Demonstration of Laboratory Experiments on Numerical Relays

Experiment 02:
Verification of Percentage biased Differential Relay Characteristic for Transformer Protection

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Transformer Failures- an idea

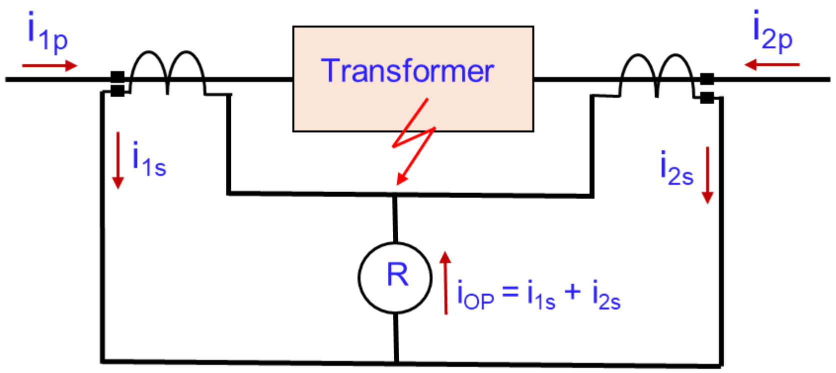
FAILURE REASON	PERCENTAGE
Electrical disturbances	28%
Stress or fatigue	2%
Line disturbance	3%
Moisture	4%
Foreign Objects	4%
Overload	4%
Electrical Connection	6%
Insulation	9%
Lightning	13%
Others	27%

FAILURE IN	Percentage
Winding Failure	40-50 %
Tapchanger	20 – 25 %
Bushing failure	10-15 %
Core failure	1 -3 %
Accessories / Others	10 – 15 %

https://www.engineeringworldchannel.com/transformer-failure/

Verification of Percentage biased Differential Relay Characteristic for Transformer Protection

- Objective
- Circuit diagram – 3 phase transformer
- Theory
- Relay Settings
- Observations and Verification



Internal Fault condition

Verification of Percentage biased Differential Relay Characteristic for Transformer Protection

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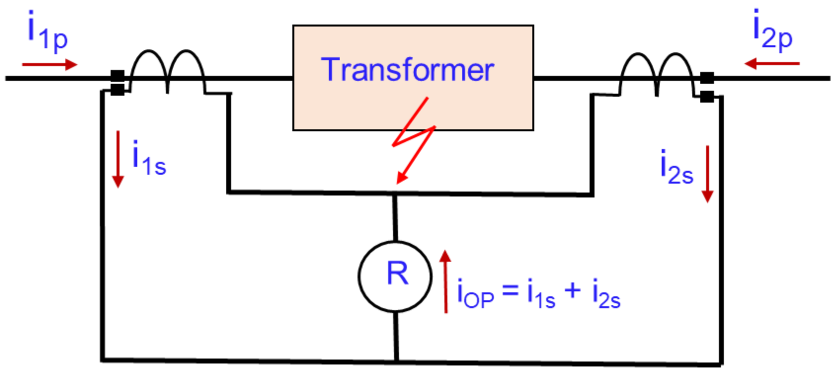


Internal Fault condition

Objective:

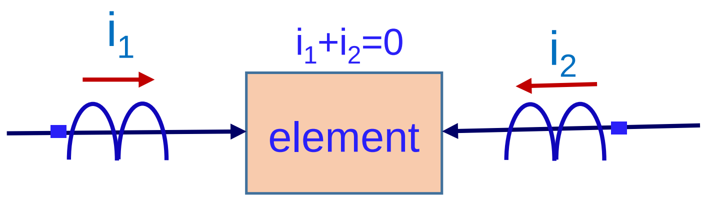
Verification of percentage biased differential relay characteristics protecting 3-PhaseTransformer

-Differential Relay- MICOM P634 (Schneider Electric) (87 T)

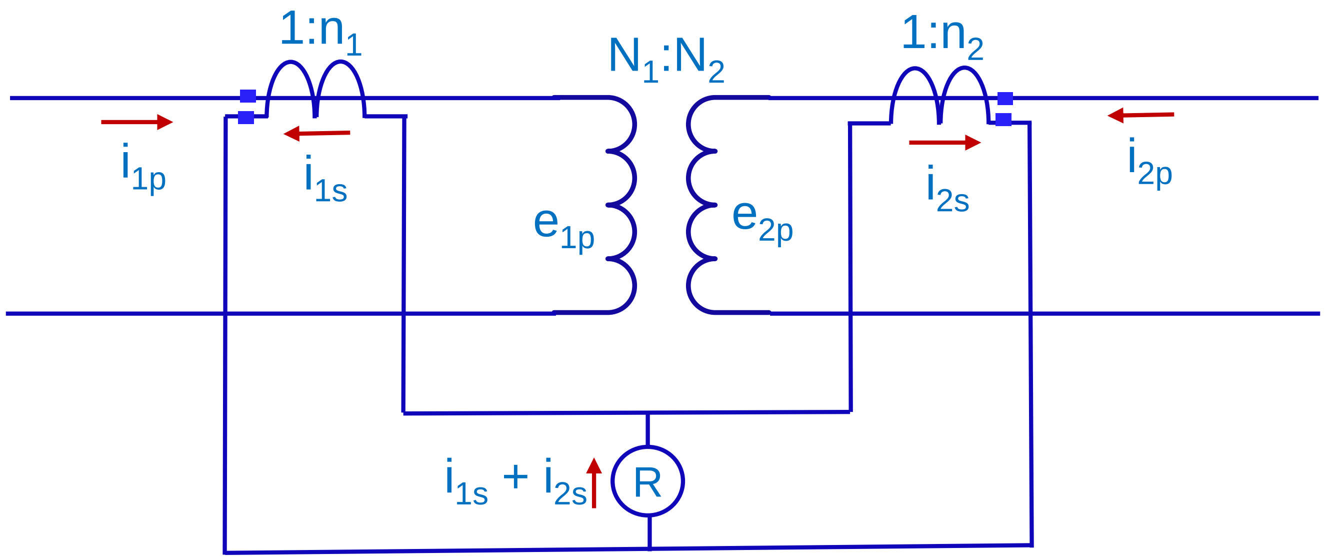
Transformer bank

Theory:

Principle of Transformer Differential Protection



KCL for differential protection principle



1-phase Transformer

Normal situation

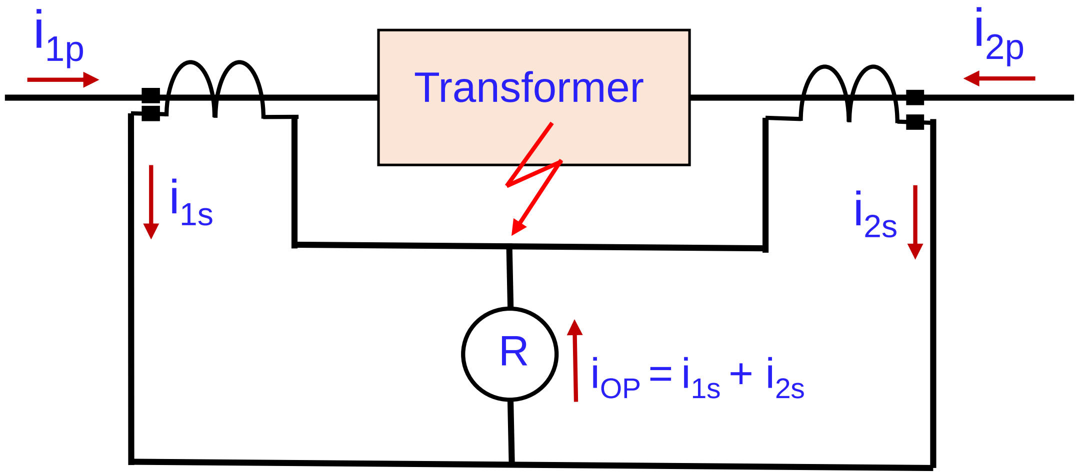
$$N_1 i_{1p} = N_2 i_{2p}$$

$$N_1 n_1 i_{1s} = N_2 n_2 i_{2s}$$

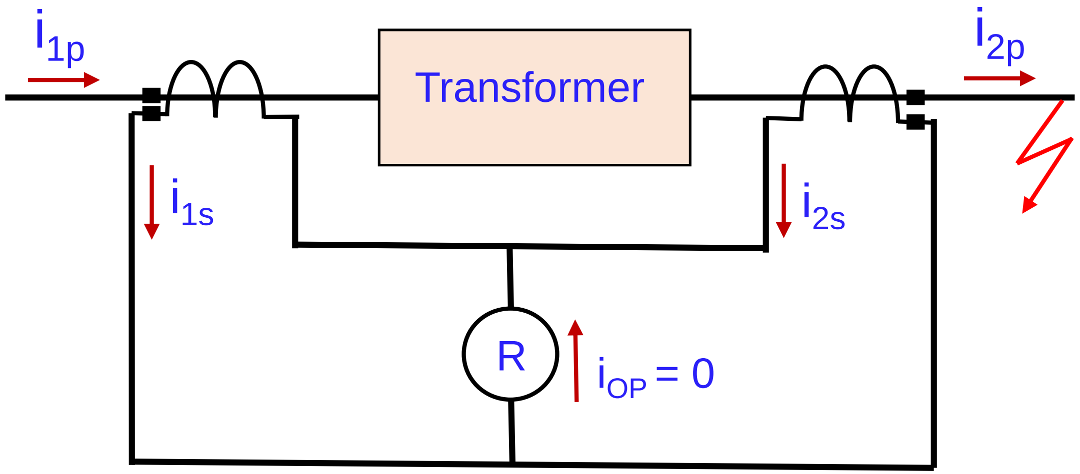
With proper selection of CT we can make $N_1 n_1 = N_2 n_2$

