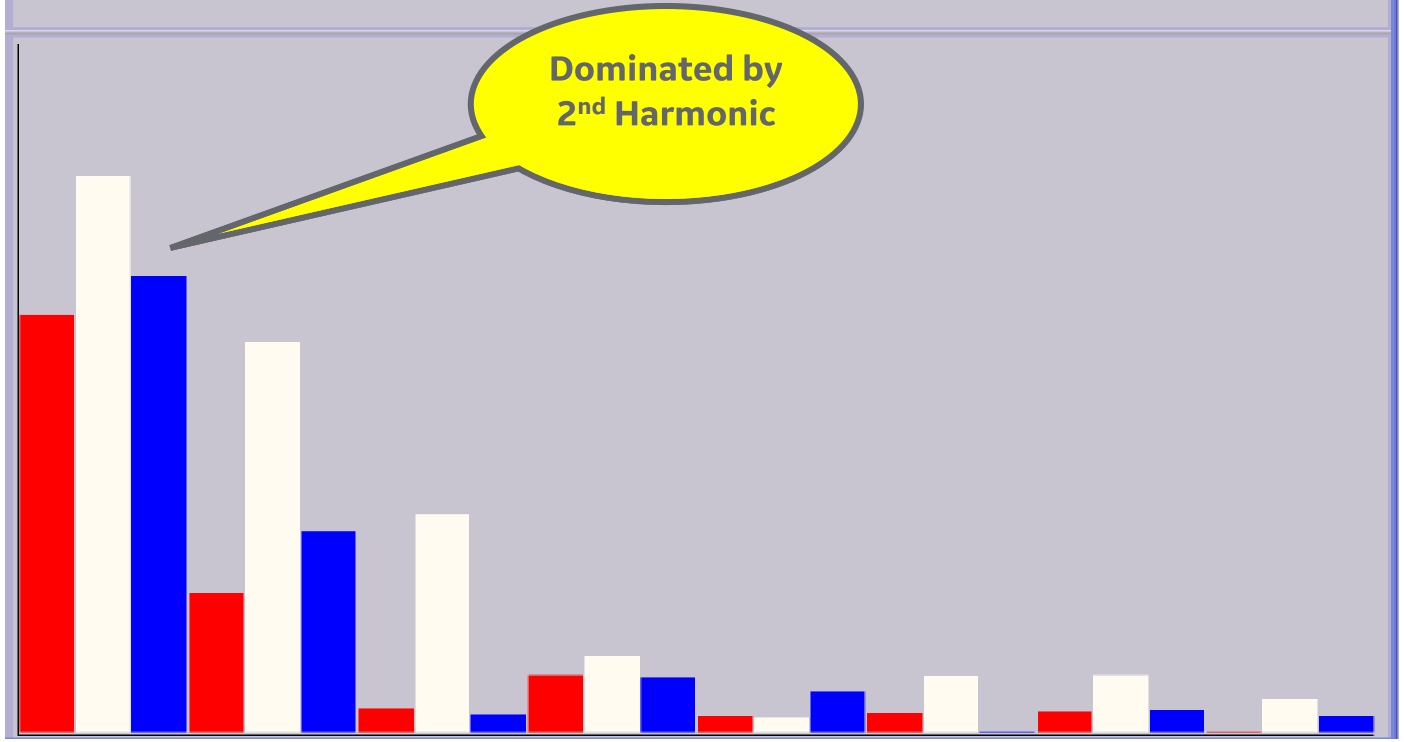


IDEAL INRUSH WAVEFORM

Challenges of Transformer Differential

Magnetizing Current Inrush – Rich in even harmonics

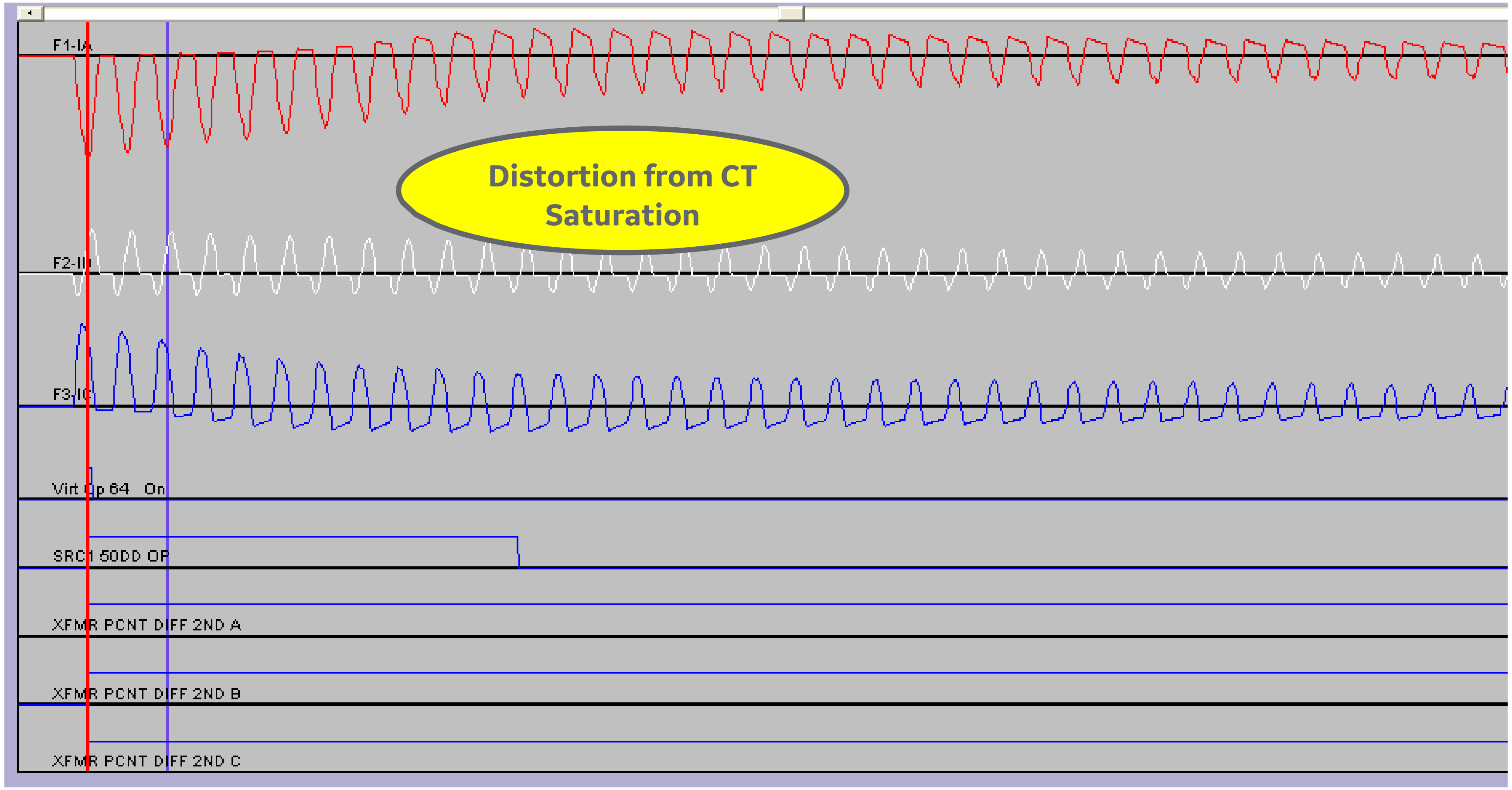
CHANNEL IDENTIFIER		GRAPH	2nd	3rd	4th	5th	6th	7th	8th	9th
IBURA4		Graph 1	60.78	20.57	3.76	8.55	2.62	3.01	3.24	0.57
IBURB4		Graph 1	80.78	56.81	31.80	11.40	2.38	8.40	8.50	5.06
IBURC4		Graph 1	66.48	29.41	2.95	8.24	6.24	0.36	3.52	2.75



