Power Systems

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(This Module shall only be Used for Educational Purpose.)

POWER SYSTEMS

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1 TRANSMISSION LINE PARAMETER

1.1. Introduction

1.1.1. Inductance

$$L = \frac{d\psi}{dI} \quad or \; \frac{\psi}{I}$$

Steps to find out Inductance

1. First find out H by ampere's circuital law $\int H \cdot dl = I_{enc}$
2. Then find out B = μH
3. Find out flux $\phi = \int B \cdot ds$

   (surface area is normal to flux)
4. Then find out flux linkage $\psi = \phi N$
5. $L = \frac{\psi}{I}$

- Flux linkage and Inductance of isolated conductor

  Internal flux linkage and Inductance $\psi_{\text{int}} = \frac{\mu I}{8\pi} = 0.5 \times 10^{-7} I$ wb –T/m

$$L_{\text{int}} = \frac{\psi_{\text{int}}}{I} = 0.5 \text{ mH/km}$$

- Flux linkage outside the conductor between two point D_1 & D_2 distance from center of conductor

$$\psi_{12} = \frac{\mu I}{2\pi} \ln \frac{D_2}{D_1} = 2 \times 10^{-7} I \; \ln \frac{D_2}{D_1}$$

Inductance of conductor due to flux between point 1 & 2

$$L_{12} = \frac{\psi_{12}}{I} = \frac{\mu}{2\pi} \ln \frac{D_2}{D_1} \quad or \quad 2 \times 10^{-7} \ln \frac{D_2}{D_1}$$

Inductance of a single conductor due to flux up to distance D

$$\psi = 2 \times 10^{-7} I \quad \ln \frac{D}{re^{-1/4}}$$

$$L = 2 \times 10^{-7} \; \ln \frac{D}{r^1} \text{ H/m} \quad \text{or} \quad L = 0.4605 \; \log \frac{D}{r^1} \text{mH/km} \; \text{ mH/km}$$

$$\boxed{r^1 = re^{-1/4} \quad or \; 0.7788r}$$

Inductance of 1ϕ 2 wire line :

- Inductance per conductor = $2 \times 10^{-7} \ln \dfrac{D}{r^1}$

$$\text{loop Inductance} = 4\times10^{-7}\ln\frac{D}{r^1}\,H/\text{m}$$

- Flux linkage of one conductor in group of conductor. If n conductor exist such that sum of current in these conductors are zero $I_1 + I_2 + I_3 .....I_n = 0$

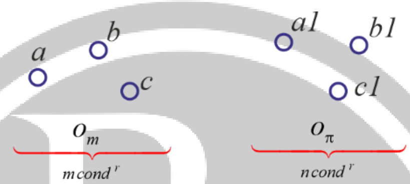
  Total flux linkage in i^{th} conductor is

$$\psi_i = 2\times10^{-7}\left[I_1\ln\frac{1}{D_{i1}} + I_2\ln\frac{1}{D_{i2}} + ...I_n\ln\frac{1}{D_{in}}\right]$$

or

$$\psi_i = 2\times10^{-7}\sum_{k=1}^{n} I_k \ln\frac{1}{D_{ik}}$$

Inductance of composite conductor:



$$L = 2\times10^{-7}\ln\frac{GMD}{GMR} \quad \text{or} \quad L = 2\times10^{-7}\ln\frac{D_m}{D_s}$$

D_m = Mutual GMD $\qquad D_S$ = self GMD

$$GMR = \left[(D_{aa}D_{ab} - D_{am})(D_{ba}D_{bb} - D_{bn})(D_{ma}D_{mb} - D_{mn})\right]^{1/m^2}$$

$$GMR = \left[(D_{aa'}D_{ab'} - D_{am})(D_{ba'}D_{bb'} - D_{bn}) - (D_{ma}D_{mb} - D_{mn})\right]^{1/mn}$$

Inductance of a 3 phase line with equilateral spacing

Inductance of any conductor = $2\times10^{-7}\ln\dfrac{D}{r^1}$ H/m/ph

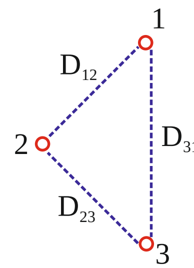
Inductance of 3 phase line with unsymmetrical spacing

$$= 2\times10^{-7}\ln\frac{Deq}{r^1}\ \text{H/m/ph}$$

or

$$= 0.4605\ \ln\frac{Deq}{r^1}\ \mu\text{H/km/ph}$$

$$D_{eq} = \sqrt[3]{D_{12}D_{23}D_{31}}$$



- Inductance of each phase are not same so we transpose these lines at regular interval so each phase has same average inductance.

