Power Systems Analysis II

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Notebook:

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Question # 1

For the distribution feeder, shown in Fig. Q1, use the per unit method to determine the magnitude of the fault current ($I_{f\text{-}3ph}$) in Amperes for a three phase fault at the feeder end. Use a system MVA base of 100 MVA and a voltage base of 13.2 kV at the feeder.

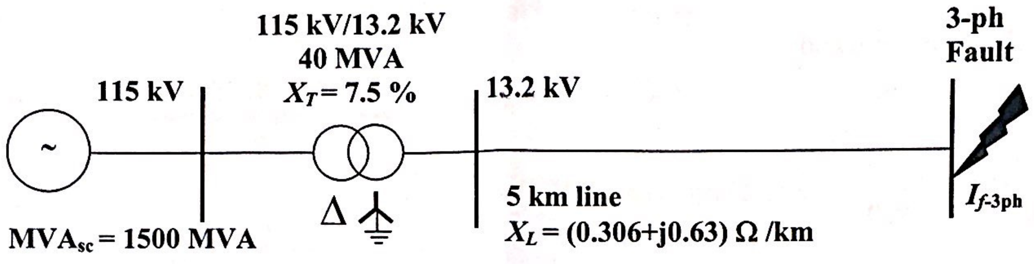


Fig. Q1

Solution:

$$X_{sc}=\frac{1}{MVA_{sc-pu}},MVA_{sc-pu}=\frac{MVA_{sc}}{MVA_{base}}=\frac{1500}{100}=15\ pu, X_{sc}=\frac{1}{15}=0.067\ pu,$$

$$X_{sc\Omega}=X_{scpu}\times X_{base-13,2kV}, X_{base-13.2kV}=\frac{kV_{base}^2}{MVA_{base}}=\frac{13.2^2}{100}=1.742\ \Omega, X_{sc\Omega}=0.067\times1.742=0.117\ \Omega$$

$$X_{Tnew}=X_{Told}\times\frac{MVA_{basenew}}{MVA_{baseold}}=\frac{7.5}{100}\times\frac{100}{40}=0.1875\ pu, X_{T\Omega}=X_{Tnew}\times X_{base-13.2kV}=0.1875\times1.742=0.327\ \Omega$$

$$Z_{L1\Omega}=(0.306+j0.63)\times5=1.53+j3.15\ \Omega,\Rightarrow Z_{L1pu}=\frac{Z_{L1\Omega}}{Z_{base-13.2kV}}=\frac{1.53+j3.15\ \Omega}{1.742\ \Omega}=0.88+j1.81\,pu$$

$$Z_{L1\Omega}=0.70\angle64.1^\circ\times5=3.5\angle64.1^\circ\ \Omega\Rightarrow X_{L1pu}=2.03\angle64.1^\circ\ pu$$

$$Z_{eq1\Omega}=jX_{sc1}+jX_{T1}+Z_{L1}=j0.117+j0.327+1.53+j3.15=1.53+j3.59\ \Omega=3.9\angle66.9^\circ\ \Omega$$

$$Z_{eq1pu}=jX_{sc1pu}+jX_{T1pu}+Z_{L1pu}=j0.067+j0.188+0.88+j1.81=0.88+j2.07\ pu=2.24\angle66.9^\circ\ pu$$

$$I_{f3phA}=\frac{E_1}{Z_{eq1}}=\frac{\frac{13.2\times10^3}{\sqrt{3}}\angle0^\circ V}{3.9\angle66.9^\circ\ \Omega}=\frac{7621\angle0^\circ V}{3.9\angle66.9^\circ\ \Omega}=1954.1\angle-66.9^\circ\ A$$

$$I_{f3phpu}=\frac{E_1}{Z_{eq1pu}}=\frac{1.0\angle0^\circ V}{2.24\angle66.9^\circ\ \Omega}=0.446\angle-66.9^\circ\ pu$$

$$I_{base-13.2kV}=\frac{MVA_{base}}{\sqrt{3}V_{LL}}=\frac{100\times1000}{\sqrt{3}\times13.2}=4373.9\ A$$

X_{sc} =	**0.067** *pu*
X_T =	**0.1875** *pu*
Z_{TL} =	**0.88 + *j* 1.81 *Pu***
Z_{eq} =	**0.88 + *j* 2.07 *Pu*** $2.24\angle66.9^\circ$ *pu*
I_{f3ph} =	**0.446** *pu*
I_b =	**4373.9** *A*
I_{f3ph} =	**1954.1** *A*

Question # 2:

For the system shown in Fig. Q2, and starting from the data that are given, calculate the three-phase and single-line-ground fault in Amperes at the Buses 3, 2, and 1 using:

a. The Ohmic method referring the system to the 115 kV bus.
b. The per-unit method.

Solution:

a. The Ohmic method

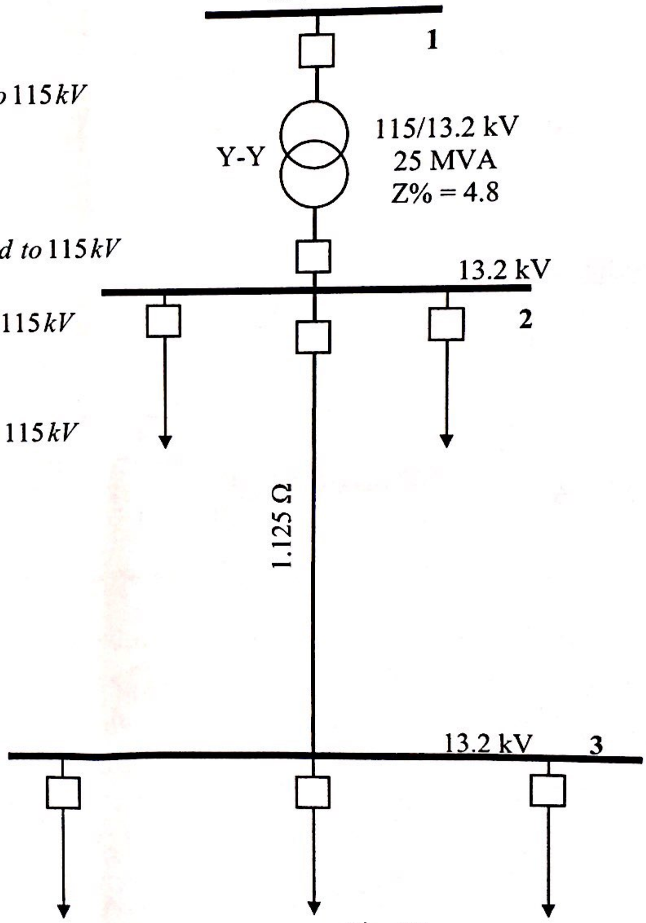


Fig. Q2

$$Z_{sc} = \frac{V_{LL}^2}{MVAsc} = \frac{(115)^2}{950} = 13.92\ \Omega\ \textit{referred to } 115kV$$

$$Z_{transformer} = Z_{pu} \times Z_{base}$$

$$Z_{base} = \frac{V_{LL}^2}{MVA-TX} = \frac{(115)^2}{25} = 529\ \Omega\ \textit{referred to } 115kV$$

$$Z_{transformer} = \frac{4.8}{100} \times 529 = 25.39\ \Omega\ \textit{referred to } 115kV$$

$$Z_{TL} = 1.125 \times \left(\frac{115}{13.2}\right)^2 = 85.35\ \Omega\ \textit{referred to } 115kV$$

a. Three-Phase Fault

$$I_{faultC} = \frac{115 \times 10^3}{\sqrt{3}(13.92 + 25.39 + 83.35)}$$
$$= 532.6\ A\ \textit{referred to } 115kV$$
$$= 532.6 \times \left(\frac{115}{13.2}\right)$$
$$= 4640.2\ A\ \textit{referred to } 13.2kV$$

$$I_{faultB} = \frac{115 \times 10^3}{\sqrt{3}(13.92 + 25.39)}$$
$$= 1689.0\ A\ \textit{referred to } 115kV$$
$$= 1689.0 \times \left(\frac{115}{13.2}\right)$$
$$= 14714.8\ A\ \textit{referred to } 13.2kV$$

$$I_{faultA} = \frac{115 \times 10^3}{\sqrt{3}(13.92)}$$
$$= 4769.8\ A\ \textit{referred to } 115kV$$

The L-G Fault $= 0$, because the TX is not grounded

b. The per-unit method

Let MVAbase = 25 MVA
kVbase = 13.2 kV at the primary feeder.

$$Z_{base-HV} = \frac{V_{LL}^2}{MVAbase} = \frac{(115)^2}{25} = 529\ \Omega\ referred\ \ to\ 115\ kV$$

$$Z_{base-LV} = \frac{V_{LL}^2}{MVAbase} = \frac{(13.2)^2}{25} = 6.97\ \Omega\ referred\ \ to\ 13.2\ kV$$

$$Z_{TX-pu} = \frac{4.8}{100} = 0.048\ pu$$

$$MVA_{sc-pu} = \frac{MVA_{sc}}{MVA_{base}} = \frac{950}{25} = 38\ pu$$

$$Z_{sc-pu} = \frac{1}{MVA_{sc-pu}} = \frac{1}{38} = 0.0263\ \ pu$$

$$Z_{Line-pu} = \frac{1.125}{6.97} = 0.1614\ \ pu$$

a. Three-Phase Fault

$$V_{C-pu} = \frac{V_c}{V_{C-base}} = \frac{13.2}{13.2} = 1\,pu$$

$$I_{fault-C} = \frac{V_{C-pu}}{\sum Z} = \frac{V_{C-pu}}{Z_{Line}+Z_{TX}+Z_{sc}} = \frac{1.0}{0.1614+0.0263+0.048} = 4.24\,pu$$

$$I_{base-13.2kV} = \frac{MVA_{base}}{\sqrt{3}\times kV_{Base}} = \frac{25\times1000}{\sqrt{3}\times13.2} = 1093.47\,\mathrm{A}$$

$$I_{fault-C(A)} = I_{fault-C}\times I_{base-13.2kV} = 4.24\,pu\times1093.47\,\mathrm{A} = 4638.6\,\mathrm{A}$$

$$V_{B-pu} = \frac{V_B}{V_{B-base}} = \frac{13.2}{13.2} = 1\,pu$$

$$I_{fault-B} = \frac{V_{B-pu}}{\sum Z} = \frac{V_{B-pu}}{Z_{TX}+Z_{sc}} = \frac{1.0}{0.0263+0.048} = 13.46\,pu$$

$$I_{base-13.2kV} = \frac{MVA_{base}}{\sqrt{3}\times kV_{Base}} = \frac{25\times1000}{\sqrt{3}\times13.2} = 1093.47\,\mathrm{A}$$

$$I_{fault-B(A)} = I_{fault-B}\times I_{base-13.2kV} = 13.46\,pu\times1093.47\,\mathrm{A} = 14713.8\,\mathrm{A}$$

$$V_{A-pu} = \frac{V_A}{V_{A-base}} = \frac{115}{115} = 1\,pu$$

$$I_{fault-A} = \frac{V_{A-pu}}{\sum Z} = \frac{V_{A-pu}}{Z_{sc}} = \frac{1.0}{0.02638} = 38\,pu$$

$$I_{base-115kV} = \frac{MVA_{base}}{\sqrt{3}\times kV_{Base}} = \frac{25\times1000}{\sqrt{3}\times115} = 125.5\,\mathrm{A}$$

$$I_{fault-A(A)} = I_{fault-C}\times I_{base-13.2kV} = 38\,pu\times125.5\,\mathrm{A} = 4769.4\,\mathrm{A}$$

Question # 3

A portion of an 11 kV radial system is shown in Fig.Q3. The system may be operated with one rather than two source transformers under certain operating conditions. Assume high voltage bus of transformer is an infinite bus. Protection system for three-phase and line-to-line faults has to be designed. Transformer and Transmission line reactances in ohms are referred to the 11 kV side as shown in the Fig. Q3. Calculate the maximum fault currents (I_{fmaxi}) and minimum fault currents (I_{fmini}) at bus 1-5.

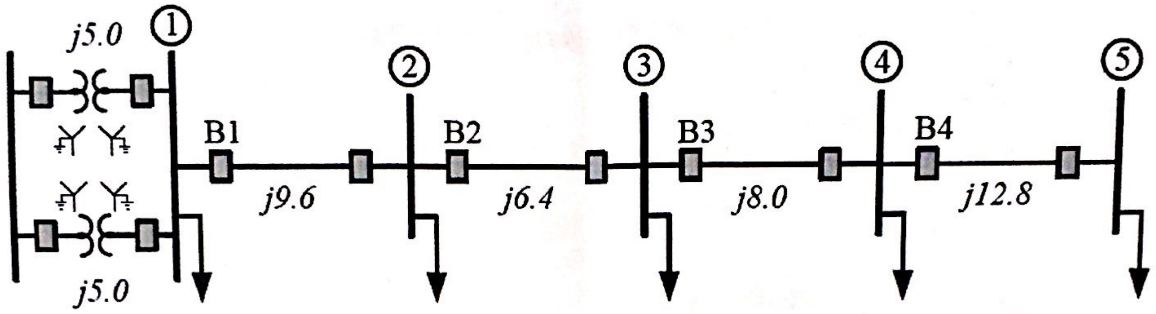


Fig. Q3

Solution Hints:

1. Maximum fault current will occur for a three-phase with both transformers in service.
2. Minimum fault in this case is assumed for a line-to-line fault. A line-to-line fault produces a fault current equal to $\sqrt{3}/2$ times the three-phase fault. Also the minimum fault current happens for line-to-line faults with one transformer in service.

The maximum and minimum fault currents are given below for faults at bus 1-5

Fault Level	Fault at Bus				
	1	2	3	4	5
Max Fault Current (A)	2540	525	343	240	162
Min Fault Current (A)	1100	377	262	190	132

Max Fault Current (A)

$$|I_{f3ph1}| = \left|\frac{V}{Z_{eq1}}\right| = \frac{11\times10^3/\sqrt{3}}{2.5} = 2540\ A$$

$$|I_{f3ph2}| = \left|\frac{V}{Z_{eq2}}\right| = \frac{11\times10^3/\sqrt{3}}{(2.5+9.6)} = 525\ A$$

$$|I_{f3ph3}| = \left|\frac{V}{Z_{eq3}}\right| = \frac{11\times10^3/\sqrt{3}}{(2.5+9.6+6.4)} = 343\ A$$

$$|I_{f3ph4}| = \left|\frac{V}{Z_{eq4}}\right| = \frac{11\times10^3/\sqrt{3}}{(2.5+9.6+6.4+8)} = 240\ A$$

$$|I_{f3ph5}| = \left|\frac{V}{Z_{eq5}}\right| = \frac{11\times10^3/\sqrt{3}}{(2.5+9.6+6.4+8+12.8)} = 162\ A$$

Min Fault Current (A)

$$|I_{fLL1}| = 0.866\times\left|\frac{V}{Z_{eq1}}\right| = 0.866\times\frac{11\times10^3/\sqrt{3}}{5} = 1100\ A$$

$$|I_{fLL2}| = 0.866\times\left|\frac{V}{Z_{eq2}}\right| = 0.866\times\frac{11\times10^3/\sqrt{3}}{(5+9.6)} = 377\ A$$

$$|I_{fLL3}| = 0.866\times\left|\frac{V}{Z_{eq3}}\right| = 0.866\times\frac{11\times10^3/\sqrt{3}}{(5+9.6+6.4)} = 262\ A$$

$$|I_{fLL4}| = 0.866\times\left|\frac{V}{Z_{eq4}}\right| = 0.866\times\frac{11\times10^3/\sqrt{3}}{(5+9.6+6.4+8)} = 190\ A$$

$$|I_{fLL5}| = 0.866\times\left|\frac{V}{Z_{eq5}}\right| = 0.866\times\frac{11\times10^3/\sqrt{3}}{(5+9.6+6.4+8+12.8)} = 132\ A$$

※ Fault Calculation:

- Three main types of fault:
  - 3-ph fault.
  - L-G fault.
  - L-L fault.

- Three main parts of any power system: Generation – Transmission – Distribution.

Source → Load called "down-stream."

load → source called "up-stream."

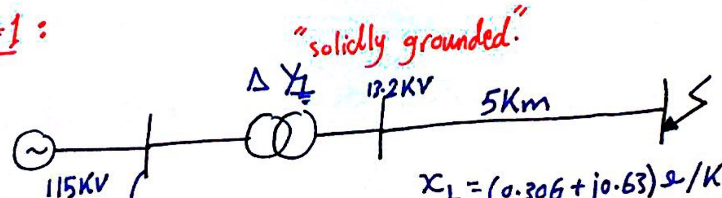
* The voltages 400V, 380V, 415V are called: "Low Tension Class" OR "Low Voltage class".

* The voltages 11KV, 33KV are called: "Medium Voltage Class."

132KV ⇒ "High Voltage" >220KV ⇒ "Extra High Voltage."

Tutorial #1:

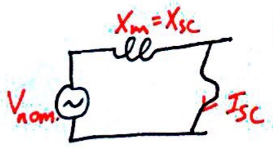
Q1



$x_L = (0.306 + j0.63)\ \Omega/Km$

Nominal Voltage "Rated Voltage" ← 115KV

$MVA_{sc} = 1500VA.$



$$\boxed{X_s = \frac{V_{nom}}{I_{sc}}}$$

$$MVA_{sc} = \sqrt{3}\ V_{LL_{nom}}\ I_{sc}$$

$$X_{sc} = \frac{V_{LL_{nom}}/\sqrt{3}}{I_{sc_{pu}}}$$

- from MVA_b & KV_b one can find I_b & Z_b.

$$Z_b = \frac{(KV_{LL_b})^2}{MVA_b} \quad , \quad I_b = \frac{MVA_b}{\sqrt{3}\ V_{LL_b}}$$

- Transformer Ratio: it is the effective turns ratio. "Line-Line voltages Ratio."
- Turns Ratio: Ratio of the phase voltages.

$$X_L = 5\,Km * (0.306 + j0.63)\frac{\Omega}{Km} \Rightarrow \underline{\underline{X_L = 1.53 + j3.15\ \Omega}}$$

$Z_b\big|_{13.2KV} = \frac{(13.2)^2}{100} = \underline{1.742\,\Omega}$ $\qquad X_{L\,(PU)} = \frac{1.53+j3.15}{1.742} = \underline{2.03\angle 64.1^\circ}$ PU

$X_{T_{new}} = X_{T_{old}} \frac{S_{new}}{S_{old}} = 0.075 * \frac{100}{40} = \underline{0.1875}$ PU $\quad$ OR $\quad Z_{T_{new}} = \underline{j0.1875}$ PU

* X_{sc} can be found by two methods:

• method (1):

$X_{sc_{PU}} = \frac{1}{MVA_{sc_{PU}}}$ $\qquad MVA_{sc_{PU}} = \frac{1500}{100} = 15$ PU

$\Rightarrow X_{sc_{PU}} = \frac{1}{15} = \underline{0.067 \text{ PU}}$. #

• method (2):

alternatively: $X_{sc_{\Omega}} = \frac{(KV_{LL})^2}{MVA_{sc}} = \frac{115^2}{1500} = \underline{8.81\,\Omega}$

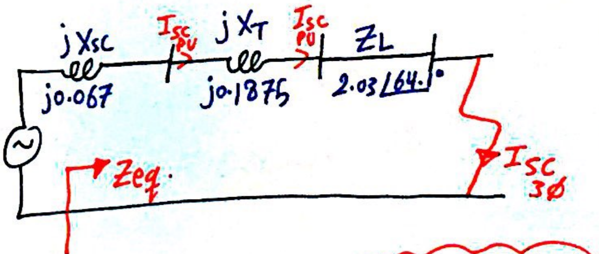
$Z_{b_{HV}} = Z_{b_{115KV}} = \frac{115^2}{100} = \underline{132.25\,\Omega}$ $\qquad \Rightarrow Z_{sc_{PU}} = j\frac{8.81}{132.25} = \underline{j0.067}$ PU #

* proof for $X_{sc_{PU}} = \frac{1}{MVA_{sc_{PU}}}$:

$S_{sc_{PU}} = V_{PU}\, I_{sc_{PU}}$; $V_{PU} = 1\angle 0 \quad \Rightarrow \quad S_{sc_{PU}} = I_{sc_{PU}}$

$X_{PU} = \frac{V/V_b}{I/I_b} = \frac{1}{I_{sc_{PU}}} = \frac{1}{S_{sc_{PU}}}$ #

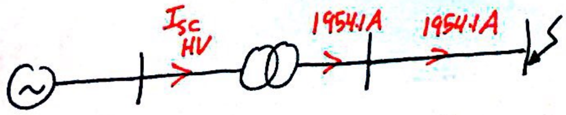
The equivalent circuit as follows:



$Z_{eq} = jX_{sc} + jX_T + Z_L = 0.88 + j2.07$ PU
$= \underline{2.24\angle 66.9^\circ}$ PU.

$I_{sc_{3\phi}} = \frac{1}{Z_{eq}} = \frac{1}{2.24\angle 66.9^\circ} = \underline{0.442\angle -66.9^\circ}$ PU

$I_b = \frac{MVA_b}{\sqrt{3}\, V_{LL_b}} = \frac{100\times 10^6}{\sqrt{3}\times 13.2\times 10^3} = \underline{4373.9\,A}$ $\quad \Rightarrow I_{sc\,(A)} = I_{sc_{PU}} \times I_b\big|_{13.2K} \Rightarrow |I_{sc}|_{LV} = 1954.1\,A$



$\Rightarrow I_{sc_{HV}} = 1954.1 \times \frac{13.2}{115}$

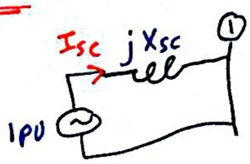
$I_{LV} = \frac{MVA_T}{\sqrt{3}\, V_{LL_{LV}}}$, $I_{HV} = \frac{MVA_T}{\sqrt{3}\, V_{LL_{HV}}}$

$I_{sc_{HV}} = 224.3\,A$

$\Rightarrow \frac{I_{HV}}{I_{LV}} = \frac{V_{LL_{LV}}}{V_{LL_{HV}}} = \frac{13.2}{115}$

Q2 for fault @ Bus ①:

$$I_{sc_{3P①}} = \frac{MVA_{sc}}{\sqrt{3}\,V_{LL}} = \frac{950\times10^6}{\sqrt{3}\times115\times10^3} = \underline{4769.4\ A}$$



another method to find $I_{sc_{3p①}}$:

$MVA_b = 100$

$MVA_{sc_{PU}} = \frac{950}{100} = 9.5\ PU$

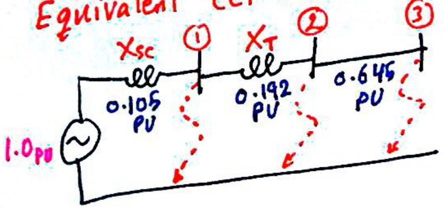
$I_{b_{115KV}} = \frac{MVA_b}{\sqrt{3}\,V_{LL}} = 502\ A.$

$I_{sc} = MVA_{sc\,PU} \Rightarrow I_{sc} = \frac{1}{X_{sc}} = 9.5\ PU$

$I_{sc_{(A)}} = I_{sc_{PU}} \times I_b = 9.5\times502 \Rightarrow I_{sc_{(A)}} = \underline{4769.4A}$ #

$X_{sc} = \frac{1}{9.5}\ PU$

Equivalent cct as follows:



• Using PU concept:

$X_{T_{pu\,old}} = \frac{4.8}{100} = 0.048\ PU$

$X_{T_{new}} = 0.048 * \frac{100}{25} = 0.192\ PU$

$X_{TL_{pu}} = \frac{X_{L\Omega}}{X_b} = \frac{1.125}{1.7424} = 0.645\ PU.$

$X_b = \frac{V_{LL}^2}{S_b} = \frac{(13.2)^2}{100} = 1.7424\ \Omega$

for fault @ bus ②:

$I_{sc_{②\,3P}} = \frac{1}{0.105+0.192} = 3.367\ PU \Rightarrow I_{sc_{②\,3P}} = 3.367\times4373.8$

$= \underline{14.73\ KA}.$ #

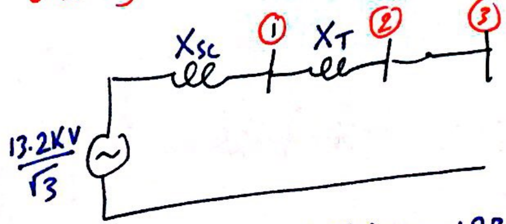
$I_b\big|_{13.2KV} = \frac{100\times10^6}{\sqrt{3}\times13.2\times10^3} = 4373.8A.$

for fault @ Bus ③:

$I_{sc_{③\,3P}} = \frac{1}{0.105+0.192+0.645} = 1.06\ PU \Rightarrow I_{sc_{③\,3P}} = 1.06\times4373.8$

$= \underline{4636.2A}.$ #

• Using ohmic concept:



$X_{sc} = 0.105\times1.74 = 0.1827\ \Omega$

$X_T = 0.192\times1.74 = 0.334\ \Omega$

$X_L = 1.125\ \Omega$

$\frac{115}{13.2} = \underline{8.7}$

for fault @ Bus ①:

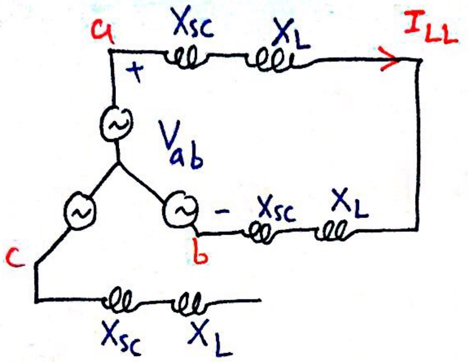
$I''_{sc_①} = \frac{13.2\times10^3/\sqrt{3}}{0.1827} = \underline{41.71\ KA}$

$I_{sc_①} = \frac{41.71K}{8.7} = \underline{4794.3\ A}$

$I_{sc_②} = \frac{13.2\times10^3/\sqrt{3}}{0.1827+0.334} = \underline{14749.4\ A}$

$I_{sc_③} = \frac{13.2\times10^3/\sqrt{3}}{0.1827+0.334+1.125} = \underline{4642.2A}$

* for L-L fault:



$$I_{LL} = \frac{|V_{ab}|}{2(X_L + X_{sc})} \quad ; \quad X_{eq} = X_L + X_{sc}$$

$$\Rightarrow I_{LL} = \frac{|V_{ab}|}{2X_{eq}} = \frac{\sqrt{3}}{2}\frac{V_{ph}}{X_{eq}} \quad ; \quad I_{3\phi\,fault} = \frac{V_{ph}}{X_{eq}}$$

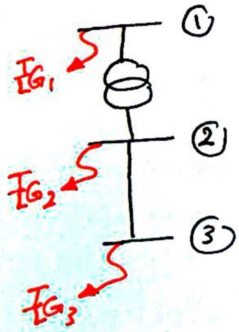
$$\Rightarrow I_{LL} = \frac{\sqrt{3}}{2} \times I_{3\phi f} \Rightarrow \boxed{I_{LL} = 0.866\, I_{3\phi f}}$$

*Note:
in fault calculations one consider the system "flat" and we neglect the loads.

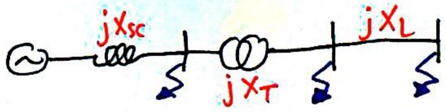
Now for L-G Fault:

$$I_{LG} = I_{a_1} + I_{a_2} + I_{a_0} \Rightarrow (I_a^+ + I_a^- + I_a^0) = I_{LG}$$

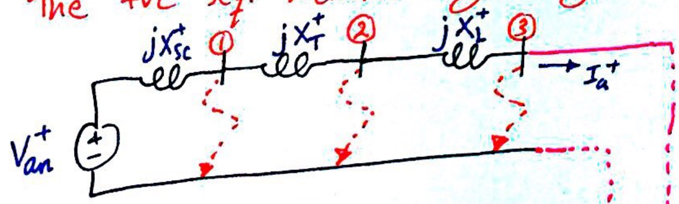
Here we need: +ve seq. network.
-ve seq. network.
zero seq. network.



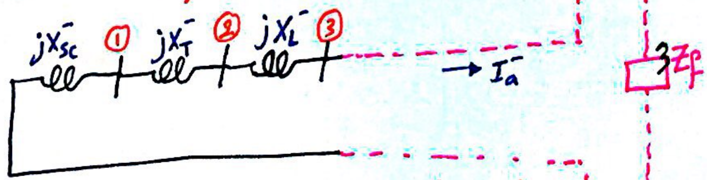
• if the system is Balanced, Then we just have +ve seq. network.



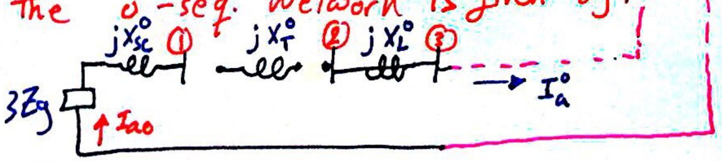
The +ve seq. NeworK is given by:



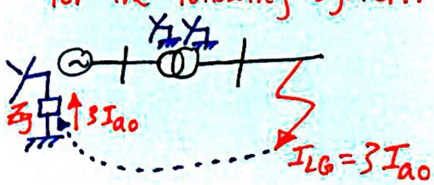
The -ve seq. NetworK is given by:



The o-seq. NetworK is given by:



for the following system:



$$I_a = I_a^+ + I_a^- + I_a^0$$
$$I_b = I_b^+ + I_b^- + I_b^0$$
$$I_c = I_c^+ + I_c^- + I_c^0$$

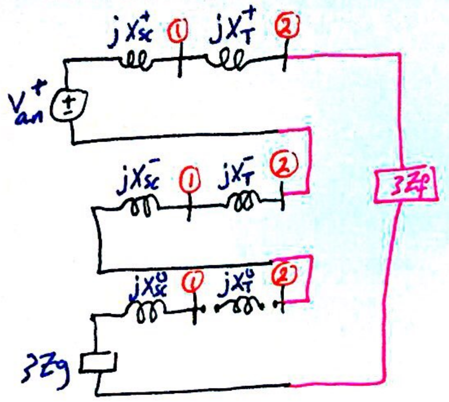
since there is an O/C:

$$\boxed{I_{LG} = Zero}$$

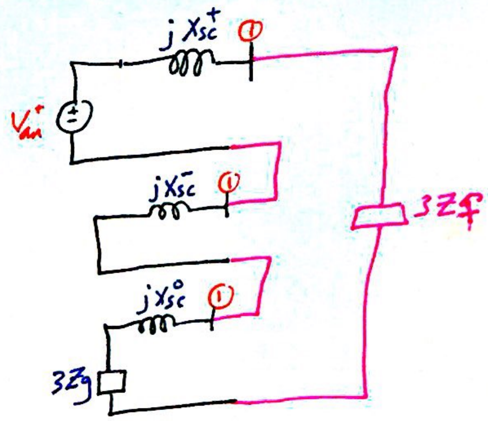
- if the previous circuit was closed, Then the current is found by:

$$\boxed{I_{LG} = 3I_{a0} = \frac{3V_{ph}}{\Sigma Z^+ + \Sigma Z^- + \Sigma Z^0}}$$

- The connection for L-G fault @ Bus ② as follows:

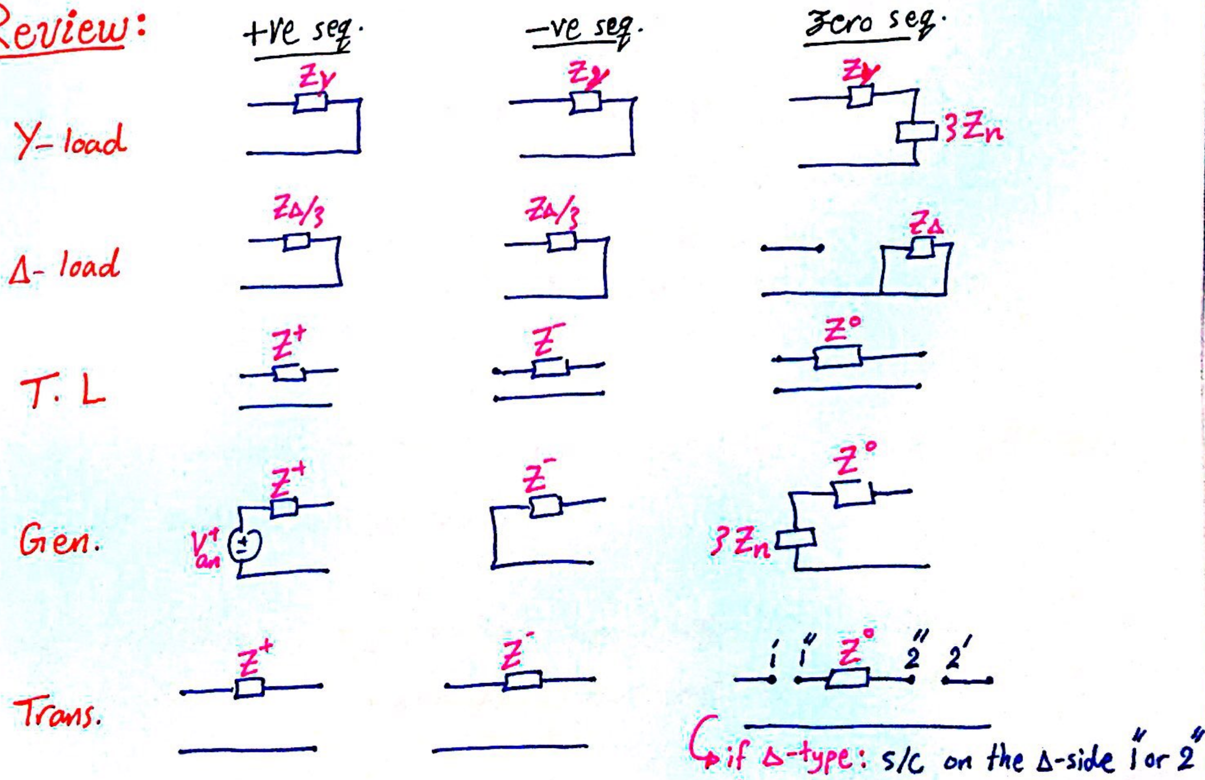


- The connection for L-G fault @ Bus ① as follows:



- **Note:**
  - ⇒ Reflecting the impedance to the Low voltage side, it will decrease $(/a^2)$.
  - ⇒ Reflecting the impedance to the High voltage side, it will increase $(*a^2)$.

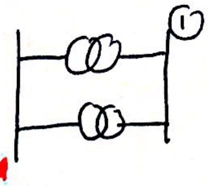
* Review:



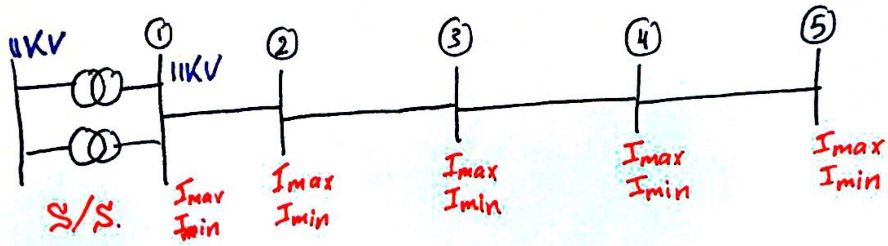
↳ if Δ-type: s/c on the Δ-side 1'' or 2''
if Y-type: connect $3Z_n$ if it is grounded.

Q3 | for Fig. Q3 represent a "distribution substation".

for substation we will use the shortcut "S/S".



infinite bus
"Connected to the Grid"



I_{min} is found when one transformer connected.
I_{max} is found when Both transformers are in service.

$$I_{f_{max}}^{①} = \frac{11\times10^3/\sqrt{3}}{2.5} = 2540\,A.$$

$$I_{f_{max}}^{②} = \frac{11\times10^3/\sqrt{3}}{2.5+9.6} = 525\,A.$$

$$I_{f_{max}}^{③} = \frac{11\times10^3/\sqrt{3}}{2.5+9.6+6.4} = 343\,A.$$

$$I_{f_{max}}^{④} = \frac{11\times10^3/\sqrt{3}}{2.5+9.6+6.4+8} = 240\,A.$$

$$I_{f_{max}}^{⑤} = \frac{11\times10^3/\sqrt{3}}{2.5+9.6+6.4+8+12.8} = 162\,A.$$

• Note:
⇒ I_{min} is found for $I_{f_{LL}}$ with one Tx in service

$$I_{f_{min}}^{①} = \frac{11\times10^3/\sqrt{3}}{5} \times \frac{\sqrt{3}}{2} = 1100\,A.$$

$$I_{f_{min}}^{②} = \frac{11\times10^3/\sqrt{3}}{5+9.6} \times \frac{\sqrt{3}}{2} = 377\,A.$$

$$I_{f_{min}}^{③} = \frac{11\times10^3/\sqrt{3}}{5+9.6+6.4} \times \frac{\sqrt{3}}{2} = 262\,A.$$

$$I_{f_{min}}^{④} = \frac{11\times10^3/\sqrt{3}}{5+9.6+6.4+8} \times \frac{\sqrt{3}}{2} = 190\,A.$$

$$I_{f_{min}}^{⑤} = \frac{11\times10^3/\sqrt{3}}{5+9.6+6.4+8+12.8} \times \frac{\sqrt{3}}{2} = 132\,A.$$

* The minimum current is represented by L-L fault current since it is smaller than 3-ph fault current. (i.e $I_{f_{LL}} = 0.866 \times I_{f_{3-ph}}$).

※ Power Systems Protection:

• The Relay that connected to the CT has a symbol "51" which indicates that is an over-current Relay.

• Voltage Transformer: → primary has large # of turns.
→ Secondary has small # of turns.

* Instrument Transformer:

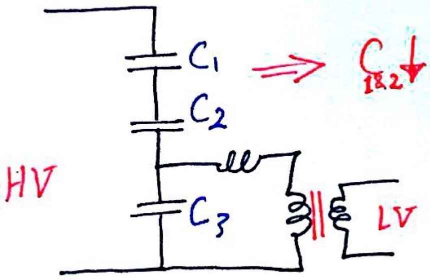
- CCVT ≡ Capacitor Couple Voltage Transformer.
- IED-Relay ≡ Intelligent Electronic Device.

* Disconnect Switch ⇒ "Isolator".

- Remember: $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$ if $I_2 << I_1 \Rightarrow N_2 >> N_1$

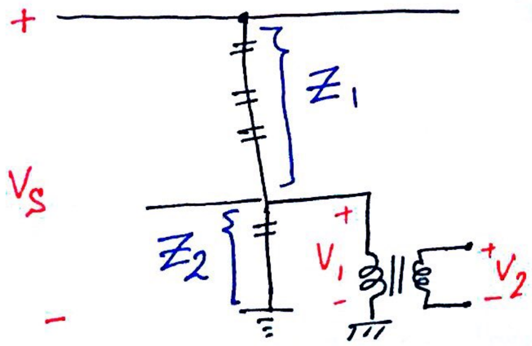
* Voltage Transformer:

we step-down the voltage using capacitor divider:



$\Rightarrow C_{1\&2}\downarrow \Rightarrow Z_C\uparrow \Rightarrow V\uparrow$

$C_3\uparrow \Rightarrow Z_C\downarrow \Rightarrow V\downarrow$



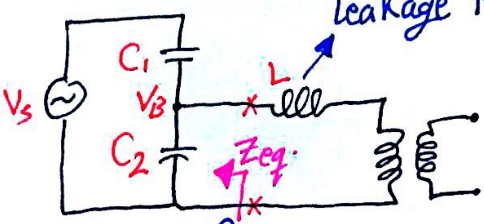
$$\Rightarrow V_1 = V_s \frac{Z_2}{Z_1+Z_2}$$

$$= V_s \frac{1/\omega C_2}{\frac{1}{\omega C_1} + \frac{1}{\omega C_2}} = V_s \frac{1}{\frac{C_2}{C_1}+1}$$

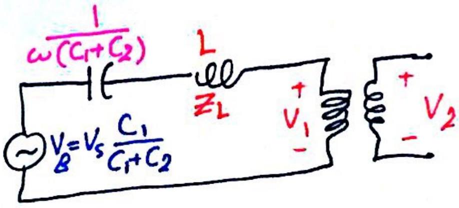
$$\Rightarrow V_1 = V_s \frac{C_1}{C_1+C_2}$$

* Electromagnetic Voltage Transformer:

Leakage Reactance.



$\Rightarrow$



$V_B = V_s \frac{C_1}{C_1+C_2}$, $Z_{eq.} = \frac{1}{j\omega(C_1+C_2)}$

@ High Freq. it will act as "LPF". $(Z_L = j\omega L)$

@ Resonance:

$$\omega L = \frac{1}{\omega(C_1+C_2)}$$

$$\Rightarrow L = \frac{1}{\omega^2(C_1+C_2)}$$

To deal with the phase shift.

* VT Ratio:

- The ratio 1:1 is used for "Isolation".