IDEAL INRUSH WAVEFORM

Challenges of Transformer Differential

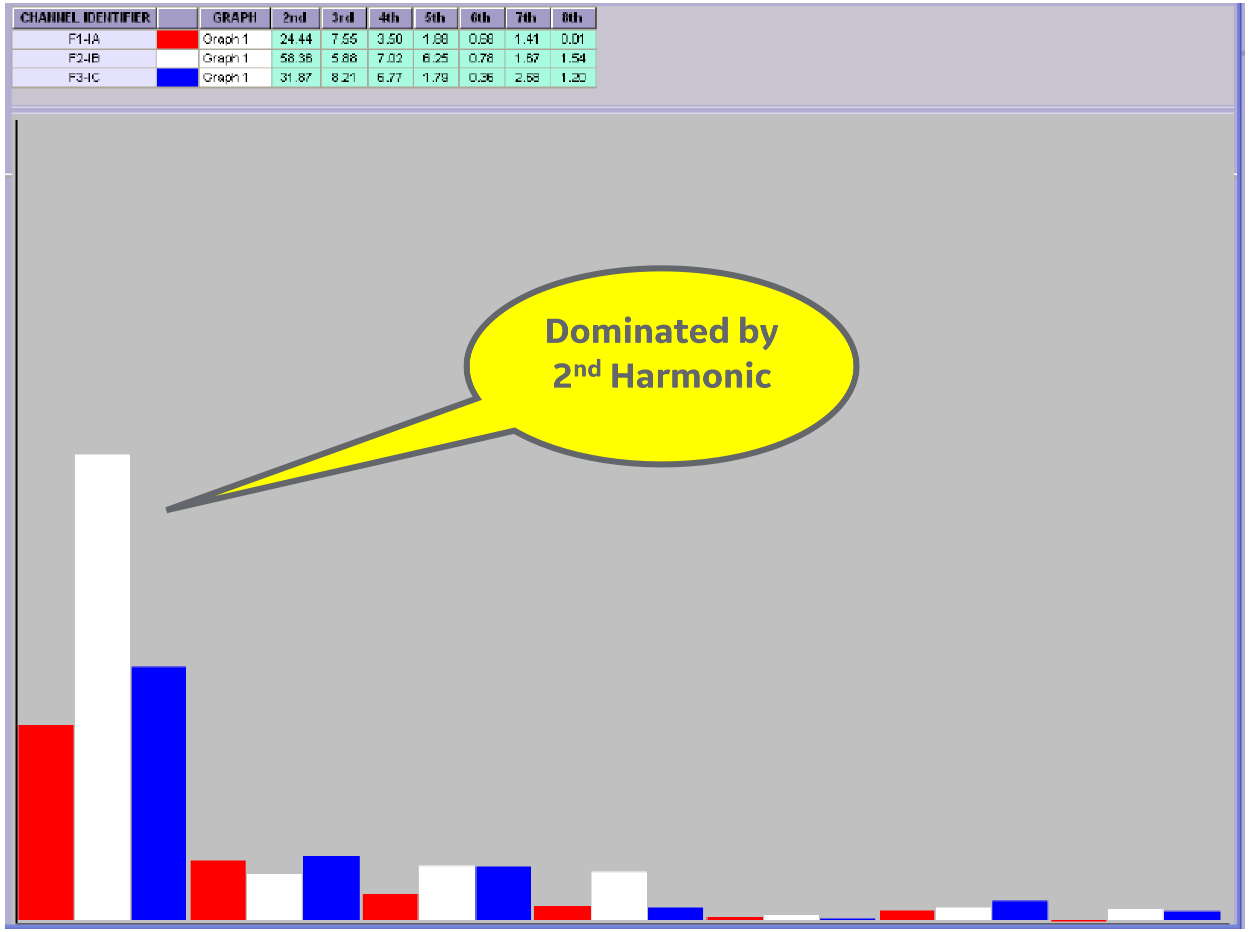
Magnetizing Current Inrush – Causes CT saturation



15MVA – 66kV to 6.9kV Transformer

Challenges of Transformer Differential

Magnetizing Current Inrush – Causes CT saturation



CHANNEL IDENTIFIER		GRAPH	2nd	3rd	4th	5th	6th	7th	8th
F1-IA		Graph 1	24.44	7.55	3.50	1.88	0.68	1.41	0.01
F2-IB		Graph 1	58.36	5.88	7.02	6.25	0.78	1.67	1.54
F3-IC		Graph 1	31.87	8.21	6.77	1.79	0.36	2.68	1.20

15MVA – 66kV to 6.9kV Transformer

Challenges of Transformer Differential

Magnetizing Current Inrush – When does it occur?

- During Transformer Energization:
  - Typically the most severe case, because excitation voltage is going from zero to maximum value
  - For three phase transformers, each phase will experience different peak values of inrush current due to the voltage angle at the time of switching

Challenges of Transformer Differential

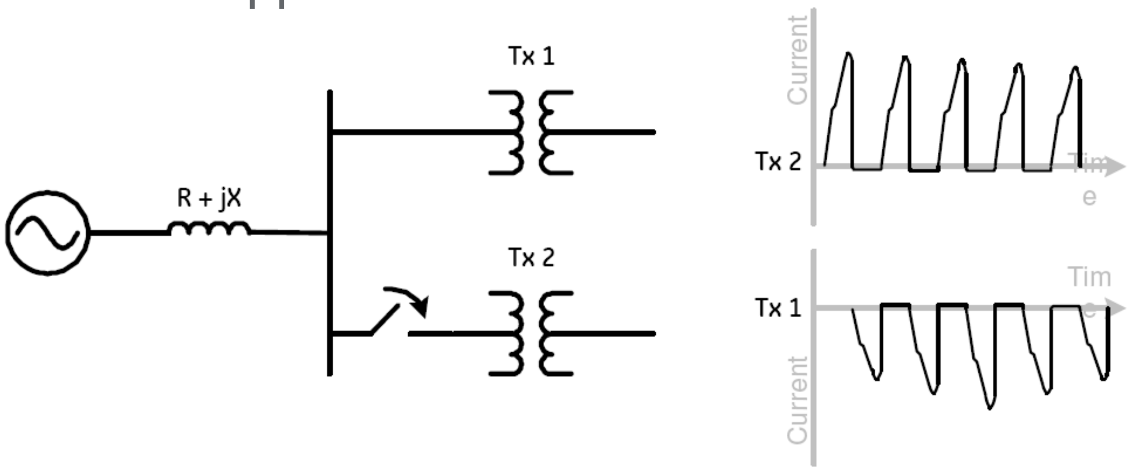
Magnetizing Current Inrush – When does it occur?

