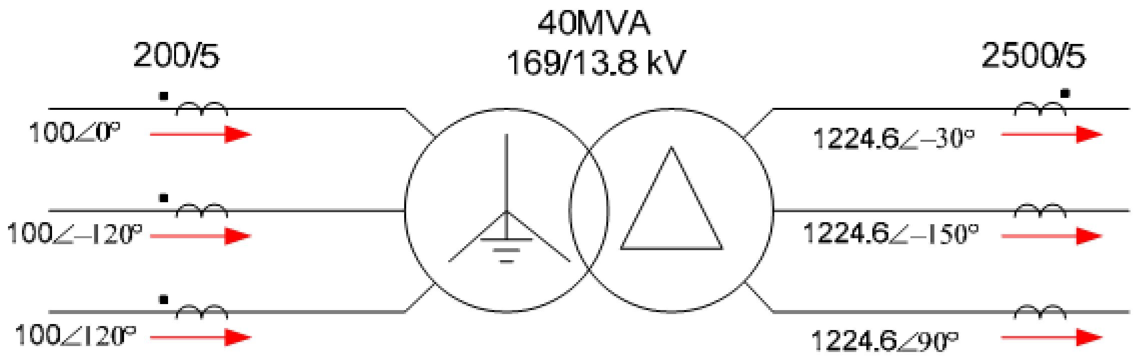
Transformer Protection Example

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.



$$MVA := 1000kW$$

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

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

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

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

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

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

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

- 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

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

- 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:

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

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

Phase B:

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

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

Phase C:

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

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

- Alternate approach

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

- Operate and Restraint Current

Phase A:

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

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

Phase B:

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

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

Phase C:

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

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

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

- Uncorrected CT Secondary Currents

$$\begin{pmatrix} IA_{HV\_sec} \\ IB_{HV\_sec} \\ IC_{HV\_sec} \end{pmatrix} := \frac{1}{CTR_{HV}} \cdot \begin{pmatrix} I_{A\_HV} \\ I_{B\_HV} \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} Ia_{LV\_sec} \\ Ib_{LV\_sec} \\ Ic_{LV\_sec} \end{pmatrix} := (-1) \cdot \left(\frac{1}{CTR_{LV}} \right) \cdot \begin{pmatrix} I_{a\_LV} \\ I_{b\_LV} \\ I_{c\_LV} \end{pmatrix}$$

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

- Corrected currents for relay

$$\begin{pmatrix} IA_{HV\_cor} \\ IB_{HV\_cor} \\ IC_{HV\_cor} \end{pmatrix} := \frac{1}{Tap_{HV}} \cdot MAT_{11} \cdot \begin{pmatrix} IA_{HV\_sec} \\ IB_{HV\_sec} \\ IC_{HV\_sec} \end{pmatrix}$$

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

- 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.

- 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.

Now repeat if the shorted CT is on the delta side:

- Uncorrected CT Secondary Currents

$$\begin{pmatrix} IA_{HV\_sec} \\ IB_{HV\_sec} \\ IC_{HV\_sec} \end{pmatrix} := \frac{1}{CTR_{HV}} \cdot \begin{pmatrix} I_{A\_HV} \\ I_{B\_HV} \\ I_{C\_HV} \end{pmatrix}$$

$$\begin{pmatrix} Ia_{LV\_sec} \\ Ib_{LV\_sec} \\ Ic_{LV\_sec} \end{pmatrix} := (-1) \cdot \left(\frac{1}{CTR_{LV}}\right) \cdot \begin{pmatrix} I_{a\_LV} \\ I_{b\_LV} \\ 0A \end{pmatrix}$$

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

- Corrected currents for relay

$$\begin{pmatrix} IA_{HV\_cor} \\ IB_{HV\_cor} \\ IC_{HV\_cor} \end{pmatrix} := \frac{1}{Tap_{HV}} \cdot MAT_{11} \cdot \begin{pmatrix} IA_{HV\_sec} \\ IB_{HV\_sec} \\ IC_{HV\_sec} \end{pmatrix}$$

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

- Operate and Restraint Current, with shorted CT

Phase A:

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

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

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:

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

$$IOP_C = 0.732 \qquad IRTA_C = 0.732$$

- Due to the delta winding (and correction matrix) two of the differential elements respond. Check the ratio of IOP to IRTA:

$$\frac{IOP_C}{IRTA_C} = 100 \cdot \%$$

So now the relay slope needs to be set larger than 100% so the relay will not operate for this condition. Otherwise it will operate.

