PSCT Protection Analytic tool

SHORT CIRCUIT STUDIES

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Short circuit study

Requirements:

1. Determining the fault level at buses
2. Selection of breaker ratings
3. Protective device co-ordination

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Symmetrical components

Unbalanced system of 'n' related phasors can be resolved to 'n' system of balanced phasors.

In each balanced phasor, angle between two phasors and magnitude of each phasor are equal.

Phase Quantities: I_a , I_b & I_c and

Sequence components are :

Ia1 stands for Positive sequence current.

Ia2 stands for Negative sequence current.

Ia0 stands for Zero sequence current.

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Sequence components

I_{a1}, I_{b1} & I_{c1} : Same phase sequence as I_a, I_b & I_c

I_{a2}, I_{b2}, & I_{c2} :Opposite phase sequence as I_a, I_b and I_c

I_{a0}, I_{b0}, & I_{c0} : All in-phase

$$I_a = I_{a1} + I_{a2} + I_{a0}$$

$$I_b = I_{b1} + I_{b2} + I_{b0}$$

$$I_c = I_{c1} + I_{c2} + I_{c0}$$

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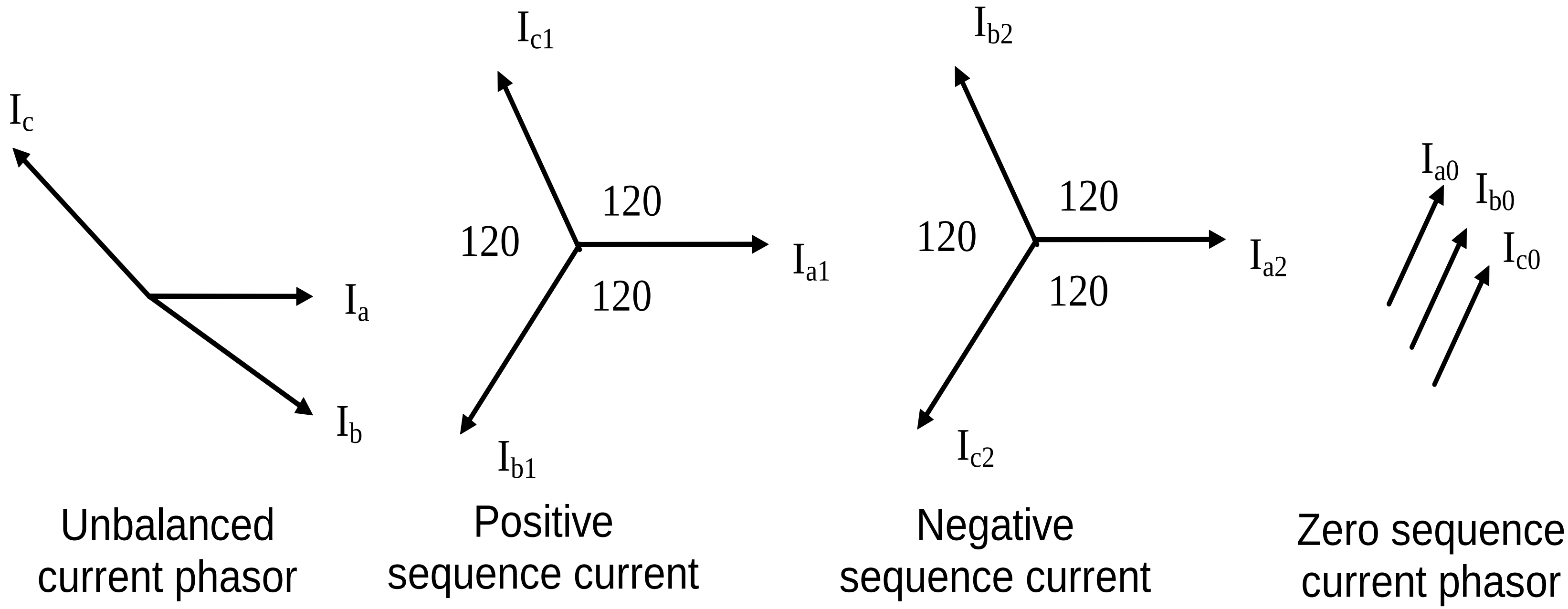
Sequence components



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Similarly for voltages:

$$V_a = V_{a1} + V_{a2} + V_{a0}$$
$$V_b = V_{b1} + V_{b2} + V_{b0}$$
$$V_c = V_{c1} + V_{c2} + V_{c0}$$

$$\begin{matrix} V_a \\ V_b \\ V_c \end{matrix} = \begin{matrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{matrix} \quad \begin{matrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{matrix}$$

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$$T_{sp} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix}$$

$$a = 1\angle 120, \quad a^2 = 1\angle 240 = 1\angle -120$$

$$and \;\; sp = Sequenceto \;\; phase$$

$$T_{ps} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}$$

$$ps = Phaseto \;\; sequence$$

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$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$V_{a0} = \frac{1}{3}(V_a + V_b + V_c)$$

$$V_{aL-L} + V_{bL-L} + V_{cL-L} = 0 \; always$$

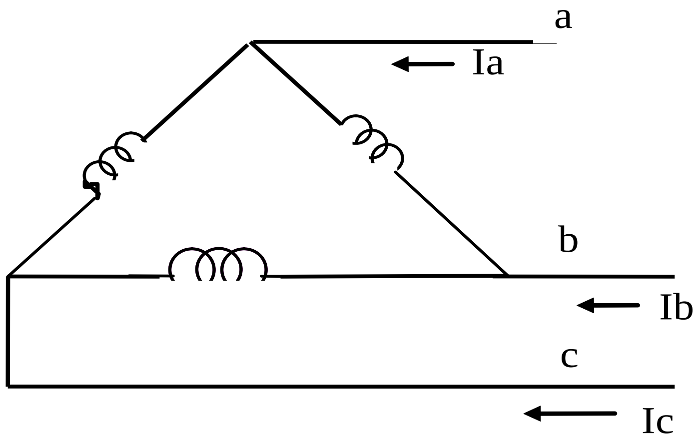
Therefore no zero sequence exists in line voltage phasor.

Since phase voltage sum is not always zero, in the phase voltage phasor, the zero sequence voltage exists.

Sequence Currents:

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

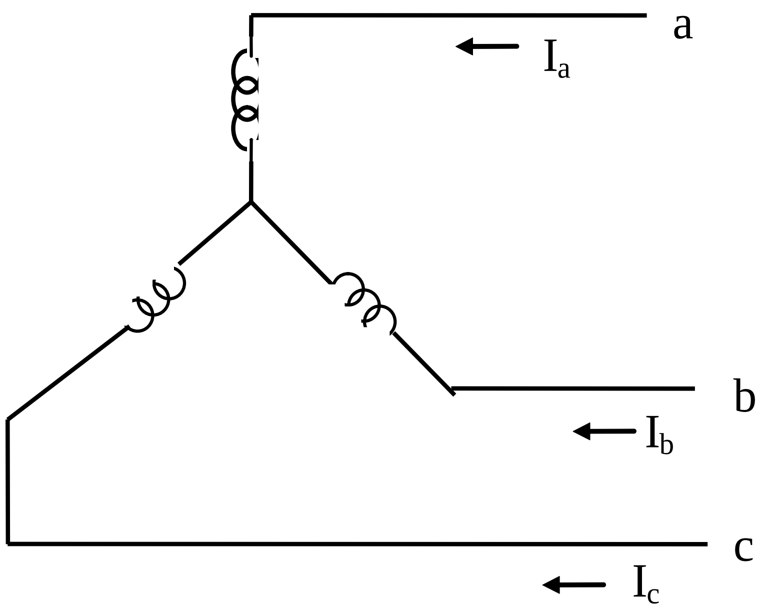
$$I_{a0} = \frac{1}{3}\left[I_a + I_b + I_c\right]$$



$I_a + I_b + I_c = 0$

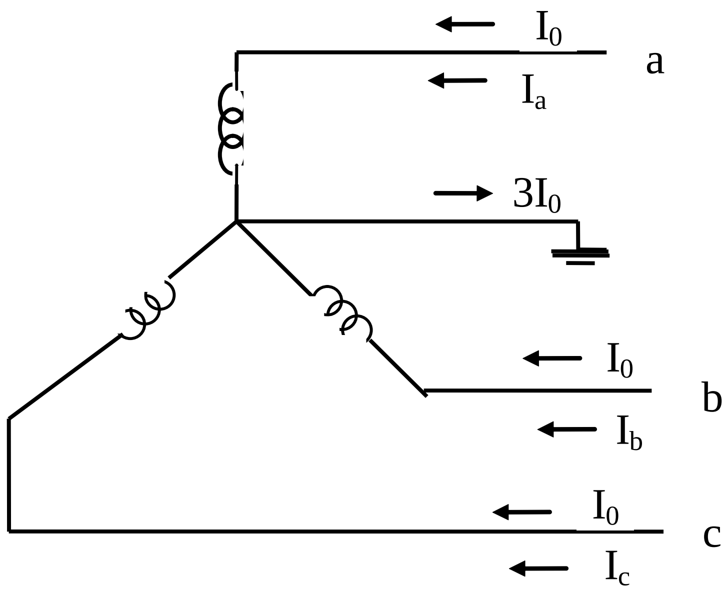
Therefore no zero sequence current flows into delta connection.

Star connection



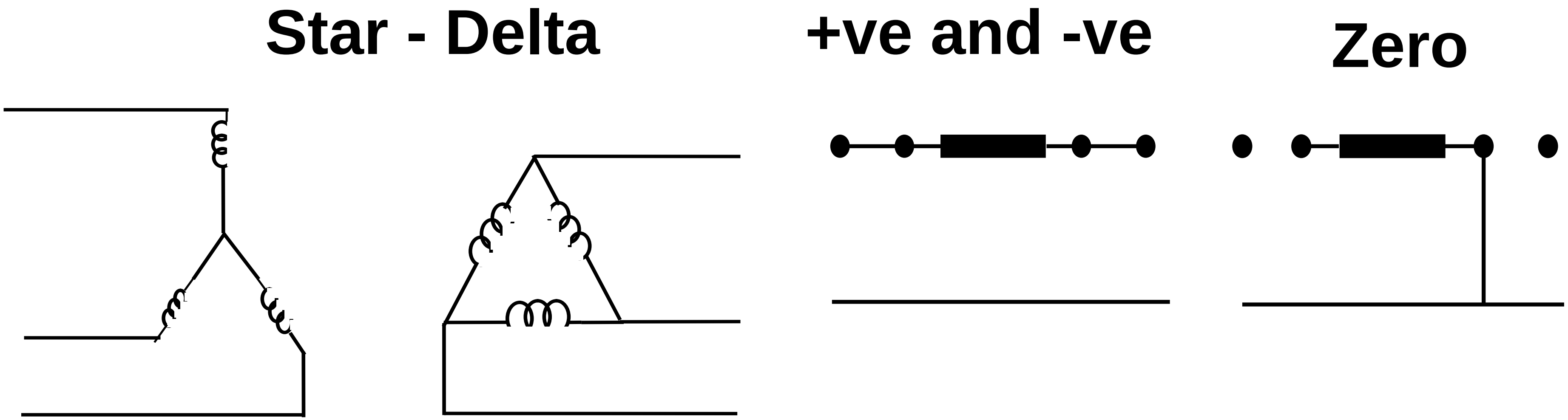
$I_a+I_b+I_c = 0$, There fore no zero sequence current flows into star connection

Star grounded



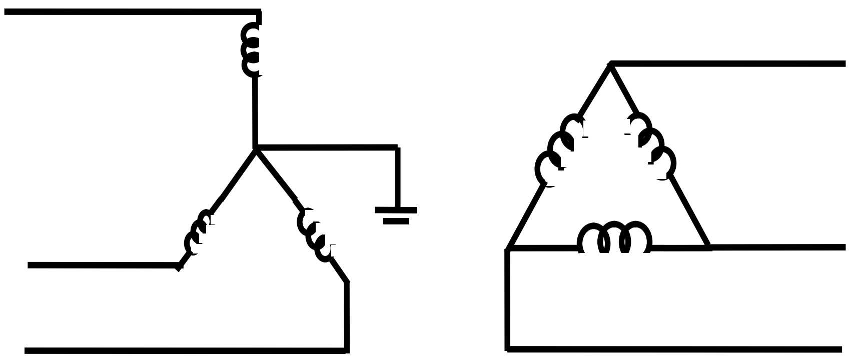
Ia+Ib+Ic may not be zero. Hence path always exists for zero sequence currents.

Transformer sequence impedance diagram

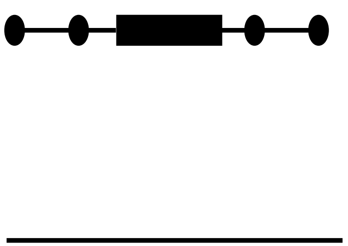


Transformer sequence impedance diagram

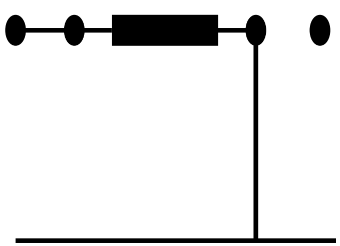
Star grounded-Delta



+ve and -ve



Zero



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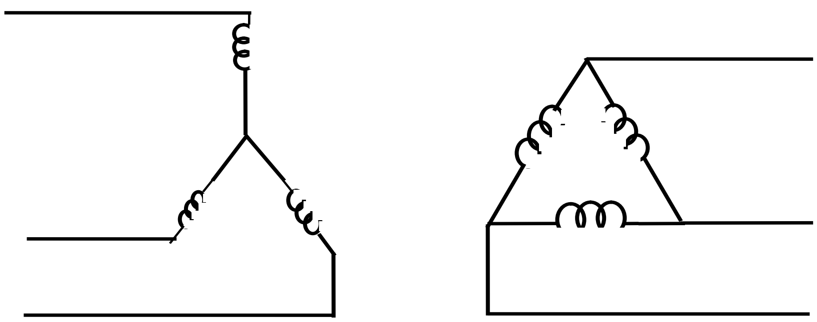
Transformer Connection to reduce the 3rd harmonic content (flow)



- Inrush current (Magnetising current)
- 3rd harmonic content : 40 to 50 % of fundamental.
- No 3rd harmonic current.

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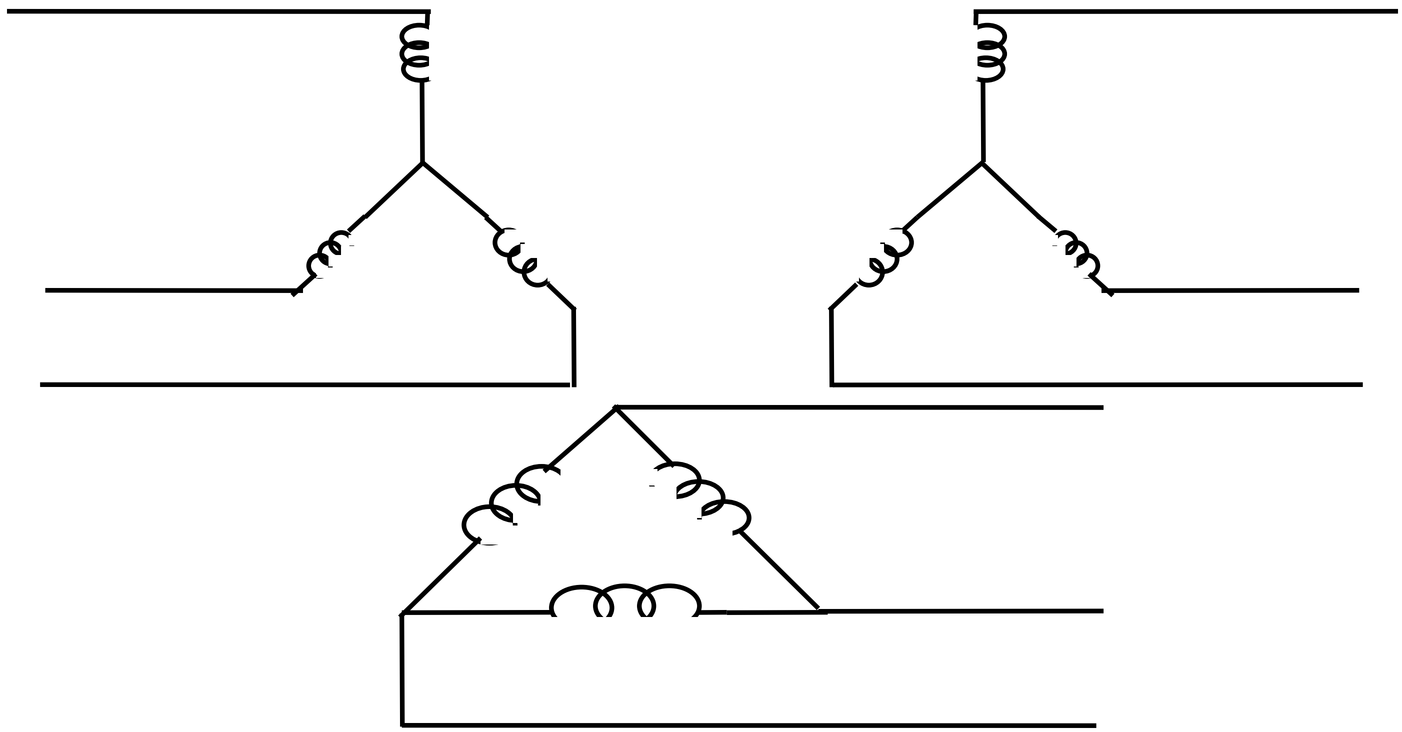
Three winding Transformer



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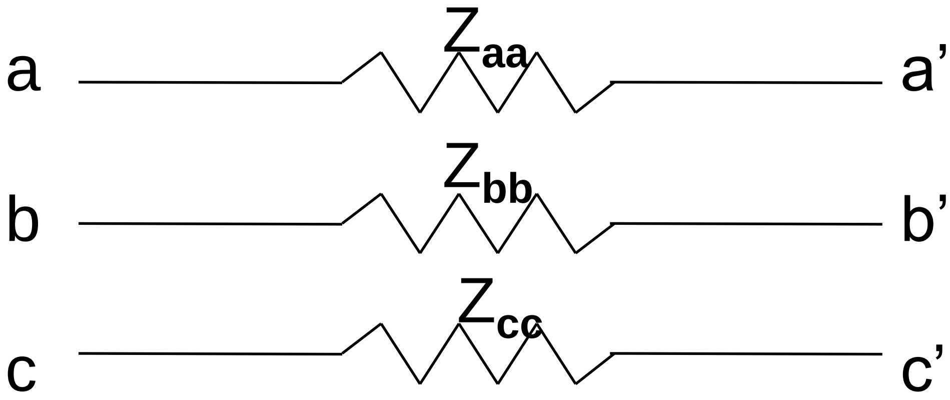
Sequence Impedance



$$\begin{bmatrix} V_{aa'} \\ V_{bb'} \\ V_{cc'} \end{bmatrix} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Let $Z_{aa} = Z_{bb} = Z_{cc} = Z_s$ and $Z_{ab} = Z_{ac} = Z_{ba} = Z_{bc} = Z_{ca} = Z_{cb} = Z_m T_{sp} V_s = [Z] . T_{sp}.I_s$

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$$\begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix}\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix}=\begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix}\begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix}\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}$$

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix}=\begin{bmatrix} Z_s - Z_m & 0 & 0 \\ 0 & Z_s - Z_m & 0 \\ 0 & 0 & Z_s + 2Z_m \end{bmatrix}\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}$$

$$Z_{1,2,0} = Z_s = \begin{bmatrix} Z_s - Z_m & 0 & 0 \\ 0 & Z_s - Z_m & 0 \\ 0 & 0 & Z_s + 2Z_m \end{bmatrix}$$

$$V_{a1} = (Z_s - Z_m) I_{a1}$$
$$V_{a2} = (Z_s - Z_m) I_{a2}$$
$$V_{a0} = (Z_s + 2Z_m) I_{a0}$$

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For Rotating Machines

$Z_{a,b,c}$ is not symmetric. Even then, the $Z_{1,2.0}$ is diagonalized.

Exercise:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_s & Z_{m1} & Z_{m2} \\ Z_{m2} & Z_s & Z_{m1} \\ Z_{m1} & Z_{m2} & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Find the expression for $Z_{1,2,0}$
and Prove that it is a diagonal matrix:

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Advantages of Sequence Component

- De-couples the equation to +ve, -ve and zero sequence and hence easy to solve.
- End conditions can be applied easily for fault studies in sequence components.
- Since the equations are de-coupled, same set of subroutines can be called for solving the +ve, -ve and zero sequence system.

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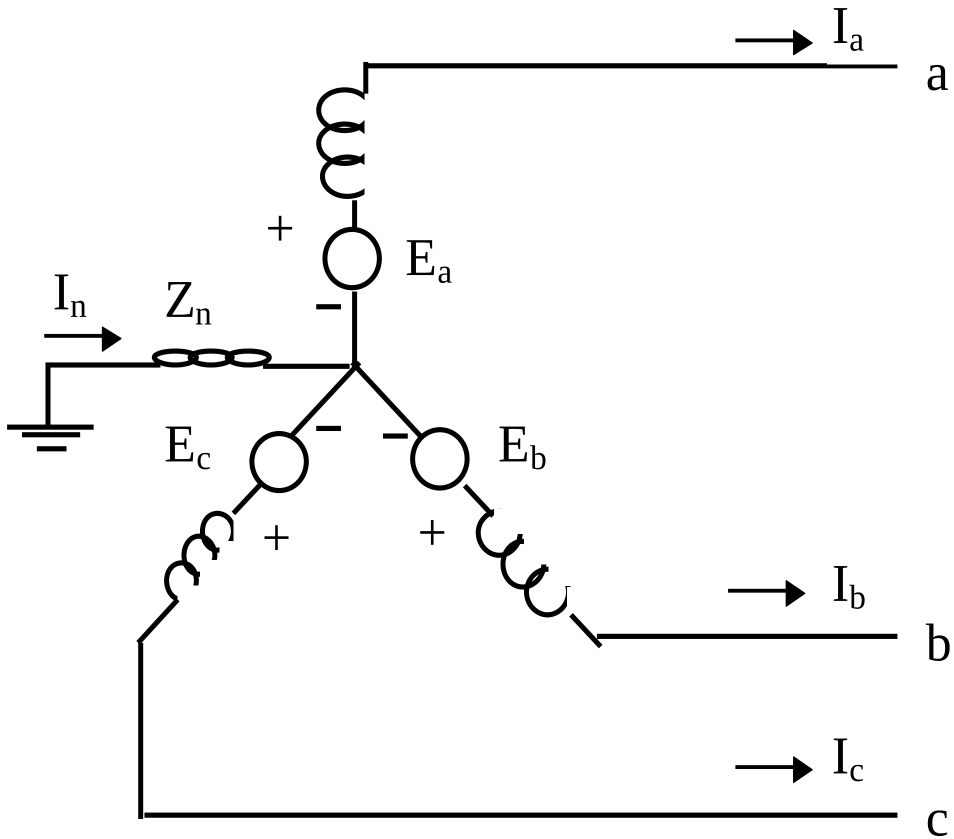
Steady State



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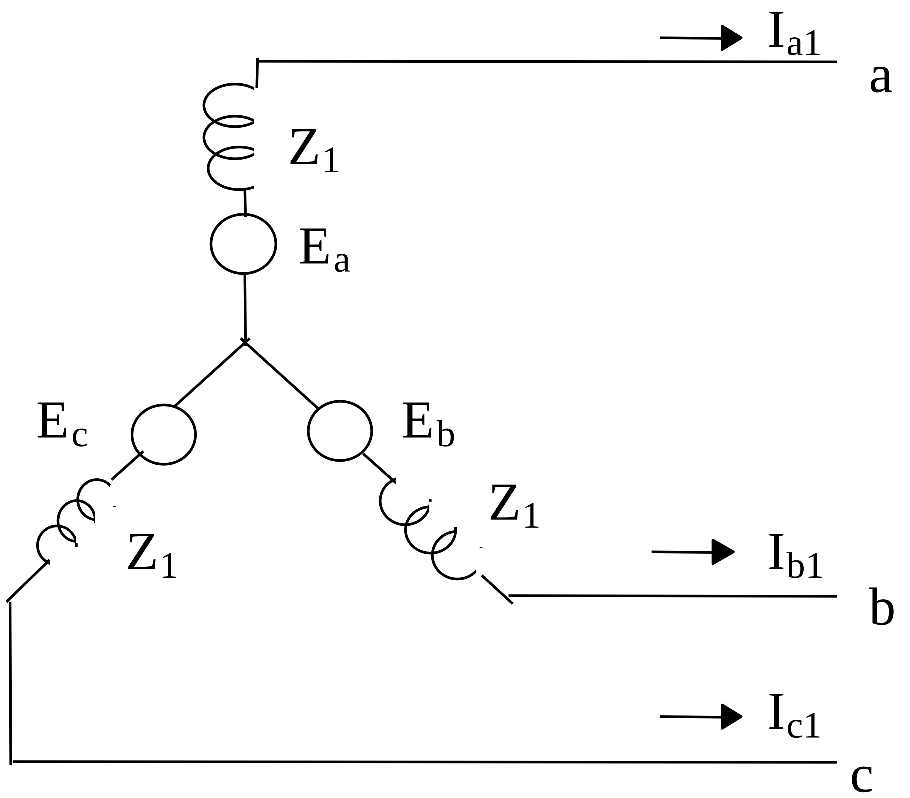
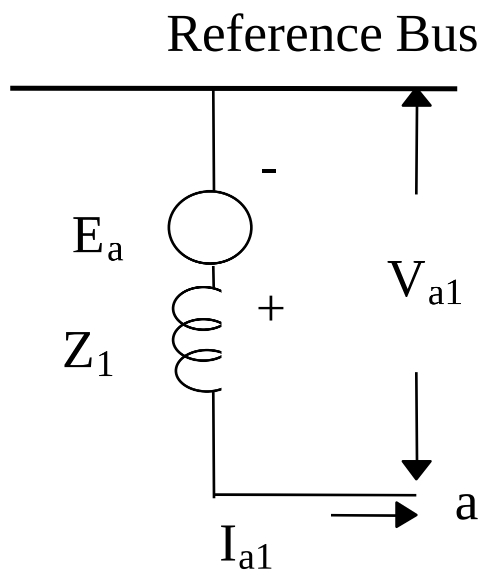
Positive Sequence Network





$$V_{a1} = E_a - I_{a1} Z_1$$

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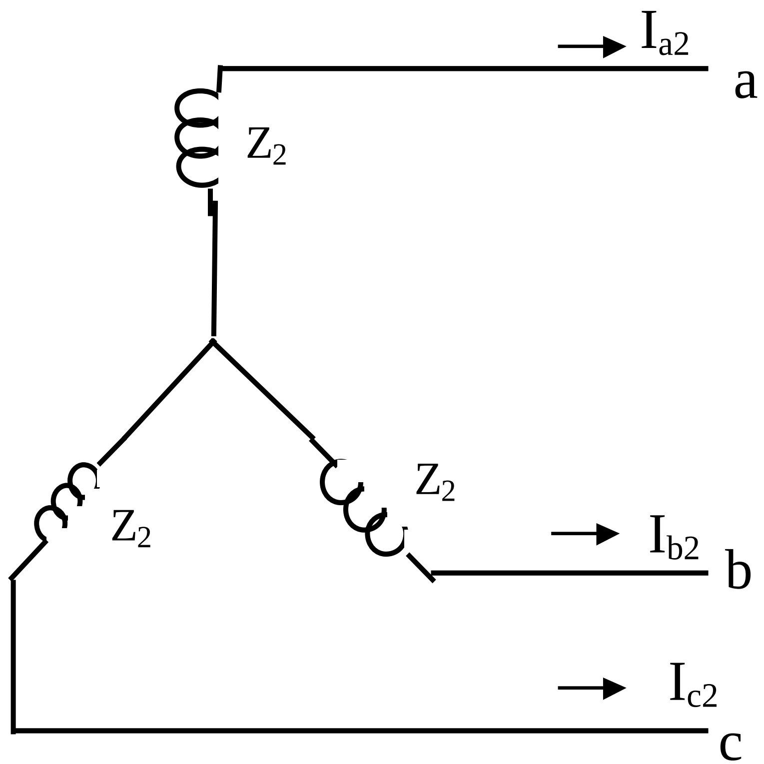
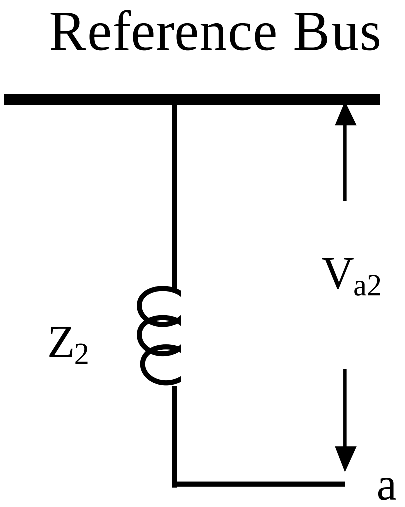
Negative Sequence Network





$$V_{a2} = - I_{a2} Z_2$$

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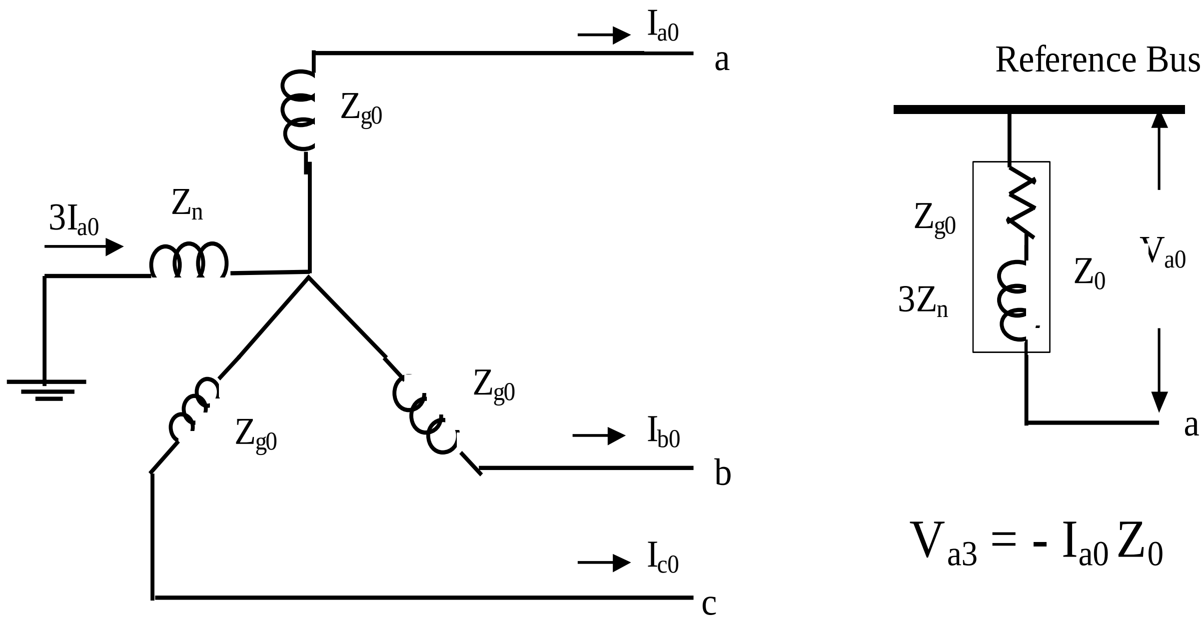
Zero Sequence Network



$$V_{a3} = - I_{a0} Z_0$$

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Generator impedance for fault study :

1.Transient (xd′) or sub-transient (xd″) is considered for positive sequence.

2. X_2 i.e. Negative sequence which is close to xd″. (Approximately).

3. X_0 is small 0.1 to 0.7 times xd″

Typical values on own rating :

Xd	100 to 200 %
X_q	60 to 200 %
X_d'	21 to 41 %
X_d''	13 to 30 %
X_2	$\cong X_d''$

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Transmission line :

Positive sequence impedance = Negative sequence impedance

Zero sequence impedance depends upon : Return path, Ground wires and Earth resistively.

Zero sequence reactance is approximately 2 - 2.5 times positive sequence impedance.

R_0 is usually large. May be 5 to 10 times also.

B_0 is 65 to 80 % of B positive sequence

Transformers :

All are equal i.e. $Z_{pt} = Z_{nt} = Z_{zt}$ for transformer.

$Z_{zt} \cong 90\%$ of Z_{pt}, if magnetising branch is neglected.