- During Post Fault Voltage Recovery:
  - During a fault, the system voltage is depressed and then returns to full value
  - This change in voltage can lead to inrush currents similar to energization of transformer
  - Not typically as severe as Energization because Flux won't be fully offset from excitation voltage
  - The presence of load current will act to lower ratio of second harmonic to fundamental current

Challenges of Transformer Differential

Magnetizing Current Inrush – When does it occur?

- Sympathetic Inrush:
  - When two or more transformer banks in parallel are energized sequentially
  - Energization of the first transformer will cause magnetizing inrush current to flow with no additional effects
  - Energization of second transformer can cause significant voltage drop
  - Voltage drop effects previously energized transformer, causing it to draw inrush current in opposite direction



Challenges of Transformer Differential

Magnetizing Current Inrush – When does it occur?

- As shown earlier, high levels of inrush current can cause differential relay misoperation

- We need to identify this condition and stop the differential relay from operating while inrush condition is present

- Many methods exist, all rely on the characteristics of the inrush waveform

Challenges of Transformer Differential

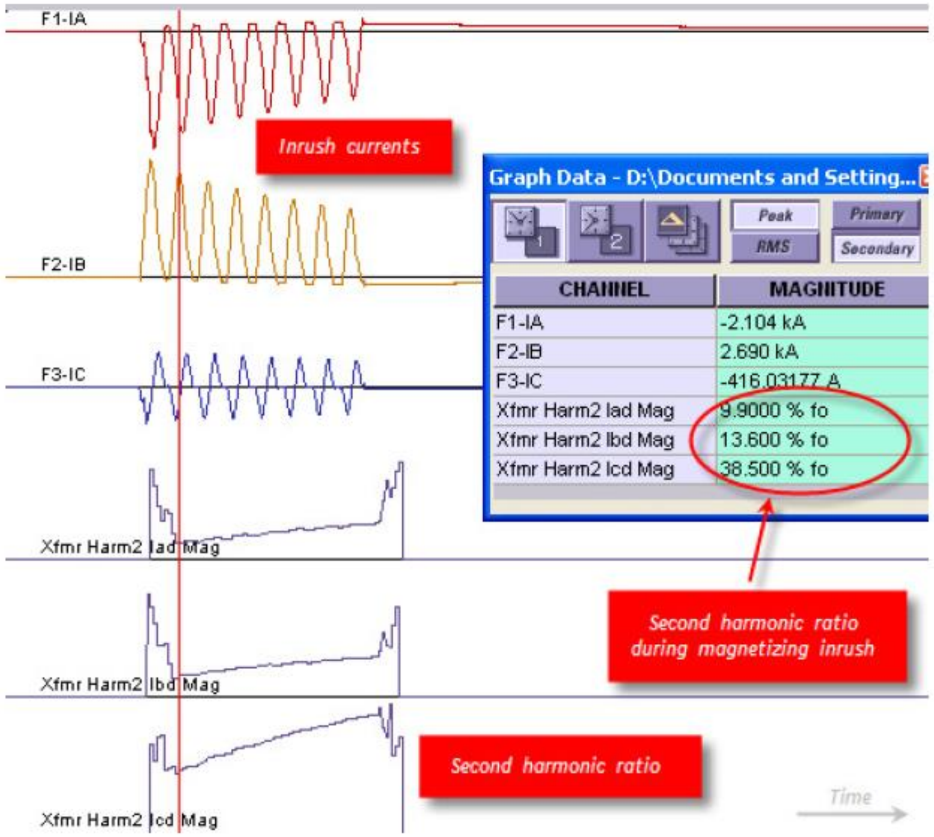
Magnetizing Current Inrush – Percentage of Total Harmonic Method

$$if \ \frac{I_{diff(2nd\ harmonic)} + I_{diff(3rd\ harmonic)} + \ldots I_{diff(n\ harmonic)}}{I_{differential(Fundamental)}} > setting, \text{then block differential}$$

- This method utilizes the fact the inrush waveform is rich in harmonics
- Typically applied in EM relays per phase
- Problems
  - More efficient core designs produce less harmonic content
  - CT Saturation essentially creates a setting “floor”

Challenges of Transformer Differential

Magnetizing Current Inrush – Percentage of Total Harmonic Method



- Typical values of 2nd harmonic to fundamental ratios are in the range of 10%-60%
- Can be much lower as shown
- Microprocessor relays have introduced methods to deal with this problem

Challenges of Transformer Differential

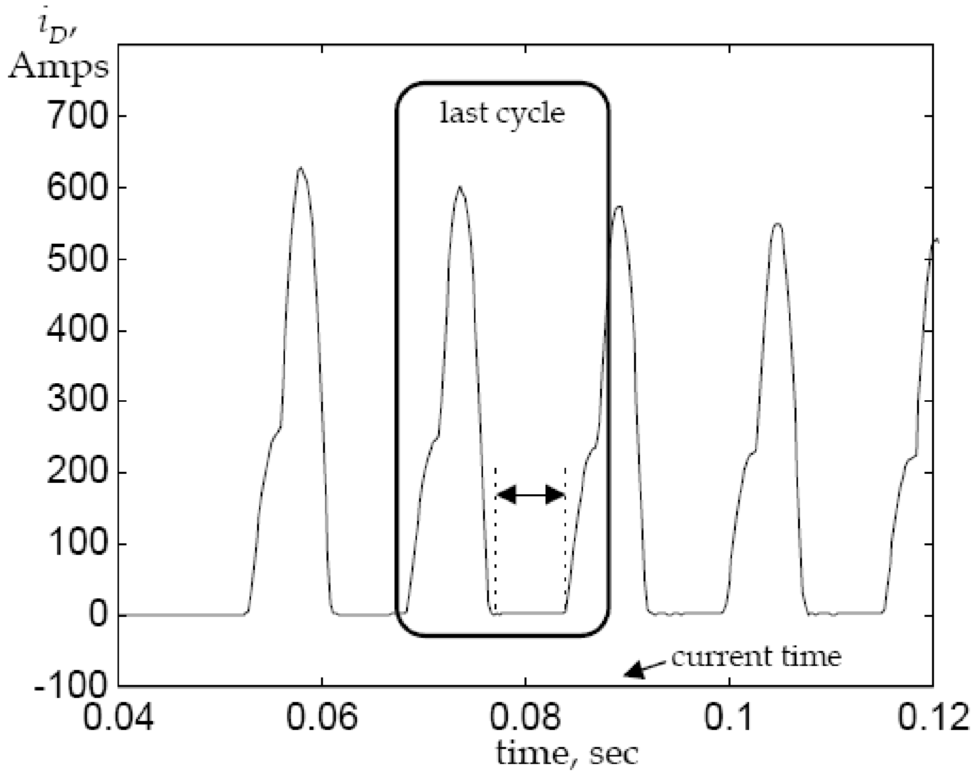
Magnetizing Current Inrush –4th Harmonic Method

$$if \ \frac{I_{differential(4th\ harmonic)}}{I_{differential(fundamental)}} > setting, \text{ then block differential}$$