* Current Transformer:

- Doughnut type:

  ⇒ what will happen when the CT circuit is opened in loading condition?

  it will induce a very High Voltage with a large sparks which will cause an explosion if the CT is isolated by oil.

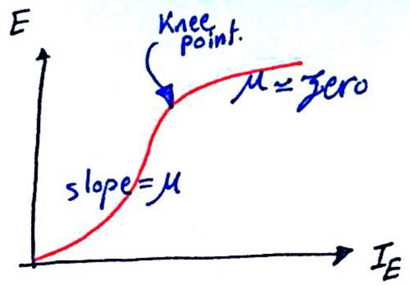
- The oil is used for: cooling & Isolation.

- CT ratio:

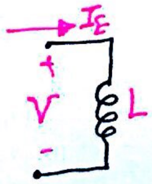
  Ex. for 1000 : 1 A

  $$\frac{N_1}{N_2} = \frac{I_2}{I_1} \Rightarrow \frac{N_1}{N_2} = \frac{1}{1000}$$ so need 1:1000 turns.

- CT - Excitation Characteristics:



μ ≡ Permability: it is a measure of How it is ease to establish the magnetic flux.

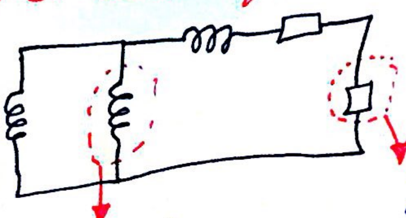


$$L = \frac{N^2}{\mathcal{R}} \;;\; \mathcal{R} \equiv \text{Reluctance} = \frac{l}{\mu A}$$

$$\Rightarrow L = \frac{N^2 \mu A}{l}$$

- we always work below the Knee point.

- CT-General Equivalent Circuit:



Magnetization Branch

it is the source of the error in the CT.

Burden of the Relay:

* CT Ratio ≡ CTR: $\frac{N_P}{N_S} = \frac{I_S}{I_P}$

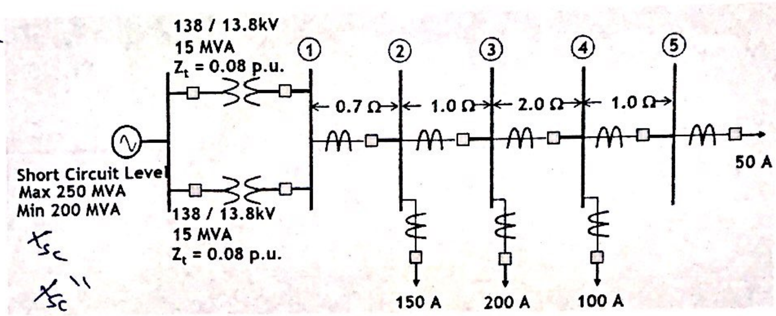
Question # 1:

For the power system shown below, use either the Ohmic or PU method to calculate the maximum 3-phase fault currents at buses 1, 2, 3, 4 and 5. For the PU method use an MVA base S_b of 100 MVA and a base voltage V_b of 13.8 kV at bus # 1.

$X''_T = \frac{(13.8)^2}{15}$

$X''_{sc\,max} = \frac{(13.8)^2}{250}$

$X_{sc\,min} = \frac{(13.8)^2}{200}$



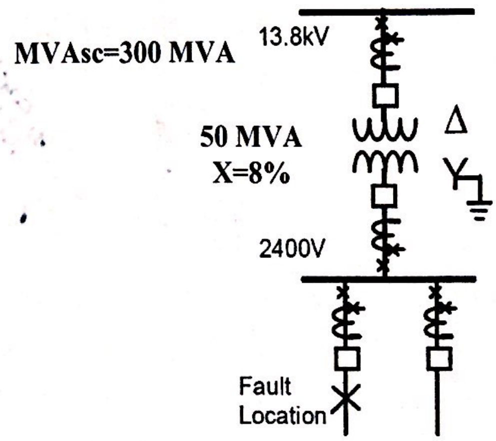
Bus #	①	②	③	④	⑤
I_{fmax} (A)					

Question # 2:

For the system shown below, use the per unit method to find the fault line currents in Amperes seen on the HV side of the transformer with those seen by at the fault location (LV side) for:

a. Three phase fault, $I_{F3ph\text{-}LV}$ and $I_{F3ph\text{-}HV}$.
b. Line-to-line fault, $I_{FLL\text{-}LV}$ and $I_{FLL\text{-}HV}$.
c. Line-to-ground fault, $I_{FLG\text{-}LV}$ and $I_{FLG\text{-}HV}$.

Use an MVA_{base}= 50 MVA and kVbase=13.8 kV at the HV side of the transformer .



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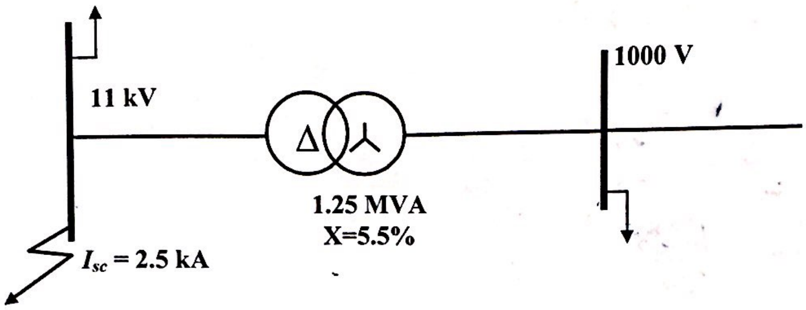
Question # 3:

For the system shown below, consider a base MVA=1.25 MVA, then calculate:

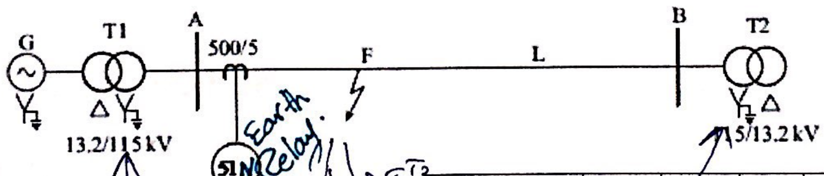
a) The short-circuit MVA at the 11 kV bus, MVA_{sc}.
b) The system short circuit impedance X_{sc} in Ohms and p.u.
c) Total system impedance in Ohms and p.u. from the source to the 1000 V bus, X_{tot}.
d) Three-phase fault current in Amperes at the 1000 V bus using Ohmic method, $I_{F\text{-}1000V}$.
e) Verify the three-phase fault current calculation at the 1000 V bus using the p.u. method.



Question # 4:

A solid line-to-ground fault on phase A is is represented by the arrow at the point F near Bus A in the power system shown below. The per unit +Ve, -Ve and zero-sequence reactances of the Generator, Transformers and Transmission line is given in the Table.

a. Draw the +Ve, -Ve and zero-sequence networks for the entire system.
b. Find the LG fault current I_{fLG} at the fault point F in pu.
c. Determine the current in Amperes that flow on both sides of the Dy1 transformer T1 and the Yd11 transformer T2. The bases at the Generator location are 13.2 kV and 100 MVA.
d. Indicate which relay(s) operate on the occurrence of the fault.



Reactance	G	T1	L	T2
X_1	0.15	0.11	0.4	0.3
X_2	0.15	0.11	0.4	0.3
X_0	0.09	0.11	1.2	0.3

※ Tutorial #1: Fault Calculations "part 2"

Q1

$$Z_{b(LV)} = \frac{(13.8)^2}{100} = 1.9\,\Omega \Rightarrow Z_{T(\Omega)} = (1.9)(0.53) = \underline{1.01\,\Omega}$$

$$Z_{T(pu)} = 0.08 \times \frac{100}{15} = \underline{0.53}$$

Max:

$$X_{sc(HV)} = \frac{(138)^2}{250} = 76.2\,\Omega \Rightarrow X_{sc(LV)} = \left(\frac{13.8}{138}\right)^2 \times X_{sc(HV)} = \underline{0.7\,\Omega}$$

for max fault current: $1.01 \,//\, 1.01 = \underline{0.505\,\Omega}$

$$I_{f_1} = \frac{13.8\times10^3/\sqrt{3}}{0.7+0.505} = 6612\,A \qquad I_{f_3} = \frac{13.8\times10^3/\sqrt{3}}{0.7+0.505+0.7+1} = 2742.7\,A.$$

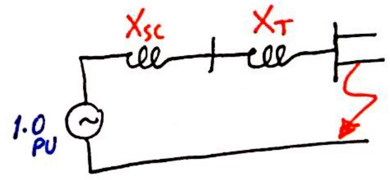
$$I_{f_5} = \frac{13.8\times10^3/\sqrt{3}}{0.7+0.505+0.7+1+2+1} = 1349.3\,A.$$

$$I_{f_2} = \frac{13.8\times10^3/\sqrt{3}}{0.7+0.505+0.7} = 4182.4\,A. \qquad I_{f_4} = \frac{13.8\times10^3/\sqrt{3}}{0.7+0.505+0.7+1+2} = 1624.3\,A.$$

Bus#	1	2	3	4	5
$I_{f_{max}}$ (A)	6612	4182.4	2742.7	1624.3	1349.3

* * *

Q2



$$MVA_{PU} = \frac{300M}{50M} = 6\ PU.$$

$$X_{sc_{PU}} = \frac{1}{6} = 0.167\ PU.$$

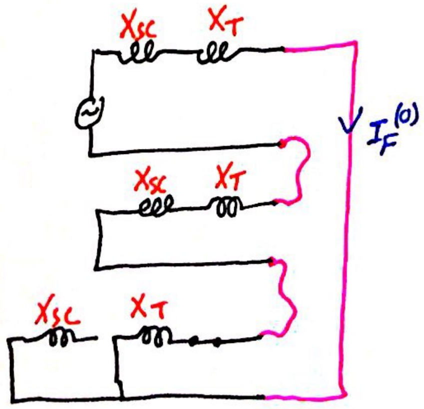
$$X_T = 0.08\ PU.$$

$$I_f = \frac{1}{0.167+0.08} = 4.05\ PU.$$

$$I_{b(LV)} = \frac{50\times10^6}{\sqrt{3}\times2400} = 12028\,A \Rightarrow \boxed{I_{f_{LV}} = 48713.4\,A} \Rightarrow I_{f_{LL}} = 0.866\, I_{f_{3\text{-}ph}}$$

$$\boxed{I_{f_{LL}} = 42185.8\,A}$$

$$I_{f_{HV}} = I_{f_{LV}} \times \frac{2400}{13.8\times10^3} \Rightarrow \boxed{I_{f_{HV}} = 8471.9\,A} \Rightarrow \boxed{I_{f_{LL}} = 7336.7\,A}$$



$$I_{f_{LG}} = 3I^{(0)} = \frac{3}{2X_{sc}+3X_T} = 5.23\ PU.$$

$$\Rightarrow \boxed{\begin{aligned} I_{LG_{LV}} &= 62906.4\,A. \\ I_{LG_{HV}} &= 10940.3\,A \end{aligned}}$$

* * *

... Continue.

Q3

a) $MVA_b = 1.25\ MVA$

$MVA = \sqrt{3}\ V_{LL}\ I_{sc}$

$= \sqrt{3}\ (2.5K)(11K)$

$= 47.6\ MVA.$

$\Rightarrow MVA_{pu} = \frac{47.6}{1.25} = 38.1\ PU.$

b) $X_{sc} = \frac{1}{MVA_{PU}}$

$= \frac{1}{38.1}$

$\Rightarrow X_{sc} = 0.026\ PU$

$Z_{b(LV)} = \frac{(1000)^2}{1.25 \times 10^6} = 0.8\Omega$

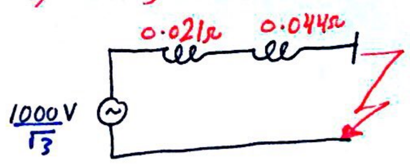
$\Rightarrow X_{sc} = 0.021\Omega$

c) in PU: $X_{tot} = 0.026 + 0.055 = 0.081\ PU$

in ohm: $X_{tot} = 0.021 + X_T$ $\quad X_{T_{LV}} = (0.055)(0.8) = 0.044\Omega$

$= 0.021 + 0.044 = 0.065\ \Omega$

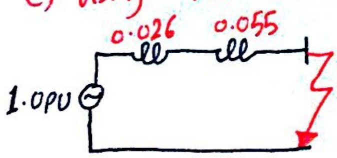
d) using ohmic method:



$\Rightarrow |I_f| = \frac{1000/\sqrt{3}}{0.065} = 8882.3\ A. \simeq 8.9\ KA$

#

e) using PU method:



$\Rightarrow I_f = \frac{1}{0.081} = 12.35\ PU.$

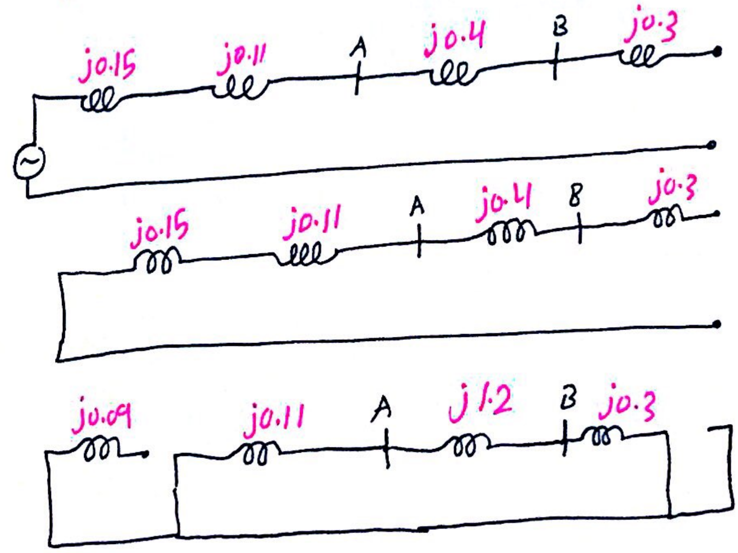
$I_{b_{LV}} = \frac{1.25 \times 10^6}{\sqrt{3} \times 1000} = 721.7A.$

$|I_f| = 721.7 \times 12.35 = 8913\ A \simeq 8.9KA.$

#

* * *

Q4 a)



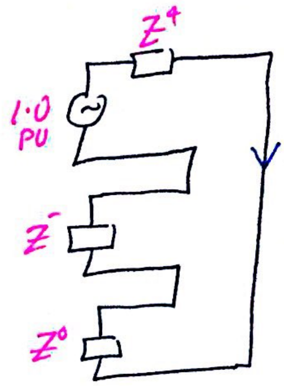
... Continue

b) for a LG fault @ point F:

$Z^+ = j0.11 + j0.15 = j0.26$

$Z^- = j0.11 + j0.15 = j0.26$

$Z^0 = (j0.11) // (j1.5) = j0.102$



$$I_{LG} = 3I^{(0)} = \frac{3}{Z^+ + Z^- + Z^0} = 4.82 \text{ PU}$$

c) By using Current Division:

for T_1: $I^{(0)} = 1.61 \dfrac{1.5}{1.5+0.11} = 1.5$ PU.

for T_2: $I^{(0)} = 1.61 - 1.5 = 0.11$ PU.

$$I_b = \frac{100 \times 10^6}{\sqrt{3} \times 115 \times 10^3} = 502 \text{ A}.$$

⇒ for T_1:

$I_{LG} = 3I^{(0)} = 4.5$ PU

$I_{LG(HV)} = (4.5) \times (502)$

⇒ $I_{LG(HV)} = 2259$ A

⇒ $I_{LG(LV)} = 2259 \times \dfrac{115}{13.2}$

⇒ $I_{LG(LV)} = 19680.7$ A

⇒ for T_2:

$I_{LG} = 3I^{(0)} = 0.33$ PU

$I_{LG(HV)} = (0.33) \times (502)$

⇒ $I_{LG(HV)} = 165.66$ A

⇒ $I_{LG(LV)} = 165.66 \times \dfrac{115}{13.2}$

⇒ $I_{LG(LV)} = 1443.25$ A

* * *

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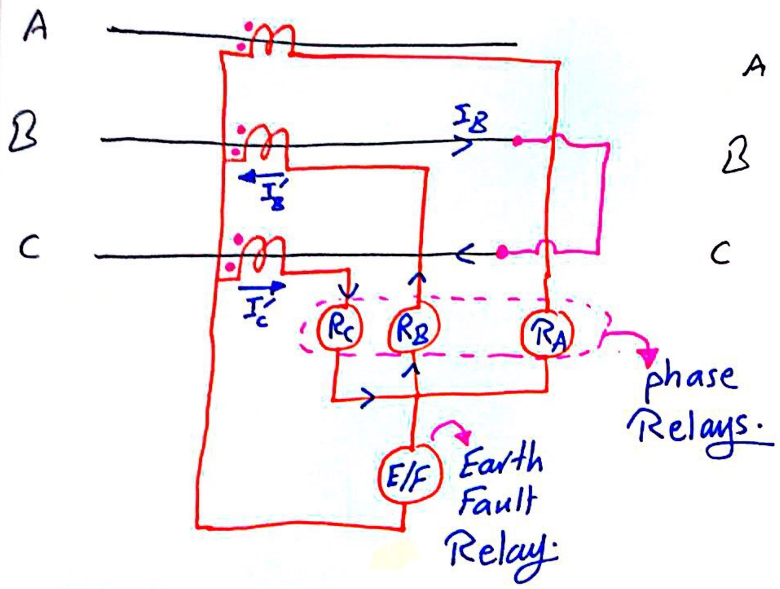
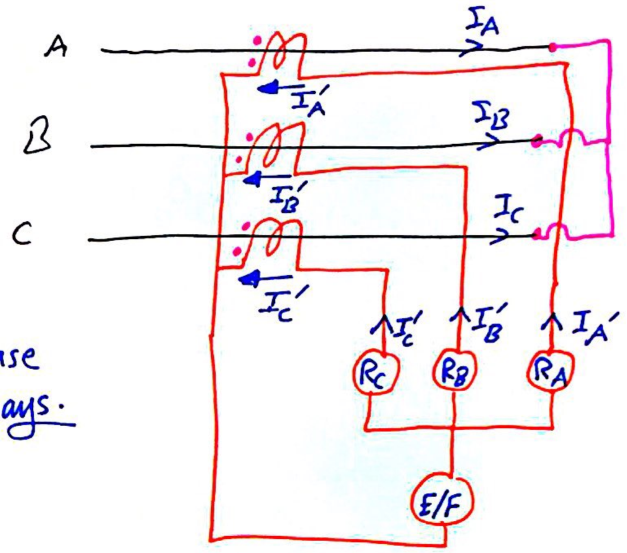
* for Example 6 in slides:

• Two-phase fault: (B&C)



• Three-phase Fault:



* Dot Convention:

- if the current entering the Dot in the primary, then it is leaving the Dot in the secondary.
- if the current leaving the Dot in the primary, then it is entering the Dot in the secondary.

* Phase Relays discover:
- L-L-L fault.
- L-L fault.

* Earth Fault Relay discover:
- L-G fault.
- L-L-G fault.
- Unbalanced fault.

* Criteria of Choosing CT's:

1) Voltage operate below the Knee point value.

2) Current base on Max. load seen by the CT.

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Question # 1:

The conductor of one phase of a three-phase transmission line operating at 345 kV, 600 MVA, has a CT and a VT connected to it. The VT is connected between the line and ground as shown in Fig. 1. The CT ratio is 1200:5 and the VT ratio is 3000:1. Determine the CT secondary current and VT secondary voltage.

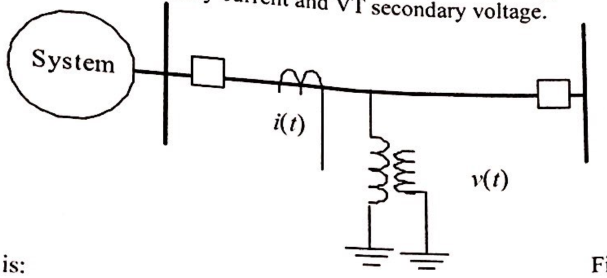

Fig. 1

The VT secondary voltage is:

$$V' = \frac{345/\sqrt{3}\times 10^3}{3000} = 66.4\ V$$

The current flowing through the line is:

$$I = \frac{600\times 10^6}{\sqrt{3}\times 345\times 10^3} = 1004.2.4\ A$$

Therefore the CT secondary current is:

$$I = \frac{1004.2.4\times 5}{1200} = 4.2\ A$$

Question # 2:

Consider the single-phase CVT shown in Fig. 2. The open circuit voltage requirement of the CVT is 100 V, while the line voltage connected across terminal A is 100 kV. Find the values of C1 and C2 such that there is no phase displacement between the line voltage and the output of the CVT. The leakage inductance (L) of the transformer is 1 mH and the supply frequency is 50 Hz.

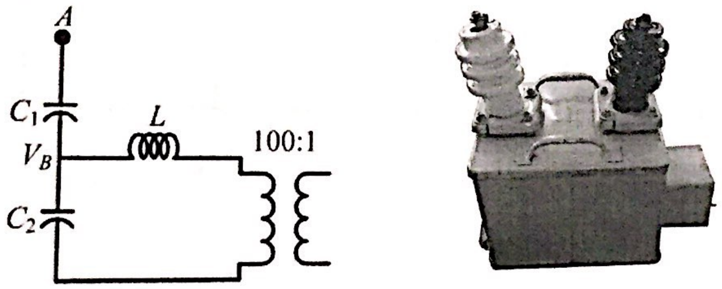

Fig. 2

Consider the circuit of Fig. 2. The open-circuit voltage across C_2 is given by

$$V_B = \frac{V_A(1/j\omega C_2)}{1/j\omega C_1 + 1/j\omega C_2} = V_A\frac{C_1}{C_1+C_2}$$

Now we want 100 V at the output of the VT, which has a turns ratio of 100:1. Therefore,

$$100\times 100 = 100\times 10^3\frac{C_1}{C_1+C_2} \Rightarrow C_1 + C_2 = 10C_1 \quad \Rightarrow C_2 = 9C_1$$

Again from the phase shift requirement, we have

$$L = \frac{1}{\omega^2(C_1+C_2)} \Rightarrow C_1 + C_2 = \frac{1}{\omega^2 L} \Rightarrow 10C_1 = \frac{10^3}{(2\pi\times 50)^2} \Rightarrow C_1 = 1013.2\ \mu F$$

$$C_2 = 9C_1 = 9\times 1013{,}2\mu F \Rightarrow C_2 = 9118.9\ \mu F$$

Question # 3:

The circuit has an A phase to ground fault on the line, with fault current magnitude of 16 kA at 0°.
The circuit of Fig.1 has 1000:5 class C100 CTs. Given the following:
CT Winding Resistance $R_C = 0.342\ \Omega$
Burden resistance for phase relay $R_{ph} = 0.50\ \Omega$
Burden resistance for E/F relay $R_E = 0.59\ \Omega$
Leed Resistance (One leed) $R_L = 0.224\ \Omega$

Calculate,

a. the current seen by the secondary of the CT, I_{as}.
b. the total connected resistance seen by the phase CT, R_T.
c. the CT Secondary Voltage for phase to ground fault, V_s.
d. Does the CT get Saturated at the above LG fault current?

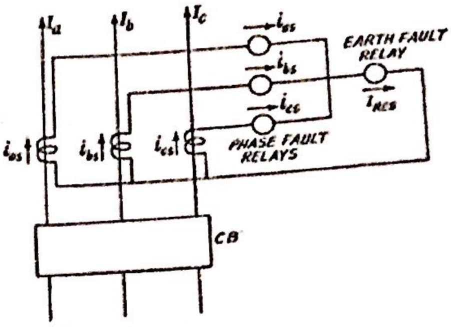

Fig. 1

Solution

a. Secondary Fault Current
$I_{as} = I_f/CTR = 16000/(1000/5) = 16000/200 = 80$ A.
b. Total connected resistance seen by the phase CT,
$R_T = R_C + R_{ph} + R_E + R_L$
$R_T = 0.342 + 0.50 + 0.59 + 0.448 = 1.88\ \Omega$.
c. CT secondary voltage for ground fault:
$V_s = I_{as} R_T$
$V_s = 80\times1.88 = 150.4V \sim 150V$

A CT with a saturation voltage of 100 V would experience substantial saturation for this fault. This saturation would cause a large reduction in the current delivered

Question #4:

A distribution feeder has 600 /5 C 100 CT with a knee point 100 Volt. A three phase fault of I_f = 10200 A occurs at F as shown in Fig. Q3.

a. Calculate the voltage developed across CT if the phase relay burden resistance Z_R =0.10Ω, the lead resistance R_L = 0.50Ω, and the CT resistance R_S = 0.40Ω.
b. Will this fault current lead to CT saturation?
c. If not, at what fault level, the CT will saturate?

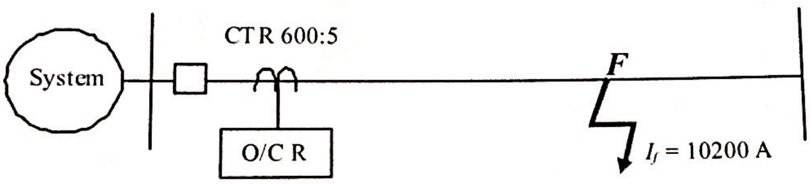

Fig. Q4

Solution:

\?

Effective impedance seen by the CT $= R_S + R_L + Z_R$

$= (0.40 + (0.5) + 0.10)$

$= 1.0$

Vs $= I_S \times 1$

$= (10200/120)\times1.0 = 85V$

Not Saturated.

Since, the knee point is 100 V the CT will saturate at 100 V corresponding to I_f = 12000 A.

\?

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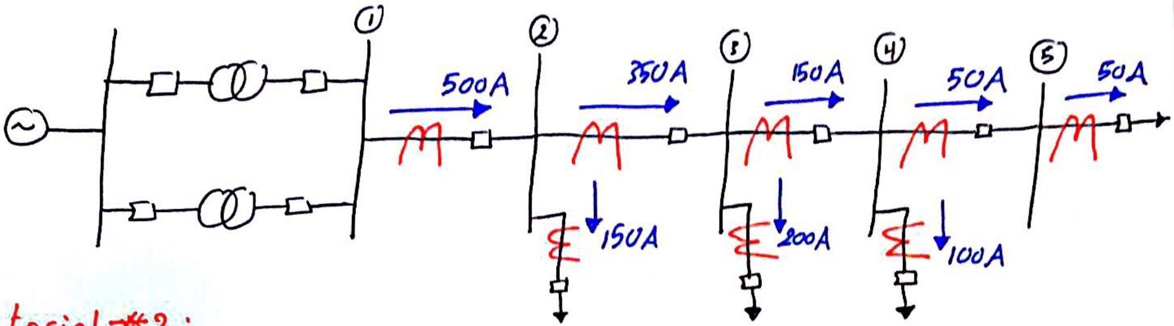
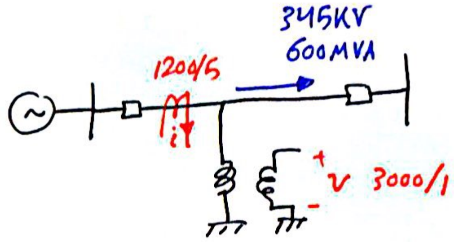
* Example 7 in slides:



* Tutorial #2:

Q1

Assume Y-Y-connected



$$CTR = \frac{1200}{5} = \frac{N_2}{1}$$

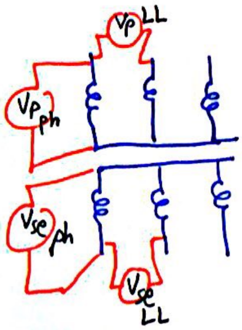
$$VTR = \frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{3000}{1}$$

$$I_L = \frac{600\times10^6}{\sqrt{3}\times345\times10^3} = \underline{1004.1\,A.}$$

$$I_{sec} = \frac{I_L}{CTR} = \frac{1004.1}{\frac{1200}{5}} = \underline{4.2\,A.}$$

$$V_{sec} = \frac{345\times10^3}{3000} = \frac{345}{3} = \underline{115\ V_{LL}}$$

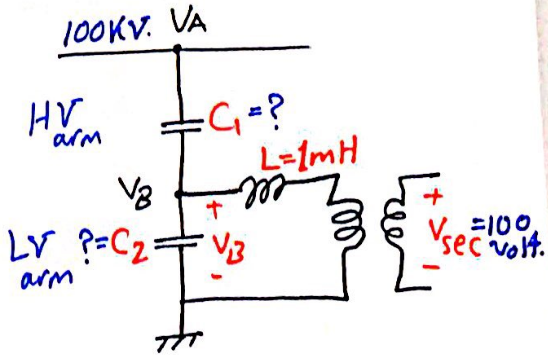
$$V_{sec_{ph}} = \frac{115}{\sqrt{3}} = \underline{66.4\text{ volt.}}$$



we can deal with both LL & phase they will give same Ratio.

* * *

Q2



$$Z_{C_1} >> Z_{C_2} \Rightarrow C_2 >> C_1$$

@ Resonance: $$L = \frac{1}{\omega^2[C_1+C_2]} \quad \cdots (1)$$

which will cancel the phase shift.

$$\Rightarrow V_B = V_A \frac{C_1}{C_1+C_2} \quad \cdots (2)$$

from equ. (1):

$$C_1+C_2 = \frac{1}{\omega^2 L} = \frac{1}{(314)^2\times10^{-3}} = 10.132\,mF. \quad \cdots (3)$$

$\Longrightarrow$ Continue.

$\Rightarrow$ from equ. ②: $V_B = \frac{C_1}{C_1+C_2} V_A$

$10K = \lambda \times 100K$

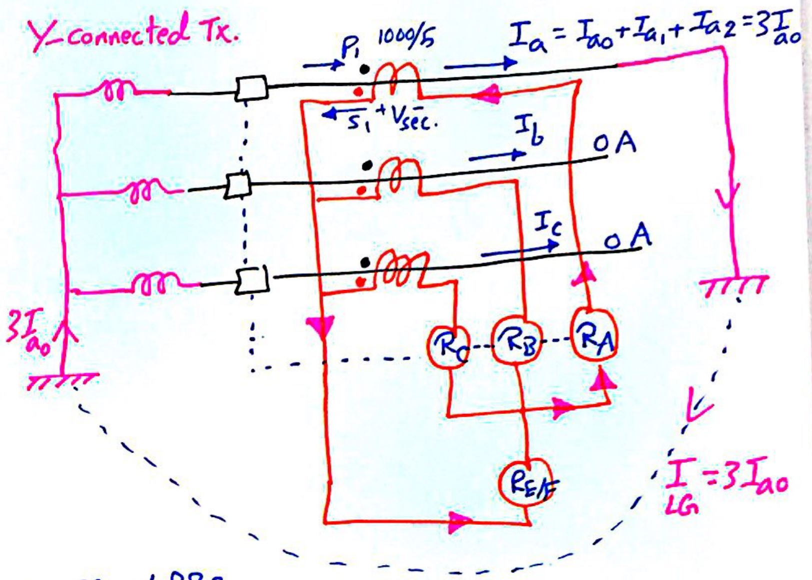
$\Rightarrow \lambda = \frac{1}{10} = \frac{C_1}{C_1+C_2} \Rightarrow C_2 = 9C_1 \cdots ④$

Solving ③ & ④:

$\boxed{C_1 = 1013.2\mu F \quad C_2 = 9118.8\mu F}$

* * *

Q3



$V_{sec} = I_f''(R_{ph} + R_{E/F} + 2R_L + R_c)$

$I_{sec} = \frac{16000}{1000} \times 5 = \underline{80A}$.

R_c: Secondary Winding Resistance.

R_{ph}: Relay A resistance. (0.5Ω).

$R_{E/F}$: E/F relay resistance (0.59).

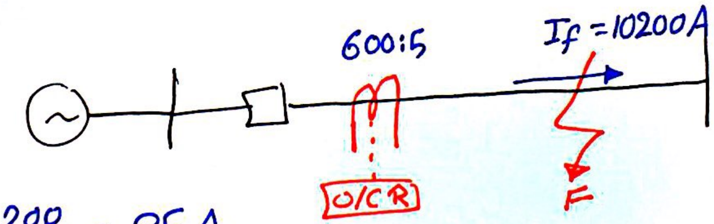
$R_{Total} = R_c + 2R_L + R_{ph} + R_{E/F}$

$= 0.342 + 2 \times 0.224 + 0.5 + 0.59 = \underline{1.88\Omega}$

$V_{sec} = 80 \times 1.88 \simeq \underline{150 \text{ volt}}$.

* * *

Q4



$I_{sec} = \frac{I_f}{CTR} = \frac{10200}{\frac{600}{5}} = \underline{85A}$.

$R_T = R_L + Z_R + R_s = 0.5 + 0.1 + 0.4 = \underline{1\Omega}$.

$V_s = (I) \times (R_T) = \underline{85 \text{ volt}}$.

* * *

Question # 1:

The current plug (tap) settings (CTS) of a GEC 5-A overcurrent relay can be varied from 1 A to 12 A and the TMS can be varied from 0.5 to 10 as shown in Fig. 1. If the input current to the overcurrent relay is 10 A, determine the relay operating time for the following current tap setting (CTS) and time dial setting (TDS):

(a) CTS = 1.0 and TDS = ½;

(b) CTS = 2.0 and TDS = 1.5;

(c) CTS = 2.0 and TDS = 7;

(d) CTS = 3.0 and TDS = 7; and

(e) CTS = 12.0 and TDS = 1.

Use the overcurrent relay characteristics

$$t_p = TDS \times \left(\frac{A}{I_r^p - 1} + B \right)$$

t_p is the pickup or operating time

I_r is the ratio of $|I_f|/|I_p|$

$A = 28.2$, $B = 0.1217$ and $p = 2.0$

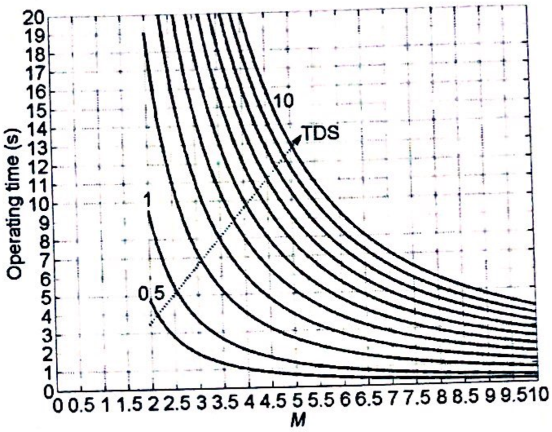


Fig. 1

Solution:

(a) CTS=1.0, then $I_r=|I_f|/|I_p|=10$. Therefore,

$$t_p = 0.5 \times \left(\frac{28.2}{10^2 - 1} + 0.1217 \right) = 0.2033\,\text{sec}$$

(b) CTS=2.0, then $I_r=|I_f|/|I_p|=5$. Therefore,

$$t_p = 1.5 \times \left(\frac{28.2}{5^2 - 1} + 0.1217 \right) = 1.945\,\text{sec}$$

(c) CTS=2.0, then $I_r=|I_f|/|I_p|=5$. Therefore,

$$t_p = 7 \times \left(\frac{28.2}{5^2 - 1} + 0.1217 \right) = 9.0769\,\text{sec}$$

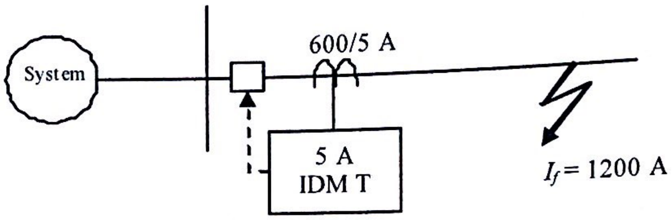
(d) CTS=3.0, then $I_r=|I_f|/|I_p|=3.33$. Therefore,

$$t_p = 7 \times \left(\frac{28.2}{3.33^2 - 1} + 0.1217 \right) = 20.418\,\text{sec}$$

(e) CTS=12.0, then $I_r=|I_f|/|I_p|<1$. Therefore, the relay does not operate.

Question # 2:

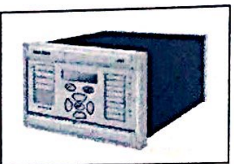
The calculated short-circuit current through a feeder is 1200 A. An overcurrent relay of rating 5 A is connected for the protection of the feeder through a 600/5 A CT as shown in Fig. 2.



PS = 50%, TMS= 0.8

Fig. 2

Calculate the operating time of the relay when it has a plug setting (PS) of 50% and time multiple setting (TMS) of 0.8. The characteristic of the relay is as follows:

PSM	1.3	2	4	6	10	20	
Time (sec)	30	10	6.5	3.5	3	2.2	

Solution:

$$I_{pickup} = PS \times I_{rated} = 0.5 \times 5 = 2.5\ A$$

$$I_{f-relay} = \frac{I_f}{CTR} = \frac{1200}{600/5} = 10\ A$$

$$PSM = \frac{I_{f-relay}}{I_{pickup}} = \frac{10}{2.5} = 4$$ ➔ operating time at TMS = 1 is 6.5 s

Actual operating time $t_p = 6.5 \times TMS$ ➔ $t_p = 6.5 \times 0.8 = 5.2\ s$

Question #3:

Figure 3 shows a radial distribution system having identical IDMT overcurrent at A, B and C. For a time delay step (Δt) of 0.5 s, calculate the time multiplier settings (TMS) at A and B.

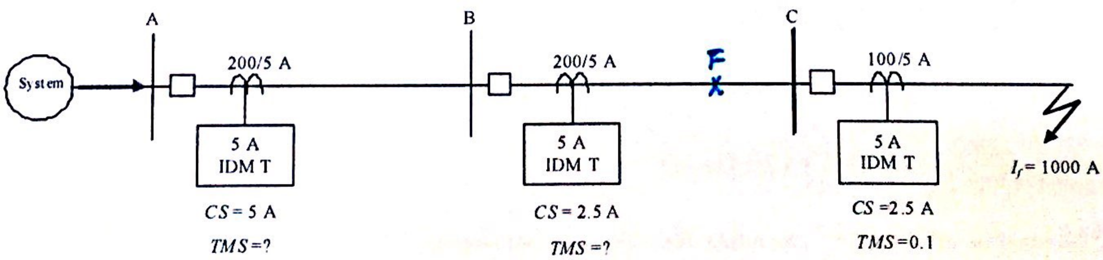


Fig. 3

The characteristic of the IDMT relay is as follows:

PSM	2	3	5	10	20
Time (sec)	10	6	4.5	3	2

Solution:

For relay C,

$TMS_C = 0.1,\ I_{C-pickup} = 2.5\ A \quad I_{C-relay} = \dfrac{I_{Cf}}{CTR_C} = \dfrac{1000}{100/5} = 50\ A \quad PSM_C = \dfrac{I_{C-relay}}{I_{C-pickup}} = \dfrac{50}{2.5} = 20$

➔ operating time at TMS = 1 is 2 s

Actual operating time of relay C is $t_p = 2 \times TMS$ ➔ $t_p = 2 \times 0.1 = 0.2\ s$

For relay B,

$I_{B-pickup} = 2.5\ A \quad I_{C-relay} = \dfrac{I_f}{CTR_C} = \dfrac{1000}{200/5} = 25\ A \quad PSM_C = \dfrac{I_{C-relay}}{I_{C-pickup}} = \dfrac{25}{2.5} = 10$

➔ operating time at TMS = 1 is 3 s

Actual operating time of relay B is t_p = 0.2 + 0.5 = 0.7 s = $3 \times TMS$ ➔ $TMS_B = \dfrac{0.7}{3} = 0.233$

For relay A,

$I_{A-pickup} = 5\ A \quad I_{A-relay} = \dfrac{I_f}{CTR_A} = \dfrac{1000}{200/5} = 25\ A \quad PSM_A = \dfrac{I_{A-relay}}{I_{A-pickup}} = \dfrac{25}{5} = 5$

➔ operating time at TMS = 1 is 4.5 s

Actual operating time of relay A is t_p = 0.2 + 0.5+0.5 = 1.2 s = $4.5 \times TMS$ ➔ $TMS_A = \dfrac{1.2}{4.5} = 0.266$

Question #4:

A 20 MVA Transformer which is used to operate at 30% overload feeds an 11 kV busbar through a circuit breaker (CB) as shown in Fig. 4. The transformer CB is equipped with a 1000/5 CT and the feeder CB with 400/5 CT and both CTs feed IDMT relays having the following characteristics

PSM	2	3	5	10	15	20
Time (sec)	10	6	4.1	3	2.5	2.2

The relay on the feeder CB has PS = 125% and TMS = 0.3. If a fault current of 5000 A flows from the transformer to the feeder, determine

a. operating time of feeder relay.

b. Suggest suitable PS and TMS of the transformer relay to ensure adequate discrimination of 0.5 s between the transformer relay and feeder relay.

