Case study: Analysis of 138/13.8 kV Transformer Differential Misoperation points to Faulty CT

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2019 MIPSYCON

Agenda

- Introduction
- History of Transformer Percentage Differential
- Enhancements to Percentage Differential
- Harmonic Restraint (Blocking) of Percentage Differential
- Securing Percentage Differential using Directionality Check and CT Saturation Detection
- Settings of Percentage Differential
- Analysis of 138/13.8 kV Transformer Differential Incorrect Operation
- Conclusion

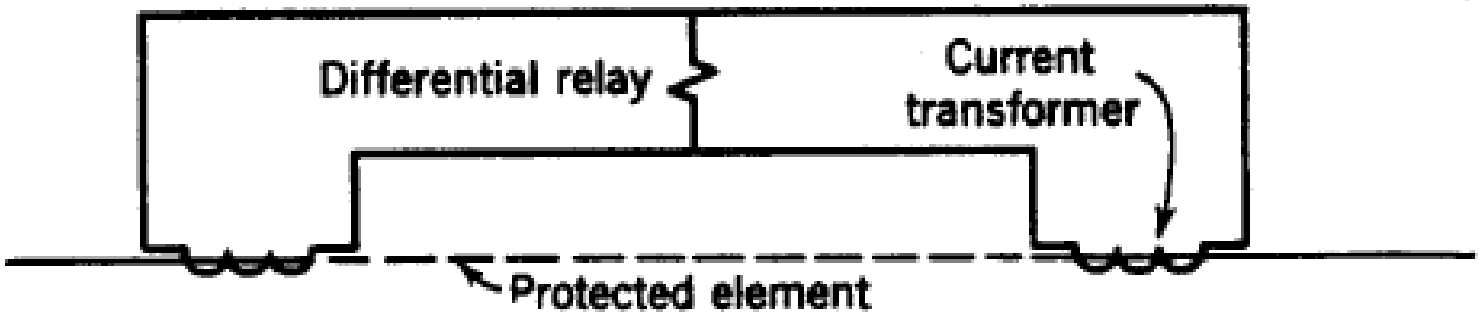
Introduction

- Transformer Protection Original fuses, later Overcurrent
- Not very selective; Current/Time used for Coordination – Internal Faults NOT Instantaneous
- Transformer Protection Evolved, Schemes can include:

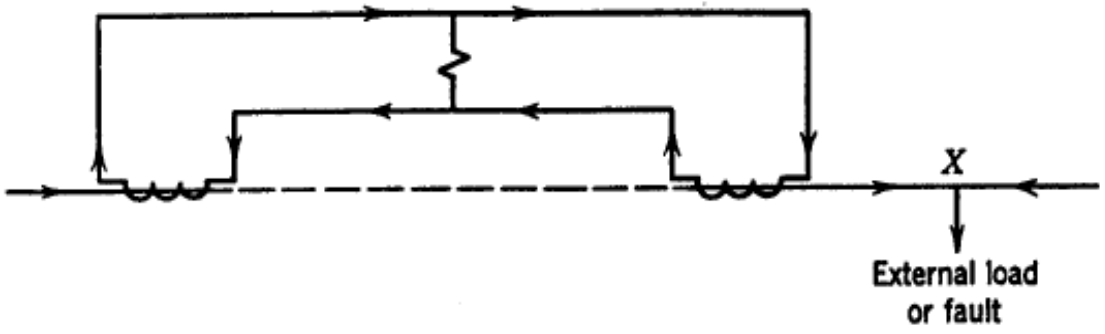
1. Percentage Differential
2. Instantaneous/Unrestraint Differential
3. Restricted Ground Fault
4. Sudden Pressure (Buchholz)
5. Oil/Winding Temperature
6. Phase/Neutral/Ground/Neg Seq Inst & Timed OC
7. Phase/Neutral/Ground/Neg Seq Dir OC
8. Breaker Fail
9. Phase and Ground Distance
10. Volts per Hertz (Over Fluxing)
11. Phase Under/Over Voltage
12. Neutral/Neg Seq Overvoltage
13. Tank Ground Fault
14. Dissolved Gas in Oil (DGA)

History of Transformer Percentage Differential

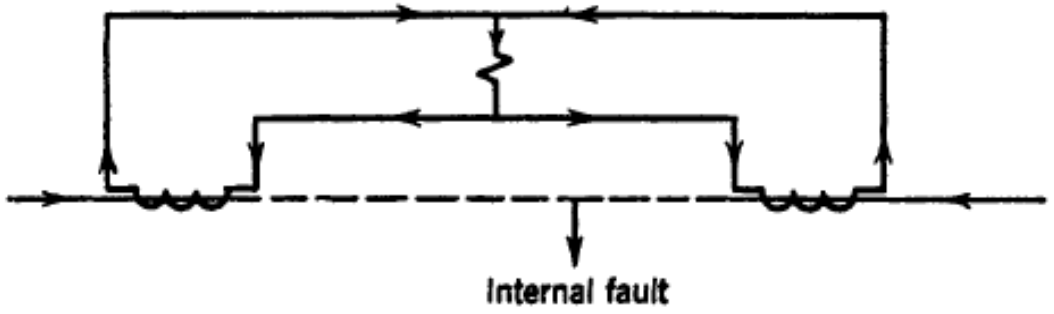
- First Transformer Differential was Overcurrent only