$$i_d = i_{1s} + i_{2s} = 0$$

Differential Protection



Internal Fault condition



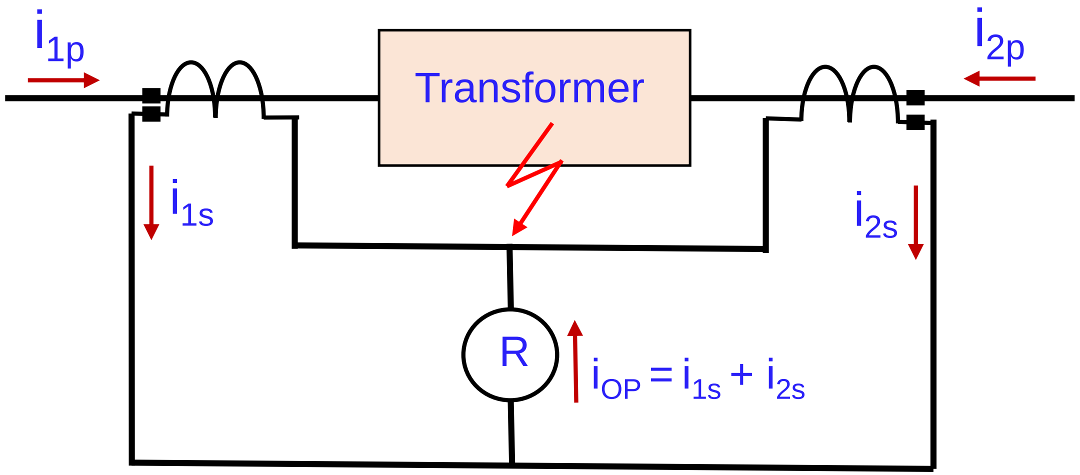
External Fault or Load condition

Now i_{2p} is reversed as compared to internal fault case;
i_{2s} will also be reversed, thus $i_{OP} = i_{1s} + (-i_{2s}) = 0$

- Differential relay operates on the **sum of the currents** entering the protected element= the differential current.
- The differential current (CT secondary) is proportional to the fault current for internal faults, approaches zero for any other operating conditions.

Applying Overcurrent Principle for the Differential Current

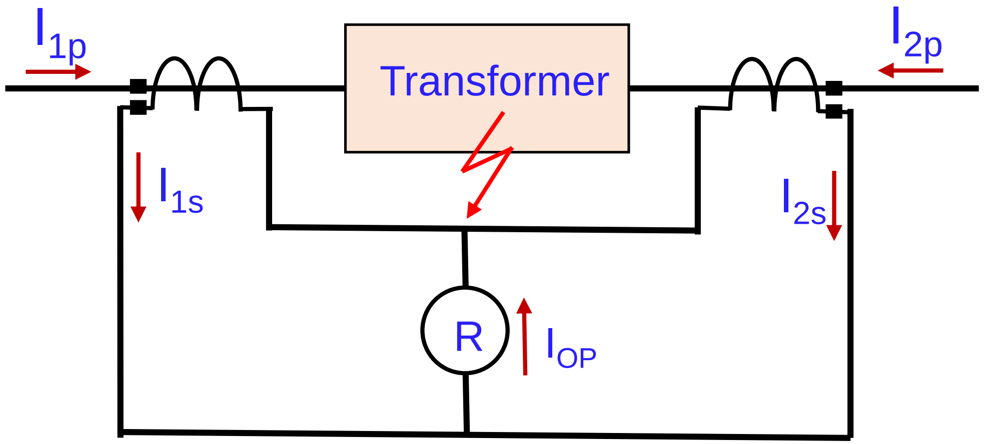
- When relay R with differential current uses Overcurrent principle for decision any spill current (magnetising current etc.) it will maloperate.
    - mismatch errors of CTs or CT-saturation error for external fault or
- To compensate all these errors, overcurrent relays should be set to operate above the anticipated maximum error value. Time delay to override inrush is also necessary.

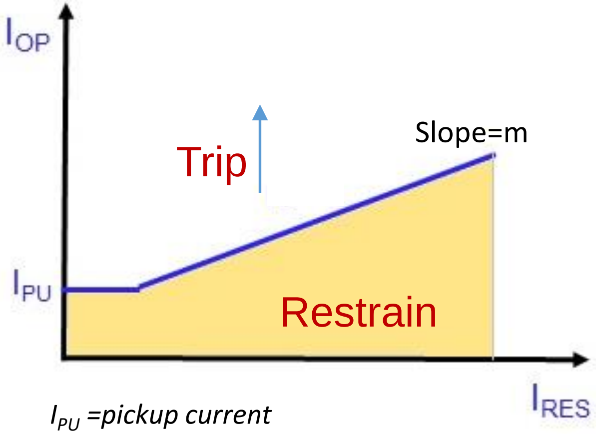


Internal Fault condition

Percentage Biased Differential Protection

- To overcome the drawbacks of applying overcurrent principle in differential relay, percentage biased differential relays are used.
- These relays offer sensitive differential protection at low currents and tolerate larger mismatches at high currents while still tripping for internal faults.





Trip condition:

$$I_{OP} > I_{PU}$$

$$I_{OP} > m\ I_{RES}$$

- I_{OP}: is the differential current, which is the phasor or instantaneous sum of the currents, flowing into the zone of protection. $I_{OP} = |I_{1s} + I_{2s}|$

- I_{RES}: A measure of the current flowing through the zone of protection. This provides the desirable feature of restraining the relay when high levels of current are flowing through the zone.

$$I_{RES} = k|I_{1s} - I_{2s}|$$

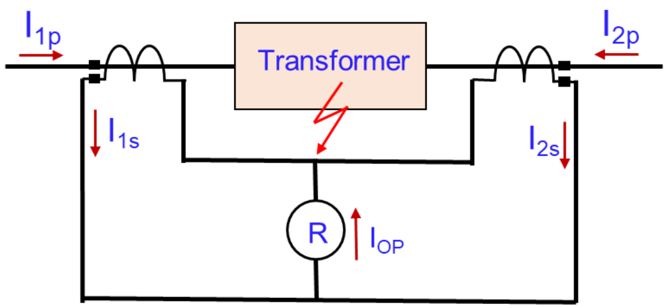
with k =0.5 or 1

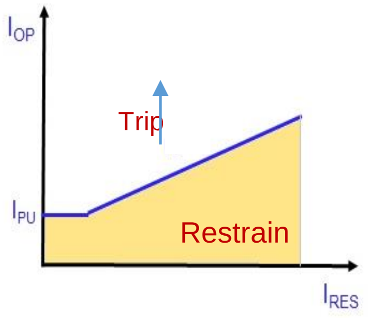
$$I_{RES} = k(|I_{1s}| + |I_{2s}|)$$

$$I_{RES} = Max(|I_{1s}|, |I_{2s}|)$$

- When high currents are present, it is more likely that a CT can saturate and cause false differential current.

- A characteristics require a higher percentage of differential current to operate at higher levels of through current.