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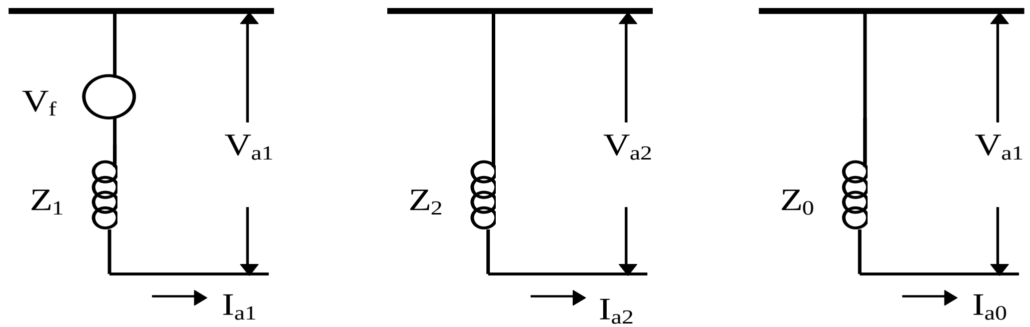
Fault Representation:



$$V_{a1} = V_f - Z_1 . I_{a1} \qquad V_{a2} = -Z_2 . I_{a2} \qquad V_{a0} = - Z_0 . Ia_0$$

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \begin{bmatrix} V_f \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} Z_1 & 0 & 0 \\ 0 & Z_2 & 0 \\ 0 & 0 & Z_0 \end{bmatrix} \begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}$$

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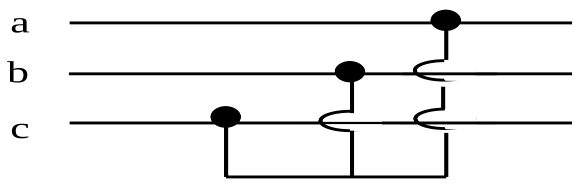
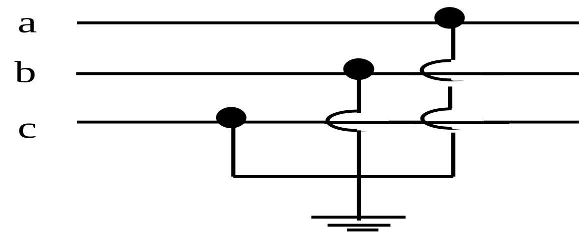
Three phase fault representation:





$$V_{ab} = 0 \qquad V_a = 0 \qquad V_{a1} = 0$$
$$V_{bc} = 0 \qquad V_b = 0 \qquad V_{a2} = 0$$
$$V_{ca} = 0 \qquad V_c = 0 \qquad V_{a0} = 0$$

$$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} V_f \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} Z_1 & 0 & 0 \\ 0 & Z_2 & 0 \\ 0 & 0 & Z_0 \end{bmatrix} \begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}$$

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Three phase fault representation:

$$I_{a1} = V_f / Z_1 \quad , \quad I_{a2} = 0 \ , \quad I_{a0} = 0$$

$$I_a = I_{a1}$$

$$I_b = a^2 I_{a1}$$

$$I_c = a I_{a1}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}$$

$$|I_a| = |I_b| = |I_c|$$

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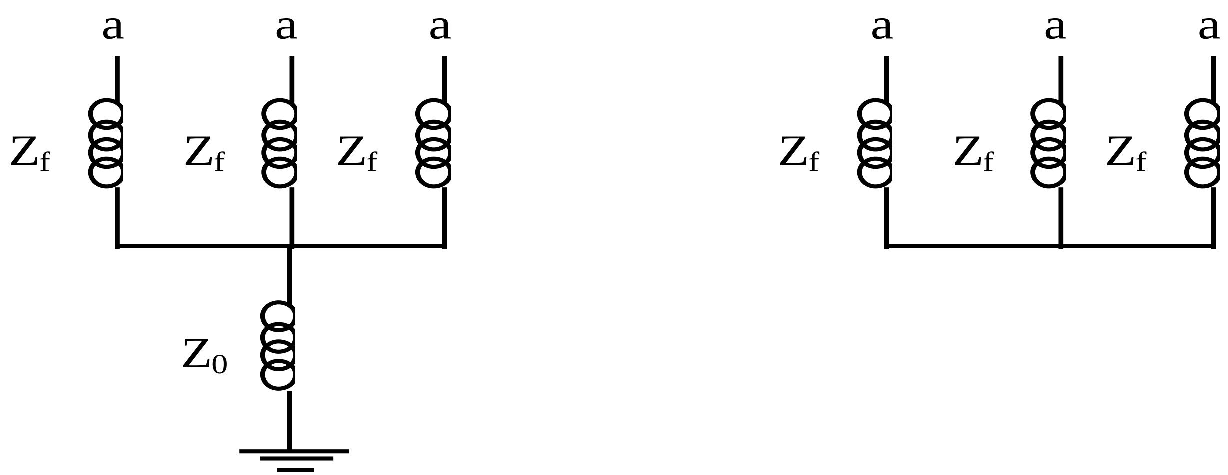
Fault Through Impedance :



$$I_{a1} = \frac{V_f}{Z_1 + Z_f} \quad , \; I_{a2} = 0 \; , \quad I_{a0} = 0$$

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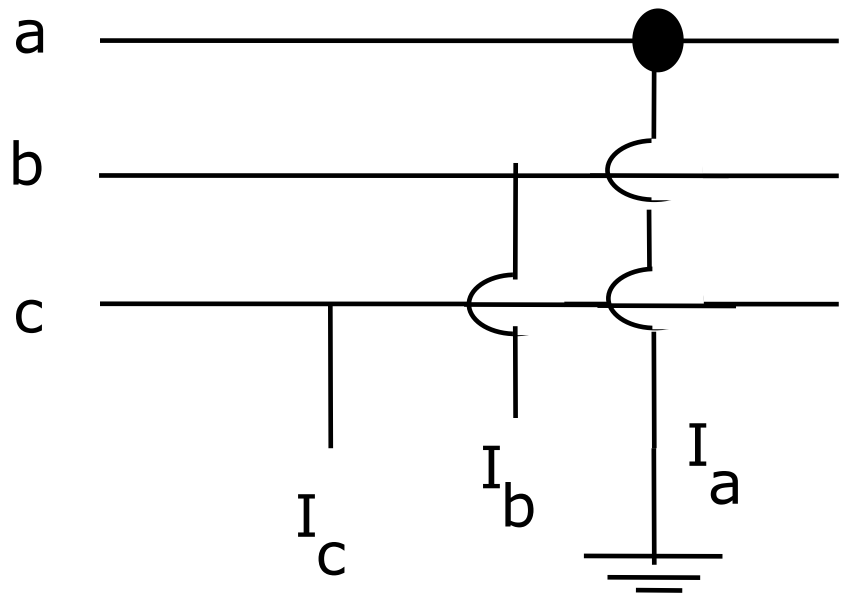
Single Line to Ground Fault Representation



$V_a = 0$

$I_b = 0$

$I_c = 0$

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$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$I_{a1} = \frac{1}{3} I_a, \quad I_{a2} = \frac{1}{3} I_a, I_{a0} = \frac{1}{3} I_a \qquad \because \; I_{a1} = I_{a2} = I_{a0}$$

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \begin{bmatrix} V_f \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} Z_1 & 0 & 0 \\ 0 & Z_2 & 0 \\ 0 & 0 & Z_0 \end{bmatrix}\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}$$

$$V_{a1} = V_f - Z_1 I_{a1} \qquad V_{a2} = - Z_2 I_{a2} \qquad V_{a0} = - Z_0 I_{a0}$$

$$V_{a1} + V_{a2} + V_{a0} = V_f - Z_1 I_{a1} - Z_2 I_{a2} - Z_0 I_{a0}$$

$$\because V_a = V_{a1} + V_{a2} + V_{a0} = 0$$

$$I_{a1} = I_{a2} = I_{a0} = \frac{V_f}{Z_1 + Z_2 + Z_0} \qquad I_a = \frac{3V_f}{Z_1 + Z_2 + Z_0}$$

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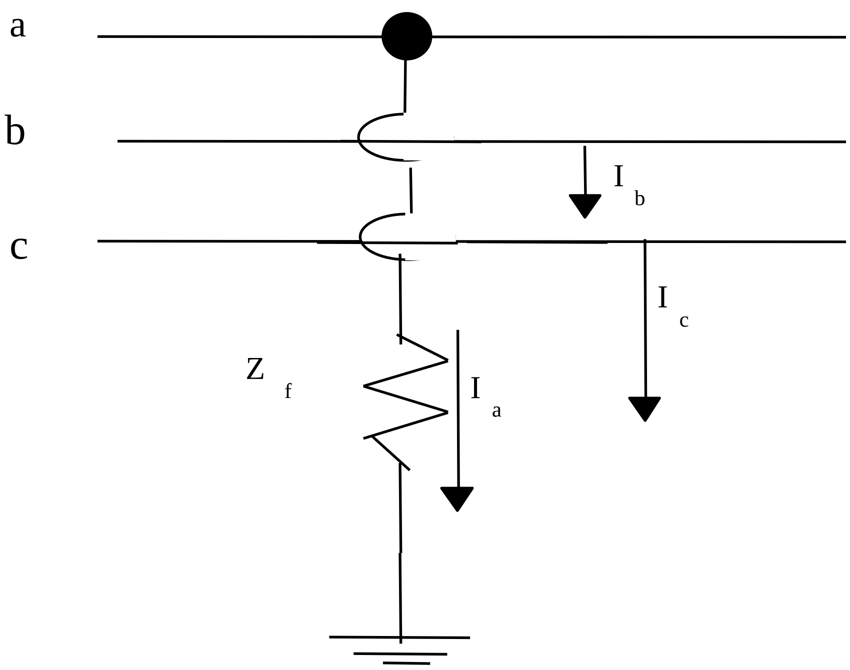
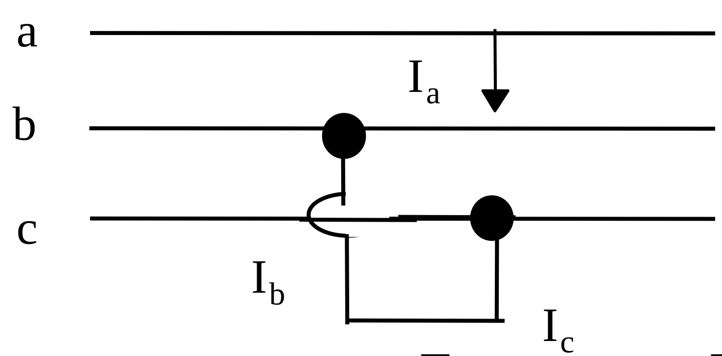
Fault Through Impedance :



$$I_{a1} = I_{a2} = I_{a0} = \frac{V_f}{Z_1 + Z_2 + Z_0 + 3z_f}$$

Line to Line Fault Representation:



$V_b = V_c$

$I_a = 0$

$I_b = -I_c$

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

V_{a1} = 1/3 [V_a+aV_b+a^2V_c] = 1/3 [V_a+aV_b +a^2V_c]

V_{a2} = 1/3 [V_a+a^2V_b+aV_c] = 1/3 [V_a+a^2V_b+aV_c]

$V_{a1} = V_{a2}$

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$I_{a0} = 1/3\ (I_a + I_b + I_c) = 1/3\ (I_b - I_b) = 0$

$I_{a1} = 1/3\ (aI_b + a^2I_c) = 1/3(aI_b - a^2I_b)$

$I_{a2} = 1/3\ (a^2I_b + aI_c) = 1/3\ (a^2I_b - aI_b)$

$\therefore\ I_{a1} = -I_{a2}$

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$V_{a1} = V_f - Z_1I_{a1}$

$V_{a2} = Z_2I_{a2} = V_{a1} = V_f - Z_1I_{a1}$

$Z_2I_{a1} = V_f - Z_1I_{a1}$

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \begin{bmatrix} V_f \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} Z_1 0\ 0 \\ 0\ Z_2 0 \\ 0\ 0\ Z_0 \end{bmatrix}\begin{bmatrix} I_{a1} \\ -I_{a1} \\ 0 \end{bmatrix}$$

$$\therefore\ I_{a1} = \frac{V_f}{(Z_1 + Z_2)} \quad \textit{and}\ \ I_{a2} = -I_{a1}, I_{a0} = 0, V_{a0} = 0$$

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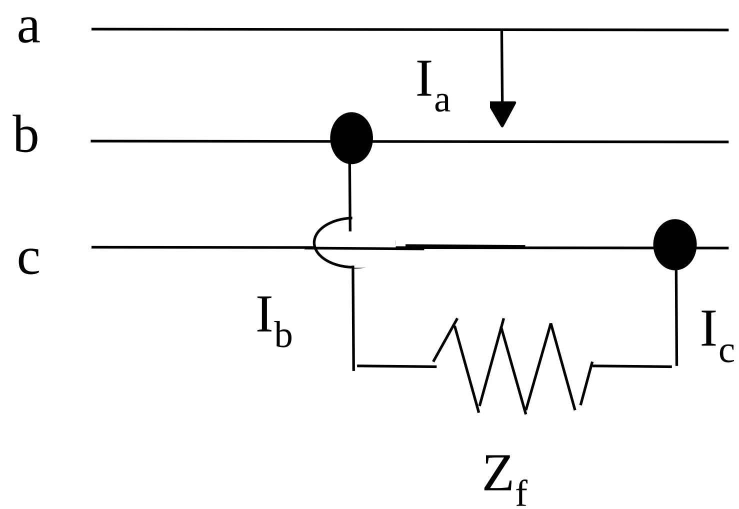
Fault Through Impedance :



$$I_{a1} = -I_{a2} = \frac{V_f}{(Z_1 + Z_2 + Z_f)}$$

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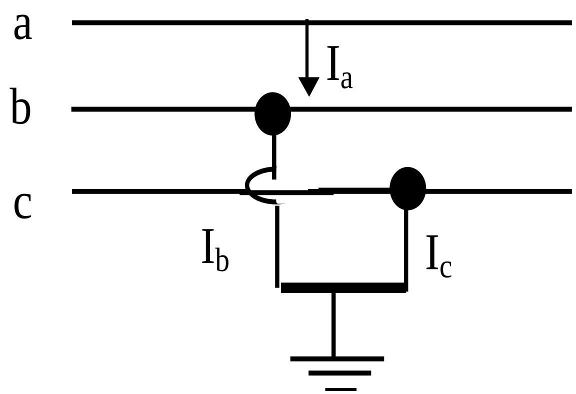
Double Line to Ground Fault Representation:



$V_b = 0$

$V_c = 0$

$I_a = 0$

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} V_a \\ 0 \\ 0 \end{bmatrix}$$

$$V_{a1} = \frac{1}{3}V_a \,, V_{a2} = \frac{1}{3}V_a \,, V_{a0} = \frac{1}{3}V_a$$

$$V_{a1} = V_{a2} = V_{a0}$$

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$$I_{a1} + I_{a2} + I_{a0} = I_a = 0$$

$$I_{a1} = 1/3\,(aI_b + a^2I_c)$$

$$I_{a2} = 1/3\,(a^2I_b + aI_c)$$

$$I_{a0} = 1/3\,(I_b + I_c)$$

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} 0 \\ I_b \\ I_c \end{bmatrix}$$

$$1/3(aI_b + a^2I_c) + 1/3(a^2I_b + aI_c) + 1/3(I_b + I_c) = 0$$

$$aI_b + a^2I_c + a^2I_b + aI_c + I_b + I_c = 0$$

$$V_{a1} = V_f - Z_1I_{a1}$$

$$V_{a2} = -Z_2I_{a2}$$

$$V_{a0} = -Z_0I_{a0}$$

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \begin{bmatrix} V_f \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} Z_1 & 0 & 0 \\ 0 & Z_2 & 0 \\ 0 & 0 & Z_0 \end{bmatrix}\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}$$

$$V_{a1} = V_{a2} = V_{a0}$$

$$\therefore V_f - Z_1I_{a1} = -Z_2I_{a2} - Z_0I_{a0}$$

$$\therefore \Rightarrow \quad I_{a1} = \frac{V_f}{\left[Z_1 + \left(\frac{Z_2Z_0}{Z_2 + Z_0}\right)\right]}$$

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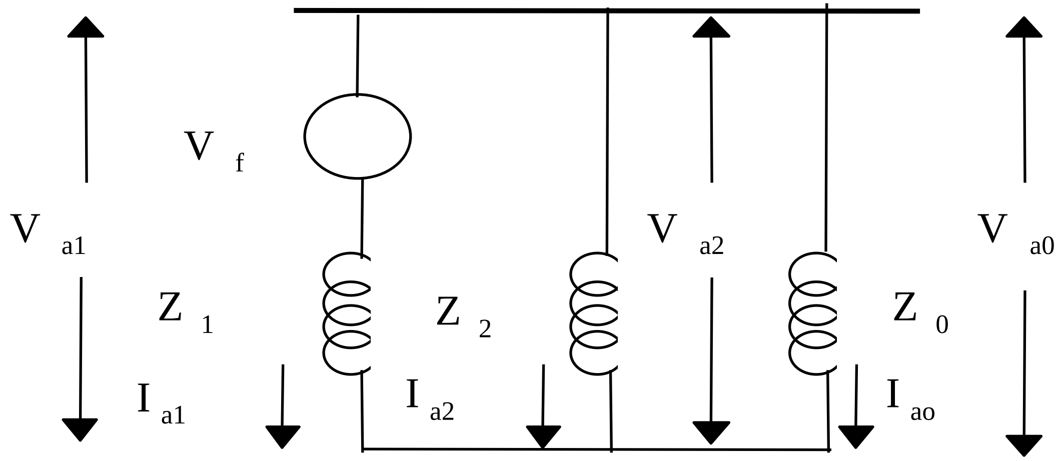
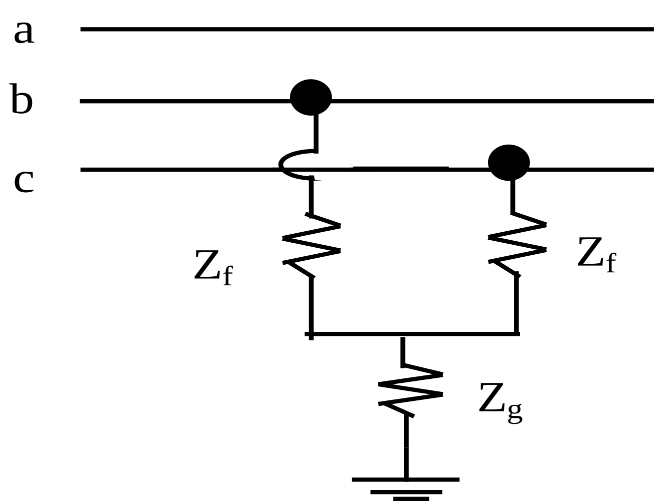


Fault Through Impedance:



$$I_{a1} = \frac{V_f}{Z_1' + \left(\frac{Z_2' Z_0'}{Z_2' + Z_0'}\right)}$$

$$Z_1' = Z_1 + Z_f$$
$$Z_2' = Z_2 + Z_f$$
$$Z_0' = Z_0 + Z_f + 3Z_g$$

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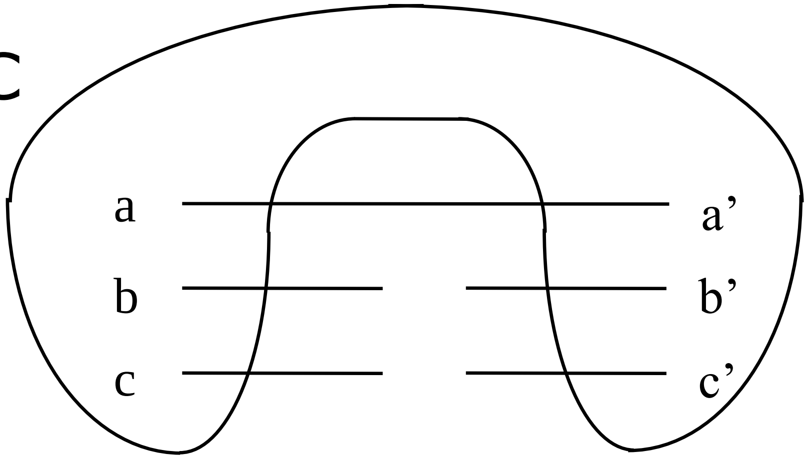
Open Faults

Open in phase B & C



$I_b = 0$ and $I_c = 0$

$$V_i^a - V_k^a = Z'_{aa}\, I_a = Z'_{aa}\, I_f$$

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix}$$

$$I_{a1} = I_{a2} = I_{a0} = \frac{1}{3} I_a = \frac{1}{3} I_f$$

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$$V_{a1} = V_f - Z_1 I_{a1}$$
$$V_{a2} = -Z_2 I_{a2}$$
$$V_{a0} = -Z_0 I_{a0}$$

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \begin{bmatrix} V_f \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} Z_1 & 0 & 0 \\ 0 & Z_2 & 0 \\ 0 & 0 & Z_0 \end{bmatrix} \begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix}$$

$$V_k^a - V_l^a = V_{kl}^1 + V_{kl}^2 + V_{kl}^0 = Z_{zz}^{'} I_f = 3Z_{aa}^{'} I_{a1}$$
$$V_f = V_{kl}$$
$$3Z_{aa}^{'} I_{a1} = V_{kl} - Z_1 I_{a1} - Z_2 I_{a2} - Z_0 I_{a0}$$

$$I_{a1} = I_{a2} = I_{ao} = \frac{V_{kl}}{Z_1 + Z_2 + Z_0 + 3Z_{aa}^{'}}$$

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V_{kl} is the Thevenin equivalent voltage, once the line is removed, between buses k & l.

$$Z_1 = Z_{kk}^1 + Z_{ll}^1 - Z_{lk}^1 - Z_{kl}^1$$
$$Z_2 = Z_{kk}^2 + Z_{ll}^2 - Z_{lk}^2 - Z_{kl}^2$$
$$Z_0 = Z_{kk}^0 + Z_{ll}^0 - Z_{lk}^0 - Z_{kl}^0$$
$$3Z_{aa}^{'} = Z_f = Z_1^f + Z_2^f + Z_0^f$$

Solution Methodology:

1. Do the load flow with the line isolated.

2. Then insert the line with two phase open.

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Open in phase A :

- Ia = 0
- Similar type of analysis like double line fault.
- Voltage is between two nodes, rather than between node and ground.
- Impedance is the Thevenin's equivalent impedance between nodes.

$$I_f^l = \frac{V_k - V_l}{Z_1^{'} + \frac{Z_2^{'} . Z_0^{'}}{Z_2^{'} + Z_0^{'}}}$$

$$Z_1^{l} = Z_{kk}^{1} + Z_{ll}^{1} - Z_{lk}^{1} - Z_{kl}^{1} + Z_{f}^{1}$$

$$Z_2^{l} = Z_{kk}^{2} + Z_{ll}^{2} - Z_{lk}^{2} - Z_{kl}^{2} + Z_{f}^{2}$$

$$Z_0^{l} = Z_{kk}^{0} + Z_{ll}^{0} - Z_{lk}^{0} - Z_{kl}^{0} + Z_{f}^{0}$$

$$I_f^2 = I_f^1 . \frac{Z_0^{'}}{Z_0^{'} + Z_2^{'}}$$

$$I_f^0 = \frac{I_f^1 . Z_2^{'}}{Z_0^{'} + Z_2^{'}}$$

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Solution Methodology:

1. Form the Y bus for +ve, -ve and zero sequence.
2. Do the LU factorisation for +ve, -ve and zero sequence.
3. To find the driving point impedance-

In fault study, particular row or column of Z bus is required.

Consider, $Yx = z$

$$x = Y^{-1}z$$

$$x = Z.z$$

Let z have 1 in p^{th} location and 0, at all other location.

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$$x = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1p} & Z_{1n} \\ Z_{p1} & Z_{p2} & \cdots & Z_{pp} & Z_{pn} \\ \vdots & & & & \\ Z_{n1} & Z_{n2} & \cdots & Z_{np} & Z_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} Z_{1p} \\ Z_{pp} \\ \vdots \\ Z_{np} \end{bmatrix}$$

$$\therefore Yx = z$$

Pass in z, 1.0 for the desired bus and 0 else where.
Call LU solution - x will be the desired column of Z bus.

4. Find the sequence fault current I_1^f, I_2^f and I_0^f.
5. Determine the post fault bus voltage

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$[V_f] = [Z]\,[I_f^1]$

$= [Z]\,\{[I_0] - [I_f]\}$

$= [Z]\,[I_0] + [Z][-I_f]$

$= [V_0] + [\Delta V]$

$\Delta V = [Z]\,[-I_f]$

$Y[\Delta V] = [-I_f]$

Solve ΔV using LU solution.

Above can be written as :

$[Y]_p[\Delta V]_p = [-If]_p$, p: positive sequence and similarly for other sequences.

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For faults other than open fault,

$$[-I_f]_p = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -I_f \\ \vdots \\ 0 \end{bmatrix}_p$$

For open fault, between k & l,

$$[-\mathrm{I}_{\mathrm{f}}]_{\mathrm{p}} = \mathrm{k} \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -\mathrm{I}_{\mathrm{f}} \\ \vdots \\ +\mathrm{I}_{\mathrm{f}} \\ \vdots \\ 0 \end{bmatrix}$$

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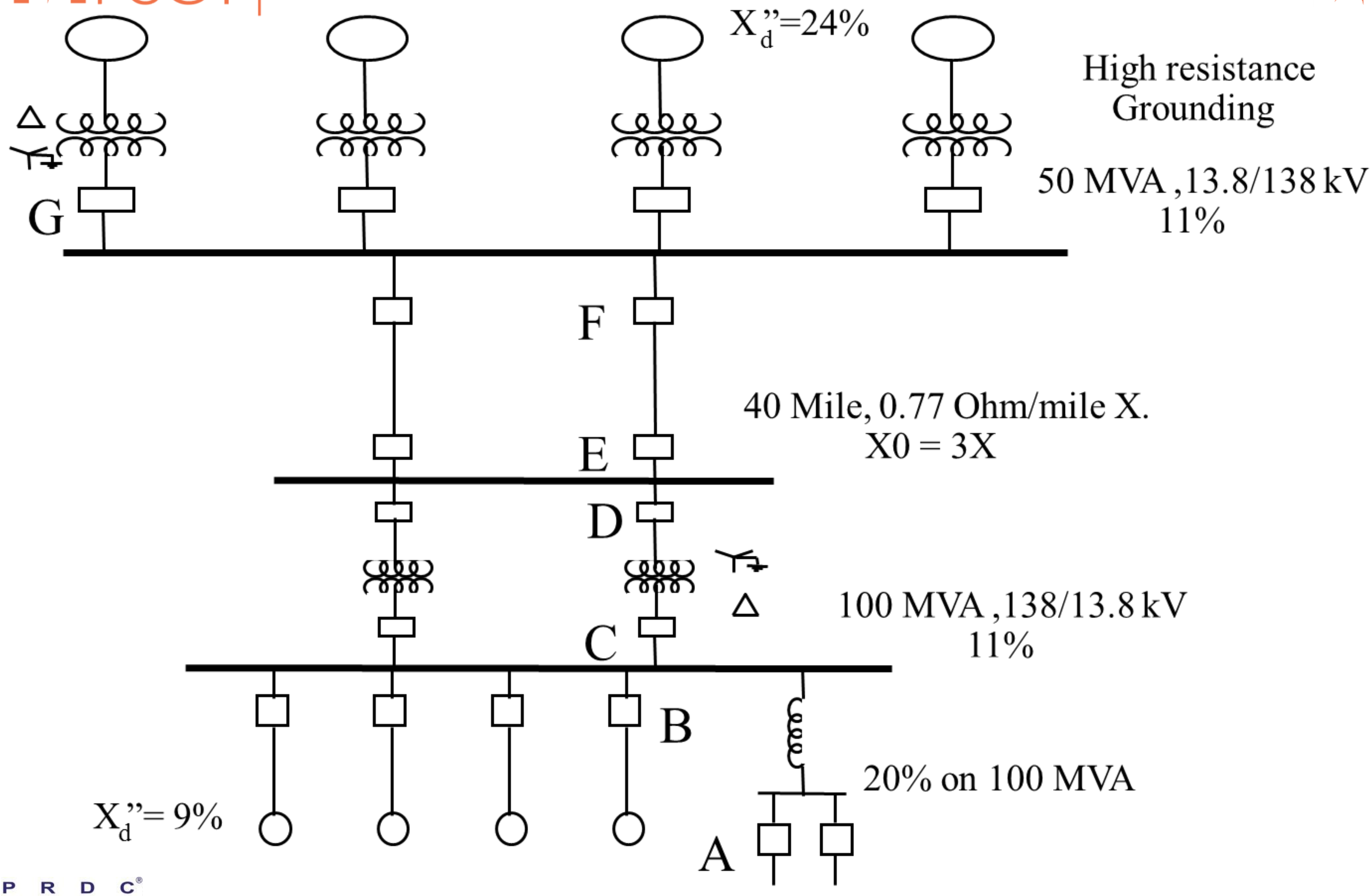
Example:



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Grounding Practice in Power System :

Advantages of ungrounded system :

- Ground connection normally doesn't carry current. Hence elimination saves the cost.
- Current can be carried in other phases, with fewer interruptions.

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Grounding Practice in Power System :

Limitations of ungrounded system :

- With the increase in voltage and line length current has increased and self clearing nature advantage couldn't be seen.
- Arcing ground : Phenomena of alternate clearing and re-striking of the arc, which cause high voltage (surge and transient).
- If grounded, the insulation can be graded in transformer from line to neutral, there by reducing the cost.
- In case of ungrounded system, influence on communication lines is more.
- Ground current can't be limited.

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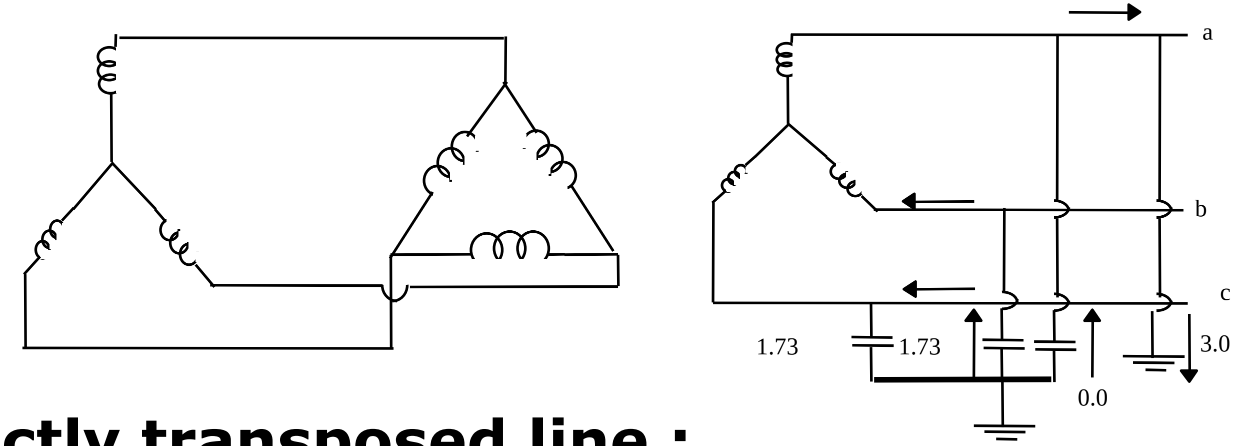
Ungrounded System :



Perfectly transposed line :

Neutral of transformer is at zero potential.

Un-transposed line :

Neutral is shifted.

Capacitance grounded :

Perfectly transposed line.

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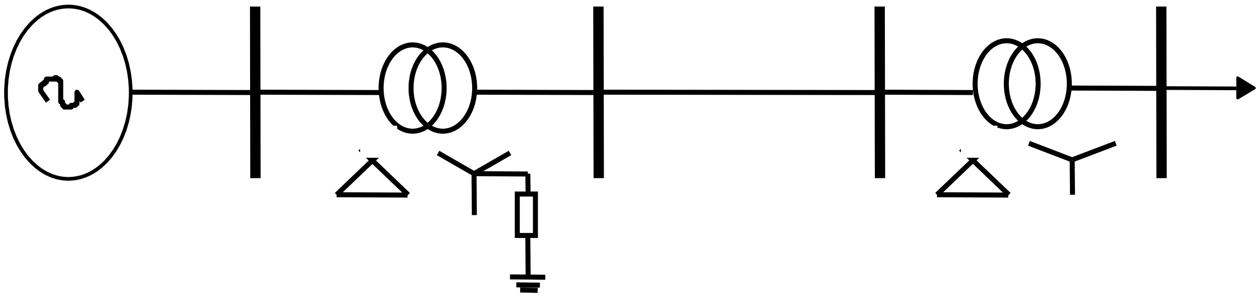
Resistance Grounded System:



The resistance to neutral limits ground current.

Selection of resistance value:

- Amount of ground fault current.
- Power loss in resistor during ground fault.

Power loss: usually expressed as a percentage of system rating.

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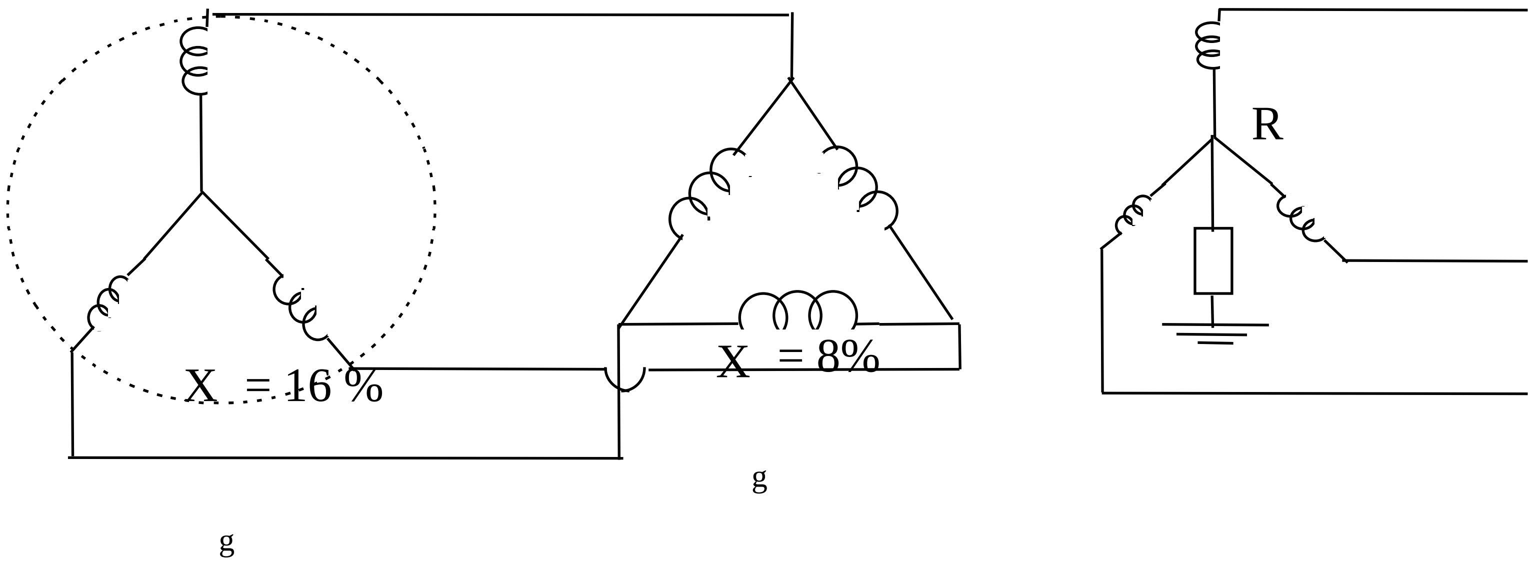

$$Z_1 = 24\% \ , \ Z_2 = 24\% \ , Z_0 = 3R + j8$$

$$I_f = \frac{3}{Z_1 + Z_2 + Z_0} = \frac{3 * 100}{j24 + j24 + 3R + j8} = \frac{300}{3R + j56}$$

$$\text{Power Loss} = I_f^2 R = \left(\frac{300}{3R + j56} \right)^2 * R$$

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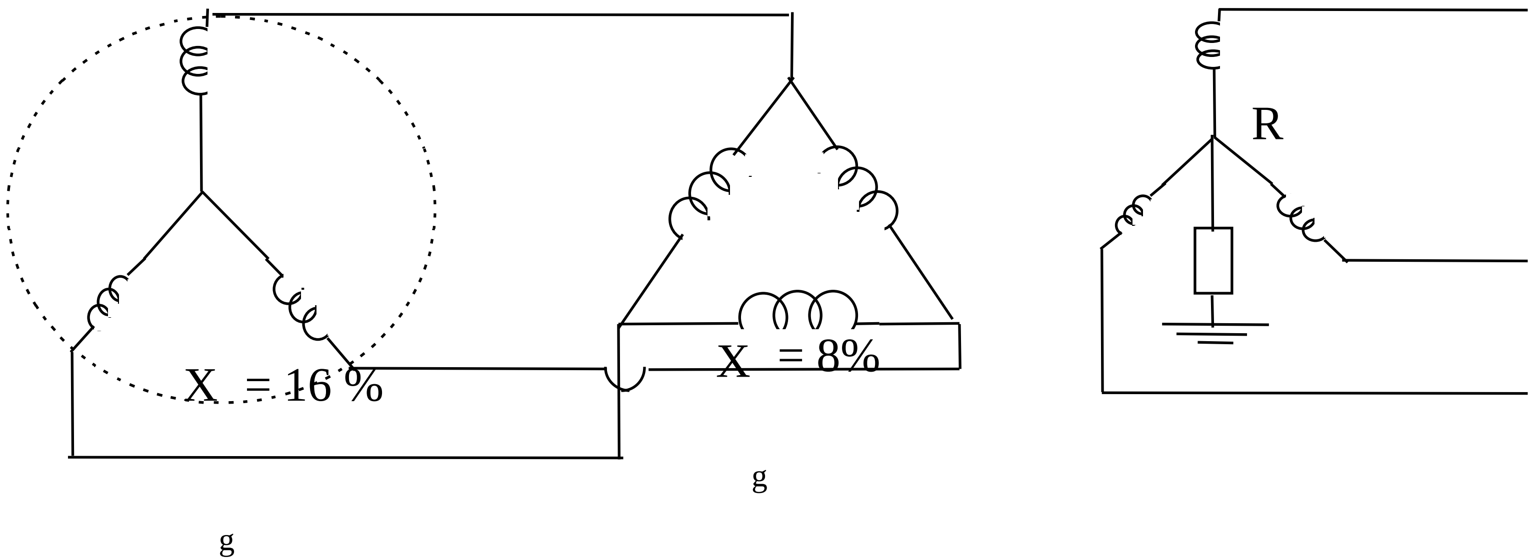

$$Z_1 = 24\% \;,\; Z_2 = 24\% \;,\; Z_0 = 3R + j8$$

$$I_f = \frac{3}{Z_1 + Z_2 + Z_0} = \frac{3 * 100}{j24 + j24 + 3R + j8} = \frac{300}{3R + j56}$$

$$\text{Power Loss} = I_f^2 R = \left(\frac{300}{3R + j56} \right)^2 * R$$

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I_f : in pu, R : in pu

For three phase system, power loss

$$= \frac{I_f^2 R}{3} \text{ percentage of 3 phase system kVA rating}$$

R is in percent p.u.

Maximum power loss = ?

Selection :

How much be the value of ground fault current ?

What should be the percent power loss in the ground resistance ?

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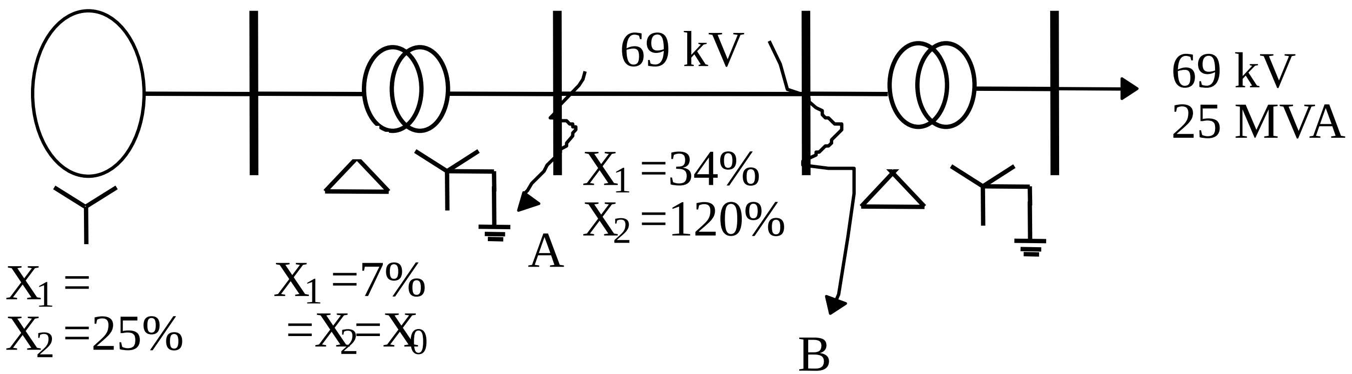
Effectively grounded system:

Solidly grounded : No impedance between neutral and earth

Effectively grounded : As per AIEE standard No.32, Section 32 - 1.05, May 1947 :

$$\frac{X_0 \ system}{X_1 \ system} \leq 3.0 \qquad \frac{R_o}{X_1 \ system} \leq 1.0$$



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Effectively grounded system:

$$\text{For fault at } A \quad \frac{X_0}{X_1} = \frac{7}{32}$$

$$\text{For fault at } B \quad \frac{X_0}{X_1} = \frac{127}{32+34} = \frac{127}{66}$$

Reactance Grounded System

$$\frac{X_0}{X_1} \quad 3.0; \textit{ but no resonance (resonance grounding)}$$

If Xg = 50 Ω at A , find the nature of grounding at A & B.

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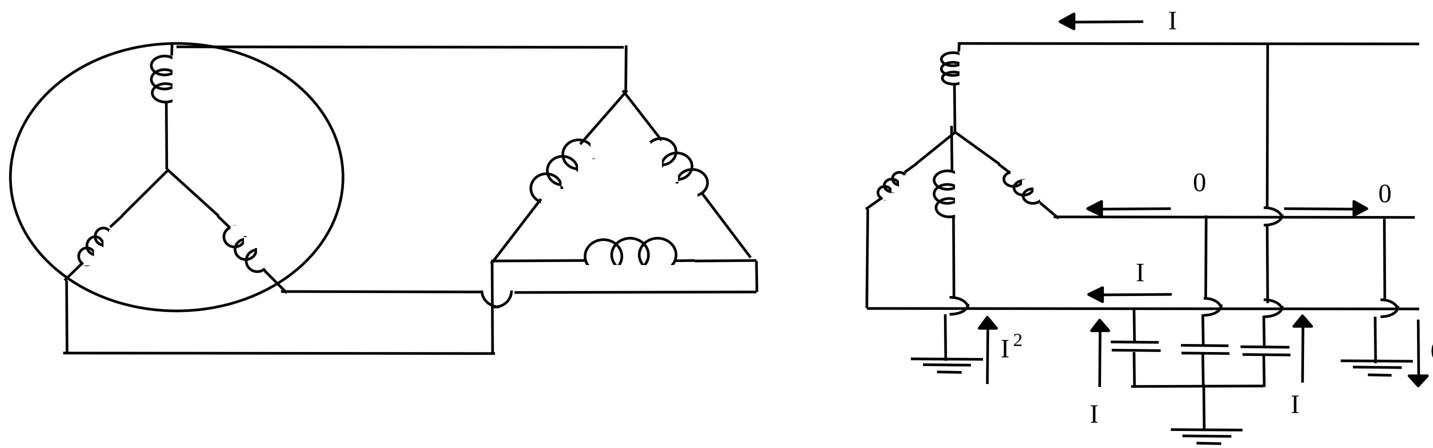
Resonant - Grounded System :

Capacitance current is tuned or neutralised by a neutral reactor or similar device.