- External Faults

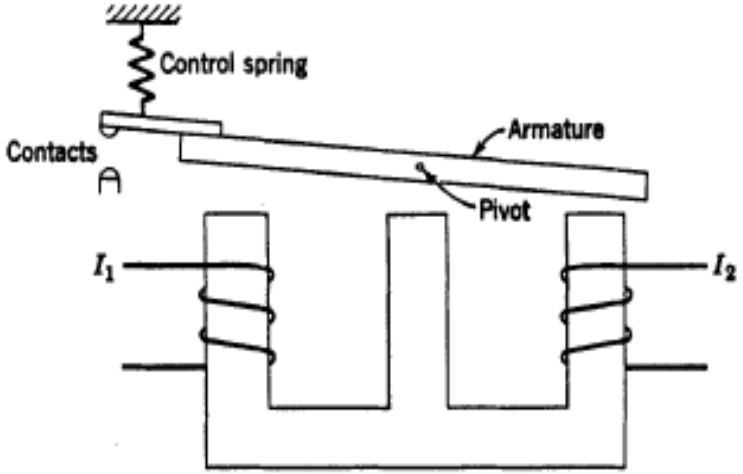


- Internal Faults

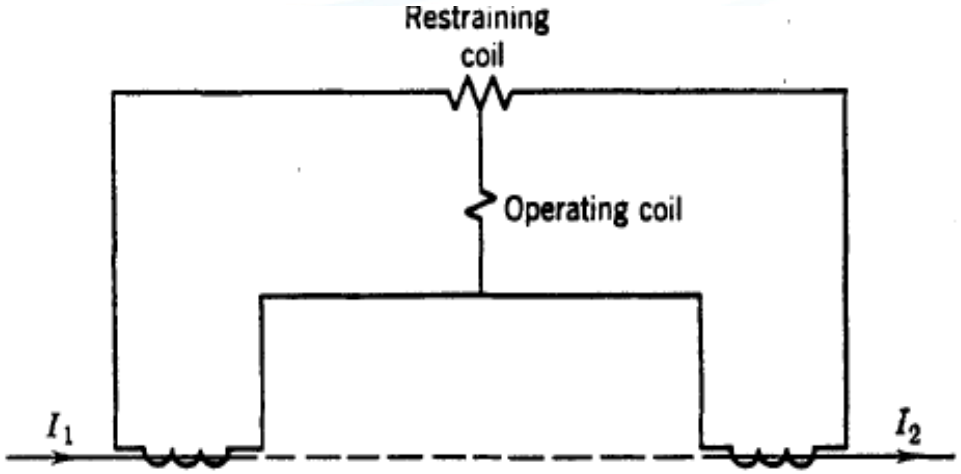


History of Transformer Percentage Differential

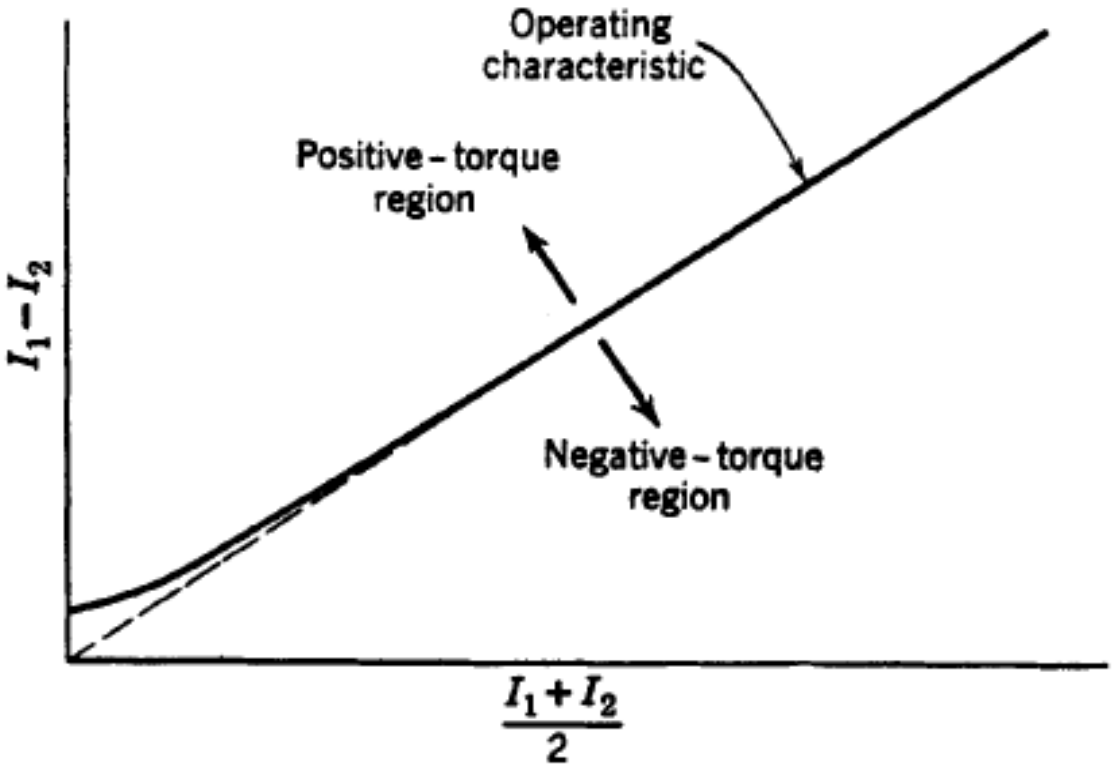
- First Transformer Differential with Restraint:



- Coils Connected

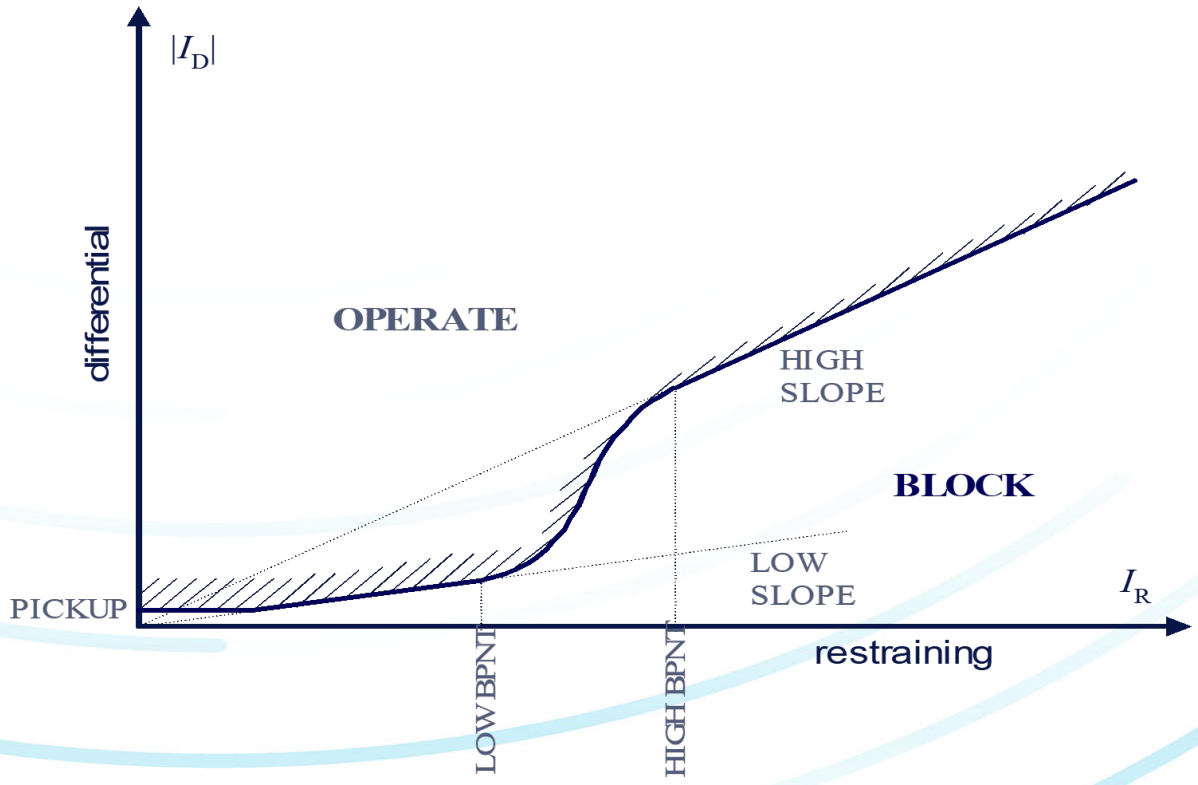


- Operating Characteristic

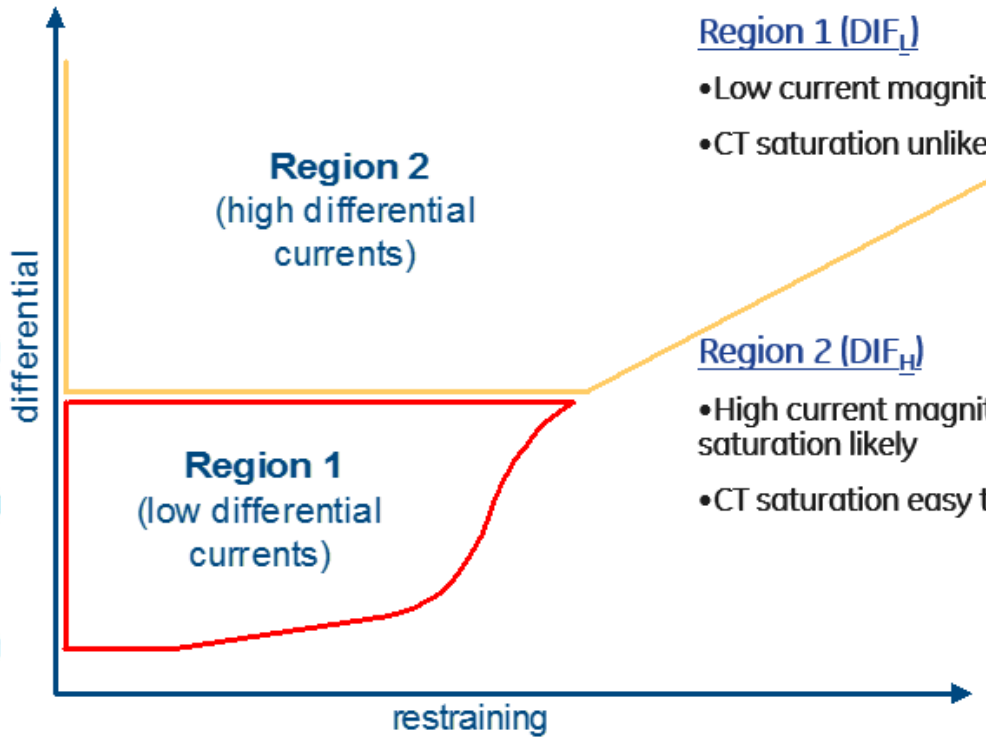


Enhancements to Percentage Differential

- Percentage Differential Enhanced in IEDs for added Sensitivity:



- Two Regions of Percentage Differential



Region 1 (DIF_L)

- Low current magnitudes
- CT saturation unlikely, due to DC offset

Region 2 (DIF_H)