Inductance of Bundled conductor :

- It use more than arc conductor per phase to reduce corona loss.
- The GMR of bundled conductor can be found in same manner as stranded conductor.
- GMD can be calculated by taking distance from center of one bundle conductor to center of second conductor of other bundle as a distance D_{12}, D_{23}, D_{31} .

$$\text{Inductance per phase} = 2\times10^{-7}\ln\frac{GMD}{RMR}$$

- If conductors are placed at regular polygon. The overall GMR can be calculated only for one conductor GMR.
- Remember in all formulas of inductance we use r^1

$$r^1 = 0.7788r$$

- All Inductance is per unit length if length is given multiply it by length to find out total inductance of line
- In 3 phase inductance formula. It is inductance per phase always.

1.1.2. Skin Effect

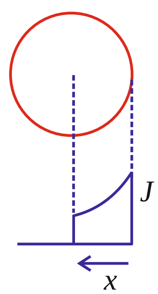
- In A.C the current flow through outer surface so effective cross section is reduce & resistance is increased.

$$J = J_\mu e^{-x/\delta}$$

$\delta =$ skin depth.

$$\delta = \sqrt{\frac{2}{w\mu\sigma}} = \sqrt{\frac{1}{\pi f\mu\sigma}}$$

$$\frac{R_{ac}}{R_{dc}} = \frac{A_{act}}{A_{eff}}$$



so, $R_{ac} > R_{d\cdot c}$

Proximity Effect:

- When direction of current are same current mainly flows through outer edge
- If current are in opposite direction current mainly flows from inner edge.
- Proximity effect increase effective resistance. It is more dominating in cable than OH line

1.1.3. Type of Conductors

1. Solid conductor

   $Ag > Cu > Au > Al$ (Conduction)

2. Hollow conductor

   Mainly use in busbar Corona loss is less.

3. Stranded conductor.

   - Multiple strand is used in a conductor it reduce skin effect.
   - Total Diameter = (2n – 1) D
   - Total number of strand = $3x^2 - 3x + 1$

     Where x = number of layer
   - All strand are made of same material

Composite Stranded Conductor:

- Generally we use steel & Al, steel increase mechanical strength.

  ASCR (x, y)

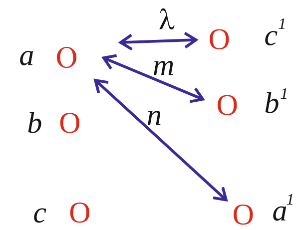
  Minimum (x,y) = Number of steel strand.

  Maximum (x,y) = Number of Aluminum strand.

Bundled Conductor :

1. GMR increase, Inductance decrease, Capacitance increase
2. Surge Impedance = $\sqrt{\frac{L\downarrow}{c\uparrow}}$ decrease and SIL increase = $\uparrow\frac{3v^2}{Z\downarrow}$

   (SIL = Surge Impedance Loading)
3. Power transfer capacity increase $\uparrow = \frac{v_s v_r}{X\downarrow}$
4. Reduce corona loss and interference with communication line.



1.1.4. Inductance of Double Circuit Line :

- Here we use two separate circuit on same tower.

$$L = 2\times10^{-7}\ln\left[2^{1/6}\left(\frac{D}{r^1}\right)^{1/2}\left(\frac{m}{n}\right)^{1/3}\right] H/Phase/m$$

1.2. Capacitance of Line

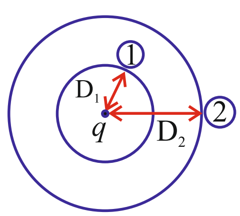
- Due to capacitance charging current flow
- Charging current reduce overall current and line losses.
- It improve Power factor and it reduce voltage drop

Electrical field due to long conductor:

$$E = \frac{q}{2\pi\in x}\text{ v/m}$$

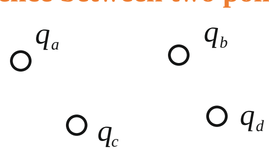
q = line charge density, charge per unit length.

