University of Idaho

ECE 525

POWER SYSTEM PROTECTION AND RELAYING

SESSION no. 27

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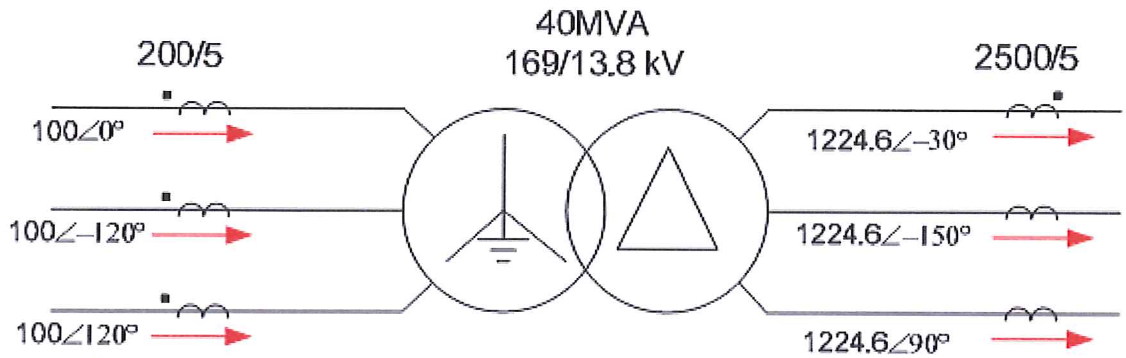
Transformer Protection Example

a) Consider the transformer shown. The transformer is protected by a digital current differential transformer relay. During routine maintenance a technician accidentally shorts out the C-phase CT on the HV side, determine whether the differential elements will operate and if so which "phase "differential elements will operate.

Both set of CT are connected in wye (star). The matrix compensation is set so that correct phase correction is achieved. The TAP is set so that under full load conditions a one per unit "phase current" exists.



$MVA := 1000kW$

$S_{rated} := 40MVA$ $\quad V_{HV} := 169kV$ $\quad V_{LV} := 13.8kV$

$CTR_{HV} := \frac{200}{5}$ $\quad CTR_{HV} = 40$

$CTR_{LV} := \frac{2500}{5}$ $\quad CTR_{LV} = 500$

Assumed Y connected CT

$Tap_{HV} := \frac{S_{rated}}{\sqrt{3} \cdot V_{HV} \cdot CTR_{HV}}$ $\quad Tap_{HV} = 3.4163\,A$

$Tap_{LV} := \frac{S_{rated}}{\sqrt{3} \cdot V_{LV} \cdot CTR_{LV}}$ $\quad Tap_{LV} = 3.347\,A$

$MAT_{11} := \frac{1}{\sqrt{3}} \cdot \begin{pmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{pmatrix}$ $\quad MAT_0 := \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$

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$$MAT_{12} := \frac{1}{3}\cdot\begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \qquad MAT_1 := \frac{1}{\sqrt{3}}\cdot\begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{pmatrix}$$

- Primary Currents

$$I_{A\_HV} := 100A\cdot e^{j\cdot 0deg} \qquad I_{a\_LV} := 1224.6A\cdot e^{-j\cdot 30deg}$$

$$I_{B\_HV} := 100A\cdot e^{-j\cdot 120deg} \qquad I_{b\_LV} := 1224.6A\cdot e^{-j\cdot 150deg}$$

$$I_{C\_HV} := 100A\cdot e^{j\cdot 120deg} \qquad I_{c\_LV} := 1224.6A\cdot e^{j\cdot 90deg}$$

- Uncorrected CT Secondary Currents

correction for CT polarity

$$\begin{pmatrix} IA_{HV\_sec} \\ IB_{HV\_sec} \\ IC_{HV\_sec} \end{pmatrix} := \frac{1}{CTR_{HV}}\cdot\begin{pmatrix} I_{A\_HV} \\ I_{B\_HV} \\ I_{C\_HV} \end{pmatrix} \qquad \begin{pmatrix} Ia_{LV\_sec} \\ Ib_{LV\_sec} \\ Ic_{LV\_sec} \end{pmatrix} := (-1)\cdot\left(\frac{1}{CTR_{LV}}\right)\cdot\begin{pmatrix} I_{a\_LV} \\ I_{b\_LV} \\ I_{c\_LV} \end{pmatrix}$$

- Note the (-1), the diagram doesn't have the LV side current matching the CT polarity