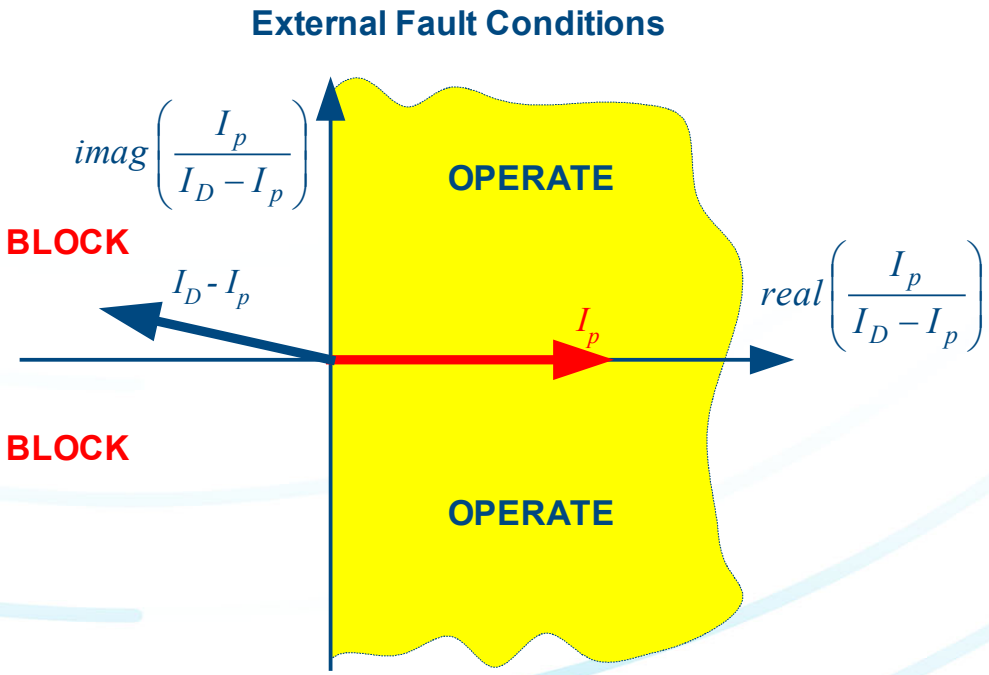
- High current magnitudes ⇒ Quick CT saturation likely
- CT saturation easy to detect

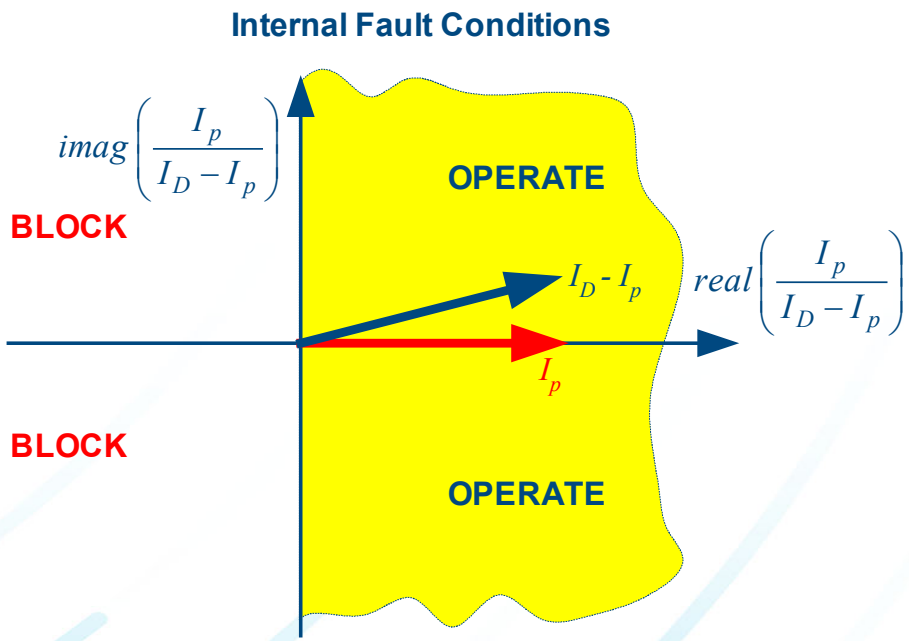
Harmonic Restraint of Percentage Differential

- Percentage Differential still challenged during Transformer Energization
- Multiple event types can cause Inrush/Harmonics:
  1. External Fault
  2. Voltage Recover after Ext Fault
  3. Fault Change eg. PG to PPG
  4. Out-of-phase Gen Synch
  5. CT Saturation during Inrush
  6. Inrush during Fault Removal
  7. Sympathetic Inrush
- Electromechanicals & early IEDs used fixed 20% of 2nd/fundamental magnitude to restrain (block) percentage differential
- Modern Transformers much lower 2nd harmonics (7-10%) – due to improvements
- Improvements to Harmonic Restraint:
  1. Adjustable levels of 2nd Harm
  2. Account for 2nd Harm Phase Angle
  3. 1-of-3, 2-of-3, 3-of-3 Inhibit
  4. 5th Harm Restraint added

Securing Percentage Differential With Dir Chec

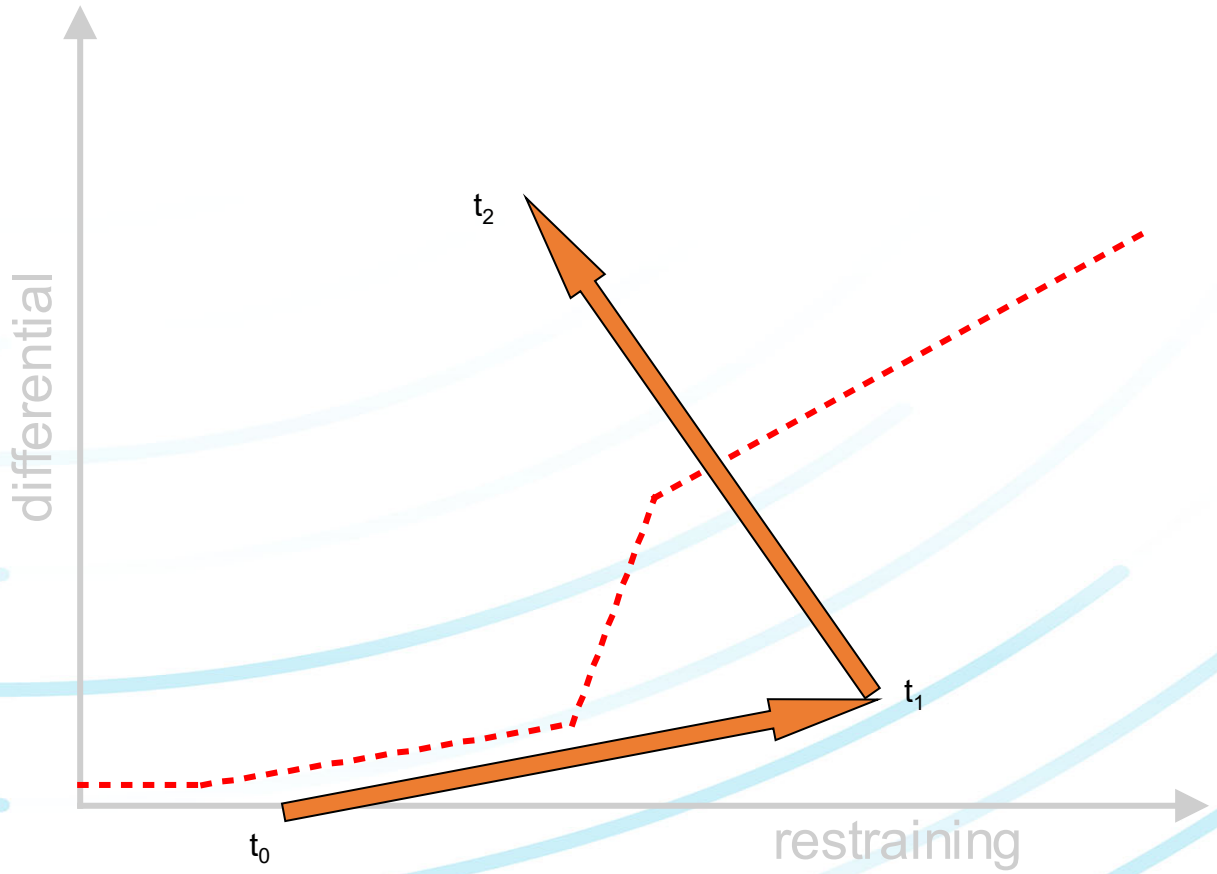
- Directionality Check of Current Phase Angles: (No Voltages Used)