Potential difference between two point:



$$v_{12} = \frac{q}{2\pi\in}\ln\frac{D_2}{D_1}$$

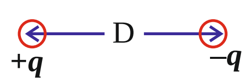
Potential difference between two point due to number of charges:



$$D - r \simeq D + r \simeq D$$

$$v_{ab} = \frac{q_a}{2\pi\in}\ln\frac{D_{ab}}{r} + \frac{q_b}{2\pi\in}\ln\frac{r}{D_{ab}} + \frac{q_c}{2\pi\in}\ln\frac{D_{cb}}{D_{ca}} + \frac{q_d}{2\pi\in}\ln\frac{D_{db}}{D_{da}}$$

1.2.1. Capacitance Between 1ϕ, 2 wire line



$$c_{ab} = \frac{q}{v_{ab}} = \frac{\pi \in}{\ln D/r} F/m$$

Or $$c_a = \frac{0.01206}{\log D/r} \mu\text{F/km}$$

- Charging current between two conductor

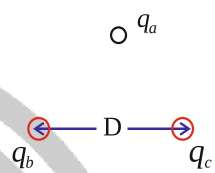
$$\boxed{I_C = jwc_{ab}v_{ab}}$$

- Capacitance to each line to neutral is

$$c_n = 2c_{ab} = \frac{2\pi \in}{\ln D/r} F/m$$

or $$c_n = \frac{0.02412}{\log D/r} \mu\text{F/km}$$

1.2.2. Capacitance of 3ph line with Equilateral Spacing :



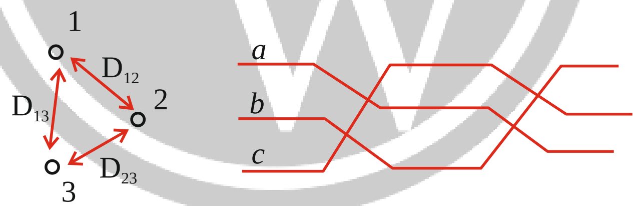
$$q_a + q_b + q_c = 0$$

Line to neutral voltage, $$c_n = \frac{2\pi \in}{\ln D/r} F/m$$

$$c_n = \frac{0.02412}{\log(D/r)} \mu F/km$$

Charging current $I_C = jwc_n v_{ph}$

1.2.3. Capacitance of 3 phase line with a Symmetrical Spacing:



$$c_n = \frac{2\pi \in}{\ln D_{eq}/r} \quad F/m$$

$$c_n = \frac{0.02412}{\ln D_{eq}/r} \quad \mu F/km$$

Charging $$v_A = \sqrt{3} v_L I_C$$

v_L = line voltage

Capacitance of Bundled Conductor:

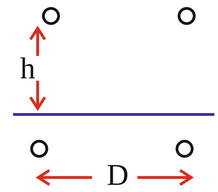
$$c_n = \frac{2\pi \in}{\ln D_{eq}/GMR(\text{mod})} \text{ F/m}$$

$$c_n = \frac{0.02412}{\ln D_{eq}/GMR(\text{mod})} \quad \mu F/km$$

In modified GMR method we use r in place of r^1

Effect of ground

1ϕ, 2 wire line



$$c_n = \frac{2\pi \in}{\ln\left(\dfrac{D}{r\sqrt{1+\dfrac{D^2}{4h^2}}}\right)}$$

So presence of ground increase the line capacitance

1.3. Resistance of TL

$$R = \frac{\rho l}{a}$$

Radius of earth = 6400 km

$$R_{earth} \simeq 0$$

- Loop resistance of 1ϕ, 2 wire line = 2R
- Resistance may vary as per temperature.
- Skin & proximity effect increase value of resistance.

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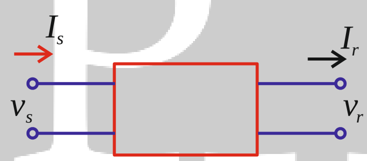
2 Performance of Transmission Line

2.1. Introduction

The voltage and current travel like a wave with λ = 6000 km (for f = 50 Hz)

1. If $lf < 4000$ ($l < 80$ km) $\Rightarrow$ Short line
2. If $4000 < lf < 8000$ ($80 < l < 160$) $\Rightarrow$ Medium line
3. If $lf > 8000$ ($l > 160$) $\Rightarrow$ Long line

2.1.1 Transmission Line as a two port Network



$$\begin{bmatrix} v_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} v_r \\ I_r \end{bmatrix}$$

$$\begin{bmatrix} v_r \\ I_r \end{bmatrix} = \begin{bmatrix} D & -B \\ -C & A \end{bmatrix} \begin{bmatrix} v_s \\ I_s \end{bmatrix}$$

For symmetrical network A = D

- Any network which consist of passive element only will be reciprocal network.

$$z_{so} = \frac{A}{C} \quad \text{(Sending end Impedance if receiving end is o/c)}$$