- Corrected currents for relay

$$\begin{pmatrix} IA_{HV\_cor} \\ IB_{HV\_cor} \\ IC_{HV\_cor} \end{pmatrix} := \frac{1}{Tap_{HV}}\cdot MAT_{11}\cdot\begin{pmatrix} IA_{HV\_sec} \\ IB_{HV\_sec} \\ IC_{HV\_sec} \end{pmatrix} \qquad \begin{pmatrix} IA_{LV\_cor} \\ IB_{LV\_cor} \\ IC_{LV\_cor} \end{pmatrix} := \frac{1}{Tap_{LV}}\cdot MAT_0\cdot\begin{pmatrix} Ia_{LV\_sec} \\ Ib_{LV\_sec} \\ Ic_{LV\_sec} \end{pmatrix}$$

- Operate and Restraint Current

Phase A: *phasor sum* *sum of magnitudes*

$$IOP_A := \left|IA_{HV\_cor} + IA_{LV\_cor}\right| \qquad IRTA_A := \left|IA_{HV\_cor}\right| + \left|IA_{LV\_cor}\right|$$

$$IOP_A = 2.252\times 10^{-5} \qquad IRTA_A = 1.464$$

Phase B:

$IOP_B := \left|IB_{HV\_cor} + IB_{LV\_cor}\right|$ $\qquad$ $IRTA_B := \left|IB_{HV\_cor}\right| + \left|IB_{LV\_cor}\right|$

$IOP_B = 2.252 \times 10^{-5}$ $\qquad$ $IRTA_B = 1.464$

Phase C:

$IOP_C := \left|IC_{HV\_cor} + IC_{LV\_cor}\right|$ $\qquad$ $IRTA_C := \left|IC_{HV\_cor}\right| + \left|IC_{LV\_cor}\right|$

$IOP_C = 2.252 \times 10^{-5}$ $\qquad$ $IRTA_C = 1.464$

- Alternate approach

$$\begin{pmatrix} IA_{HV\_cor} \\ IB_{HV\_cor} \\ IC_{HV\_cor} \end{pmatrix} := \frac{1}{Tap_{HV}} \cdot MAT_{12} \cdot MAT_0 \cdot \begin{pmatrix} IA_{HV\_sec} \\ IB_{HV\_sec} \\ IC_{HV\_sec} \end{pmatrix} \qquad \begin{pmatrix} IA_{LV\_cor} \\ IB_{LV\_cor} \\ IC_{LV\_cor} \end{pmatrix} := \frac{1}{Tap_{LV}} \cdot MAT_1 \cdot \begin{pmatrix} Ia_{LV\_sec} \\ Ib_{LV\_sec} \\ Ic_{LV\_sec} \end{pmatrix}$$

- Operate and Restraint Current

Phase A:

$IOP_A := \left|IA_{HV\_cor} + IA_{LV\_cor}\right|$ $\qquad$ $IRTA_A := \left|IA_{HV\_cor}\right| + \left|IA_{LV\_cor}\right|$

$IOP_A = 2.252 \times 10^{-5}$ $\qquad$ $IRTA_A = 1.464$

Phase B:

$IOP_B := \left|IB_{HV\_cor} + IB_{LV\_cor}\right|$ $\qquad$ $IRTA_B := \left|IB_{HV\_cor}\right| + \left|IB_{LV\_cor}\right|$

$IOP_B = 2.252 \times 10^{-5}$ $\qquad$ $IRTA_B = 1.464$

Phase C:

$IOP_C := \left|IC_{HV\_cor} + IC_{LV\_cor}\right|$ $\qquad$ $IRTA_C := \left|IC_{HV\_cor}\right| + \left|IC_{LV\_cor}\right|$

$IOP_C = 2.252 \times 10^{-5}$ $\qquad$ $IRTA_C = 1.464$

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Repeat with the phase C CT shorted on the HV side:

- Uncorrected CT Secondary Currents

$$\begin{pmatrix} IA_{HV\_sec} \\ IB_{HV\_sec} \\ IC_{HV\_sec} \end{pmatrix} := \frac{1}{CTR_{HV}} \cdot \begin{pmatrix} I_{A\_HV} \\ I_{B\_HV} \\ 0 \end{pmatrix} \qquad \begin{pmatrix} Ia_{LV\_sec} \\ Ib_{LV\_sec} \\ Ic_{LV\_sec} \end{pmatrix} := (-1) \cdot \left(\frac{1}{CTR_{LV}} \right) \cdot \begin{pmatrix} I_{a\_LV} \\ I_{b\_LV} \\ I_{c\_LV} \end{pmatrix}$$

due to shorted CT

- Note the (-1), the diagram doesn't have the LV side current matching the CT polarity