Securing Percentage Differential With CT Satur

- CTs provide typically 2-4 ms unsaturated current
- Fault starts at t_0, CT starts to saturate at t_1, fully saturated at t_2



Settings of Percentage Differential

- Electromechanical relays needed secondary currents to be same phase and magnitude, hence Wye-winding CTs connected in Delta and Aux CTs needed
- All CTs on IEDs Wye-connected; magnitude and phase angle compensated numerically
- Compensated currents calculated based on Magnitude and Phase, eg. for 30deg lag:

$\Phi_{comp}[w]$	Grounding[w] = "Not within zone"	Grounding[w] = "Within zone"
30° lag	$I_A^P[w] = \frac{1}{\sqrt{3}} I_A[w] - \frac{1}{\sqrt{3}} I_C[w]$ $I_B^P[w] = \frac{1}{\sqrt{3}} I_B[w] - \frac{1}{\sqrt{3}} I_A[w]$ $I_C^P[w] = \frac{1}{\sqrt{3}} I_C[w] - \frac{1}{\sqrt{3}} I_B[w]$	$I_A^P[w] = \frac{1}{\sqrt{3}} I_A[w] - \frac{1}{\sqrt{3}} I_C[w]$ $I_B^P[w] = \frac{1}{\sqrt{3}} I_B[w] - \frac{1}{\sqrt{3}} I_A[w]$ $I_C^P[w] = \frac{1}{\sqrt{3}} I_C[w] - \frac{1}{\sqrt{3}} I_B[w]$

- Differential current calculated as: $I_d = \overrightarrow{i_{1(comp)}} + \overrightarrow{i_{2(comp)}}$
- Restraint can be: Sum of, scaled sum of, geometrical average, maximum of
- Most commonly used: "Max Of"

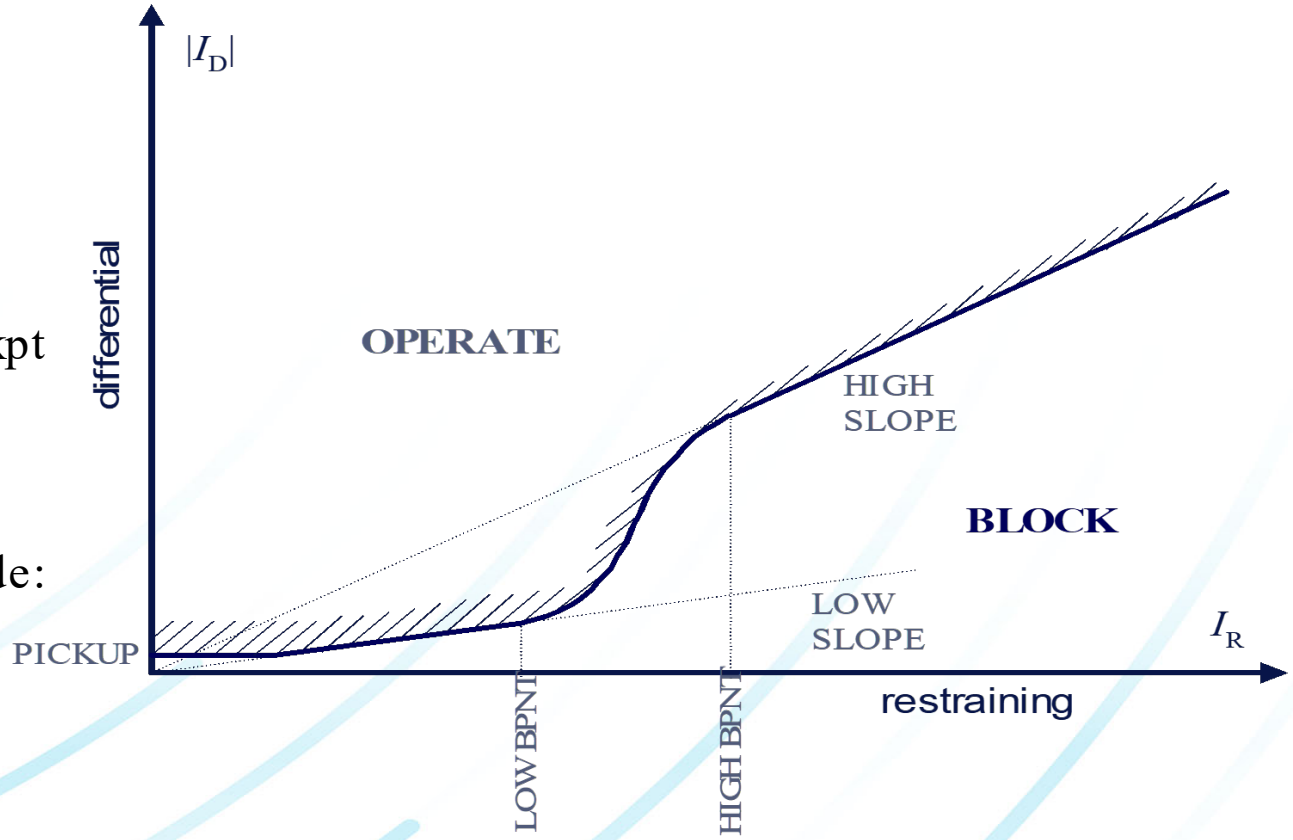
Settings of Percentage Differential (2)

- The Following Setting must be calculated:

- Minimum Pickup
  1. Defines Minimum Differential Pickup at 0 Restraint
  2. Compensates for CT Errors at low currents
  3. Must be above leakage current not zoned

- Low Slope
  1. Defines Percent Bias for Restraint A0 to Low Breakpt
  2. Determines Sensitivity at Low-current Int Faults
  3. Must be above CT errors in Linear Operating Mode
  4. Include errors due to Tap Changers
  5. Based on CT performance in Linear Operating mode:

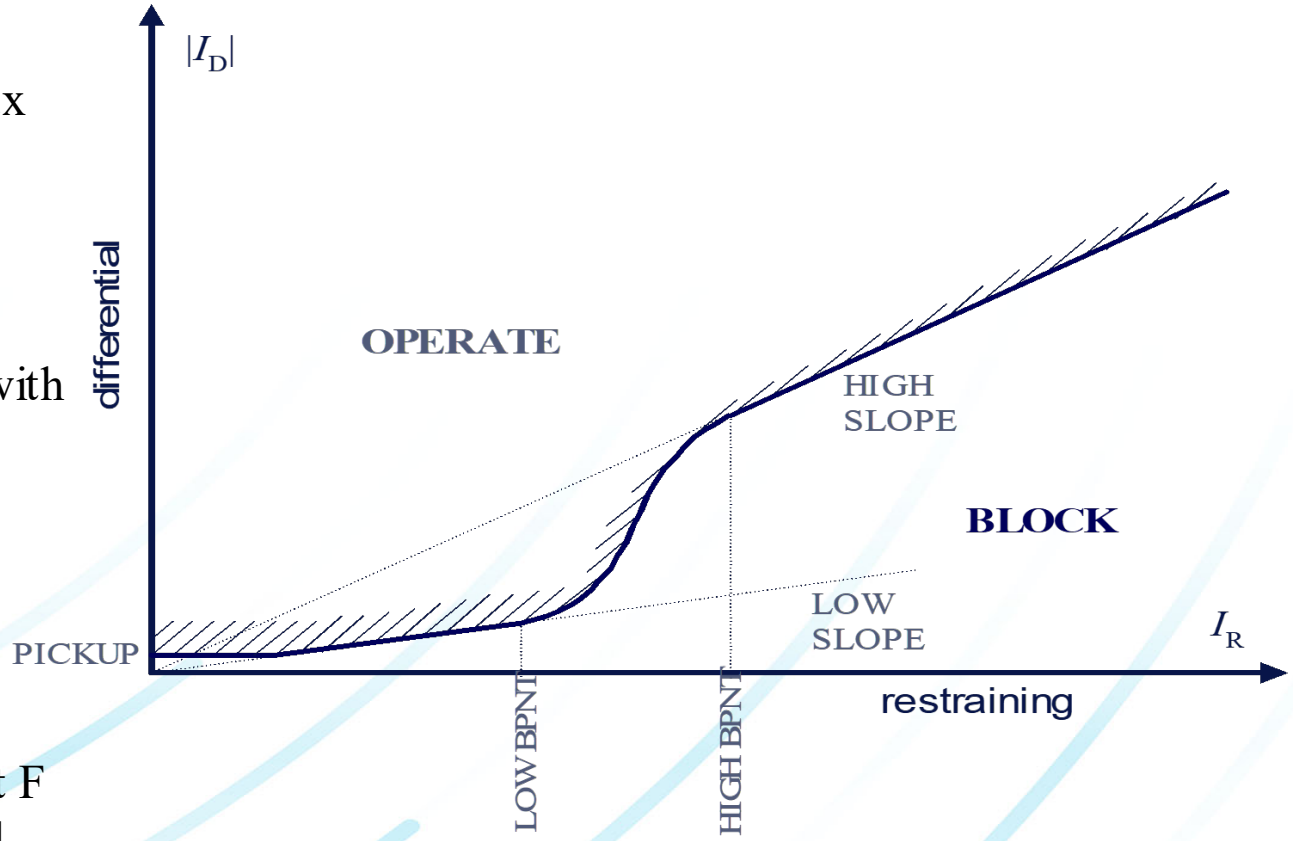
$$\text{Slope} = \frac{\Delta I_d}{\Delta I_r} \times 100\% \ \text{(in pu)}$$