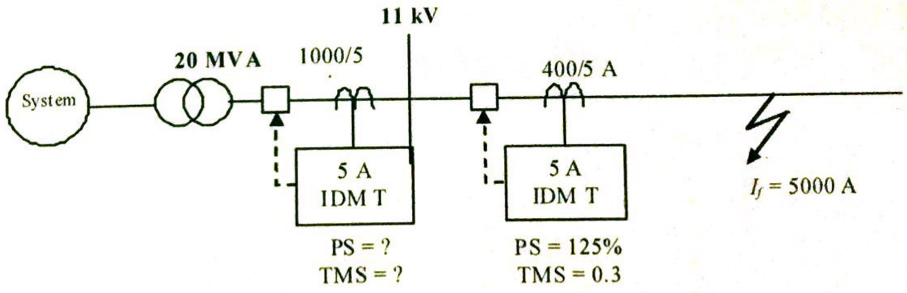


Fig. 4

Solution:

For Feeder relay

$TMS_{Feeder} = 0.3$, $PS = 125\%$ ➔ $I_{Feeder-pickup} = PS \times I_{rated} = 1.25 \times 5 = 6.25\ A$

$$I_{Feeder-relay} = \frac{I_f}{CTR_{Feeder}} = \frac{5000}{400/5} = 62.5\ A \quad PSM_{Feeder} = \frac{I_{Feeder-relay}}{I_{Feeder-pickup}} = \frac{62.5}{6.25} = 10$$

➔ operating time at TMS = 1 is 3 s

Actual operating time of the Feeder relay is $t_p = 3 \times TMS$ ➔ $t_p = 3 \times 0.3 = 0.9\ s$

For Transformer relay, $I_{Transformer-pickup} = PS \times I_{rated}$

Transformer overload current, $I_T = 1.3 \times \dfrac{S_{rated}}{\sqrt{3}V_{LL}} = 1.3 \times \dfrac{20 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 1365\ A$

$$I_{Transformer-relay} = \frac{I_{Transformer-overload}}{CTR_{Transformer}} = \frac{1365}{1000/5} = 6.825\ A$$

Since the transformer relay must not operate to overload current, $\mathrm{PS}_{\mathrm{Transformer}} > \dfrac{\mathrm{I}_{\mathrm{Transformer\text{-}relay}}}{\mathrm{I}_{\mathrm{relay\text{-}rated}}}$

$\mathrm{PS}_{\mathrm{Transformer}} > \dfrac{6.825}{5} > 1.365$ *or* 136.5%, the PS are restricted to standard values in steps of 25%, so the nearest value but higher than 136.5% is 150% ➔ $\mathrm{PS}_{\mathrm{Transformer}} = 150\%$

$$I_{Transformer-pickup} = PS_{Transformer} \times I_{rated} = 1.5 \times 5 = 7.5\ A$$

$$PSM_{Transformer} = \frac{I_{f-Transformer-relay}}{I_{Transformer-pickup}} = \frac{5000/(1000/5)}{7.5} = \frac{25}{7.5} = 3.3$$

Operating time corresponding to $PSM_{Transformer} = 3.3$ and TMS=1 from the PSM-time curve is

t_p **= 5.6 s,** Actual operating time of transformer relay is $t_p = 0.9 + 0.5 = 1.4$ s $= 3 \times TMS$

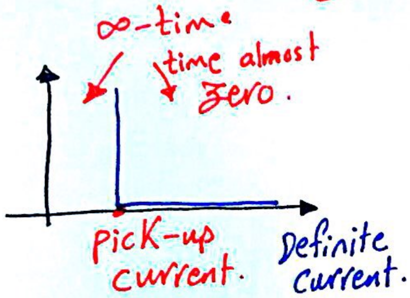
$$➔ TMS_{Transformer} = \frac{1.4}{5.6} = 0.25$$

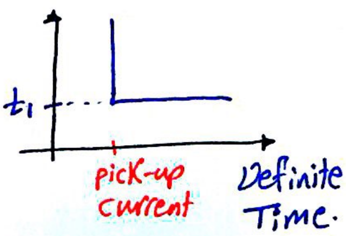
※ Over Current Protection:

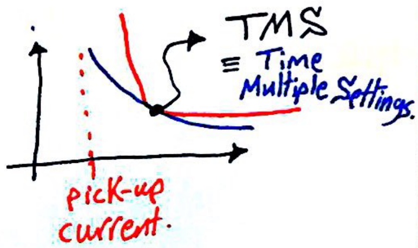
- every 50HZ cycle ⇒ 20msec period.

- **Note:**
  - ⇒ If the current is high, then the contact will be opened faster.
  - ⇒ If the current is Low, then the contact will take a longer period to be opened.

* Over current Types: "slide 7"







* IDMT Relay:

⇒ The movement of the disc needs force (Torque) depends on:
The induced current & the flux which is also produced by the current, so $\tau \propto I^2$. $(\tau = K \phi I)$

- PSM could be found from the ratio of primary currents or secondary currents
  Ex in slides: $PSM = \frac{1000}{100}$ or $\frac{50}{5} = 10$

$$PSM = \frac{I_{relay}}{I_{pickup}} = \frac{I_f''}{I_p}$$

* * *

※ Tutorial #3:

Q1 Note that it could be given an equation for t_p or the characteristics table for finding t_p.

Here an equation is given.

$$t_p = TDS \times \left[\frac{28.2}{I_r^2 - 1} + 0.1217 \right]$$

(a) CTS = 1 & TDS = 1/2.

$$I_r = \frac{I_f''}{I_{pick\text{-}up}} = \frac{10}{1} = 10 \Rightarrow t_p = 0.2033 \text{ sec.}$$

& so on for the other parts ...

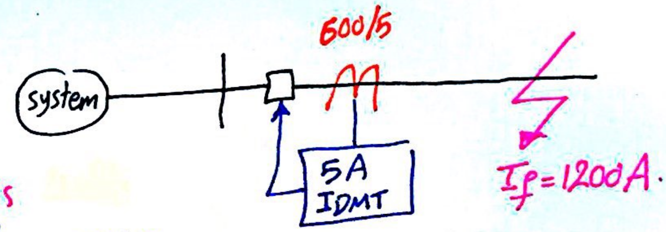
(e) CTS = 12 & TDS = 1

since $I_r = \frac{10}{12} < 1$ ⇒ the relay does NOT operate.

* * *

Q2 PS = 50% ⇒ 2.5A.

TMS = 0.8



The equation that corrisponds to this is given (@ TMS = 1): $t_p = \frac{3}{\log(PSM)} \times TMS$.

$$I_f'' = \frac{1200}{\frac{600}{5}} = 10A \Rightarrow \text{so } PSM = \frac{I_f''}{I_p} = \frac{10}{2.5} = 4$$

* This Table is given @ TMS = 1.

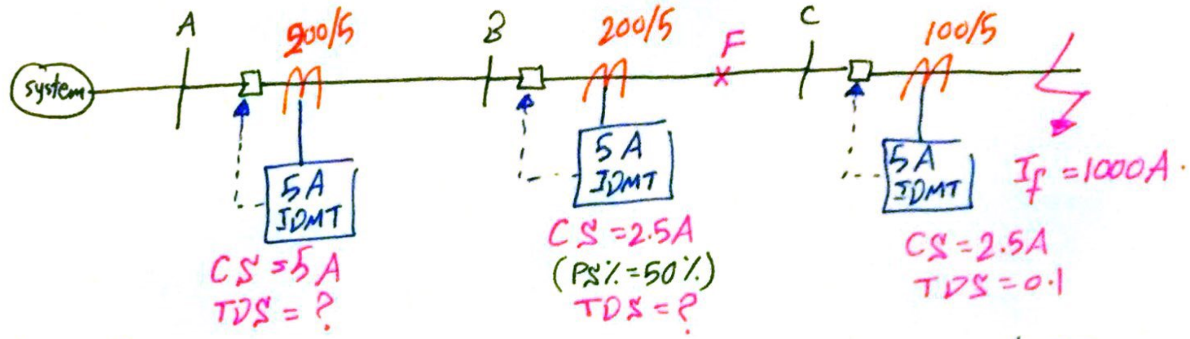
$$t_{p\,@TMS=1\,\&\,PSM=4} = 6.5 \text{ sec.} \Rightarrow t_{p\,@TMS=0.8} = 6.5 \times 0.8 = 5.2 \text{ sec.}$$

* By using the equation:

$$t_p = \frac{3}{\log(4)} \times 0.8 = 4 \text{sec.}$$

* * *

Q3



$\Delta T(CI) = 0.5s$
↳ Coordination Interval.

$PSM = \frac{I_f}{I_P}$ — I_f → the current seen by the relay. I_P → the current setting.

Need to find TDS_A & TDS_B ?

$t_{op} = [f(PSM)] \times TDS$

- for C: $I_f'' = \frac{1000}{\frac{100}{5}} = 50A$.

$PSM_C = \frac{I_f''}{I_{P_C}} = \frac{50}{2.5} = \frac{50}{2.5} = 20$

from the table: $t_{op} = 2$ sec for $PSM = 20$ @ $TDS = 1.0$

so for $TDS = 0.1 \Rightarrow t_{op} = 2 \times 0.1 = 0.2$ sec. #

- for B:

$t_{op_B} = t_{op_C} + \underbrace{0.5}_{\Delta T} = 0.7$ sec.

$PSM_B = \frac{I_f''}{I_{P_B}} = \frac{1000/200/5}{2.5} = 10$

from the table: $t_{op} = 3$ sec for $PSM = 10$ @ $TDS = 1.0$

$\Rightarrow t_{op} = f(PSM) \times TDS$

$\Rightarrow TDS_B = \frac{t_{op_B}}{f(PSM)} = \frac{0.7}{3} = 0.233$ #

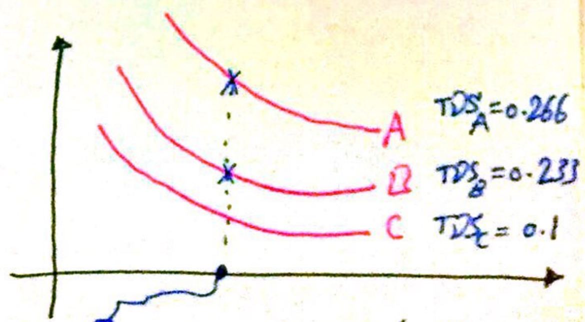
- for A:

$t_{op_A} = t_{op_C} + 0.5 + 0.5 = 1.2$ sec.

$PSM_A = \frac{I_f''}{I_{P_A}} = \frac{25}{5} = 5$

from the table: $t_{op} = 4.5$ sec.

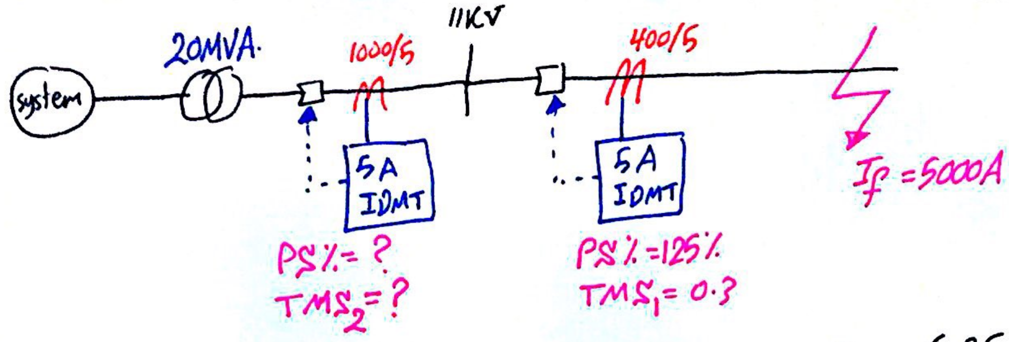
$TDS_A = \frac{1.2}{4.5} = 0.266$ #



if a fault ocurr @ point F
B & A will work.

* * *

Q4



$I''_{f_1} = \frac{5000}{400/5} = 62.5A.$, $PS\% = 125\% \Rightarrow I_{PicKup_1} = 1.25 \times 5 = 6.25A.$

$PSM_1 = \frac{62.5}{6.25} = 10$ ⇒ from the table: $t_{op} = 3\,sec.$ for $TMS = 1.0$

$t_{op} = f(PSM_1) \times TMS_1 = 3 \times 0.3 = \underline{0.9\,sec}.$

$t_{op_2} = 0.9 + 0.5 = \underline{1.4\,sec}.$

$I''_{f2} = \frac{5000}{1000/5} = 25A. \Rightarrow PSM_2 = \frac{25}{I_{P_2}}$

• since it operate @ 30% overload, Then:

$I_{P_2} = 1.3 \times I_{FL}$

$I_{FL} = \frac{S_{FL}}{\sqrt{3}\,V_L} = \frac{20 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 1049.7\,A.$

$\Rightarrow I_{P_2} = 1.3 \times 1049.7 = \underline{1364.6A}.$

@ secondary.

$\Rightarrow \frac{1364.6}{\frac{1000}{5}} = 6.82A.$

As a percentage:

$\% PS_2 = \frac{6.82}{5} \times 100\% = 136.4\%$

from the standards we choose 150% #

so Now $I_{P_2} = 1.5 \times 5 = \underline{7.5A}$ "in Secondary"

OR $I_{P_2} = 1.5 \times 1000 = \underline{1500\,A}$ "in primary"

• Now calculating PSM_2: $PSM_2 = \frac{25}{7.5} = 3.3$

⇒ 3.3 is between PSM = 3 & 5, By interpolation find t_{op} @ PSM = 3.3

solving ⇒ $t_{op} = 5.6\,sec$

$t_{op} = f(PSM) \times TDS_2 \Rightarrow 1.4 = 5.6 \times TDS_2 \Rightarrow TDS_2 = \frac{1.4}{5.6} = \underline{0.25}$ #

* * *

Question # 1:

Consider the 11-kV radial system shown in Fig 1-a. Assume that all loads have the same power factor. Determine relay settings to protect the system assuming relay type CO-7 (with characteristics shown in Fig 1-b) is used.

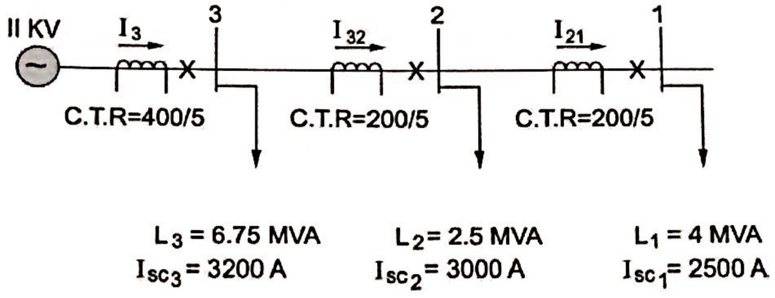


Fig.1-a: An Example Radial System

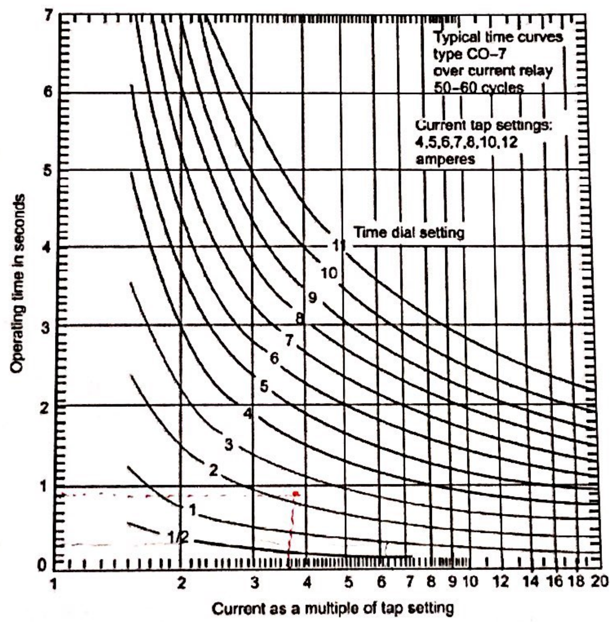


Fig. 1-b: CO-7 Time-Delay Overcurrent Relay Characteristics

Solution:

$$I_1 = \frac{4\times10^6}{\sqrt{3}\left(11\times10^3\right)} = 209.95\text{ A} \quad I_2 = \frac{2.5\times10^6}{\sqrt{3}\left(11\times10^3\right)} = 131.22\text{ A} \quad I_3 = \frac{6.75\times10^6}{\sqrt{3}\left(11\times10^3\right)} = 354.28\text{ A}$$

The normal currents through the sections are calculated as

$$I_{21} = I_1 = 209.95\text{ A} \quad I_{32} = I_{21} + I_2 = 341.16\text{ A} \quad I_S = I_{32} + I_3 = 695.44\text{ A}$$

With the current transformer ratios given, the normal relay currents are

$$i_{21} = \frac{209.92}{\frac{200}{5}} = 5.25\text{ A} \quad i_{32} = \frac{341.16}{\frac{200}{5}} = 8.53\text{ A} \quad i_S = \frac{695.44}{\frac{400}{5}} = 8.69\text{ A}$$

We can now obtain the current tap settings (C.T.S.) or pickup current in such a manner that the relay does not trip under normal currents. For this type of relay, the current tap settings available are 4, 5, 6, 7, 8, 10, and 12 amperes.

- For position 1, the normal current in the relay is 5.25 A; we thus choose $(C.T.S.)_1 = 6$ A,
- For position 2, the normal relay current is 8.53 A, and we choose (C.T.S.)2 = 10 A,
- Similarly for position 3, (C.T.S.)3 = 10 A.

Observe that we have chosen the nearest setting higher than the normal current.

The next task is to select the intentional delay indicated by the time dial setting (T.D.S.). We utilize the short-circuit currents calculated to coordinate the relays. The current in the relay at 1 on a short circuit at 1 is

$$i_{sc_1} = \frac{2500}{\left(\frac{200}{5}\right)} = 62.5\text{ A}$$

Expressed as a multiple of the pickup or C.T.S. value, we have

$$\frac{i_{sc_1}}{(\text{C.T.S.})_1} = \frac{62.5}{6} = 10.42$$

We choose the lowest T.D.S. for this relay for fastest action. Thus

$$(\text{T.D.S.})_1 = \frac{1}{2}$$

By reference to the relay characteristic, we get the operating time for relay 1 for a fault at 1 as

$$T_{1_1} = 0.15\text{ s}$$

To set the relay at 2 responding to a fault at 1, we allow 0.1 second for breaker operation and an error margin of 0.3 second in addition to T_{11}. Thus,

$$T_{2_1} = T_{1_1} + 0.1 + 0.3 = 0.55\text{ s}$$

The short circuit for a fault at 1 as a multiple of the C.T.S. at 2 is

$$\frac{i_{sc_1}}{(\text{C.T.S.})_2} = \frac{62.5}{10} = 6.25$$

From the characteristics for 0.55-second operating time and 6.25 ratio, we get $(\text{T.D.S.})_2 \approx 2$.
The final steps involve setting the relay at 3. For a fault at bus 2, the short-circuit current is 3000 A, for which relay 2 responds in a time $T22$ obtained as follows:

$$\frac{i_{sc_2}}{(\text{C.T.S.})_2} = \frac{3000}{\left(\frac{200}{5}\right)10} = 7.5$$

For the $(\text{T.D.S.})_2 = 2$, we get from the relay's characteristic, $T_{22} = 0.50$ s .

Thus allowing the same margin for relay 3 to respond to a fault at 2, as for relay 2 responding to a fault at 1, we have

$$T_{32} = T_{22} + 0.1 + 0.3 = 0.90\text{ s}$$

The current in the relay expressed as a multiple of pickup is

$$\frac{i_{sc_2}}{(\text{C.T.S.})_3} = \frac{3000}{\left(\frac{400}{5}\right)10} = 3.75$$

Thus for $T3 = 0.90$, and the above ratio, we get from the relay's characteristic, $(\text{T.D.S.})_3 \approx 2.5$

We note here that our calculations did not account for load starting currents that can be as high as five to seven times rated values. In practice, this should be accounted for.

Question # 2:

Relay coordination on radial feeders using Use Extremely Inverse Relay Characteristics

For the radial power system shown i, Fig. 2.1 the CTR of the CTs and the relay current settings at buses 1-5 are given in Table 2.1. The relay current setting (CS) are given in % and in primary Amperes. Also, the minimum and maximum faults at buses 1-5 are given in Table 2.2.

Design an overcurrent protection for the above radial feeder using **Extremely Inverse Relay Characteristics**:

$$t = \left(\frac{28.2}{M^2 - 1} + 0.1217 \right) \times TDS$$

i.e. find the TDS considering a coordination time interval set to 0.4 s, and a TDS of relay at bus 5 (R5) set to TDS5 = 1.0.

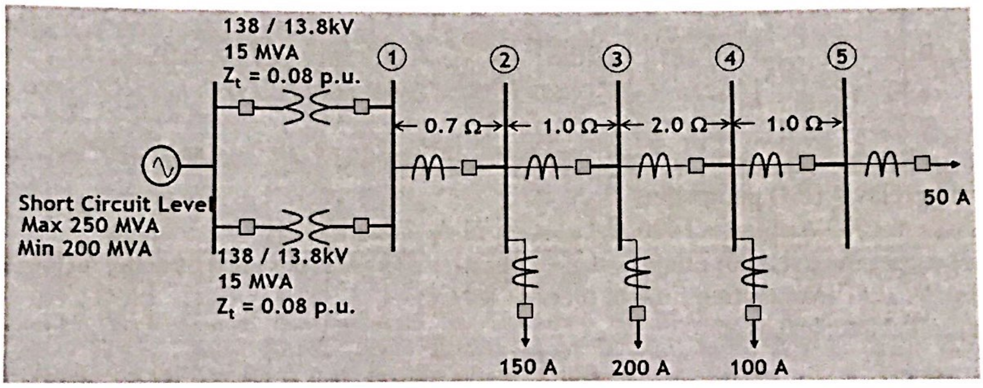


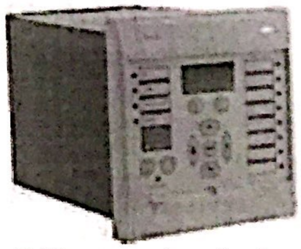
Figure 2.1: Radial system considered for relay overcurrent relay coordination study.

Table 2.1: CT Ratio and Relay Current Settings

Relay Location Bus	Maximum Load Current (A)	Selected CT Ratio	Relay Current Setting	
			Percent	Primary Current (A)
1	500	800/5	75 %	600
2	350	500/5	100 %	500
3	150	200/5	100 %	200
4	50	100/5	75 %	75
5	50	100/5	75 %	75

Table 2.2: Fault Current Calculations

Fault Location Bus	Minim Fault Current (A)	Maximum Fault Current (A)
1	4049	6274
2	2986	4045
3	2172	2683
4	1406	1603
5	1195	1335



Arreva P14x O/C protective devise.

Solution:

The principle of backup protection with O/C relays is that for any relay X backing up the next downstream relay Y, relay X must pick up:

a. **For one third of the minimum fault current seen by Y.**
b. **For the maximum fault current seen by Y but not sooner than 0.4 s after Y should have picked up for that current.**

Extremely Inverse overcurrent characteristic: $t_p = \left(\frac{28.2}{M^2 - 1} + 0.1217\right) \times TDS$

1. Choosing relay 5 (R5) parameters

$I_{5fmax} = 1335$ A, $I_{5fmin} = 1195$ A, $I_{5pickup} = 75$ A, TDS_5=1.0

$$t_{p5} = \left(\frac{28.2}{\left(\frac{1335}{75}\right)^2 - 1} + 0.1217\right) \times 1.0 = \left(\frac{28.2}{(17.8)^2 - 1} + 0.1217\right) \times 1.0 = 0.21s$$

2. Choosing relay 4 (R4) parameters

$I_{4fmax} = 1603$ A, $I_{4fmin} = 1406$ A, $I_{4pickup} = 75$ A, TDS_4=?

The operating time of relay 5 (R5) for $I_{5fmax} = 1335$A is 0.21 s. The relay 4 (R4) will pickup for I_{5fmax}. The operating time of relay 4 (R4) is:

$t_{p4} = 0.21+0.4=0.61$ s.

$$t_{p4} = \left(\frac{28.2}{\left(\frac{1335}{75}\right)^2 - 1} + 0.1217\right) \times TDS_4 \quad \Rightarrow 0.61 = \left(\frac{28.2}{(17.8)^2 - 1} + 0.1217\right) \times TDS_4$$

$$0.61 = 0.21 \times TDS_4 \quad \Rightarrow TDS_4 = \frac{0.61}{0.21} = 2.9 \quad \Rightarrow TDS_4 = 3$$

The <u>actual</u> operating time of relay 4 (R4) for I_{5fmax} and TDS_4=3.0 is:

$$t_{p4} = \left(\frac{28.2}{(17.8)^2 - 1} + 0.1217\right) \times 3 = 0.63s$$

The operating time of relay 4 (R4) for $I_{4fmax} = 1603$A is:

$$t_{p4} = \left(\frac{28.2}{\left(\frac{1603}{75}\right)^2 - 1} + 0.1217\right) \times TDS_4 \quad = \left(\frac{28.2}{(21.37)^2 - 1} + 0.1217\right) \times 3 = 0.55s$$

The operating time of relay 4 (R4) for $I_{4fmin} = 1406$A is:

$$t_{p4} = \left(\frac{28.2}{\left(\frac{1406}{75}\right)^2 - 1} + 0.1217\right) \times TDS_4 \quad = \left(\frac{28.2}{(21.37)^2 - 1} + 0.1217\right) \times 3 = 0.20 \times 3 = 0.60s$$

3. Choosing relay 3 (R3) parameters

$I_{3fmax} = 2683$ A, $I_{3fmin} = 2172$ A, $I_{3pickup} = 200$ A, TDS_3=?

The operating time of relay 4 (R4) for $I_{4fmax} = 1603$A is 0.55 s. The relay 3 (R3) will pickup for I_{4fmax}. The operating time of relay 4 (R4) is:

$t_{p3} = 0.55+0.4=0.95$ s.

$$t_{p3} = \left(\frac{28.2}{\left(\frac{1603}{200}\right)^2 - 1} + 0.1217 \right) \times TDS_3 \quad \Rightarrow 0.95 = \left(\frac{28.2}{(8.015)^2 - 1} + 0.1217 \right) \times TDS_3$$

$$0.95 = 0.568 \times TDS_3 \quad \Rightarrow TDS_3 = \frac{0.95}{0.568} = 1.67 \quad \Rightarrow TDS_3 = 1.7$$

The <u>actual</u> operating time of relay 3 (R3) for I_{4fmax} and TDS_3=1.7 is:

$$t_{p3} = \left(\frac{28.2}{(8.015)^2 - 1} + 0.1217 \right) \times 1.7 = 0.568 \times 1.70 = 0.965\,s$$

The operating time of relay 3 (R3) for $I_{3fmax} = 2683$A is:

$$t_{p3} = \left(\frac{28.2}{\left(\frac{2683}{200}\right)^2 - 1} + 0.1217 \right) \times TDS_3 \quad = \left(\frac{28.2}{(13.415)^2 - 1} + 0.1217 \right) \times 1.7 = 0.48\,s$$

The operating time of relay 3 (R3) for $I_{3fmin} = 2172$A is:

$$t_{p3} = \left(\frac{28.2}{\left(\frac{2172}{200}\right)^2 - 1} + 0.1217 \right) \times TDS_3 \quad = \left(\frac{28.2}{(21.37)^2 - 1} + 0.1217 \right) \times 1.7 = 0.363 \times 1.7 = 0.62\,s$$

4. Choosing relay 2 (R2) parameters

$I_{2fmax} = 4045$ A, $I_{2fmin} = 2986$ A, $I_{2pickup} = 500$ A, TDS_2=?

The operating time of relay 2 (R2) for $I_{3fmax} = 2683$A is 0.48 s. The relay 2 (R2) will pickup for I_{3fmax}. The operating time of relay 2 (R2) is:

$t_{p2} = 0.48+0.4=0.88$ s.

$$t_{p2} = \left(\frac{28.2}{\left(\frac{2683}{500}\right)^2 - 1} + 0.1217 \right) \times TDS_2 \quad \Rightarrow 0.88 = \left(\frac{28.2}{(5.366)^2 - 1} + 0.1217 \right) \times TDS_2$$

$$0.88 = 1.136 \times TDS_2 \quad \Rightarrow TDS_2 = \frac{0.88}{1.136} = 0.77 \quad \Rightarrow TDS_2 = 0.8$$

The <u>actual</u> operating time of relay 2 (R2) for I_{3fmax} and TDS_2=0.8 is:

$$t_{p2} = \left(\frac{28.2}{(5.366)^2 - 1} + 0.1217 \right) \times 0.8 = 1.136 \times 0.8 = 0.90\,s$$

The operating time of relay 2 (R2) for $I_{2fmax} = 4045\text{A}$ is:

$$t_{p2} = \left(\frac{28.2}{\left(\frac{4045}{500}\right)^2 - 1} + 0.1217 \right) \times TDS_2 \quad = \left(\frac{28.2}{(8.09)^2 - 1} + 0.1217 \right) \times 0.9 = 0.50\,s$$

The operating time of relay 2 (R2) for $I_{4fmin} = 2986\text{A}$ is:

$$t_{p2} = \left(\frac{28.2}{\left(\frac{2986}{500}\right)^2 - 1} + 0.1217 \right) \times TDS_2 \quad = \left(\frac{28.2}{(5.972)^2 - 1} + 0.1217 \right) \times 0.9 = 0.935 \times 0.9 = 0.84\,s$$

5. Choosing relay 1 (R1) parameters

$I_{1fmax} = 6274$ A, $I_{1fmin} = 4049$ A, $I_{1pickup} = 600$ A, TDS_1=?

The operating time of relay 2 (R2) for $I_{2fmax} = 4045\text{A}$ is 0.5 s. The relay 1 (R1) will pickup for I_{2fmax}. The operating time of relay 1 (R1) is:
$t_{p1} = 0.5+0.4=0.9$ s.

$$t_{p1} = \left(\frac{28.2}{\left(\frac{4045}{600}\right)^2 - 1} + 0.1217 \right) \times TDS_1 \quad \Rightarrow 0.9 = \left(\frac{28.2}{(6.74)^2 - 1} + 0.1217 \right) \times TDS_1$$

$$0.9 = 0.756 \times TDS_1 \quad \Rightarrow TDS_1 = \frac{0.9}{0.756} = 1.19 \quad \Rightarrow TDS_1 = 1.2$$

The actual operating time of relay 1 (R1) for I_{2fmax} and TDS_1=1.2 is:

$$t_{p1} = \left(\frac{28.2}{(6.74)^2 - 1} + 0.1217 \right) \times 1.2 = 0.756 \times 1.2 = 0.908\,s$$

The operating time of relay 2 (R2) for $I_{1fmax} = 6274\text{A}$ is:

$$t_{p1} = \left(\frac{28.2}{\left(\frac{6274}{600}\right)^2 - 1} + 0.1217 \right) \times TDS_1 \quad = \left(\frac{28.2}{(10.46)^2 - 1} + 0.1217 \right) \times 1.2 = 0.46\,s$$

The operating time of relay 1 (R1) for $I_{1fmin} = 4049\text{A}$ is:

$$t_{p1} = \left(\frac{28.2}{\left(\frac{4049}{600}\right)^2 - 1} + 0.1217 \right) \times TDS_1 \quad = \left(\frac{28.2}{(6.748)^2 - 1} + 0.1217 \right) \times 1.2 = 0.755 \times 1.2 = 0.905\,s$$

Table 2.3: CT Ratio and Relay CS and TD Settings

Relay Location Bus	Selected CT Ratio	Relay Current Setting			Time Dial Setting
		Percent	Primary Current (A)	Secondary Current (A)	TDS
1	800/5	75 %	600	3.75	1.2
2	500/5	100 %	500	5	0.8
3	200/5	100 %	200	5	1.7
4	100/5	75 %	75	3.75	3
5	100/5	75 %	75	3.75	1

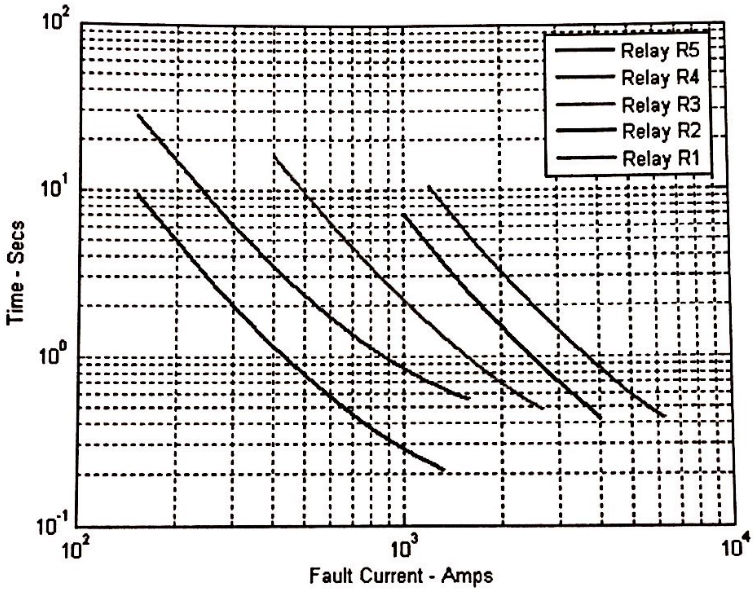
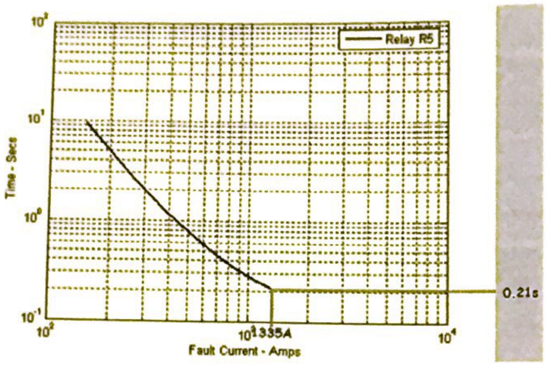
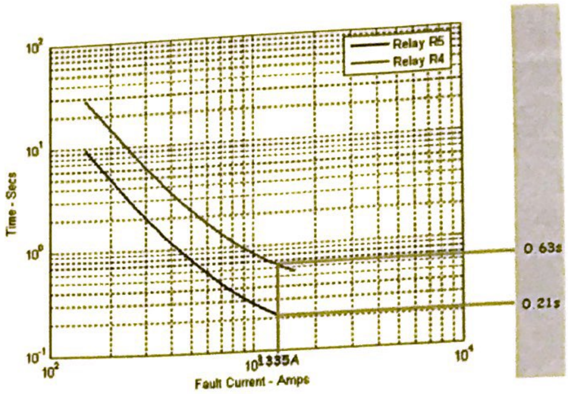
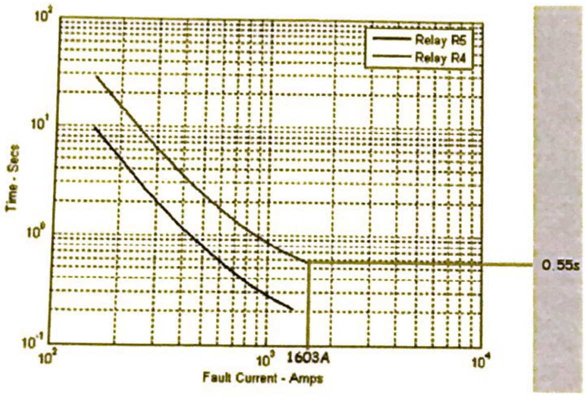
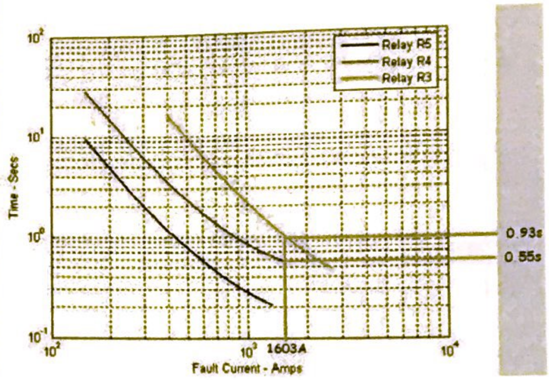


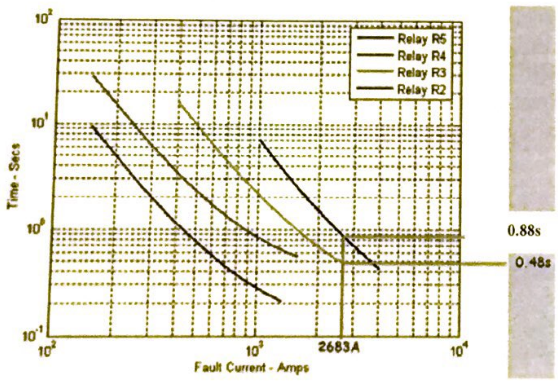
Fig. 2.2: overcurrent relay operating characteristic of R1-R5

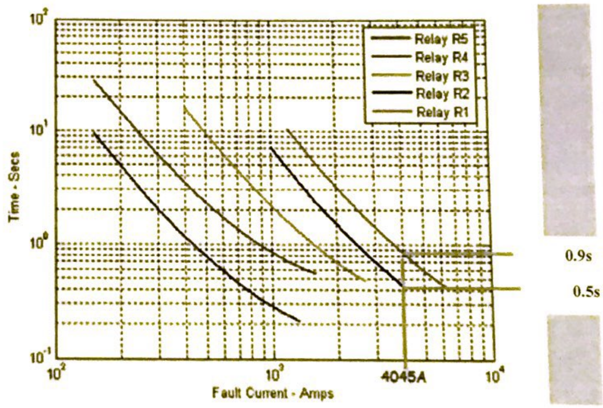

Relay R5
Time - Secs
Fault Current - Amps
1335A
0.21s


Relay R5
Relay R4
Time - Secs
Fault Current - Amps
1335A
0.63s
0.21s


Relay R5
Relay R4
Time - Secs
Fault Current - Amps
1603A
0.55s


Relay R5
Relay R4
Relay R3
Time - Secs
Fault Current - Amps
1603A
0.93s
0.55s


Relay R5
Relay R4
Relay R3
Relay R2
Time - Secs
Fault Current - Amps
2683A
0.88s
0.48s


Relay R5
Relay R4
Relay R3
Relay R2
Relay R1
Time - Secs
Fault Current - Amps
4045A
0.9s
0.5s

Question # 3:

Figure 3 shows a network that is protected by Normal Inverse Overcurrent IDMT relays whose *t-I* relay characteristic and *PS%* are given by:

$$t = \frac{3}{\log_{10}(PSM)} \times TSM = \frac{3}{\log_{10}\left(\frac{I_f}{I_{pickup}}\right)} \times TSM$$

PS%: 50%, 75%, 100%, 125%, 150%, 175% and 200%.

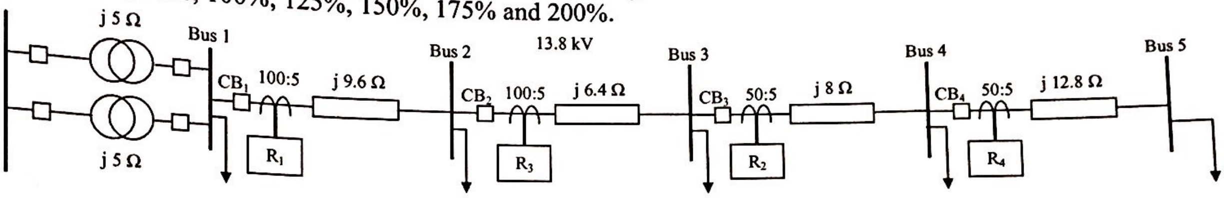


Fig. 3.

The minimum and maximum fault currents are given in Table 3-a.

Table 3-a: Minimum and Maximum Fault Currents

Bus No.	1	2	3	4	5
Minimum Fault Current (A), I_{fmin}	1380	472.6	328.6	237.9	165.1
Maximum Fault Current (A), I_{fmax}	3187	658	431	301	203

a. Select the plug setting multiplier (PSM) and time dial settings (TMS) for the relays R_4, R_3, R_2, and R_1 of the above system and fill the results in Table Q3-b, by evaluating the minimum CT pickup current (I_{pickup}), the plug setting multiplier (PSM), plug setting (*PS%*) and time setting multiplier (*TMS*). Set the *TMS* of R_4 at its minimum *TMS*=0.5. Use a grading margin (coordination time) of **0.3 seconds**.

b. Sketch the o/c characteristics of the four relays on a *t-I* characteristic.