- Corrected currents for relay

$$\begin{pmatrix} IA_{HV\_cor} \\ IB_{HV\_cor} \\ IC_{HV\_cor} \end{pmatrix} := \frac{1}{Tap_{HV}} \cdot MAT_{11} \cdot \begin{pmatrix} IA_{HV\_sec} \\ IB_{HV\_sec} \\ IC_{HV\_sec} \end{pmatrix} \qquad \begin{pmatrix} IA_{LV\_cor} \\ IB_{LV\_cor} \\ IC_{LV\_cor} \end{pmatrix} := \frac{1}{Tap_{LV}} \cdot MAT_{0} \cdot \begin{pmatrix} Ia_{LV\_sec} \\ Ib_{LV\_sec} \\ Ic_{LV\_sec} \end{pmatrix}$$

- Operate and Restraint Current, with shorted CT

Phase A:

$IOP_A := \left| IA_{HV\_cor} + IA_{LV\_cor} \right|$ $\qquad$ $IRTA_A := \left| IA_{HV\_cor} \right| + \left| IA_{LV\_cor} \right|$

$IOP_A = 0.422$ $\qquad$ $IRTA_A = 1.154$

Phase B:

$IOP_B := \left| IB_{HV\_cor} + IB_{LV\_cor} \right|$ $\qquad$ $IRTA_B := \left| IB_{HV\_cor} \right| + \left| IB_{LV\_cor} \right|$

$IOP_B = 2.252 \times 10^{-5}$ $\qquad$ $IRTA_B = 1.464$

Phase C:

$IOP_C := \left| IC_{HV\_cor} + IC_{LV\_cor} \right|$ $\qquad$ $IRTA_C := \left| IC_{HV\_cor} \right| + \left| IC_{LV\_cor} \right|$

$IOP_C = 0.422$ $\qquad$ $IRTA_C = 1.154$

- Due to the delta winding (and correction matrix) two of the differential elements respond.

Check the ratio of IOP to IRTA:

$$\frac{IOP_A}{IRTA_A} = 36.602 \cdot \%$$

So if the relay slope is set larger than 36.602% the relay will not operate for this condition. Otherwise it will operate.

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- Alternate approach

$$\begin{pmatrix} IA_{HV\_cor} \\ IB_{HV\_cor} \\ IC_{HV\_cor} \end{pmatrix} := \frac{1}{Tap_{HV}} \cdot MAT_{12} \cdot MAT_0 \cdot \begin{pmatrix} IA_{HV\_sec} \\ IB_{HV\_sec} \\ IC_{HV\_sec} \end{pmatrix} \qquad \begin{pmatrix} IA_{LV\_cor} \\ IB_{LV\_cor} \\ IC_{LV\_cor} \end{pmatrix} := \frac{1}{Tap_{LV}} \cdot MAT_1 \cdot \begin{pmatrix} Ia_{LV\_sec} \\ Ib_{LV\_sec} \\ Ic_{LV\_sec} \end{pmatrix}$$

- Operate and Restraint Current, with shorted CT

Phase A:

$$IOP_A := \left|IA_{HV\_cor} + IA_{LV\_cor}\right| \qquad IRTA_A := \left|IA_{HV\_cor}\right| + \left|IA_{LV\_cor}\right|$$

$$IOP_A = 0.244 \qquad IRTA_A = 1.377$$

Phase B:

$$IOP_B := \left|IB_{HV\_cor} + IB_{LV\_cor}\right| \qquad IRTA_B := \left|IB_{HV\_cor}\right| + \left|IB_{LV\_cor}\right|$$

$$IOP_B = 0.244 \qquad IRTA_B = 1.377$$

Phase C:

$$IOP_C := \left|IC_{HV\_cor} + IC_{LV\_cor}\right| \qquad IRTA_C := \left|IC_{HV\_cor}\right| + \left|IC_{LV\_cor}\right|$$

$$IOP_C = 0.488 \qquad IRTA_C = 0.976$$

- Due to the delta winding (and correction matrix) two of the differential elements respond.