- Maximum Differential Current can be calculated based on CT Performance using IEEE PSRC CT Saturation Calculator

Settings of Percentage Differential (3)

- Low Breakpoint
  1. Defines Upper Limit of Diff/Restraint of Low Slope
  2. Must be above Max Load and all CTs still Linear (including Remanence Flux)
  3. CTs Must be Linear with up to 80% Remanence Flux up to Low Breakpoint
- High Breakpoint
  1. Defines Min Limit of Diff/Restraint of High Slope
  2. Must be Minimum A where weakest CT Saturates with no Remanence Flux
- High Slope
  1. Defines Percent Bias for Restraint A above High Breakpoint
  2. Determines Stability of Diff at High External Faults
  3. Must be high to tolerate Spurious Diff CT Sat on Ext F
  4. Can be relaxed if Dir Check and CT Sat Detect used



- Maximum Differential Current can be calculated based on CT Performance using IEEE PSRC CT Saturation Calculator

Settings of Percentage Differential (4)

- CT Saturation Calculator

CONTENTS
Sheet 1: CALCULATOR (this sheet)
Sheet 2: INSTRUCTIONS
Sheet 4: BACKGROUND

CT Saturation Calculator

Excel Spread Sheet
See IEEE publication C37.110: "IEEE Guide for the Application of CurrentTransformers Used for Protective Relaying Purposes"

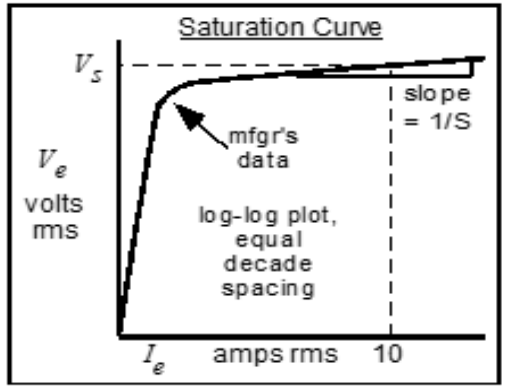
A document of the
IEEE Power Systems Relaying Committee
Contact: gswift@nxtphase.com
Refer also to "CT SAT Theory (PSRC)".

VERSION:
30 Dec 2002

ASSUMPTIONS: CT core losses and sec'y reactance zero (thru-hole primary). Frequency: 60 Hz
CT primary current is zero for t<0. CT is 5 amp nominal Time step = 1/12,000 second.

INPUT PARAMETERS:

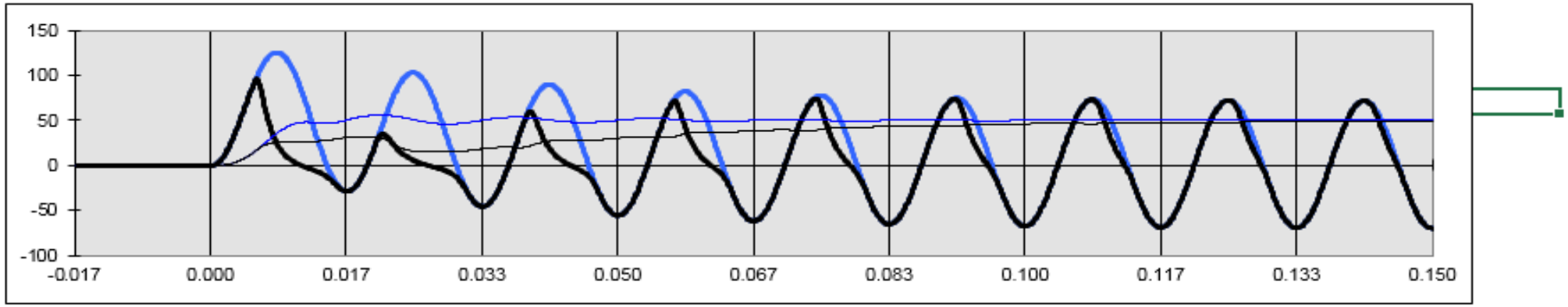
		ENTER:	
Inverse of sat. curve slope =	S =	22	---
RMS voltage at 10A exc. current =	Vs =	400	volts rms
Turns ratio = n2/1=	N =	240	---
Winding resistance =	Rw =	0.000	ohms
Burden resistance =	Rb =	4.000	ohms
Burden reactance =	Xb =	2.000	ohms
System X/R ratio =	XoverR =	12.0	---
Per unit offset in primary current =	Off =	1.00	-1<Off<1
Per unit remanence (based on Vs) =	λrem	0.00	---
Symmetrical primary fault current =	Ip =	12,000	amps rms



CALCULATED:

Rt =	Total burden resistance = Rw + Rb =	4.000	ohms
pf =	Total burden power factor =	0.894	---
Zb =	Total burden impedance =	4.472	ohms
Tau1 =	System time constant =	0.032	seconds
Lamsat =	Peak flux-linkages corresponding to Vs	1.501	Wb-turns
ω =	Radian freq =	376.99	rad/s
RP =	Rms-to-peak ratio =	0.34584	
A =	Coefficient in instantaneous ie versus lambda curve: ie = A * l^S :	3.83E-03	---
dt =	Time step =	0.000083	seconds
Lb =	Burden inductance =	0.00531	henries