Fault current is made zero by selecting the suitable tap on the ground reactor.

Circuit Breaker Selection

1. Determine the symmetrical current (maximum) for any type of fault.

2. Multiply the current by factor obtained from standard tables depending on the duty cycle.

(2 cycles clearing, 5 cycles clearing etc.)

Use the above current to specify the interrupting current

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3. George L. Kusic, "Computer Aided Power System Analysis", Prentice-Hall, International, N.J.,New Delhi, 1989.

4. J. Arrilllaga, C.P. Arnold and B.J.Harker ,"Computer Modeling of Electrical Power Systems", John Wiley and Sons,1983.

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Queries & Discussions

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Thank You

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पूर्वी क्षेत्रीय विद्युत समिति

प्रगति के पथ को रोशन

TRANSIENT STABILITY STUDIES

विज्ञानेन जातानि जीवन्ति

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Stability

- Rotor angle stability
  Study period: 0-10 sec
  - Transient stability
    Large disturbance
    (First swing)
  - Small signal stability
    - Non-oscillatory
      Sufficient synchronizing torque
    - Oscillatory
      Unstable control action
- Mid-term/long-term stability
  Study period: seconds to several minutes
  (slow dynamics)
- Voltage stability

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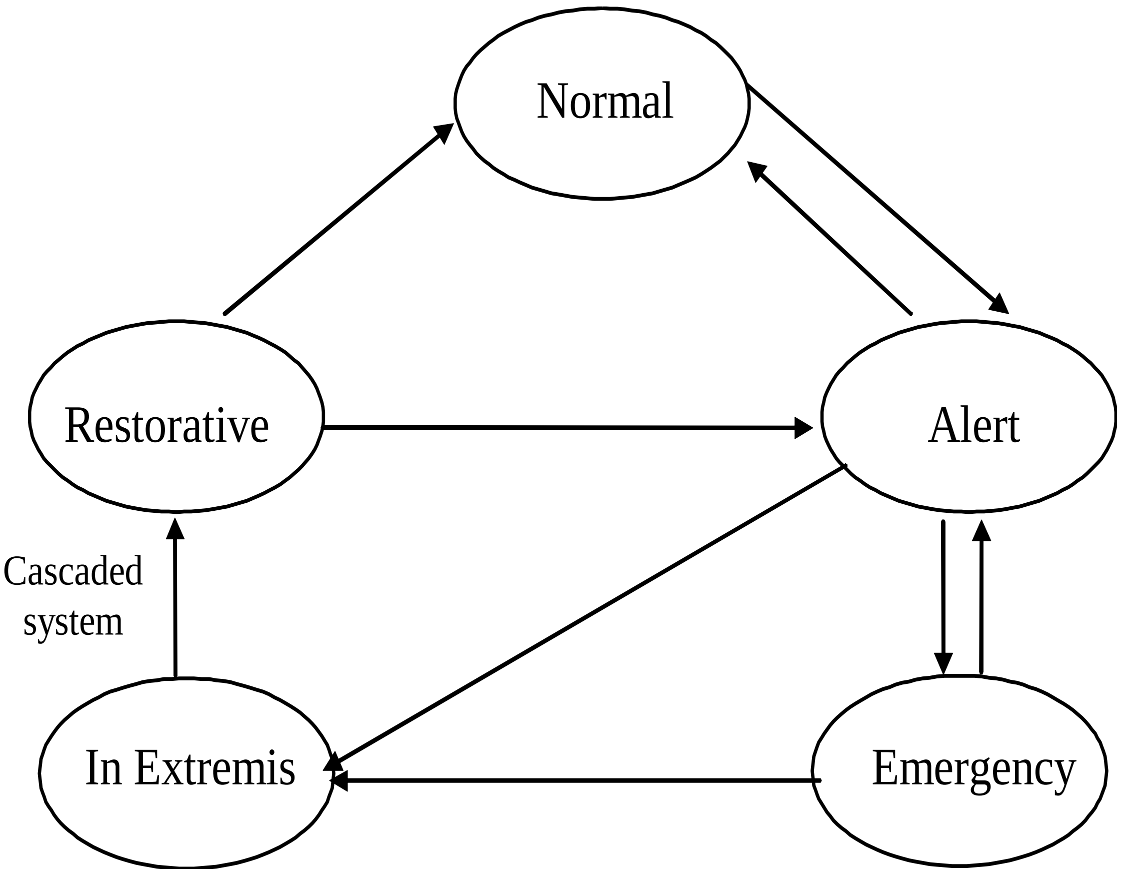
Power System Operating States



f, v, loading acceptable, load met, n-1 or n-2 contingency acceptable

f, v, loading acceptable, load met
n-1 or n-2 contingency not satisfied

f, v, loading not acceptable,
load not met

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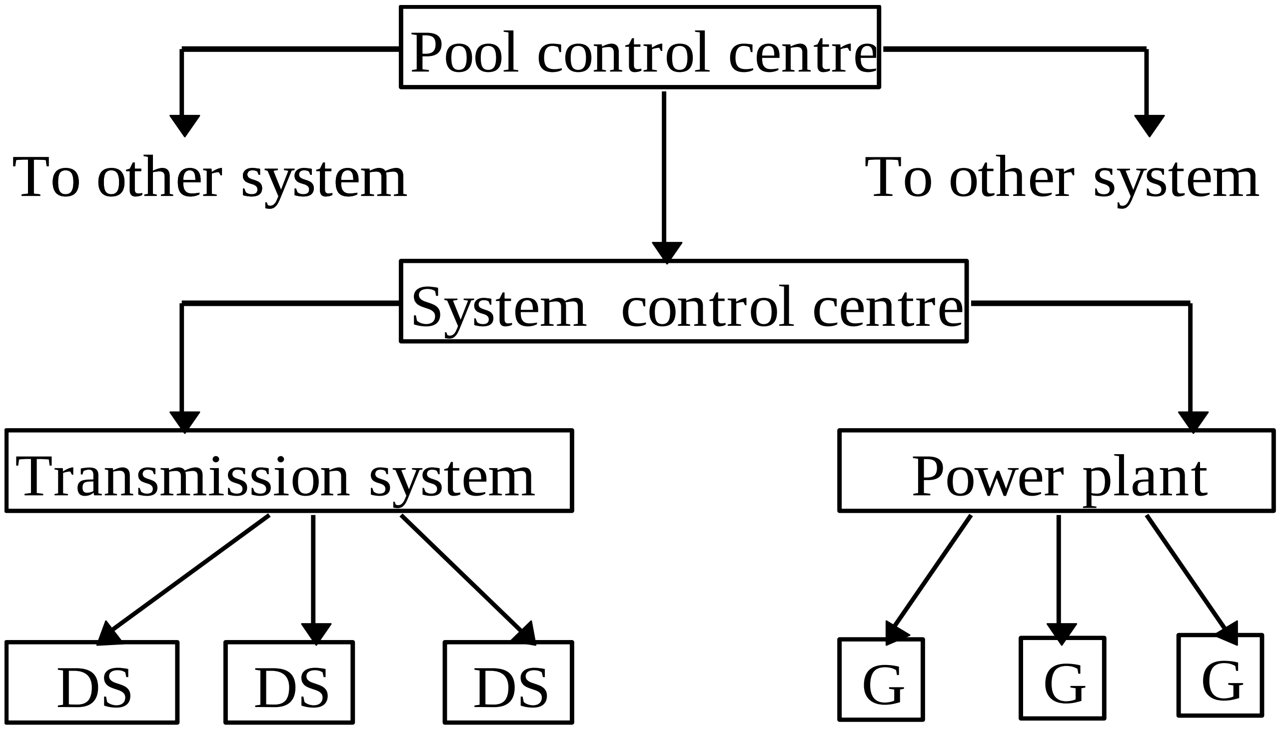
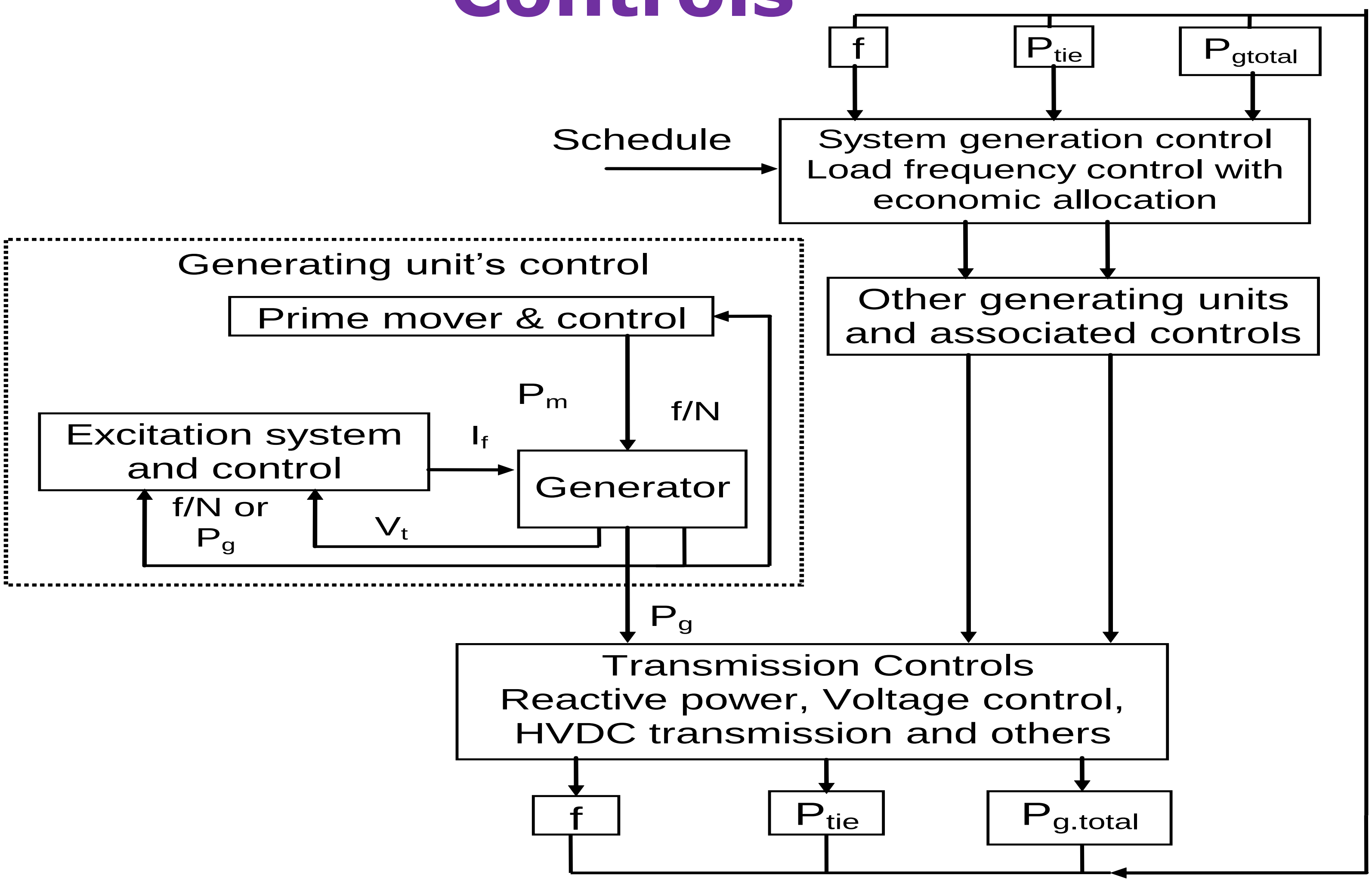
Control Hierarchy



DS: Distribution System

G : Generator

Power System Subsystem & Controls



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Power System Stability

Ability of a power system to remain in synchronism.
Classification of transients : Electromagnetic and Electromechanical

Stability classification

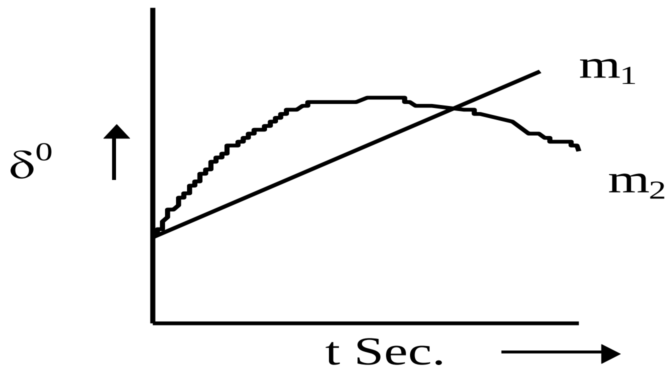
- Transient stability : Transmission line faults, sudden load change, loss of generation, line switching etc.

- Dynamic stability : Slow or gradual variations. Machine, governor-Turbine, Exciter modeling in detail.

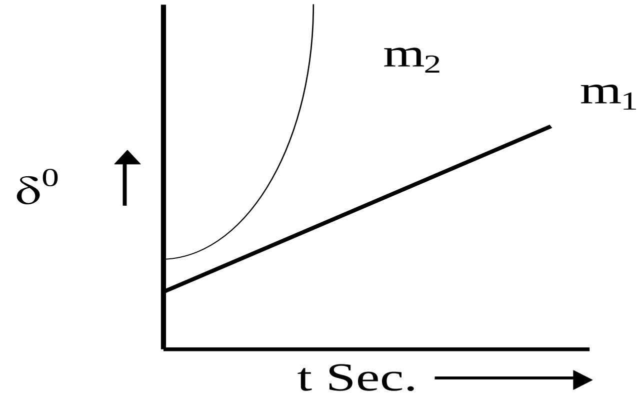
- Steady state stability : Changes in operating condition. Simple model of generator.

Transient Stability:

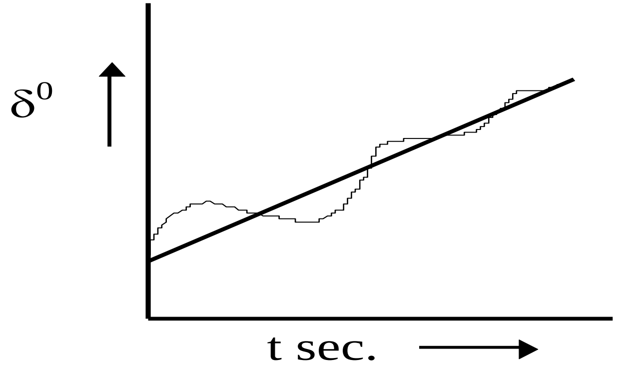
First swing stability problem
Multi-swing stability problem. (normal size)



Stable



Unstable



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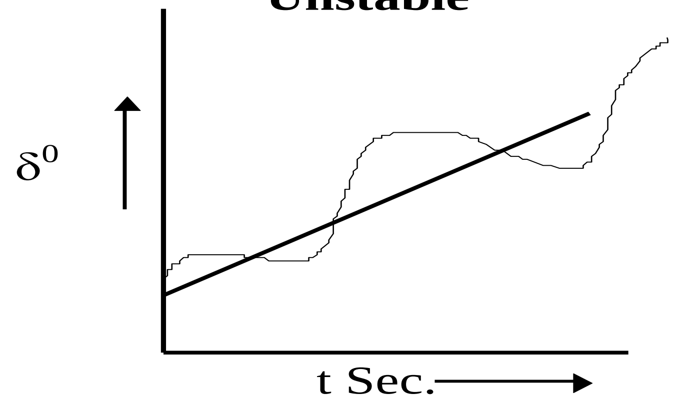

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Assumptions :

- Synchronous speed current and voltage are considered.
- DC off set currents, harmonics are neglected.
- Symmetrical components approach.
- Generated voltage is independent of machine speed.
- Circuit parameters are constant at nominal system frequency.(Frequency variation of parameter neglected).

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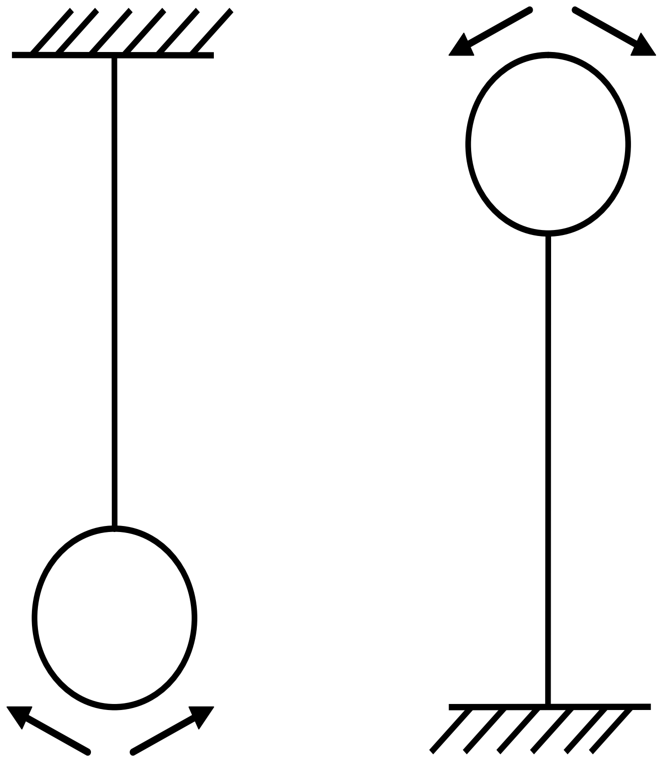
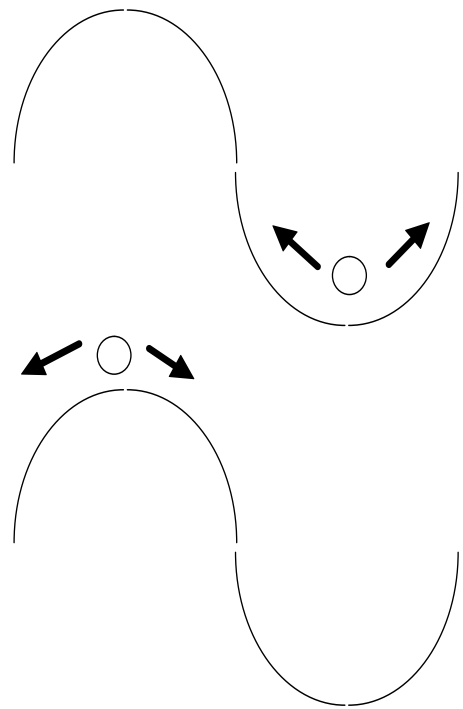
Steady State Stability



Stable Unstable



Stable

Unstable

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Mechanical Equation :

$$J * \frac{d^2\theta_m}{d\ t^2} = T_a = T_m - T_e \qquad N-m$$

J : Moment of inertia of rotor masses (kg-mt^2)

θ_m : Angular displacement of rotor w.r.t. a stationary axis (mechanical radians)

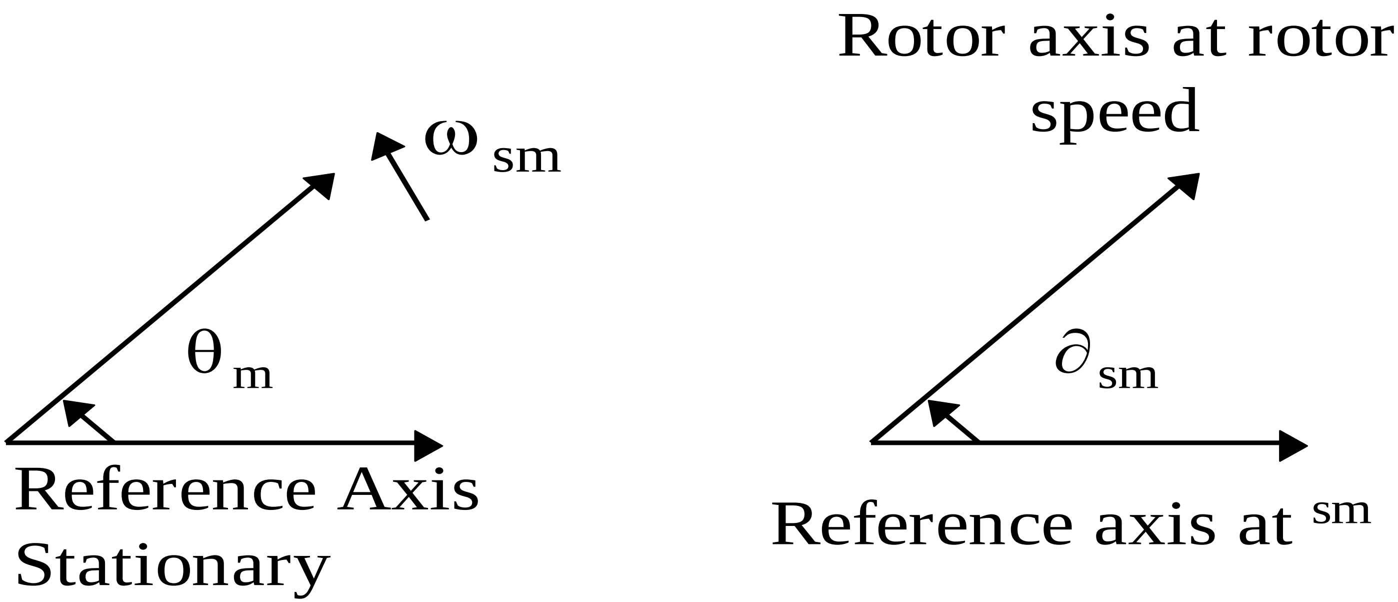
t : Time (seconds)

T_m : Mechanical or Shaft Torque (N-m)

T_e : Net electrical torque (N-m)

T_a : Net accelerating torque (N-m)

For generator, T_m and T_e are +ve.



δ_m : Angular displacement of the rotor in mechanical radians.

$$\theta_m = \omega_{sm} t + \delta_m$$

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$$\frac{d\theta_m}{dt}=\omega_{sm}+\frac{d\delta_m}{dt}$$

$$\frac{d^2\theta_m}{dt^2}=\frac{d^2\delta_m}{dt^2}$$

$$J\frac{d^2\delta_m}{dt^2}=T_m-T_e N-m$$

$$\omega_m=\frac{d\theta_m}{dt}\Rightarrow Angular velocity in radians per sec.$$

$$J\omega_m\frac{d^2\delta_m}{dt^2}=P_m-P_e watts$$

$$M\frac{d^2\delta_m}{dt^2}=P_m-P_e(Approx)$$

Where M : Inertia constant = at synchronous speed in Joules-sec per mechanical radian.

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Constant is defined as the ratio of stored Kinetic Energy in Mega Joules at synchronous speed and machine rating in MVA

$$H = \frac{\frac{1}{2} J \varpi_{sm}^{2}}{S} = \frac{\frac{1}{2} M \omega_{sm}}{S} MJ/MVA$$

$$M = \frac{2HS}{\omega_{sm}} MJ \; per \; mechanical \; radian$$

$$M \frac{d^2\delta_m}{dt^2} = P_m - P_e \, watts$$

$$\frac{2HS}{\varpi_{sm}} \frac{d^2\delta_m}{dt^2} = P_m - P_e$$

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$$\frac{2H}{\omega_{sm}}\frac{d^2\delta_m}{dt^2} = \frac{P_m - P_e}{S}$$

$$\frac{2H}{\omega_{sm}}\frac{d^2\delta_m}{dt^2} = P_m - P_e\, pu$$

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e$$

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$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2}=P_m - P_e\, pu\, Swing\, Equation$$

$$If\, \delta\, in\, electrical\, \deg rees$$

$$\frac{H}{180f}\frac{d^2\delta}{dt^2}=P_m - P_e\, pu$$

$$\frac{2H}{\omega_s}\frac{d\omega}{dt}=P_m - P_e \Rightarrow \frac{d\delta}{dt}=\omega - \omega_s$$

$$Let\, P_m - P_e = 1pu$$

$$\frac{2H}{\omega_s}\frac{d\omega}{dt}=1pu, \Delta\omega=\frac{\omega_s}{2H}\Delta t$$

$$If\, \Delta t=2H, \Delta\omega=\omega_s$$

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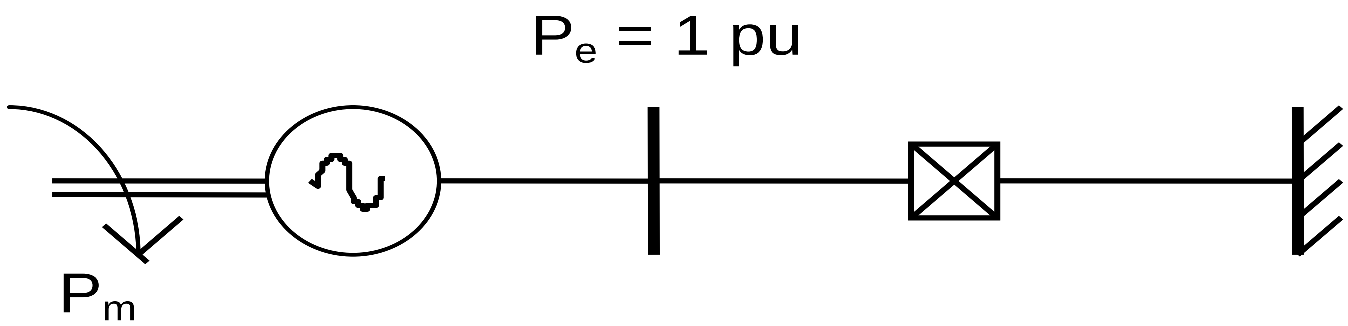

At t = 0, breaker is opened.
Initially Pe = 1 pu on machine rating Pm = 1pu and kept unchanged.

In 2H seconds, the speed doubles.

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$$H = \frac{Stored\,KE}{Machine\,Rating}$$

$$H_{mech} \times Machine\ Rating = H_{system} \times system\ MVA$$

$$\therefore H_{system} = H_{mech} \times \frac{Machine\ rating}{System\ MVA}$$

Inertia constant (H) is in the range 2 - 9 for various types of machines. Hence H-constant is usually defined for machine.

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Relation between H constant and Moment of Inertia is given by:

$$Moment\,of\,Inertia = \frac{WR^2}{32.2}\,lb - ft^2$$

$$W: Weight\,of\,rotational\,part\,in\,pounds$$

$$R: Radius\,of\,gyration\,in\,feet$$

$$KE = \frac{1}{2}\frac{WR^2}{32.2}\left[\frac{2\pi N}{60}\right]^2 ft - lb$$

$$550\,ft - lb/\sec = 746\,Watts$$

$$H = \frac{\frac{1}{2}\frac{WR^2}{32.2}\left[\frac{2\pi N}{60}\right]^2 \times \frac{746}{550} \times 10^{-6}}{S_{machine}}$$

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Example :

S_{mach} = 1333 MVA

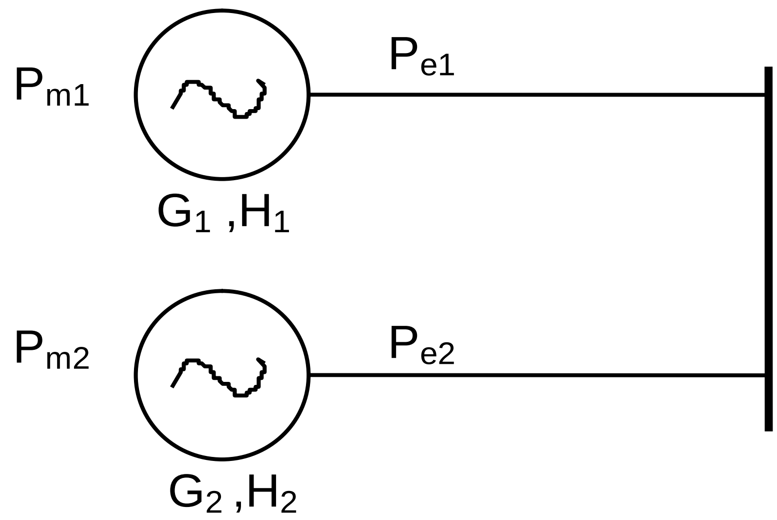
WR^2 = 5820000 lb - ft^2

N = 1800 RPM

$$H = \frac{\left[\frac{746}{550}\right] \times 10^{-6} \frac{1}{2} \times \frac{5820000}{32.2} \times \left[\frac{2\pi 1800}{60}\right]^2}{1333}$$

= 3.2677575 pu (MJ/ MVA)

On 100 MVA base : H = 1333 / 100 = 43.56 (MJ / MVA)



$$\frac{H_1}{f\pi}\times\frac{d^2\delta_1}{dt^2}=P_{m1}-P_{e1} \qquad \frac{H_2}{f\pi}\times\frac{d^2\delta_2}{dt^2}=P_{m2}-P_{e2}$$

$$\left[\frac{H_1+H_2}{f\pi}\right]\frac{d^2(\delta)}{dt^2}=\left(P_{m1}+P_{m2}\right)-\left(P_{e1}+P_{e2}\right)$$

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$\delta_1 = \delta_2 = \delta$; since the machines swing together

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = (P_m - Pe)$$

$H = H_1 + H_2$

$P_m = P_{m1} + P_{m2}$

$P_e = P_{e1} + P_{e2}$

G_1 and G_2 are called coherent machines.

Inertia Constant

$$\mathrm{H} = \frac{\text{Stored energy at rated speed in MWs}}{\text{MVA rating}}$$

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MKS System

$$Stored\ energy = Kinetic\ energy = \frac{1}{2}J[\omega_{om}]^2\ watts$$

$$= \frac{1}{2}J[\omega_{om}]^2 \times 10^{-6}\ MWs$$

$$J: Moment\ of\ inertia\ in\ kg\text{–}m^2$$

$$\omega_{om}: Rated\ speed\ in\ mechanical\ radian/\sec = \frac{2\pi}{60}RPM$$

$$\therefore H = \frac{\frac{1}{2}J\omega_{om}{}^2 \times 10^{-6}}{MVArating} = 5.48 \times 10^{-9}\left[\frac{J(RPM)^2}{MVArating}\right]$$

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British Units

Given

$$WR^2 = (Weight\ of\ rotating\ part) \times (square\ of\ radius\ of\ gyration)(lb - ft^2)$$

$$\therefore J = \frac{WR^2}{32.2} \times 1.356\ kg - m^2$$

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Example: MVA rating : 555 WR^2 : 654158 lb-ft^2

$$J = \frac{WR^2}{32.2} \times 1.356 = 27547.77168\, kg - mt^2$$

$$H = 5.48 \times 10^{-6} \frac{J(RPM)^2}{MVArating} = MWs / MVA$$

$$Stored\ energy$$

$$= H \times MVArating = MWs$$

$$Mechanical\ starting\ time$$

$$= 2H = \text{sec}$$

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Typical values

Unit Type	H Constant
Hydo unit	2 to 4
Thermal unit	
2 pole - 3600 RPM	2.5 to 6
4 pole - 1800 RPM	4 to 10

Non coherent machines

$$\frac{H_1}{\pi f}\frac{d^2\delta_1}{dt^2}=Pm_1-Pe_1$$

$$\frac{d^2\delta_1}{dt^2}=\frac{\pi f}{H_1}\left[P_{m1}-P_{e1}\right]$$

$$\frac{H_2}{\pi f}\frac{d^2\delta_2}{dt^2}=P_{m2}-P_{e2}$$

$$\frac{d^2\delta_2}{dt^2}=\frac{\pi f}{H_2}\left[P_{m2}-P_{e2}\right]$$

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$$\frac{d^2}{dt^2}(\delta_1-\delta_2)=\frac{\pi f}{H_1}(P_{m1}-P_{e1})-\frac{\pi f}{H_2}(P_{m2}-P_{e2})$$

$$\frac{1}{\pi f}\frac{d^2(\delta_1-\delta_2)}{dt^2}=\frac{H_2(P_{m1}-P_{e1})-(P_{m2}-P_{e2})H_1}{H_1H_2}$$

$$\frac{H_1H_2}{H_1+H_2}\times\frac{1}{\pi f}\frac{d^2(\delta_1-\delta_2)}{dt^2}=\frac{H_2}{H_1+H_2}(P_{m1}-P_{e1})-\frac{H_1}{H_1+H_2}(P_{m2}-P_{e2})$$

$$\frac{H_1H_2}{H_1+H_2}\times\frac{1}{\pi f}\times\frac{d^2(\delta_1-\delta_2)}{dt^2}=\frac{H_2P_{m1}-H_1P_{m2}}{H_1+H_2}-\frac{H_2P_{e1}-H_1P_{e2}}{H_1+H_2}$$

$$\frac{H}{\pi f}\times\frac{d^2\delta_{12}}{dt^2}=P_{m12}-P_{e12}$$

Where,

$$H=\frac{H_1H_2}{H_1+H_2}\quad P_{m12}=\frac{H_2P_{m1}-H_1P_{m2}}{H_1+H_2}$$

$$P_{e12}=\frac{H_2P_{e1}-H_1P_{e2}}{H_1+H_2}$$

Relative swing (with reference to one machine) is more important, rather than absolute swing.

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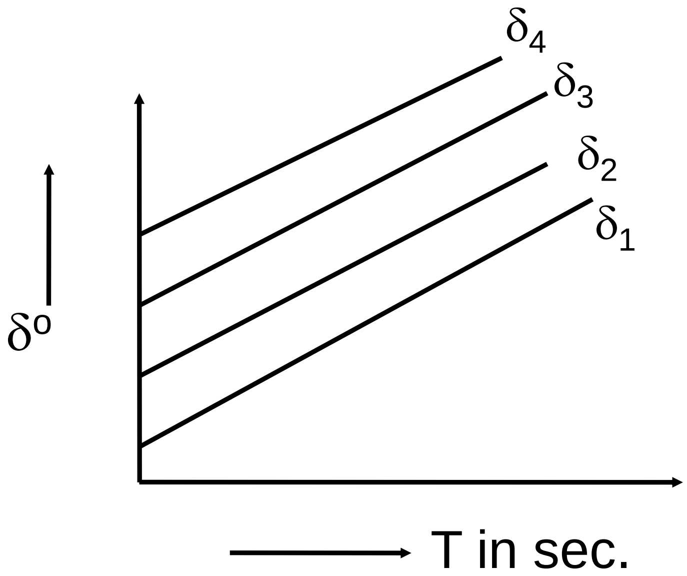
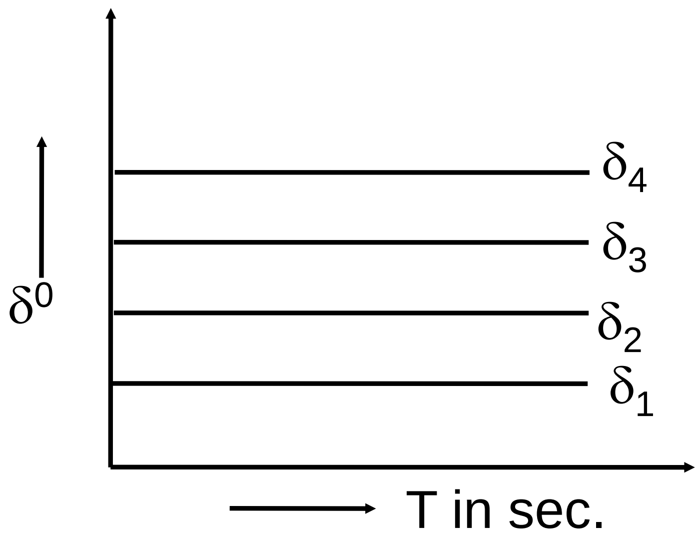
Swing Curves



Absolute Plot



Relative Plot (δ_i-δ)

Relative swing (with reference to one machine) is more important, rather than absolute swing.