Check the ratio of IOPC to IRTC and IOPA to IRTA:

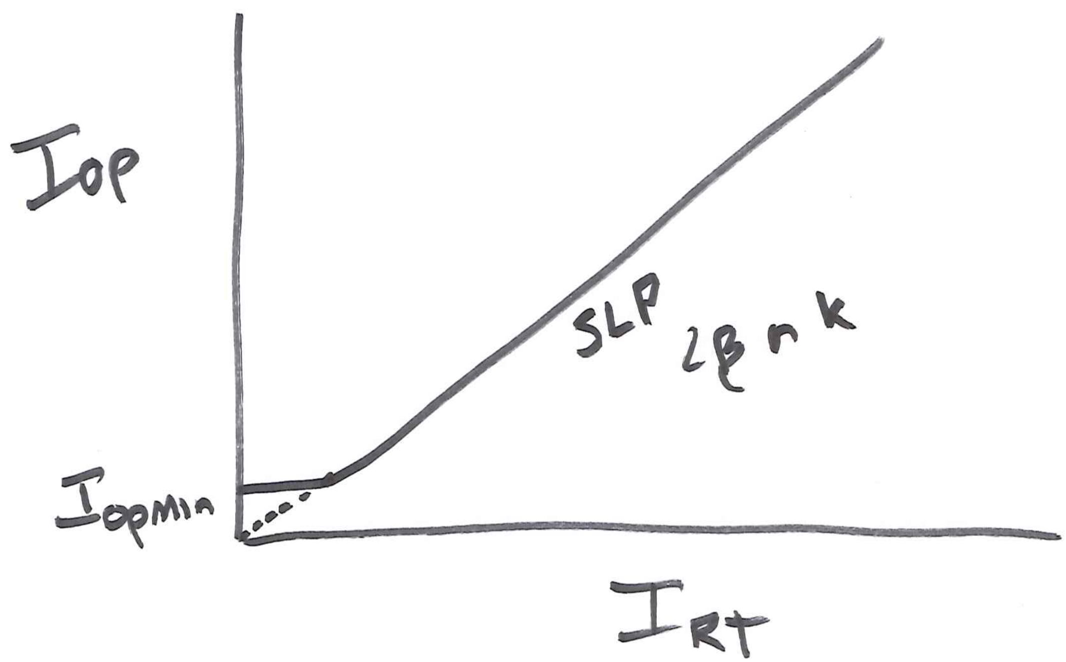
$$\frac{IOP_A}{IRTA_A} = 17.712 \cdot \%$$

$$\frac{IOP_C}{IRTA_C} = 49.999 \cdot \%$$

Note that the error is more significant in this case because the shorted CT was on HV side, and we are no longer scaling the current down as much.

So if these correction matrices are used, the relay slope need to be set larger than50% the relay so the relay not operate for this condition. Otherwise it will operate.

SLOPE setting



TRIP = $(I_{op} > SLP \cdot I_{RT})$ AND $I_{op} > I_{opmin}$

I_{opmin} considerations

→ C-Class CTs

- can have up to 3% error in nominal currents

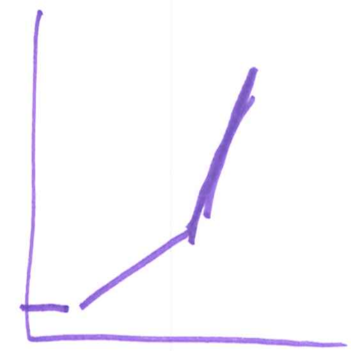
→ 3% for every CT → consider is Base 5A or 1A

- minimum setting on relay 0.1 pu

- Steady-state magnetizing current 2-4% of rated current

→ I_{opmin} 0.2 pu – 1 pu

SLOPE Setting



① CT error w/o saturation

(if dual slope, the higher slope will handle saturation, IF single slope, handle it here)

→ Add 10% for each CT input to differential element

② filter overreach ~3-5% added to slope

Other considerations

(3) Shorted CT / No current from CT due to single pole open...