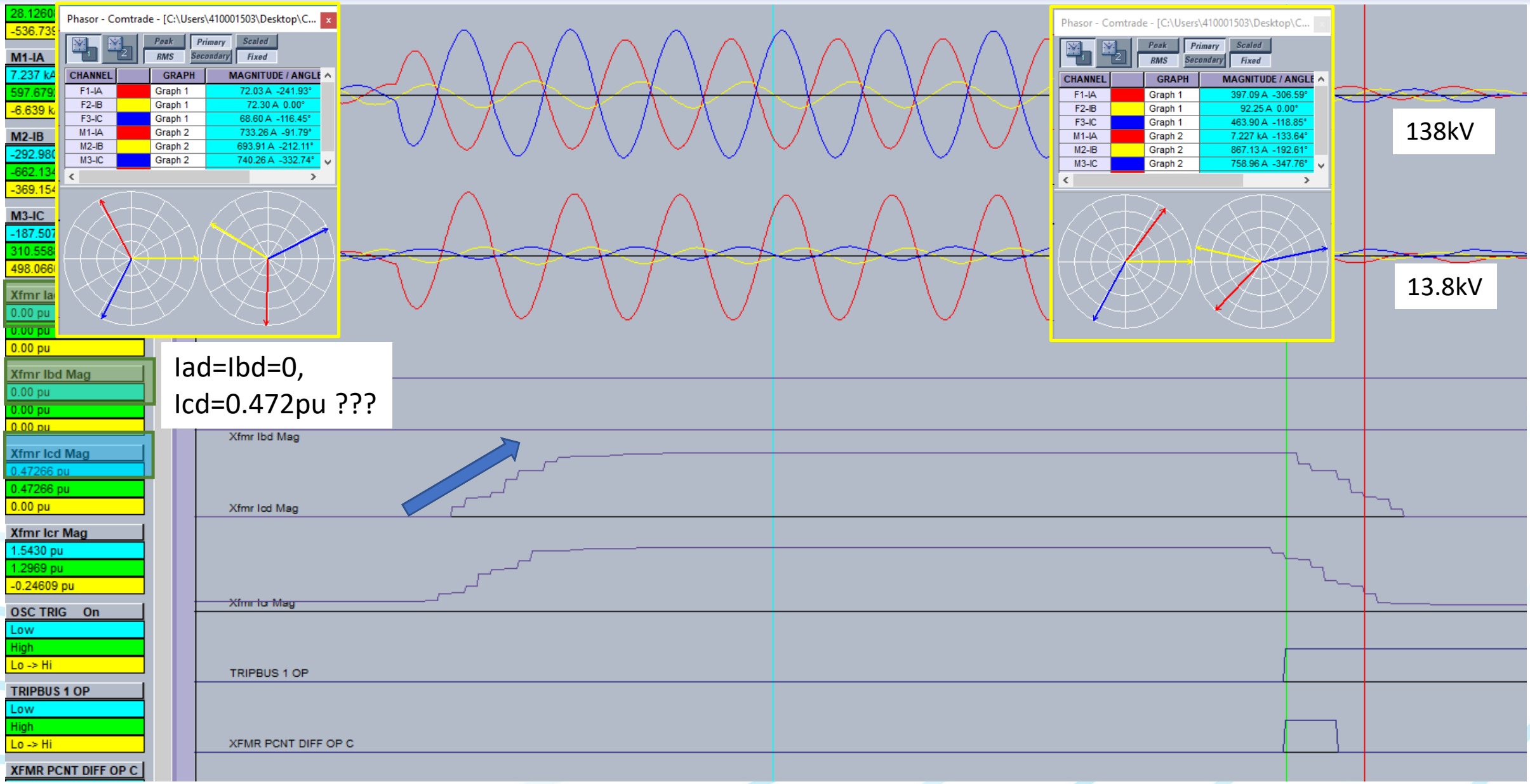
Thick lines: **Ideal (blue)** and **actual (black)** secondary current in amps vs time in seconds.
Thin lines: **Ideal (blue)** and **actual (black)** secondary current extracted fundamental rms value, using a simple DFT with a one-cycle window.



Analysis of 138/13.8kV Diff Incorrect Operation

- Percentage differential operated incorrectly during an external AG fault on the 13.8kV side of the 30MVA, 138kV/13.8kV Dy-1 transformer.
- Differential operation happened in phase C, 140ms into the fault when external fault was cleared and restraint became smaller than differential.
- Other transformer protection relays (OC and B-Protection) did not operate.
- Both windings waveforms looked perfect, however differential current built very rapidly.
- No CT saturation observed
- Directional Check and CT Saturation Detection NOT used
- Why did it happened and what may be wrong?

Introduction



Introduction

TRANSFORMER SETTINGS AND CTs

Nomber of Windings:	2					
	W1	W2				
Rated(MVA)	30	30	150	50	50	50
Nom. (kV)	138	13.8				
Connection	DELTA	WYE				
Grounding	NO	YES				
Angle WRT	0	-30				
CT primary	600	3000				
CT sec. tap	5	5				
Inom. Prim.	125.5	1255.1				
Inom.Sec.	1.046	2.092				
Rotations	ABC	*Select Magnitude Ref. Winding:*				2

DIFF / RSTR CHARACTERISTIC

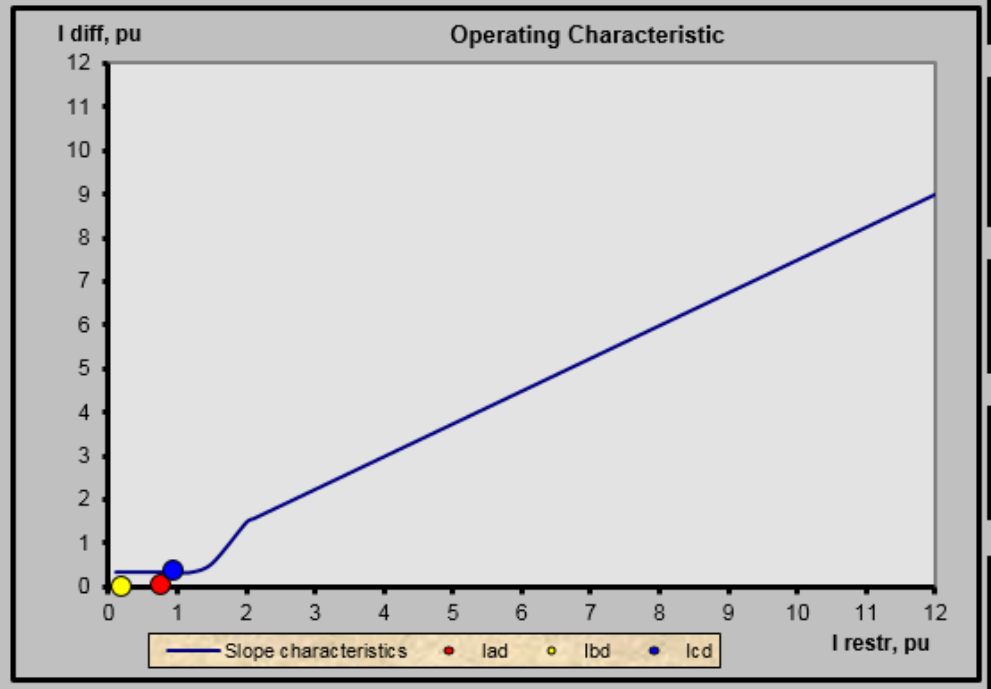
DIFFERENTIAL- RESTRAINT GRAPH			
Diff. min. PKP	0.35	Slope1	25.0
Kneepoint 1	1.30		
Kneepoint 2	2.00	Slope2	75.0

Pre-calculated graph points			
Id/Ir, (%)	Ph A	Ph B	Ph C
	25.0	25.0	25.0

>>Pre-calculated ratio of the point from the characteristic, corresponding to the same restraint as per the actual Id/Ir ratio. The trip occurs, when the actual Id/Ir ratio,(%) is bigger than the pre-calculated Id/Ir ratio, (%)

TEST CURRENTS

	IA	IB	IC
W1			
Magnitude	1.93	0.49	2.39
Angle	-89.0	-150.2	-258.8
W2			
Magnitude	6.70	0.92	0.91
Angle	-277.7	-353.7	-128.5
	4.48	4.48	4.48
	-210.0	-330.0	-90.0
	4.18	4.18	4.18
	-210.0	-330.0	-90.0
	3.47	3.47	3.47
	-150.0	-270.0	-30.0
	4.96	4.96	4.96



ACTUAL VALUES

Magnitude Ref. Winding #:	2

DIFFERENTIAL CURRENTS			
	Iad	Ibd	Icd
Magnitude	0.02	0.00	0.37
Angle	-55.3	-75.8	-194.0