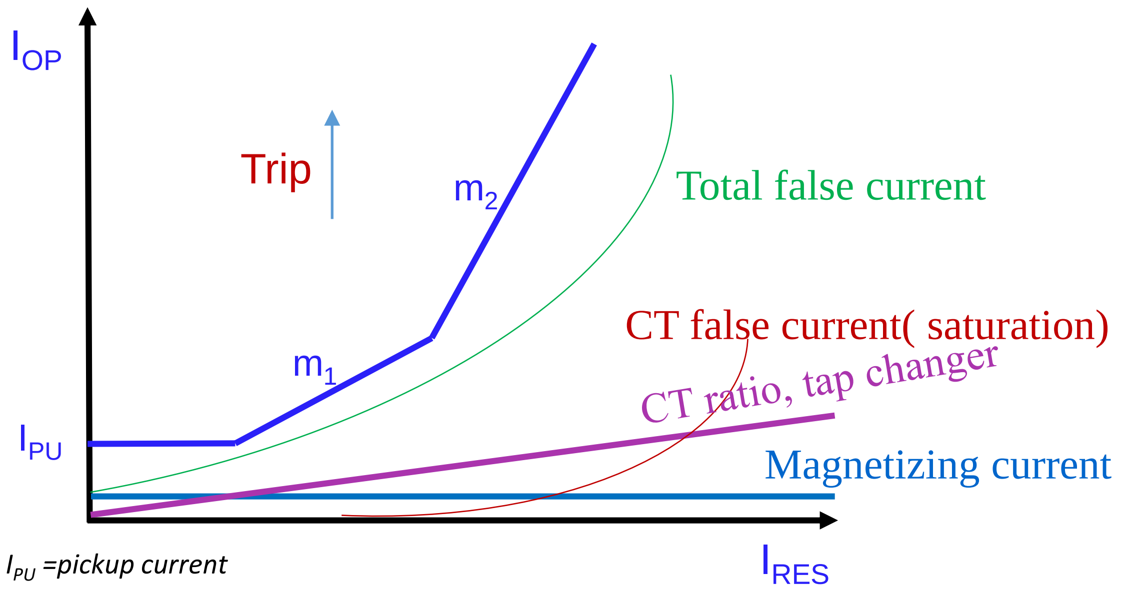




I_{PU} =*pickup current*

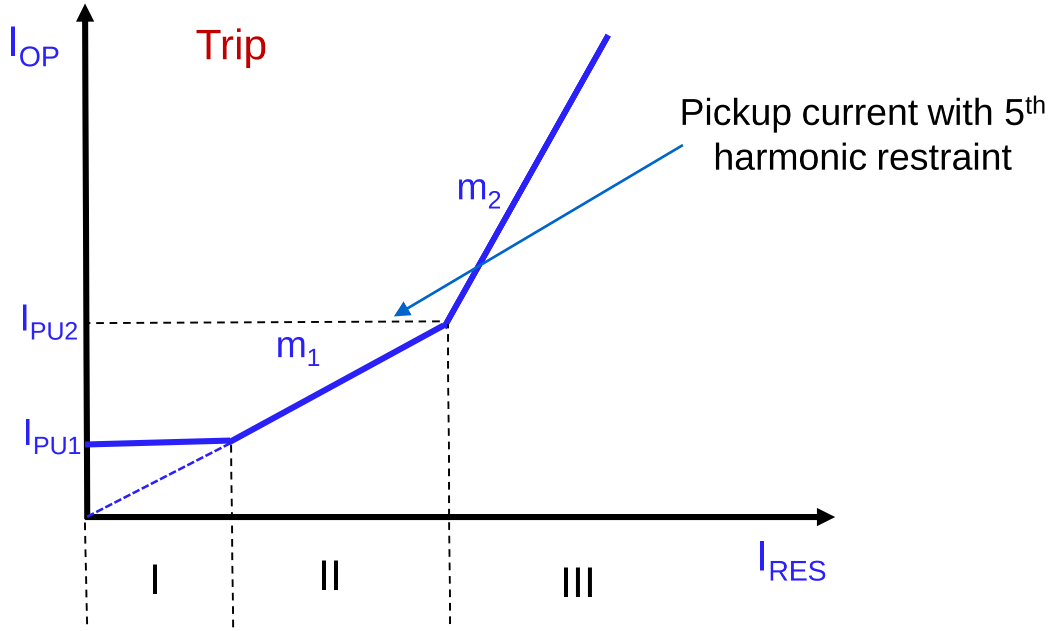
Percentage Biased Differential Relay

- The percentage difference can be fixed or variable, based on the relay design.
- There is also a minimum differential current threshold before tripping even for zero restraint current.
- Settings for minimum pickup, restraint current, and characteristic slope vary among manufacturers.
- Slope may not be a straight line but can be a curve
- This curve allows even larger percentage mismatches during large through-currents.



I_{PU} =pickup current

Setting for Dual slope Percentage Biased Differential Protection



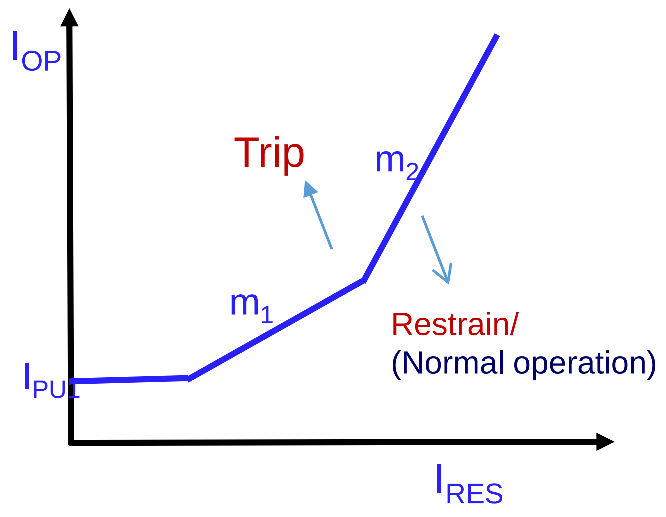
I_{PU} =pickup current

Preparing both side currents for comparison

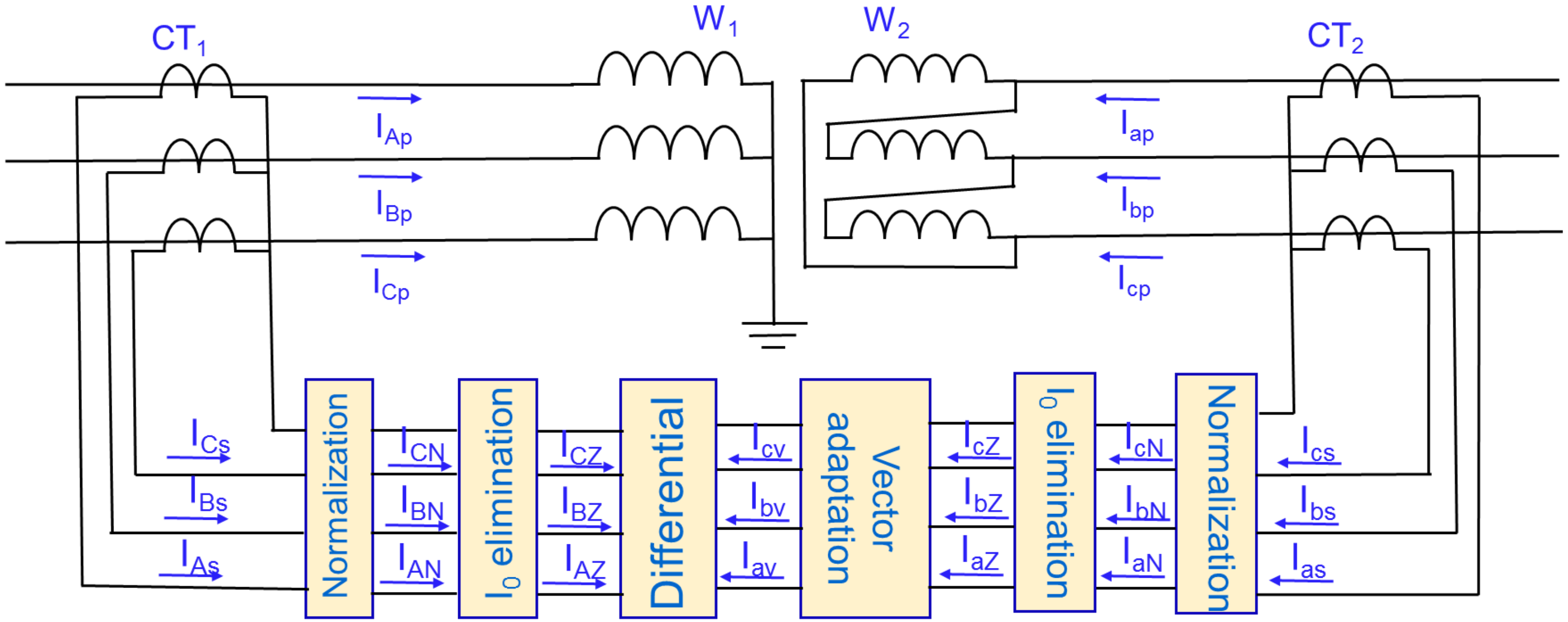
- Normalization of current
- Prior to the current comparison, two adaptations are required:

(i) on the earthed star-point winding side the zero-sequence component must be eliminated