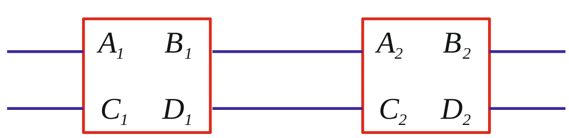
$$z_{ss} = \frac{B}{D} \quad \text{(Sending end impedance if receiving end is s/s)}$$

$$z_c = \sqrt{z_{so} z_{ss}} = \sqrt{\frac{AB}{CD}}$$

z_c = characteristic impedance for T.L (Symmetrical) A = D

So, $$z_c = \sqrt{\frac{B}{C}}$$

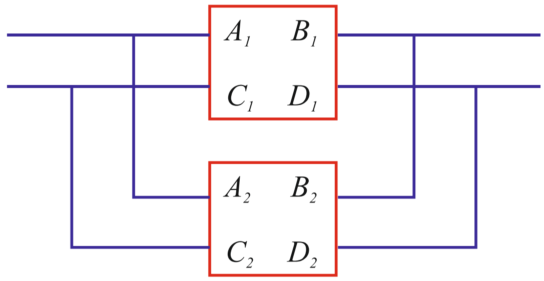
- Two network connected in cascade



$$= \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix}$$

- Cascaded network is also a symmetrical network.

2.1.2. Two Network Connected in Parallel



Overall

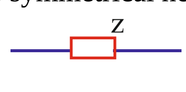
$$A = \frac{A_1B_2 + B_1A_2}{B_1 + B_2}$$

$$B = \frac{B_1B_2}{B_1 + B_2}$$

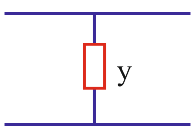
$$C = (C_1 + C_2) + \frac{(A_1 - A_2)(D_2 - D_1)}{B_1 + B_2}$$

$$D = \frac{D_1B_2 + D_2B_1}{B_1 + B_2}$$

Resultant network is symmetrical network.



$$= \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix}$$



$$= \begin{bmatrix} 1 & 0 \\ y & 1 \end{bmatrix}$$

2.2. Performance Parameter

1. Efficiency

$$\eta = \frac{p_r}{p_r + losses} = \frac{p_r}{p_r + 3I^2R}$$

While calculating *n* we will neglect corona loss & loss due to leakage current.

Here we use p_r = 3ϕ receiving end power

2. Voltage Regulation

$$V.R = \frac{|V_{RO}| - |V_R|}{|V_R|} \times 100\%$$

V_{RO} = No load receiving end voltage

V_R = On load receiving end voltage

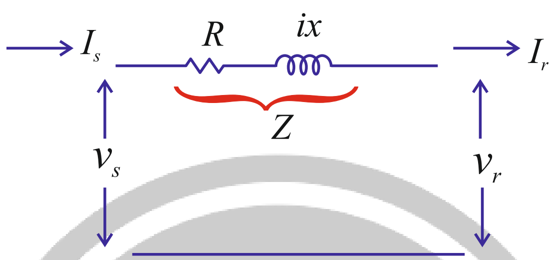
$$V_{RO} = \frac{v_s}{A}$$

So, $$V.R = \frac{\left|\frac{v_s}{A}\right| - |v_r|}{|v_r|} \times 100\%$$

3. Charging current

$$I_C = cv_{ro} = \frac{cv_s}{A}$$

2.2.1. Short Transmission Line



$$v_s^2 = (v_r \cos\phi_r + I_r R)^2 + (v_r \sin\phi_r + I_r X)^2$$

$$\tan\phi_s = \frac{v_r \sin\phi_r + I_r X}{v_r \cos\phi_r + I_r R}$$

ϕ_s = sending end Pf

ϕ_r = receiving end Pf = $\tan^{-1}\frac{X_L}{R_L}$

ϕ_r = +ve for lag (current lag by voltage)

ϕ_r = –ve for lead

- Condition of zero V.R $\boxed{\cos(\theta - \phi_r) = \frac{-I_r z}{2v_r}}$

It occur at leading P.f.