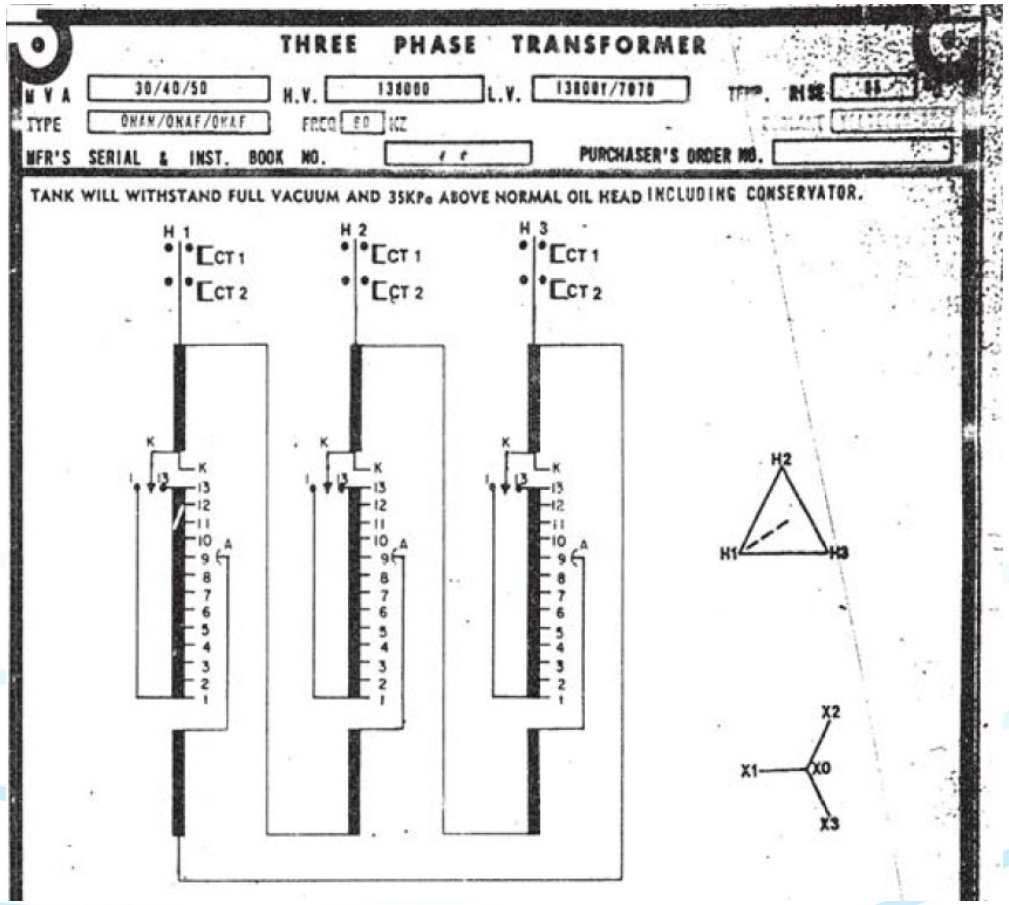
RESTRAINT CURRENTS			
	Iar	Ibr	Icr
Magnitude	0.77	0.20	0.96

Actual Differential/Restraint Ratio			
Actual	ph A %	ph B %	ph C %
Id/Ir ratio	2.7	1.9	38.3

DIFF. OPERATION		
TRIP		
Ia	Ib	Ic
No Trip	No Trip	Trip

Investigation

- Setting error?



Windings // 11_1TR_18-03-20 09-28-17.urs : C:\Users\410001503\Desktop\Cust...

Save | Restore | Default | Reset | VIEW ALL mode

PARAMETER	WINDING 1	WINDING 2
Source	HV (SRC 1)	LV (SRC 2)
Rated MVA	30.000 MVA	30.000 MVA
Nominal Phs-phs Voltage	138.000 kV	13.800 kV
Connection	Delta	Wye
Grounding	Not within zone	Within zone
Angle Wrt Winding 1	0.0 deg	-30.0 deg
Resistance	10.0000 ohms	10.0000 ohms

11_1TR_18-03-20 09-28-17.urs | System Setup: Transformer | Screen ID: 166

Current // 11_1TR_18-03-20 09-28-17.urs : C:\Users\410001503\Desktop\Custo...

Save | Restore | Default | Reset | VIEW ALL mode

PARAMETER	CT F1	CT M1
Phase CT Primary	600 A	3000 A
Phase CT Secondary	5 A	5 A

Doesn't look like…

Investigation

- Relay algorithm error?

Phase	Pre-fault		Fault	
	Delta 138kV	Wye 13.8kV	Delta 138kV	Wye 13.8kV
A	0.600A∠-241.9°	1.222A∠-91.8°	3.309A∠-306.6°	12.045A∠-133.6°
B	0.603A∠0°	1.157A∠-212.1°	0.769A∠-0°	1.445A∠-192.6°
C	0.572A∠-116.5°	1.234A∠-332.7°	3.866A∠-118.9°	1.265A∠-347.8°

We can verify relay response to these phasors. For given transformer group D/Yg-1, compensation currents are calculated:

Delta

$\Phi_{comp}[w]$	Grounding[w] = "Not within zone"
0°	$I_A^P[w] = I_A[w]$ $I_B^P[w] = I_B[w]$ $I_C^P[w] = I_C[w]$

Wye-grounded

330° lag	$I_A^P[w] = \frac{1}{\sqrt{3}} I_A[w] - \frac{1}{\sqrt{3}} I_B[w]$ $I_B^P[w] = \frac{1}{\sqrt{3}} I_B[w] - \frac{1}{\sqrt{3}} I_C[w]$ $I_C^P[w] = \frac{1}{\sqrt{3}} I_C[w] - \frac{1}{\sqrt{3}} I_A[w]$

Investigation

- Relay algorithm error?

$$I_d = m_1 \cdot \begin{bmatrix} IA_{1c} \\ IB_{1c} \\ IC_{1c} \end{bmatrix} + m_2 \cdot \begin{bmatrix} IA_{2c} \\ IB_{2c} \\ IC_{2c} \end{bmatrix}$$

$m_1 = 2$ and $m_2 = 1$ are magnitude compensation factors for each winding

For phase C, where high differential current was observed. <u>Pre-fault</u>:

$$IC_d = 2 \cdot IC_1 + 1 \cdot \left[IA_2 \frac{-1}{\sqrt{3}} + IC_2 \frac{1}{\sqrt{3}} \right] = 2 \cdot 0.572 e^{-j116.5^\circ} + 1 \cdot \left[1.222 e^{-j91.8^\circ} \cdot \frac{-1}{\sqrt{3}} + 1.234 e^{-j332.7^\circ} \cdot \frac{1}{\sqrt{3}} \right]$$
$$= 0.14A \ or \ 0.029pu$$

<u>Fault</u>:

$$IC_d = 2 \cdot IC_1 + 1 \cdot \left[IA_2 \frac{-1}{\sqrt{3}} + IC_2 \frac{1}{\sqrt{3}} \right] = 2 \cdot 3.866 e^{-j118.9^\circ} + 1 \cdot \left[12.045 e^{-j133.6^\circ} \cdot \frac{-1}{\sqrt{3}} + 1.265 e^{-j347.8^\circ} \cdot \frac{1}{\sqrt{3}} \right]$$
$$= 2.374A \ or \ 0.476pu$$

Investigation

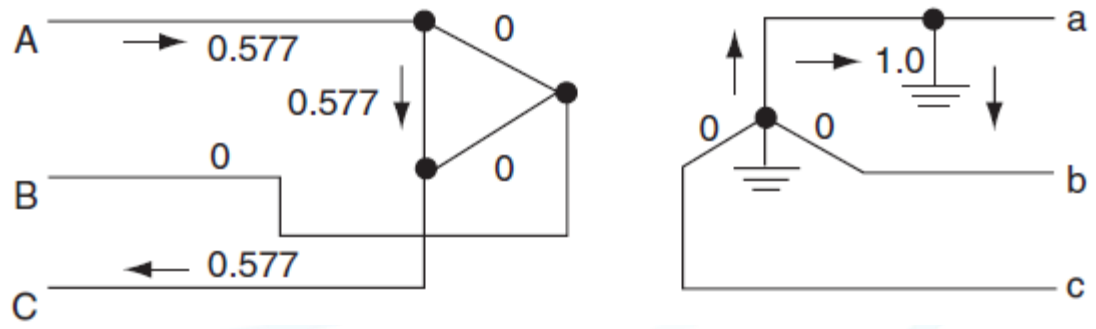
- Time out! Time to think where we are…
- Settings seems correct
- Waveforms look credible (No CT saturation)
- Differential current relay calculated from waveforms and settings seems correct as well.
- Let's dig in…something must be wrong!

$$I_d = m_1 \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} IA_1 \\ IB_1 \\ IC_1 \end{bmatrix} + m_2 \cdot \begin{bmatrix} \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} & 0 \\ 0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} \\ \frac{-1}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} \end{bmatrix} \cdot \begin{bmatrix} IA_2 \\ IB_2 \\ IC_2 \end{bmatrix} = \begin{bmatrix} 0.02pu \\ 0.006pu \\ 0.475pu \end{bmatrix}$$

- Only Differential phase C is high, out of 6 currents, incorrect IC_1 only from delta side can cause high phase C differential without affecting other phases.