(4) Tap changer

- CT ratio, relay settings don't adapt
- Normalized Voltage Transformation Ratio

$$1:(1 \pm \varepsilon)$$

1 : 1.05

1 : 1.025

1 : 1

1 : 0.975

⋮

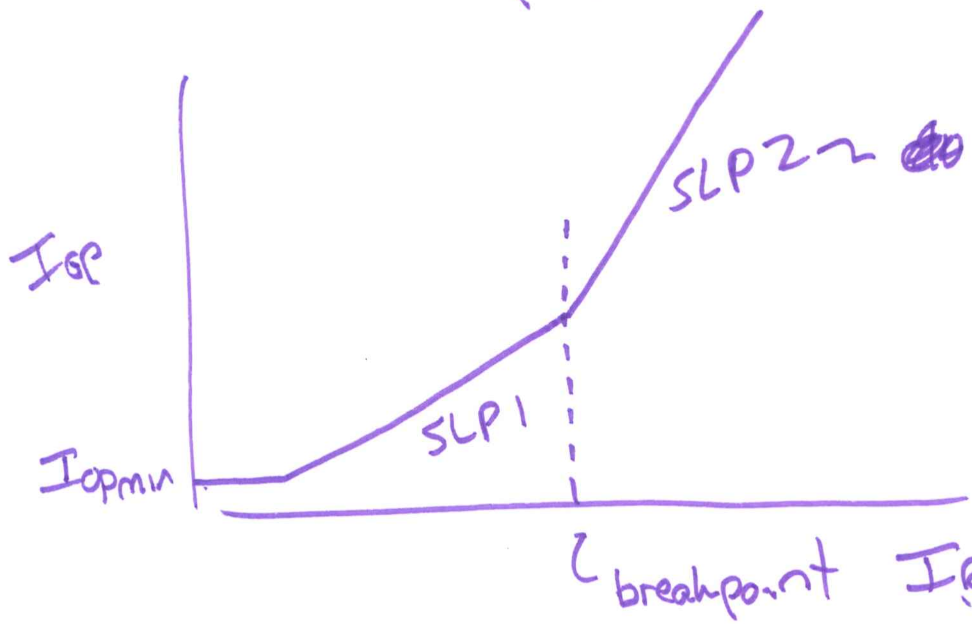
Slope setting needs to be secure for the extremes

$$\frac{1+\varepsilon_{max}}{1} \quad \text{or} \quad \frac{1-\varepsilon_{max}}{1}$$

$$\frac{1.1}{1} \qquad \frac{0.9}{1}$$

→ increase slope by this % mismatch

Dual Slope . . .



SLP2 ~ chosen based on CT on one side saturated

breakpoint $I_{RT} = |I_{prim\ corr}| + |I_{sec\ correct}|$

Recall formula to never saturate

$$\left(1 + \frac{X}{R}\right)\left(\frac{I_{sec}}{I_{rated}}\right)\left(\frac{Z_{Burden}}{Z_{rated}}\right) \leq 20$$

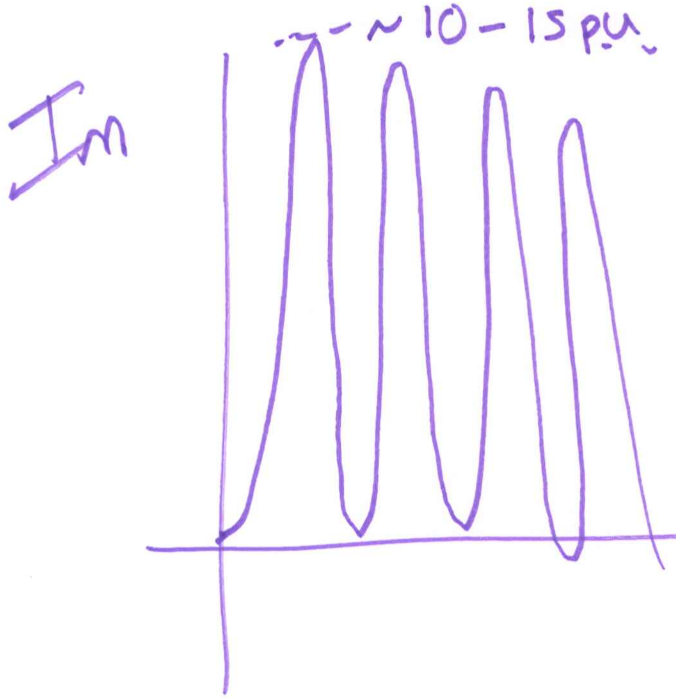
- breakpoint is looking at Iscc for either CT

$$\left(1 + \frac{X}{R}\right)\left(I_{scc}\right)\left(Z_B\right) \leq 50\%\ V_{knee}$$

- Other Differential Element

Concerns for Transformers

Inrush - large current possible



- Don't want to trip on inrush
  - DC offset decaying
    → Filters remove it
  - ~~Harmonic terms~~
    - 2nd harmonic
    - 4th harmonic
    - ~~5th~~ - used for overexcitation detection

need filters to record these

Solutions to avoid false trip on inrush

- Time delay - disable differential element while energizing
  ⇒ electromechanical solution
- Harmonic Blocking -
- Harmonic Restraint
- morphological Solutions - pattern matching