- This method utilizes the fact the inrush waveform is not symmetric, leading to even harmonics
- Used in some microprocessor relays
- CT Saturation still a problem
- No significant benefit over 2^{nd} harmonic method

Challenges of Transformer Differential

Magnetizing Current Inrush – Wave Shape Method



- Relies on flat spots near zero value (>1/4 cycle)
- CT saturation can compromise security and dependability
- Were used widely in solid-state relays
- Differential element delayed by 1 full cycle

Challenges of Transformer Differential

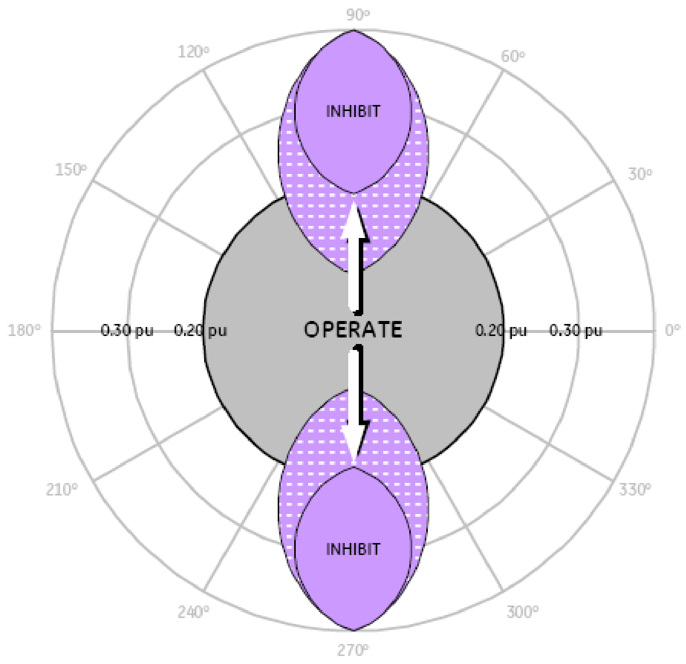
Magnetizing Current Inrush – Adaptive Method

$$\vec{I}_{21} = \frac{\vec{I}_2}{\vec{I}_1 \times e^{j\omega t}}$$

where $\vec{I}_2$ is the 2nd harmonic differential current phasor,

$\vec{I}_1$ is the fundamental differential current phasor,

ω is the system frequency.



- Method utilizes 2nd Harmonic Magnitude and Angle
- Dynamically restrains over a maximum of 6 cycles
- May slow operation by a few cycles if 2nd harmonic current is present