(ii) vector group – the phase angle must be compensated



Steps in Differential Relay processing

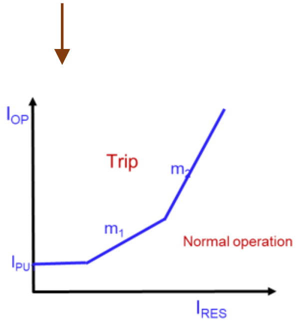


Step-1: Normalization, pu- calculation

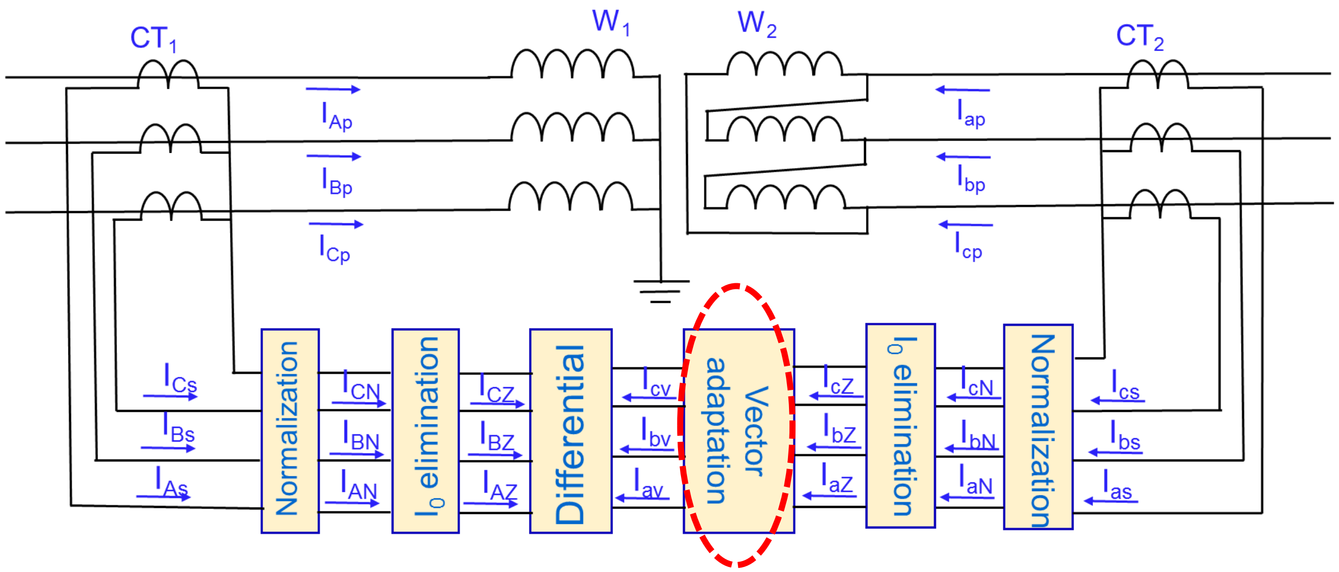
Step-2: I_0-elimination

Step-3: Vector group adaptation

Step-4: Decision applying Differential Protection Principle



Step-3: Vector group adaptation



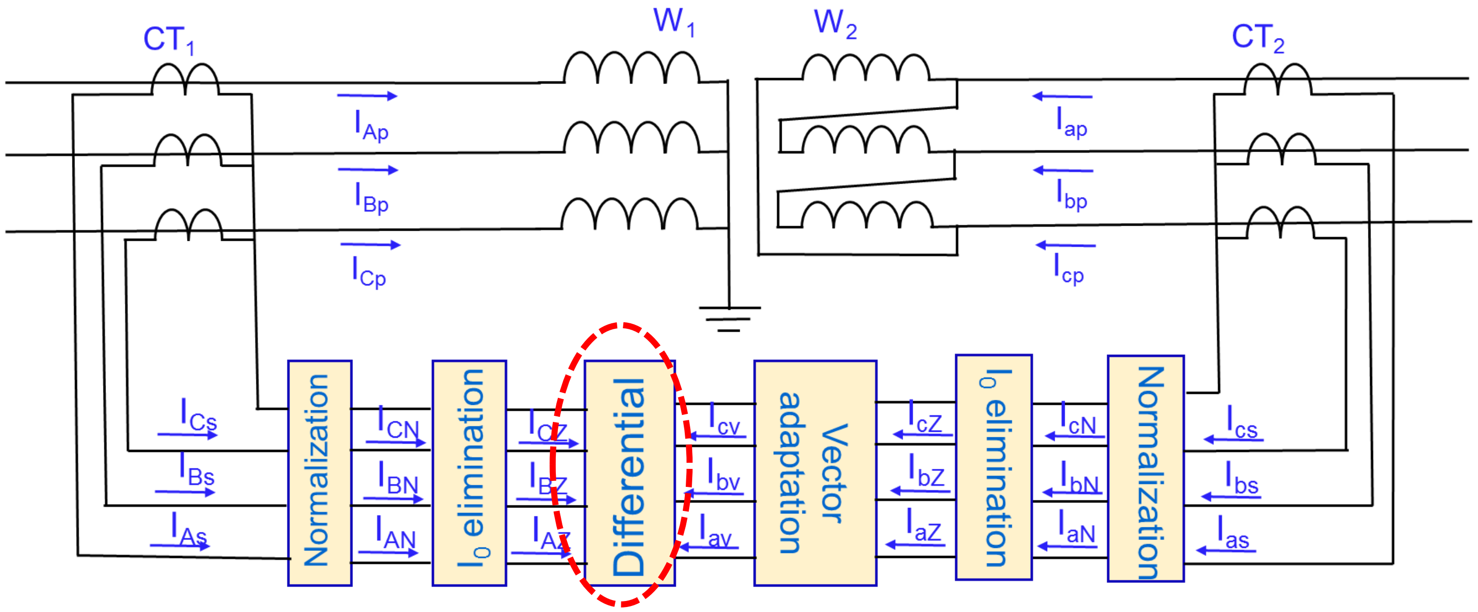
- The high voltage winding is used as the reference for the purpose.
- the low voltage winding lags in accordance with the vector group number (k) in each phase (=k x 30^0)
- Vector adaption is applied in the low voltage winding.
- The adaptation can be determined directly from the connection of the winding.

Say, vector group number is ‘k’ for a transformer then the transformation matrix,

$$\begin{bmatrix} I_{av} \\ I_{bv} \\ I_{cv} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos[k\cdot 30°] & cos[(k+4)\cdot 30°] & cos[(k-4)\cdot 30°] \\ cos[(k-4)\cdot 30°] & cos[k\cdot 30°] & cos[(k+4)\cdot 30°] \\ cos[(k+4)\cdot 30°] & cos[(k-4)\cdot 30°] & cos[k\cdot 30°] \end{bmatrix}\begin{bmatrix} I_{aZ} \\ I_{bZ} \\ I_{cZ} \end{bmatrix}$$

Yd5, implies k=5, similarly Yd1, k=1

Step-4: Decision with Differential Protection Principle



$$\begin{bmatrix} I_{OP\_A} \\ I_{OP\_B} \\ I_{OP\_C} \end{bmatrix} = \begin{bmatrix} I_{AZ} \\ I_{BZ} \\ I_{CZ} \end{bmatrix} + \begin{bmatrix} I_{av} \\ I_{bv} \\ I_{cv} \end{bmatrix}$$

operating current

- This operating current is applied to differential relay for final decision

Example: Internal fault case, ag- type fault, HV side

Prefault

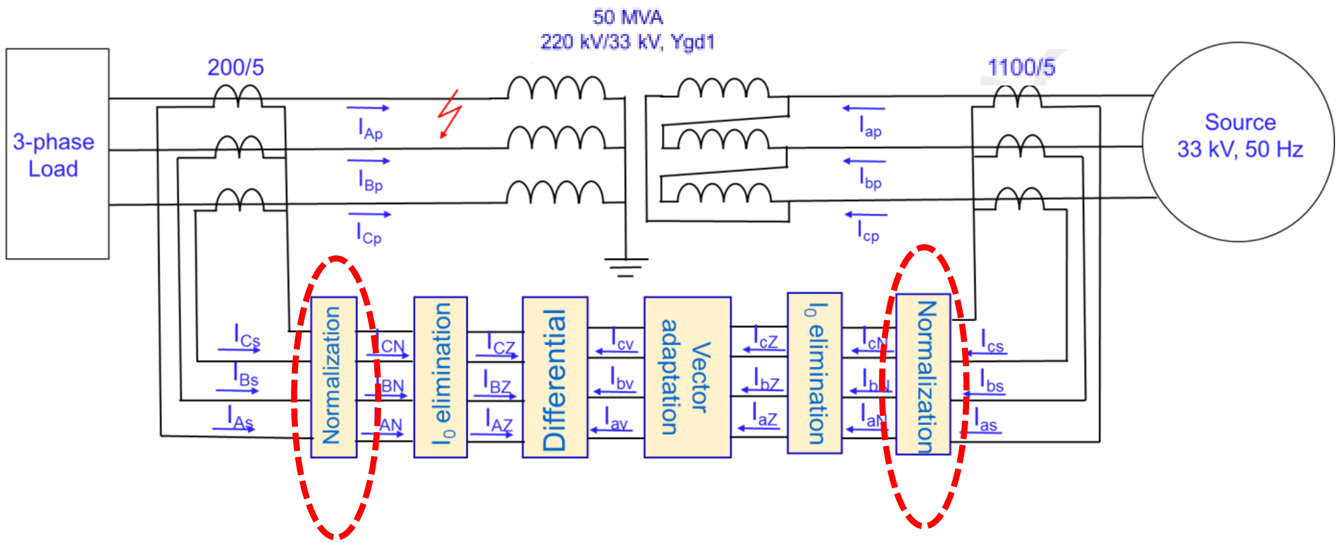
High Voltage side CT secondary Currents
I_{As}: 1.23∠- 2.17⁰ A
I_{Bs}: 1.36∠- 128.92⁰ A
I_{Cs}: 1.16∠108.56⁰ A