Table Q3-b: PS and TSM of O/C Relays

Parameter	**R_1**	**R_2**	**R_3**	**R_4**
CT ratio	**100:5**	**100:5**	**50:5**	**50:5**
PS %				
TMS				**0.5**

Solution:

The principle of backup protection with O/C relays is that for any relay X backing up the next downstream relay Y, relay X must pick up:

a. **For one third of the minimum fault current seen by Y.**

b. **For the maximum fault current seen by Y but not sooner than 0.4 s after Y should have picked up for that current.**

Setting for Relay **R_4:** This relay must operate for a current above 165.1 A (the minimum fault current at Bus-5). However for reliability, we must set this relay such that it picks up a current that is one third of the minimum, i.e.,

$$I'_{pickup4} = \frac{I_{f\,\min}}{3} = \frac{165.1}{3} = 55.03\ A$$

For a CT ratio of 50:5, the pickup current at the secondary of the CT will be

$$I_{pickup4} = \frac{I'_{pickup4}}{CTR_4} = \frac{55.03}{50/5} \times = 5.5\ A \Rightarrow PS\% = \frac{5.5}{5} \times 100 = 110\% \Rightarrow \text{Select } PS\%_4 = 125\%.$$

$\therefore$ Pick up Current (Effective Current) =Rated CT Primary Current × PS

$I'_{Pickup} = 50 \times 1.25 = 62.5\ A$ (Secondary current) or $I_{Pickup} = 5 \times 1.25 = 6.25\ A$ (Secondary current)

This means if the CT primary current exceeds 62.5 A (6.25 A secondary current), relay will start operating after some time delay.

Since the relay R_4 is located at the end of the network, i.e. does not coordinate with downstream relays. The *TMS* is restricted to a minimum of ½ for electro-mechanical relays $\Rightarrow TMS_4 = 0.5$.

Setting for Relay R_3: This relay must provide backup for R_4. Therefore it must pick up the minimum current seen by relay R_4. We therefore choose the same CT ratio CTR_4=50:5 and pick up current $I_{pickup3}$= 6.25 A. To determine the TMS_3, we must provide a discrimination time of 0.3 s. This time is provided such that R_3 operates 0.3 s after the highest (not lowest) fault current seen by R_4. Therefore, R_3 operates in no less than 0.3 s after every possible fault seen by R_4.

For a maximum fault immediately after Bus 4, it will see a fault current that is equal to the fault current seen by Bus 4. Therefore the highest fault current seen by R_4 is 301 A (see Table 1). The current seen by both secondary of CTS of relay R_3 and R_4 for this fault will be

$$I_{f\max(\sec)4} = \frac{I'_{f\max 4}}{CTR_4} = \frac{301}{50/5} = 30.1\ A$$

Hence, $PSM_4 = \frac{I_{f\max 4}}{I_{pickup4}} = \frac{30.1}{6.25} = 4.82$. The tripping time with TMS_4= 0.5 is

$t_4 = \frac{3.0}{\log(PSM_4)} \times TMS_4 = \frac{3.0}{\log(4.82)} \times 0.5 = 2.2\ s$, therefore for any failure of R_4, relay R_3 must operate at 2.2 + 0.3 = 2.5 s.

Since relay R_3 also has PSM_3= 1.25 (6.25 A), we can calculate the TMS_3 from

$$t_3 = \frac{3.0}{\log(PSM_3)} \times TMS_3 = \frac{3.0}{\log(4.82)} \times TMS_3 = 4.39 \times TMS_3 = 2.5\ s$$

$$\Rightarrow TMS_3 = \frac{2.5}{4.39} = 0.569 \Rightarrow Let\ TMS_3 = 0.6$$

$\Rightarrow$ TMS_3= 0.6. This gives an operating time of

$t_3 = \frac{3.0}{\log(PSM_3)} \times TMS_3 = \frac{3.0}{\log(4.82)} \times 0.6 = 2.64\ s$. This maintains a minimum discrimination time of 0.3 s.

Setting for Relay R_2: This relay must provide a backup for relay R_3. The smallest fault current seen by R_2 to provide a backup for R_3 is 237.9 A (see Table 1). For reliable operation, we choose one-third of this current, i.e., 79.3 A. For a CTR_2=100:5.

$$I_{pickup(\sec)2} = \frac{I_{f\min 3}/3}{CTR_2} = \frac{237.9/3}{100/5} = \frac{79.3}{100/5} = 3.97\ A \Rightarrow PS\% = \frac{3.97}{5} \times 100 = 79.3\%$$

$\Rightarrow$ Select $PS\%_2$=100%.We now have to determine TMS_2 of R_2 from the maximum fault current seen by R_3.

The maximum current seen by R_3 is 431 A. Then, at R_3, for a CT ratio of CTR_3=50:5 and a PS_3= 6.25 A, we get a PSM_3 of

$$PSM_3 = \frac{\left(\frac{I_{f\max 3}}{CTR_3}\right)}{I_{pickup3}} = \frac{\left(\frac{431}{50/5}\right)}{6.25} = 6.9$$

For the above PSM_3=6.9 and a TMS_3 =0.6, the operating time of relay R_3 is

$$t_3 = \frac{3.0}{\log(PSM_3)} \times TMS_3 = \frac{3.0}{\log(6.9)} \times 0.6 = 2.15\ s$$

Thus, relay R_2 should add discrimination time of 0.3 s., i.e., the operating time should be 2.15 + 0.3 = 2.45 s.

Now relay R_2 is a backup for relay R_3 and therefore, it will see the same fault current of 431 A.

Then, PSM_2 for this fault is $PSM_2 = \frac{\left(\frac{I_{f\max 3}}{CTR_2}\right)}{I_{pickup2}} = \frac{\frac{431}{100/5}}{5} = 4.31$

For this value of PSM_2, we get a TMS_2 from

$$t_2 = \frac{3.0}{\log(PSM_2)} \times TMS_2 = \frac{3.0}{\log(4.31)} \times TMS_2 = 4.73 \times TMS_2 = 2.45\ s$$

$$\Rightarrow TMS_2 = \frac{2.45}{4.73} = 0.518 \Rightarrow Let\ TMS_2 = 0.6$$

This gives an operating time of $t_2 = \frac{3.0}{\log(PSM_2)} \times TMS_2 = \frac{3.0}{\log(4.31)} \times 0.6 = 2.84\ s$

Setting for Relay R_1: This relay must provide a backup for relay R_2. The smallest fault current seen by R_2 to provide a backup for R_3 is 328.6 A. For reliable operation, we choose one-third of this current, i.e., 109.5 A. A CT ratio CTR_1=100:5 is suitable.

For a CTR_1=100:5.

$$I_{pickup(\text{sec})1} = \frac{I_{f\min 3}/3}{CTR_1} = \frac{328.6/3}{100/5} = \frac{109.5}{100/5} = 5.48\ A \Rightarrow PS\% = \frac{5.48}{5} \times 100 = 109.5\%$$

$\Rightarrow$ Select $PS\%_1$=125% (PS_1 =5×1.25=6.25 A).

We now have to determine TMS_1 of R_1 from the maximum fault current seen by R_2. Thus we choose the same CT ratio and PS% for this relay as well. The maximum fault current seen by R_2 is 658 A. Then, at R_2, for a CT ratio of CTR_2=100/5 and a PS_2 of (5×100=5.00 A), we get

$$PSM_2 = \frac{\left(\frac{I_{f\max 2}}{CTR_2}\right)}{I_{pickup2}} = \frac{\frac{658}{100/5}}{5} = 6.58$$

For PSM_2=6.58 and TMS_2=0.6, the operating time of relay R_2 is

$$t_2 = \frac{3.0}{\log(PSM_2)} \times TMS_2 = \frac{3.0}{\log(6.58)} \times 0.6 = 2.2\ s.$$

Thus relay R_1 should add discrimination time of 0.3 s., i.e., the operating time should be 2.2 + 0.3 = 2.5 s.

Now relay R_1 is a backup for relay R_2 and therefore it will see the same maximum fault current of 658 A. Then for the same $PS\%_1$=6.25

$$PSM_1 = \frac{\left(\frac{I_{f\max 2}}{CTR_1}\right)}{I_{pickup1}} = \frac{\frac{658}{100/5}}{6.25} = 5.26$$. Then, TMS_1 can be calculated from

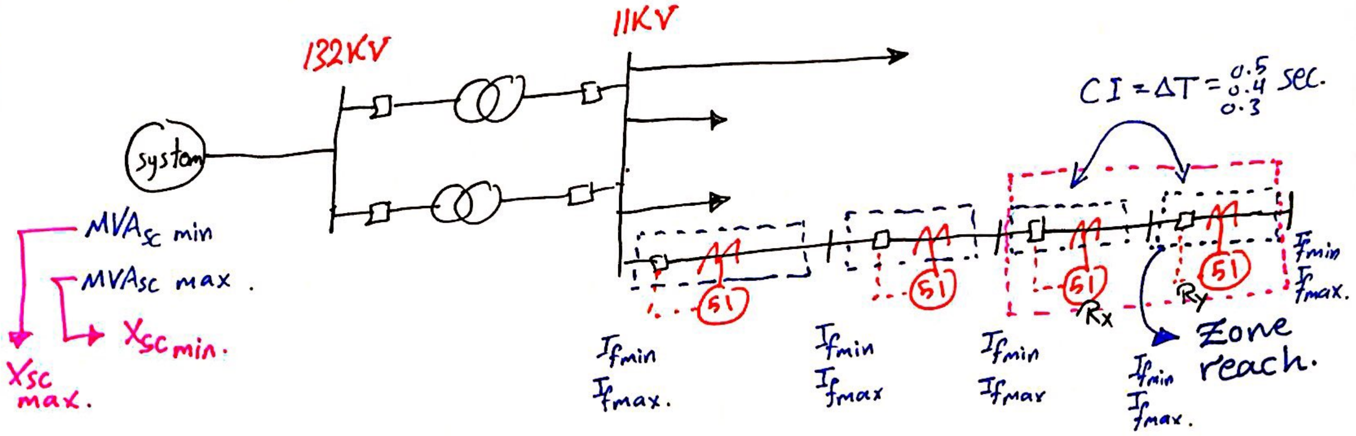
$$t_1 = \frac{3.0}{\log(PSM_1)} \times TMS_1 = \frac{3.0}{\log(5.26)} \times TMS_1 = 4.16 \times TMS_1 = 2.5\ s \Rightarrow TMS_1 = \frac{2.5}{4.16} = 0.60 .$$

Table Q3-b: PS and TSM of O/C Relays

Parameter	**R$_1$**	**R$_2$**	**R$_3$**	**R$_4$**
CT ratio	**100:5**	**100:5**	**50:5**	**50:5**
***PS* %**	125%	100%	125%	125%
TMS	0.6	0.6	0.6	**0.5**

* Coordination :

consider the following system:

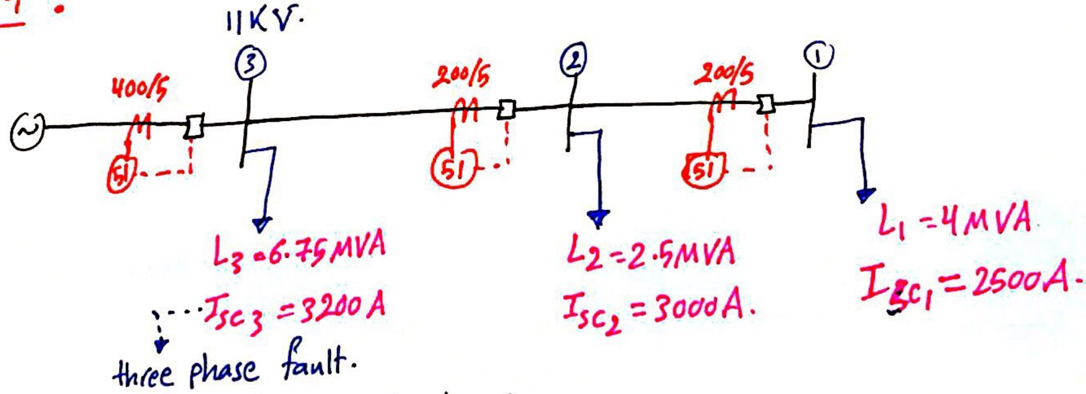


- **Notes :**

* R_x should back up Relay R_y & pick-up for min fault seen by R_y.
* The weakage fault current is that at the most right of the system.
* Ipick-up Based on MAX Load.
* The minimum fault current obtained from (L-L) when one transformer working.

※ Tutorial #4 :

Q1



- we always start calculating for the Last relay.

$$I_{L_1} = \frac{4 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 210 A.$$

$$I_{L_2} = \frac{2.5 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 131 A.$$

$$I_{L_3} = \frac{6.75 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 354 A.$$

$I_{21} = 210 A.$, $I_{32} = 341 A.$, $I_{source} = 695 A.$

$$I_{21}' = I_{r_1}' = \frac{210}{\frac{200}{5}} = 5.25 A. \Rightarrow CTS_1 = 6A.$$

$$I_{32}' = I_{r_2}' = \frac{341}{\frac{200}{5}} = 8.5 A. \Rightarrow CTS_2 = 10A.$$

$$I_S' = I_{r_3}' = \frac{695}{\frac{400}{5}} = 8.7 A \Rightarrow CTS_3 = 10A.$$

C07-CTS {4, 5, 6, 7, 8, 10, 12}.

C07 – $TDS = \{1/2, 1, 2, \ldots, 11\}$

$\Rightarrow$ Now choose $TDS_1 = \frac{1}{2}$ # $\rightarrow$ "since it is the top of the right relay we choose the min. time TDS"

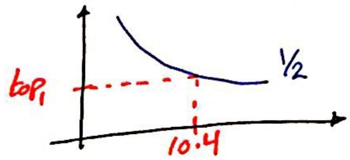
$TDS_2 = ?$

$TDS_3 = ?$

$CTS_1 = 6A \equiv 240$ primary.

$CTS_2 = 10A \equiv 400A$ primary.

$CTS_3 = 10A \equiv 800A$ primary.



for $I_{sc_1} = 2500A \Rightarrow PSM_1 = \frac{2500}{240} = 10.4$

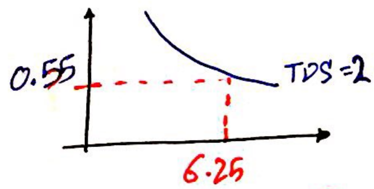
from the c/c $\Rightarrow t_{op_1} = 0.15$ sec.

* choose $CI = 0.4$ sec.

$t_{op_2} = 0.4 + 0.15 = 0.55$ sec.

$\Rightarrow t_{op_2} = f(PSM_2) \times TDS_2$

$PSM_2 = \frac{2500}{400} = 6.25$



from the given curve:

$\Rightarrow TDS_2 = 2$ #

Now for R_3 & a fault @ Bus ②:

$PSM_2 = \frac{3000/200/5}{10} = 7.5$

$\Rightarrow TDS_2 = 2$

from the curve:

$t_{op_2} = 0.5$ sec.

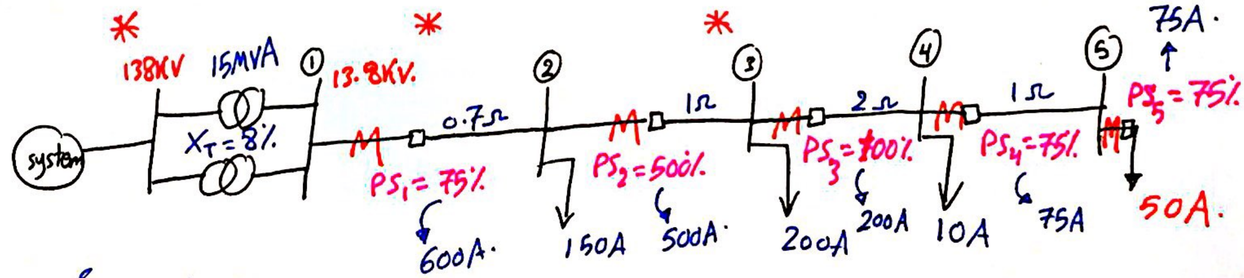
$\Rightarrow t_{op_3} = 0.5 + 0.4 = 0.9$ sec.

$PSM_3 = \frac{3000/400/5}{10} = 3.75$

from the curve:

$TDS_3 = 2.5$ #

Q2



minimum & maximum fault current given @ each busbar.

we want to find $TDS_{1,2,3,4,5}$.

$\Rightarrow$ choose $TDS_5 = 1$

* We calculate for the MAX. Fault current.

$\Rightarrow$

$$t_{p_5} = \left[\frac{28.2}{\left(\frac{1335}{75}\right)^2-1} + 0.1217\right] \times 1.0 = 0.21\ sec.$$

* CI = 0.4 sec.

R_4 will back-up R_5 after 0.4 sec. $\Rightarrow t_{op_4} = 0.4 + 0.21 = 0.61\ sec.$

Back to the main equation: $0.61 = \left[\frac{28.2}{\left(\frac{1335}{75}\right)^2-1} + 0.1217\right] \times TDS_4$

$\Rightarrow TDS_4 = 2.9 \Rightarrow$ choose $TDS_4 = 3$

$$\Rightarrow t_{op_4} = \left[\frac{28.2}{\left(\frac{1335}{75}\right)^2-1} + 0.1217\right] \times 3 \Rightarrow t_{op4} = 0.63\ sec.$$

$$t_{op_4} = \left[\frac{28.2}{\left(\frac{1603}{75}\right)^2-1} + 0.1217\right] \times 3 \Longrightarrow t_{op_4} = 0.55\ sec.$$

$$t_{op_3} = 0.55 + 0.4 = 0.95\ sec. = \left[\frac{28.2}{\left(\frac{1603}{200}\right)^2-1} + 0.1217\right] \times TDS_3$$

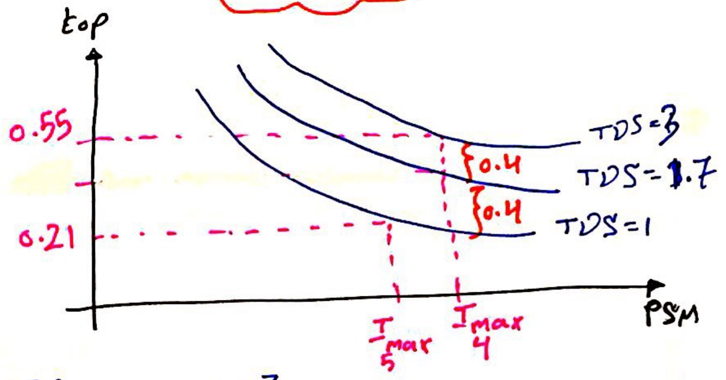
$\Rightarrow TDS_3 = 1.7$

for R_3:

$I_{f_{max_3}} = 2683A.$

$$t_{op_3} = \left[\frac{28.2}{\left(\frac{2683}{200}\right)^2-1} + 0.1217\right] \times 1.7$$

$\Rightarrow t_{op_3} = 0.48\ sec.$



$$t_{op_2} = 0.48 + 0.4 = 0.88\ sec. = \left[\frac{28.2}{\left(\frac{2683}{500}\right)^2-1} + 0.1217\right] \times TDS_2$$

$\Rightarrow TDS_2 = 0.8$

@ Bus 2 $\quad I_{f_{max_2}} = 4045A.$

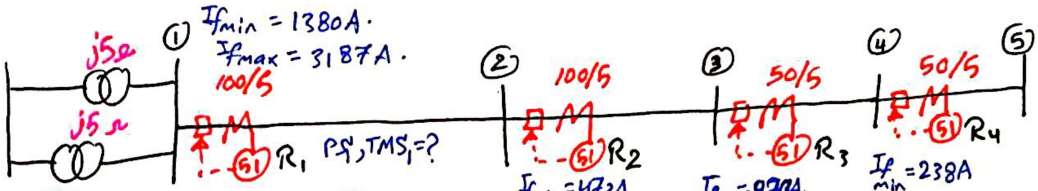
$$t_{op_2} = \left[\frac{28.2}{\left(\frac{4045}{500}\right)^2-1} + 0.1217\right] \times 0.8 = 0.45\ sec$$

R_1 back-up R_2: $t_{op_1} = 0.45 + 0.4 = 0.85\ sec. = \left[\frac{28.2}{\left(\frac{4045}{600}\right)^2-1} + 0.1217\right] \times TDS_1$

$\Rightarrow TDS_1 = 1.1$

* * *

Q_3



$I_{f_{min}} = 473A$, $I_{f_{max}} = 658A$, $PS_2, TMS_2 = ?$

$I_{f_{min}} = 329A$, $I_{f_{max}} = 431A$, $PS_3, TMS_3 = ?$

$I_{f_{min}} = 238A$, $I_{f_{max}} = 301A$, $PS_4 = ?$, $TMS_4 = 0.5$

$I_{f_{min}} = 165A$, $I_{f_{max}} = 203A$

$$t_{op} = \frac{3}{\log(PSM)} \times TSM = \frac{3}{\log\left[\frac{I_f}{I_p}\right]} \times TMS.$$

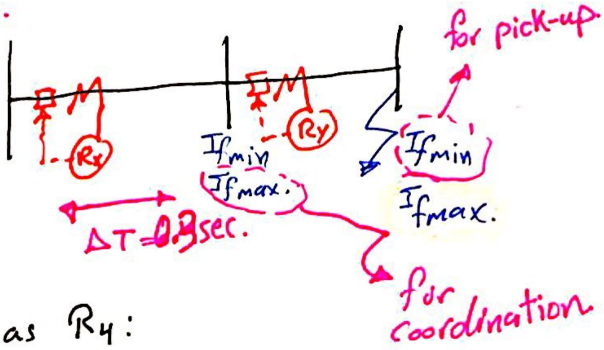
$\%PS \Rightarrow \{50\%, 75\%, 100\%, 125\%, 150\%, 175\%, 200\%\}$.

$I_{pick\text{-}up} = \frac{1}{3} I_{f_{5_{min}}} = \frac{1}{3} \times 165 = 55A$. (primary).

$I'_{pick\text{-}up} = 5.5\ A$ (secondary).

so $\%PS_4 = \frac{5.5}{5} \times 100\% = 110\%$

choose $\boxed{PS_4\% = 125\%}$ #



for $PS_3\%$ it must be the same setting as R_4:

$\boxed{PS_3\% = 125\%}$ #

$t_{op_4} = \frac{3}{\log \frac{301}{62.5}} \times 0.5 = 2.2\ sec \Rightarrow t_{op_3} = 0.3 + 2.2 = 2.5\ sec = \frac{3}{\log \frac{301}{62.5}} \times TMS_3$

$\Rightarrow \boxed{TMS_3 = 0.6}$ #

$I_{pick\text{-}up_2} = \frac{1}{3} \times 238 = 79.3A$

$I'_{p_2} = \frac{79.3}{20} \simeq 4A$. so $\%PS_2 = \frac{4}{5} \times 100\% = 80\%$ choose: $\boxed{PS_2\% = 100\%}$ #

$t_{op_3}\Big|_{@ I_{f_{max}} = 431A} = \frac{3}{\log \frac{431}{62.5}} \times 0.6 = 2.15\ sec. \Rightarrow t_{op_2} = 0.3 + 2.15 = 2.45\ sec = \frac{3}{\log \frac{431}{100}} \times TMS_2$

$\Rightarrow \boxed{TMS_2 = 0.6}$ #

$I_{p_1} = \frac{1}{3} \times 329 \simeq 110\ A$.

$I'_{p_1} = \frac{110}{20} = 5.5A$. so $\%PS_1 = \frac{5.5}{5} \times 100\% = 110\%$. choose: $\boxed{PS_1\% = 125\%}$ #

$t_{op_2}\Big|_{@ I_{f_{max}} = 658A} = \frac{3}{\log \frac{658}{100}} \times 0.6 = 2.2\ sec \Rightarrow t_{op_1} = 0.3 + 2.2 = 2.5\ sec = \frac{3}{\log \frac{658}{125}} \times TMS_1$

$\Rightarrow \boxed{TMS_1 = 0.6}$ #

* * *

Power Systems Analysis II

Second Semester
2018

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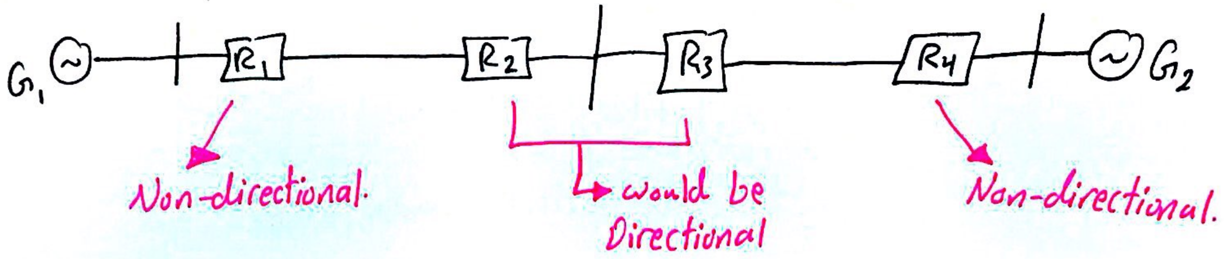
Notebook:

By. Mohammad
Abu Hashya.

* * *

※ Over Current Protection :

- Unit Relay: it protect a certain part of the system.



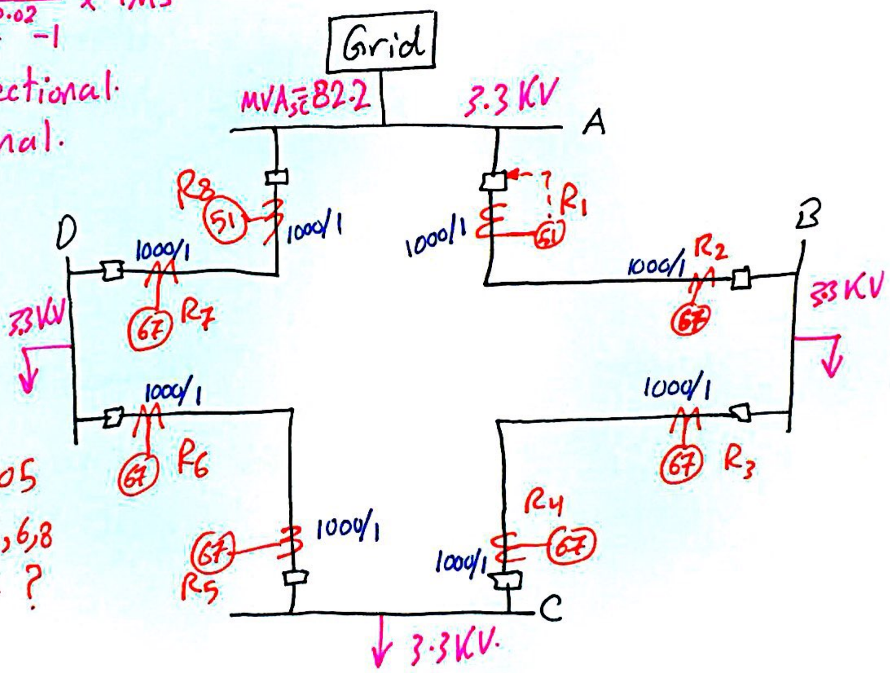
***Example:** Consider the following simple ring main:

Given that: $t_p = \frac{0.14}{I_r^{0.02} - 1} \times TMS$

R_1 & R_8 are Non-directional.
$R_2 - R_7$ are directional.

a) Draw the radial networks when CB_1 & CB_8 are open?

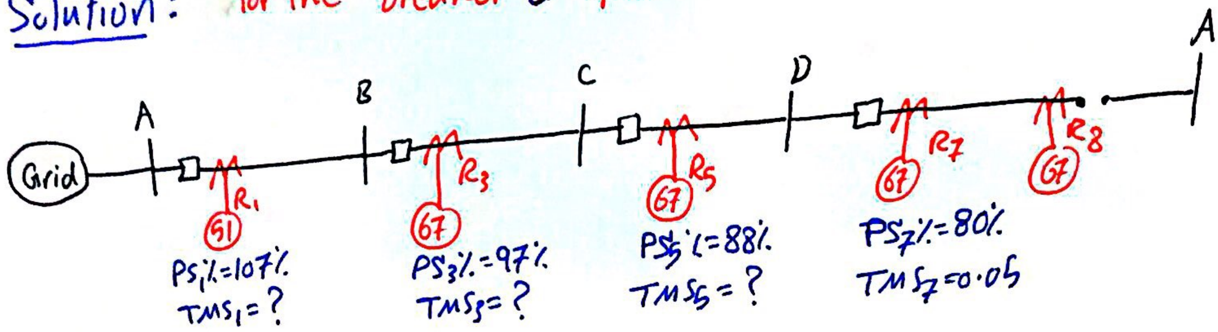
b) Given R_2 & R_7 TMS = 0.05 Then find $TMS_{1,3,4,5,6,8}$ using $\Delta T = 0.3$ sec ?



Also the following informations are given:

CW (CB_8 open) Bus	$I_{f max}$ (KA)	PS%	CCW (CB_1 open) Bus	$I_{f max}$ (KA)	PS%
D	3376	R_7 (80)	B	3376	R_2 (80)
C	4259	R_5 (88)	C	4259	R_4 (88)
B	7124	R_3 (97)	D	7124	R_6 (97)
A	14387	R_1 (107)	A	14387	R_8 (107)

Solution: for the breaker 8 open:



* $PS_7\% = 80\%$ (800A prim. = 0.8A secondary)

$$t_{op_7} = \frac{0.14}{\left(\frac{3376}{800}\right)^{0.02} - 1} \times 0.05 = \underline{0.24\,sec}$$

* $PS_5\% = 88\%$ (880 A primary) ; $t_{op_5} = 0.3 + 0.24 = \underline{0.54\,sec.}$

$$0.54 = \frac{0.14}{\left(\frac{3376}{880}\right)^{0.02} - 1} \times TMS_5 \rightarrow TMS_5 = 0.105 \; \#$$

$$t_{op_5}\Big|_{@\,I_f = 4259A} = \frac{0.14}{\left(\frac{4259}{880}\right)^{0.02} - 1} \times 0.105 = \underline{0.46\,sec.}$$

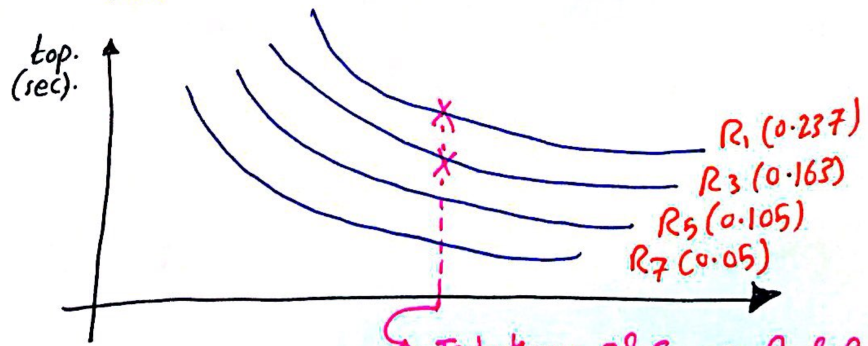
* $PS_3\% = 97\%$ (970A primary). ; $t_{op_3} = 0.3 + 0.46 = \underline{0.76\,sec.}$

$$0.76 = \frac{0.14}{\left(\frac{4254}{970}\right)^{0.02} - 1} \times TMS_3 \rightarrow TMS_3 = 0.163 \; \#$$

$$t_{op_3}\Big|_{@\,7129A} = \frac{0.14}{\left(\frac{7129}{970}\right)^{0.02} - 1} \times 0.163 = \underline{0.56\,sec.}$$

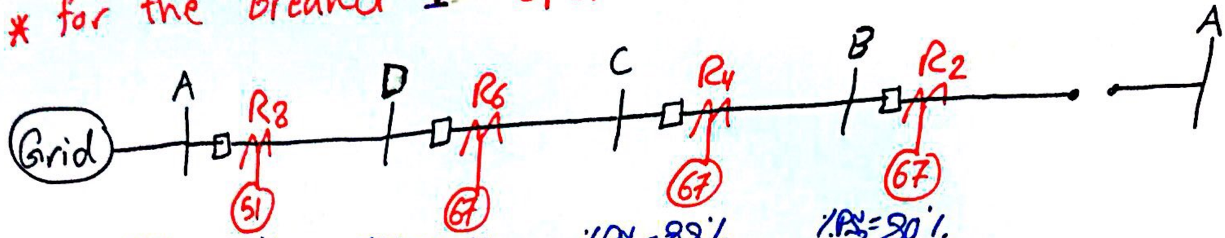
* $PS_1\% = 107\%$ (1070A primary) ; $t_{op_1} = 0.3 + 0.56 = \underline{0.86\,sec.}$

$$0.86 = \frac{0.14}{\left(\frac{7129}{1070}\right)^{0.02} - 1} \times TMS_1 \rightarrow TMS_1 = 0.237 \; \#$$



If between B&C ⇒ R_3 & R_1 will work.

* for the breaker 1 open:

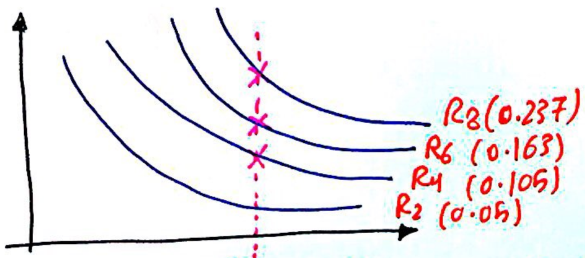


$\%PS_8 = 107\%$ $\quad$ $\%PS_6 = 97\%$ $\quad$ $\%PS_4 = 88\%$ $\quad$ $\%PS_2 = 80\%$

$TMS_8 = ?$ $\quad$ $TMS_6 = ?$ $\quad$ $TMS_4 = ?$ $\quad$ $TMS_2 = 0.05$

You will obtain the same previous answers such that:

$TMS_4 = 0.105$, $TMS_6 = 0.163$, $TMS_8 = 0.237$



$\hookrightarrow$ I_f (between B&C) $\Rightarrow$ $R_{4,6,8}$ will work.

* * *

* Transformer Protection:

- 87G, 87T $\Rightarrow$ differential protection, also called unit protection.

* Why tap changer put on HV side?

① Since HV side is accessable.

② Since the HV side has Lower current (Lower sparks).

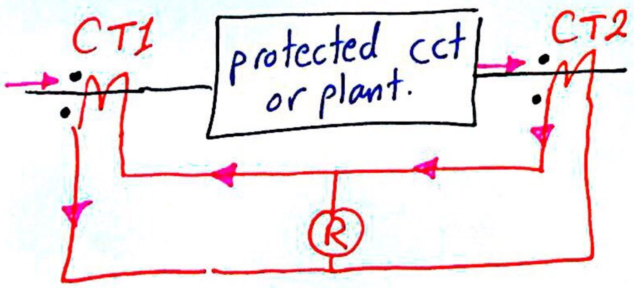


Fig. 1.

* Some comments on Fig. 1:

① The currents in the transformer are NOT equal But we choose CT1 & CT2 such that they give the same current through the secondary i.e zero current through the relay.

$\Longrightarrow$ Continue.

② at No-load condition, $I_2 = 0$ so all the current will pass through the relay so we need to have settings for the relay to work for current higher than the rated current.

* Balanced Circulating Current:

* External fault case: The contacts will be normally opened ⇒ (No tripping).
* Internal fault case: ⇒ tripping will occur.

* Winding Polarity:

for Δ λ connection: (phase voltages are in-phase)

Fig.2

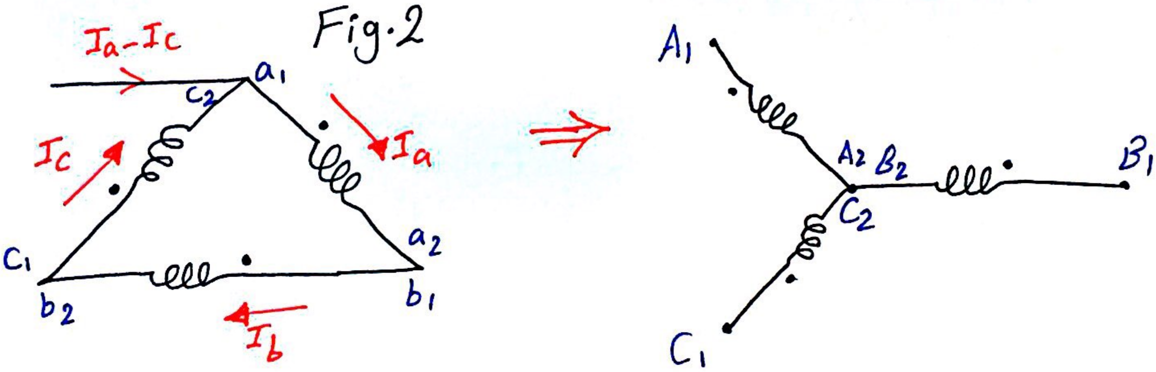
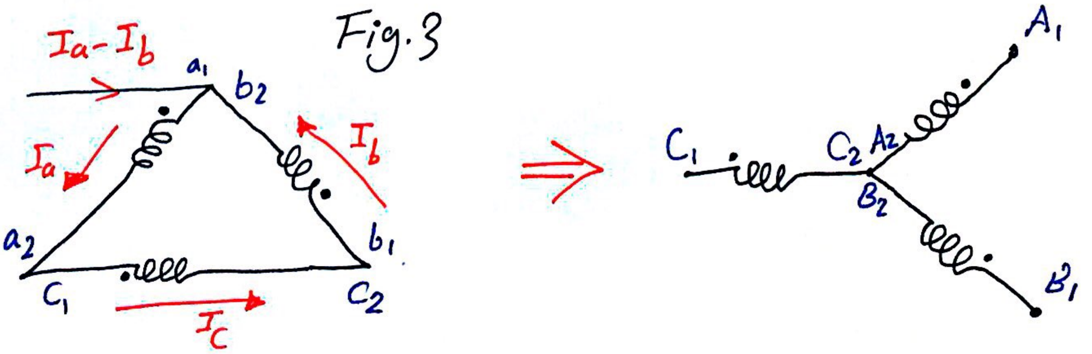
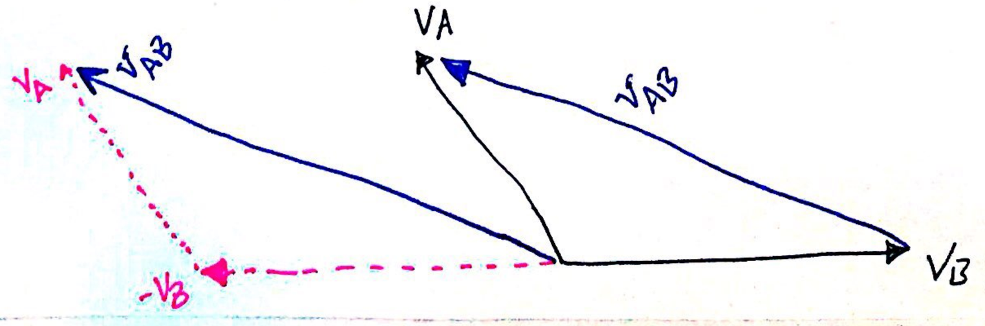
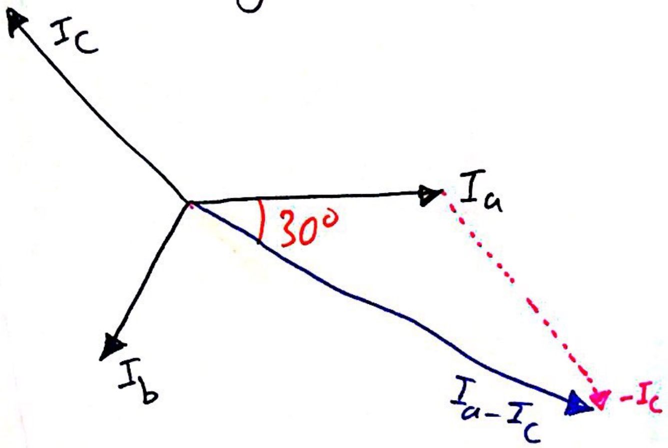


Fig.3

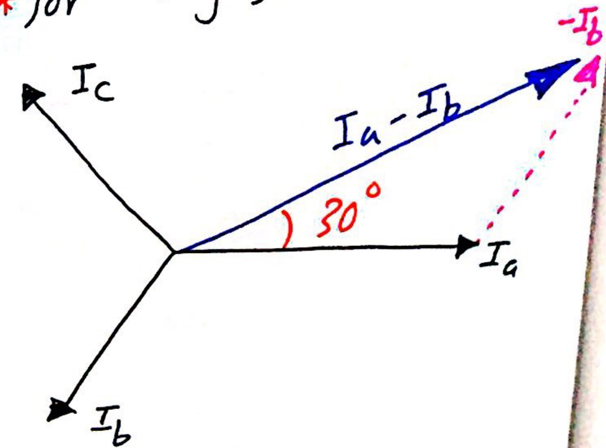




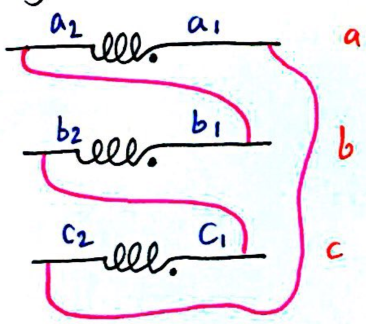
* for Fig. 2:



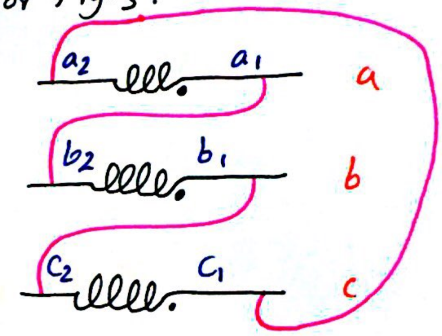
* for Fig. 3:



* for Fig. 2:



* for Fig. 3:



* Consider Y-Y connected transformer 10 MVA, 33/11 KV (HV/LV)

HV (capital letter), LV (small letter).