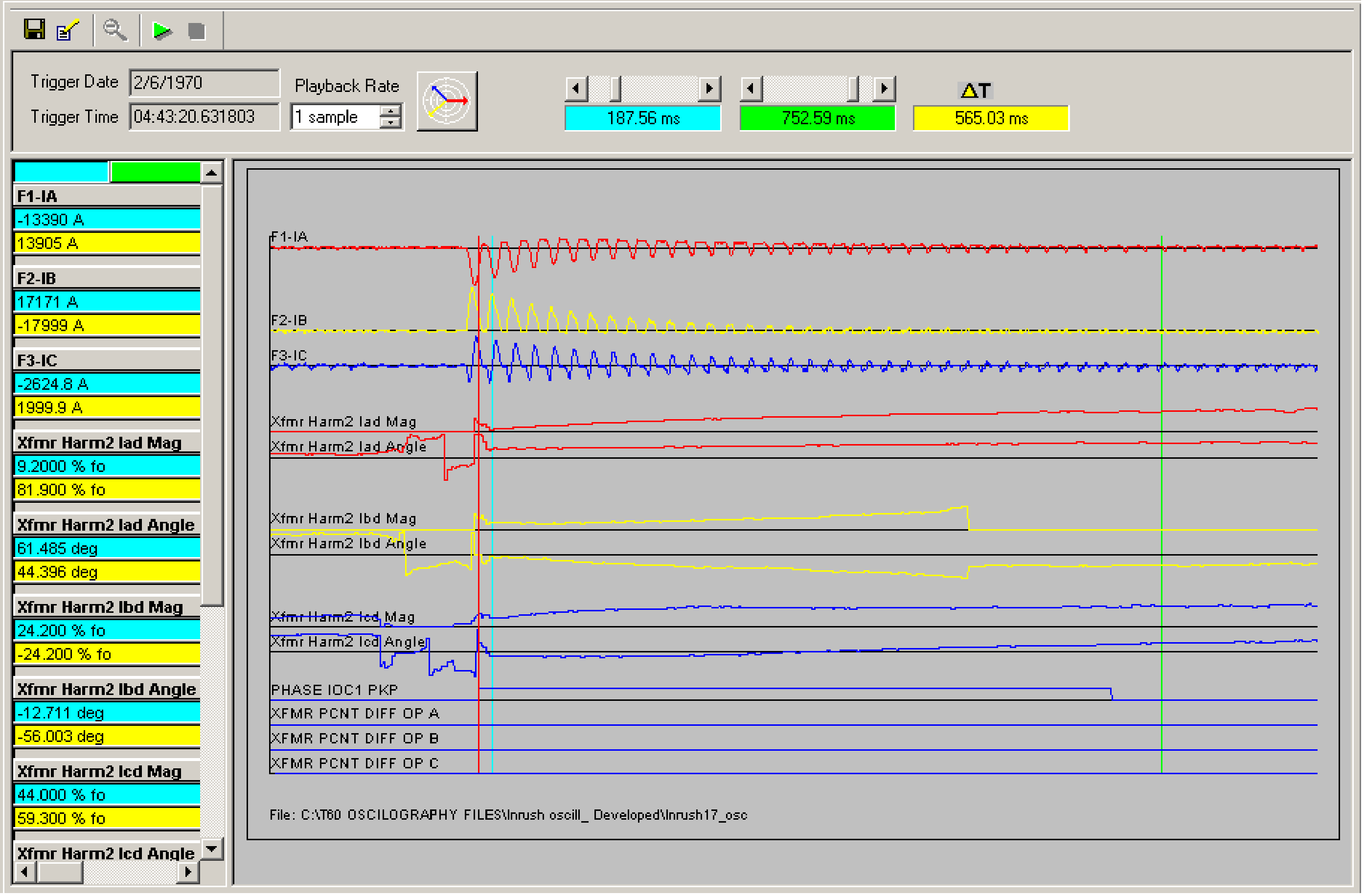
Challenges of Transformer Differential

Magnetizing Current Inrush – Adaptive Method

- If the second harmonic drops magnitude-wise below 20%, the phase angle of the complex second harmonic ratio (I2/I1) is close to either +90 or -90 degrees during inrush conditions
- The phase angle may not display the 90-degree symmetry if the second harmonic ratio (I2/I1) is above some 20%
- If the second harmonic ratio (I2/I1) falls bellow 20% making an angle of ± 90° with the fundamental current, the algorithm applies adaptive lenses, and time for which the 87T protection is inhibited
- Method dynamically lowers the restraint threshold at the beginning of inrush event and gradually increases back to the setting value
- CT saturation impacts speed

Challenges of Transformer Differential

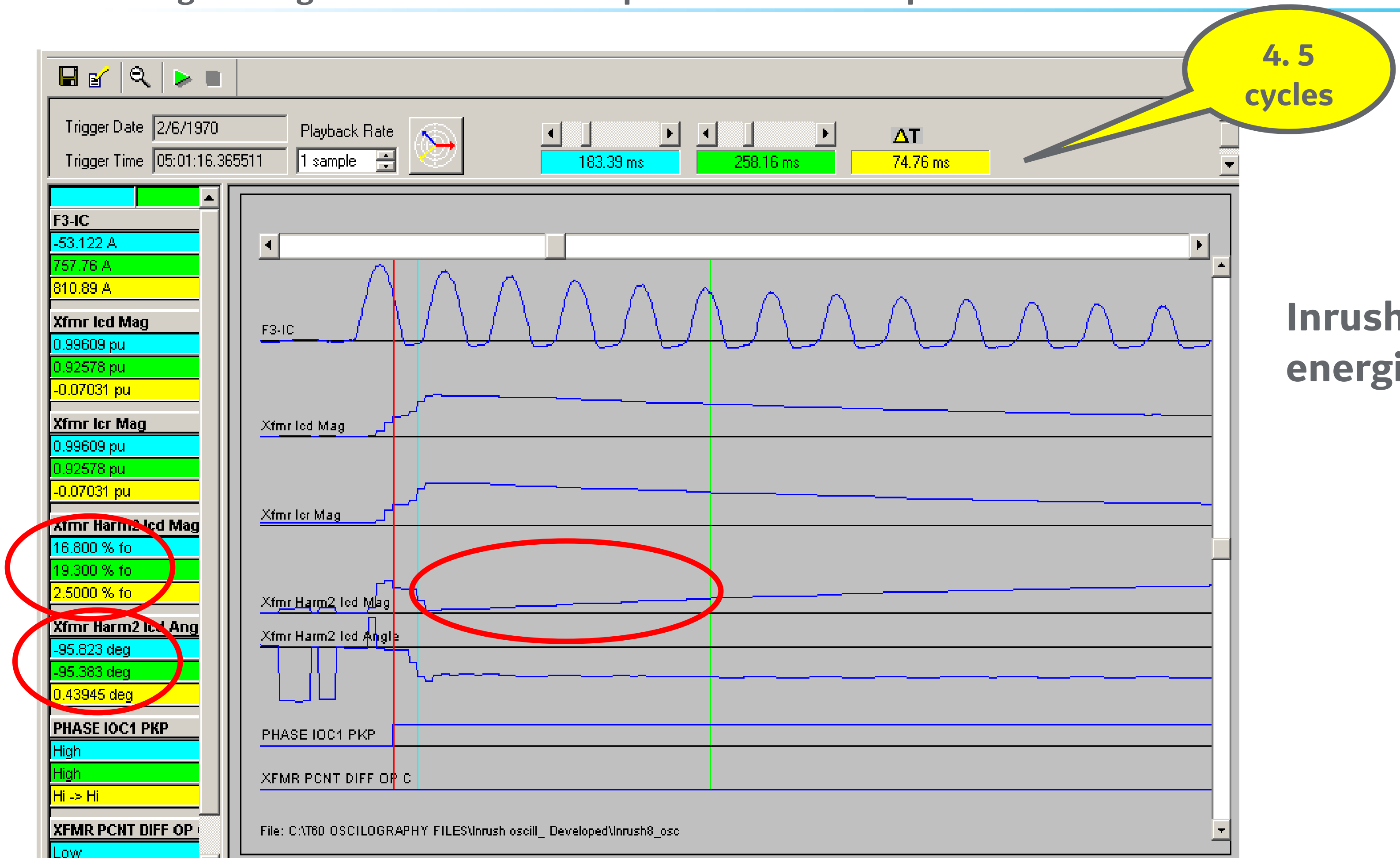
Magnetizing Current Inrush – Adaptive Method Example