Low Voltage side CT secondary Currents
I_{as}: 1.38∠144.17⁰ A
I_{bs}: 1.62∠25.93⁰ A
I_{cs}: 1.55∠-102.62⁰ A

Fault

High Voltage side CT secondary Currents
I_{As}: 0.09∠-166.04⁰ A
I_{Bs}: 1.22∠60.82⁰ A
I_{Cs}: 1.10∠-83.65⁰ A

Low Voltage side CT secondary Currents
I_{as}: 6.35∠-163.48⁰ A
I_{bs}: 5.76∠2.91⁰ A
I_{cs}: 1.55∠77.37⁰ A



$$I_{1rated} = \frac{50}{220 \times \sqrt{3}} \times 1000\ A = 131\ A$$

$$I_{2rated} = \frac{50}{33 \times \sqrt{3}} \times 1000\ A = 875\ A$$

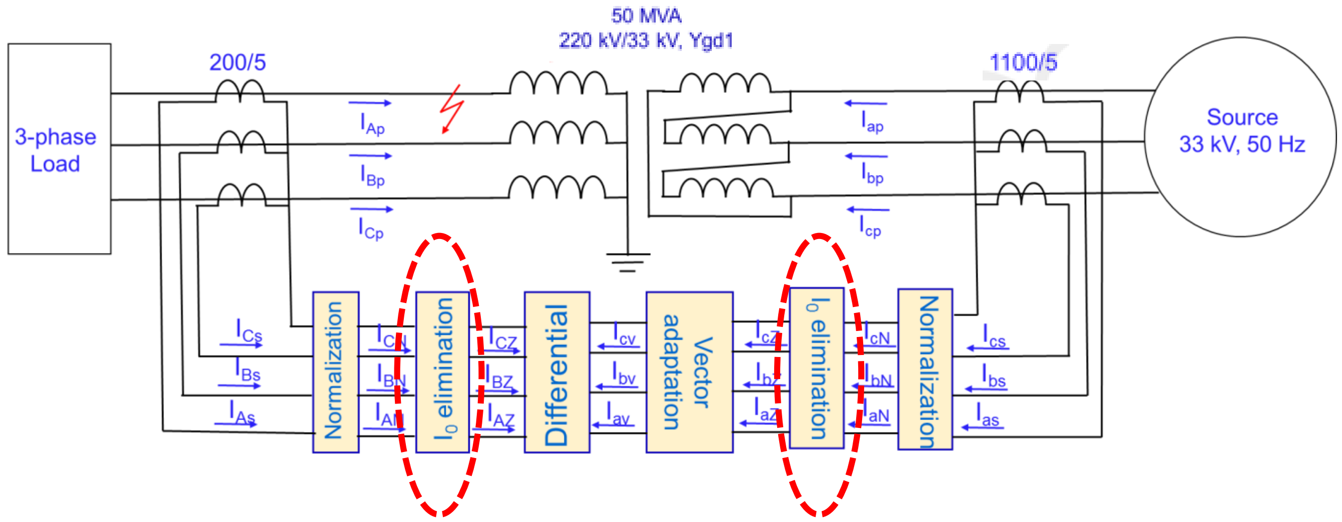
Step-1: Normalization

CTR_1=200/5 = 40 CTR_2=1100/5 = 220

$$\begin{bmatrix} I_{AN} \\ I_{BN} \\ I_{CN} \end{bmatrix} = \frac{CTR_1}{I_{1rated}} \begin{bmatrix} I_{As} \\ I_{Bs} \\ I_{Cs} \end{bmatrix} = \begin{bmatrix} 0.03\angle-166.04° \\ 0.37\angle 60.82° \\ 0.34\angle-83.65° \end{bmatrix} A$$

$$\begin{bmatrix} I_{aN} \\ I_{bN} \\ I_{cN} \end{bmatrix} = \frac{CTR_2}{I_{2rated}} \begin{bmatrix} I_{as} \\ I_{bs} \\ I_{cs} \end{bmatrix} = \begin{bmatrix} 1.60\angle-163.48° \\ 1.45\angle 2.91° \\ 0.39\angle 77.37° \end{bmatrix} A$$

Example: Internal fault case, ag- type fault, HV side

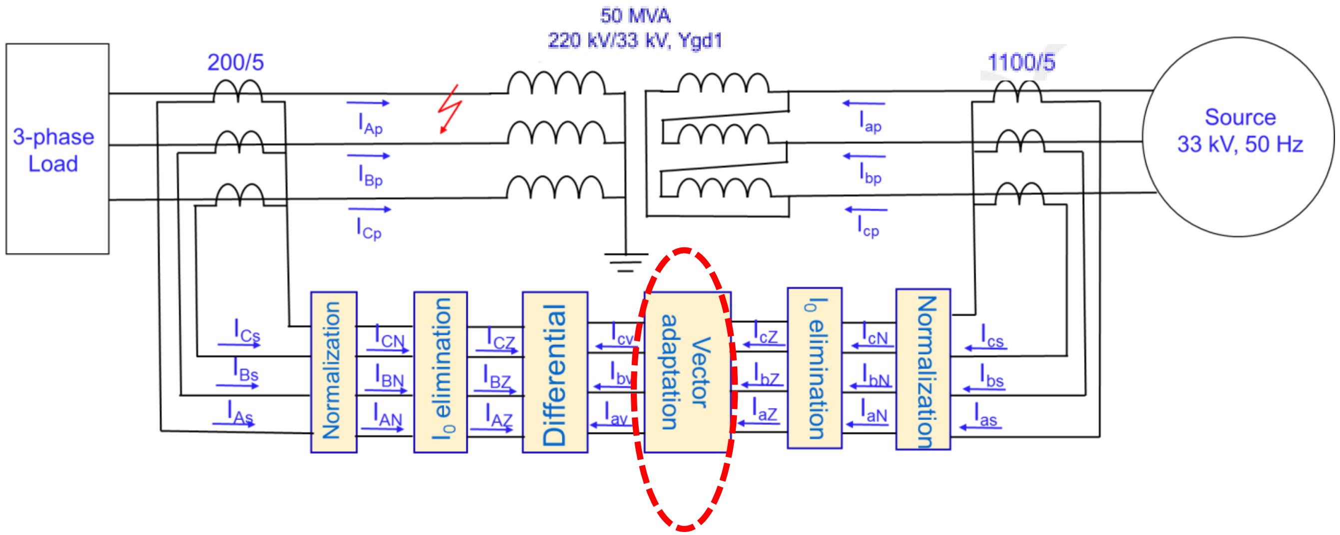


Step-2: I_0 elimination

$$\begin{bmatrix} I_{AZ} \\ I_{BZ} \\ I_{CZ} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} I_{AN} \\ I_{BN} \\ I_{CN} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} 0.03\angle-166.04° \\ 0.37\angle 60.82° \\ 0.34\angle-83.65° \end{bmatrix} = \begin{bmatrix} 0.09\angle-179.08° \\ 0.35\angle 70.39° \\ 0.33\angle-94.61° \end{bmatrix} \text{A}$$

$$\begin{bmatrix} I_{aZ} \\ I_{bZ} \\ I_{cZ} \end{bmatrix} = \begin{bmatrix} I_{aN} \\ I_{bN} \\ I_{cN} \end{bmatrix}$$