$S_{3\phi} = \sqrt{3}\, V_H I_H = \sqrt{3}\, V_L I_L = 10\,M$

$\Rightarrow \sqrt{3} \times 33 \times 10^3\, I_H = \sqrt{3} \times 11 \times 10^3 \times I_L = 10\,M$

$I_H = \frac{10 \times 10^6}{\sqrt{3} \times 33 \times 10^3} = 174.9 \simeq 175\,A.$

$I_L = \frac{10 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 524.8 \simeq 525\,A$

$\frac{I_L}{I_H} = \frac{V_H}{V_L} = \frac{33}{11} = 3$

• Now choosing a proper CTR for the both sides:

$CTR_{HV} = 200/5$ & $CTR_{LV} = 600/5$

$I_A' = \frac{I_A}{CTR_{HV}} = 175 / {}^{200}\!/_5 = 4.38\,A.$

$I_a' = \frac{I_a}{CTR_{LV}} = {}^{525}/_{600/5} = 4.38\,A.$

Continue ...

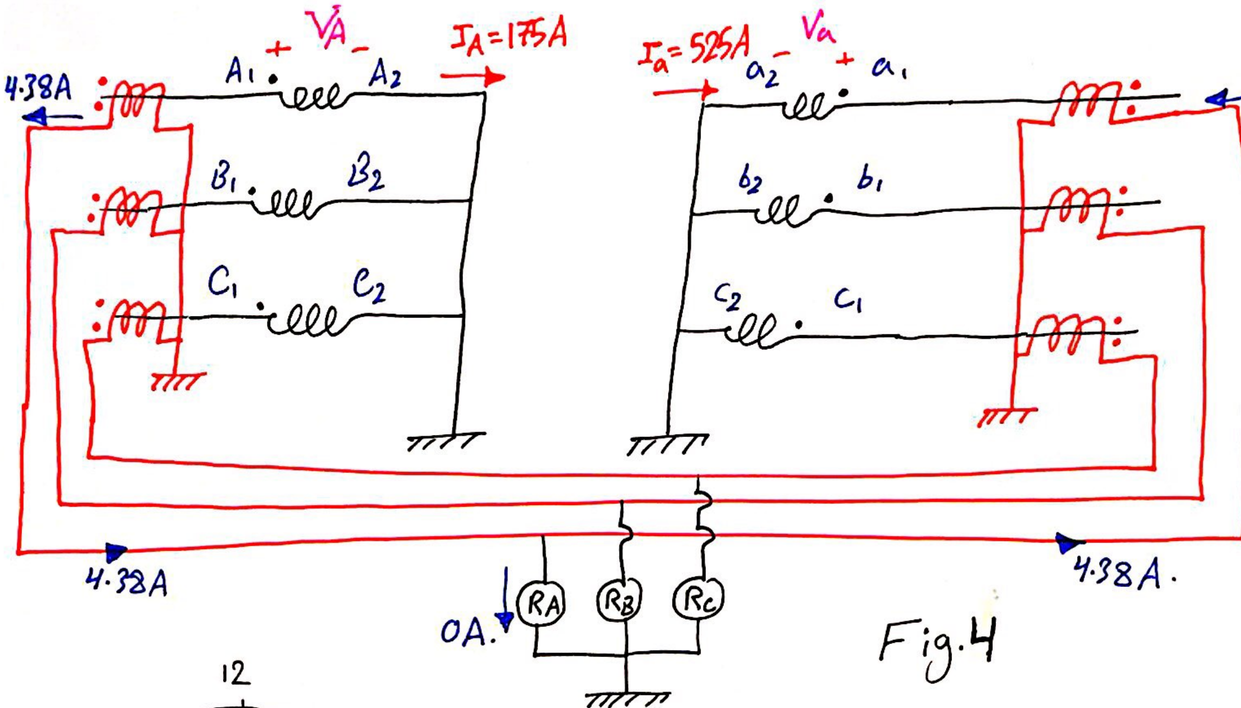
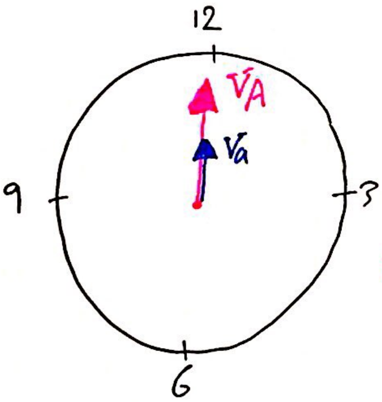


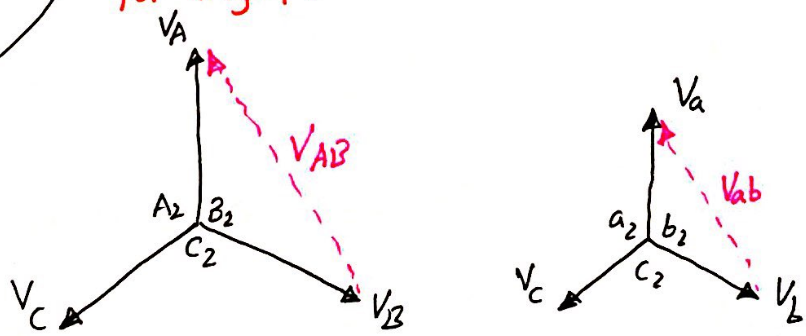
Fig.4



⇒ 0-phase shift

This is represented as: $Y_N y_n 0$

for Fig.4:



* Now Consider the same previous case But with grounding a_1, b_1, c_1 in the LV side:

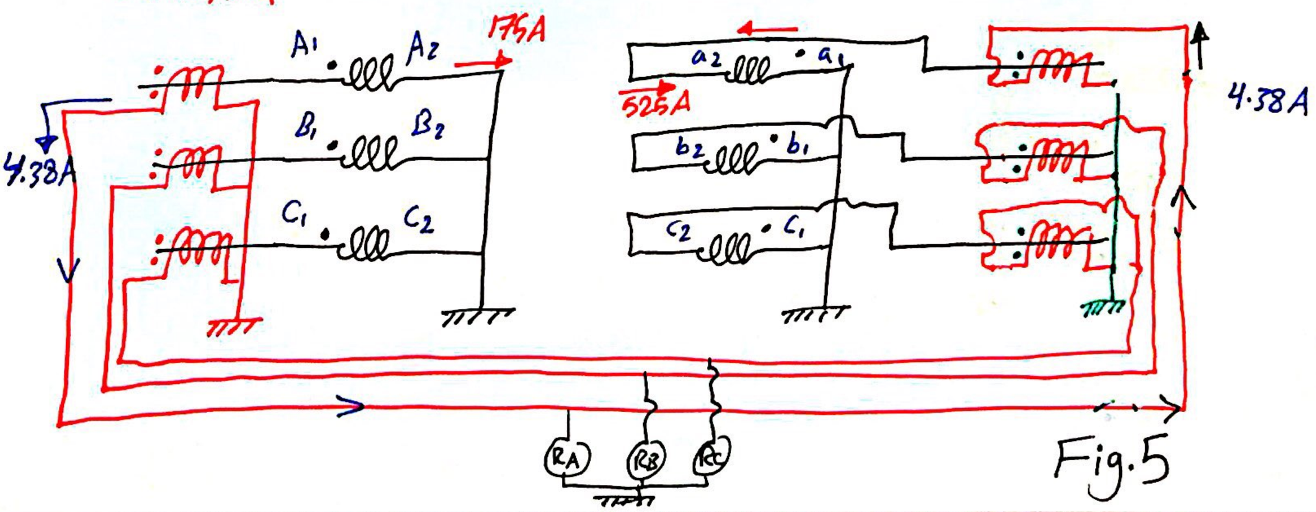
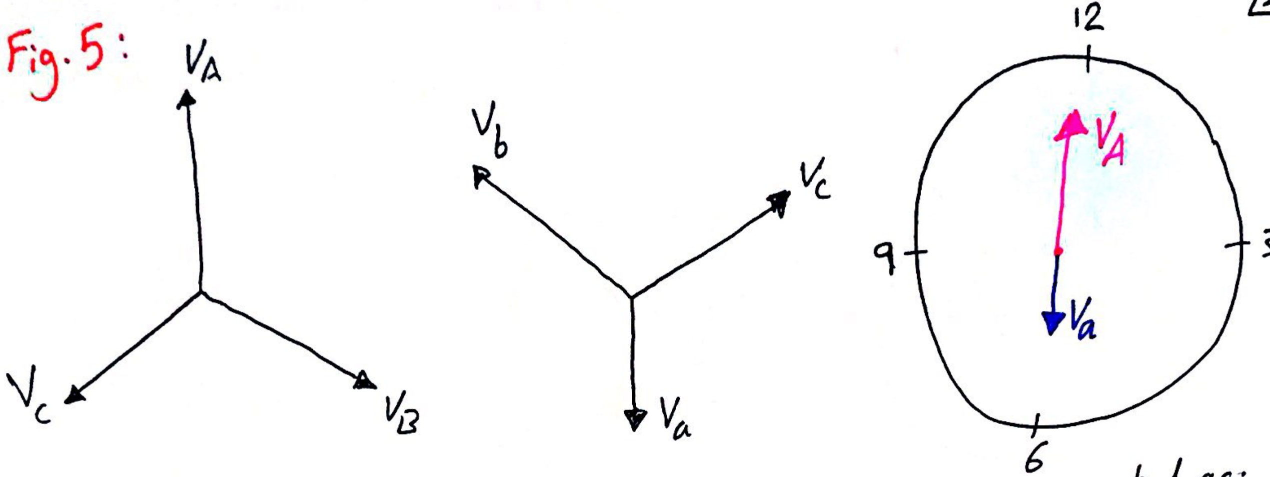


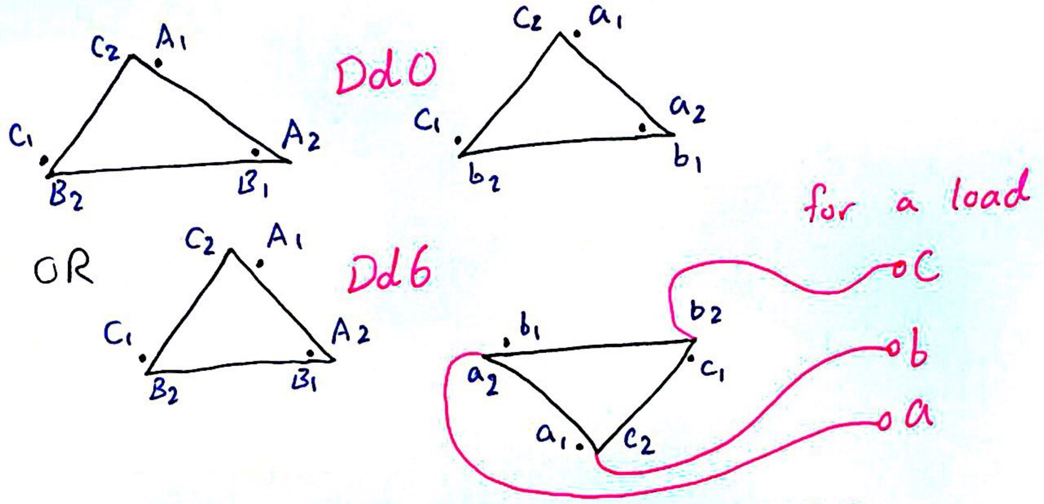
Fig.5

for Fig. 5:



This is represented as:
$Y_N y_n 6$ (180° phase shift).

* for Δ-Δ :



* Consider $\underline{\perp}$Y-Δ connected transformer:

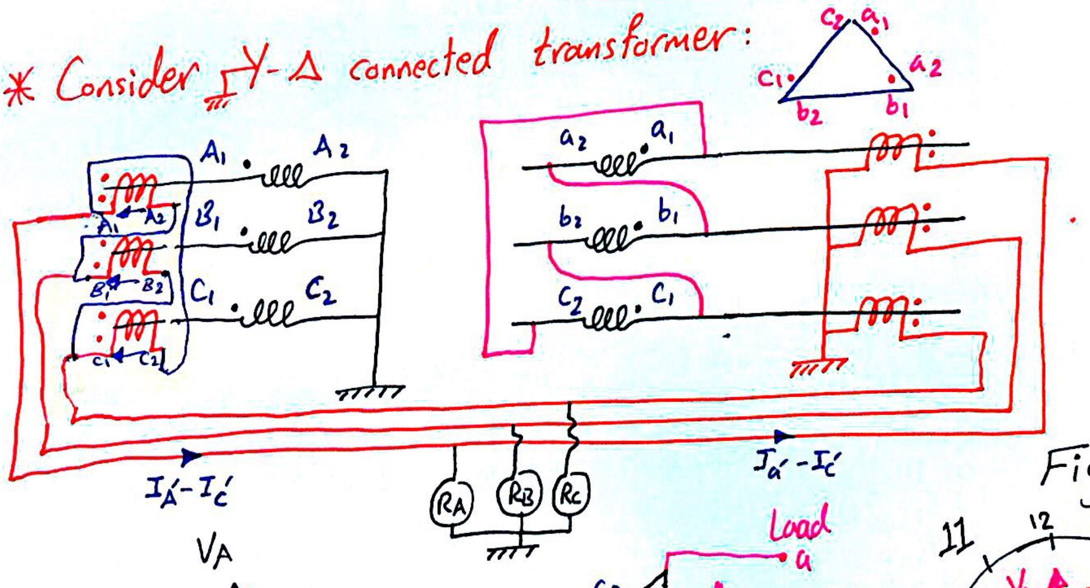
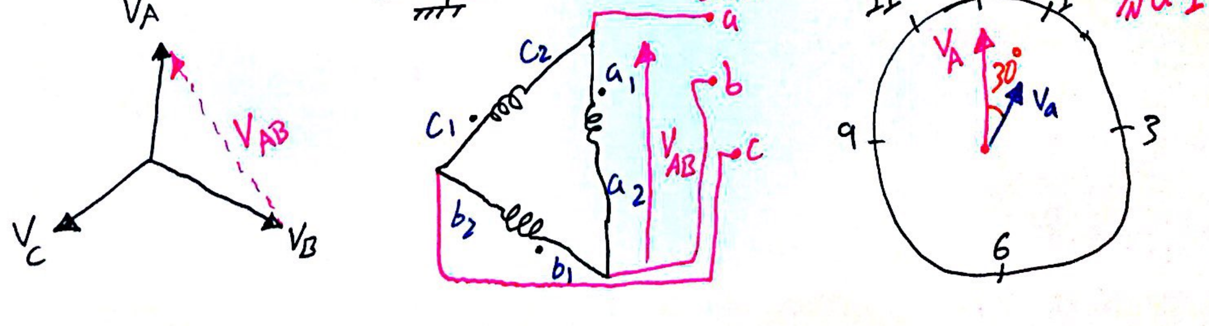
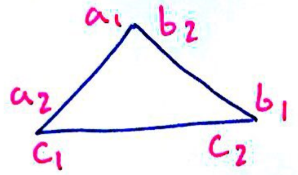


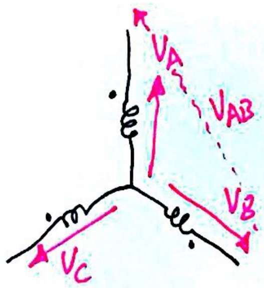
Fig. 6

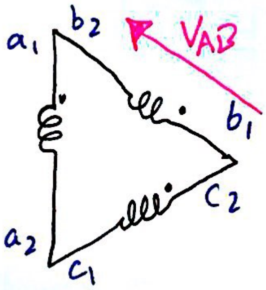


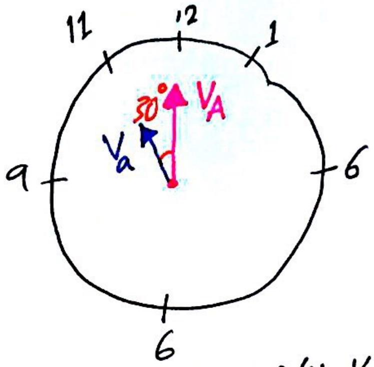
for another case:



$Y_N d11$

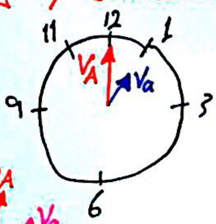




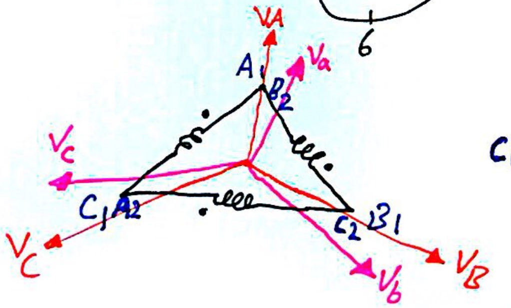


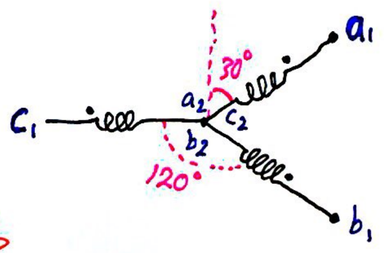
* Consider Δ-Y connected Transformer (Dy_n1) with 10MVA, 132/11 KV.

for Dy_n1

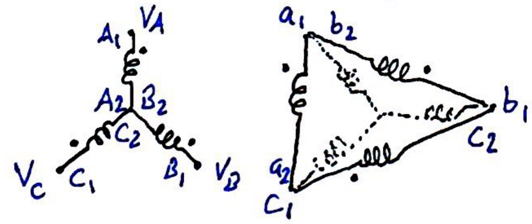


HV leads LV By 30°.





* CT connection would be $Y_N d11$



$$I_{HV\ rated} = \frac{10\times10^6}{\sqrt{3}\times132\times10^3} = 43.7A \Rightarrow CTR_{HV} = 50/1$$

$$I_{LV\ rated} = \frac{10\times10^6}{\sqrt{3}\times11\times10^3} = 524.4A \Rightarrow CTR_{LV} = 600/1$$

• Note that: the current through the secondary (CT):

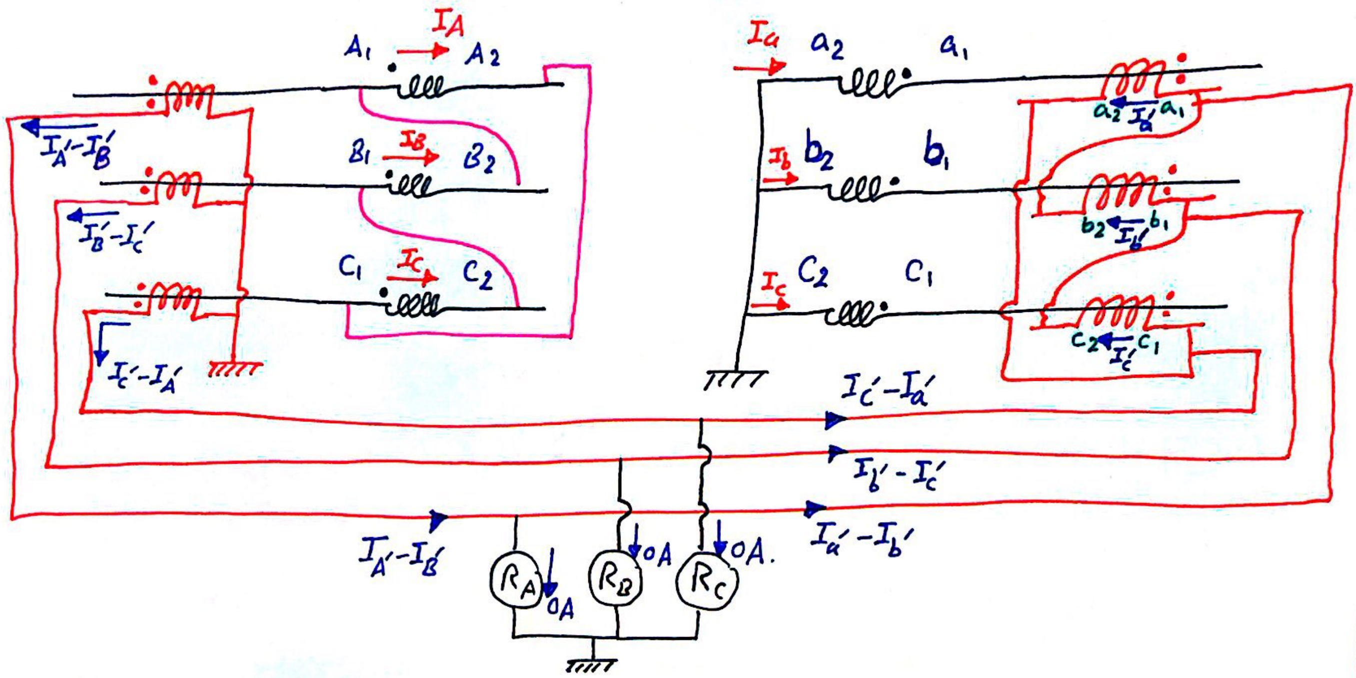
$$I'_{HV} = \frac{43.7}{50} = 0.874\,A.$$

$$I'_{LV} = \frac{524.4}{600\sqrt{3}} = 0.874\,A.$$

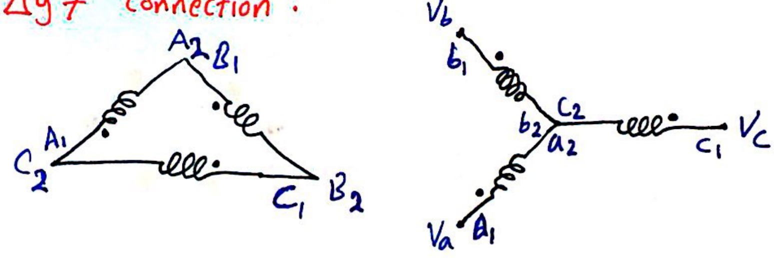
$\Rightarrow$ current passes through the Relay = Zero.

→ This obtained choosing an appropriate $CTR_{LV} = 600\sqrt{3}/1$

Continue...



* for a Δy7 connection :



Problem # 1

Consider a Δ/Y-connected, 20-MVA, 33/11-kV transformer with differential protection applied, for the current transformer ratios shown in Fig. P1. Calculate:

a. the relay currents on full load.
b. the minimum relay current setting to allow 125 percent overload.

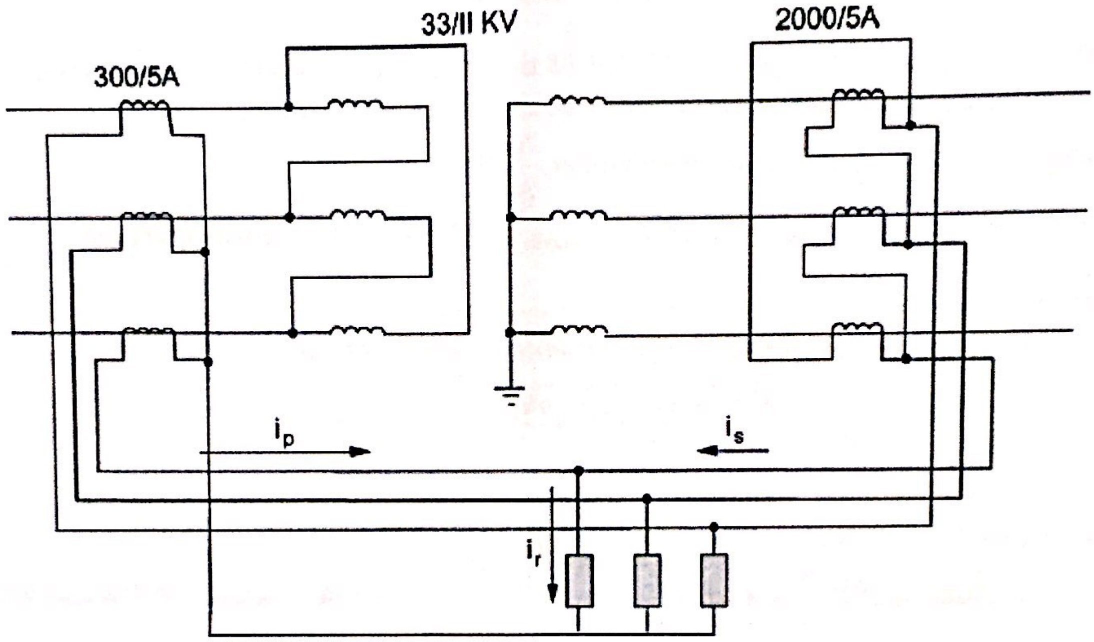


Fig. P1

Solution:

The primary line current is given by

$$I_p = \frac{20\times10^6}{(\sqrt{3})(33\times10^3)} = 349.91\,\text{A}$$

$$i_p = 349.91\left(\frac{5}{300}\right) = 5.832\,\text{A}$$

The secondary line current is

$$I_s = \frac{20\times10^6}{(\sqrt{3})(11\times10^3)} = 1049.73\,\text{A}$$

The C.T. current in the secondary side is

$$i_s = 1049.73\left(\frac{5}{2000}\right)\sqrt{3} = 4.545\,\text{A}$$

Note that we multiply by √3 to obtain the values on the line side of the Δ-connected C.T.'s. The relay current on normal load is therefore

$$i_r = i_p - i_s = 5.832 - 4.545 = 1.287\,\text{A}$$

With 1.25 overload ratio, the relay setting should be

$$I_r = (1.25)(1.287) = 1.61\,\text{A}$$

Problem # 2

For the $\Delta y11$ transformer shown in Fig. P4, there is a phase angle difference between primary and secondary equal to -30°. So, an auxiliary current transformer (matching) is installed in the secondary circuit of 11 kV current transformer side to compensate the magnitude and phase. Determine:

a. the primary (I_{L66P}) and secondary (I_{L11S}) currents of the ΔY-connected transformer when the transformer is delivering its rated MVA.
b. the currents seen by the CTs on the Δ-connected primary ($I_{CTA\Delta\text{-}S}$, $I_{CTB\Delta\text{-}S}$, and $I_{CTC\Delta\text{-}S}$) side and the currents seen by the Y-connected secondary ($I_{CTAY\text{-}S}$, $I_{CTBY\text{-}S}$, and $I_{CTCY\text{-}S}$) side of the transformer.
c. the line current of the primary Y-side of the matching transformer ($I_{P\text{-}match\text{-}L}$) and of the line current of the secondary Δ-side of the matching transformer ($I_{S\text{-}match\text{-}L}$).
d. the turns ratio of the matching transformer $\dfrac{N_{P-match}}{N_{S-match}}$.
e. the currents seen by each relay (I_{relayA}, I_{relayB}, and I_{relayC}) under normal conditions.

Solution:

$$I_{L66P} = (MVA\times 1000)/(\sqrt{3}\times 66\,kV) = (25\times 1000)/(\sqrt{3}\times 66) = 218.7\ A$$

$$I_{CTA\Delta-S} = \frac{I_{L66P}}{CTR_P} = \frac{218.7}{400/5} = \frac{(25\times 1000)/(\sqrt{3}\times 66)}{80} = \frac{}{80} = 2.73\ A$$

$I_{CTA\Delta\text{-}S} = I_{CTB\Delta\text{-}S} = I_{CTC\Delta\text{-}S} = 2.73$ A

$$I_{L11S} = (MVA\times 1000)/(\sqrt{3}\times 11\,kV) = (25\times 1000)/(\sqrt{3}\times 11)1312.2\ A$$

$$I_{CTAY-S} = \frac{I_{L11S}}{CTR_S} = \frac{1312.2}{1500/5} = 4.37\ A$$

$I_{CTAY\text{-}S} = I_{CTBY\text{-}S} = I_{CTCY\text{-}S} = 4.37$ A – (Input to the matching transformer)

For equilibrium of differential relay:-
Current of 11 kV of differential relay must be equal to current of 66 kV side of differential relay.
$\Rightarrow I_{CT\Delta\text{-}S} = I_{CTY\text{-}S} = 2.73$ A.
But, input current of matching transformer is $I_{match\text{-}P} = 4.37$ A. Therefore, the output current of the matching transformer (input to the differential relay) must be equal $I_{match\text{-}S} = 2.73$ A.

Note: the connection of the matching transformer must be YΔ1 to compensate the original angle of the power transformer.

The turns ratio of the matching transformer $N_{Pmatch}/ N_{Smatch} = I_{Smatch\text{-}ph}/ I_{Pmatch\text{-}ph}$.

$$\frac{N_{P-match}}{N_{S-match}} = \frac{I_{S-match-ph}}{I_{P-match-ph}} = \frac{I_{Smatch-L}/\sqrt{3}}{I_{Pmatch-L}} = \frac{2.73/\sqrt{3}}{4.37} = \frac{1.58}{4.37} \cong 0.36$$

$$\Rightarrow I_{Smatch-L} = 1.58\ A.$$

$$I_{relayA} = I_{CTA\Delta-S} - I_{S-mactch-L} = 2.73 - 2.73 = 0\ A$$

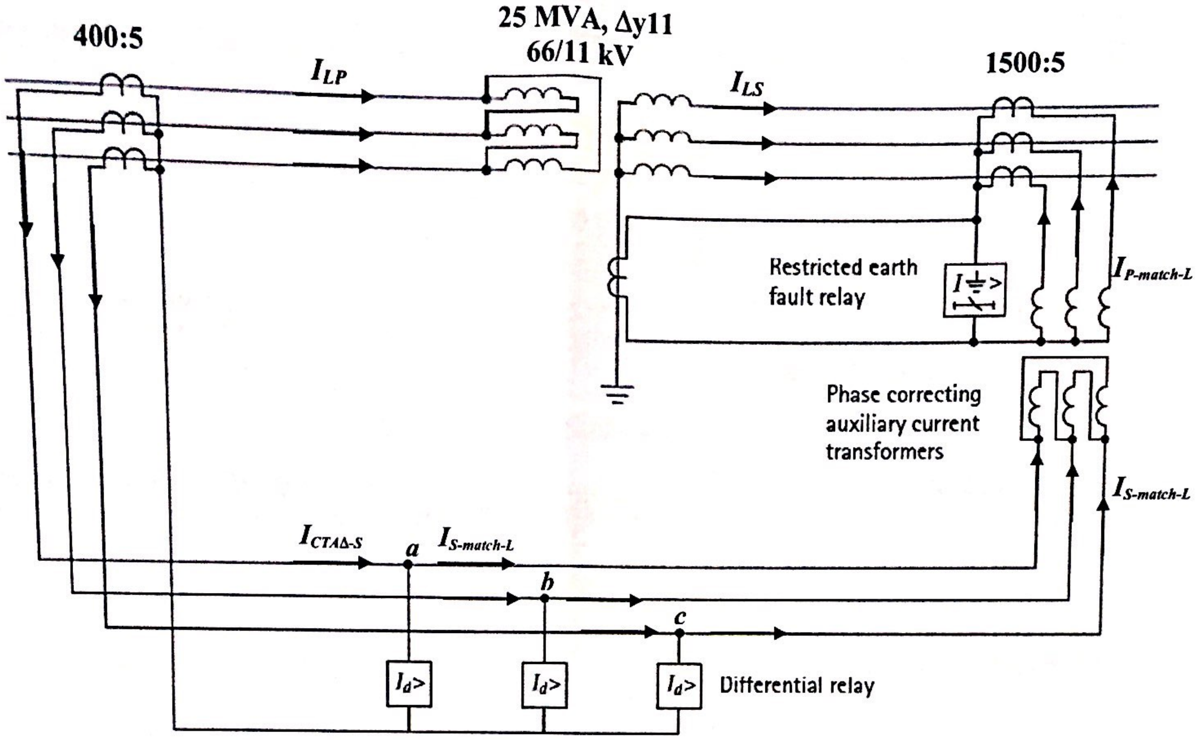


Fig. P4: Transformer Differential Protection

Problem # 3

Design the protection of a three-phase, 50-MVA, 230/34.5 kV power transformer, Fig. P3, using available standard CT ratios. The high-voltage side is Y-connected and the low-voltage side is Δ-connected. Specify the CT ratios, and show the three phase wiring diagram indicating the CT polarities. Determine the currents in the transformer and the CTs. Specify the rating of an autotransformer, if one is needed.

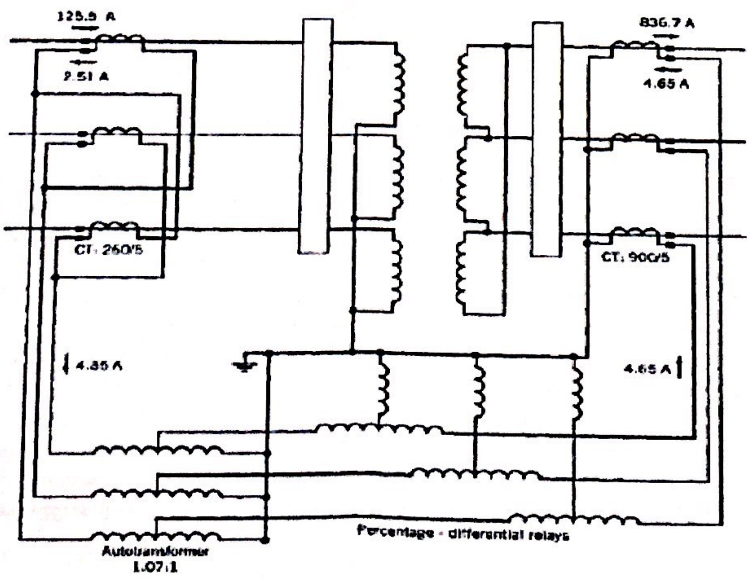


Fig P3: Y- Δ transformer protection

Solution:

When the transformer is carrying rated load, the line currents on the high-voltage side and low-voltage side are

$$I_{HV} = \frac{50{,}000}{\sqrt{3}(230)} = 125.5\text{ A}$$

$$I_{LV} = \frac{50{,}000}{\sqrt{3}(34.5)} = 836.7\text{ A}$$

The CTs on the low-voltage side are Y-connected, and the CT ratio selected for this side is 900/5. The current in the leads flowing to the percentage-differential relay on this side is equal to the CT secondary current and is given by

$$I_{LV\,lead} = 836.7\left(\frac{5}{900}\right) = 4.65\text{ A}$$

The current in the leads to the relay from the low-voltage side must be balanced by an equal current in the leads connected to the Δ-connected CTs on the high-voltage side. This requires a CT secondary current equal to

$$I_{CT\,sec} = \frac{4.65}{\sqrt{3}} = 2.68\text{ A}$$

To obtain a CT secondary current of 2.68 A, the CT ratio of the high-voltage CTs is chosen as

$$\text{CT ratio} = \frac{125.5}{2.68} = 46.8$$

The nearest available standard CT ratio is 250/5. If this CT ratio is selected, the CT secondary currents will actually be

$$I_{CT\,sec} = 125.5\left(\frac{5}{250}\right) = 2.51\text{ A}$$

Therefore, the currents in the leads to the Δ-connected CTs from the percentage-differential relays will be

$$I_{HV\,lead} = \sqrt{3}(2.51) = 4.35\text{ A}$$

It is seen that the currents in the leads on both sides of the percentage-differential relay are not balanced. This condition cannot just be ignored because it could lead to improper tripping of the circuit breaker for an external fault. This problem can be solved by using an autotransformer as shown in Fig. P3. The autotransformer should have a turns ratio of

$$N_{autotransformer} = \frac{4.65}{4.35} = 1.07$$

In the design of the transformer protection of Problem 3, the magnetizing current of the transformer has been assumed to be negligible. This is a reasonable assumption during normal operating conditions because the magnetizing current is a small percentage of the rated load current. However, when a transformer is being energized, it may draw a large magnetizing inrush current that soon decays with time to its normal value. The inrush current flows only in the primary, causing an unbalance in current, and the differential relay will interpret this an internal fault and will pick up to trip the circuit breakers. To prevent the protection system from operating and tripping the transformer during its energization, percentage-differential relaying with harmonic restraint is recommended. This is based on the fact that the magnetizing inrush current has high harmonic content, whereas the fault current consists mainly of fundamental frequency sinusoid. Thus, the current supplied to the restraining coil consists of the fundamental and harmonic components of the normal restraining current of $(I_A + I_B)/2$, plus another signal proportional to the harmonic content of the differential current $(I_A - I_B)/2$. Only the fundamental frequency of the differential current is supplied to the operating coil of the relay.

Problem # 4

A 3-phase 200 kVA, 11/0.4 kV 3-phase transformer is connected as ΔY as shown in Fig. P4. The CT on the 0.4 kV side has a CTR of 500/5 and the CT on the 11 kV side has a CTR of 10/5.

An earth fault of I_f =750 A fault current occurred on the **blue phase** within the protection zone. If the load current is negligible, find the following:

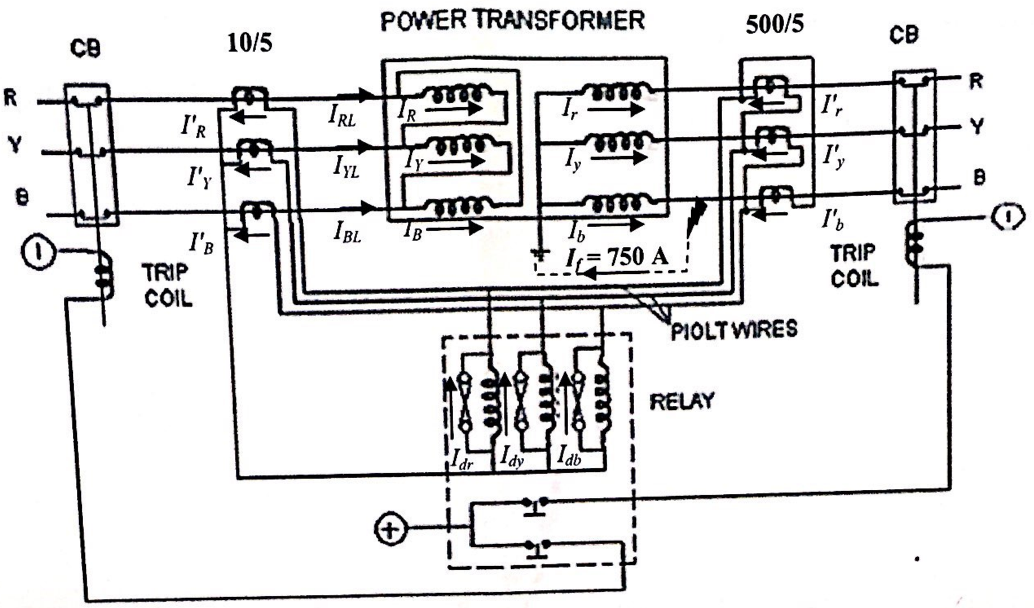


Fig. P4

1.	the LV red phase winding current, I_r	0 A
2.	the LV yellow phase winding current, I_y	0 A
3.	the LV blue phase winding current, I_b	750 A
4.	the HV red phase winding current, I_R	0 A
5.	the HV yellow phase winding current, I_Y	0 A
6.	the HV blue phase winding current, I_B	15.75 A
7.	the HV red phase line current, I_{RL}	-15.75 A
8.	the HV yellow phase line current, I_{YL}	0 A
9.	the HV blue phase line current, I_{BL}	15.75 A
10.	the HV red phase CT current, I'_R	-7.87 A
11.	the HV yellow phase CT current, I'_Y	0 A
12.	the HV blue phase CT current, I'_B	7.87 A
13.	the LV red phase CT current, I'_r	0 A
14.	the LV yellow phase CT current, I'_y	0 A
15.	the LV blue phase CT current, I'_b	0 A
16.	the red phase differential current, I'_{dr}	(7.87) A
17.	the yellow phase differential current, I'_{dy}	0 A
18.	the blue phase differential current, I'_{db}	(7.87) A

Problem # 5

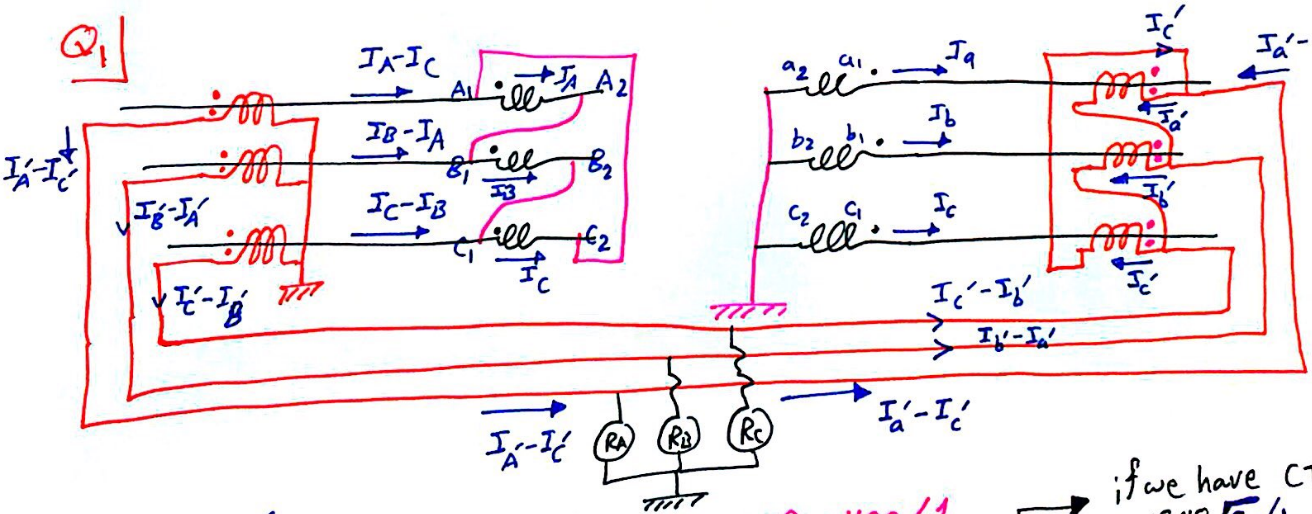
A three-phase step-down transformer bank is rated 10 MVA and 69/13.8kV. The high-voltage side is Y-connected, and the low-voltage side is Δ-connected. Sketch the developed three-phase wiring diagram for the protection of the transformer bank using differential relays. Show all CT ratings, connections, and polarities. Also show the values of the current in the lines, leads, relay windings, and transformer windings. Indicate the connections and ratings of any autotransformer that may be needed.