Transformer D/Y30, 13.8/115 kV energized from Wye side

Challenges of Transformer Differential

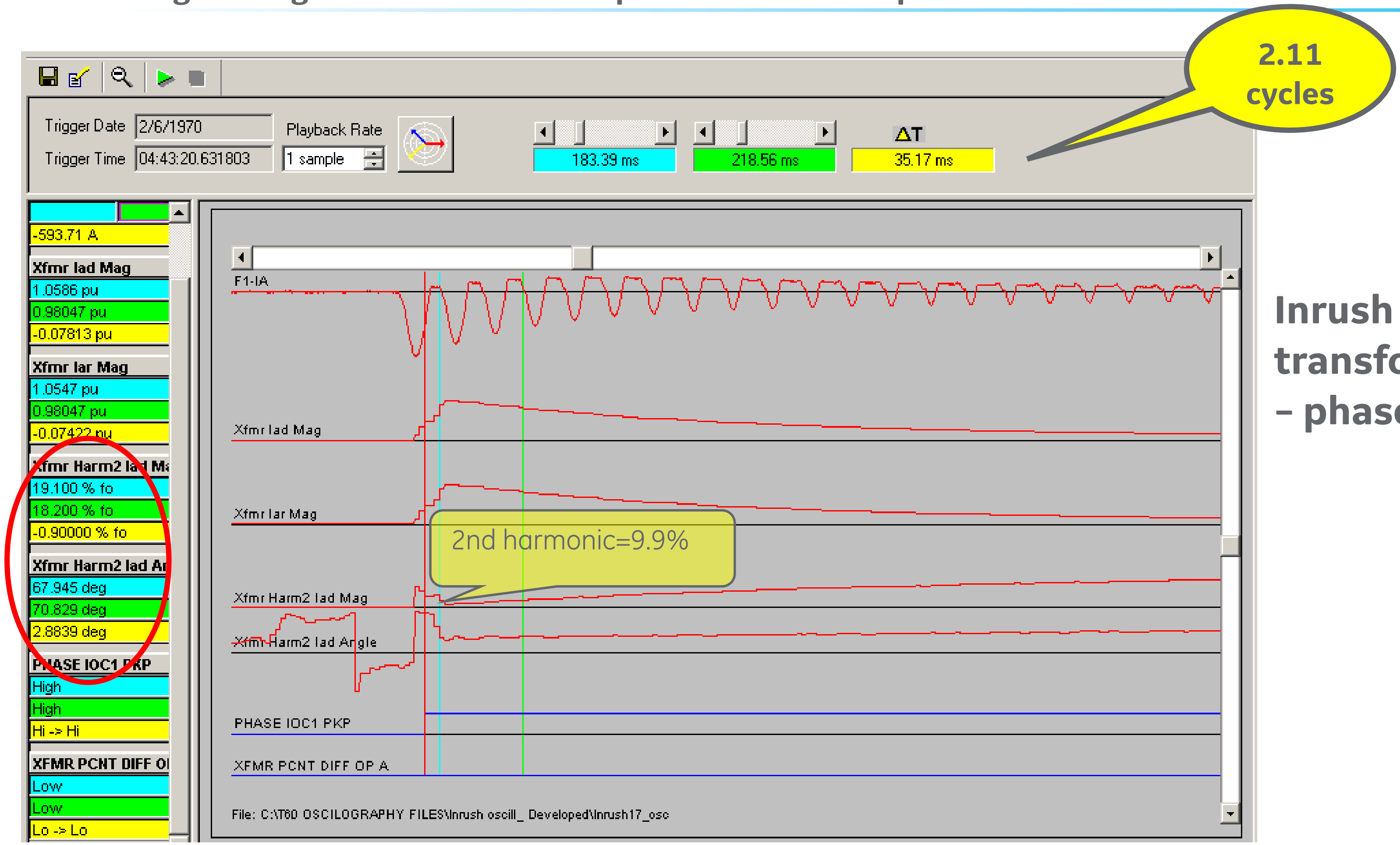
Magnetizing Current Inrush – Adaptive Method Example



Inrush current on transformer energization – phase C

Challenges of Transformer Differential

Magnetizing Current Inrush – Adaptive Method Example



Inrush current on transformer energization – phase A

Challenges of Transformer Differential

Magnetizing Current Inrush – How should these methods be applied?

- Electromechanical relays typically used either % total harmonic or % 2nd harmonic methods
- Electromechanical relays applied them on a per-phase basis
- Microprocessor relays can apply many methods on a per-phase, 1 out of 3 (cross blocking), 2 out of 3, or average basis
- Pros and Cons to each

Challenges of Transformer Differential

Magnetizing Current Inrush – How should these methods be applied?

- 1 out of 3 (Cross Blocking)– Very secure, but can reduce reliability or speed:
  - Consider fault during energization
- Per Phase – Less secure, very reliable:
  - Consider low 2nd harmonic inrush
  - Use on three-phase bank of single phase XFMRS
- 2 out of 3 – More secure than Per Phase, potentially less reliable
- Averaging Method – More secure then Per Phase or 2 out of 3, no compromise on reliability

Challenges of Transformer Differential

Magnetizing Current Inrush – How should these methods be applied?

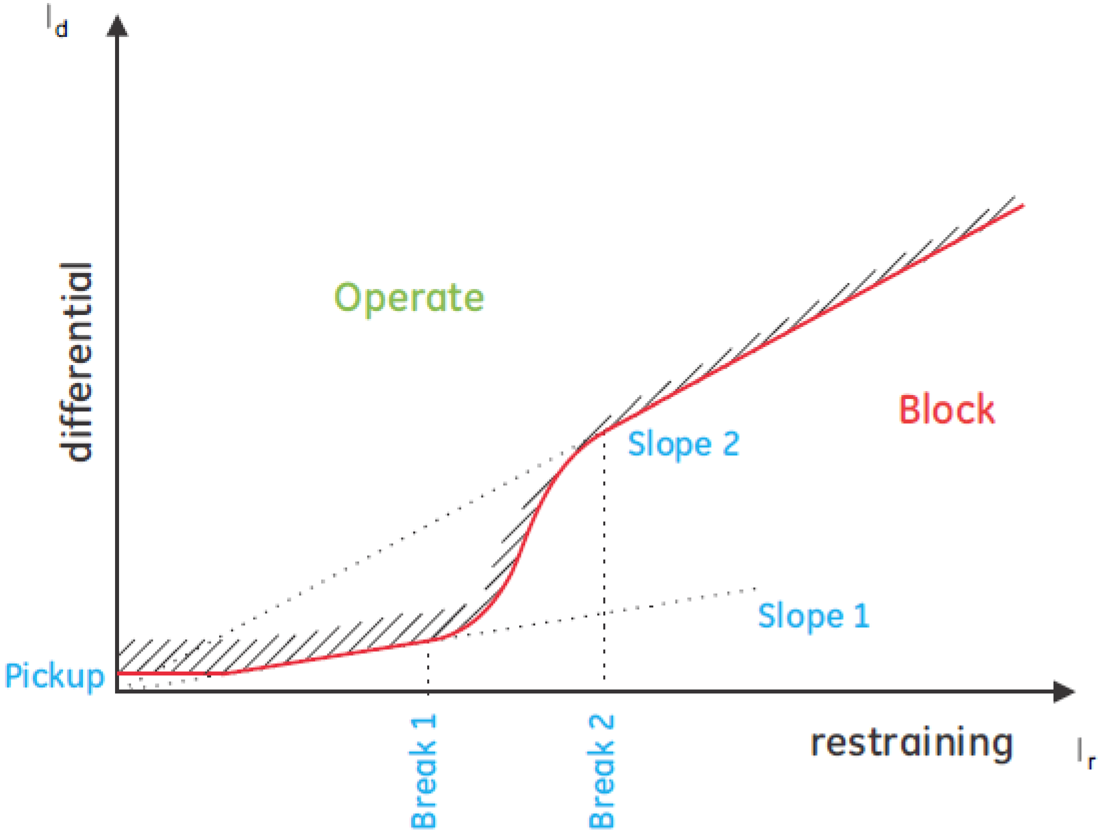
- Security & Speed:
  - 2nd harmonic method and cross blocking or averaging mode
- Security (speed not important):
  - Adaptive method and per phase
- Dependability & Speed:
  - 2nd harmonic method and per phase or averaging mode
- Dependability, Security & Speed:
  - 2nd harmonic method and averaging mode

Challenges of Transformer Differential

CT Performance – Pickup, Slope, Breakpoint

Pickup

- CT's can be within measurement accuracy and still be +/- 10%. Weight benefits vs consequences before setting below 0.2 per unit.
- In MV petrochemical applications, consider setting the pickup at 2 x load. The benefit of this conservative approach is to prevent a nuisance trip even in the case that someone wired the CT polarities backwards. Alarm on high diff current.