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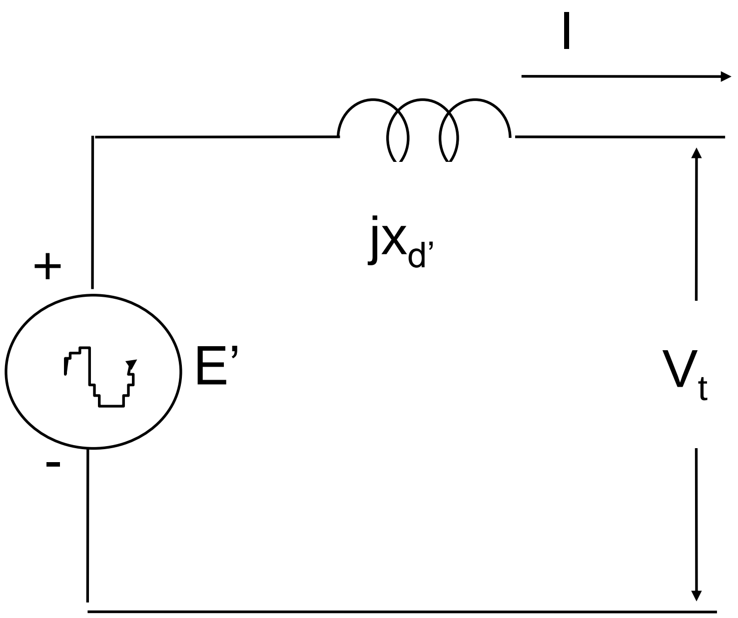
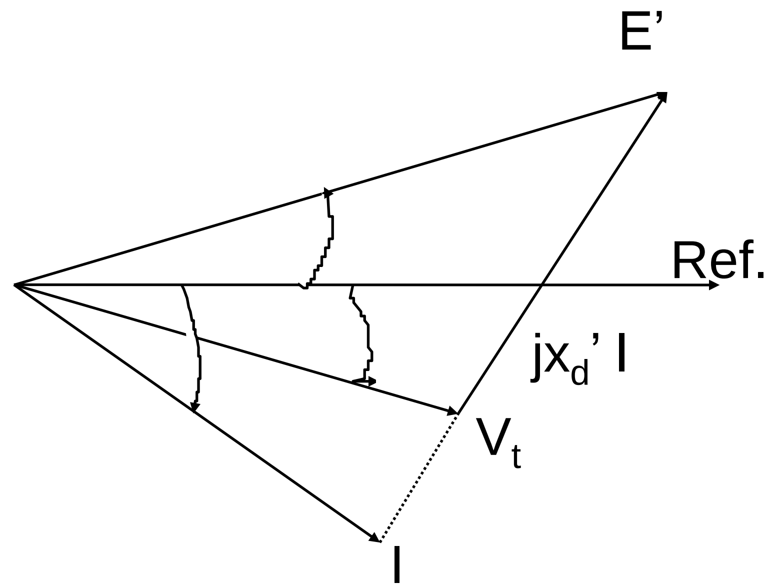
Classical model : (Type 1)
Constant voltage behind transient reactance.





$$E' = V_t + (0 + jx_d')\,I$$

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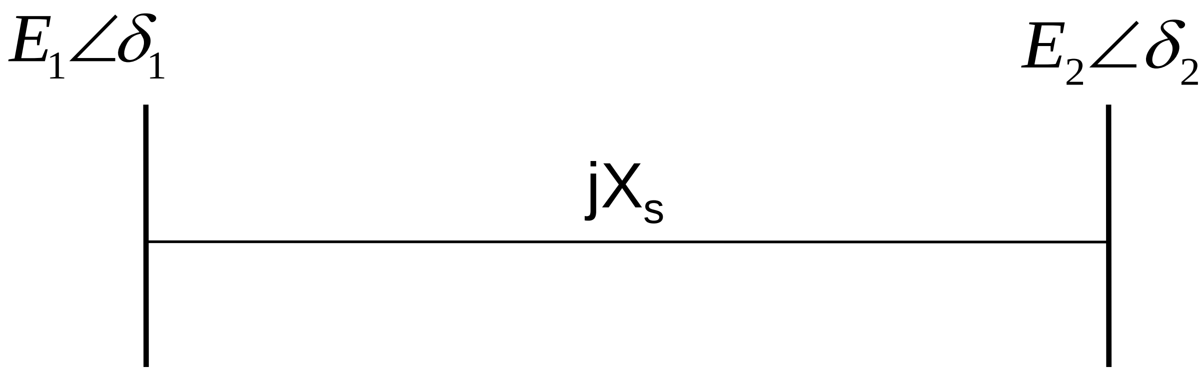
Power angle equation jX_s



$$P = \frac{E_1 E_2}{X_s}\sin\delta$$

E_1 : Magnitude of voltage at bus1

E_2 : Magnitude of voltage at bus2

δ : δ_1 - δ_2

X_s : Reactance

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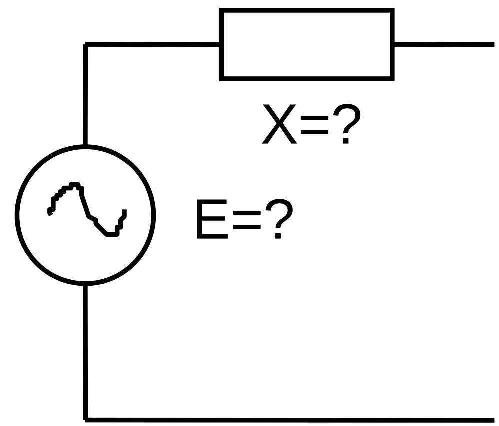
Machine Parameters

Synchronous : Steady state, sustained.

Transient : Slowly decaying

Sub-transient : Rapidly decaying



$$X_d \geq X_q \geq X_q' > X_q'' \geq X_d''$$

$$T_{d0}' > T_{do}''$$

$$T_{qo}' > T_{qo}''$$

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Typical values

Parameter	Hydro (pu)	Thermal (pu)
x_d	0.6 - 1.5	1.0 - 2.3
x_q	0.4 - 1.0	1.0 - 2.3
x_d'	0.2 - 0.5	0.15 - 0.4
x_q'	--------	0.3 - 1.0
x_d''	0.15 - 0.35	0.12 -0.25
x_q''	0.2 - 0.45	0.12 -0.25
T_{d0}'	1.5 - 9.0 s	3.0 -10.0 s
T_{q0}'	--------	0.5 - 2.0 s
T_{d0}''	0.01 - 0.05 s	0.02 - 0.05 s
T_{q0}''	0.01 - 0.09 s	0.02 - 0.05 s
R_a	0.002 - 0.02	0.0015 - 0.005

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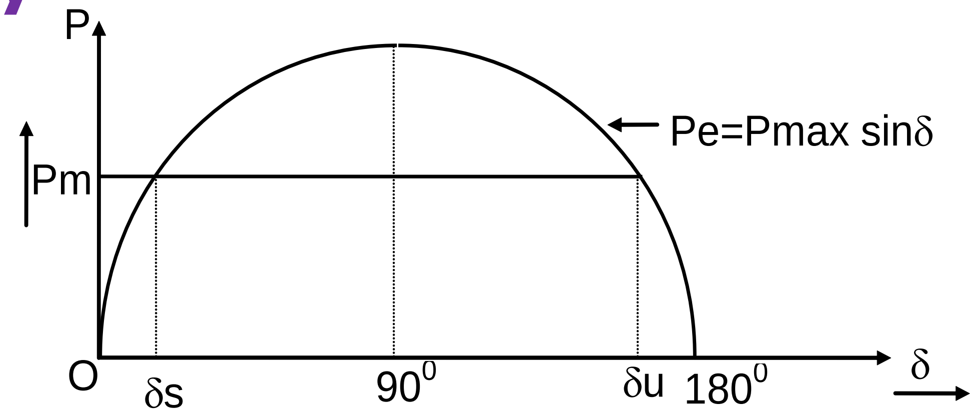
Stability



Stable

- At δ_s ; $P_m = P_e$; net accelerating torque = 0.
- Let P_e decrease slightly.
- $$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_m - P_e \, is + ve$$

δ increase (acceleration)

δ comes back to original position.

- Stable region . Hence δ_s is stable operating point.

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Unstable

- At δ_u; Pm = Pe ; Net accelerating torque = 0
- Let P_e decrease slightly.
- $$\frac{H}{\pi f}\frac{d^2\delta}{dt^2}=P_m-P_e is+ve$$

δ increases, (acceleration)

- P_e further decreases.
- Chain reaction $\rightarrow \delta$ never comes back to

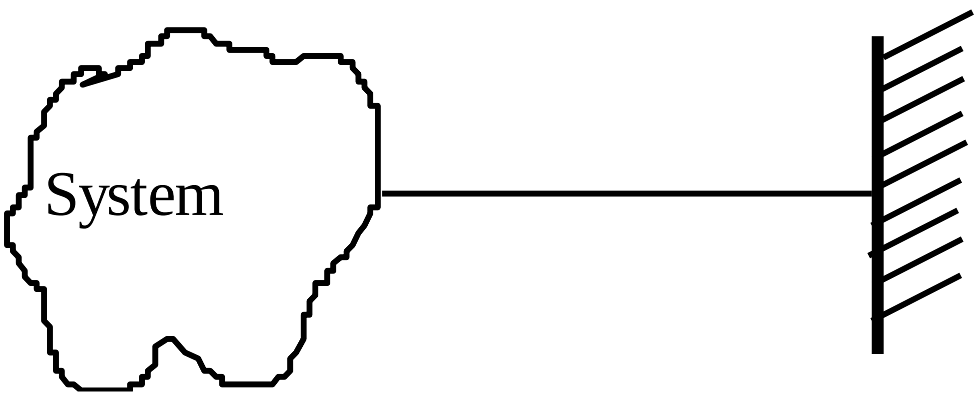
normal value .

Hence δ_u is unstable operating point.

Infinite bus

Generator connected to infinite bus.

- High inertia. H >> compared to other machines in the system.
- Frequency is constant.
- Low impedance. X_d' is very small.
- E′ is constant and V_t is fixed.
- Infinite fault level symbol.



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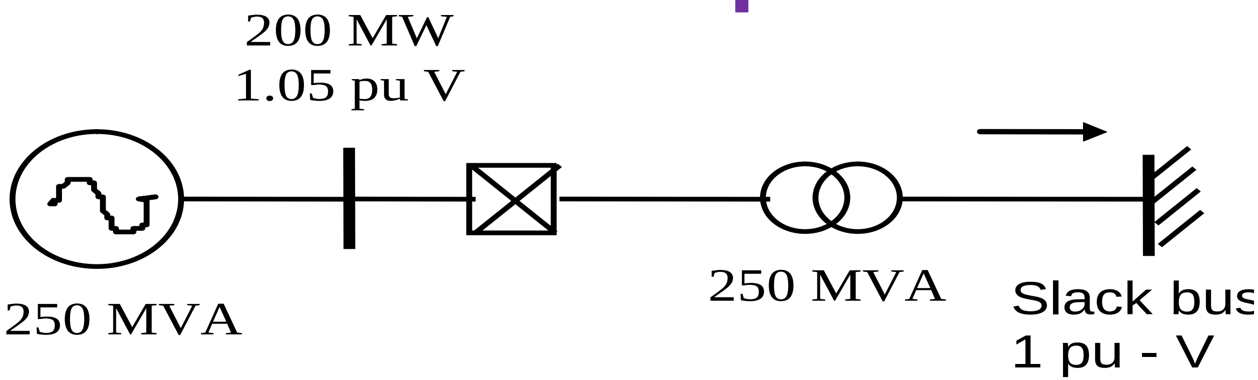
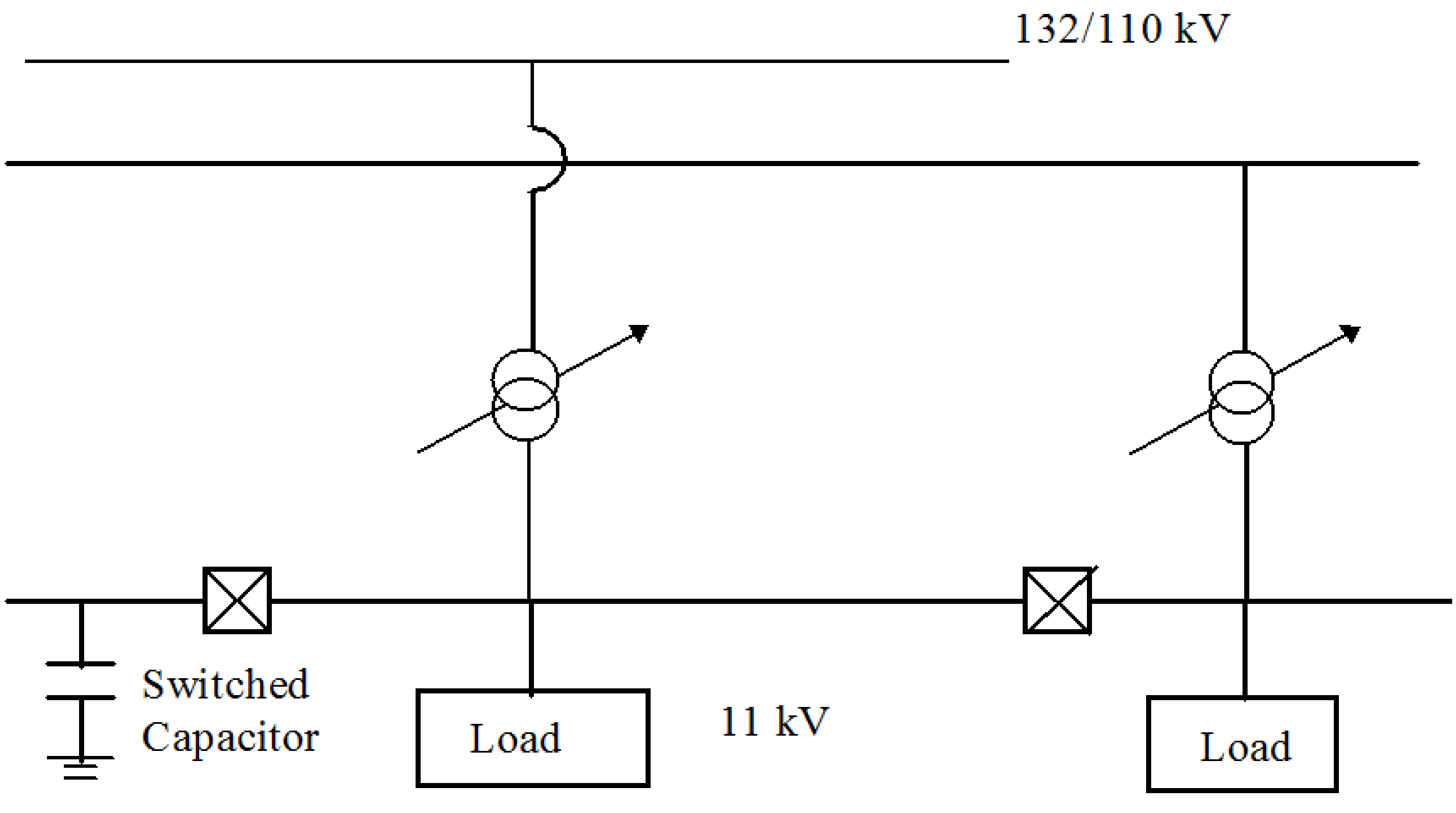
Example :



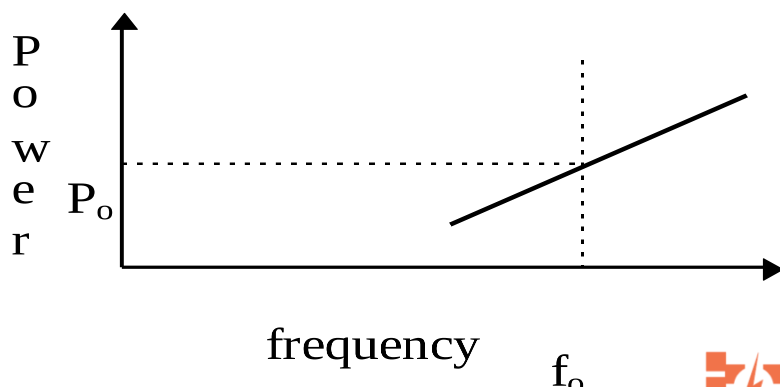
H = 3.2 , Z = 10% on own rating , X_d^1 = 25% , tap = 1, R_a = 0.0 and neglect R.

1. Establish the initial condition.
2. Perform the transient stability without disturbance.
3. Open the transformer as outage & do the study.
4. How long the breaker can be kept open before closing, without loosing synchronism.

Load Modeling



- Vary the tap.
- Switch on the capacitor.
- Determine the response (charge) in load.
- Compute the parameters. $P = P_0 \left(C_P + C_I \cdot V + C_Z \cdot V^2\right)\left(1+K_f \cdot f\right)$
- P varies with time, voltage and frequency.
- P_0 varies with time - can be constant at a given time of a day.
- C_P, C_I, C_Z & K_f are constants.
- V & f are known at any time instant.
- P is known from measurements.
- Solve the non linear problem over a set of measurements.



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Let the load be 10,000 MW. i.e. P_0 = 10,000

Let for 1 Hz change in frequency, let the load change be 700 MW.

$$P_o \times \Delta f \times C_f^{\,p} = -700 (decrease\ in\ load)$$

$$P_o (f - f_o) \times C_f^{\,p} = \frac{-700}{-1} = 700\, power\ number$$

$$C_f^{\,p} = \frac{700}{10{,}000} \Rightarrow 7\%$$

$$If\, P is in\, pu; \Delta f\, is the\, per unit change in\, frequency$$

$$then on 100 MVA base:$$

$$C_f^{\,p} = \frac{7/100}{1/50} = 3.5$$

What it implies :

- Initial load 10,000 MW.
- Loss of generation 700 MW
- Increase in load 700 MW
- Frequency 49 Hz.

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Load Model Parameters

Load model paraters

Measurement based approach
Input: Connected load
Measurement: P,V, f over a period
Out put: Parameters

Component based approach
Industrial
Commercial
residential
Agricultural

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Component	pf	∂P/∂V	∂Q/∂V	∂P/∂f	∂Q/∂f
Air conditioner 3 p central heating	0.90	0.088	2.5	0.98	-1.3
Arc furnace	0.7	2.3	1.6	-1.0	-1.0
Industrial Motors	0.88	0.07	0.5	2.5	1.2
Agricultural pumps	0.85	1.4	1.4	5.0	4.0
Residential					
Summer	0.9	1.2	2.9	0.8	-2.2
winter	0.99	1.5	3.2	1.0	-1.5
Commercial					
summer	0.85	0.99	3.5	1.2	-1.6
winter	0.9	1.3	3.1	1.5	-1.1
Industrial	0.85	0.18	6.0	2.6	1.6
Power plant	0.8	0.1	1.6	2.9	1.8

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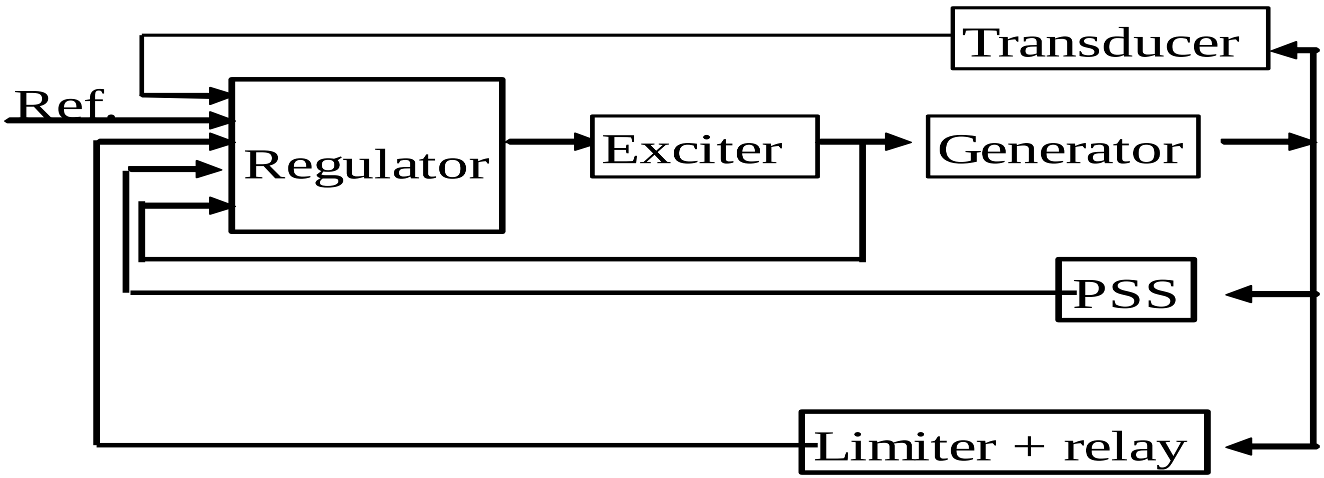
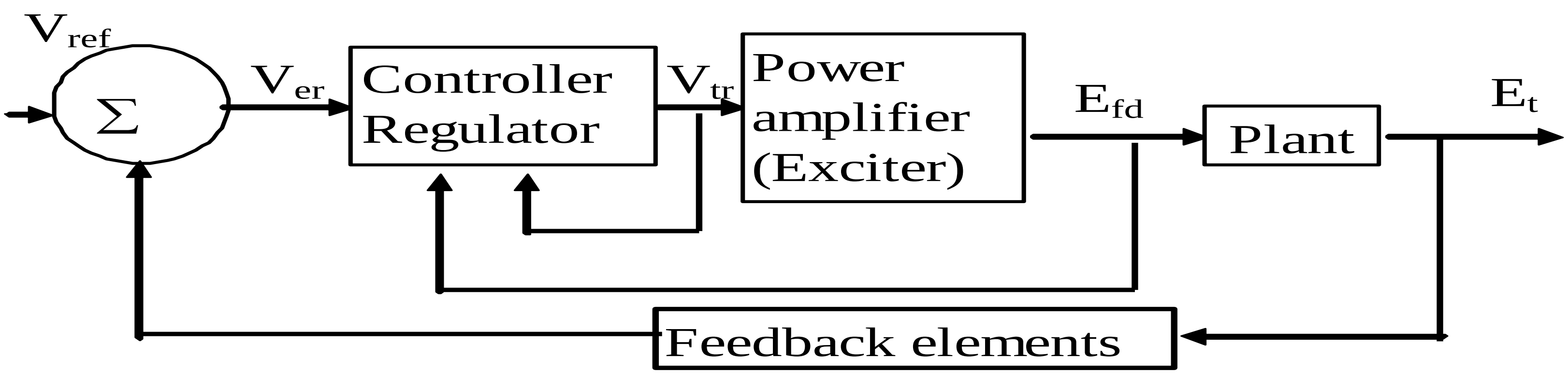
Excitation System Components





Block Schematic

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Reactive Power Control

- Synchronous generators
- Overhead lines / Under ground cables
- Transformers
- Loads
- Compensating devices

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Control Devices:

- Sources /Sinks --- Shunt capacitor, Shunt inductor (Reactor), Synchronous condenser, and SVC.
- Line reactance compensation --- Series capacitor
- Transformer -----OLTC, boosters

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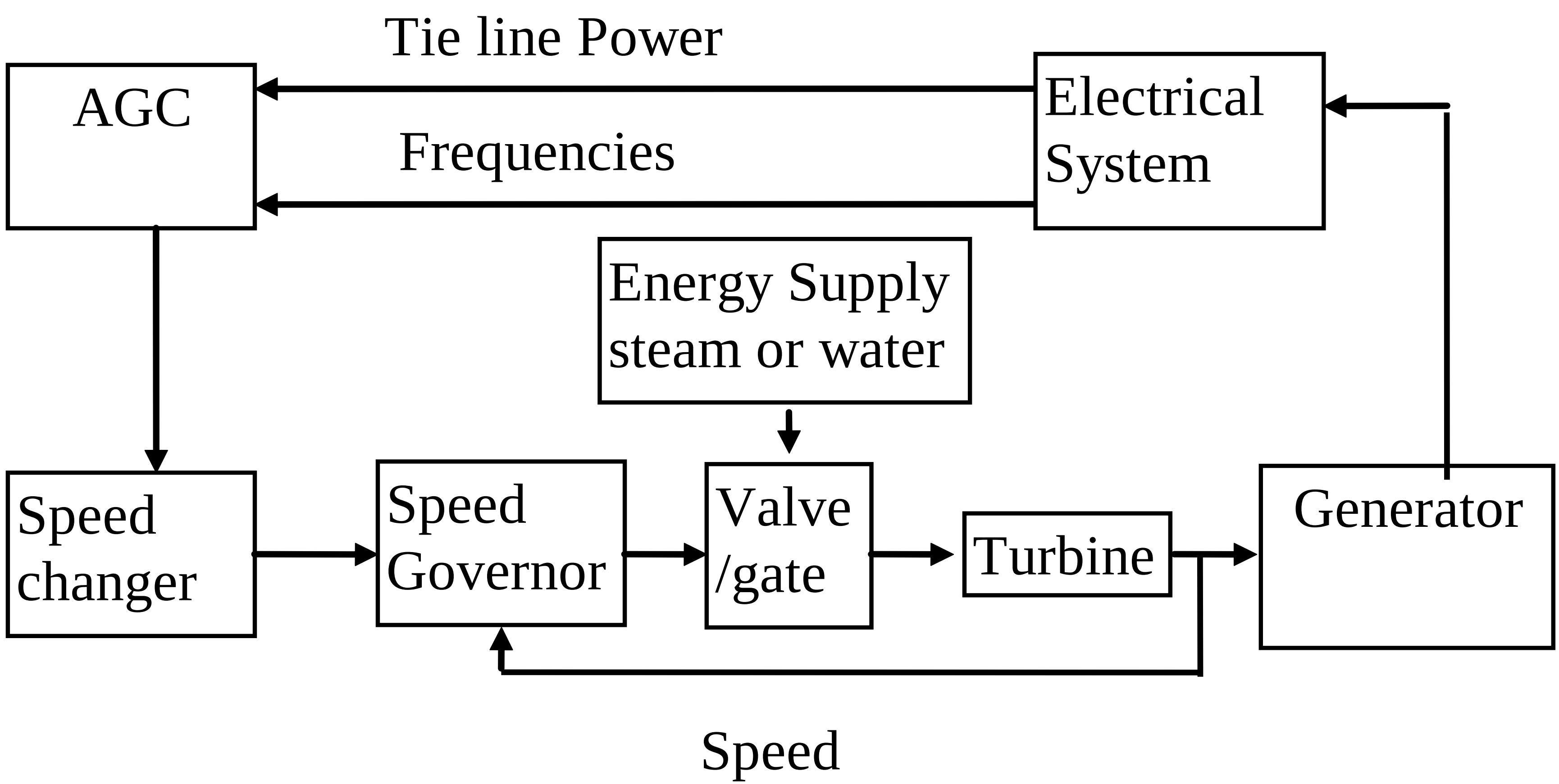
Speed Governor Systems :



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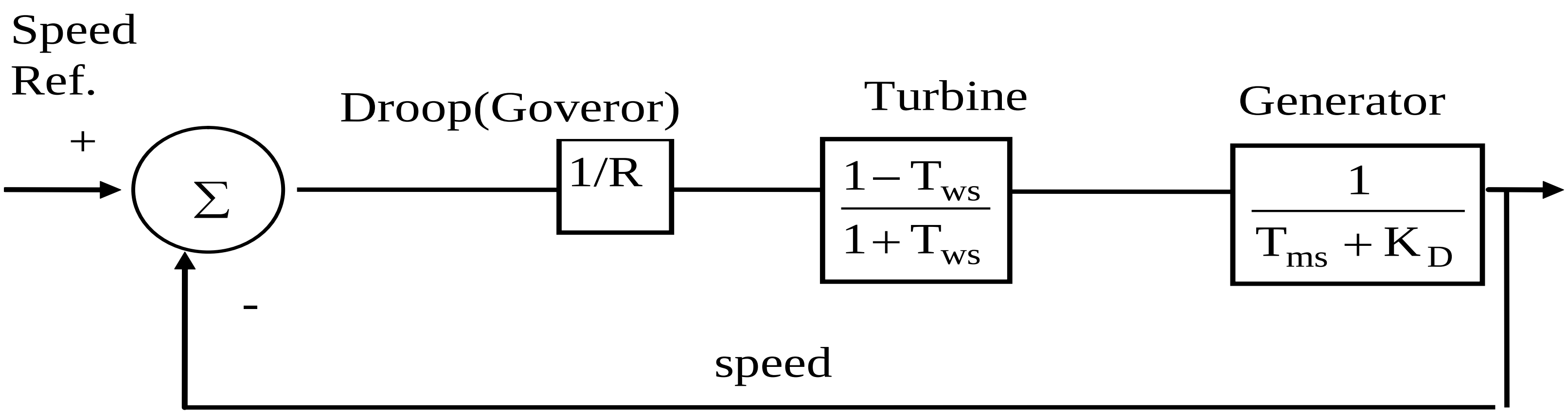
Types of Control:

- Primary Control : Governor action
- Secondary Control : AGC, load frequency control (For selected generators)



Under Frequency operation:

- Vibratory stress on the long low pressure turbine blades
- Degradation in the performance of plant auxiliaries say, induction motor.

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Limitations:

- Only maximum spinning reserve can be achieved
- Turbine pickup delay
- Boiler slow dynamics
- Speed governor delay

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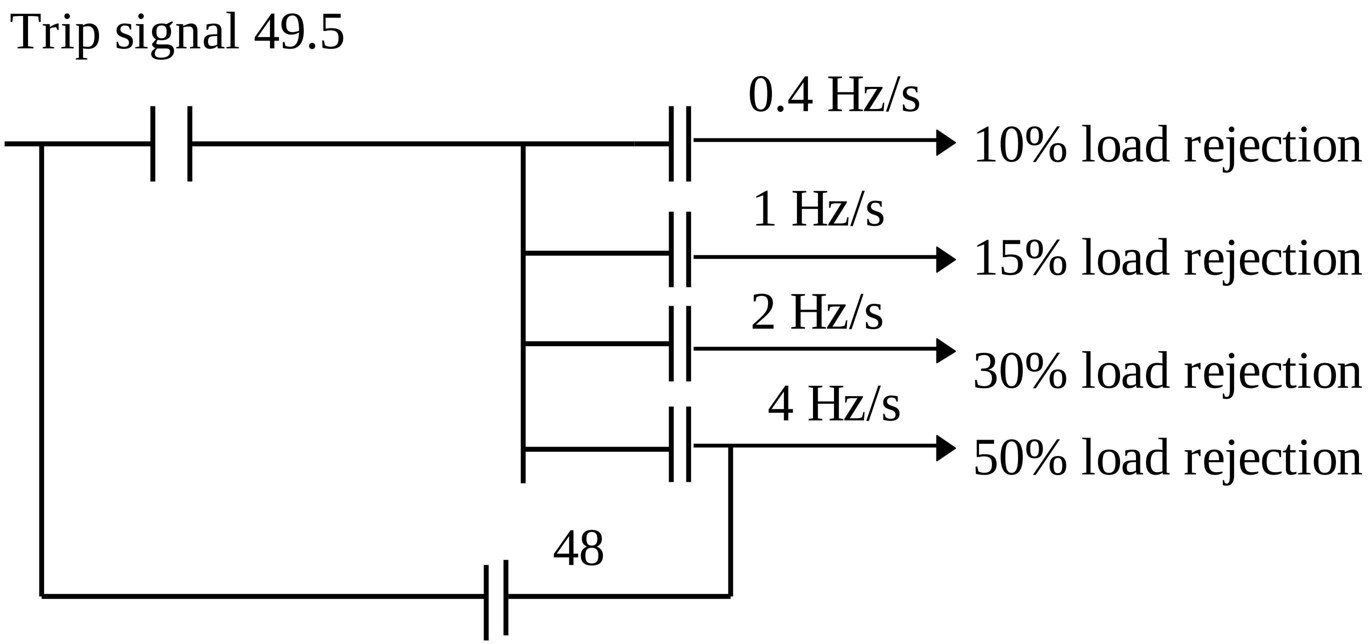
Load Shedding:



Other measures:

* Fast valving
* Steam by-passing

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Modules in a Program:

1. Data reading
2. Initialization
   - Steady state load flow
   - Control block parameter AVR, Gov., Machine, Motor, PSS, VDC, SVC.
3. Disturbance model
4. Control block modeling
5. Machine modeling
6. Load flow solution
7. Protective relay modeling
8. Special functions
   - Cyclic load
   - Arc furnace
   - Re-closure
9. Results output
   - Report
   - Graph

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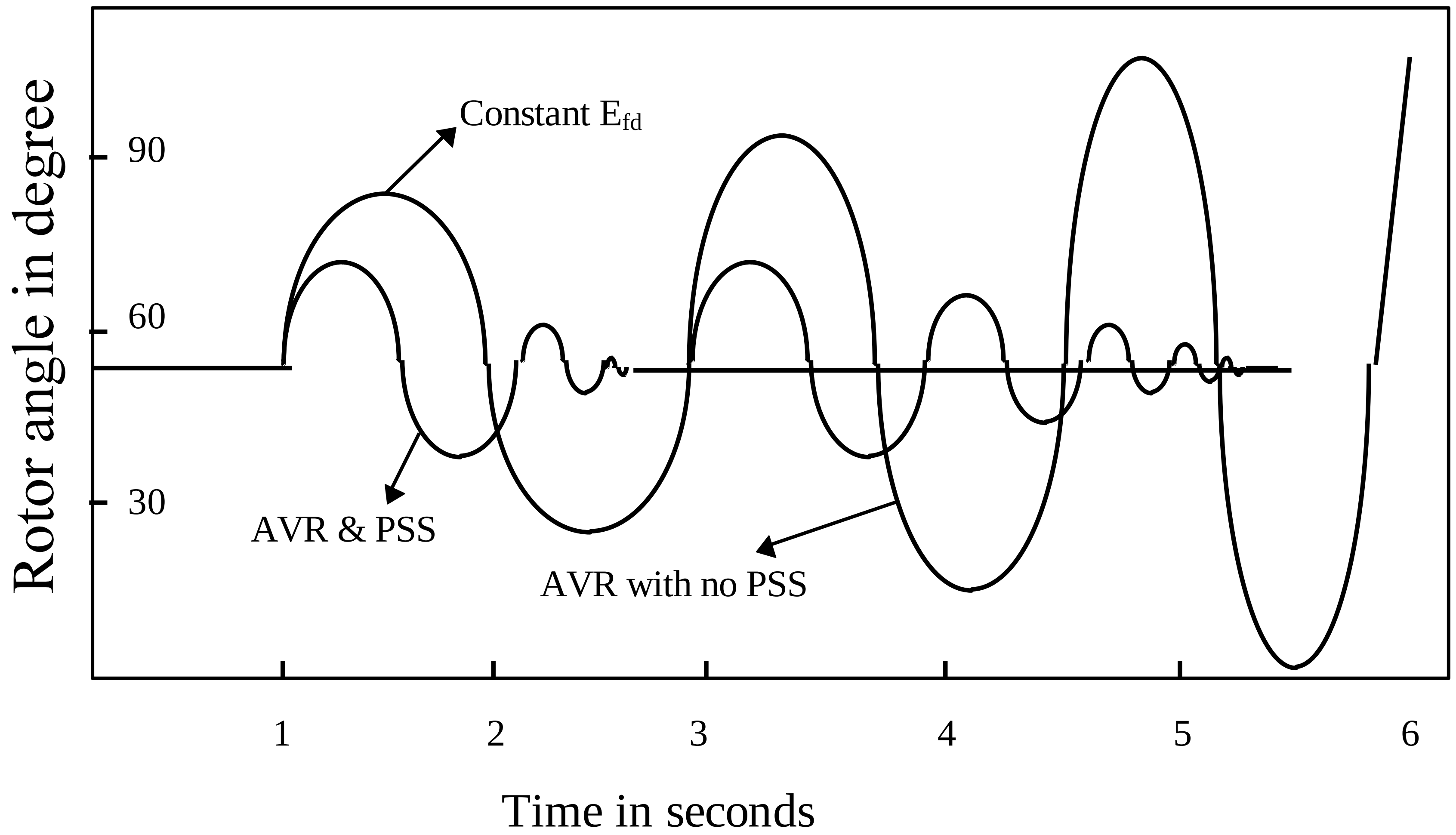
Typical Swing Curve :



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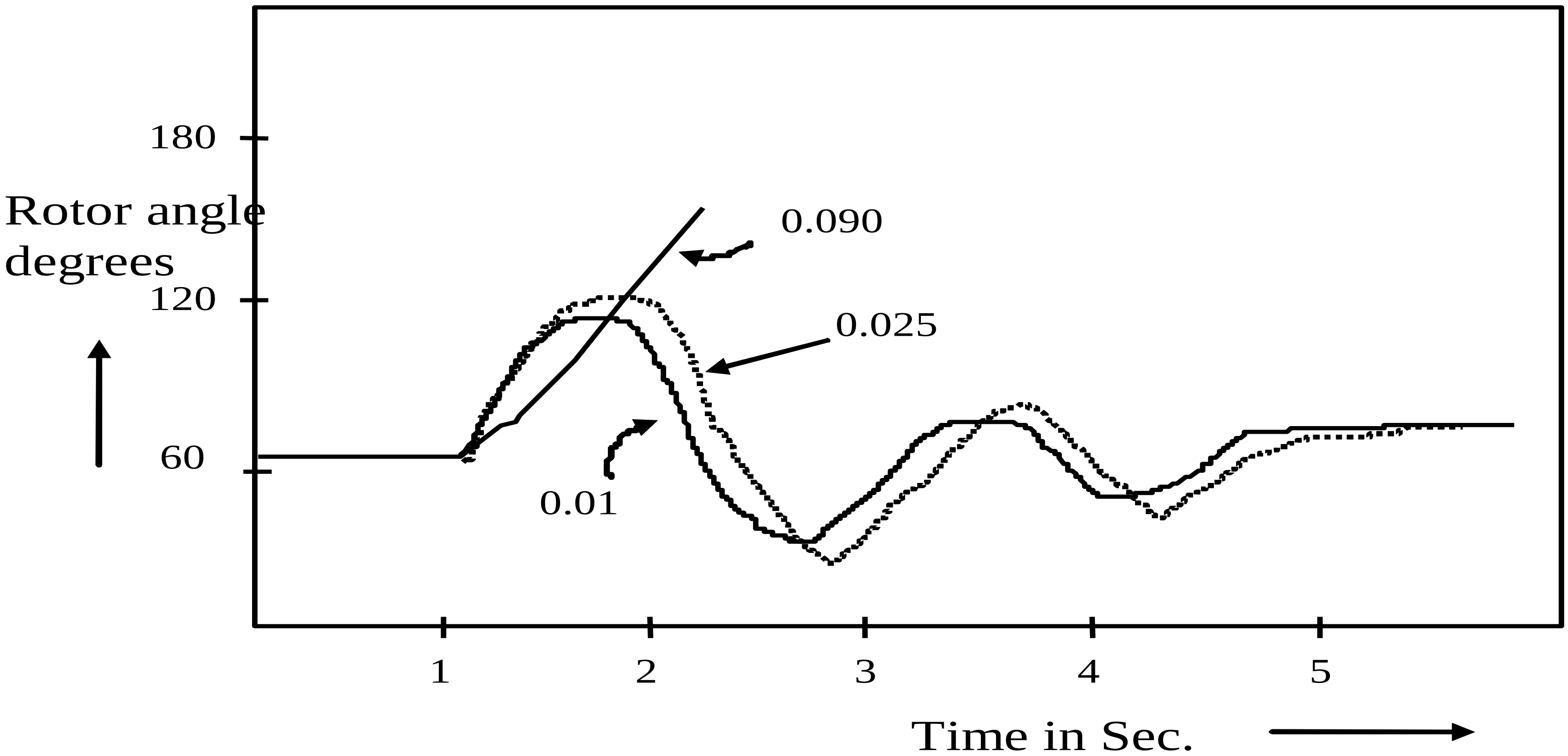
Typical Swing Curve :