- 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:

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

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

Phase B:

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

$$IOP_B = 0.423 \qquad IRTA_B = 1.154$$

Phase C:

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

$$IOP_C = 0.423 \qquad IRTA_C = 1.154$$

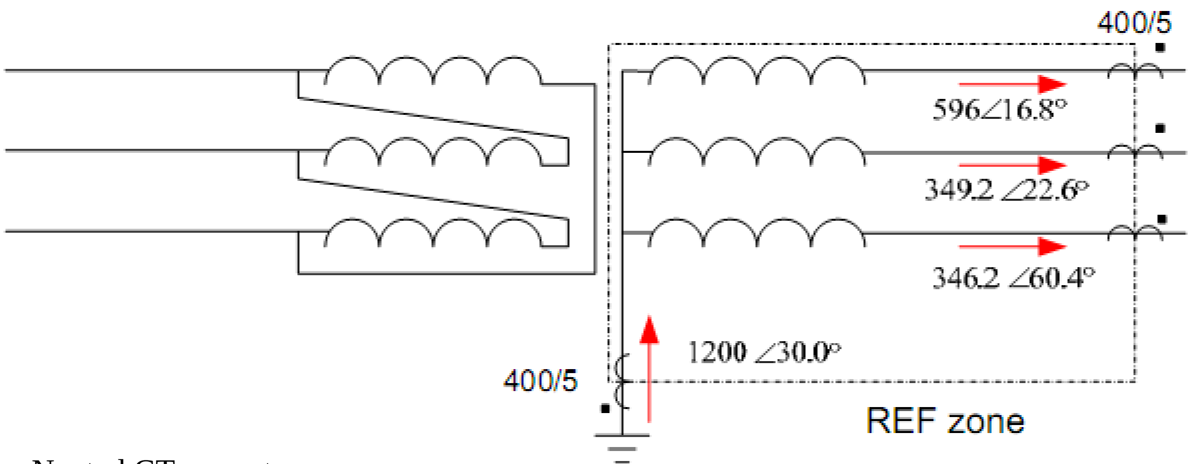
- Due to the delta winding (and correction matrix) two of the differential elements respond.

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

$$\frac{IOP_C}{IRTA_C} = 36.604 \cdot \%$$

So now we back to the case that if the relay slope is set larger than 36.602% the relay will not operate for this condition. Otherwise it will operate.

b) Consider the restricted earth fault protection scheme shown below. Determine whether the earth fault is inside or outside the protected zone, give reasons for your answer.



Neutral CT current:

$$I_N := 1200 \cdot e^{j \cdot 30deg} \qquad CTR_{Neutral} := \frac{400}{5}$$

LV CT currents (note negative sign due to polarity of CT comparted to labelled current)

$$I_{A\_LV} := -596 \cdot e^{j \cdot 16.8deg} \qquad CTR_{phase} := \frac{400}{5}$$

$$I_{B\_LV} := -349.2 \cdot e^{j \cdot 22.6 \cdot deg}$$

$$I_{C\_LV} := -346.2 \cdot e^{j \cdot 60.4deg}$$

$$I_R := I_{A\_LV} + I_{B\_LV} + I_{C\_LV} \qquad \left|I_R\right| = 1225.161 \qquad \arg\left(I_R\right) = -150.275 \cdot deg$$

$$I_{N\_sec} := \frac{I_N}{CTR_{Neutral}} \qquad I_{R\_sec} := \frac{I_R}{CTR_{phase}}$$

$$Torque_{REF} := Re\left(I_{N\_sec} \cdot \overline{I_{R\_sec}}\right) \qquad Torque_{REF} = -229.715$$

- Negative torque implies fault is out of zone.

Alternate approach:

$$I_{OP} := \left|I_{N\_sec} + I_{R\_sec}\right| \qquad I_{OP} = 0.323$$

$$I_{RT} := \left|I_{N\_sec}\right| + \left|I_{R\_sec}\right| \qquad I_{RT} = 30.315$$

$$\frac{I_{OP}}{I_{RT}} = 0.011$$

Note, if we don't reverse the polarity on the phase CT currents we get:

$$I_{OP} := \left|I_{N\_sec} - I_{R\_sec}\right| \qquad I_{OP} = 30.314$$

Then $\frac{I_{OP}}{I_{RT}} = 1$ and the relay would operate.