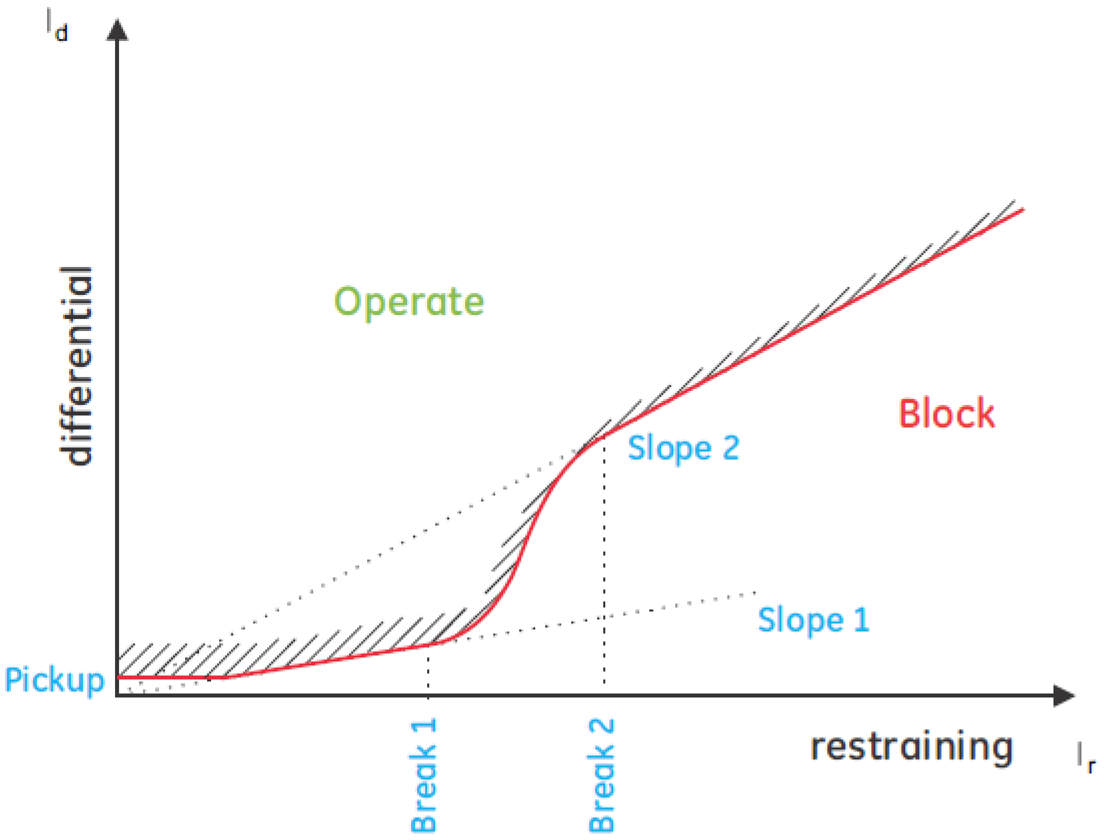


Challenges of Transformer Differential

CT Performance – Pickup, Slope, Breakpoint

Slope 1

- Protection Class CT's can be within measurement accuracy and still be +/- 10%. One measuring at +10, the other measuring at -10% at full load results in a Idiff/Irest = 20% for a two-winding transformer. Weight benefits vs. consequences before setting lower than 30%.



Challenges of Transformer Differential

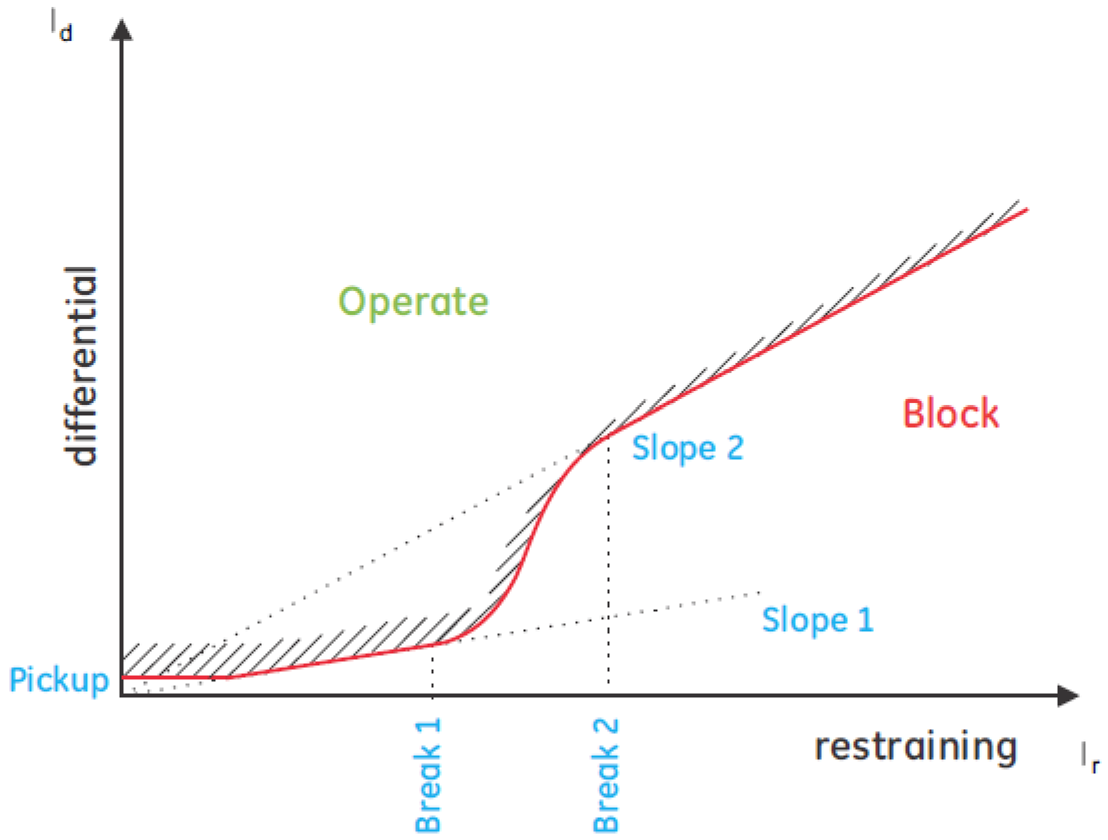
CT Performance – Pickup, Slope, Breakpoint

Breakpoint 1

- Divide CT kneepoint voltage by CT burden then multiply by 20%. This method accounts for extremely poor CT performance at low magnitudes due to remanence.