Problem # 6

Repeat Problem # 2 for the protection of a three-phase power transformer rated 100 MVA and 230/69kV. Assume that the transformer windings are Y-connected in both the primary and secondary sides.

Tutorial #5 :

Q1



$I_H = \dfrac{20\times10^6}{\sqrt{3}\times33\times10^3} \simeq 350\,A.$ so choose CTR = 400/1

$I_L = \dfrac{20\times10^6}{\sqrt{3}\times11\times10^3} = 1050\,A$ choose CTR = 1000/1

These CTR's will result $I_A'-I_C' = 0.875$, $I_a'-I_c' = 1.81$ so we need to increase the settings of the relay.

if we have CTR $= 1200\sqrt{3}/1$

$\Rightarrow$ this will result $I_a'-I_c' = 0.875$

Also choosing $CTR_{HV} = 300/5$, $CTR_{LV} = 2000/5$

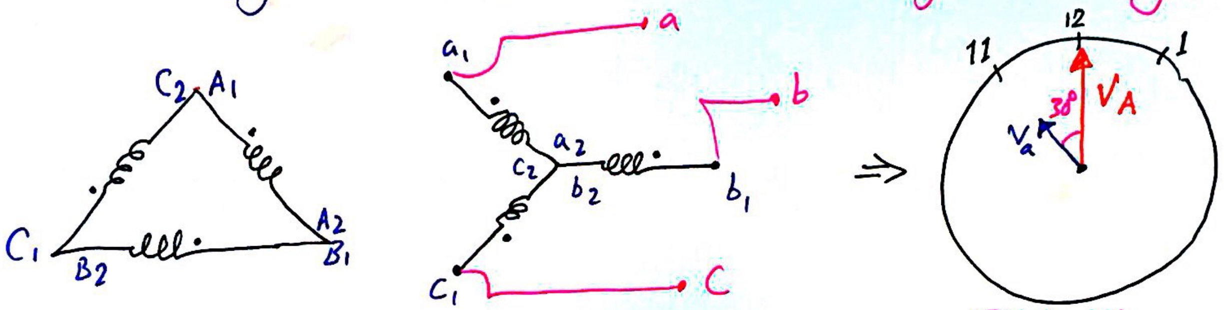
it will result: $I_{A'} - I_{C'} = 5.83$, $I_{a'} - I_{c'} = 4.5\,A$.

also need to increase the settings of the relay.

OR manipulate the CTR's so that they would give 0 A through the relay;

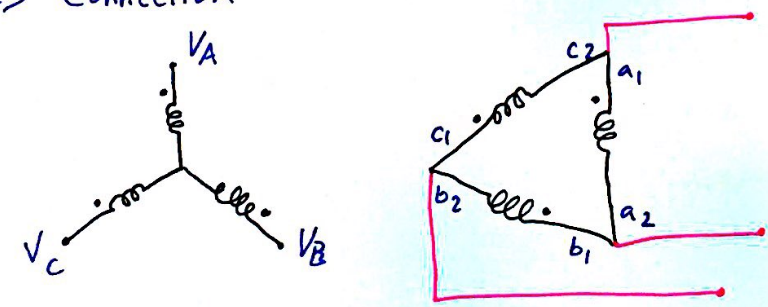
$5.8 - 4.5 = 1.3\,A$, consider 25% overload.

$\Rightarrow I_{relay} = 1.25 \times 1.3 = \underline{1.6\,A}$. $\Rightarrow$ this is the settings of the Relay.



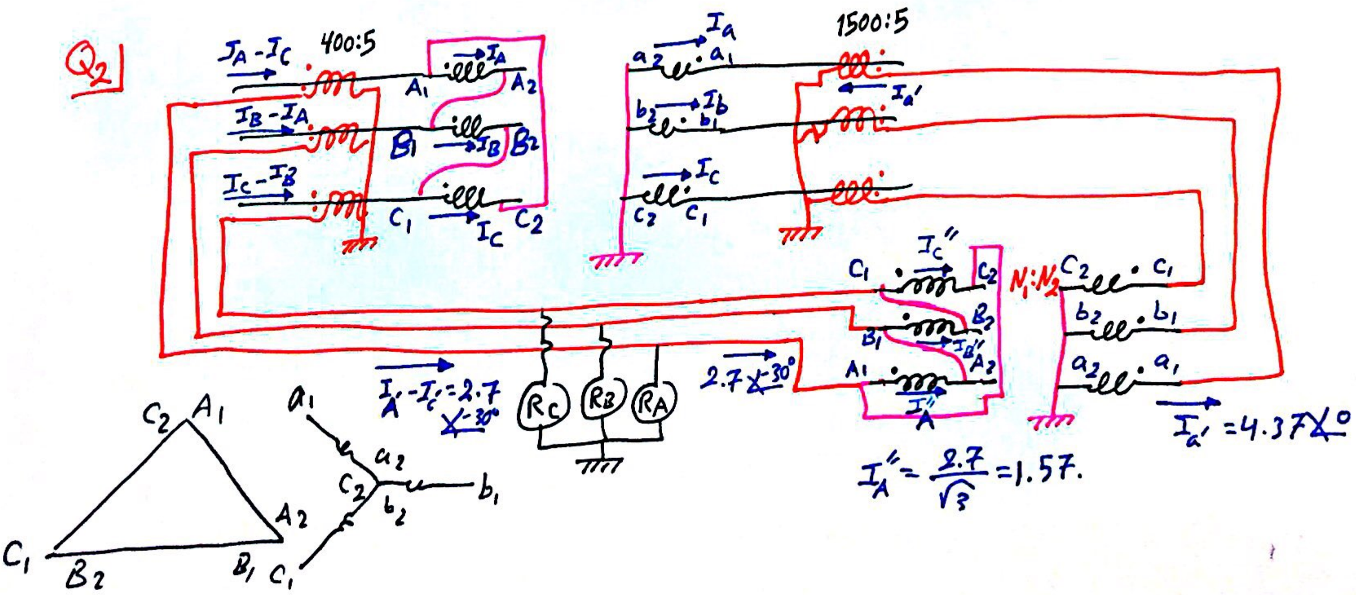
Dyn 11

$\Rightarrow$ Connection of the CT Ynd 1

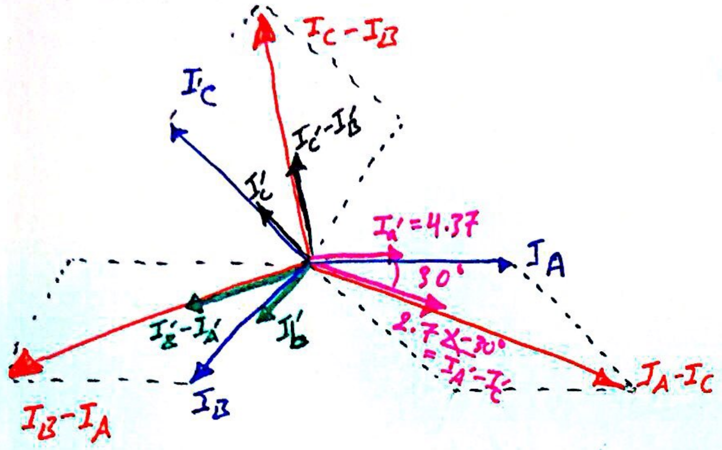


* * *

Q2



$I_A'' = \frac{2.7}{\sqrt{3}} = 1.57.$



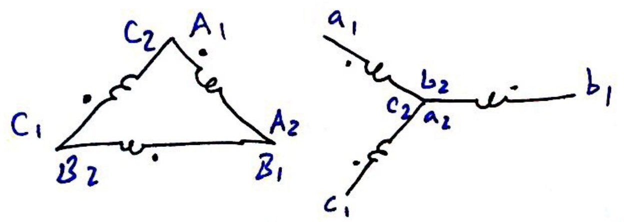
$$* \quad I_{H_{FL}} = \frac{25 \times 10^6}{\sqrt{3} \times 66 \times 10^3} = \underline{218.7}$$
$$= |I_A - I_C|$$

$$|I_A' - I_C'| = \frac{218.7}{400/5} = \underline{2.73A}.$$

$$* \quad I_{L_{FL}} = \frac{25 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 1312.2A = |I_a|$$

$$|I_a'| = \frac{1312.2}{1500/5} = \underline{4.37A}.$$

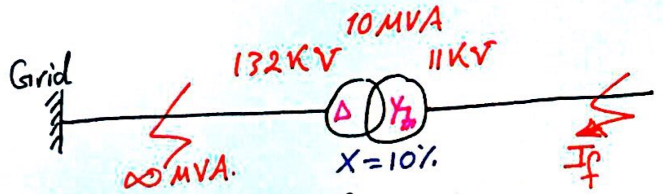
for the matching transformer: ($\Delta Y11$)

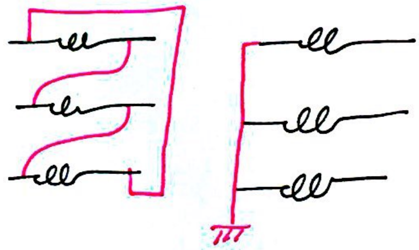


$$\Rightarrow \frac{I_a'}{I_A''} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$

$$\frac{N_1}{N_2} = \frac{4.37}{1.57} = \underline{2.77}.$$

* * *





Take 10MVA as Base value.

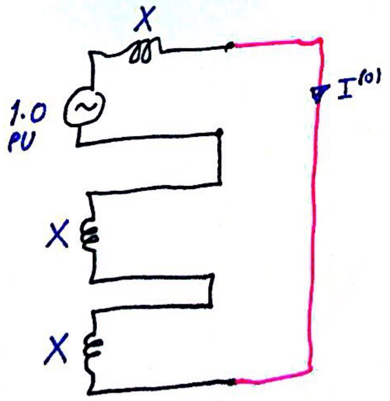
* for 3-ph. fault:

$$I_b = \frac{10 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 524.86A.$$

$$I_{sc} = \frac{1}{0.1} = 10 \text{ PU} = MVA_{sc}(\text{PU}).$$

$$\Rightarrow I_{sc} = 10 \times 524.86$$
$$= \underline{5248.6}A.$$

* for L-G fault:

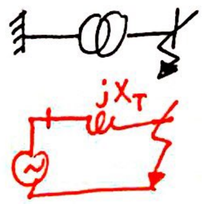


$$I_{LG} = 3I^{(0)} = 3 * \frac{1.0}{3X} = \frac{1}{X} = I_{f_{3\text{-ph.}}}$$

$$I_{LG} = \underline{5248.6}A.$$

* If the system is solidly grounded & the fault occur @ the terminal of the transformer then the Line to Ground current approaches to the three phase fault current.

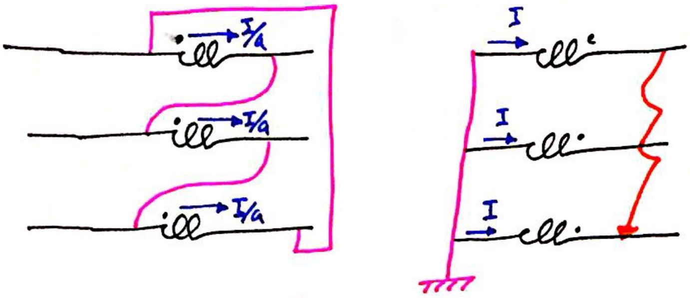
* Consider 3-ph fault:



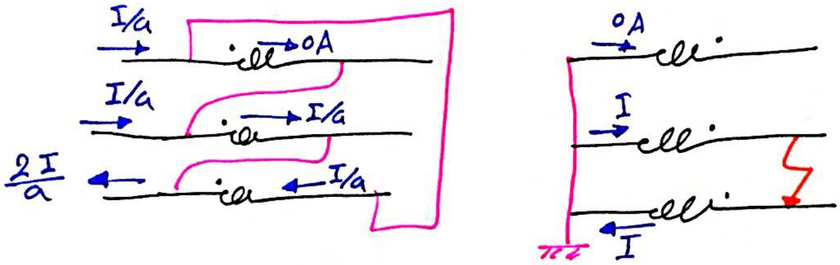
$I_{3\phi} = \frac{1}{X_T} = I$

$I_{LL} = 0.866\, I_{3\phi} = \frac{\sqrt{3}}{2} I$

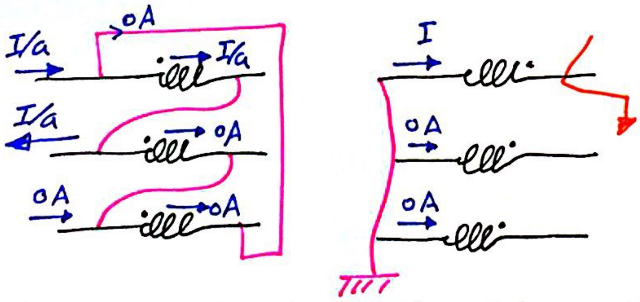
$I_{LG} = I$



* Consider LL fault:



* Consider LG fault:

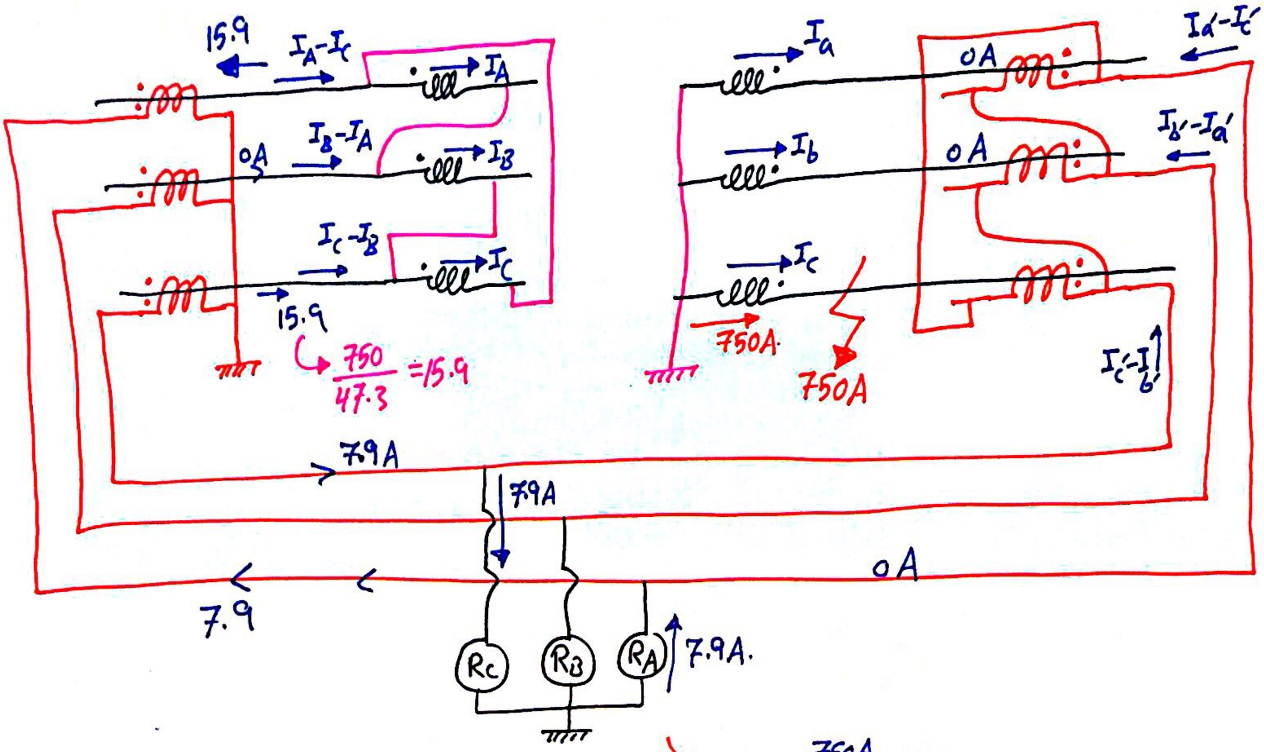


Q4

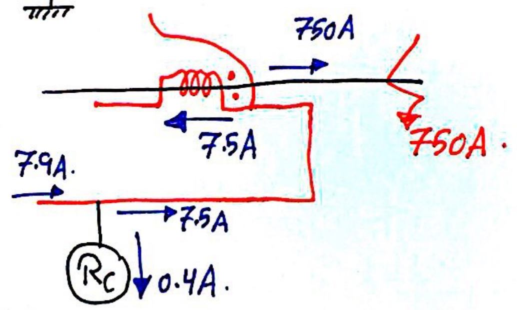
- $I_{11KV} = \frac{200 \times 10^3}{\sqrt{3} \times 11 \times 10^3} = 10.5\ A.$
- $I_{0.4KV} = \frac{200 \times 10^3}{\sqrt{3} \times 400} = 288.6\ A$
- for the Turns Ratio:

$$\frac{N_1}{N_2} = \frac{I_2}{I_1} = \frac{V_{1ph}}{V_{2ph}} = a = \frac{11000}{400/\sqrt{3}} = \sqrt{3}\ \frac{V_{LL\ HV}}{V_{LL\ LV}}$$

$$\Rightarrow \frac{N_1}{N_2} = \sqrt{3} \times \frac{11000}{400} = 47.6 \qquad I_1 = \frac{I_2}{a}$$



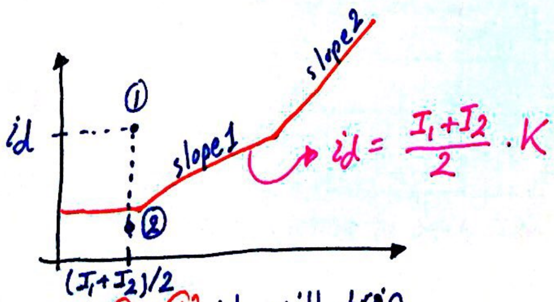
⇒ for External Fault:



*   *   *

*Differential Relay:

- differential relay works only for internal faults, But in certain case of very high external fault the CT could have saturation & there would be a current pass through the relay, lead it to work, But it will give wrong readings.



@ ① it will trip.

@ ② No tripping.

* the second slope to solve the problem of External Fault.

Problem # 7

A 115/13.2 kV Dy1 transformer rated at 25MVA has differential protection as indicated below. The transformer is connected to a radial system, with the source on the 115 kV side. The minimum operating current of the relays is 1 A. The transformer 13.2 kV winding is earthed via a resistor which is set so that the current for a single-phase fault on its secondary terminals is equal to the nominal load current. Draw the complete three-phase diagram and indicate on it the current values in all the elements for:

(i) Find the value of the grounding resistance R.

(ii) When a fault occurs at the middle of the winding on phase C, on the 13.2 kV side, assuming that the transformer is not loaded. For both cases indicate if there is any relay operation.

Solution:

Full load conditions

The full load conditions for the maximum load of the transformer are as follows:

$$I_{FL(13.2kV)} = \frac{25\times10^6}{\sqrt{3}\times13.\times10^3} = 1093.5\,A, \qquad R = \frac{13.2\times10^3/\sqrt{3}}{1093.46} = 6.97\,\Omega$$

Fault at the middle of 13.2 kV winding C

Since the transformer is earthed through a resistor that limits the current for faults at the transformer 13.2 kV bushings to the rating of the winding, and since the fault is at the middle of the winding, the fault current is then equal to half the rated value as follows:

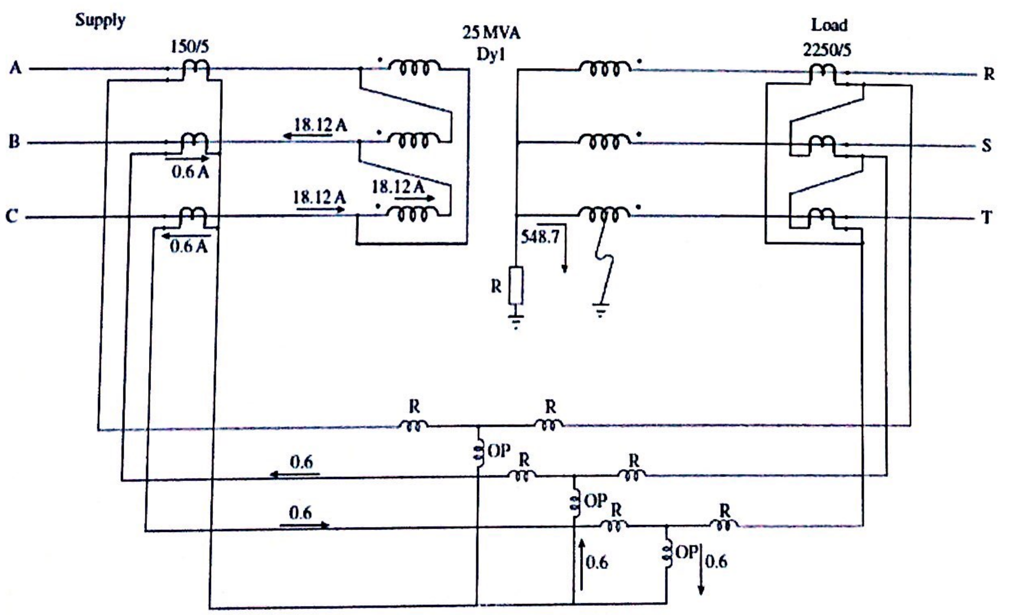
$$I_{fault} = (I_{nom(13.2\text{kV})})/2 = 1093.47/2 = 546.7\text{ A}$$

The primary current within the delta winding is

$$I_{prim} = I_{fault}\times\frac{(N_2/2)}{N_1}, \quad \frac{N_2}{N_1} = \frac{V_2/\sqrt{3}}{V_1}$$

$$I_{prim} = \frac{1}{\sqrt{3}\times VR} = 546.5\times\frac{\left(13.2/\sqrt{3}\right)/2}{115} = 18.1\,A$$

The differential relays **do not operate** since the current through their operating coils is only 0.6 A, which is less than the 1A required for relay operation.



Conditions for a fault at the middle of the winding on phase C on the 13.2 kV side

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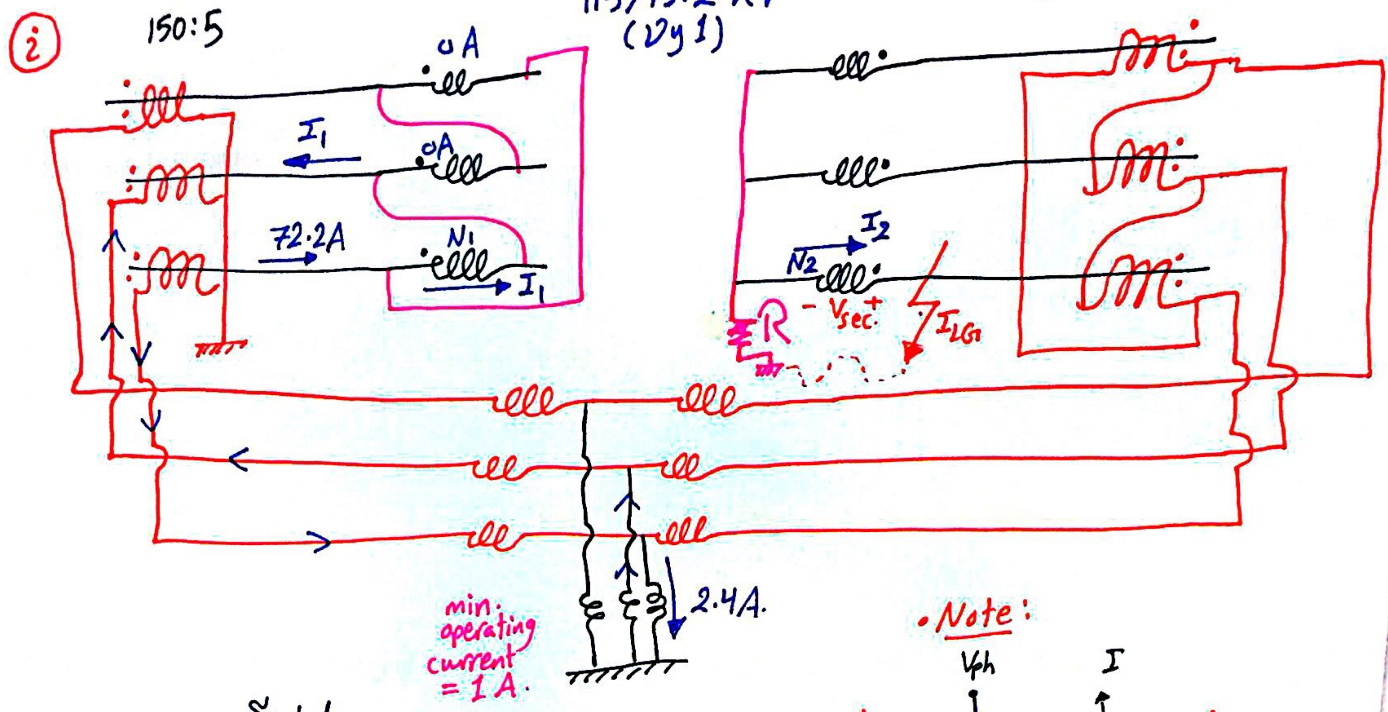
* problem #7:

(i)

Fig.1

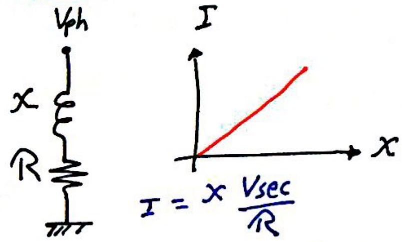


$$I_{LV\,rated} = \frac{S_{rated}}{\sqrt{3}\ V_{L\,rated}} = \frac{25\times10^6}{\sqrt{3}\ \times 13.2\times10^3} = \underline{1093.5\,A}$$

so $R = \dfrac{V_L/\sqrt{3}}{I_{LV}} = \dfrac{13.2\times10^3/\sqrt{3}}{1093.5} = 6.97 \simeq 7\Omega$

* $R = 7\Omega$ *

• Note:



$I = x\ \dfrac{V_{sec}}{R}$

R will Limit the fault current $\left(R = \dfrac{V_{sec}}{I_{rated}}\right)$

• remember: N

$V = N\, d\phi/dt$

$N\uparrow \Rightarrow V\uparrow$

(ii) * Consider the first case for a fault occur as shown in Fig.1.

$$I_{HV} = \frac{25\times10^6}{\sqrt{3}\times115\times10^3} = \underline{125.5\,A}.$$

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} = \frac{V_{2\,ph}}{V_{1\,ph}} = \frac{13.2\times10^3/\sqrt{3}}{115\times10^3} = 0.066$$

so * $\dfrac{N_1}{N_2} = 15.08$ *

$I_1 = 0.066\times1093.5 = \underline{72.2\,A}.$

• CAUTION: we used the turns ratio to find I_1, since the system isn't Balanced so we can't just divide By $\sqrt{3}$.

* The current in the CT:

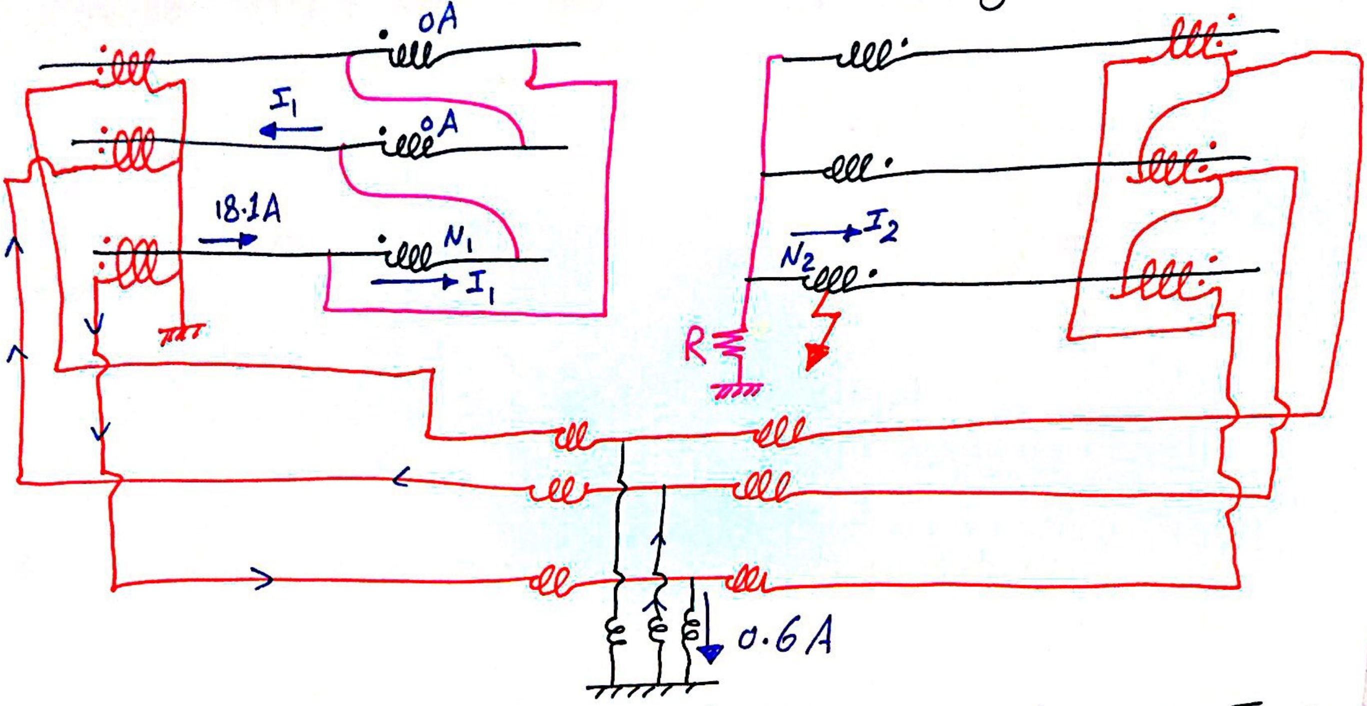
$$I_{CT} = \frac{72.2}{150/5} = \underline{2.4\,A}.$$

. Note that 2.4A > 1 A

∴ the relay will pick-up.

Continue ...

Fig.2



* Consider the second Case for a fault occur as shown in Fig.2.

$I_2 = \frac{1093.5}{2} = \underline{546.5A}$. $\Rightarrow$ $I_1 = \frac{N_2}{N_1} \times 546.5 = \frac{0.066}{2} \times 546.5$

$= \underline{18.1\ A}$.

* The current in the CT: $I_{CT} = \frac{18.1}{150/5} = \underline{0.6A}$.

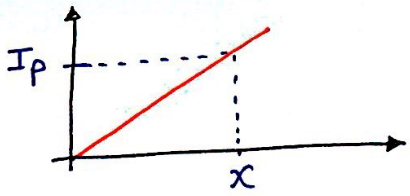
. Note that $0.6A < 1A$ $\therefore$ the relay won't pick-up.

* * *

* Now we want to find a relation between I_{pickup} & the value of x:

Consider the same exact connection in the previous figures (Fig.1 & Fig.2).

$I_1 \equiv I_{sc}'$, $I_2 \equiv I_{sc}''$, Voltage on the winding $\equiv x V_{sec}$.



$\Rightarrow I_{sc}'' = \frac{x V_{sec}}{R}$

$I_{sc}' = x \frac{N_2}{N_1} \cdot \frac{x V_{sec}}{R}$

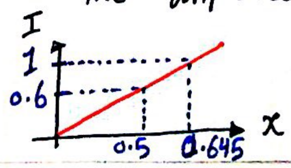
$x^2 = R \frac{N_1}{N_2} \frac{I_{sc}'}{V_{sec}}$ $\Rightarrow$ $x = \sqrt{R \frac{N_1}{N_2} I_p \frac{CTR_\Delta}{V_{sec}}}$ * 100%.

$I_{pickup\ (primary)} = I_p \times CTR_\Delta$

* Gives the percentage of the unprotected windings.

. you can use this relation to find x @ 1A pick up for previous problem.

$1A \Rightarrow (30A)_{primary} \Rightarrow \underline{x = 0.645}$



Power Systems Analysis II

Second Semester 2018

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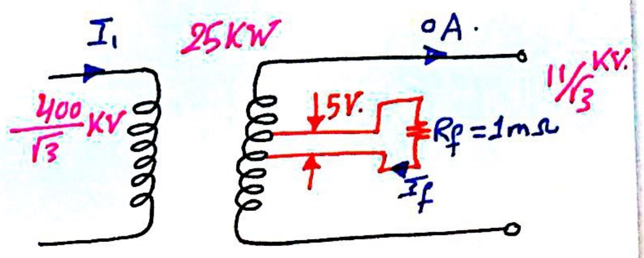
Notebook:
By. Mohammad Abu Hashya.

* * *

* Consider Inter-Turn Fault in Transformer:

"consider No-load Case"

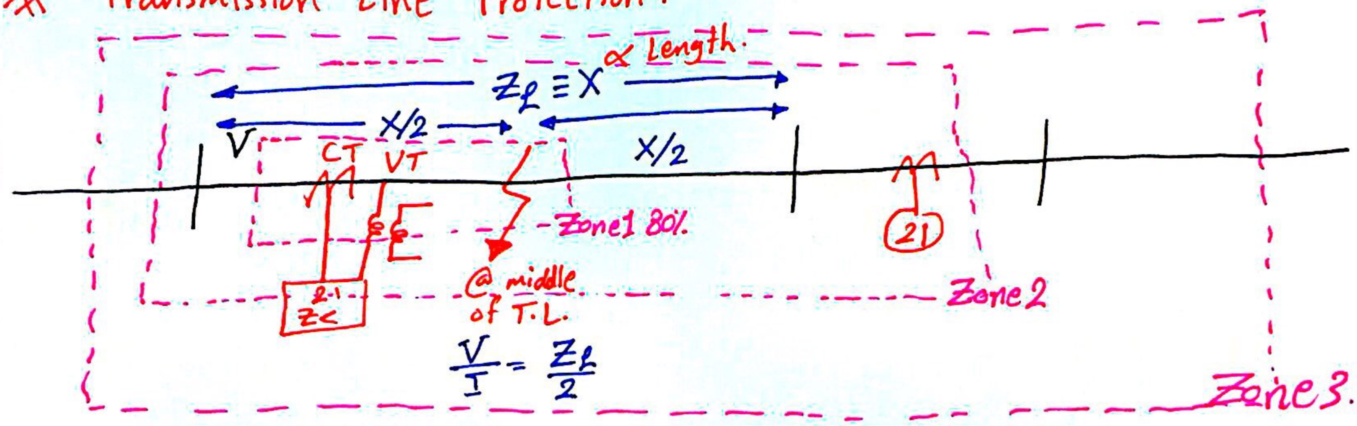


$$I_f = \frac{5}{1\times10^{-3}} = 5000\,A.$$

$$P_{dissapated} = I_f^2 R_f = (5000)^2 * 1\times10^{-3} = 25KW.$$

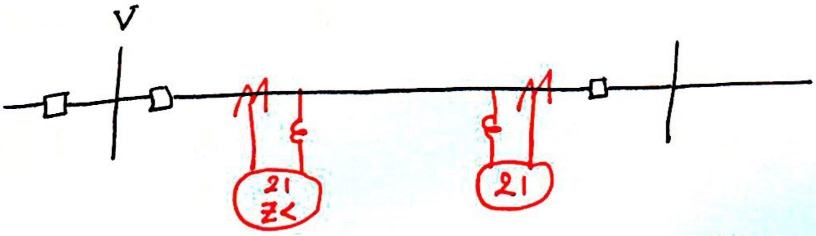
$$V_1 I_1 = 25K \Rightarrow I_1 = \frac{25\times10^3}{\frac{400}{\sqrt{3}}\times10^3} = 0.11\,A.$$

* Transmission Line Protection: "Distance Protection"



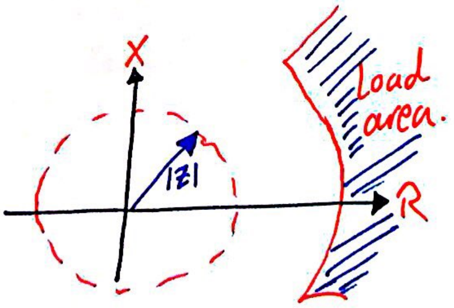
*Communications between Relays could be done using:

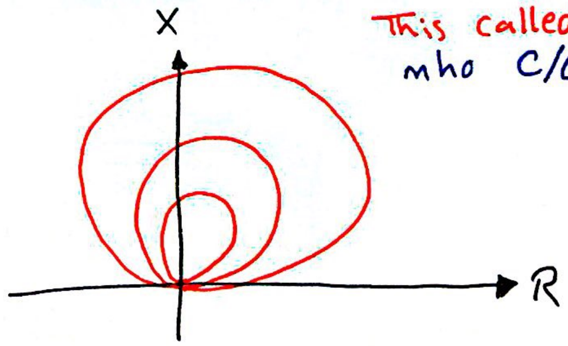
- Conductor itself.
- fiber optic.
- Micro waves.



$Z_{seen} < Z_{setting}$ $\quad Z = \frac{V}{I}$; apparent impedance.

$Z = R + jX \quad |Z|^2 = R^2 + X^2$



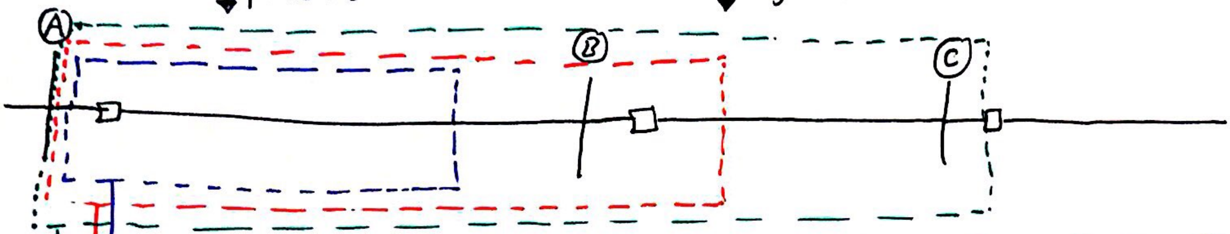


This called: mho C/C.

Directional Distance Relay.

* Consider the following system:

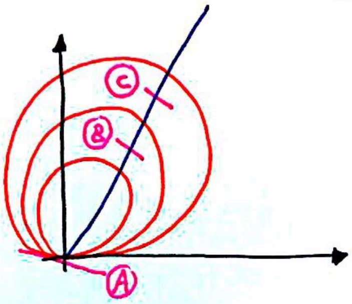
↓ protected Line ↓ adjacent Line.



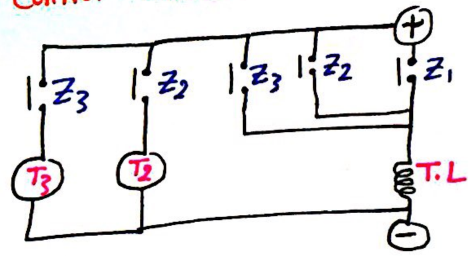
Zone 1 (80-90)% of the protected Line ⇒ "Under reach Zone".

Zone 2 (120)% of the protected line ⇒ "over reach".

Zone 3 (100)% of the protected line + (120)% of the adjacent Line. ⇒ "over reach".