Investigation

- Can we prove that delta side IC_1 is erroneous?
- We know that for unloaded transformer (ignoring magnetizing current), delta currents should be 180° apart for P-G fault on Wye.



- If we remove load current and rotate delta side phase A current by 180°, we should get "correct" phase C current.

Investigation

$IC_1' = (IA_{1F} - IA_{1L}) \cdot 1e^{j180°} + IC_{1L} = (3.309e^{-j306.6°} - 0.6e^{-j241.9°}) \cdot 1e^{j180°} + 0.572e^{-j116.5°} = 3.643e^{-j133.6°}$

IC_{1L} is highlighted because as we suspect CT or CT wiring problem, we cannot 100% trust even pre-fault value.

Again differential calculation with assumed delta phase C current fault value

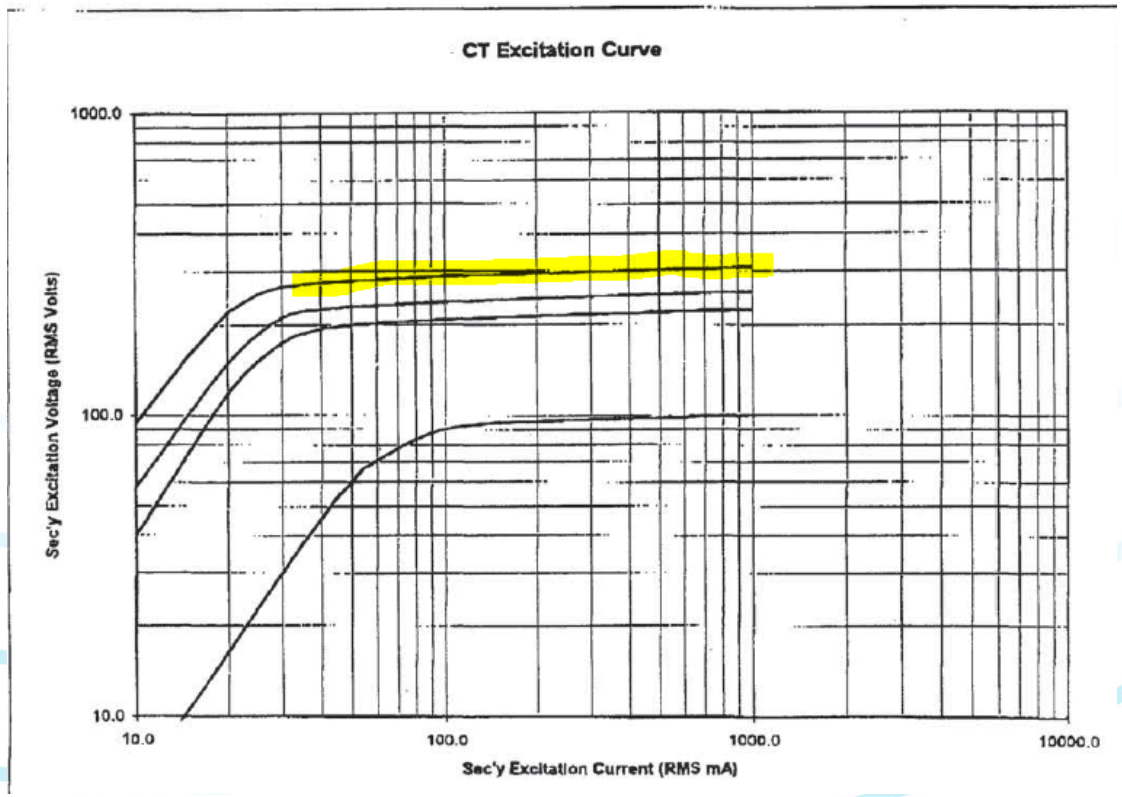
$$IC_d = 2 \cdot IC_1 + 1 \cdot \left[IA_2 \frac{-1}{\sqrt{3}} + IC_2 \frac{1}{\sqrt{3}}\right] = 2 \cdot 3.643e^{-j133.6°} + 1 \cdot \left[12.045e^{-j133.6°} \cdot \frac{-1}{\sqrt{3}} + 1.265e^{-j347.8°} \cdot \frac{1}{\sqrt{3}}\right]$$
$$= 0.496A \text{ or } 0.099pu$$

Investigation

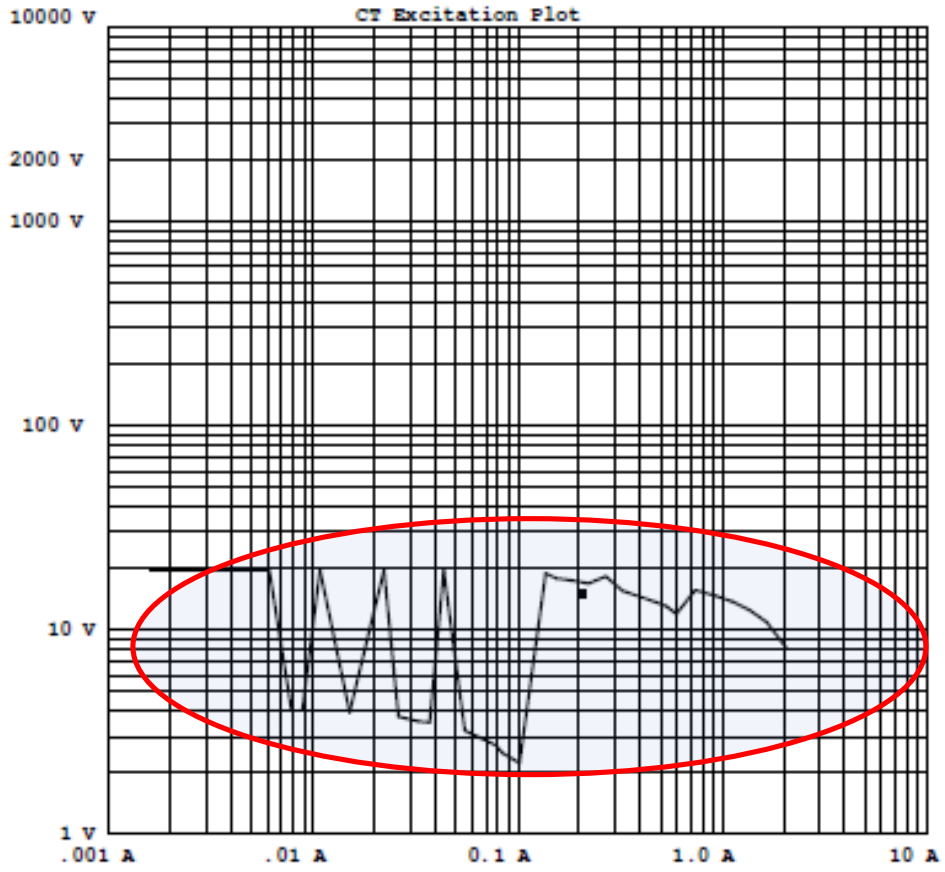
- We proved that differential reduced from 0.476pu to 0.099pu by using assumed IC current derived from healthy IA current.
- Differential is not reduced to zero, because we still use untrusted IC pre-fault value and ignore magnetizing current.
- Now we have reasonable confidence that CT or CT wiring of the C phase is faulty
- CT Testing will reveal will reveal the truth!!!

Testing

Connection	Ratio	Accuracy Metering	Accuracy Relaying	Sec'y Resistance (ohms) @ 75 C
X1-X2	1000-5			
X1-X3	2200-5			
X1-X4	2500-5			
X1-X5	3000-5		C200	0.861



Phase A test



Conclusions

- Percentage Differential is fast, dependable and secure; forms important part of Transformer Protection Scheme
- This function was enhanced with added sensitivity (changes to characteristic) and security (CT saturation detection and Directionality check)
- When investigating suspicious relay operation, don't take anything for granted; consider settings errors, wiring errors, instrument transformers errors and relay h/w or s/w issues.
- Use analytical skills, literature, s/w analytical programs to identify possible causes and prove these possible causes right or wrong.
- Consult with colleagues, equipment manufacturers and Industry Experts.
- Don't rush to blame the relay h/w or s/w, as we learnt from this case, even unlikely, but CT failure can happen as well.

Thank You

Questions?