Breakpoint 2

- Divde CT kneepoint voltage by CT burden.
- In MV petrochem applications, consider settings same or very close to Breakpoint 1. This adds security and makes testing easier.



Challenges of Transformer Differential

CT Performance – Pickup, Slope, Breakpoint

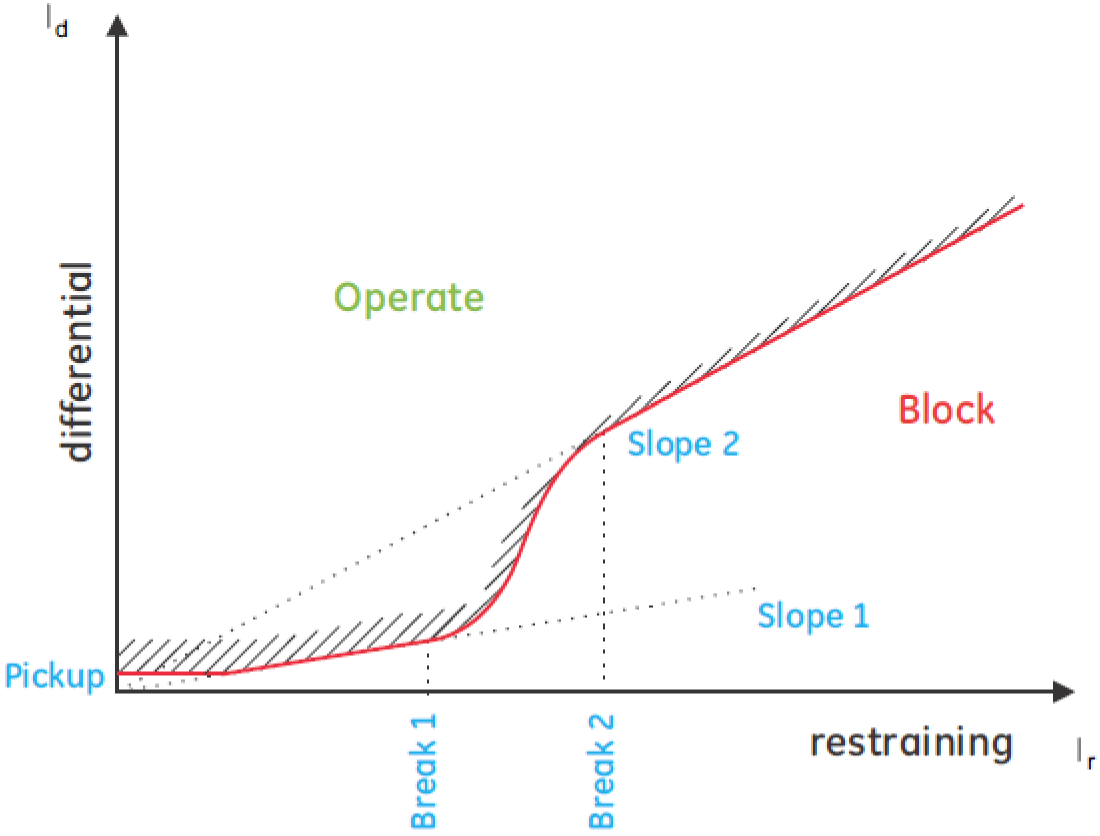
Slope 2

- Slope 2 accounts for CT measurement errors during worst-case fault condition:

Maximum fault current Worst-performing CT

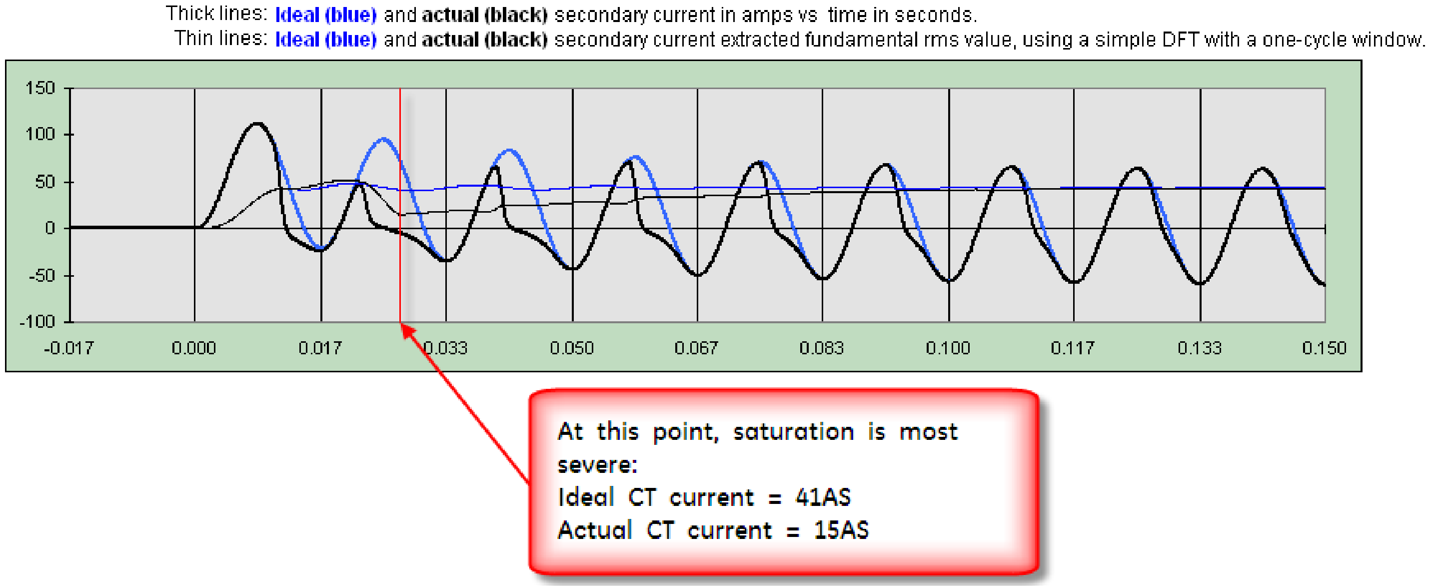
- Slope 2 setting should be high enough to override differential current created by worst case CT saturation condition

- A worst-case scenario occurs when only one of the differential CTs saturates severely due to a through (external) fault current, and other differential CTs do not saturate



Challenges of Transformer Differential

CT Performance – IEEE PSRC CT Saturation Tool



The IEEE PSRC CT Saturation Tool is a great, freely downloadable spreadsheet that helps visualize what your actual CT performance is most likely to resemble.

Use it to set your slope 2 setting according to the maximum deviation of the Actual & Ideal RMS Values.

- Based on the discrepancy between Ideal CT RMS value and Acutal RMS value in this example, we can estimate $I_{diff}/_{Irestr} = 0.63$ so Slope 2 could be set to 63% or higher.