* Control Circuit:

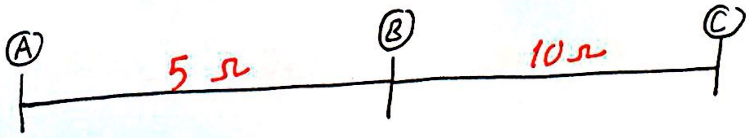


• Define $Z_\ell \equiv$ Line impedance. $= \frac{V}{I}$

$$Z_{\text{seen by the relay}} = \frac{V/VTR}{I/CTR} = Z_\ell \times \frac{CTR}{VTR}$$

$Z_{r_1} = 0.8\, Z_{AB}$, $Z_{r_2} = 1.2\, Z_{AB}$, $Z_{r_3} = Z_{AB} + 1.2\, Z_{BC}$

Example:



for A:

$Z_{r_1} = 4\Omega$

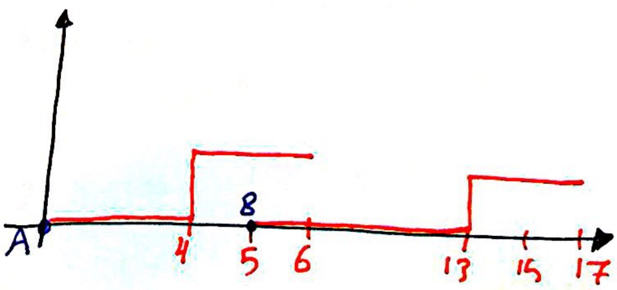
$Z_{r_2} = 6\Omega$

$Z_{r_3} = 17\Omega$

for B:

$Z_{r_1} = 8\Omega$

$Z_{r_2} = 12\Omega$



* * *

Question # 1:

Consider the system of Fig. Q1 where the values given are impedance in per-unit. Draw the per-phase equivalent circuit and find the impedance as seen by the impedance relay looking into the circuit for the following cases:

a. normal load conditions, Z_n
b. 3-phase fault at F_1, Z_{F1}
c. 3-phase fault at F_2, Z_{F2}

Plot the impedance as seen by the impedance relay on the R-X diagram.

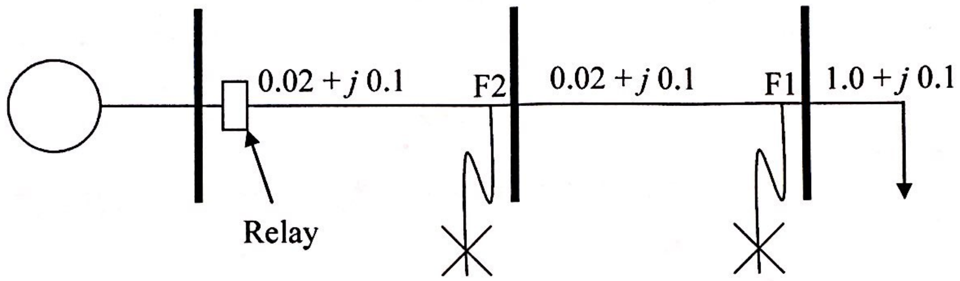
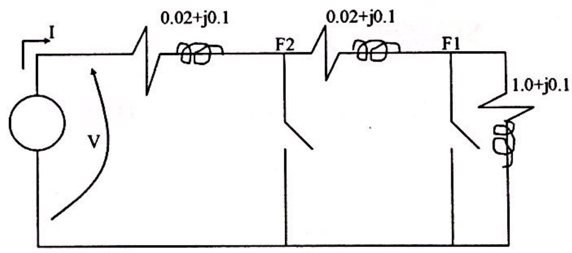


Fig. Q1

Solution:

The per-phase circuit is shown.

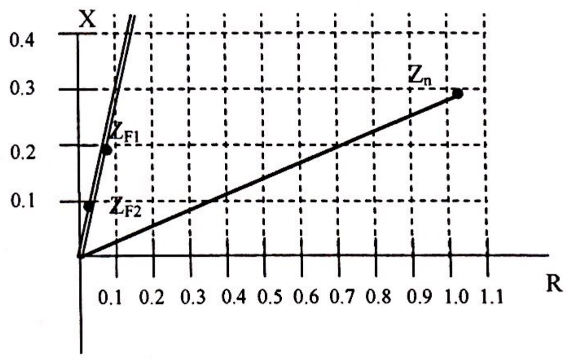


The desired impedance is $Z = \dfrac{V}{I}$

(a) Under normal load, $Z_n = \dfrac{V}{I} = 1.04 + j0.3\,pu$

(b) For a fault at F_1, $Z_{F1} = \dfrac{V}{I} = 0.04 + j0.2\,pu$

(c) For a fault at F_2, $Z_{F2} = \dfrac{V}{I} = 0.02 + j0.1\,pu$



Question # 2:

Consider a 132 kV transmission system as shown in Fig. Q2. The positive sequence impedances of the lines 1-2 and 2-3 are $Z_{12} = 3 + j\,40\ \Omega$ and $Z_{23} = 7 + j\,30\ \Omega$ respectively. The maximum peak load supplied by the line 1-2 is 110 MVA with a lagging power factor of 0.8. Assume a L-L fault of I_f=500 A occurs midway of the line 1-2 and line spacing of 3.5 m is equal to arc length. Design a distance protection system using Mho relays by determining the following:

a. Maximum load current
b. Suitable CT ratio. Secondary standard 5 A.
c. Suitable VT ratio. Secondary standard 67 V.
d. Line impedance measured by the relay.
e. Load impedance measured by the relay.
f. Zones 1, 2, and 3 setting of relay R12.
g. Value of arc resistance at fault point in Ω.
h. Show graphically, whether or not relay will clear the fault instantaneously.

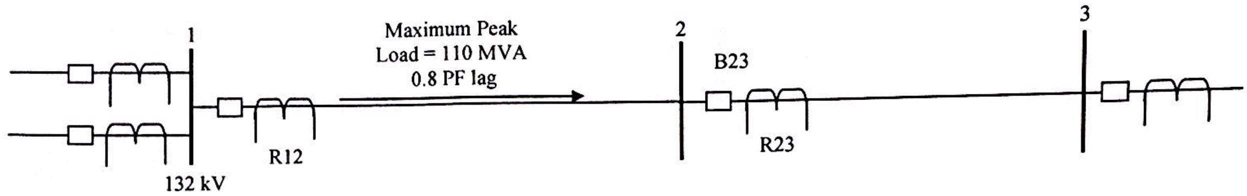


Fig. Q2

Solution:

a. Maximum load current

$$I_{L\max} = \frac{S_L}{\sqrt{3}VLL} = \frac{110\times 10^6}{\sqrt{3}132\times 10^3} = 481.13\ A$$

b. CT ratio

Choose $CTR = \dfrac{500}{5} = 100:1$

c. VT ratio

$$V_{ph} = \frac{V_{LL}}{\sqrt{3}} = \frac{132\times 10^3}{\sqrt{3}} = 76210.2\ V = 76.21\ kV$$

Choose $VTR = \dfrac{76210}{67} = 1137.46:1$

d. Line impedance measured by the relay

$$Z_{line-secondary} = \frac{V_p}{I_p}\times\frac{CTR}{VTR} = Z_{line}\times\frac{CTR}{VTR}$$

$$Z_{line-secondary} = Z_{line}\times\frac{100}{1137.46} = Z_{line}\times 0.0879$$

Thus the impedances of the two lines as seen by the relay R12 are approximately

Line 1-2 $\quad Z_{12} = (3 + j40)\times 0.0879 = 0.26 + j3.52\ \Omega$

Line 2-3 $\quad Z_{23} = (7 + j30)\times 0.0879 = 0.615 + j2.64\ \Omega$

e. Load impedance seen by the relay.

The maximum load impedance with 0.9 power factor lagging is

$$Z_{load} = \frac{V_{ph}}{I_{L\max}}\angle\cos^{-1}(0.8) = \frac{76.21\times10^3}{481.13}\angle36.9° = \frac{76.21\times10^3}{481.13}(0.8+j0.6)$$

$$= 158.4\angle36.9°\ \Omega = 126.7 + j95.1\ \Omega$$

$$Z'_{load} = Z_{load-primary}\times\frac{CTR}{VTR} = Z_{load-primary}\times0.0879$$

$$Z'_{load} = 158.4\angle36.9°\ \Omega\times0.0879 = 13.9\angle36.9°\ \Omega$$

$$= 126.7 + j95.1\ \Omega\times\frac{40}{1189.1} = 11.1 + j8.4\ \Omega$$

$$= 13.9\angle37.1°\ \Omega$$

f. Zones 1, 2, and 3 setting of relay R12.

The zone 1 setting of the relay R12 must **under reach** the line 1-2, so that the setting should be

$Z_{r1} = 0.8\times Z'_{12} = 0.8\times(0.26+j3.52)\ \Omega = 0.21+j2.82\ \Omega = 2.83\angle85.7°\ \Omega$

The zone 2 setting should reach past terminal 2 of the line 1-2. Zone 2 is usually set at about 1.2×the length of the line being protected.

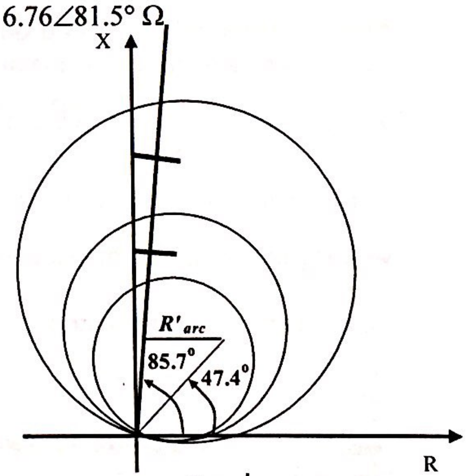
Zone 2 for R12 is therefore set at

$Z_{r2} = 1.2\times Z'_{12} = 1.2\times(0.26+j3.52) = 0.31+j4.22\ \Omega = 4.2\angle85.8°\ \Omega$

The zone 3 setting should reach beyond the longest line connected to bus 2. Thus the zone-3 setting must be

$$Z_{r3} = Z'_{12} + 1.2\times Z'_{23}$$

$$= (0.26+j3.52) + 1.2\times(0.615+j2.64) = 1.0+j6.69\ \Omega = 6.76\angle81.5°\ \Omega$$



g. Value of arc resistance at fault point in Ω.

The empirical fault arc resistance is given by:

$$R_{arc} = \frac{2.9\times10^4 L}{I^{1.4}}$$

Where

L is the length of arc (m) in still air

I is the fault current in A.

$$R_{arc} = \frac{2.9\times10^4\times3.5}{500^{1.4}} = \frac{101500}{6005.6} = 16.9\ \Omega$$

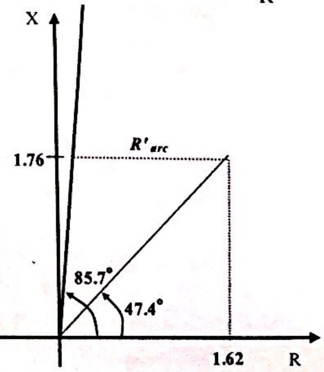
$$R'_{arc} = 16.9\times0.0879 = 1.486\ \Omega$$

Show graphically, whether or not relay will clear the fault instantaneously.

The total impedance seen by the relay up to the fault point is Z'_f

$$Z'_f = 0.5\times Z'_{12} + R'_{arc} = 0.5\times(0.26+j3.52) + 1.486$$

$$Z'_f = 0.13 + 1.486 + j1.76 = 1.62 + j1.76\ \Omega = 2.39\angle47.4°\ \Omega$$

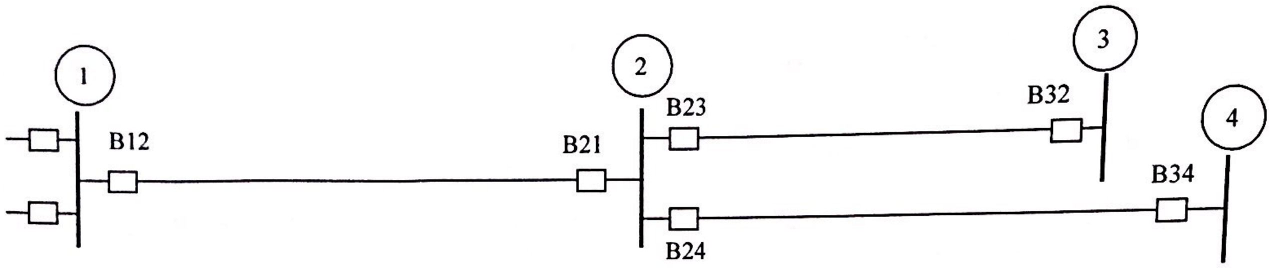


The fault lays lies in the zone 1, so it will be cleare

Question # 3:

Consider the portion of a 138 kV transmission system shown below. Lines 1-2, 2-3 and 2-4 are respectively 64, 64, and 96 km long. The positive sequence impedance of the transmission lines is $(0.05 + j\,0.5)$ Ω/km. The maximum load carried by line 1-2 under emergency condition is 50 MVA.

Design a 3-zone step distance relaying system to the extent of determining for R12 the zone setting which are the impedance values in terms of CT and VT secondary quantities. The zone settings give points on the R-X plane through which the zone circles of the relay characteristics must pass.



Solution:

The positive sequence impedances of the three lines are:

Line 1-2	$Z12 = 3.2 + j\,32.0\ \Omega$
Line 2-3	$Z23 = 3.2 + j\,32.0\ \Omega$
Line 2-4	$Z24 = 4.8 + j\,48.0\ \Omega$

Since distance relays depend on the ratio of voltage to current ($Z=V/I$), both a CT and VT are needed for each phase. The maximum load current is

$$I_{L\max} = \frac{50\times10^6}{\sqrt{3}\times138\times10^3} = 209.2\ A$$

Then, select a CT ratio of CTR=CTR $= \frac{200}{5} = 40$ which will produce about 5 A in the secondary winding under maximum loading conditions (209.2/200/5=5.23 A).

The system voltage to neutral is:

$$V_{ph} = \frac{138\times10^3}{\sqrt{3}} = 79.67\ kV$$

The industry standard for VT secondary voltage is 67 V for line-to-neutral voltages. Consequently, select a VT ratio (VTR) of

$$VT = \frac{79.67\times10^3}{67} = \frac{1189.1}{1}.$$

Denoting primary voltage of VT at bus 1 as V_p and the primary current of the CT as I_p, then the impedance measured by the relay is given by

$$Z_{line-secondary} = \frac{V_p}{I_p}\times\frac{CTR}{VTR} = Z_{line}\times\frac{CTR}{VTR}$$

$$Z_{line-secondary} = \frac{V_p/1189.1}{I_p/40} = \frac{V_p}{I_p}\times\frac{40}{1189.1} = Z_{line}\times0.0336$$

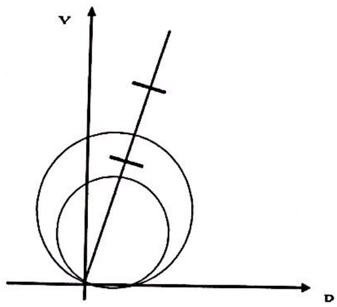
Thus the impedances of the three lines as seen by the relay R12 are approximately

Line 1-2	$Z12 = 0.11 + j1.1\ \Omega$
Line 2-3	$Z23 = 0.11 + j\ 1.1\ \Omega$
Line 2-4	$Z24 = 0.16 + j\ 1.6\ \Omega$

The maximum load impedance assuming a power factor of 0.8 lagging is

$$Z_{load} = \frac{V_{ph}}{I_{L\max}} \angle \cos^{-1}(0.8) = \frac{79.67\times10^3}{209.2}\angle 36.9^\circ = \frac{79.67\times10^3}{209.2}(0.8 + j0.6)$$

$$= 380.83\angle 36.9^\circ\ \Omega = 304.6 + j228.5\ \Omega$$



The load impedance seen by the relay is

$$Z_{load-secondary} = Z_{load-primary} \times \frac{CTR}{VTR}$$

$$Z_{load-secondary} = (304.6 + j228.5)\times\frac{40}{1189.1} = 10.2 + j7.7\ \Omega$$

The zone 1 setting of the relay R12 must **under reach** the line 1-2, so that the setting should be

$$Z_{r-setting-zone1} = 0.8\times Z_{line-secondary} = 0.8\times(0.11 + j1.1) = 0.088 + j0.88\ \Omega$$

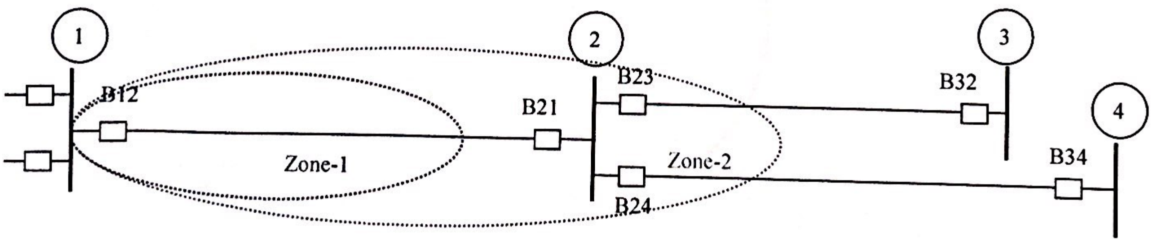
The zone 2 setting should reach past terminal 2 of the line 1-2. Zone 2 is usually set at about 1.2×the length of the line being protected.
Zone 2 for R12 is therefore set at

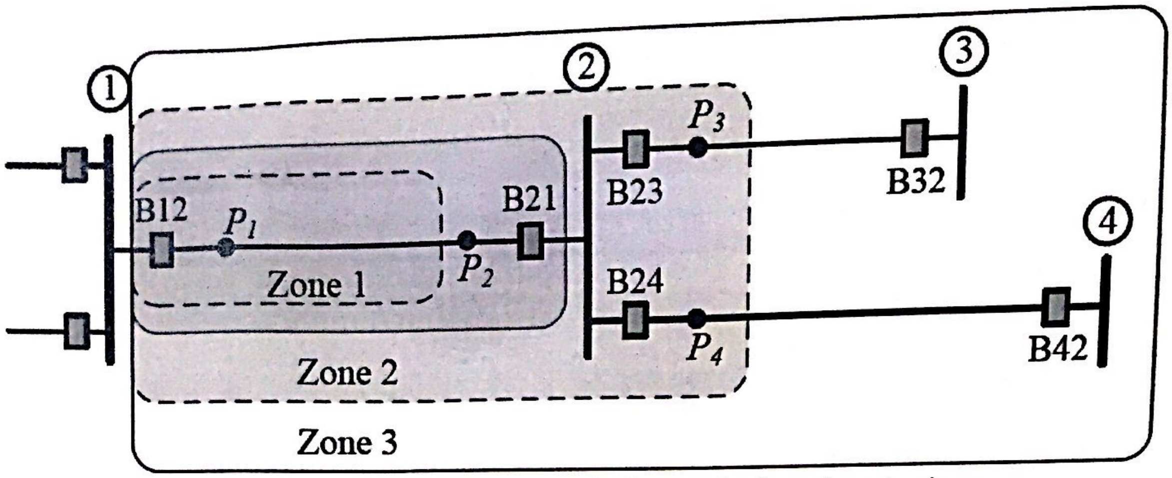
$$Z_{r-setting-zone2} = 1.2\times Z_{line-secondary} = 1.2\times(0.11 + j1.1) = 0.13 + j1.32\ \Omega$$

The zone 3 setting should reach beyond the longest line connected to bus 2. Thus the zone-3 setting must be

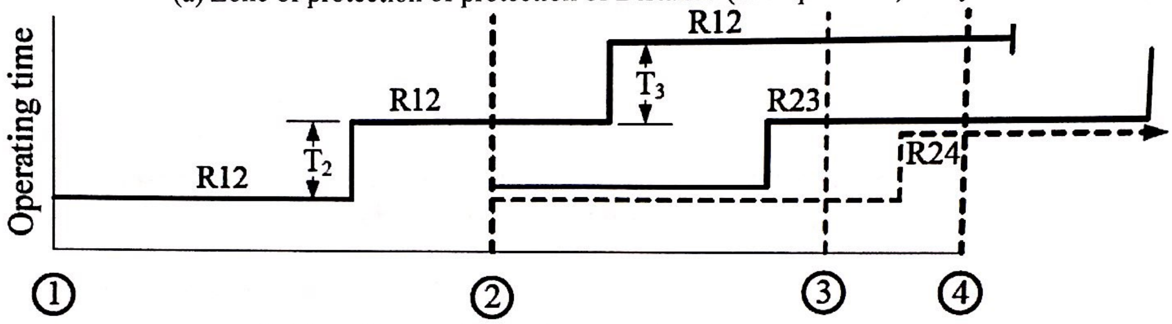
$$Z_{r-setting-zone3} = Z'_{12} + 1.2\times Z_{longest-line-secondary}$$

$$= (0.11 + j1.1) + 1.2\times(0.16 + j1.6) = 0.302 + j3.02\ \Omega$$

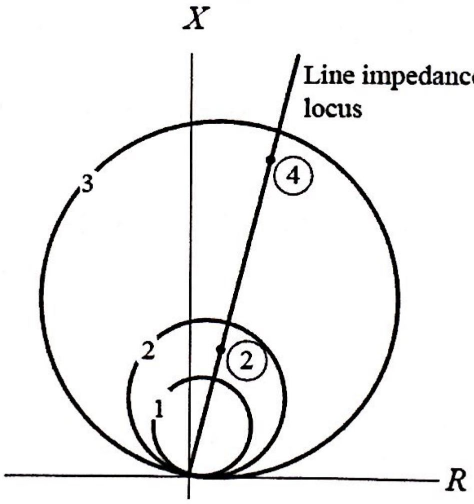




(a) Zone of protection of protection of Distance (or impedance) relays.



(b) Time delay and operating time for R12, R23 and R24



Question # 4

A 345 kV transmission network is protected by distance protection with Mho characteristics as shown in Fig. Q4. The CT and VT ratios of B12 are CTR=1500:5 and VTR=3000:1, respectively. The line data for the system are given below. The maximum load carried by line 1-2 under emergency condition is 1500 A at 0.95 PF lagging.

Line	Positive Sequence Impedance Zij	Line	Positive Sequence Impedance
1-2	$8 + j50\ \Omega$	2-4	$5.3 + j33\ \Omega$
2-3	$8 + j50\ \Omega$	3-1	$3 + j27\ \Omega$

Design a a 3-zone step distance protection system using Mho relays to the extent of determining for B12 the zone setting which are the impedance values by determining the following:

a.	impedance measured by the relay Z'_{ij} for lines 1-2, 2-3, 2-4 and 3-1	$Z'_{12} = 0.8 + j5\ \Omega$ $Z'_{23} = 0.8 + j5\ \Omega$ $Z'_{24} = 0.53 + j3.3\ \Omega$ $Z'_{31} = 0.3 + j5\ \Omega$
b.	impedance settings of B12 for Zones 1, 2, and 3, Z_{r1}, Z_{r2} and Z_{r3}	$Z_{r1} = 0.64 + j4 = 4.05\angle 80.9°\ \Omega$ $Z_{r2} = 0.96 + j6 = 6.08\angle 80.9°\ \Omega$ $Z_{r3} = 1.55 + j8.96 = 9.07\angle 80.9°\ \Omega$
c.	the load equivalent impedance in Ohm	$Z_L = 132.8\angle 18.2°\ \Omega$
d.	the load equivalent impedance as seen by the distance relay	$Z_{L\text{-relay}} = 13.28\angle 18.2°\ \Omega$
e.	Will any of the relays trip during this condition?	Yes / NO

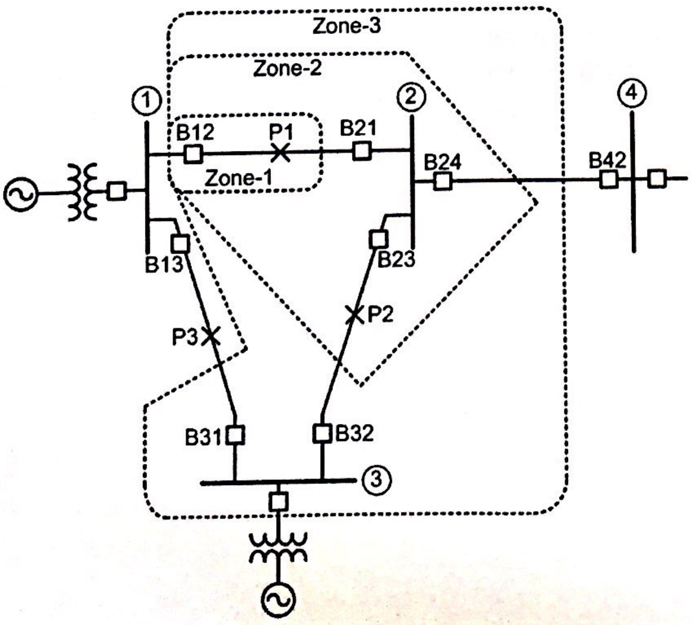


Fig.Q4a. Protection of a loop system using distance protection.

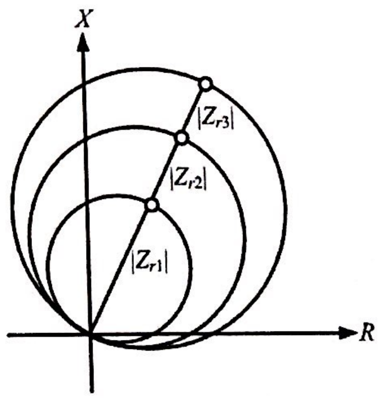


Fig.Q4b. Mho relay characteristics for the three zones

Solution:

Using the CT ratio of 1500:5 and PT ratio of 3000:1 at B12, the impedance seen by B12 is:

$$Z = \frac{V_{1(L-N)}}{I_{12}}\ \Omega$$

Using the CT and PT ratios mentioned above we have

$$Z' = \frac{V_{1(L-N)} \Big/ \left(\dfrac{3000}{1}\right)}{I_{12} \Big/ \left(\dfrac{1500}{5}\right)} = \frac{Z}{10}\ \Omega$$

Now we set Zone-1 of B12 relay for 80% reach, i.e., 80% of line 1-2 (secondary) impedance. Therefore

$$Z_{r1} = 0.80 \times \frac{8 + j50}{10} = 0.64 + j4 = 4.05\angle 80.9°\ \Omega$$

The setting for Zone-2 for B12 relay, with a reach of 120%, is

$$Z_{r2} = 1.2 \times \frac{8 + j50}{10} = 0.96 + j6 = 6.08\angle 80.9°\ \Omega$$

From Table Q2, we see that line 2-4 has a larger impedance than line 2-3. Therefore we set B12 for Zone-3 as 100% of line 1-2 and 120% of line 2-4. Therefore

$$Z_{r3} = 1 \times \frac{8 + j50}{10} + 1.2 \times \frac{8 + j50}{10} = 1.55 + j8.96 = 9.07\angle 80.9°\ \Omega$$

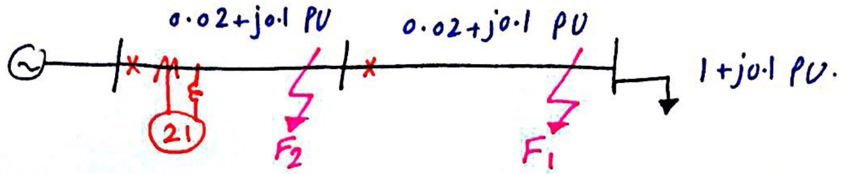
Suppose now the bus voltage at Bus-1 is 345 kV and the maximum current for an emergency loading condition is 1500 A. Then we have

$$Z' = \frac{Z}{10} = \frac{1}{10} \times \frac{345 \times 10^3 / \sqrt{3}}{1500\angle -18.2°} = 13.28\angle 18.2°\ \Omega$$

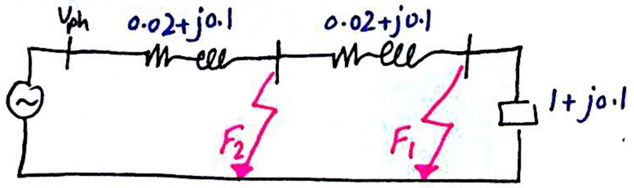
Since this impedance exceeds the Zone-3 trip setting, the impedance during the emergency loading condition is outside the trip settings of any of the zones. Therefore none of the relays will trip. Moreover, the impedance during normal loading condition will be even less and hence it will be further away from the trip regions.

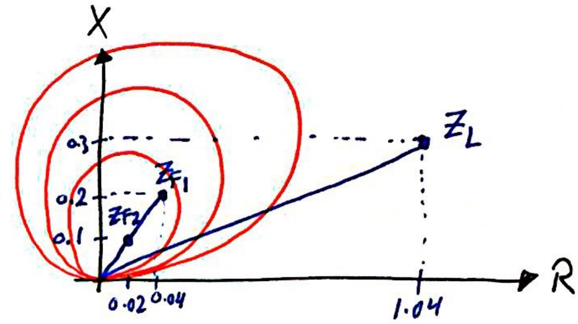
※ Tutorial #6 :

Q1



• The equivalent circuit:





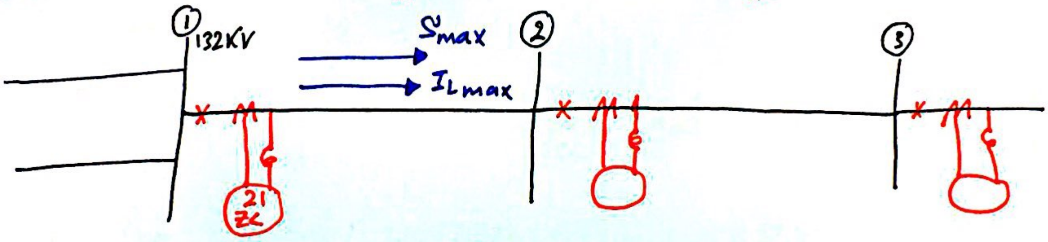
a) $Z_{apparent} = \frac{V}{I} = 0.02 + j0.1 + 0.02 + j0.1 + 1 + j0.1$
$= \underline{1.04 + j0.3}$ PU.

b) $Z_{F1} = 0.02 + j0.1 + 0.02 + j0.1 = \underline{0.04 + j0.2}$ PU.

c) $Z_{F2} = \underline{0.02 + j0.1}$ PU.

* * *

Q2



Given: $Z_{12}^{+} = 3 + j40\,\Omega$ $\quad S_{L_{max}} = 110$ MVA. $\quad I_{f_{LL}} = 500$ A.
$Z_{23}^{+} = 7 + j30\,\Omega$ $\quad pf = 0.8$ lag.

a) $|I_{L_{max}}| = \frac{110 \times 10^6}{\sqrt{3} \times 132 \times 10^3} = \underline{481.1\text{A}}$.

b) Choose CTR $= \underline{500/5}$.

c) $VTR = \frac{132 \times 10^3/\sqrt{3}}{67} = \frac{1137.47}{1}$

d) $Z_{relay} = \frac{V}{I} \times \frac{CTR}{VTR} = Z_{apparent} \times \frac{CTR}{VTR}$

$\Rightarrow Z_{relay} = \frac{500/5}{1137.47} \times Z_L = \underline{0.0879 \times Z_L}$

$Z_{12\,sec} = Z_{12\,primary} \times 0.0879 = (3+j40) \times 0.0879 = \underline{0.26 + j3.52}\,\Omega$

$Z_{23\,sec} = Z_{23\,prim.} \times 0.0879 = (7+j30) \times 0.0879 = \underline{0.615 + j2.64}\,\Omega$

e) $Z_L = \frac{V}{I_{L_{max}}} = \frac{132 \times 10^3/\sqrt{3}}{481.1\angle{-36.9^\circ}} = 126.7 + j95.1 = \underline{158.4\angle{36.9^\circ}}\,\Omega$.

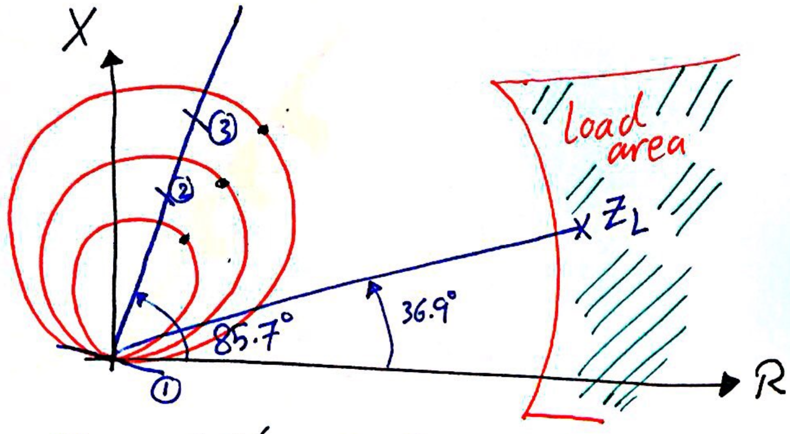
Continue ...

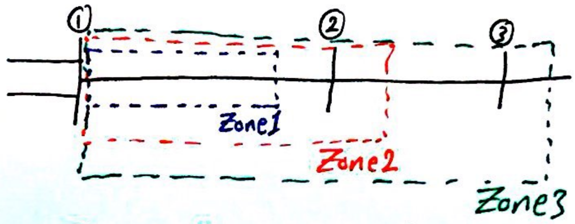
f) for the Zones:

Zone 1: 80% of protected line (Z_{12}) $= 0.8 \times Z_{12}$

Zone 2: 120% of protected line (Z_{12}) $= 1.2 \times Z_{12}$

Zone 3: 100% of protected line (Z_{12}) + 120% of adjacent line (Z_{23}) $= Z_{12} + 1.2\, Z_{23}$





● Zone 3 should NOT ENCROACH the load area.

$Z_{r_1} = 0.8\, Z_{12}' = 0.8 \times (0.26 + j3.52) = 0.21 + j2.82 = \underline{2.83 \angle 85.7^\circ}\ \Omega$

$Z_{r_2} = 1.2\, Z_{12}' = 1.2 \times (0.26 + j3.52) = \underline{4.2 \angle 85.7^\circ}\ \Omega$

$Z_{r_3} = Z_{12}' + 1.2\, Z_{23}' = (0.26 + j3.52) + 1.2 \times (0.615 + j2.64) = 1 + j6.7 = \underline{6.76 \angle 81.5^\circ}\ \Omega$

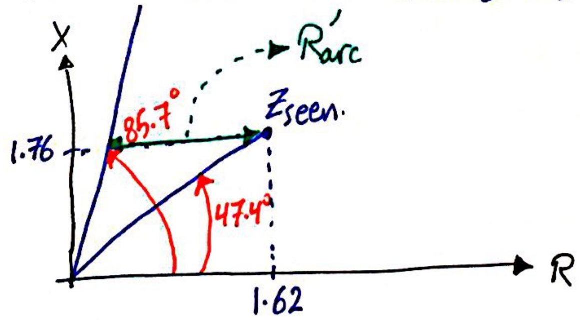
g) $R_{arc} = \dfrac{2.9 \times 10^4\, L}{I_f^{1.4}}$ ⇒ would be given in the Exam.

→ @ primary side.

$R_{arc\ prim.} = \dfrac{2.9 \times 10^4 \times 3.5}{(500)^{1.4}} = \underline{16.9\ \Omega}$ ⇒ $R_{arc\ sec.} = R_{arc}' = 16.9 \times 0.0879 = \underline{1.49}\ \Omega$

$Z_{seen} = \frac{1}{2} Z_{12}' + R_{arc}' = 0.5 \times (0.26 + j3.52) + 1.49 = \underline{2.4 \angle 47.4^\circ}\ \Omega$.

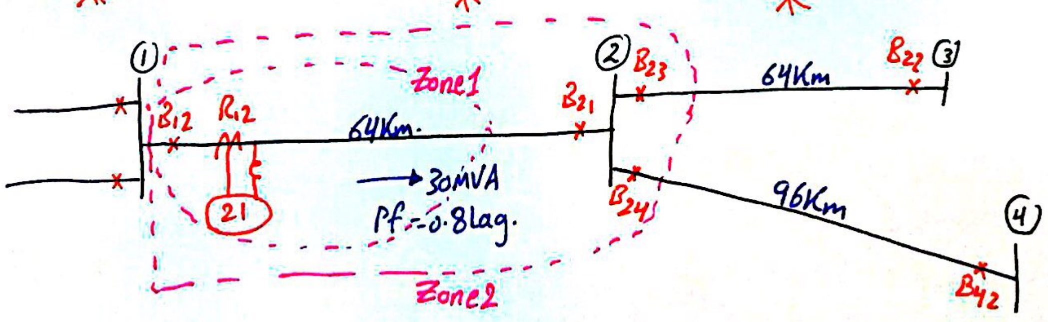
h)



Since the fault occur in Zone 1, the fault will be cleared.

* * *

Q3



$Z^+ = 0.05 + j0.5\ \Omega/\text{Km}$.

* Before starting to solve this problem there are some required Notes indicated as follows:

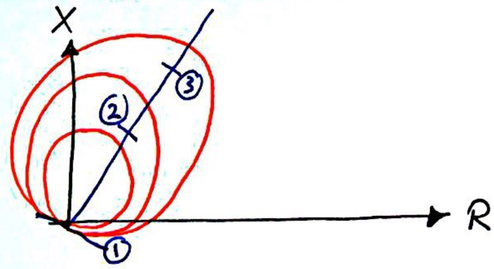
- In case we have two adjacent lines, we calculate Z_{r_2}: $1.2\,Z_{12}'$ & $Z_{12}'+0.5\,Z_{23}$ → Shortest Line. & we choose the Longer reach between both of them.
- for Z_{r_3}: $Z_{r_3} = Z_{12}' + 1.2\,Z_{34}'$ → here we always take the Longest.

$Z_{12} = (0.05+j0.5)\times 64K = 3.2+j32\ \Omega$

$Z_{23} = (0.05+j0.5)\times 64K = 3.2+j32\ \Omega$

$Z_{24} = (0.05+j0.5)\times 96K = 4.8+j48\ \Omega$

$|I_L|_{max} = \dfrac{50\times10^6}{\sqrt{3}\times 138\times10^3} = 209\ A.$



- CHOOSE: $CTR = \dfrac{200}{5}$, $VTR = \dfrac{138\times10^3/\sqrt{3}}{67} = \dfrac{1189.1}{1}$

$Z_{relay} = Z_L \times \dfrac{CTR}{VTR} = 0.0336\times Z_L$ $\Rightarrow$ $Z_{12}' = (3.2+j32)\times0.0336 = 0.11+j1.1\ \Omega$

$Z_{23}' = (3.2+j32)\times0.0336 = 0.11+j1.1\ \Omega$

$Z_{24}' = (4.8+j48)\times0.0336 = 0.16+j1.6\ \Omega$

* $Z_{r_1} = 0.8\times Z_{12}' = 0.8\times(0.11+j1.1) = 0.088+j0.88\ \Omega$

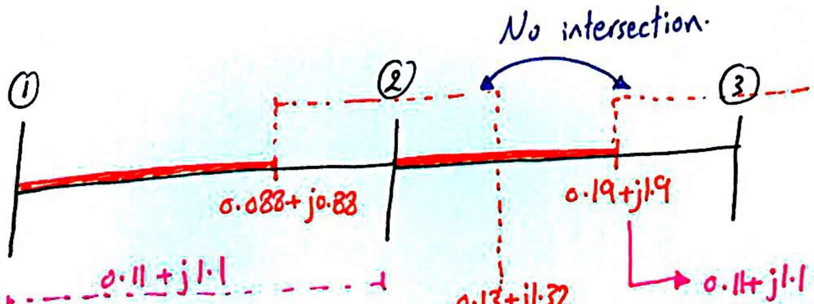
* $Z_{r_2} = 1.2\,Z_{12}' = 1.2\times(0.11+j1.1) = 0.13+j1.32\ \Omega$

OR $Z_{r_2} = Z_{12}' + 0.5\,Z_{23}' = (0.11+j1.1)+\frac{1}{2}\times(0.11+j1.1) = 0.16+j1.6\ \Omega$ $\Rightarrow$ choose: $Z_{r_2} = 0.16+j1.6\ \Omega$ "longer reach"

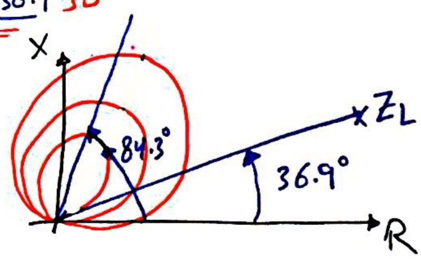
* $Z_{r_3} = Z_{12}' + 1.2\,Z_{34}' = (0.11+j1.1)+1.2\times(0.16+j1.6) = 0.3+j3\ \Omega$

$|Z_{load}| = \left|\dfrac{V_{LL}^2}{S_L}\right| = \left|\dfrac{138^2}{50}\right| = 380 \Rightarrow Z_L = 380\angle 36.9^\circ\ \Omega$

$Z_L' = (380\angle36.9)\times0.0336 = 10.2+j7.7 = 12.77\angle36.9^\circ\ \Omega$



$\rightarrow 0.11+j1.1+0.088+j0.88 = 0.19+j1.9$



* * *

Q4 The Given Data as follows:

$V_L = 345\,KV.$

$|I_L|_{max} = 1500\,A.$

$Pf = 0.95$ Lagging.