Example: Internal fault case, ag-type fault, HV side



Step-3: Vector group adaptation

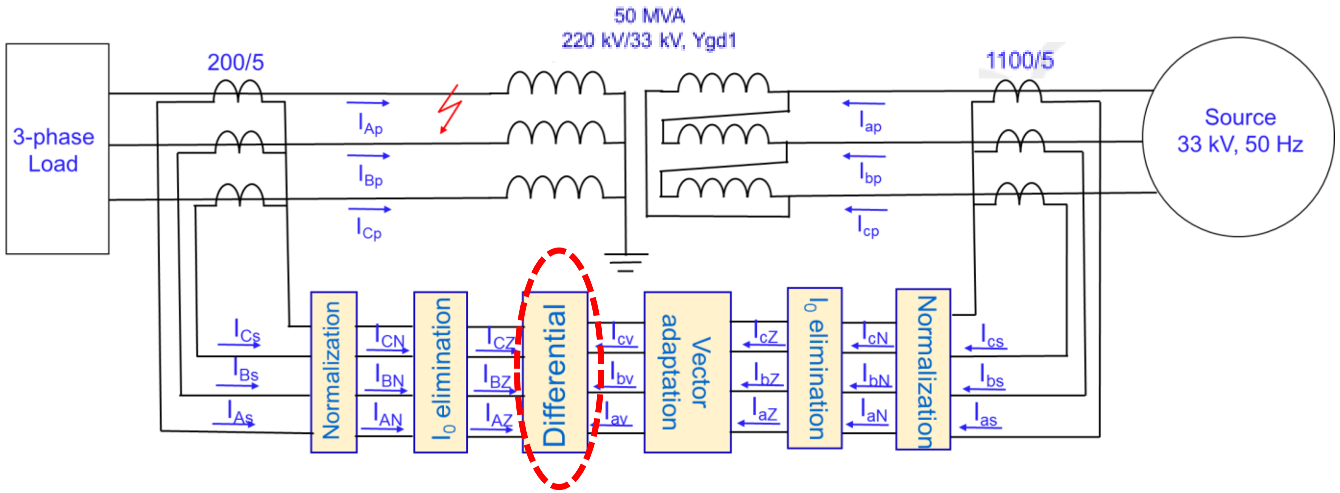
$$\begin{bmatrix} I_{av} \\ I_{bv} \\ I_{cv} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos[k\cdot 30°] & cos[(k+4)\cdot 30°] & cos[(k-4)\cdot 30°] \\ cos[(k-4)\cdot 30°] & cos[k\cdot 30°] & cos[(k+4)\cdot 30°] \\ cos[(k+4)\cdot 30°] & cos[(k-4)\cdot 30°] & cos[k\cdot 30°] \end{bmatrix}\begin{bmatrix} I_{a0} \\ I_{b0} \\ I_{c0} \end{bmatrix}$$

k=1

$$\begin{bmatrix} I_{av} \\ I_{bv} \\ I_{cv} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos[30°] & cos[150°] & cos[-90°] \\ cos[-90°] & cos[30°] & cos[150°] \\ cos[150°] & cos[-90°] & cos[30°] \end{bmatrix}\begin{bmatrix} I_{aZ} \\ I_{bZ} \\ I_{cZ} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sqrt{3}/2 & -\sqrt{3}/2 & 0 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ -\sqrt{3}/2 & 0 & \sqrt{3}/2 \end{bmatrix}\begin{bmatrix} 1.60\angle-163.48° \\ 1.45\angle 2.91° \\ 0.39\angle 77.37° \end{bmatrix}$$

$$= \begin{bmatrix} 1.75\angle-169.95° \\ 0.81\angle-12.71° \\ 1.05\angle 27.31° \end{bmatrix} \text{A}$$

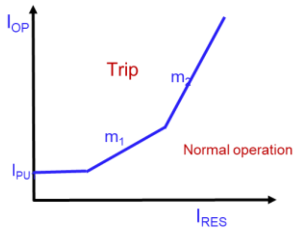
Example: Internal fault case, ag-type fault, HV side



Step-4: Decision using Differential Protection Principle

$$\begin{bmatrix} I_{OP\_A} \\ I_{OP\_B} \\ I_{OP\_C} \end{bmatrix} = \begin{bmatrix} I_{AZ} \\ I_{BZ} \\ I_{CZ} \end{bmatrix} + \begin{bmatrix} I_{av} \\ I_{bv} \\ I_{cv} \end{bmatrix} = \begin{bmatrix} 0.09\angle-179.08° \\ 0.35\angle70.39° \\ 0.33\angle-94.61° \end{bmatrix} + \begin{bmatrix} 1.75\angle-169.95° \\ 0.81\angle-12.71° \\ 1.05\angle27.31° \end{bmatrix} = \begin{bmatrix} \mathbf{1.84}\angle-170.40° \\ \mathbf{0.92}\angle9.60° \\ \mathbf{0.92}\angle9.60° \end{bmatrix}$$

operating current



$I_{RES\_A}=0.5|(I_{AZ}-I_{av})|= 0.83$ A

$m_1=0.2, m_2=0.5$

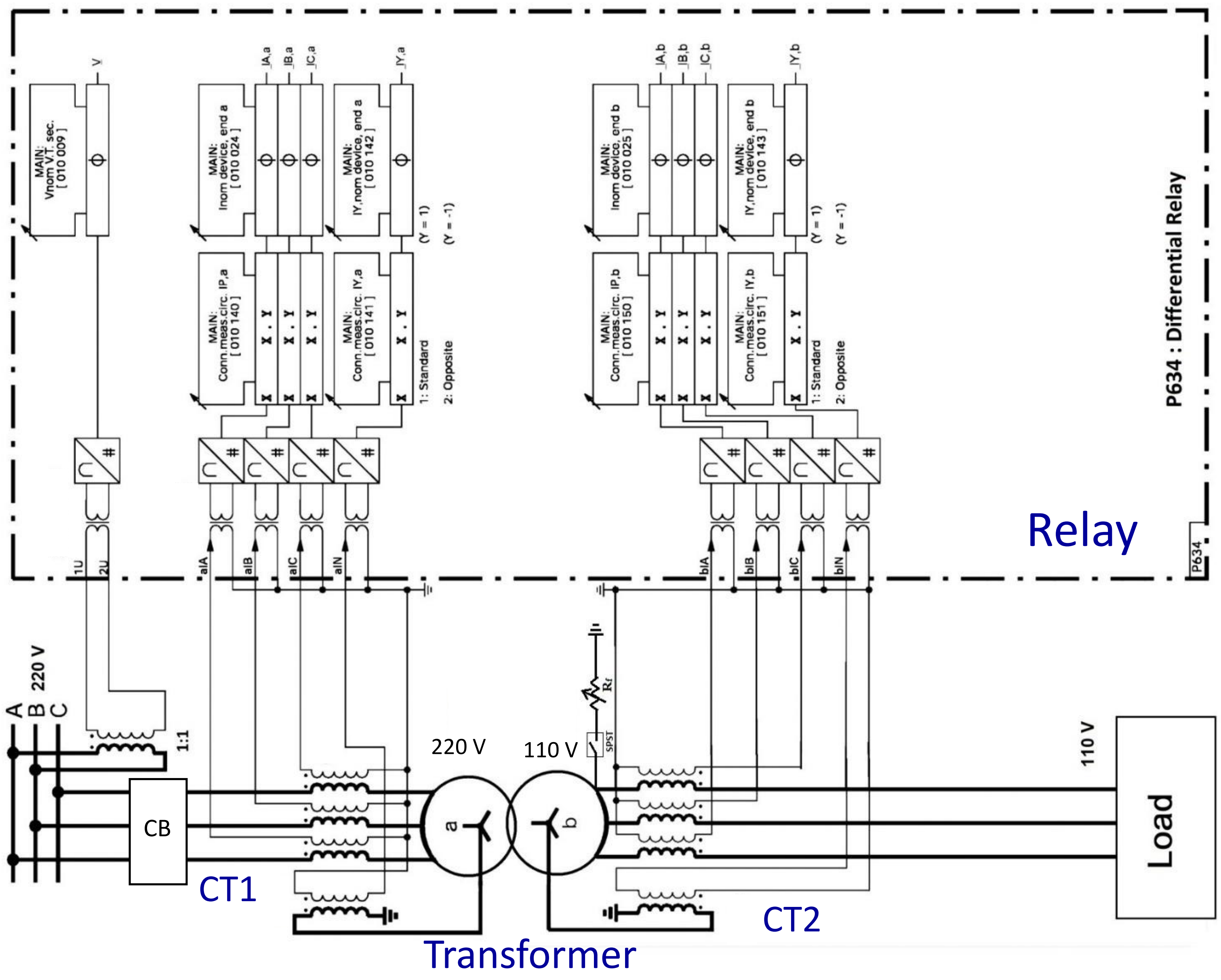
$I_{pu}=0.2$ A

$I_{OP\_A} > I_{pu}$, $I_{OP_A}>(0.2x0.83)=0.17$A

$I_{OP_A}=1.84$A

an internal fault case

Circuit Diagram:



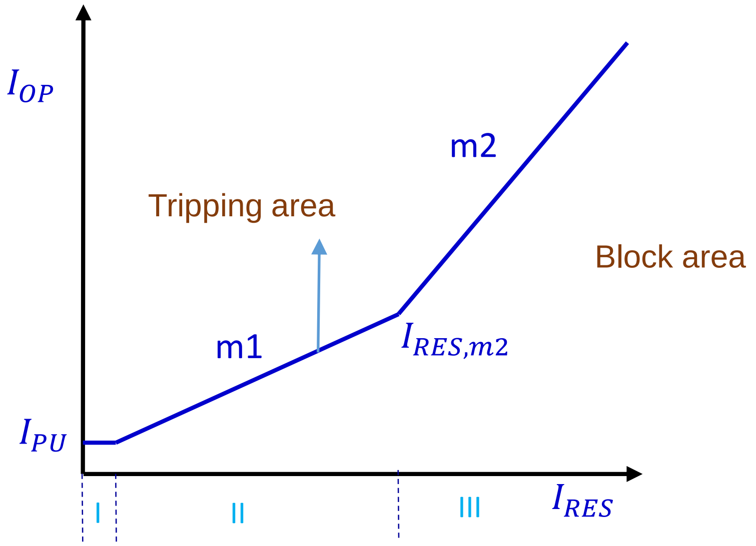
Settings

Settings	
Base Power	47.7 MVA
Base Voltage (HV)	220 kV
I (reference) HV	125 A
I (reference) LV	250 A
PT ratio (HV)	220kV/110V
PT ratio (LV)	110kV/110V
CT Ratio (HV)	2000/5
CT Ratio (LV)	1700/5
CT Ratio (HV) Neutral	2000/5
CT Ratio (LV) Neutral	1700/5

Relay Settings

$$I_{ref,HV} = \frac{S_{ref}}{\sqrt{3}V_{nom,HV}}$$

$$I_{ref,LV} = \frac{S_{ref}}{\sqrt{3}V_{nom,LV}}$$



For each phase

$$I_{OP} = |I_{HV} + I_{LV}|$$

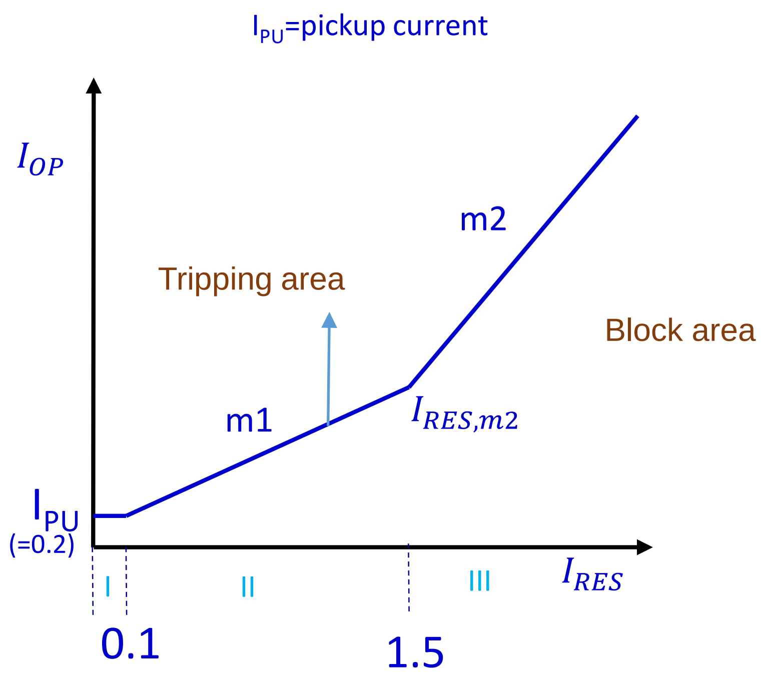
$$I_{RES} = 0.5|I_{HV} - I_{LV}|$$

$$I_{ref,HV} = \frac{S_{ref}}{\sqrt{3}V_{nom,HV}} = \frac{47.7 \times 10^6}{\sqrt{3} \times 220 \times 10^3} = 125A$$

$$I_{ref,LV} = \frac{S_{ref}}{\sqrt{3}V_{nom,LV}} = \frac{47.7 \times 10^6}{\sqrt{3} \times 110 \times 10^3} = 250A$$

Reference characteristic for the differential relay experiment

- Use following information to obtain the reference characteristics for different cases



Trip condition:

$I_{OP} > I_{PU}$ for the range $0 \leq I_{RES} \leq 0.1$

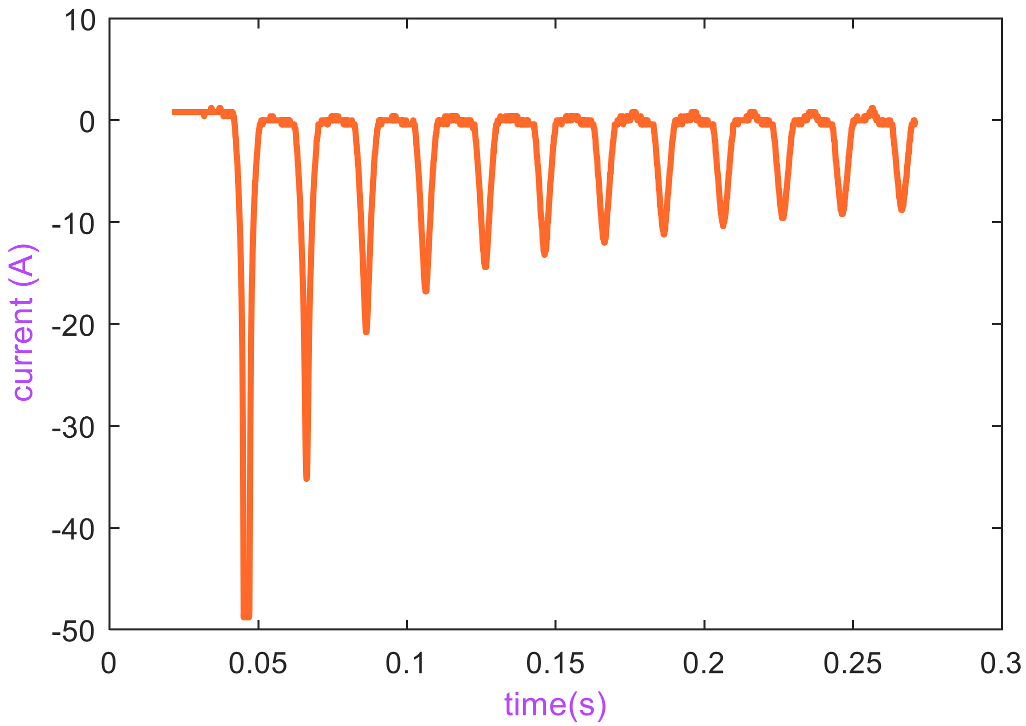
$I_{OP} > m_1 I_{RES}$ for the range $0.1 < I_{RES} \leq 1.5$

$I_{OP} > m_2 I_{RES}$ for the range $I_{RES} > 1.5$

Reference:

https://rza.by/upload/iblock/bce/P634_EN_M_R-21-A__310_651.pdf Page no: 3-132

Inrush waveform in one phase

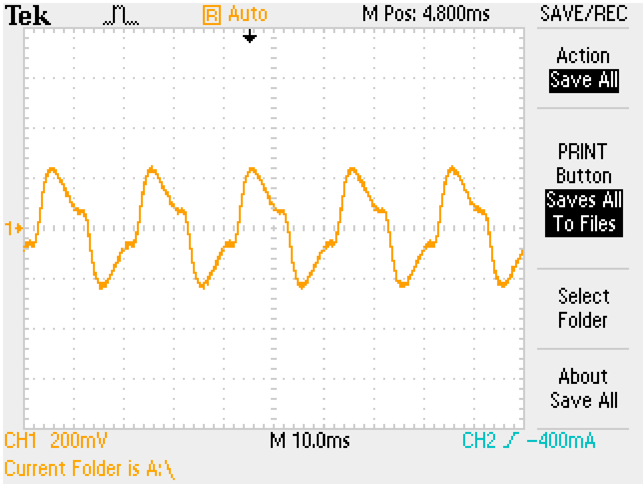


FFT analysis

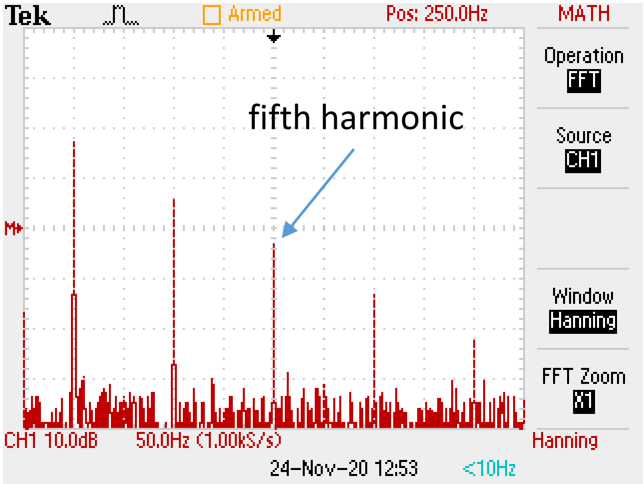
Harmonic order	% of fundamental
2nd	75%
4th	28%
5th	18%