Integration step size : Typical value : 0.01 seconds, Range : 0.005 to 0.02 seconds

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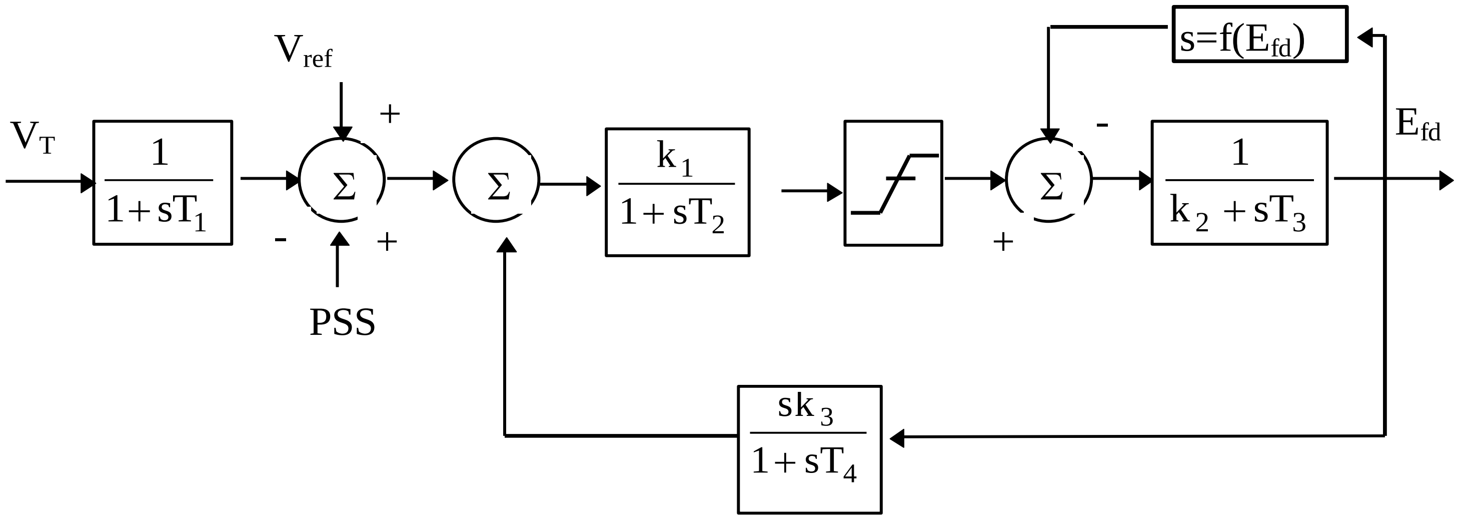
AVR : Type 1



Mapping		Range
T_1	T_r	0.01 -- 0.10
T_2	T_a	0.025 -- 0.2
T_3	T_E	0.5 -- 1.0
T_4	T_{F1}	0.5 -- 1.0
K_1	K_A	25 -- 200
K_2	K_E	-0.5 -- 1.0
K_3	K_F	0.01 -- 0.1

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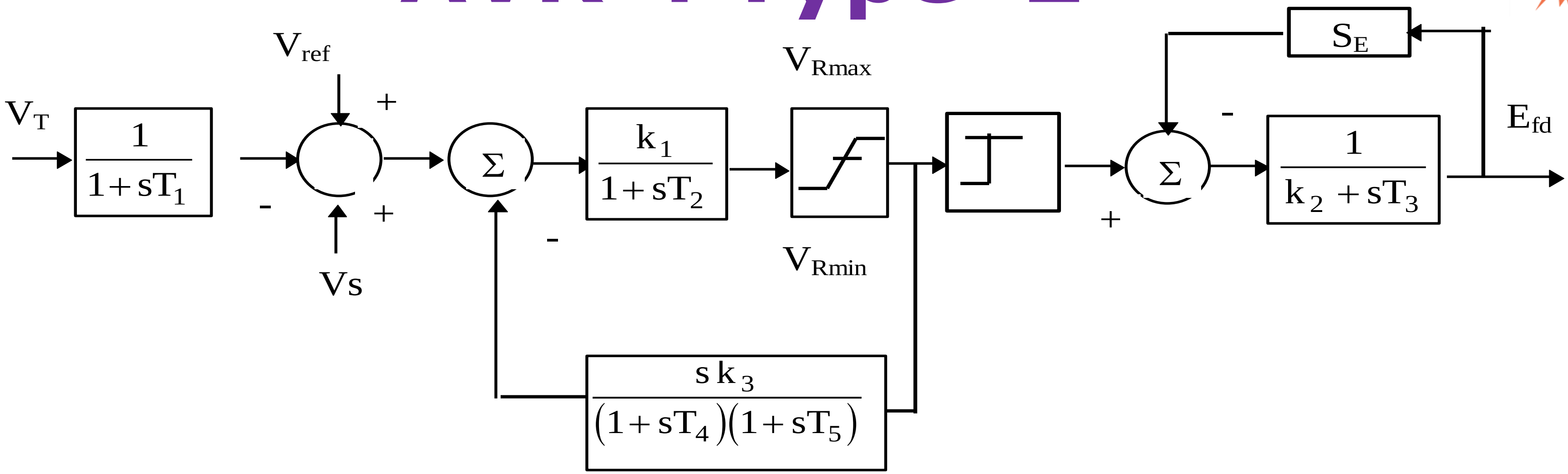
AVR : Type 2



Mapping		Range
T_1	T_R	0.01 --- 0.05
T_2	T_A	0.01 --- 0.05
T_3	T_E	0.5 --- 1.0
T_4	T_{F1}	$\cong$ 1.0
T_5	T_{F2}	$\cong$ 0.1
k_1	K_A	50--200-400-600
k_2	K_E	$\cong$ 1.0
k_3	K_f	0.01 - 0.05

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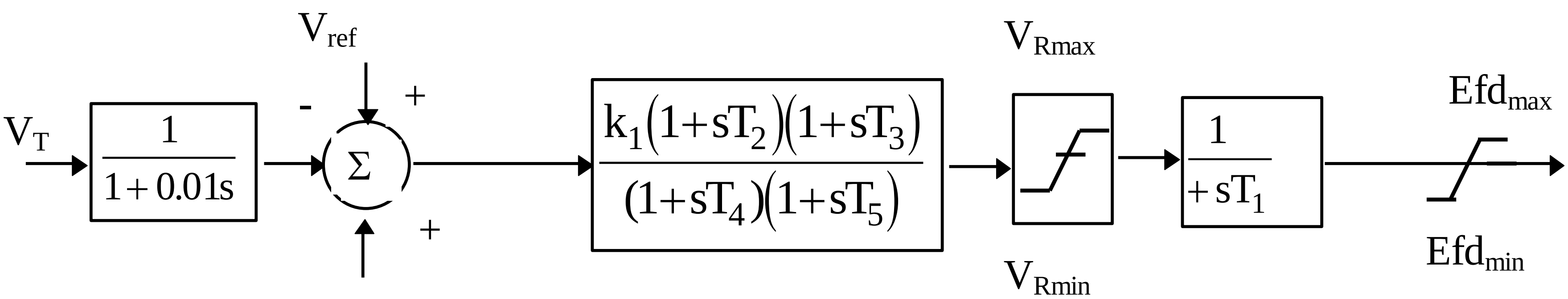
AVR TYPE – 5



Mapping		Range
0.01	Tr	0.01 -- 0.025
T_1	Ts	0.025
T_2	T_E	≅ 1.0
T_3	T_{F1}	≅ 0.06
T_4	T_A	40.0
T_5	T_{F2}	≅ 0.024
k_1	k_A	≅ 200.0

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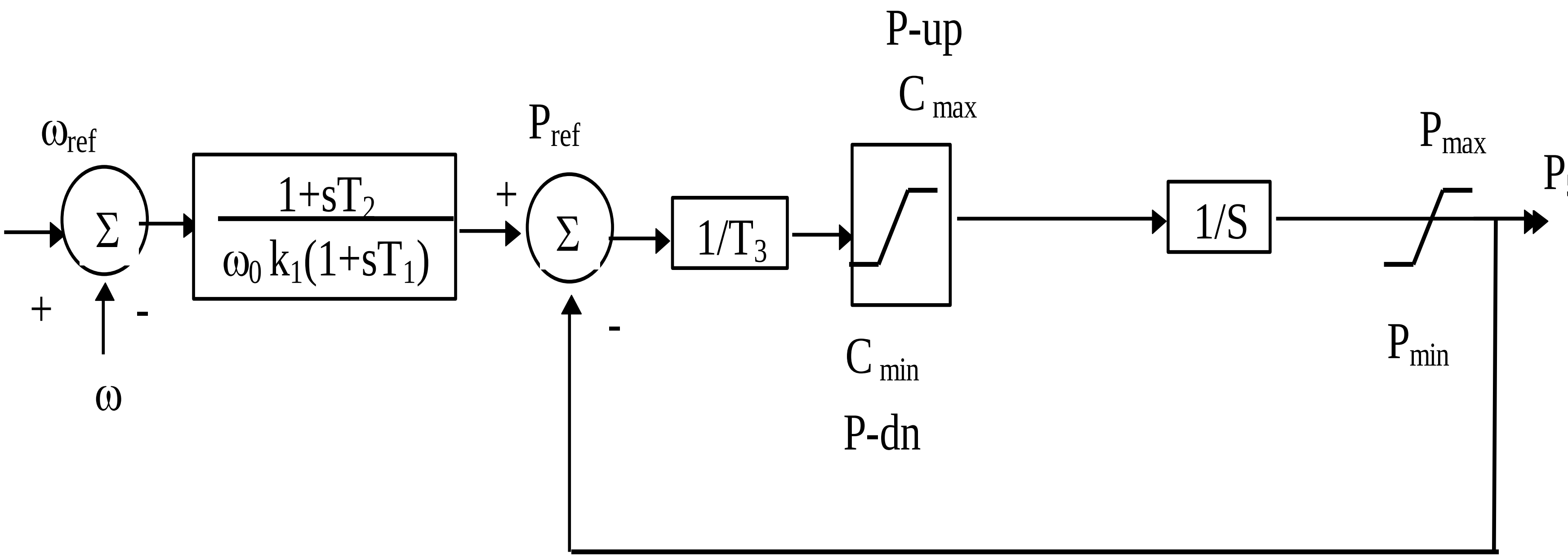
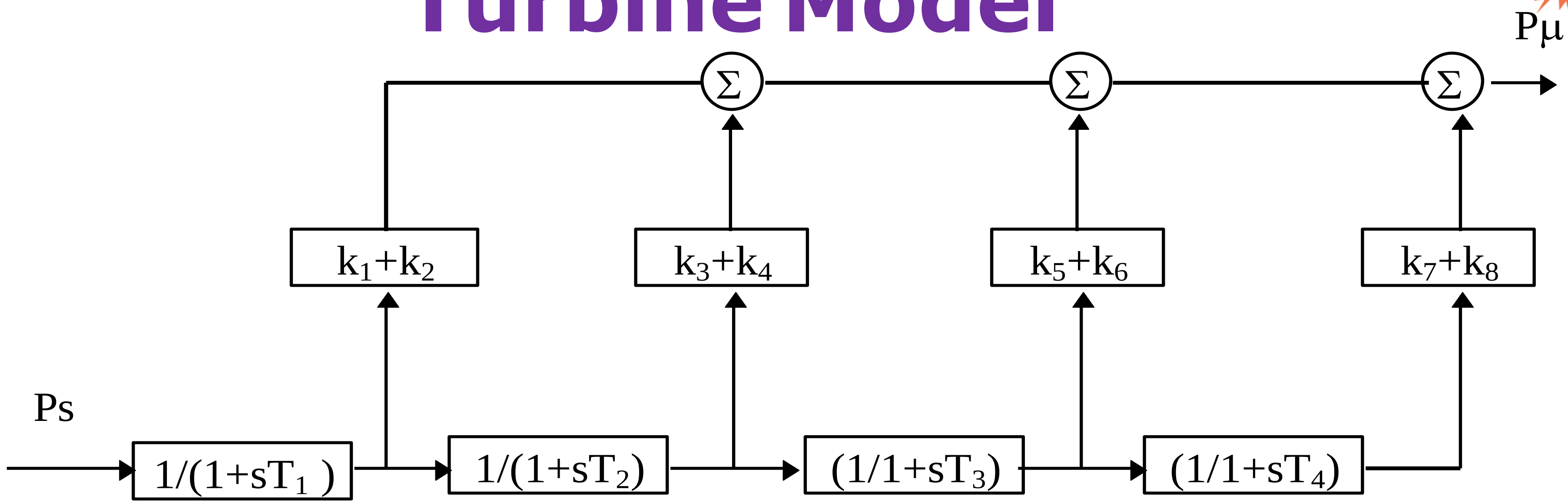
Steam Turbine Governing System



K_1 : 0.05 - 0.04	P_{max} : 1.0
T_1 : 0.1	P_{min} : 0.0
T_2 : 0.03	P_{up} : 0.1
T_3 : 0.4	P_{dn} : -1.0

Turbine Model



T_1 : 0.26	k_1 : 0.2760	$k_1 + k_2$: VHP
T_2 : 10.0	k_3 : 0.324	$k_3 + k_4$: HP
T_3 : 0.5	k_5 : 0.4	$k_5 + k_6$: IP
T_4 : 99.9	k_7 : 0.0	$k_7 + k_8$: LP

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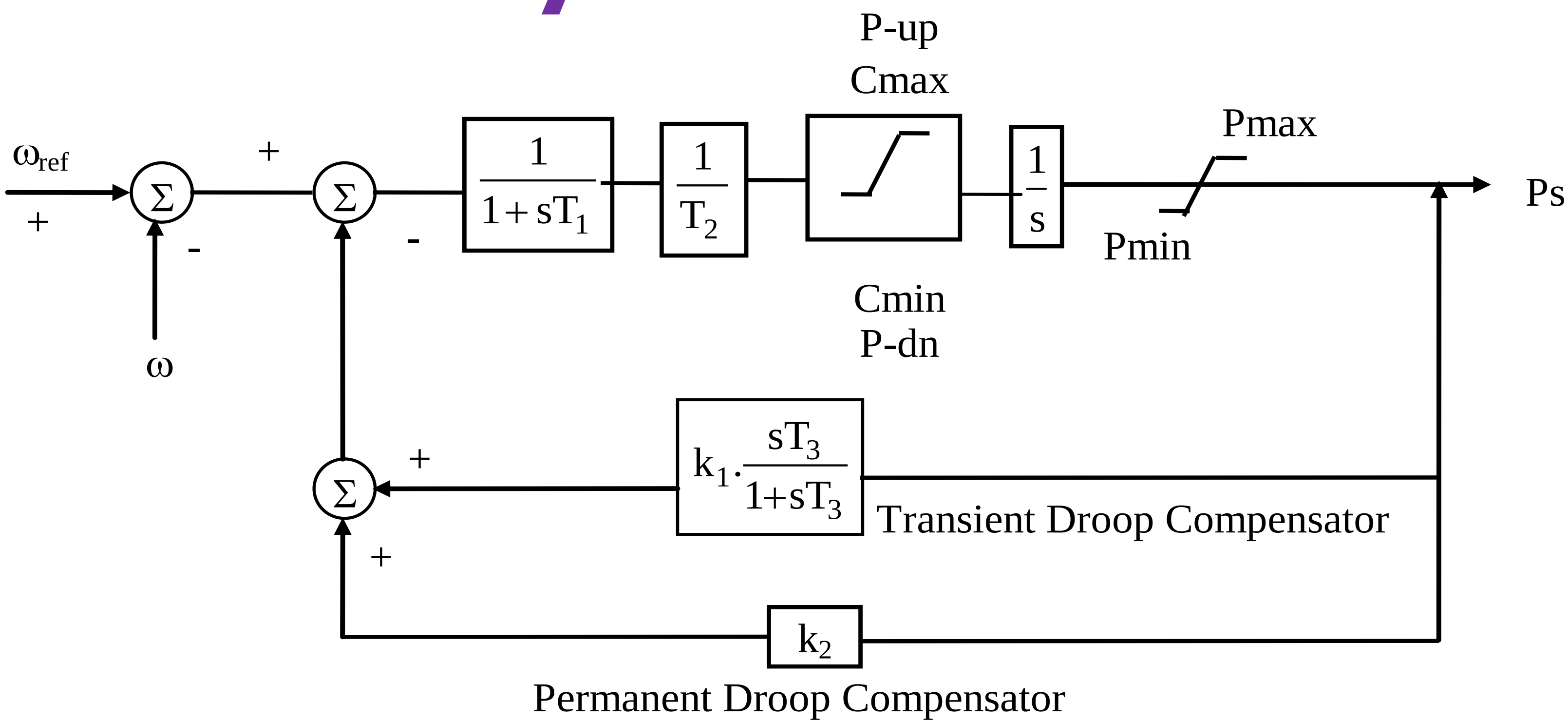
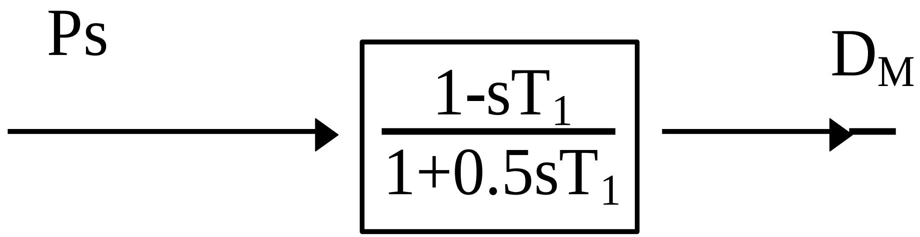
Hydro Governor



k_1 : 0.36	P_{max} : 1.1	T_2 : 0.2
k_2 : 0.04	P_{min} : 0.0	T_3 : 5.0
T_1 : 0.05	P_{up} : 0.1	P_{down} : -1.0

Hydro Turbine



T_1 (Tω) : 1.0

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Transient Stability Enhancement

Philosophy :

1. Minimize the disturbance influence by minimizing the fault severity and duration.
2. Increase the restoring synchronizing forces.
3. Reduce accelerating torque.

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Transient Stability Enhancement

Methods :

1. High speed fault clearing.
2. Reduction of transmission system reactance.
3. Regulated shunt compensation.
4. Dynamic Braking.
5. Reactor switching.
6. Independent pole operation of circuit breaker.
7. Single pole switching
8. Fast valaving.
9. Generator tripping.
10. Controlled system separation and load shedding.
11. High speed excitation systems.
12. HVDC transmission link control.

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Major references used in the development of Transient Stability Studies Module

1. Dommel, N. Sato "Fast Transient Stability Solutions", IEEE Transactions on Power Apparatus and Systems, 1972, PP 1643 - 1650.
2. W. Dommel, "Digital computer solution of electromagnetic transients in single and multiphase networks", IEEE Transactions on Power Apparatus and Systems, April 1969, Vol. PAS-88, PP 388 - 399.
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Queries & Discussions

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Thank You

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Introduction to Power System Protection

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Topics for Discussion

- Protective relaying
- Need for protection
- Types of Protection
- General Philosophy
- Over-Current Relays
- Distance Relays

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Introduction

Protective Relaying

- Safeguard equipment from damage during abnormal operating conditions.

- Protective Relaying should:
  - ✓ Ensure normal operation
  - ✓ Prevent equipment failure
  - ✓ Limit the effects of disturbances

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Need for Protection

- Loss of equipment (Permanent or Partial damage)
- Loss of production
- Revenue loss
- Fire hazard, loss of life
- Loss of confidence level in using electricity as a commodity

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Functions of Protection

- Primary function - Prompt removal of faulty element suffering a short circuit, or when it starts to operates in an abnormal manner
- Secondary function, to provide indication of location and type of failure

Types of Protection

- Over voltage protection – Lightning/Surge arrestors, Insulation co-ordination
- Fault protection (over loading/current) - Application of Relays
- Protection for human (safety) – Earthing and Earth mats, clearances, insulation

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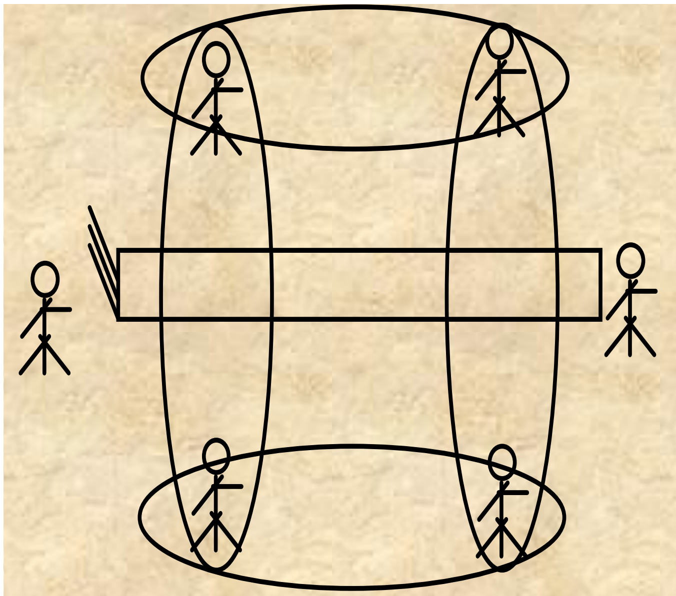
Protection Philosophy



Cricket	Protection
Position the fielders	Designs the system and sets the relays
Delivers the ball	Charges the system
Batsman hits the ball	Fault occurs
Mid-off stops/fails	Primary relay operates/ fails
Long-off stops/ fails	Backup relay operates / fails
Match lost ?	Loss of Power/Revenue

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Protection Features

- Sensitive – detection of short circuit or abnormal condition
- Selectivity – ensure that only the unhealthy part of the system is disconnected
- Speed – to prevent or minimize damage and risk of instability of machines
- Reliability – to ensure proper action even after long periods of inactivity and also after repeated operations under severe conditions

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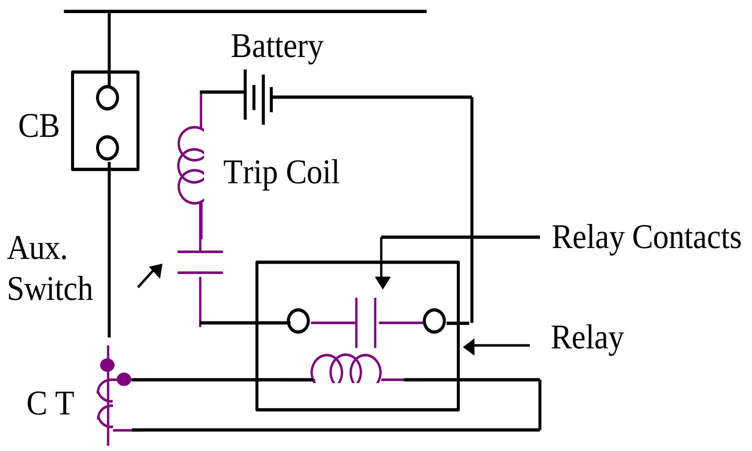
Protection System Design

- Design of circuit breakers and isolating devices
- Transducer (sensing devices)
- Relay design
- Relay application and co-ordination
- Simulation and testing



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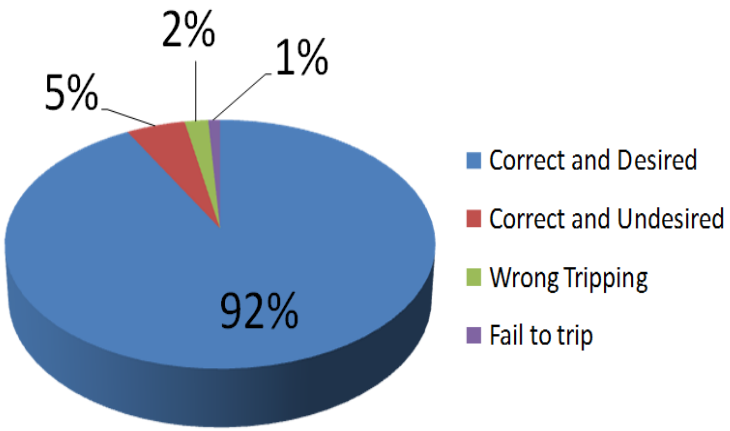
Protection Statistics



- ❖ Correct and Undesired
  - ❖ Operation as per the settings.
  - ❖ Settings are wrong, not updated
- ❖ Human Error
  - ❖ Leaving the trip circuit open after test
  - ❖ Open circuited trip coils
  - ❖ Mechanical failure of circuit breaker

Causes of Protection Failure

- Current or voltage supply to the relays
- DC-tripping voltage
- Protective relays
- Tripping circuit or breaker mechanism
- Circuit breaker

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Equipment Selection

- Relay selection
  - ✓ Selecting a relay scheme to recognize the existence of a fault within a given protective zone
  - ✓ Initiate circuit breaker operation
- Circuit breaker selection
  - ✓ Determine the interruption requirement
  - ✓ Normal current and voltage rating
  - ✓ Selection of breakers and location

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Fault Characteristics

- Magnitude
- Frequency
- Phase angle
- Duration
- Rate of change
- Direction or order of change
- Harmonics or the wave shape

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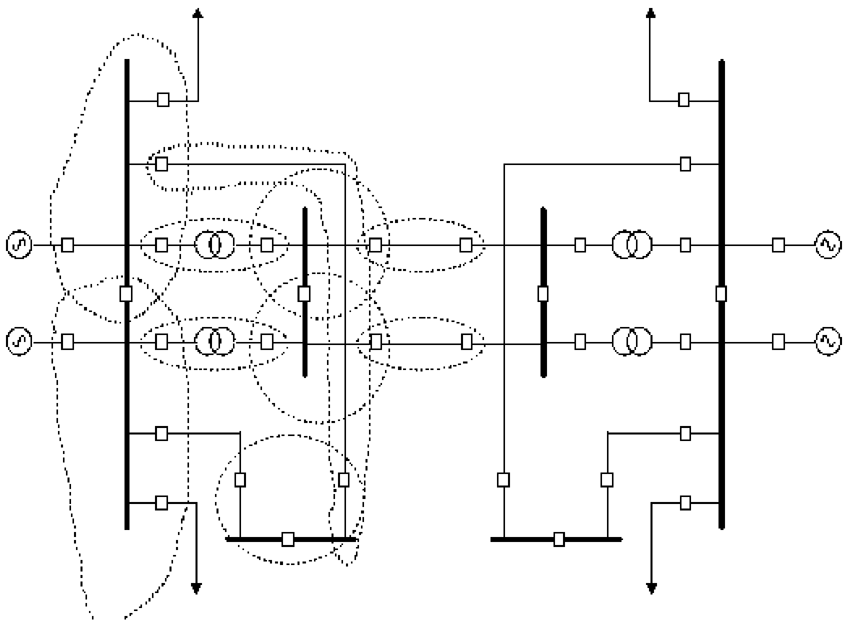
Protection Scheme Design

- Divide the system into zones
- Design appropriate breakers
- Minimize the amount of load being disconnected



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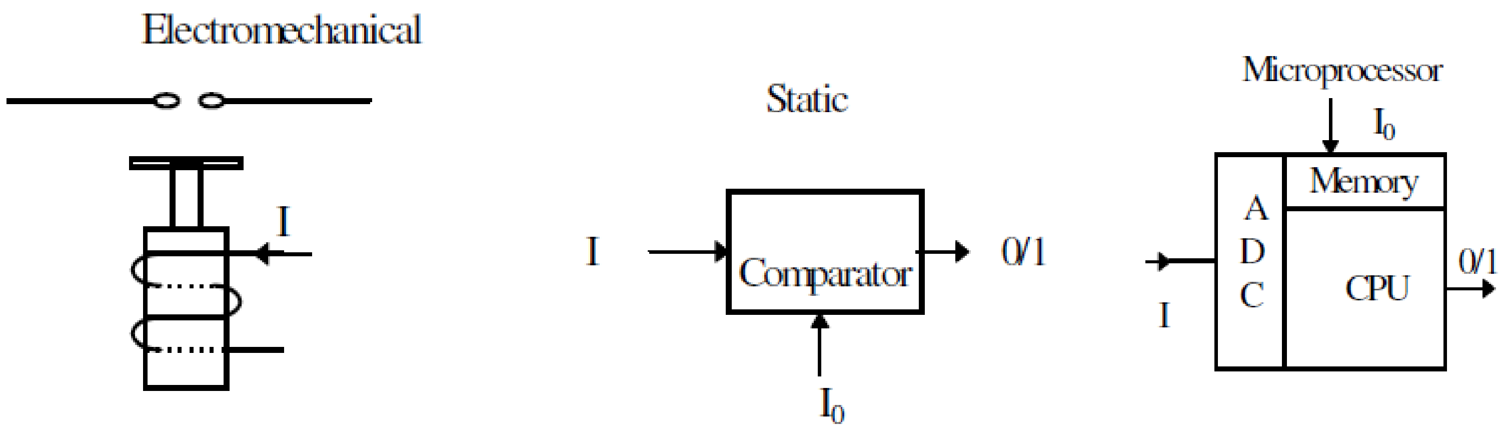
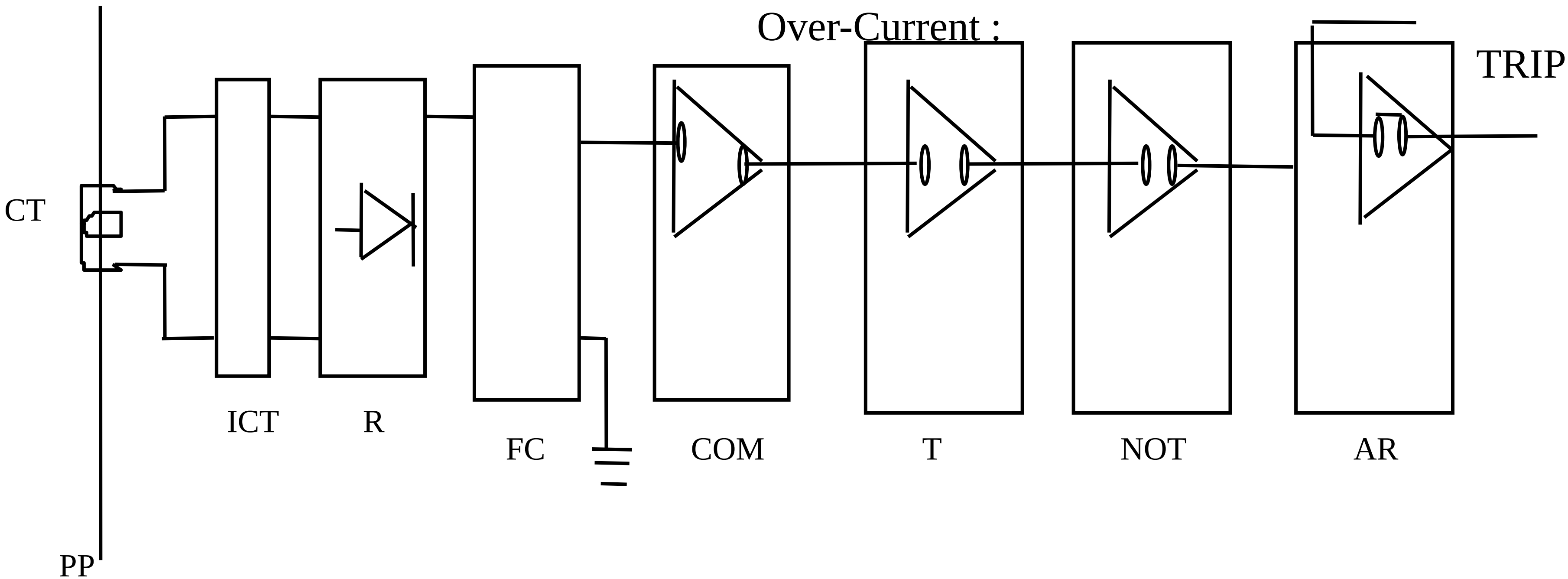
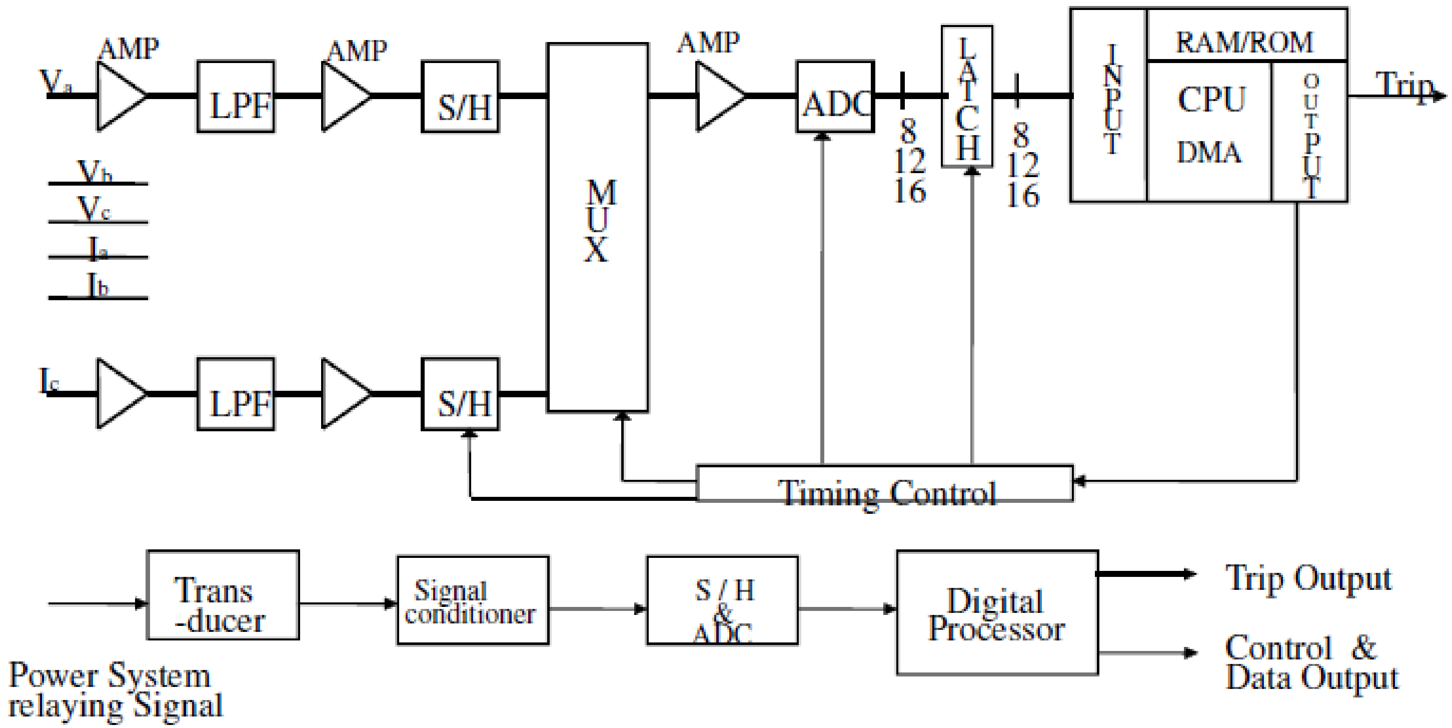
Types of Relays



Schematic of a Static Relay



Schematic of an NR



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Over-Current Relays

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Basics

- Relays operate based on the current sensed.
- Can be used as primary or backup protection
- May be directional or non-directional
- Operation time depends on curve selected
- Settings involve selecting the plug setting and the time setting

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Definitions

- **Plug Setting**

Plug setting is that value of current above which the relay should operate.

- **Time dial setting**

The time dial setting of the relay provides the discrimination between the primary and backup relay.