$Z_{12} = 8+j50\,\Omega$

$Z_{23} = 8+j50\,\Omega$

$Z_{24} = 5.3+j33\,\Omega$

$Z_{31} = 3+j27\,\Omega$

$CTR = 1500/5$

$VTR = 3000/1$

a) $Z_{relay} = Z_\ell \times \frac{CTR}{VTR} = Z_\ell \times \frac{1500/5}{3000/1} = \underline{0.1 \times Z_\ell}$

$Z'_{12} = 0.1 \times (8+j50) = \underline{0.8 + j5}\,\Omega.$

$Z'_{23} = 0.1 \times (8+j50) = \underline{0.8 + j5}\,\Omega.$

$Z'_{24} = 0.1 \times (5.3+j33) = \underline{0.53 + j3.3}\,\Omega.$

$Z'_{31} = 0.1 \times (3+j27) = \underline{0.3 + j2.7}\,\Omega.$

b) $Z_{r_1} = 0.8 \times Z'_{12} = 0.8 \times (0.8+j5) = \underline{0.64+j4}\,\Omega$

$Z_{r_2} = 1.2 \times Z'_{12} = 1.2 \times (0.8+j5) = 0.96+j6\,\Omega$

OR

$Z_{r_2} = Z'_{12} + 0.5\,Z'_{24} = (0.8+j5) + \frac{1}{2} \times (0.53+j3.3) = 1.07+j6.65\,\Omega$

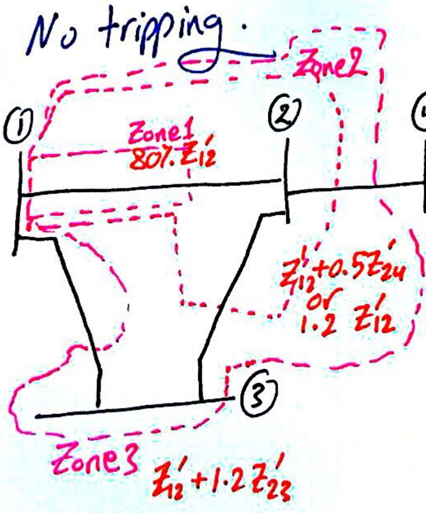
$\Rightarrow$ choose: $\underline{Z_{r_2} = 1.07+j6.65}\,\Omega$

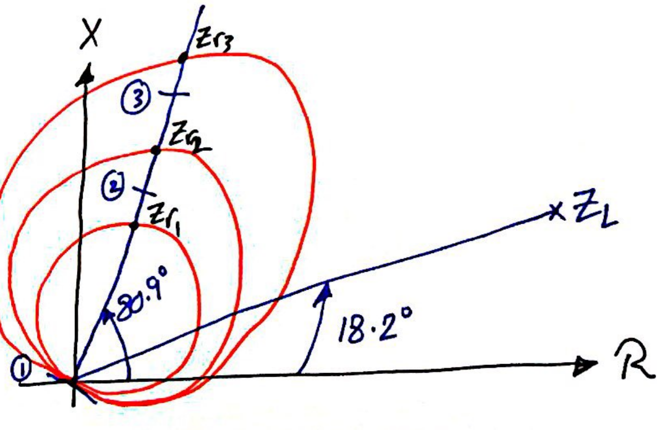
$Z_{r_3} = Z'_{12} + 1.2\,Z'_{23} = (0.8+j5) + 1.2 \times (0.8+j5) = \underline{1.76+j11}\,\Omega$

c) $Z_L = \frac{V}{I} = \frac{345 \times 10^3/\sqrt{3}}{1500} = \underline{132.8\,\angle 18.2^\circ}\,\Omega$

d) $Z'_L = 0.1 \times 132.8\,\angle 18.2^\circ = \underline{13.28\,\angle 18.2^\circ}\,\Omega$

e) No tripping.





* * *

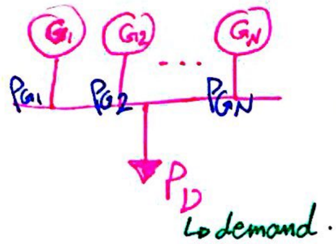
* Economic Dispatch:

- every generator has : minimum power Limit & maximum power Limit.
- Load / Demand ⇒ Both represent real power.

$$C(P_{G_i}) = \underline{\alpha_i} + \beta_i P_{G_i} + \gamma_i P_{G_i}^2$$

↳ Fixed operating cost.

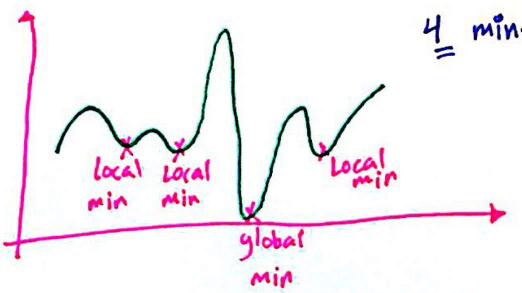
α, β & γ are Known for each machine.



⇒ must satisfy $\sum P_{G_N} = P_D$.

$$\lambda = \frac{P_D + \sum_{i=1}^{n_{gen.}} \frac{\beta_i}{2\gamma_i}}{\sum_{i=1}^{n} \frac{1}{2\gamma_i}}$$

$$P_i = \frac{\lambda - \beta_i}{2\gamma_i}$$



4 min. points.

* for the Example in the Slides:

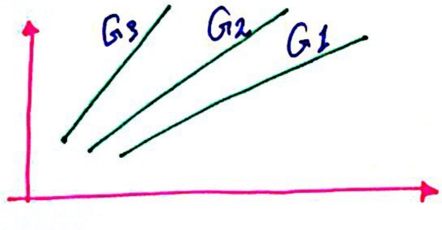
$$C = \alpha_i + \beta_i P + \gamma_i P^2$$

$$\frac{dC}{dP} = \beta_i + 2\gamma_i P$$

β_i ↳ intersection with Y-axis

$2\gamma_i$ ↳ slope.

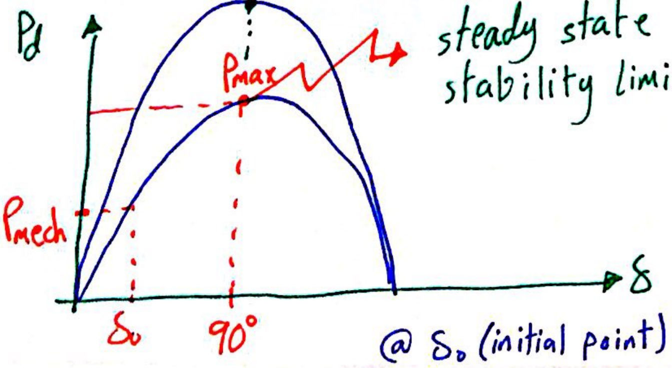
we have $\gamma_3 > \gamma_2 > \gamma_1$

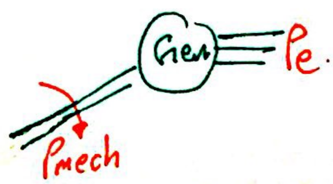


* Stability:

↳ Increased By Increasing the excitation.

↳ steady state stability limit.





$$P_d = \frac{E \cdot V_t \sin\delta}{X_s}$$

@ δ_o (initial point) ⇒ $P_{mech} = P_d$.

Question # 1:

The fuel-cost functions in \$/h for two 800 MW thermal plants are given by

$$C_1 = 400 + 6.0P_1 + 0.004P_1^2$$
$$C_2 = 500 + \beta P_2 + \gamma P_2^2$$

where P_1 and P_2 are in MW.

a. The incremental cost of power λ is \$8/MWh when the total power demand is 550 MW. Neglecting losses, determine the optimal generation of each plant.

b. The incremental cost of power λ is \$10/MWh when the total power demand is 1300 MW. Neglecting losses, determine the optimal generation of each plant.

c. From the results of (a) and (b) find the fuel-cost coefficients β and γ of the second plant.

Solution:

$$\frac{dC_1}{dP_1} = 6 + 0.008P_1 = \lambda$$
$$\frac{dC_2}{dP_2} = \beta + 2\gamma P_2 = \lambda$$

(a) For $\lambda = 8$, and $P_D = 550$ MW, we have

$$P_1 = \frac{8-6}{0.008} = 250 \text{ MW}$$
$$P_2 = P_D - P_1 = 500 - 250 = 300 \text{ MW}$$

(b) For $\lambda = 10$, and $P_D = 1300$ MW, we have

$$P_1 = \frac{10-6}{0.008} = 500 \text{ MW}$$
$$P_2 = P_D - P_1 = 1300 - 500 = 800 \text{ MW}$$

(c) The incremental cost of power for plant 2 are given by

$$\beta + 2\gamma(300) = 8$$
$$\beta + 2\gamma(800) = 10$$

Solving the above equations, we find $\beta = 6.8$, and $\gamma = 0.002$

Question # 2:

The fuel-cost functions in \$/h for three thermal plants are given by

$$C_1 = 350 + 7.20P_1 + 0.0040P_1^2$$
$$C_2 = 500 + 7.30P_2 + 0.0025P_2^2$$
$$C_3 = 600 + 6.74P_3 + 0.0030P_3^2$$

where P_1, P_2, and P_3 are in MW. The governors are set such that generators share the load equally. Neglecting line losses and generator limits, find the total cost in \$/h when the total load is

(i) $PD = 450$ MW
(ii) $PD = 745$ MW
(iii) $PD = 1335$ MW

Solution:

(i) For $P_D = 450$ MW, $P_1 = P_2 = P_3 = \frac{450}{3} = 150$ MW. The total fuel cost is

$$C_t = 350 + 7.20(150) + 0.004(150)^2 + 500 + 7.3(150) + 0.0025(150)^2 + 600 + 6.74(150) + 0.003(150)^2 = 4,849.75 \ \$/\mathrm{h}$$

(ii) For $P_D = 745$ MW, $P_1 = P_2 = P_3 = \frac{745}{3}$ MW. The total fuel cost is

$$C_t = 350 + 7.20\left(\frac{745}{3}\right) + 0.004\left(\frac{745}{3}\right)^2 + 500 + 7.3\left(\frac{745}{3}\right) + 0.0025\left(\frac{745}{3}\right)^2 + 600 + 6.74\left(\frac{745}{3}\right) + 0.003\left(\frac{745}{3}\right)^2 = 7,310.46 \ \$/\mathrm{h}$$

(iii) For $P_D = 1335$ MW, $P_1 = P_2 = P_3 = 445$ MW. The total fuel cost is

$$C_t = 350 + 7.20(445) + 0.004(445)^2 + 500 + 7.3(445) + 0.0025(445)^2 + 600 + 6.74(445) + 0.003(445)^2 = 12,783.04 \ \$/\mathrm{h}$$

Question # 3:

Neglecting line losses and generator limits, determine the optimal scheduling of generation for each loading condition in Question # 2

a. by analytical technique.
b. find the savings in $/h for each case compared to the costs in Question # 2 when the generators shared load equally.

Solution:

(a) (i) For $P_D = 450$ MW, from (7.33), λ is found to be

$$\lambda = \frac{450 + \frac{7.2}{0.008} + \frac{7.3}{0.005} + \frac{6.74}{0.006}}{\frac{1}{0.008} + \frac{1}{0.005} + \frac{1}{0.006}}$$
$$= \frac{450 + 3483.333}{491.666} = 8.0 \ \$/\text{MWh}$$

Substituting for λ in the coordination equation, the optimal dispatch is

$$P_1 = \frac{8.0 - 7.2}{2(0.004)} = 100$$
$$P_2 = \frac{8.0 - 7.3}{2(0.0025)} = 140$$
$$P_3 = \frac{8.0 - 6.74}{2(0.003)} = 210$$

(a) (ii) For $P_D = 745$ MW, from (7.33), λ is found to be

$$\lambda = \frac{745 + 3483.333}{491.666} = 8.6 \ \$/\text{MWh}$$

Substituting for λ in the coordination equation, the optimal dispatch is

$$P_1 = \frac{8.6 - 7.2}{2(0.004)} = 175$$
$$P_2 = \frac{8.6 - 7.3}{2(0.0025)} = 260$$
$$P_3 = \frac{8.6 - 6.74}{2(0.003)} = 310$$

(a) (iii) For $P_D = 1335$ MW, from (7.33), λ is found to be

$$\lambda = \frac{1335 + 3483.333}{491.666} = 9.8 \ \$/\text{MWh}$$

Substituting for λ in the coordination equation, the optimal dispatch is

$$P_1 = \frac{9.8 - 7.2}{2(0.004)} = 325$$
$$P_2 = \frac{9.8 - 7.3}{2(0.0025)} = 500$$
$$P_3 = \frac{9.8 - 6.74}{2(0.003)} = 510$$

(c)(i) For $P_1 = 100$ MW, $P_2 = 140$ MW, and $P_3 = 210$ MW, the total fuel cost is

$$C_t = 350 + 7.20(100) + 0.004(100)^2 + 500 + 7.3(140) + 0.0025(140)^2 + 600 + 6.74(210) + 0.003(210)^2 = 4,828.70 \quad \$/\text{h}$$

Compared to Question #2 (i), when the generators shared load equally, the saving is 4,849.75 - 4,828.70 = 21.05 $/h.

(c)(ii) For $P_1 = 175$ MW, $P_2 = 260$ MW, and $P_3 = 310$ MW, the total fuel cost is

$$C_t = 350 + 7.20(175) + 0.004(175)^2 + 500 + 7.3(260) + 0.0025(260)^2 + 600 + 6.74(310) + 0.003(310)^2 = 7,277.20 \quad \$/\text{h}$$

Compared to Question #2 (ii), when the generators shared load equally, the saving is 7,310.46 - 7,277.20 = 33.25 $/h.

(c)(iii) For $P_1 = 325$ MW, $P_2 = 500$ MW, and $P_3 = 510$ MW, the total fuel cost is

$$C_t = 350 + 7.20(325) + 0.004(325)^2 + 500 + 7.3(500) + 0.0025(500)^2 + 600 + 6.74(510) + 0.003(510)^2 = 12,705.20 \quad \$/\text{h}$$

Compared to Question #2 (iii), when the generators shared load equally, the saving is 12,783.04 - 12,705.20 = 77.84 $/h.

Question # 4:

Repeat Question # 3 (a), but this time consider the following generator limits (in MW)

$$122 \le P_1 \le 400$$
$$260 \le P_2 \le 600$$
$$50 \le P_3 \le 445$$

Solution:

In Question # 3, in part (a) (i), the optimal dispatch are $P_1 = 100$ MW, $P_2 = 140$ MW, and $P_3 = 210$ MW. Since P_1 and P_2 are less that their lower limit, these plants are pegged at their lower limits. That is, $P_1 = 122$, and $P_2 = 260$ MW. Therefore, $P_3 = 450 - (122 + 260) = 68$ MW.

In Question # 3, in part (a) (ii), the optimal dispatch are $P_1 = 175$ MW, $P_2 = 260$ MW, and $P_3 = 310$ MW, which are within the plants generation limits.

In Question # 3, in part (a) (iii), the optimal dispatch are $P_1 = 325$ MW, $P_2 = 500$ MW, and $P_3 = 510$ MW. Since P_3 exceed its upper limit, this plant is pegged at $P_2 = 445$. Therefore, a load of 1335 - 445 = 890 MW must be shared between plants 1 and 2, with equal incremental fuel cost give by

$$\lambda = \frac{890 + \frac{7.2}{0.008} + \frac{7.3}{0.005}}{+\frac{1}{0.008} + \frac{1}{0.005}}$$

$$= \frac{890 + 2360}{325} = 10 \ \$/\text{MWh}$$

Substituting for λ in the coordination equation, the optimal dispatch is

$$P_1 = \frac{10 - 7.2}{2(0.004)} = 350$$

$$P_2 = \frac{10 - 7.3}{2(0.0025)} = 540$$

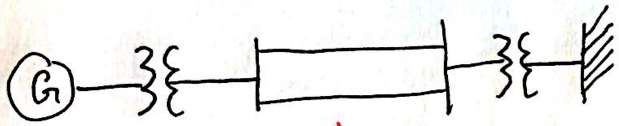
Since P_1 and P_2 are within their limits the above result is the optimal dispatch.

* The subjects that NOT included in the course this semester:

- stability Ex1. & Ex2.
- Derivation of swing Equation.
- Stability of a synchronous motor connected to ∞-Bus.
- Steady State Stability.

* when $P_m > P_e$ the machine will accelerate & δ will increase.

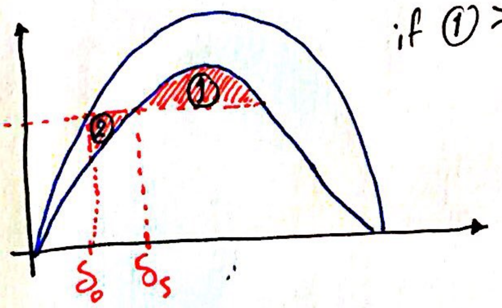
* Opening of one of the parallel Line:



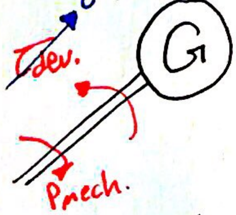
↳ we usually use this double circuit to decrease the value of X_s which gives more power ($P\uparrow = \frac{V_t E \sin\delta}{X_s \downarrow}$).

- so if one of the Lines opened the power will be reduced.

if ① > ② then the system would be stable.



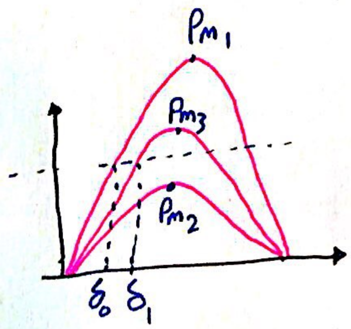
* Short Circuit Occuring in the System:



o in fault case the machine will accelerate.

$$\boxed{\delta_{cc} = \frac{\pi f_0}{H} P_m t_{cc}^2 + \delta_0}$$ Critical Clearing Angle.

$$\Rightarrow \boxed{t_{cc} = \sqrt{\frac{2H(\delta_{cc} - \delta_0)}{\pi f_0 P_m}}}$$



$$\boxed{\cos\delta_{cc} = \frac{P_s(\underbrace{\delta_m}_{\pi-\delta_s} - \delta_0) + \underbrace{P_{m_3}}_{\text{Post fault}} \cos\delta_m - \underbrace{P_{m_2}}_{\text{during fault}} \cos\delta_0}{P_{m_3} - P_{m_2}}}$$

* *** * *** *

End of Material.

Example # 1:

A transmission line is acting as an interconnector between two constant voltage networks as shown in Fig. E1. Determine graphically or otherwise the maximum additional load which can be suddenly applied to this interconnector already carrying 50 MW if the power angle equation is $P_e = 100\sin\delta$.

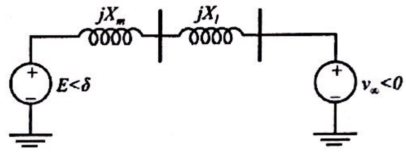
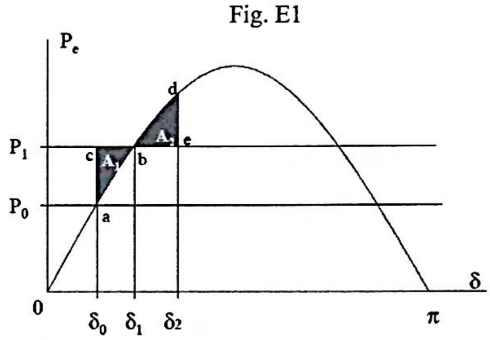


Fig. E1



Solution:

$P_o = 100\sin\delta_o = 50 \Rightarrow \delta_o = 30°$ 0.5236 rad

Accelerating Area is A_1 and decelerating area is A_2.

$$A_1 = \int_{\delta_o}^{\delta_1}(P_1 - 100\sin\delta)d\delta = P_1(\delta_1 - \delta_o) + 100(\cos\delta_1 - \cos\delta_o)$$

$$A_2 = \int_{\delta_1}^{\delta_2}(100\sin\delta - P_1)d\delta = -100(\cos\delta_2 - \cos\delta_1) - P_1(\delta_2 - \delta_1)$$

For limiting case $\delta_2 = \delta_{max} = \pi - \delta_1$.

Moreover, $P_1 = 100\sin\delta_1$.

Equating areas A_1 and A_2

and substituting these values we get the equation

$$A_1 = A_2$$

$$P_1(\delta_1 - \delta_o) + 100(\cos\delta_1 - \cos\delta_o) = -100(\cos(\pi - \delta_1) - \cos\delta_1) - P_1(\pi - \delta_1 - \delta_1)$$

$$P_1\delta_1 - P_1\delta_o + 100\cos\delta_1 - 100\cos\delta_o = -100(\cos(\pi).\cos(\delta_1) + \sin(\pi).\sin(\delta_1)) + 100\cos(\delta_1) - P_1(\pi - \delta_1) + P_1\delta_1$$

$$-P_1\delta_o + 100\cos\delta_1 - 100\cos\delta_o = 100\cos(\delta_1) + 100\cos(\delta_1) - P_1(\pi - \delta_1)$$

$$-100\sin(\delta_1)\delta_o - 100\cos\delta_o = 100\cos(\delta_1) - 100\sin(\delta_1)(\pi - \delta_1)$$

$$-\sin(\delta_1)\delta_{o1} - \cos\delta_o = \cos(\delta_1) - \sin(\delta_1)(\pi - \delta_1)$$

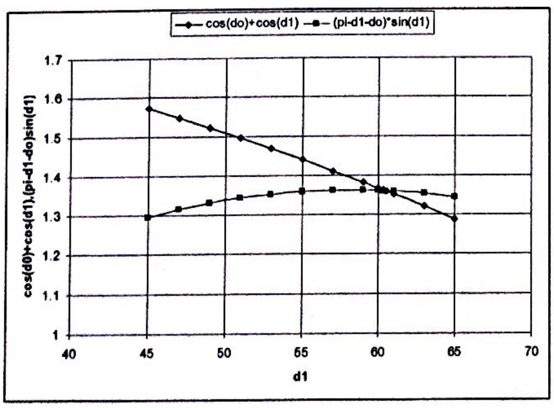
$$\sin(\delta_1)(\pi - \delta_1) - \sin(\delta_1)\delta_o + \cos\delta_1 = \cos(\delta_1) + \cos\delta_o$$

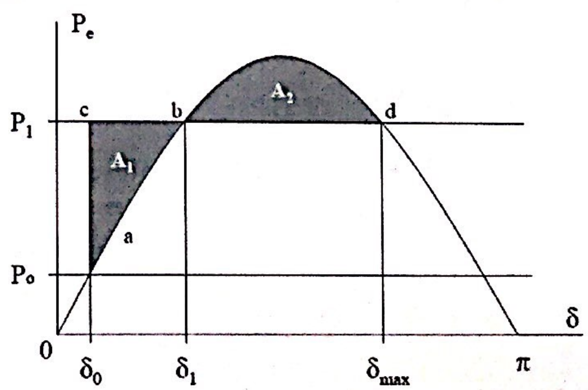
$$\cos\delta_o + \cos\delta_1 = (\pi - \delta_1 - \delta_o)\sin\delta_1$$

The angles δ_1 and δ_o in this equation are in radians.

The equation can be solved by hit and trail. The results is δ_1 =1.054179=60.4°.

$$\cos\delta_o + \cos\delta_1 = (\pi - \delta_1 - \delta_o)\sin\delta_1 = (\delta_{max} - \delta_o)\sin\delta_1$$





transient stability:

Example # 2:

For the system shown in Fig. E2, the per unit value of the system are: $|E| = 1.2$ pu, $|V_\infty| = 1.0$ pu, $X_d' = 0.2$ pu, $X_1 = X_2 = 0.4$ pu. The system is operating in equilibrium with $P_o = P_{eo} = 1.5$ pu when one of the lines is suddenly switched out. Predict whether the system will be stable or not. If the system is stable find the maximum value of δ attains.

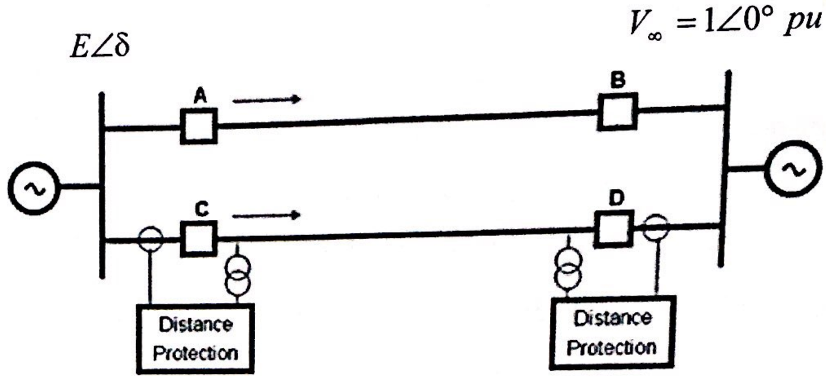


Fig. E2

Solution:

$$P_e = \frac{EV_\infty}{X_{eq}}\sin\delta = \frac{EV_\infty}{X_d' + \dfrac{X_1 \times X_2}{X_1 + X_2}}\sin\delta = \frac{1.2\times 1}{0.2 + \dfrac{0.4\times 0.4}{0.4+0.4}}\sin\delta = \frac{1.2}{0.4}\sin\delta = 3\sin\delta$$

$$P_e(\delta_o) = 3\sin\delta_o = 1.5 \Rightarrow \delta_o = 30°\ (0.524\ radians)$$

when one line is switched out

$$P_e' = \frac{EV_\infty}{X_{eq}}\sin\delta = \frac{EV_\infty}{X_d' + X_1}\sin\delta = \frac{1.2\times 1}{0.2+0.4}\sin\delta = \frac{1.2}{0.6}\sin\delta = 2\sin\delta$$

$$P_e = P_e'(\delta_s) = 2\sin\delta_s = 1.5 \Rightarrow \delta_s = 48.6°\ (0.848\ radians)$$

$$P_e = P_e'(\delta_m) = 2\sin\delta_m = 1.5 \Rightarrow \delta_m = 131.4°\ (0.2.293\ radians)$$

$$A_1 = \int_{\delta_o}^{\delta_s}(P_s - 2\sin\delta)d\delta = P_s(\delta_s - \delta_o) + 2(\cos\delta_s - \cos\delta_o)$$

$$= 1.5(0.848 - 0.524) + 2(\cos(48.6°) - \cos(30°)) = 0.0773$$

$$A_{2\max} = \int_{\delta_s}^{\delta_{\max}}(2\sin\delta - P_s)d\delta = -2(\cos\delta_{\max} - \cos\delta_s) - P_s(\delta_{\max} - \delta_s)$$

$$= -2(\cos(131.4°) - \cos(48.6°)) - 1.5(2.293 - 0.848) = 0.0478$$

since A_{2max} (0.478) > A_1 (0.0773), the system is stable.

$$A_2 = \int_{\delta_s}^{\delta_2}(2\sin\delta - P_s)d\delta = -2(\cos\delta_m - \cos\delta_s) - P_s(\delta_m - \delta_s) = -2(\cos(\delta_m) - \cos(\delta_s)) - 1.5(\delta_m - \delta_s)$$

$$= -2(\cos(\delta_m) - \cos(48.6°)) - 1.5(\delta_m - 0.848)$$

$$A_2 = \int_{\delta_s}^{\delta_2}(2\sin\delta - P_s)d\delta = -2(\cos\delta_m - \cos\delta_s) - P_s(\delta_m - \delta_s)$$

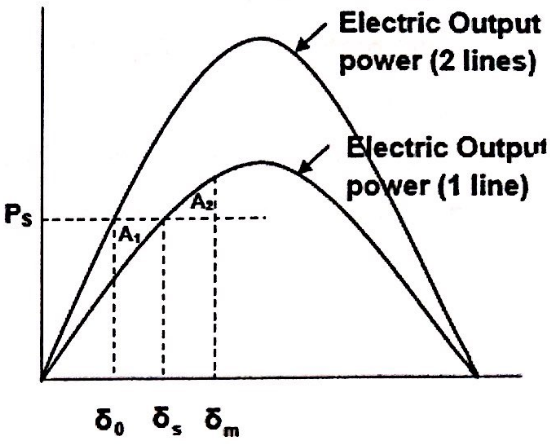
$$= -2(\cos(\delta_m) - \cos(\delta_s)) - 1.5(\delta_m - \delta_s)$$

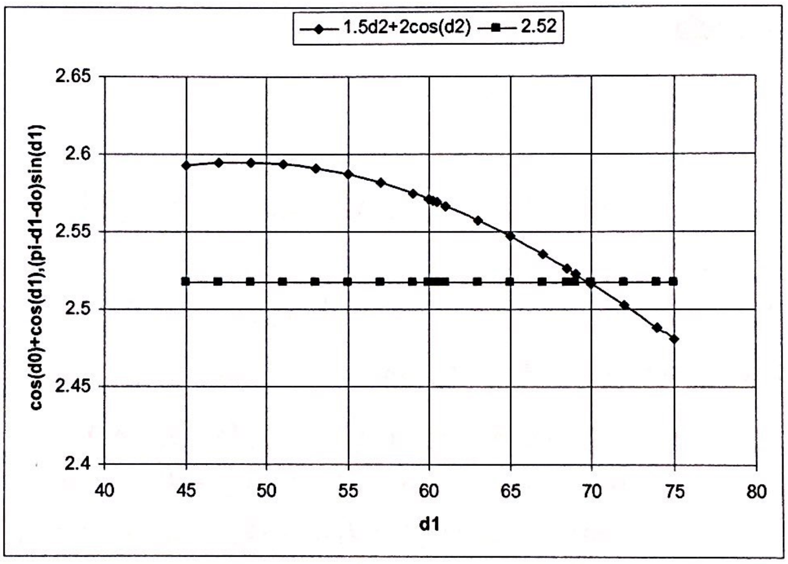
$$= -2(\cos(\delta_m) - \cos(48.6°)) - 1.5(\delta_m - 0.848)$$

$$-2(\cos(\delta_m) - \cos(48.6°)) - 1.5(\delta_m - 0.848) = 0.0773$$

$$1.5\delta_m + 2\cos(\delta_m) = 1.5 \times 0.848 + 2\cos(48.6°) - 0.0773$$

$$1.5\delta_m + 2\cos(\delta_m) = 2.52$$





δ1	δ1		
45	0.785398	2.592311	2.517
47	0.820305	2.594454	2.517
49	0.855211	2.594935	2.517
51	0.890118	2.593818	2.517
53	0.925025	2.591167	2.517
55	0.959931	2.58705	2.517
57	0.994838	2.581535	2.517
59	1.029744	2.574693	2.517
60	1.047198	2.570796	2.517
60.3	1.052434	2.569568	2.517
60.5	1.055924	2.568733	2.517
61	1.064651	2.566596	2.517
63	1.099557	2.557317	2.517
65	1.134464	2.546933	2.517
67	1.169371	2.535518	2.517
68.5	1.195551	2.526328	2.517
69	1.204277	2.523152	2.517
70	1.22173	2.516636	2.517
72	1.256637	2.50299	2.517
74	1.291544	2.48859	2.517
75	1.308997	2.481133	2.517

Example # 3:

A generator is transferring power to a load through a short line as shown in Fig. E3. The power angle equation is $P_e = P_{max}\sin\delta$. The initial power is P_m pu when a 3-phase fault occurs at the terminals of generator.

a. Use equal are criterion to find equation for critical clearing angle and the critical clearing time.
b. Find the critical clearing time angle δ_{cc} if $P_{max} = 2$ and $P_m = 1.0$ pu. H=6 MJ/MVA and f_o=50Hz.

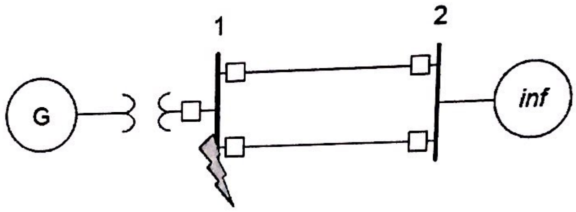


Fig. E3

Solution:

$$A_1 = \int_{\delta_o}^{\delta_c} P_m d\delta = P_m(\delta_c - \delta_o)$$

$$A_2 = \int_{\delta_c}^{\delta_{max}} (P_{mac}\sin\delta - P_m)d\delta = -P_{max}(\cos\delta_{max} - \cos\delta_c) - P_m(\delta_{max} - \delta_c)$$

For stability $A_1 = A_2$.

$$P_m(\delta_c - \delta_o) = -P_{max}(\cos\delta_{max} - \cos\delta_c) - P_m(\delta_{max} - \delta_c)$$

but $\delta_{max} = \pi - \delta_o$ and $P_m = P_{max}\sin\delta_o$

$$P_m(\delta_c - \delta_o) = P_{max}\cos\delta_c - P_{max}\cos\delta_{max} - P_m(\pi - \delta_o - \delta_c)$$

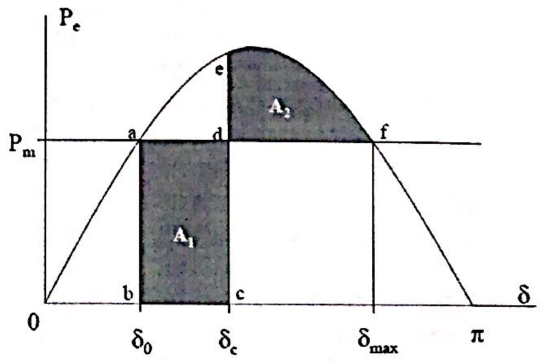
$$P_{max}(\delta_c - \delta_o)\sin\delta_o = P_{max}\cos\delta_c - P_{max}\cos\delta_{max} - P_{max}(\pi - \delta_o - \delta_c)\sin\delta_o$$

$$P_{max}(\delta_c - \delta_o)\sin\delta_o = P_{max}\cos\delta_c + P_{max}\cos\delta_o - P_{max}(\pi - \delta_o - \delta_c)\sin\delta_o$$

$$(\delta_c - \delta_o)\sin\delta_o = \cos\delta_c + \cos\delta_o - (\pi - \delta_o - \delta_c)\sin\delta_o$$

$$\cos\delta_c = (\pi - 2\delta_o)\sin\delta_o - \cos\delta_o$$

$$\delta_c = \cos^{-1}[(\pi - 2\delta_o)\sin\delta_o - \cos\delta_o]$$



During fault, power transfer is zero.

$$M\frac{d^2\delta}{dt^2} = P_m - 0 = P_{\max}\sin\delta_o$$

$$\frac{d^2\delta}{dt^2} = \frac{P_m - 0}{M} = \frac{P_{\max}\sin\delta_o}{M}$$

$$\frac{d}{dt}\left(\frac{d\delta}{dt}\right) = \frac{P_m}{M} \Rightarrow d\left(\frac{d\delta}{dt}\right) = \frac{P_m}{M}dt$$

$$(d\omega) = \frac{P_m}{M}dt$$

$$\int_{\omega_s}^{\omega} d\omega = \int_0^t \frac{P_m}{M}dt$$

$$\omega - \omega_s = \omega_r = \frac{d\delta}{dt} = \frac{P_m}{M}t \Rightarrow d\delta = \frac{P_m}{M}tdt$$

$$\int_{\delta_o}^{\delta} d\delta = \int_0^t \frac{P_m}{M}tdt$$

$$\delta(t) = \frac{P_m}{2M}t^2 + \delta_o$$

$$at\ t = t_c \Rightarrow \delta = \delta_c \Rightarrow \delta_c = \frac{P_m}{2M}t_c^2 + \delta_o$$

$$t_c = \sqrt{\frac{2M}{P_m}(\delta_c - \delta_o)} = \sqrt{\frac{2H}{\pi f_o P_m}(\delta_c - \delta_o)}$$

b. P_{max} = 2 and P_m =1.0 pu. H=6 MJ/MVA and f_o=50Hz.

$$\Rightarrow M = \frac{H}{\pi f_o} = \frac{6}{\pi \times 50},\quad P_m = P_{\max}\sin\delta_o \Rightarrow 1.0 = 2\sin\delta_o \Rightarrow \delta_o = 30^\circ\ (0.5236\ rad)$$

$$\delta_c = \cos^{-1}[(\pi - 2\delta_o)\sin\delta_o - \cos\delta_o] = \cos^{-1}\left[(\pi - 2\times 0.5236)\sin 30^\circ - \cos 30^\circ\right]$$

$$\delta_c = 79.6^\circ\ 1.389\ rad$$

$$t_c = \sqrt{\frac{2H}{\pi f_o P_m}(\delta_c - \delta_o)} = \sqrt{\frac{2\times 6}{\pi\times 50\times 1}(1.389 - 0.52336)}$$

$$t_c = 0.257\ s$$

$$t_c = 12.85\ cycles\ of\ 50\ Hz$$

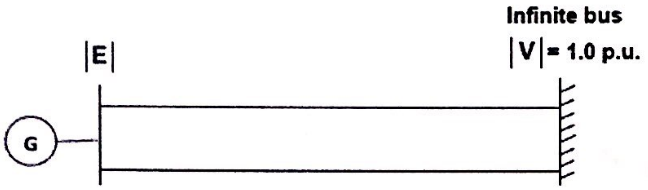
Example # 4:

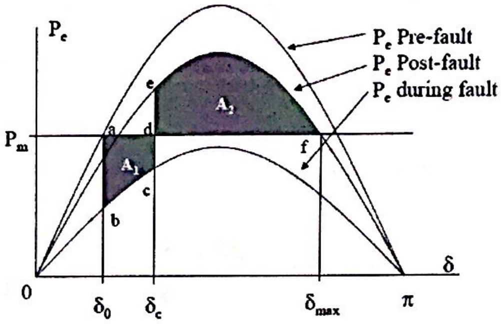
A balanced 3-phase fault occurs at middle point of line 2 when the power transfer is 1.5 pu in the system. The system data are $|E| = 1.2$ pu, $|V_\infty| = 1.0$ pu, $X_d' = 0.2$ pu, $X_1 = X_2 = 0.4$ pu.

a. Determine whether the system is stable for a sustained fault.

b. The fault is cleared at $\delta = 60°$. Is the system stable? If so find the maximum rotor swing.

c. Find the critical clearing angle





Solution:

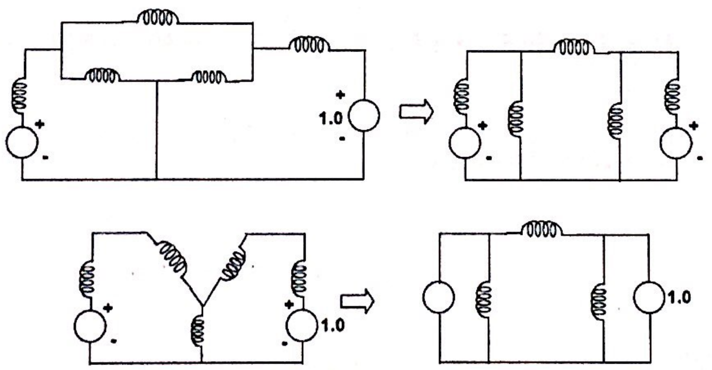
a. Pre-fault condition

Transfer reactance X_{eq}= 0.2+0.4//0,4=0.4 pu

$$P_e = \frac{EV_\infty}{X_{eq}}\sin\delta = \frac{EV_\infty}{X_d' + \dfrac{X_1 \times X_2}{X_1 + X_2}}\sin\delta = \frac{1.2\times 1}{0.2 + \dfrac{0.4\times 0.4}{0.4+0.4}}\sin\delta = \frac{1.2}{0.4}\sin\delta = 3\sin\delta$$

b. During-fault condition

$$P_e' = \frac{1.2\times 1}{1.0}\sin\delta = 1.2\sin\delta$$



Since the initial load is 1.5 pu , and the maximum possible value of power transfer during faut is condition is 1,2 pu, therefore stability is impossible for a sustained fault.

c. Post-fault condition

$$P_e'' = \frac{1.2\times 1}{0.2+0.4}\sin\delta = \frac{1.2}{0.6}\sin\delta = 2\sin\delta$$

$$1.5\delta_2 + 2\cos(\delta_2) = 2.225 \Rightarrow \delta_2 = 1.848\ rad\ (105.9°)$$

$$\cos\delta_{cc} = \frac{P_m(\delta_{\max} - \delta_o) + P_{3\max}\cos\delta_{\max} - P_{2\max}\cos\delta_o}{P_{3\max} - P_{2\max}} = \frac{1.5(2.293 - 0.524) + 2\cos(2.293) - 1.2\cos(0.524)}{2 - 1.2}$$

$$\delta_{cc} = 1.196\, rad\ (68.6°)$$