switching on the bank of three 1 kVA transformer 220 V/110V, 50 Hz

Overfluxing –shows high fifth harmonic



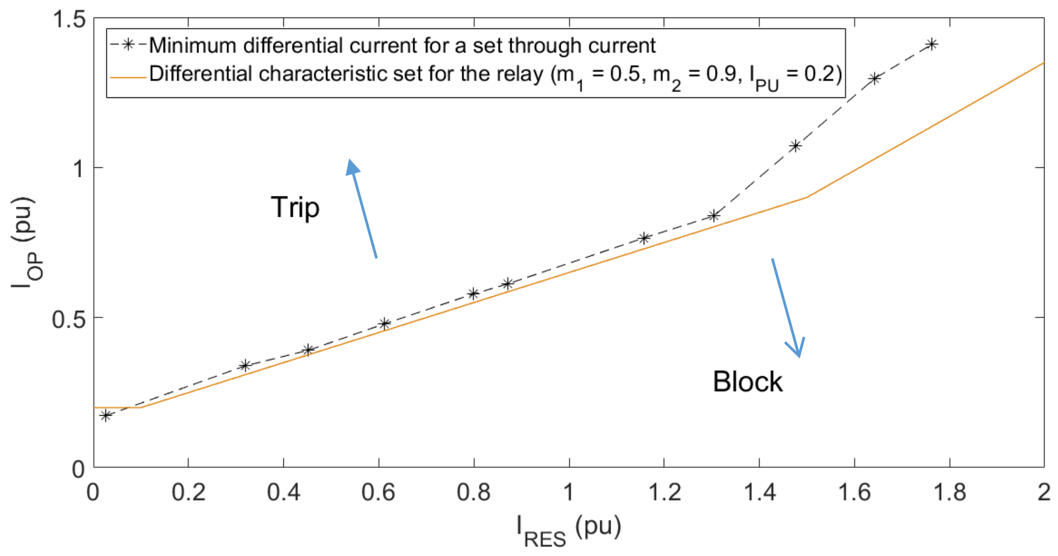
Current signal in one phase



FFT of the signal

Test Case 1:

Settings: m1=0.5, m2=0.9, I_{PU} = 0.2



Measurements Transformer		Observed Relay data	
Load current (A)	Fault current (A)	Restraining current (pu)	Differential current (pu)
0.2	1.213	0.026	0.173
2.4	1.568	0.319	0.339
3.4	1.877	0.452	0.391
4.5	2.03	0.612	0.479
5.8	2.389	0.798	0.578
6.5	2.419	0.871	0.612
8.4	3.126	1.157	0.765
9.5	3.442	1.304	0.838
10.8	4.823	1.477	1.071
12	6.416	1.643	1.297
12.8	7.351	1.763	1.41

Differential and restraining current as in the relay:

$$I_{ref,HV} = \frac{S_{ref}}{\sqrt{3}V_{nom,HV}} = \frac{47.7 \times 10^6}{\sqrt{3} \times 220 \times 10^3} = 125A$$

$$I_{ref,LV} = \frac{S_{ref}}{\sqrt{3}V_{nom,LV}} = \frac{47.7 \times 10^6}{\sqrt{3} \times 110 \times 10^3} = 250A$$

Measurement for one instant during internal fault

HV side phase-a current

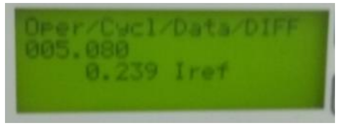
005.021	MAIN	Current IA,a prim.	60 A

LV side phase-a current

005.022	MAIN	Current IA,b prim.	60 A

Operating current:

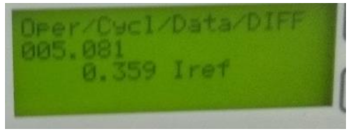
$$I_{OP} = \left(\frac{60}{125}\right)_{HV} - \left(\frac{60}{250}\right)_{LV} = 0.24\ A$$



As seen in the relay screen

Restraining current:

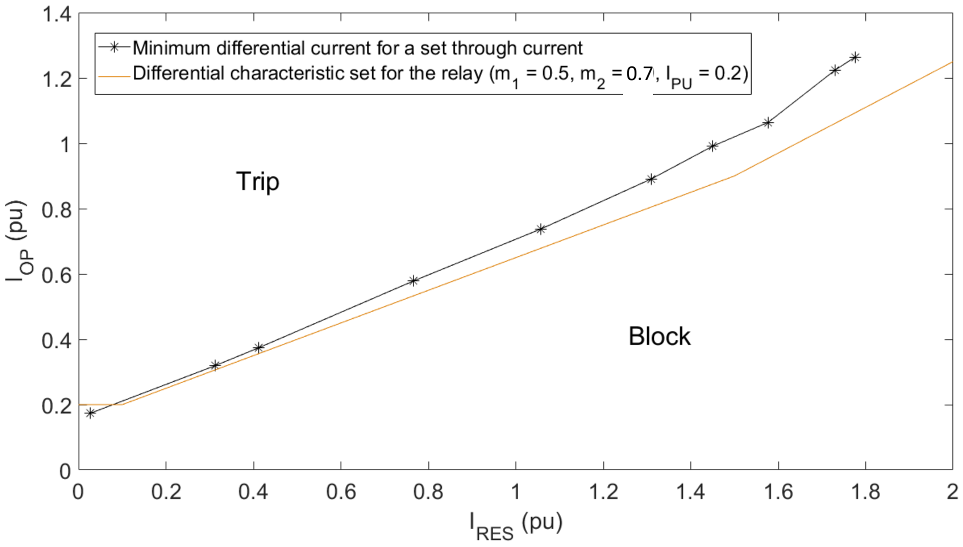
$$I_{RES} = 0.5\left[\left(\frac{60}{125}\right)_{HV} + \left(\frac{60}{250}\right)_{LV}\right] = 0.36\ A$$



As seen in the relay screen

Test Case 2:

Settings: m1=0.5, m2=0.7, I_{PU} = 0.2



Measurements Transformer | Observed Relay data

Load current (A)	Fault current (A)	Restraining current (pu)	Differential current (pu)
0.2	1.18	0.026	0.173
2.3	1.58	0.312	0.319
2.9	1.82	0.412	0.374
5.5	2.59	0.765	0.578
8.3	3.37	1.058	0.738
9.4	3.68	1.31	0.891
10.4	4.38	1.45	0.991
11.3	5.19	1.577	1.064
12.3	5.87	1.73	1.224
12.8	6.05	1.776	1.264

Materials/ Demonstration available :

Alstom book link on transformer protectiongeneric)
https://www.se.com/ww/en/tools/npag-online/pdf/C7-Transformer_and_Transformer-Feeder_Protection.pdf
https://www.youtube.com/watch?v=TBI5pGV3YW0&feature=emb_logo

NPTEL videos
https://www.youtube.com/watch?v=4O4TQDodoRY&feature=emb_logo

https://www.youtube.com/watch?v=qzZFFCwLUL4&feature=emb_logo

https://www.youtube.com/watch?v=W_rZ7WqO2VI&feature=emb_logo

https://www.youtube.com/watch?v=hzxZf8fLM-M&feature=emb_logo

Experiment demonstration:
https://www.youtube.com/watch?v=8E7B_IQXiyE&feature=emb_logo

Report Submission Guidelines:

1. Plot the percentage biased differential characteristics for the two data sets provided in two graph sheets. (Write your roll number and name at the top of the sheets)
2. Plot the reference characteristic for the mentioned setting for each graph plotted.
3. Write on your assessment for each experimental data set compared to reference graph.
4. Write your suggestions how the performance of the relay can be improved further.
5. A transformer differential relay observes the presence of 2nd, 4th and 5th harmonic components as (11%, 5% and 36%) respectively of the fundamental component in the differential current. Such a situation indicates which of the following situation?

   a) Inrush
   b) Overexcitation
   c) High loading
   d) CT saturation

   Have your detail explanation for this considering all the above 4 conditions of the transformer. (in 100 words)
6. High voltage and low voltage CT ratios for a 25 MVA, 220 kV/33 kV, 50 Hz, Yy0 transformer with both side grounded are 100/5 and 600/5 respectively. For an internal phase-A-to-ground fault condition, phase A current measured at high voltage and low voltage sides are 440 A and 1800 A respectively. What will be the maximum bias setting for a single-slope percentage bias differential relay to detect such a fault condition? Consider the transformer to be in unloaded condition.

Pages to be submitted

- Page-1 :roll No, Name at the top, discussion on observations of the 2 cases as mentioned in the earlier slide
- Page-2 –page-3- graph papers with plots (roll No, Name at the top)
- Page 4- the assignment given in point-5 in earlier slide (roll No, Name at the top)
- Page-5 for point5 in the earlier slide (roll No, Name at the top)
- Page6- for ponit6 in the earlier slide (roll No, Name at the top)
- Create a pdf of all the pages in order and submit (moodle)

Differential protection is also applied to –line protection, generator protection…

Thanks

Queries/Questions