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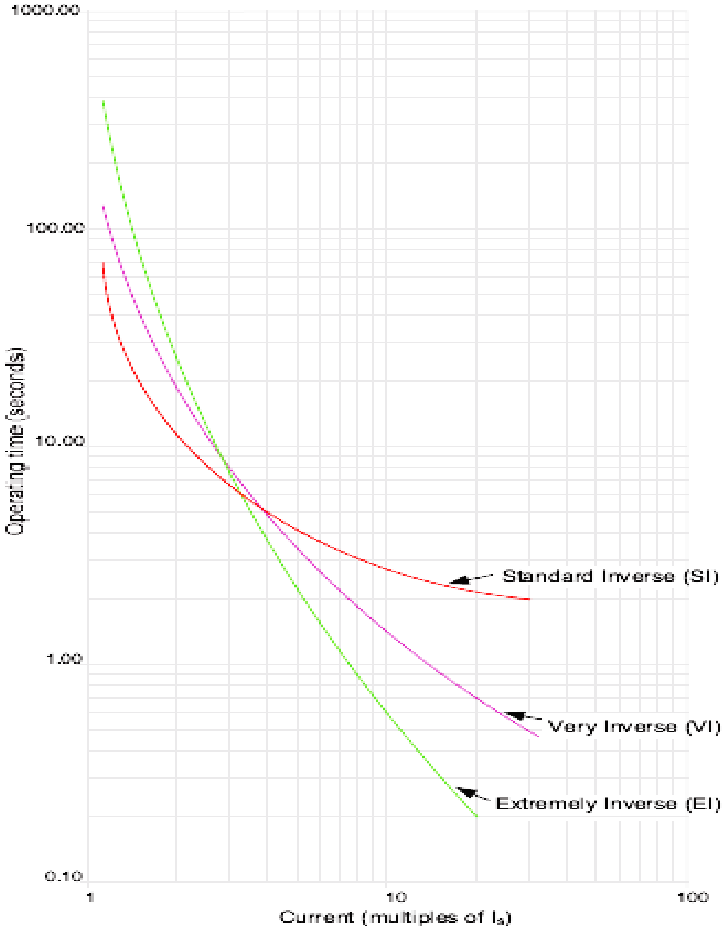
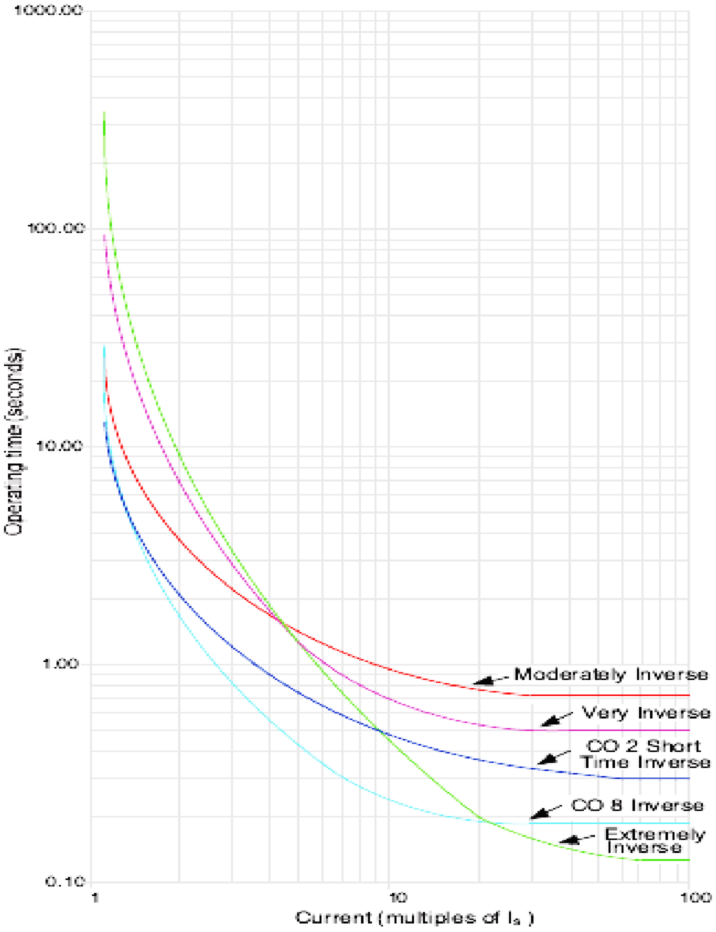
Standard Curves





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Curve Equations

Relay Characteristic	Equation (IEC 60255)
Standard Inverse (SI)	$t = TMS \times \frac{0.14}{I_r^{0.02} - 1}$
Very Inverse (VI)	$t = TMS \times \frac{13.5}{I_r - 1}$
Extremely Inverse (EI)	$t = TMS \times \frac{80}{I_r^2 - 1}$
Long time standby earth fault	$t = TMS \times \frac{120}{I_r - 1}$

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Relay Co-ordination

- Identification of main and backup relays
- Steady state analysis
- Determination of plug setting
- Determination of definite time setting
- Determination of time dial setting

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Distance Relays

Basics

*Distance relays are the most widely used relays for transmission lines protection.

*The relay measures the distance in terms of impedance by measuring the voltage and current.

*Major advantage is that relay acts as primary as well as remote back up.

*The present digital distance relays offer more functionalities in terms of protection, monitoring and control rather than just impedance measurement

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Types of Characteristics

- Mho
- Quadrilateral
- Lentical
- Quadra-Mho
- Elliptical Characteristics
- Circular

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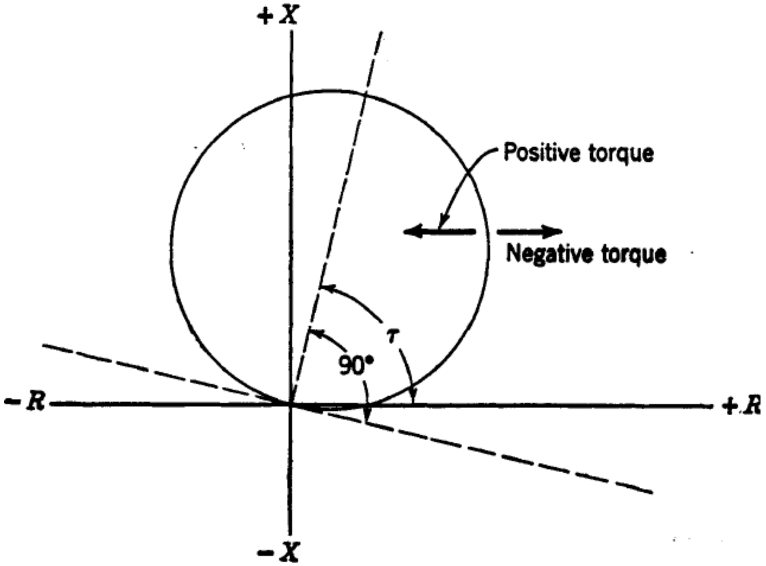
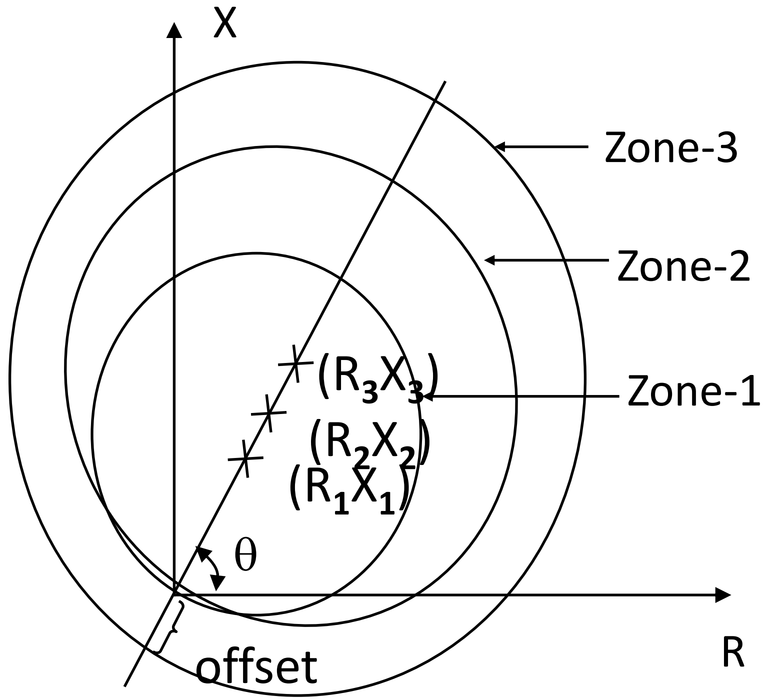
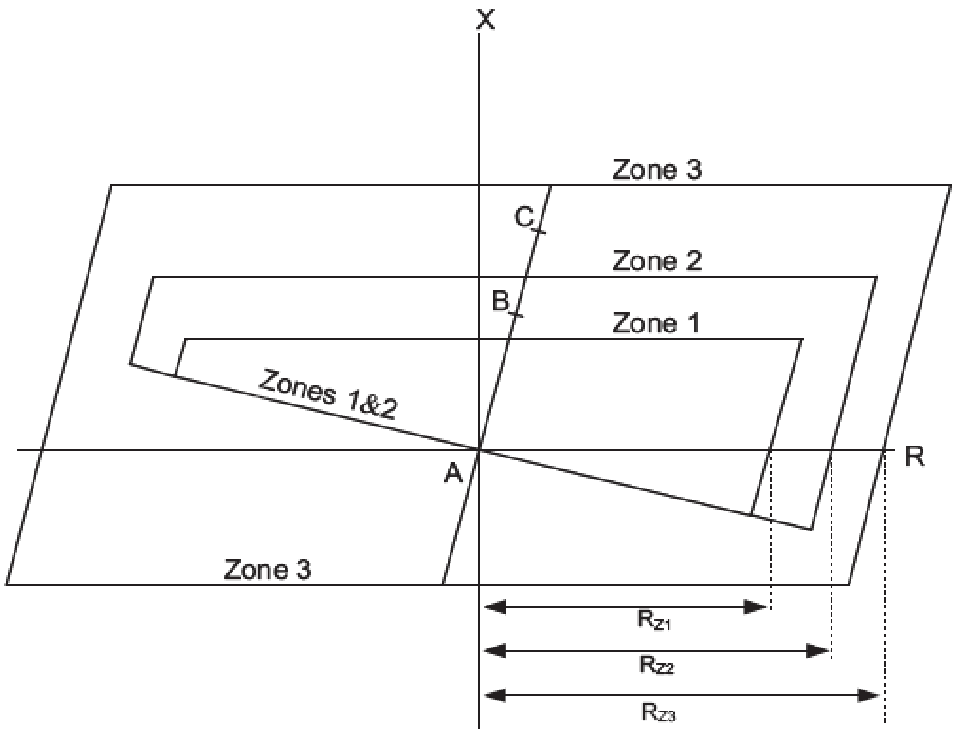
Mho Characteristic

$$Z = \frac{K_1}{K_2} \cos(\theta - \tau)$$





Quadrilateral Characteristics



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Impedance Calculation

- Relays operate if the impedance seen is within the set characteristics known as zones.
- Separate zones are present for phase and earth loops.

$$Z_{AB} = \frac{V_B - V_A}{I_B - I_A}$$

$$Z_{AE} = \frac{V_{AE}}{I_A - \frac{Z_E}{Z_L} I_E}$$

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Philosophy

Zone	Direction	Protected Reach	Time Setting (s)
Zone 1	Forward	80 % of the PL	Instantaneous
Zone 2 (for 400kV and above)	Forward	For Single Circuit – 120 % of the PL	0.35
		For Double Circuit – 150 % of PL	0.5 to 0.6 – If Z2 reach overreaches 50% of the shortest line; 0.35 – otherwise
Zone 2 (for 220kV and below	Forward	120% of PL or 100% of PL + 50% of ASL	0.35

PL: Protected Line, ASL: Adjacent Shortest Line, ALL: Adjacent Longest Line

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Philosophy

Zone	Direction	Protected Reach	Time Setting (s)
Zone 3	Forward	120% Of (PL + ALL)	0.8 to 1.0
Zone 4	Reverse	10% for the Long line (>100 km) 20% for short line (<100 km)	0.5 if Z4 overreaches 50% of reverse shortest line 0.35: otherwise

Note : Z2 reach should not encroach the next lower voltage level
: If Z3 reach encroaches next voltage level (after considering in feed), Z3 time must be coordinated
: If utility uses carrier blocking scheme, then the Z4 reach may be increased as the requirement. It should cover the LBB of local bus bar and should be coordinated with Z2 time of the all other lines.

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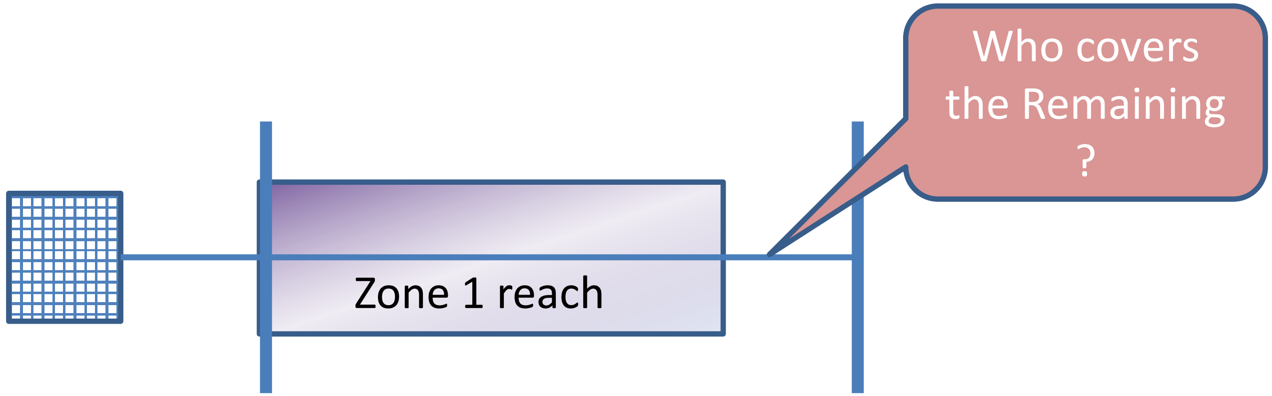
Zone 1

- Instrument Transformer errors
- Transmission line is not completely balanced
- Hence apparent impedance is susceptible to an error of 20%.
- Zone 1 is under reached to prevent incorrect operation for fault on next line (Eg. Close to adjacent bus)



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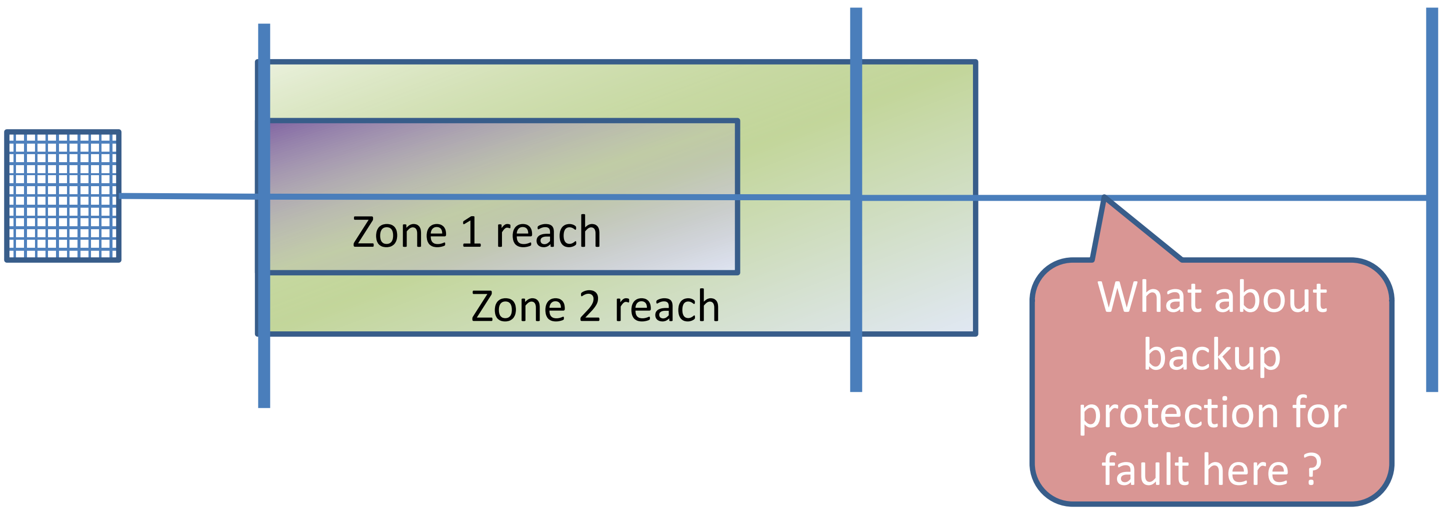
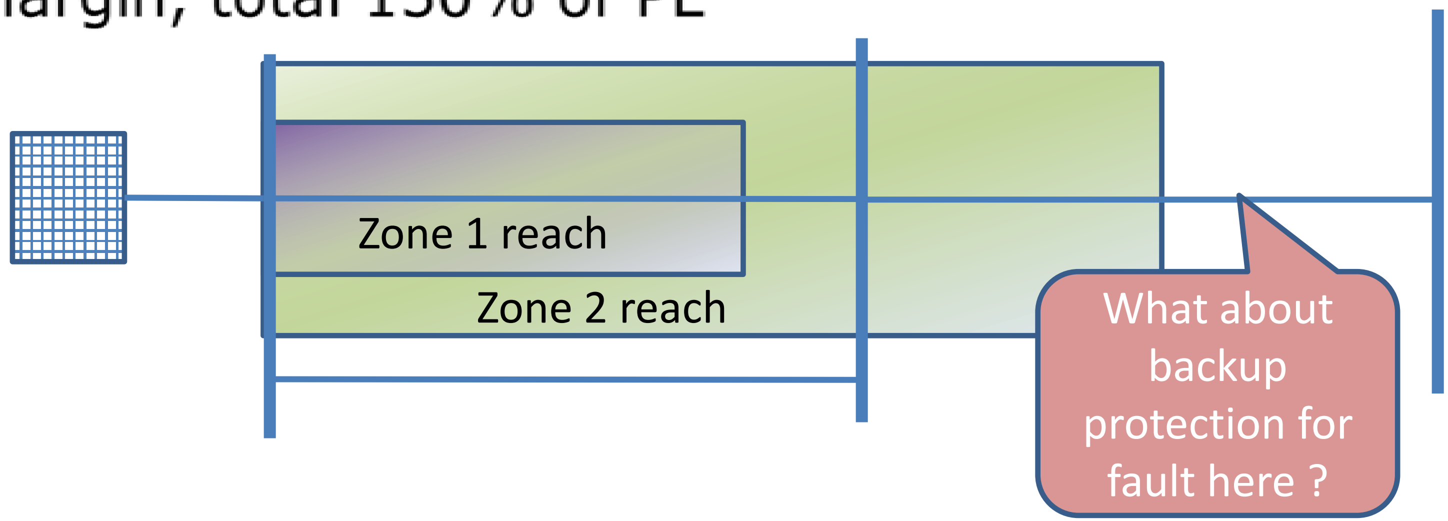
Zone 2 for single circuit line

- To provide coverage to remaining portion of protected line
- Over reach margin should be min 20% (for reason discussed in Zone1)



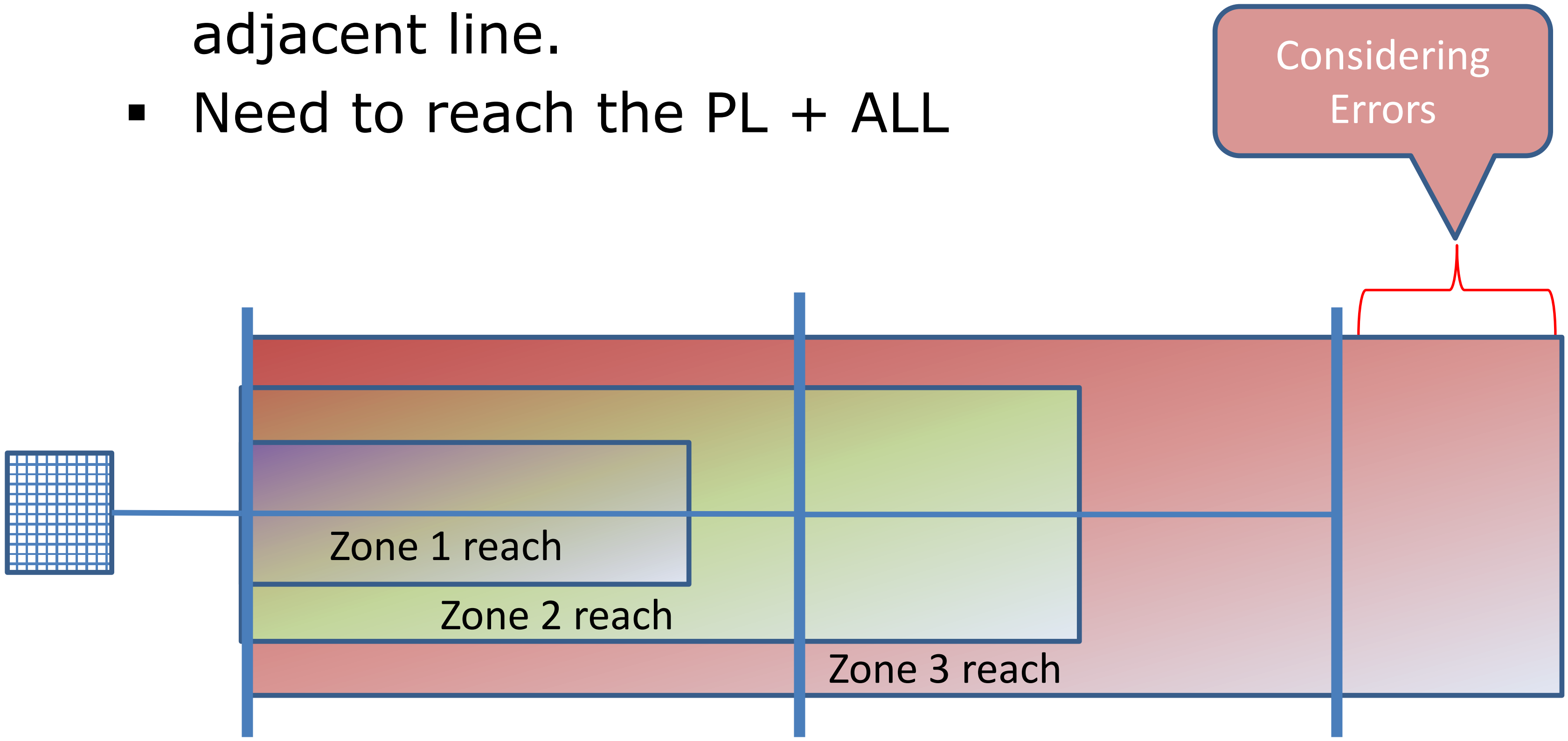
Zone 2 for double circuit line

- Under reach due to mutual coupling between parallel line
- $\Delta Z = \frac{k_{0m}}{1+k_0}$, $k_{0m} = \frac{Z_{0m}}{3Z_1}$, $k_0 = \frac{Z_0 - Z_1}{3Z_1}$
- For twin moose, ΔZ = 27% considering additional 20% margin, total 150% of PL



Zone 3

- Zone 3 protection is backup protection for fault on adjacent line.
- Need to reach the PL + ALL



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Resistive Reach (Zone 1)

- Earth
  - ✓ Should provide maximum coverage considering fault resistance, arc resistance and tower footing resistance.
  - ✓ Should be <4.5 * X1 (X1=Zone 1 reach)
- Phase
  - ✓ Reach should be set to provide coverage against all types of anticipated phase to phase faults subject to check of possibility against load point encroachment
  - ✓ Should be <3*X1

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Resistive Reach (Zone 2 and Zone 3)

- The philosophy used for Zone 1 is applicable here also.
- Additionally
  - ✓ Due to in-feeds, the apparent fault resistance seen by relay is several times the actual value, this should be considered before arriving at the setting.

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Queries and Discussions

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Thank You

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Protection Case Studies

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Topics for Discussion

- Overcurrent Relays
- Distance Relays
- Differential Relays

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Overcurrent relays

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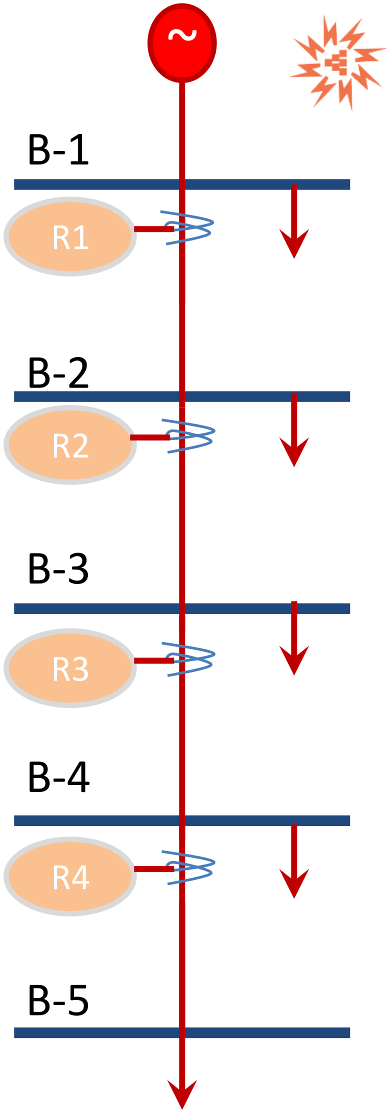
Relay coordination sample

- Generator data
  - Generator fault level :
    - Maximum : 1000 MVA
    - Minimum : 500 MVA

Transmission Line Details			
Sl. No	From Bus	To Bus	Impedance(pu)
1	1	2	0.1
2	2	3	0.1
3	3	4	0.1
4	4	5	0.1



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Relay data

Sl No	Relay Name	Maximum Load Current(A)	CT rating	Relay Characteristics
1	R1	800	800/1	3s
2	R2	400	400/1	3s
3	R3	200	200/1	3s
4	R4	100	100/1	3s

Relay Pairs

Sl No	Primary Relay	Backup Relay
1	R4	R3
2	R3	R2
3	R2	R1

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Fault Studies results

Relay	Impedance	Fault Bus	Fault MVA	Fault Current in A
R1	0.1	1	1000	52486.388
R2	0.2	2	500	26243.194
R3	0.3	3	333.33	17495.288
R4	0.4	4	250	13121.590

Sl No	Primary Relay	Backup Relay	Fault Bus	Backup Relay Current in A
1	R4	R3	4	13121.590
2	R3	R2	3	17495.288
3	R2	R1	5	26243.194

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Plug setting computation

For Relay R4		
% Setting	Primary Setting	Remarks
50	50	< Load Current
75	75	< Load Current
100	100	= Load Current

Relay	Load Current	CT Rating	% Setting	Primary Current
R1	800	800/1	100	800
R2	400	400/1	100	400
R3	200	200/1	100	200
R4	100	100/1	100	100

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Time setting computation

- Time of operation given by
- $t = \frac{3}{\log M} * TMS$
- $M = \frac{I_{sensed}}{I_{PS}}$
- Assuming minimum TMS of 0.05 for R4, time of operation is computed as:
- $t = \frac{3}{\log \frac{13121.59}{100}} * 0.05 \approx 0.071\, s$

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Time setting computation

- For R3,
- $t_{backup} = t_{primary} + t_{discrimination}$
- $= 0.07 + 0.4 = 0.47$
- Therefore, the TMS for R3 is given by:
  - $$TMS = \frac{0.47 * \log \frac{13121.59}{200}}{3} \approx 0.29$$
- Similarly for other relay pairs

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Final relay settings

Relay	Plug Setting	TMS
R1	800	0.6
R2	400	0.47
R3	200	0.29
R4	100	0.05

Operating times for a fault at Bus 5, with a fault current of 10, 500 A	
R1	≈ 1.61 s
R2	≈ 1.00 s
R3	≈ 0.51 s
R4	≈ 0.07 s

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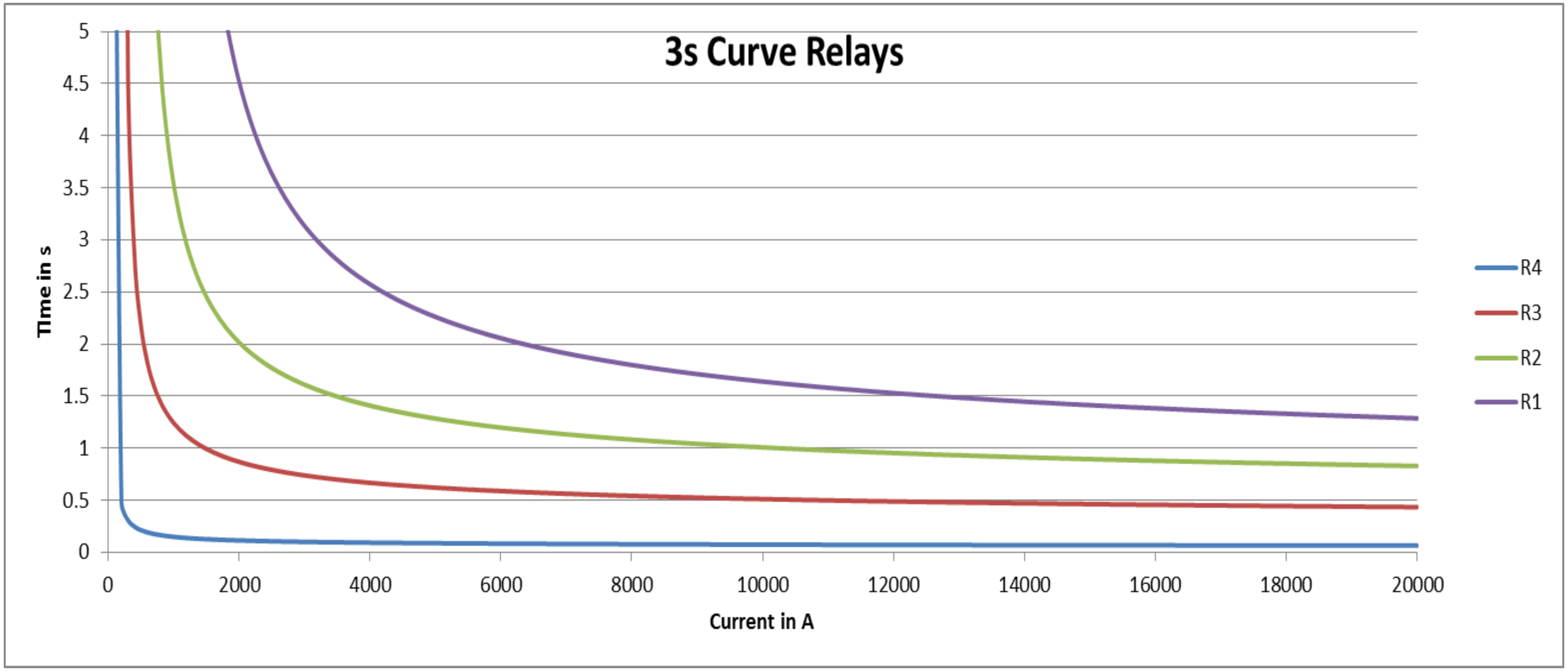
Co-ordinated Curves



Application

- Backup to distance relays (220/132 kV and below)
- HV and LV side of ICT as backup to differential relays
- DEF is used in 400 kV line as protection for high impedance earth faults.
- Non directional OC is also used in 400kV line under fuse fail condition

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DOC Setting Philosophy

- For 220 kV and 132 kV line with only one main distance protection, DOC must be set in such a way that for fault at remote bus the DOC (IDMT) is coordinated with Zone 2 time typically 1.1 s
- For DOC at 400 kV side of ICT, it is to be set such that for fault at remote end bus (longest line), DOC (IDMT) is coordinated with Zone 3 time
- Instantaneous DOC can be used at 400 kV side of ICT, set such that
  - It does not pickup for fault on 220 kV bus
  - It does not pickup for transformer charging current
  - Time setting of **0.05 s** to 0.1 s can be considered.

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DEF Setting Philosophy

- For 220 kV and 132 kV line with only one main distance protection, DEF (IDMT) must be set in such a way that it is coordinated with Zone 2 time
- For 400 kV line or where two main distance protection is used, DEF is used only for protection against high impedance faults and is coordinated with Zone 3 time
- For DEF at 400 kV side of ICT, it is to be set such that for fault at remote end bus (longest line), DEF (IDMT) is coordinated with Zone 3 time
- Instantaneous DEF can be used at 400 kV side of ICT, set such that
  - It does not pickup for fault on 220 kV bus
  - It does not pickup for transformer charging current
  - Time setting of **0.05 s** to 0.1 s can be considered.

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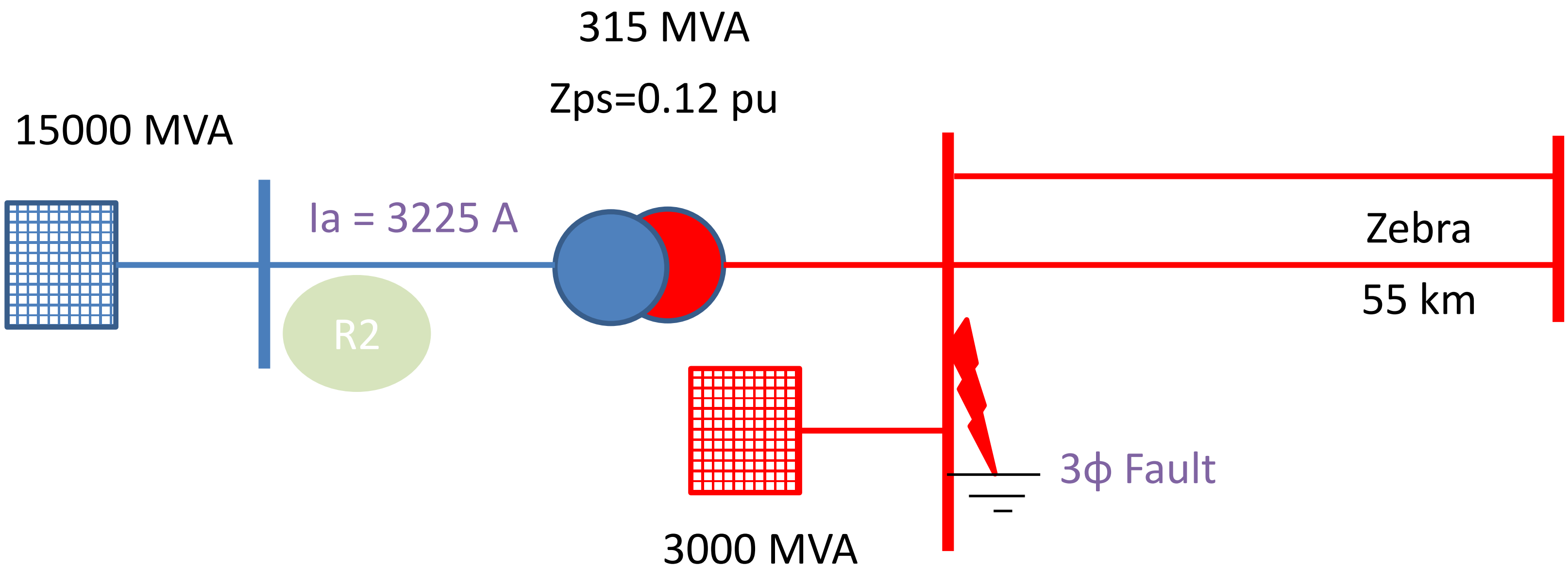
Instantaneous Setting calculation



- Reflected Current = 1.3 * 3225 = 4195 A
- Inrush Current = 8*450 = 3600 A
- Ip>> = Highest of the above two = 4200 A (Set value).

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Distance relays

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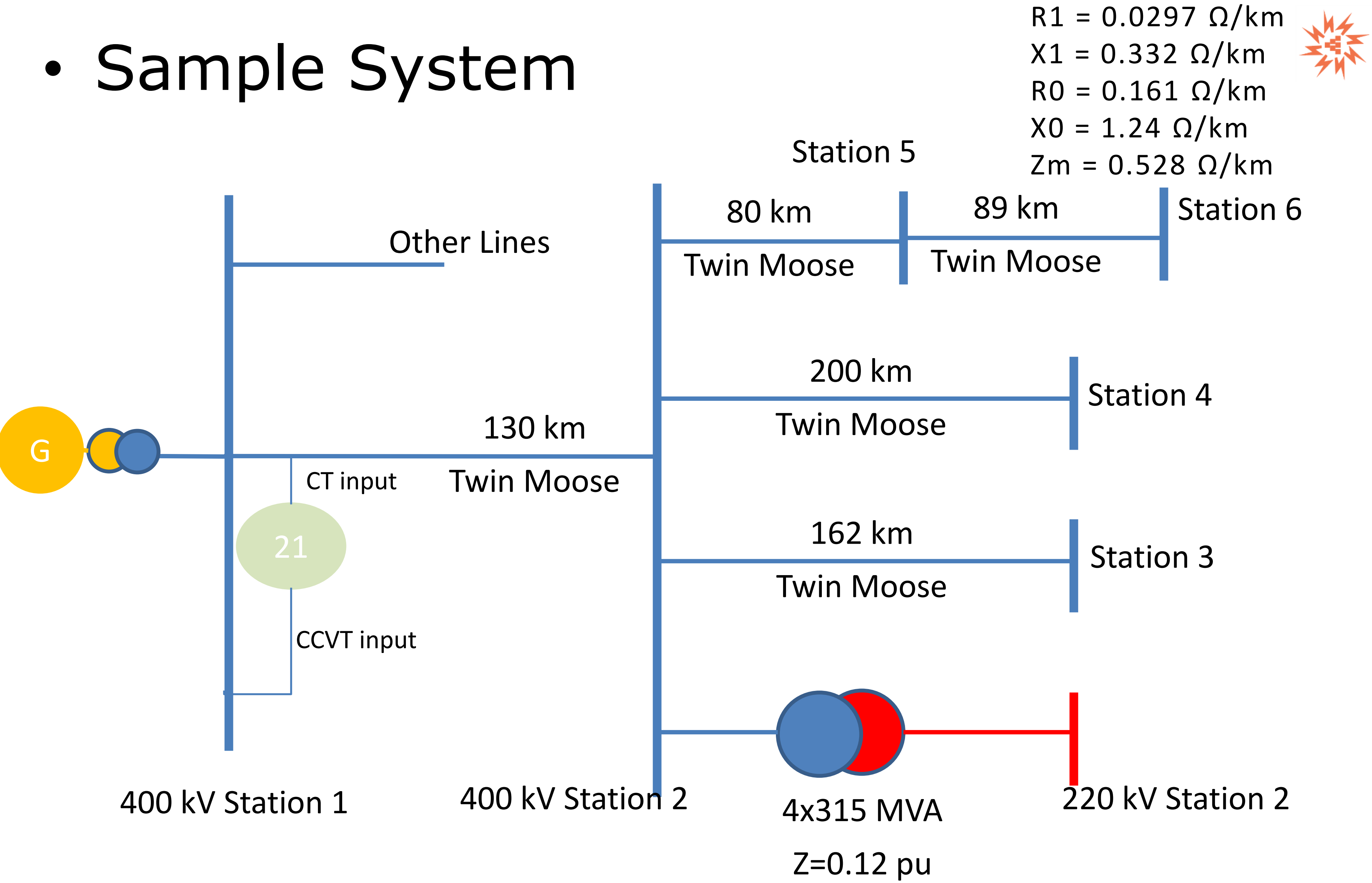
- # Sample System



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Zone 1

- Primary referred
  - X1_prim = 0.332 *130*0.8 = 34.5 Ω
- Secondary referred
  - X1_sec = 34.5*CTR/PTR, CTR:CT Ratio, PTR: PT Ratio
- Operating Time: Instantaneous

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Zone 2

- Protected line is single circuit
- Adjacent Shortest Line: 80 km to Station 5
- X2_Prim = 0.332*130*1.2 = 51.79 Ω (130+26 km)
- X2 covers only 32% of Adjacent Shortest Line.
- Operating Time : 0.35s

Zone 3

- Adjacent Longest Line is 200 km to Station 4
- X3_Prim = 0.332*(130+200)*1.2 = 131.47 Ω
  - That is 130 km PL + additional 266 km
- Time Setting
  - Check if Zone 3 of PL encroach Zone 3 of adjacent line protection
  - Zone 3 of Station 2- Station 5 line is 202.8 km.
  - The Two Zone 3 are overlapping and hence must be time coordinated.
  - Time = 0.8+ 0.06 (t_{cb})+0.03 (t_{reset})+0.06 (t_{sf})= 0.95 (set 1s)
  - t_{cb}, t_{reset} and t_{sf} values are as per CEA report

Points to be Considered

- Obtain the actual line parameters from line impedance test results. If not available, consider the standard values.
- Check Relay Setting type
  - Primary or secondary referred values
  - RX or Zθ
  - Computation of Zero sequence compensation factor. (K0, Kn or Kr-Kx

$$k_0 = \frac{Z_0 - Z_1}{3Z_1} \qquad k_n = \frac{Z_0 - Z_1}{Z_1} \qquad k_r = \frac{R_0 - R_1}{3R_1} \qquad k_x = \frac{X_0 - X_1}{3X_1}$$

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Points to be Considered

- Note the shortest and longest line emanating from the adjacent substation, along with impedance values
- For double circuit lines, check if it is two single circuit tower or one double circuit tower
- If necessary, carry out system study to study the effect of in feed, mutual coupling, power swing to achieve coordinated setting.

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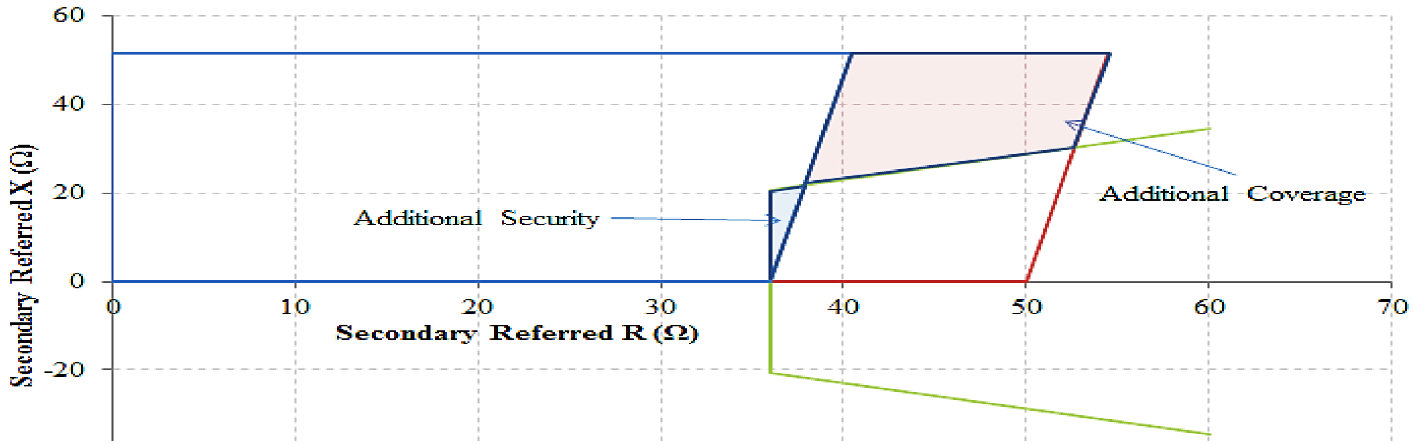
Load Encroachment Consideration

- Basic Check
  - Rated V = 63.5 V and Rated I = 1 A. (Secondary Referred)
  - Phase Impedance = (0.85*V)/(1.5*I) = 36 Ω
  - R reach must always be less than 36 Ω



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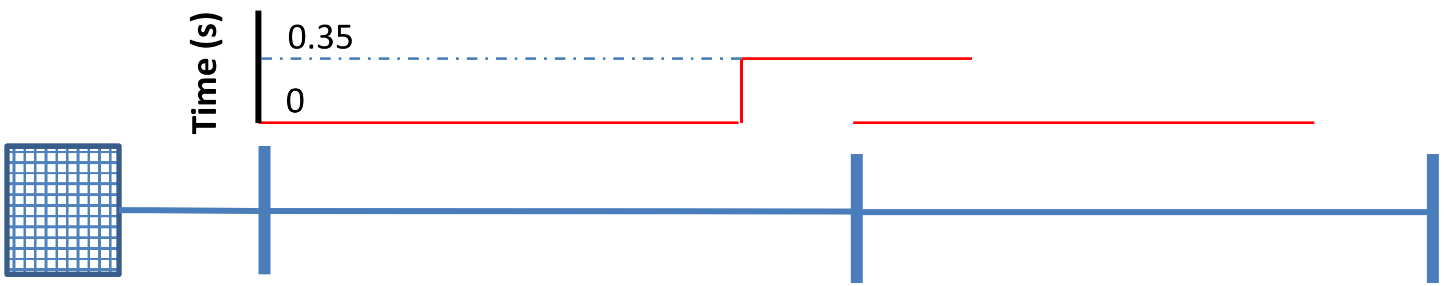
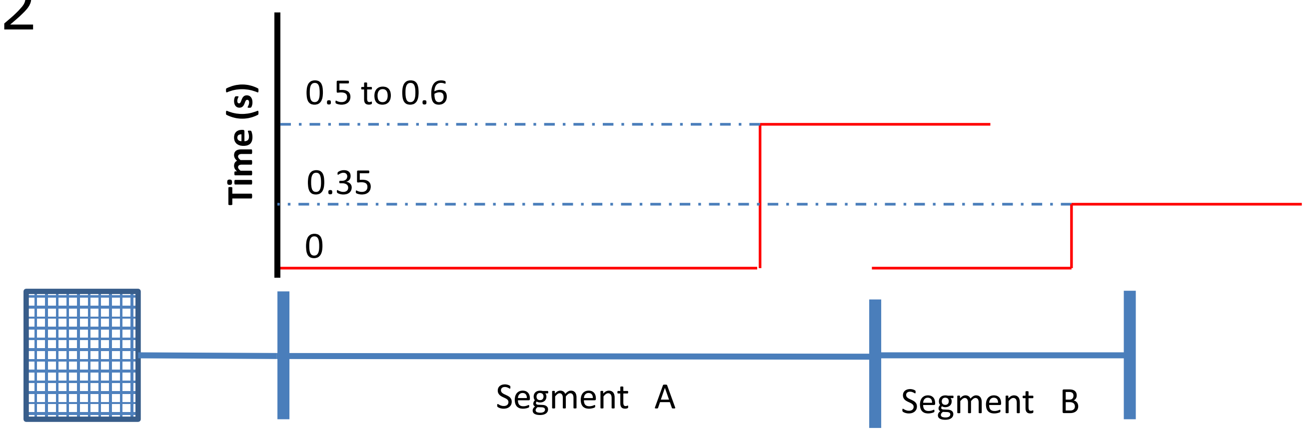
Operating Time coordination

- Zone 1 is primary protection, hence instantaneous operation
- Zone 2 is a overreach zone and hence needs to be delayed.
  - If errors involved is less, then Zone 2 can trigger for Zone 1 fault of adjacent line. Hence Zone 2 is to be coordinated with Zone 1.



Operating Time Coordination

- For fault at 80% of segment B, Segment B zone 1 can also under reach by 20%
- Hence only Zone 2 of Segment B pick up
- Segment A Zone 2 can also pickup.
- Hence segment A Z2 to be coordinated with segment B Z2



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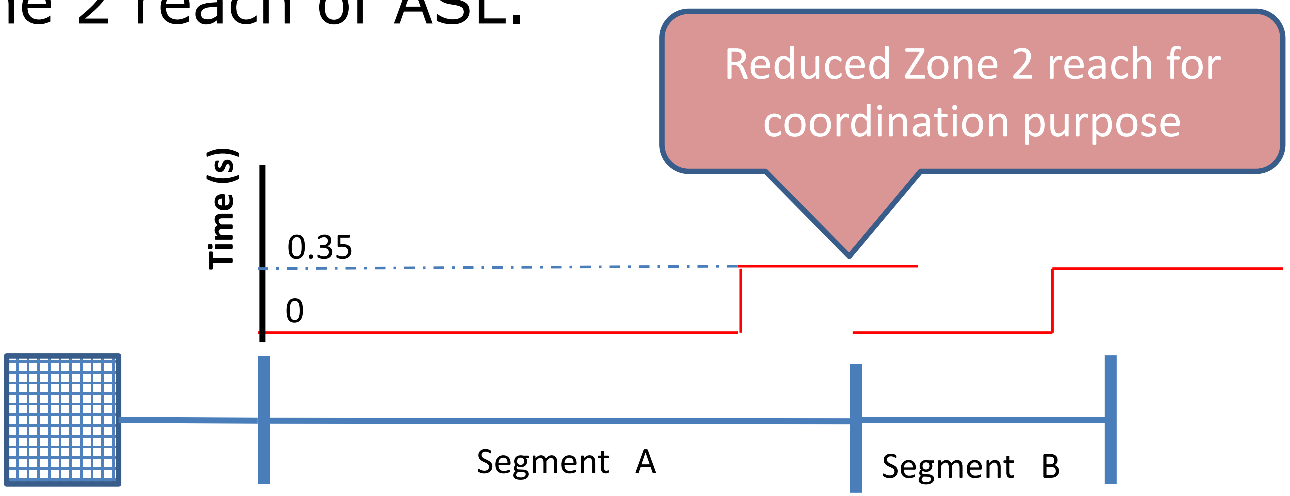
Operating Time coordination

- For 220 kV and below, if Zone 2 of PL can encroach the Zone 2 of ASL, then coordination is achieved by reducing the Zone 2 reach of PL to coordinate with Zone 2 reach of ASL.



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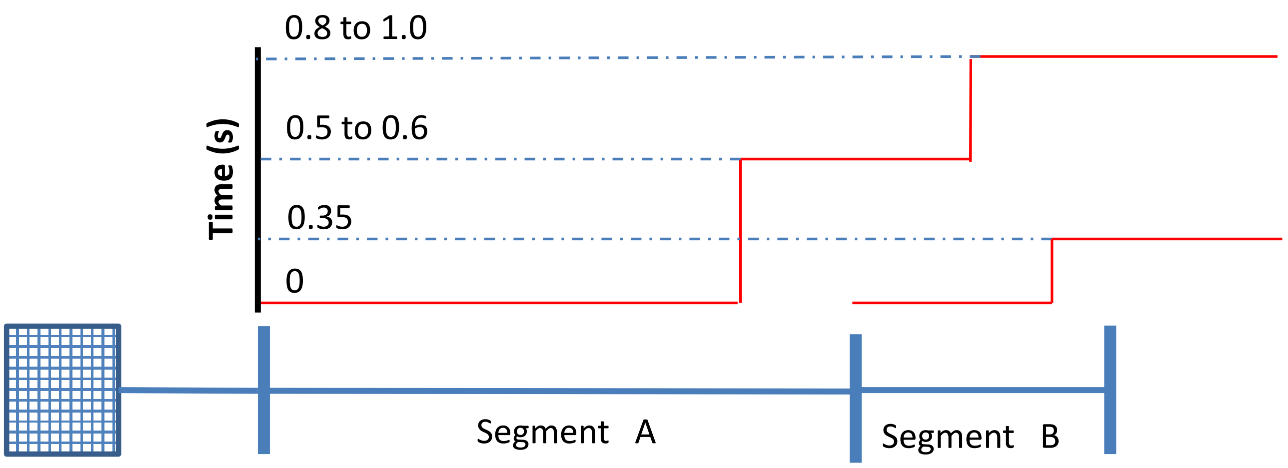
Operating Time coordination

- Zone 3 is the backup protection and hence needs to be operate after Zone 1 or Zone 2 has failed to clear the fault.
- Zone 3 is coordinated with Zone 2 time of adjacent line relay.



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Load Encroachment Consideration

- Reach setting is given considering the various "under reach" effect that can occur. This makes the resistive setting "high"
- Phase loop measures the phase impedance and hence has to be set such that it does not trip for abnormal or emergency system loading condition
- Emergency loading condition is to be used to decide the load encroachment point.

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Load Encroachment Consideration

- Following criteria may be considered
  - 1.5 times the thermal rating of line

    OR
  - 1.5 times associated bay equipment rating (minimum of all equipment)

  - Minimum voltage of 0.85 pu to be considered

  Load encroachment angle can be considered as 30° (approx. 0.85 pf)

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Power Swing Blocking

- During power system disturbances, unbalance exist between generators which cause the operating point to oscillate
- R-X trajectory might enter the zones of protection
- Blinder schemes are traditionally used to detect swings and prevent unnecessary tripping
- The rate of change of impedance is used to differentiate between power swings and faults

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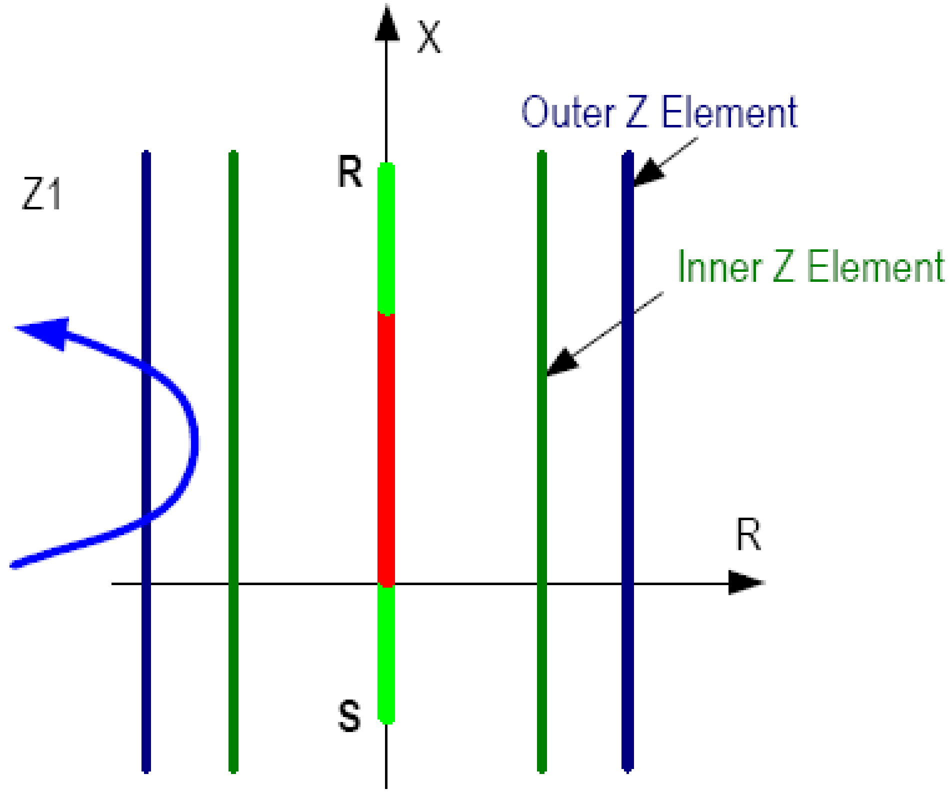
Power Swing Blocking Schemes



PSB Options

- No power swing blocking
- Block all zones
- Block zone 2 and higher
- Block all zones but allow OST

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Stability Studies for PSB Settings

- Identify the generators which are prone to instability and the lines where power swings are observed.
- Determine the location where system should be separated
- Time and reach settings are calculated
- Outermost zone reach should be within the inner boundary
- Outer boundary should be less than load impedance

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Carrier Aided Protection

- Transfer
- Unblocking
- Direct
- Blocking
- Permissive

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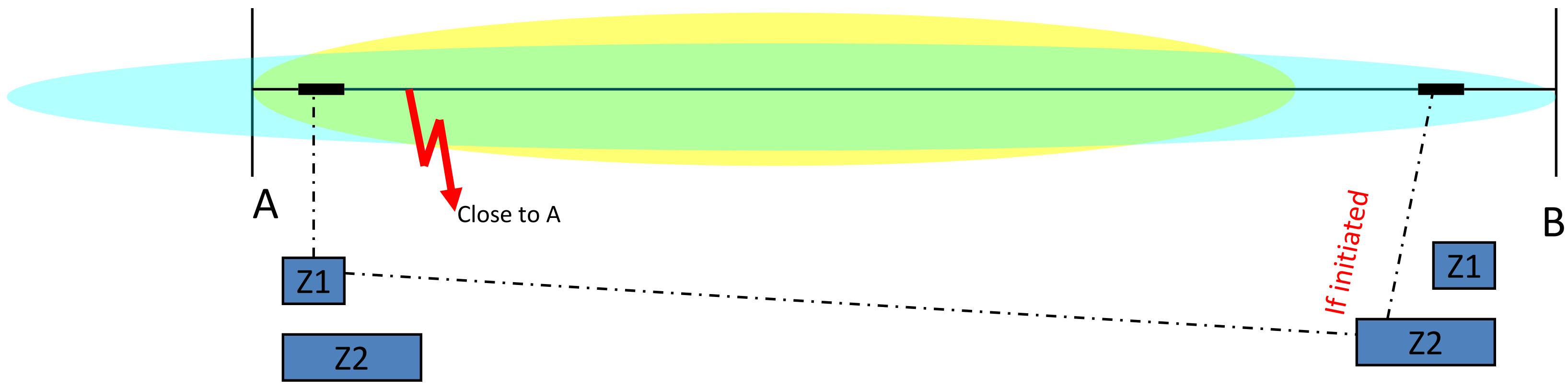
Permissive Under-Reach



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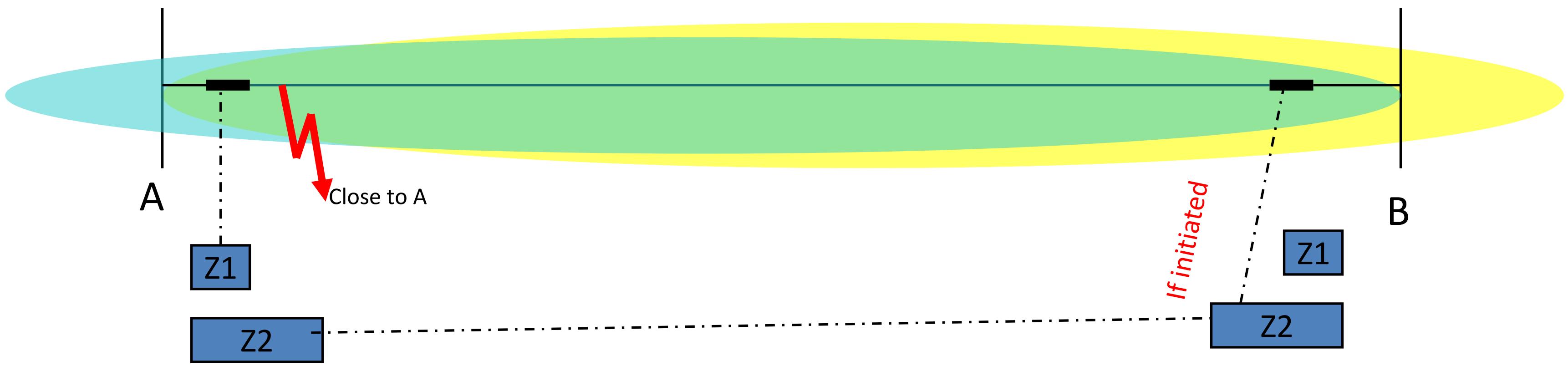
Permissive Over-Reach



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Queries & Discussions

PSCT | *Protection Analytic tool*

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Principles of Unit Protection

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Topics for Discussion

- Introduction to Unit Protection
- Differential Protection – Simple, Percentage Biased and High Impedance
- Applications
- Setting Examples

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Introduction

Meaning

- Protection which responds to faults only in one zone
- No need for time grading
- Normally fast acting – not affected by fault severity
- Operates based on the comparison of boundary conditions

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Types of Unit Protection

- Differential Protection
  - ✓ Utilizes Current
- Over-Fluxing Protection
  - ✓ Utilizes Voltage and Frequency
- Backup-Impedance Protection
  - ✓ Utilizes Current and Voltage

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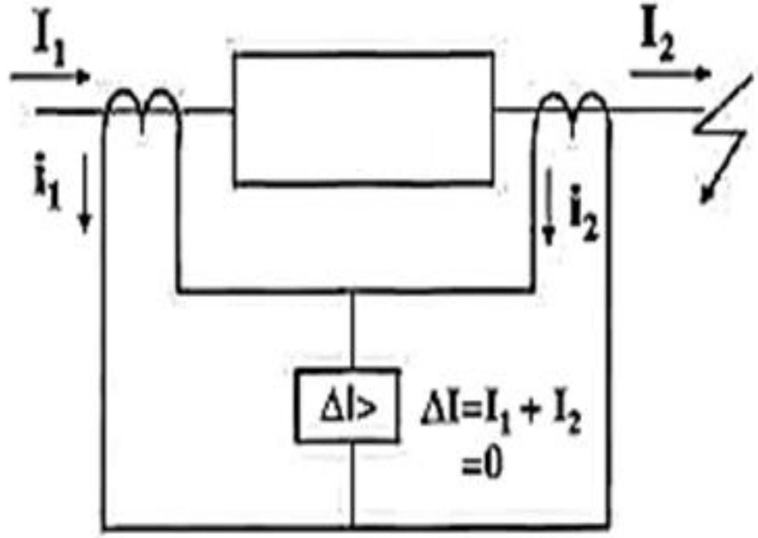
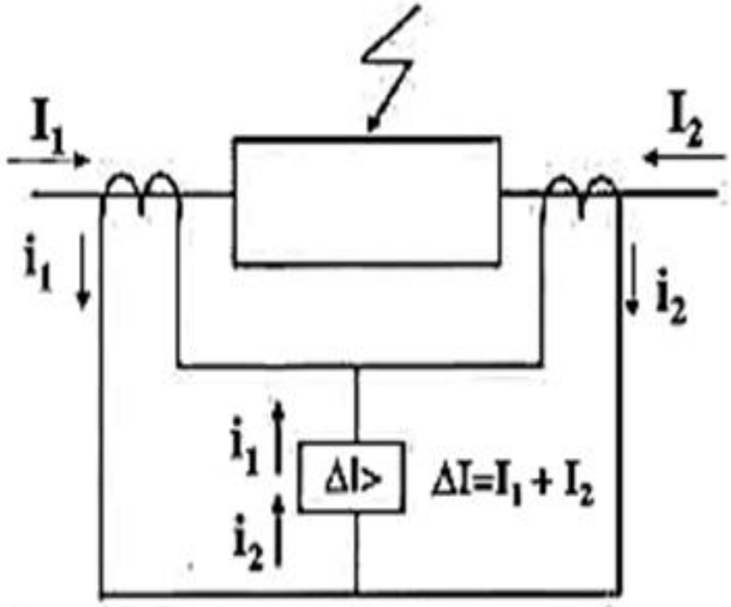
Differential Protection

Simple Differential Protection





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Setting Consideration

- The effect of magnetizing inrush during initial energization should be considered.

- Correction for possible phase shift across the transformer windings (phase correction)

- The effects of different earthing and winding arrangements (filtering of zero sequence currents)

- Correction for possible unbalance of signals from current transformers on either side of the windings (ratio correction)

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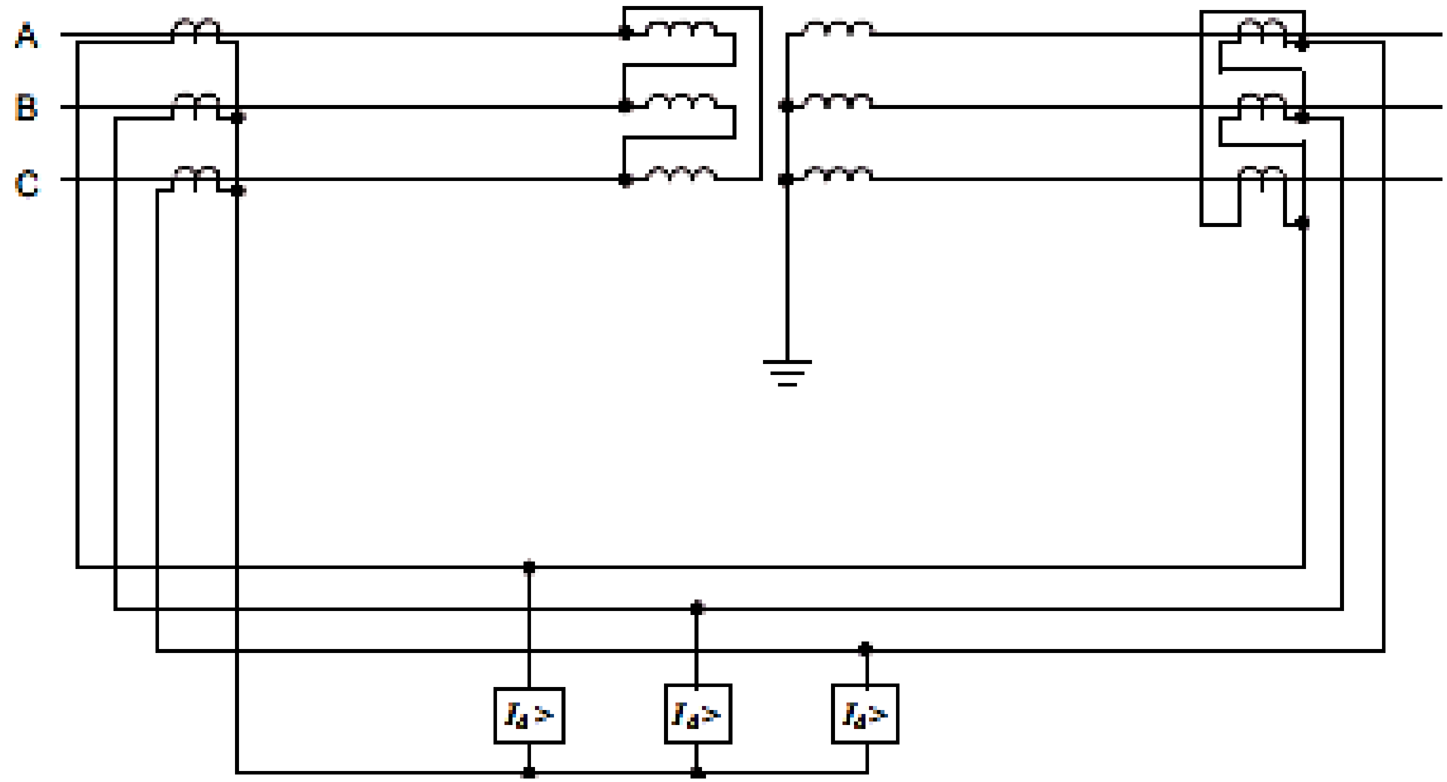
Phase Correction and Zero Sequence Filtering



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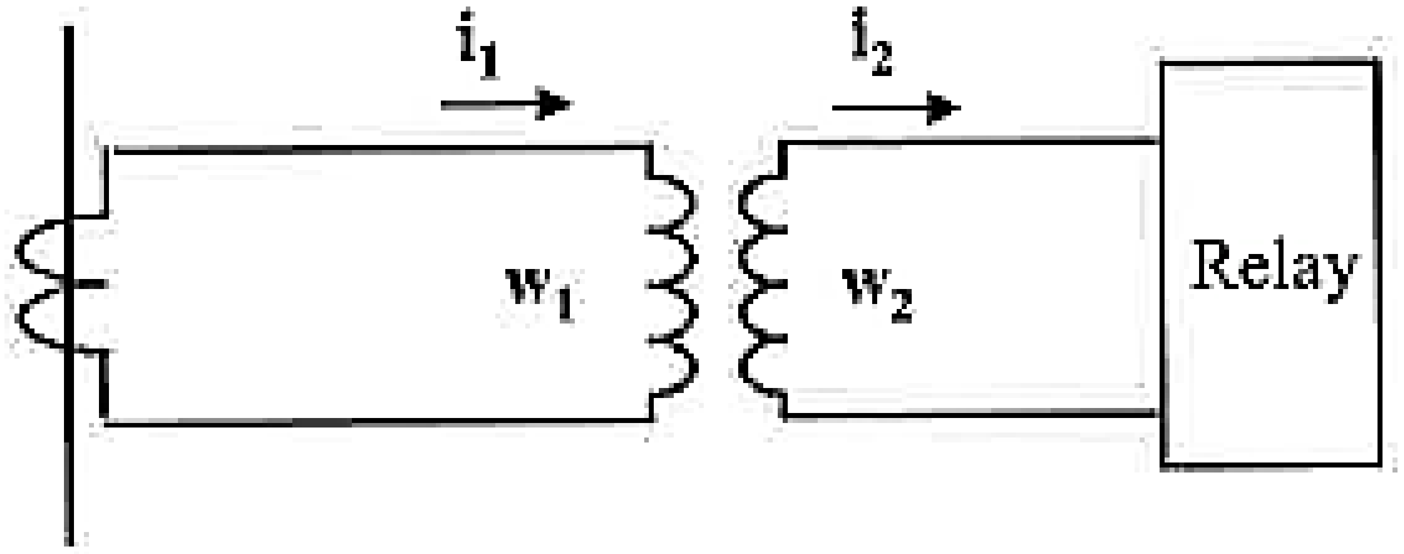
Ratio Correction



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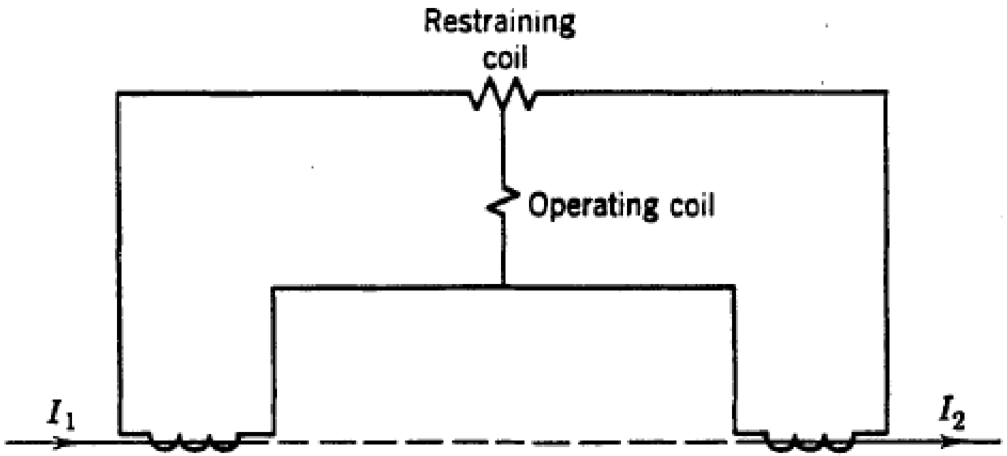
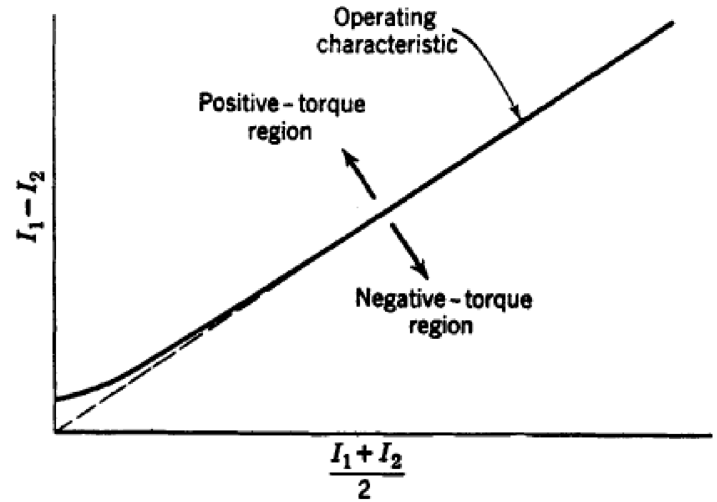
Biased Differential Relay





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Requirement of Biased Relays

Errors which vary proportionally with the operating conditions such as:

- Errors due to transformer taps
- CT errors
- Ratio Mismatch – Difficulty in obtaining exactly similar currents in both secondaries

Transient Errors

- CT Saturation

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Operating Characteristics

$$I_r = N_r * \frac{(I_1 + I_2)}{2}$$

$$I_o = N_o * (I_1 - I_2)$$

For relay operation,

$$I_o > K * I_r$$

Where, $K = \frac{N_r}{N_o}$

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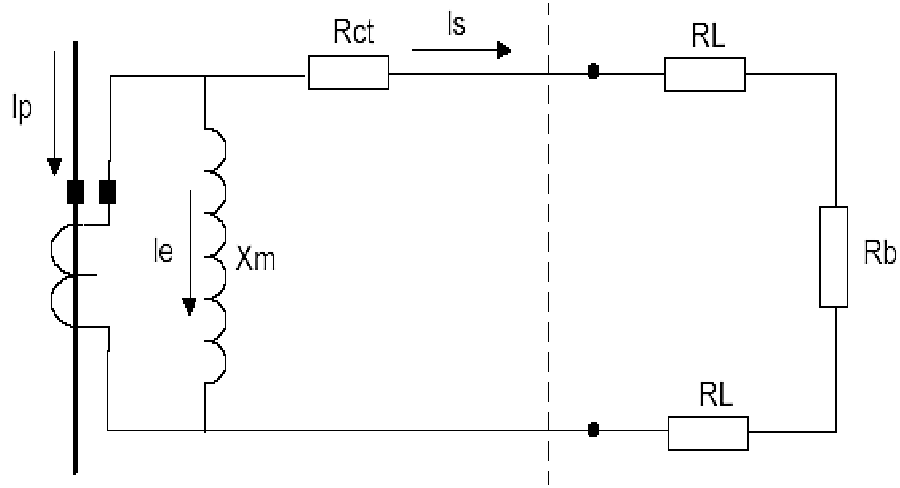

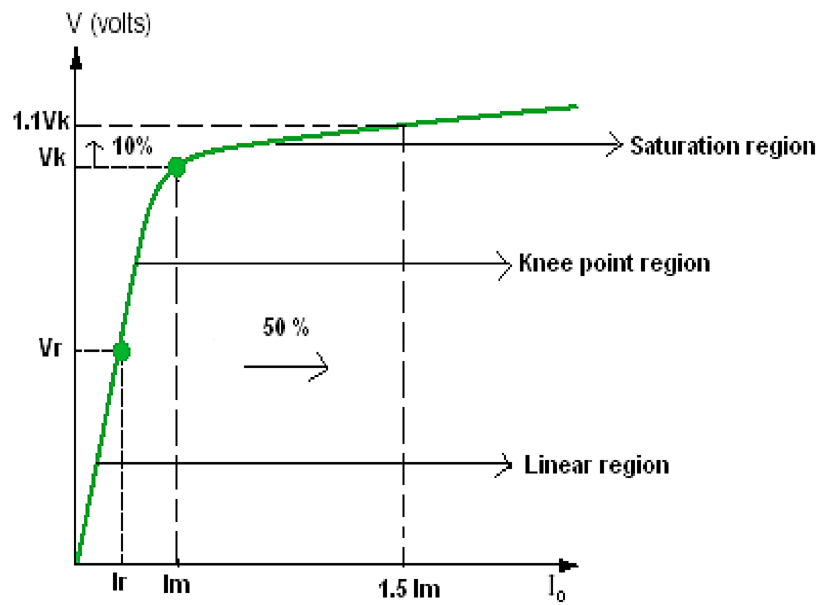

CT Saturation

- During CT saturation magnetizing impedance = zero
- Infinite magnetizing current will flow in the shorted path.
- Secondary of the network acts as open circuit.
- During this situation secondary current Is = zero

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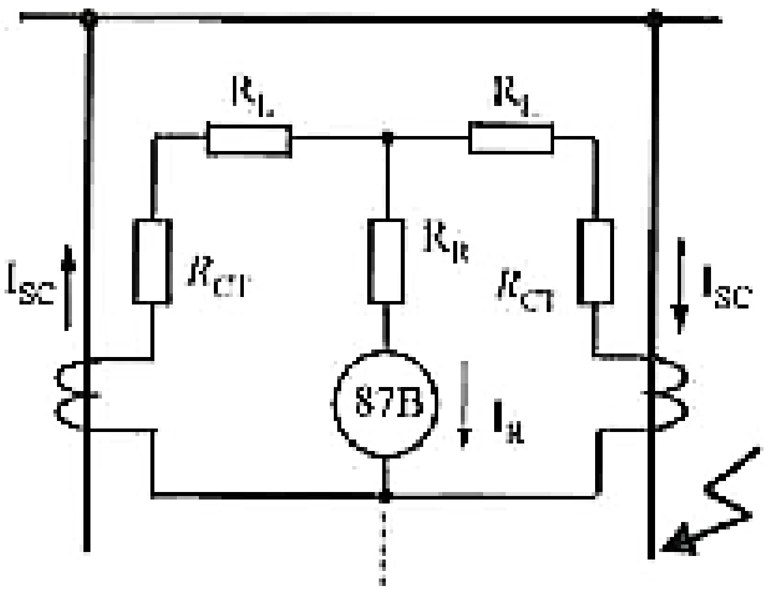
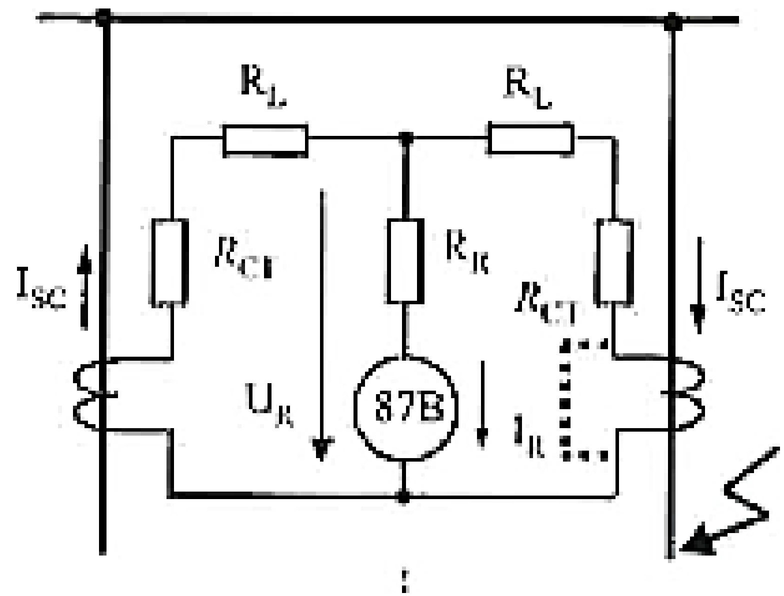
High Impedance Differential Protection





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Comparison of Differential Schemes

Low Impedance	High Impedance
• Identical CTs not required	• Stable for CT saturation for external faults
• Not stable for CT Saturation for external faults	• Identical CTs are preferred for sensitive operation
• No protection for over-voltage required	• May require an MOV to protect Relay against voltage developed during external faults

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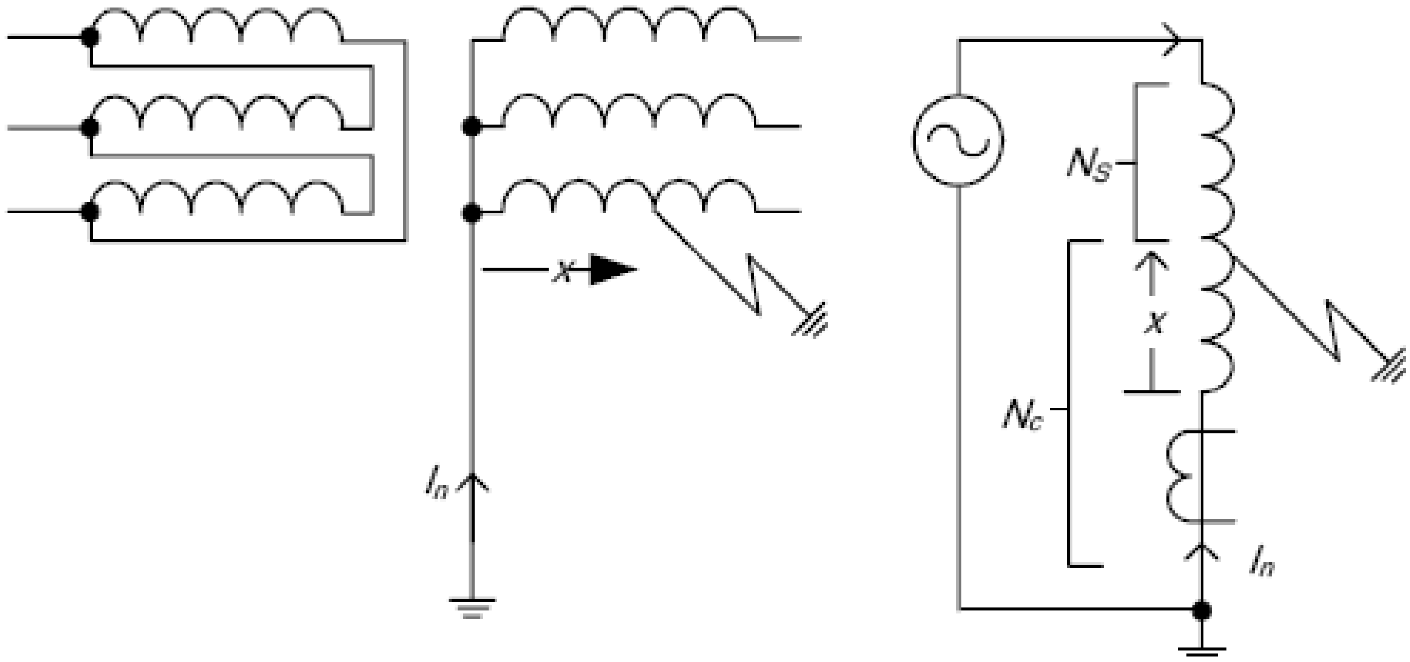
Restricted Earth Fault Protection



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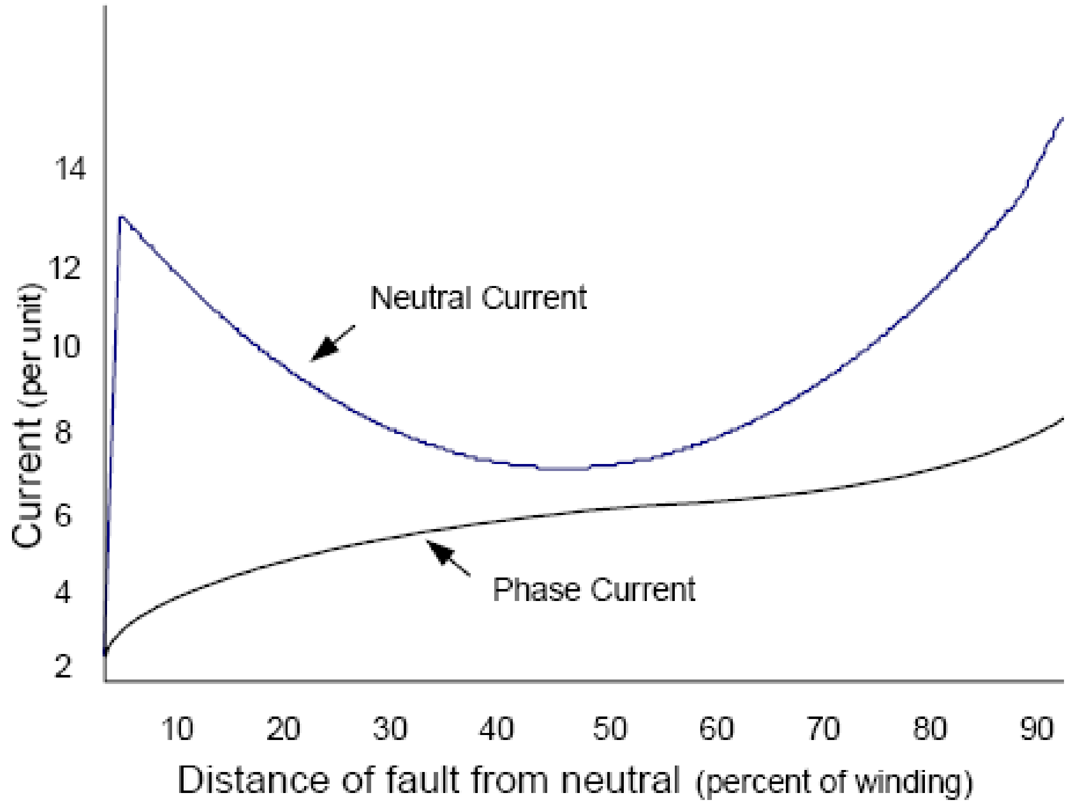
Amplification of Neutral Current



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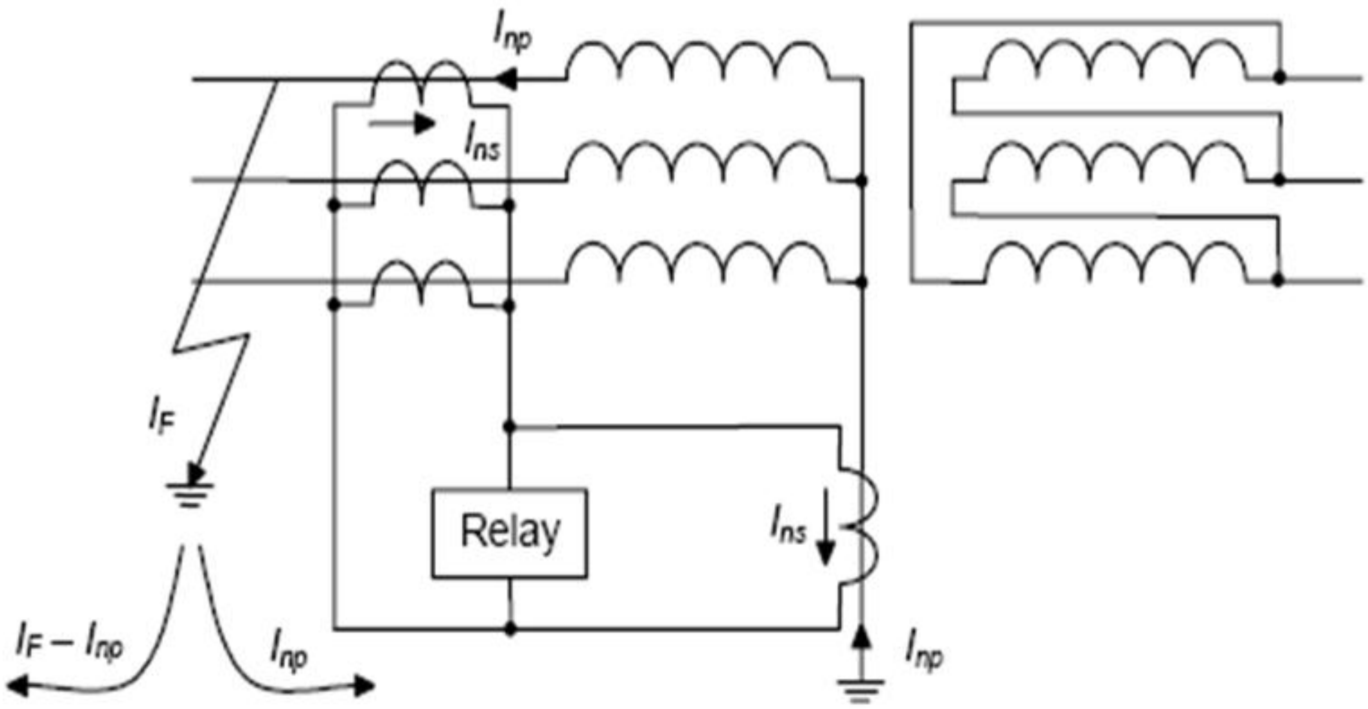
Currents During External Faults



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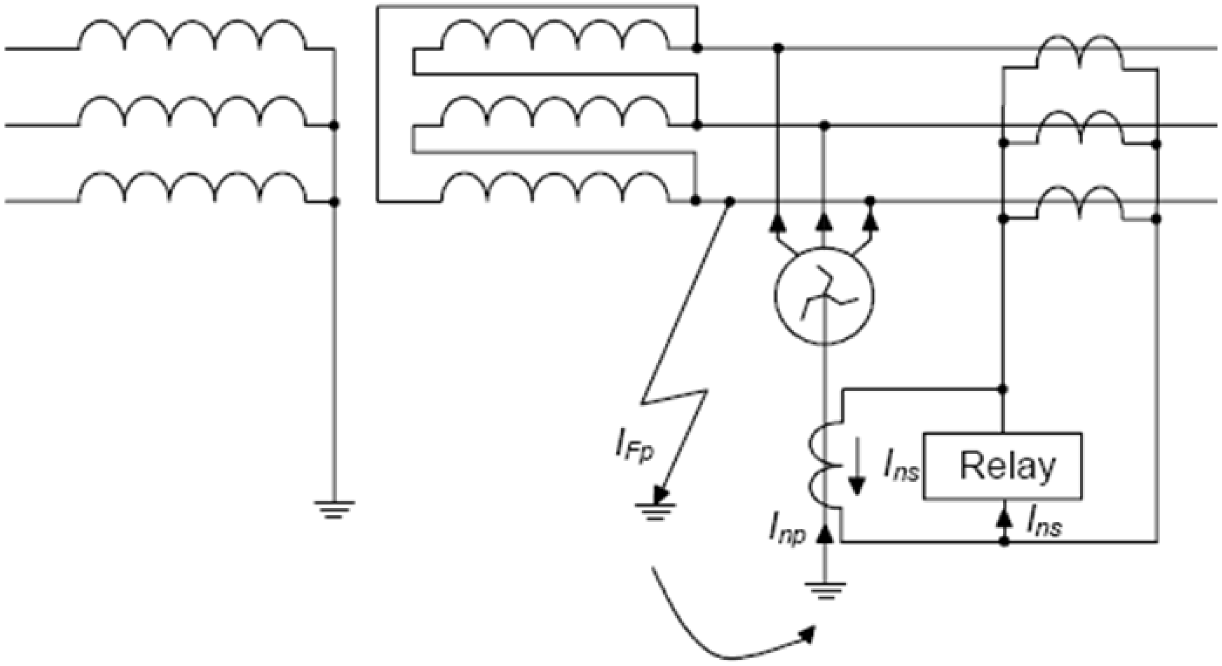
Currents During an Internal Fault



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Applications

Transformer Protection

- Differential Relays
  - ✓ Mainly percentage biased relays
  - ✓ 2^{nd} and 5^{th} harmonic restraints are provided
  - ✓ High Set may be provided on HV winding

- Restricted Earth Fault Relay
  - ✓ High Impedance Schemes are popular

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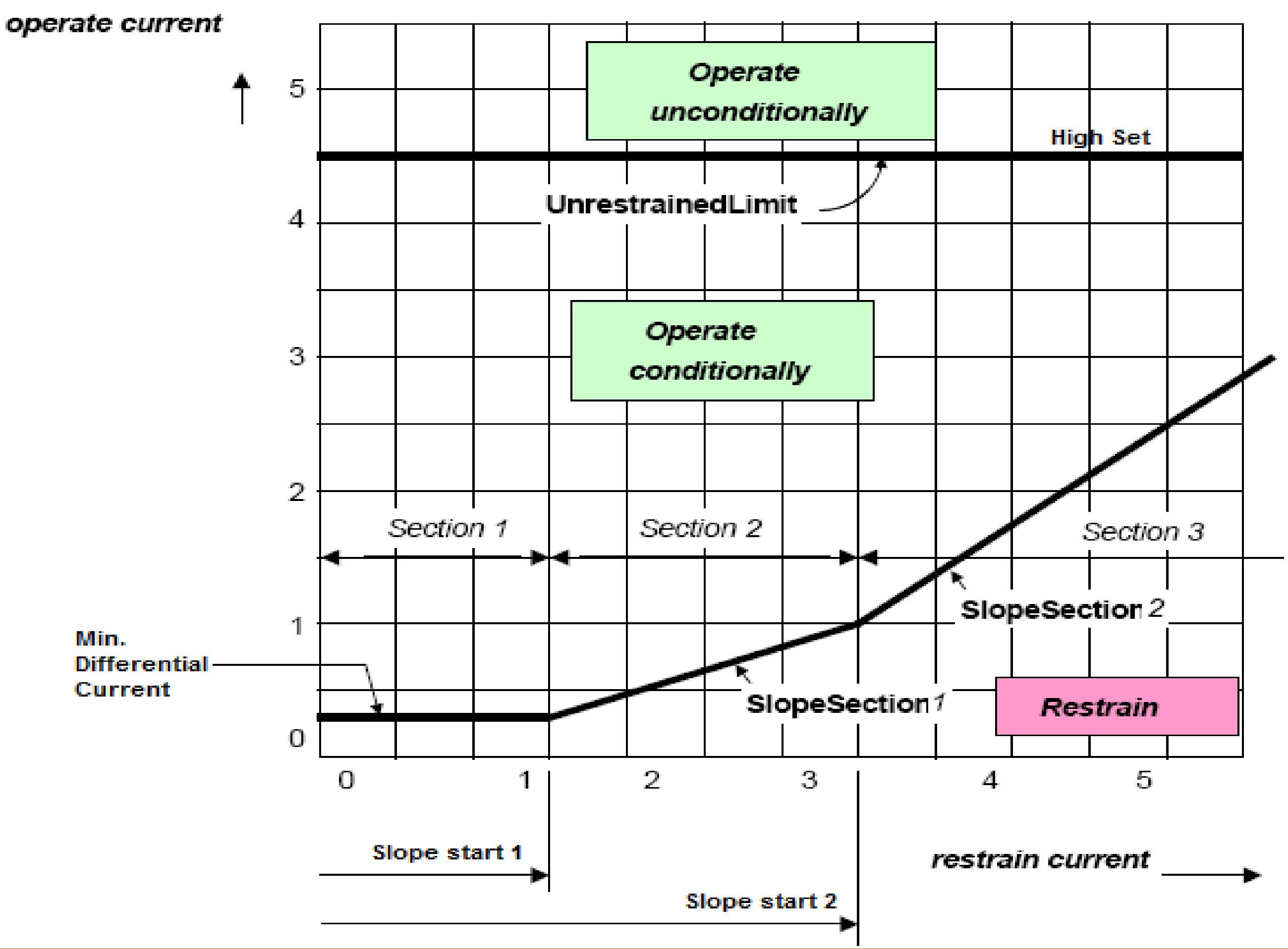
Modern Day Transformer Protection



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Line/Cable Protection

Differential Protection

- Percentage biased schemes are used
- Inrush currents are considered
- Major challenge was the distance between two ends

Pilot Wire Protection

- Measurements communicated over the pilot wire
- Balanced voltage as well as circulating current schemes are used

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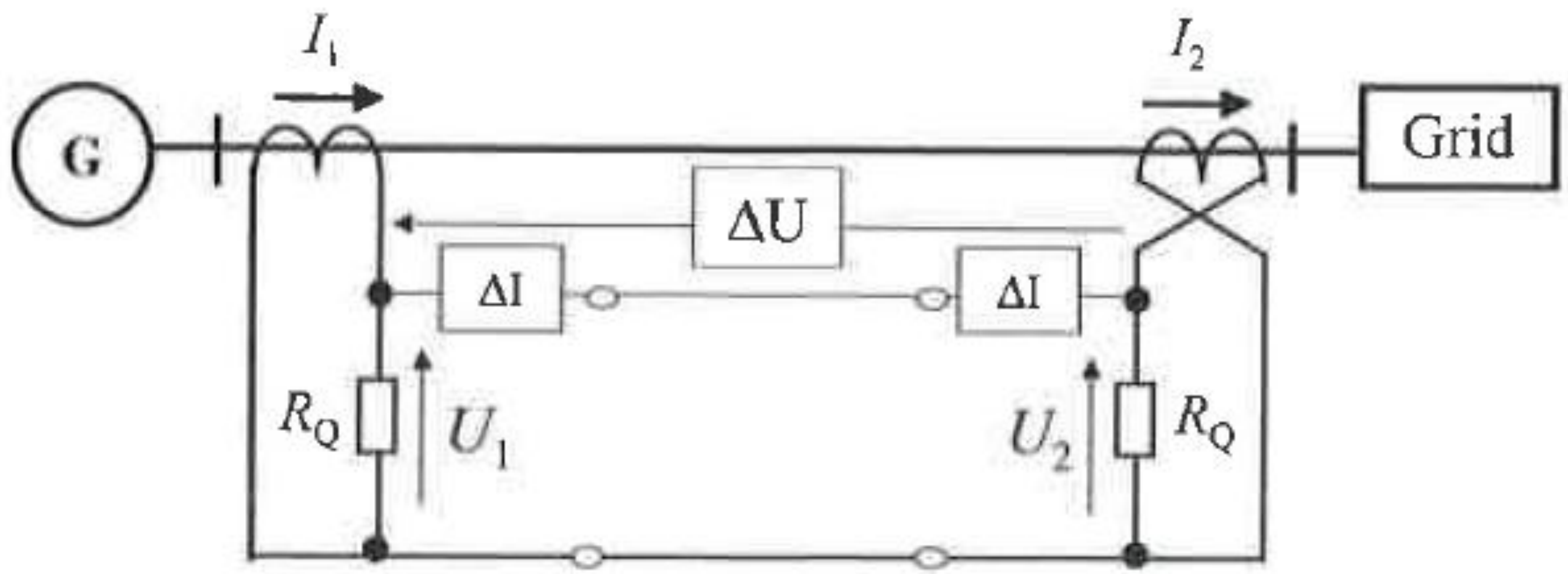
Balanced Voltage Scheme



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Comparison of Pilot Wire Schemes

Balanced Voltage	Circulating Current
▪ Works on the tripping principle	▪ Works on blocking principle
▪ Interruption to the pilot wires causes blocking	▪ Interruption of the pilot wires causes tripping
▪ Short circuit of pilot wires leads to tripping	▪ Short circuit of pilot wires leads to blocking
▪ Overcurrent protection required to prevent incorrect tripping due to short circuit of pilot wires	▪ Overcurrent protection required to block operation for large currents due to pilot wire interruption

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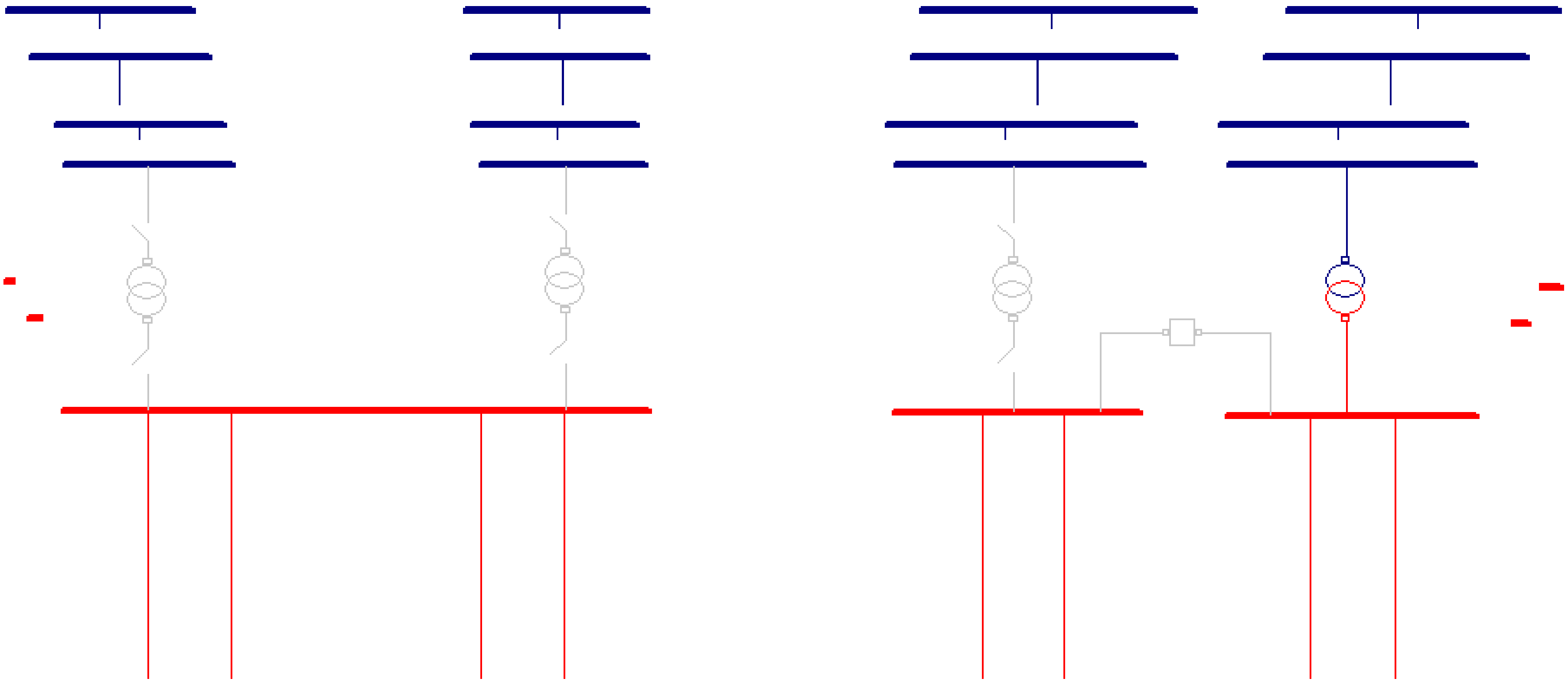
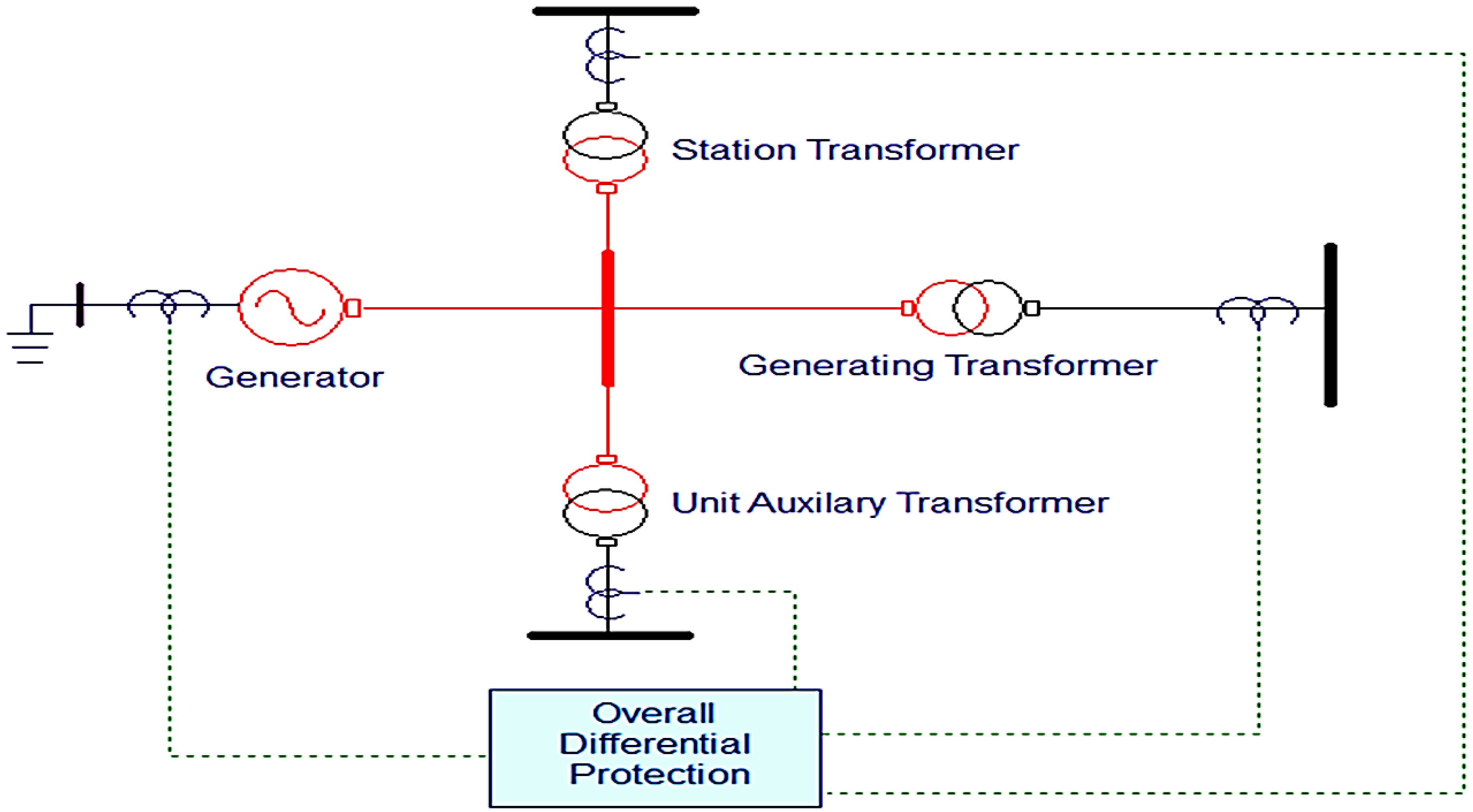
Bus-Bar Protection

- Differential Schemes
  - ✓ Incoming and outgoing currents are balanced
  - ✓ Multiple CT connections
  - ✓ Both High and Low Impedance Schemes are used
- Partial Bus Bar Relay
  - ✓ Retention of supply to healthy portion of the network

Partial Bus Bar Relay Example



Overall Differential Protection



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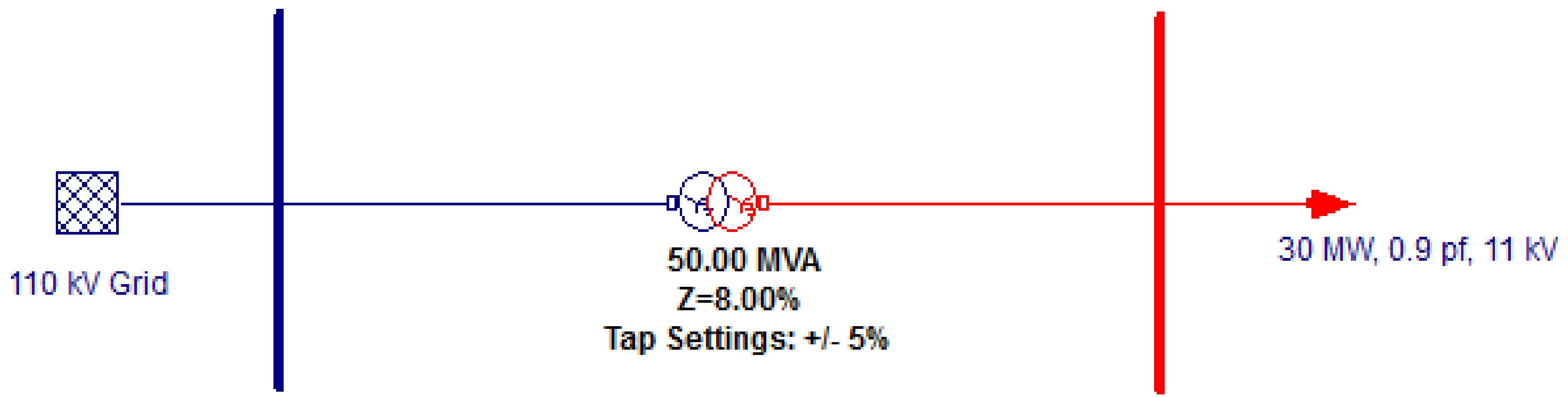
Setting Examples

Sample Network



General Parameters

Parameter	Value	Unit
Mid tap Voltage in %	0	
Primary side Full load Current at Mid tap Voltage	262.4319405	A
Secondary side Full load current	2624.319405	A

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Secondary Ratio Compensation

Parameter	Value	Unit
Secondary side Full load Current on CT secondary	0.874773135	A
Secondary side ratio compensation	1.143153533	
Secondary Full load CT secondary current with ratio correction	1	A

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Primary Side Ratio Compensation

Parameter	Value	Unit
Primary full Load current At Maximum tap Voltage	249.9351815	A
Primary full Load current At Minimum tap Voltage	276.2441479	A
Primary side Full load Current on CT secondary side at Mid tap Voltage	0.874773135	A
Primary full Load current on CT secondary side At Maximum tap Voltage	0.833117272	A
Primary full Load current on CT secondary side At Minimum tap Voltage	0.920813826	A
Primary side ratio compensation	1.143153533	

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Differential Current Computation

Parameter	Value	Unit
Primary full Load current on CT secondary with ratio correction At Maximum tap Voltage	0.952380952	A
Primary full Load current on CT secondary with ratio correction At Minimum tap Voltage	1.052631579	A
Differential current at maximum tap	0.047619048	A
Differential current at minimum tap	0.052631579	A

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Restraint Current Calculation

Parameter	Value	Unit
Restraint current at maximum tap	0.976190476	A
Restraint current at minimum tap	1.052631579	A
Setting Error at maximum tap	4.87804878	%
Setting Error at minimum tap	5.00	%

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Relay Settings

Setting	Value	Unit
Min Current	0.15	A
Slope 1 Start	0.75	A
Slope 1	20	
Slope 2 Start	1.33	A
Slope 2	75	
High Set	12.5	A

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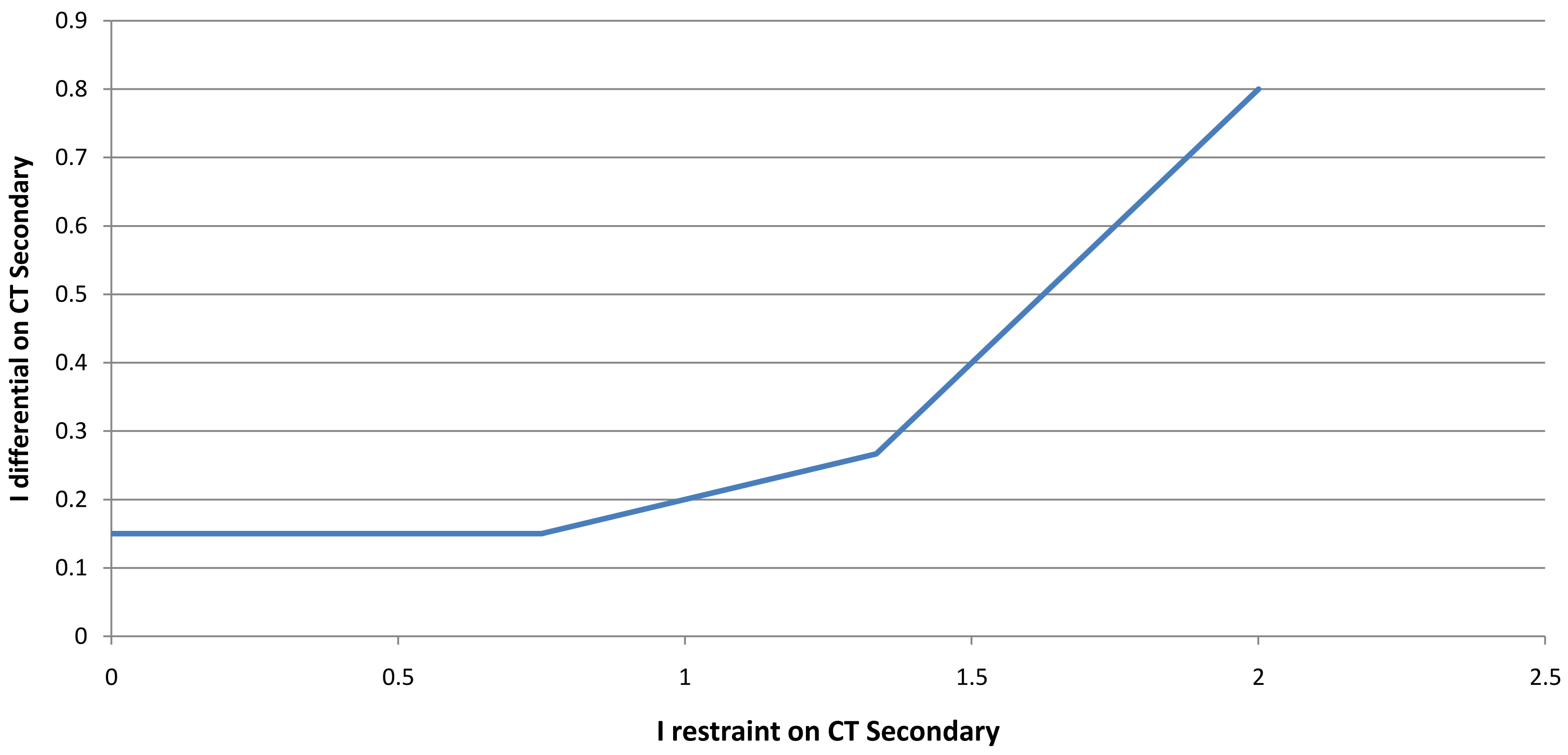
Relay Characteristics



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REF - CT Selection

- The voltage across the stabilizing resistor at maximum through fault current is given by

  $Vs = k*I_{kmax}*(R_{CT} + 2.\ R_L)/\ n$ volts

  Where:

  R_{CT}= current transformer secondary winding resistance

  R_L = One way maximum lead resistance from the CT to the relaying point

  I_{kmax} = maximum external fault current

  k = stabilizing factor used to account for the distorted voltage wave due to faults.

  n = transformation ratio of the CT

- **The knee point voltage of the CTs should be chosen at least 2 times the stability voltage setting**

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REF - Voltage Settings Considerations

- Always, relay operating voltage should be less than Vk/2 but more than Vs.
- If stability voltage increases beyond Vk, CT enters saturation region for which there is infinite Magnetization (Current), but voltage remains at the same level (no huge change in voltage). This condition is seen as open circuited on the secondary.
- Vset >Vs, such that relay will not operate for external fault with CT saturation condition.

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REF - Stabilizing Resistor Design

- The value of the I_{prim} at which the relay operates at certain settings can be calculated as follows:

  $I_{prim} = n * (Ir + m*(Vs/V_k)*Io)$ A

  Where,

  n = the transformation ratio of the current transformer

  Ir = the current value representing the relay setting

  m = the number of current transformers included in the protection

  Io = the magnetizing current of one current transformer at knee point voltage, V_k.

- The relay setting current Ir can be computed as

  $Ir = (I_{prim} / n) - m*(Vs/V_k)*Io$ A

- The setting of the stabilizing resistor (Rs) must be calculated in the following manner, where the setting is a function of the required stability voltage setting (Vs) and the relay current setting (Ir).
- Stabilizing Resistor value, **Rs = Vs/Ir**

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REF - Metrosil Requirement

- The following equations should be used to estimate the peak transient voltage that could be produced for an internal fault.

$Vp = 2 * sqrt(2. Vk(V_f – Vk))$ volts

$V_f = If *(R_{CT} + 2.R_L + Rs)$ volts

Where:

Vp = Peak voltage developed by the CT under internal fault conditions.

V_k = Current transformer knee-point voltage.

V_f = Maximum voltage that would be produced if CT saturation did not occur.

If = Maximum internal secondary fault current.

R_{CT} = Current transformer secondary winding resistance.

R_L = One way maximum lead burden from current transformer to relay.

Rs = Stabilizing resistor.

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Queries & Discussions

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