- Condition for maximum V.R. $\boxed{\theta = \phi_r}$

  Maximum V.R = $\frac{I_r z}{v_r} = \text{p} \cdot \text{u}$ impedance

  * where θ = T.L impedance angle = $\tan^{-1}\frac{X}{R}$

Approx :

$$v_s = v_r + I_r R\cos\phi_r + I_r X\sin\phi_r$$

$$\boxed{V.R. = \frac{v_s - v_r}{v_r} = \frac{I_r R\cos\phi_r + I_r X\sin\phi_r}{V_r}}$$

$V.R = \nu_r \cos\phi_r + \nu_x \sin\phi x$

ν_r = P.U voltage drop across resistance/ P.U resistance

ν_x = P.U voltage drop across reactance / P.U reactance

- Condition for zero voltage regulation $\boxed{\theta - \phi_r = \frac{\pi}{2}}$ it occur at leading p.f.

$$\theta \ = \text{line Impedance angle} = \tan^{-1}\frac{X}{R}$$

$$\phi_r = \text{load P.f /receiving end P.f} = \tan^{-1}\frac{X_L}{R_L}$$

***R_L* & *X_L* :** Load resistance and reactance
***R* & *L* :** T.L resistance and reactance

- Condition for maximum voltage regulation $\boxed{\theta = \phi_r}$

Case I if $\theta > \phi_r$
then $\phi_s > \phi_r$

$$(P.f)_s < (P.f)_r$$

Case II if $\theta > \phi_r$
$\phi_s < \phi_r$

$$(P.f)_s > (P.f)_r$$

Case III if $\theta = \phi_r$
$\phi_s = \phi_r$

$$(P.f)_s = (P.f)_r$$

ϕ_s = sending end P.f angle
ϕ_r = receiving end P.f angle
θ = T.L Impedance angle

2.3. ABCD Parameter

$$\begin{bmatrix} v_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_r \\ I_r \end{bmatrix}$$

2.3.1. Voltage Regulation

$$V.R. = \frac{|V_S| - |v_r|}{|V_r|} \times 100\%$$

Efficiency $$\eta = \frac{p_r}{p_r + 3I_r{}^2 R} \times 100\%$$

Charging current $$I_C = \frac{C}{A} v_s \quad = \frac{0}{A} v_s = 0$$

Phasor Equations :

1. Take receiving end voltage as a reference $\vec{v_r} = |v_r| < 0$
2. Always take angle of I_r

$$\vec{I_r} = |I_r| \angle -\phi_r \begin{bmatrix} -\phi_r = for\,lag \\ +\phi_r = for\,lead \end{bmatrix}$$

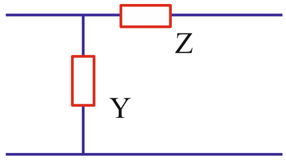
3. Now apply formula $\vec{v_s} = \vec{v_r} + \vec{I_r}(R + jX)$

This will give $|v_s|$ as well as ϕ_s

- All v_s and v_r are per phase quantity.

2.3.2. Medium Transmission Line

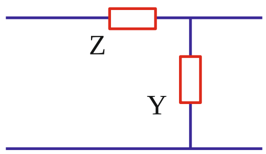
1. Sending end C Model



$$= \begin{bmatrix} 1 & Z \\ Y & 1+YZ \end{bmatrix}$$

$\rightarrow$ It is not a symmetrical model.

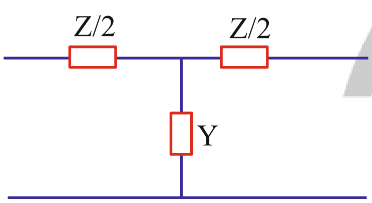
2. Receiving end C model.



$$= \begin{bmatrix} 1+YZ & Z \\ Y & 1 \end{bmatrix}$$

$\rightarrow$ it is not a symmetrical model.

Nominal T Model :



$$Z = R + jwL$$

$$Y = \frac{1}{jwc}$$

$$\begin{bmatrix} v_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1+\frac{YZ}{2} & z\left(1+\frac{YZ}{4}\right) \\ Y & 1+\frac{YZ}{2} \end{bmatrix} \begin{bmatrix} v_r \\ I_r \end{bmatrix}$$

It is symmetrical & reciprocal network.

Voltage Regulation:

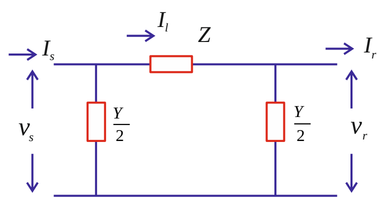
$$V.R. = \frac{\frac{v_s}{1+\frac{YZ}{2}} - v_r}{v_r} \times 100\%$$

Charging Current :

$$I_C = \frac{Y}{1+\frac{YZ}{2}} v_s$$

$$\text{Efficiency } \eta = \frac{p_r}{p_r + 3\frac{R}{2}\left(I_s^2 + I_r^2\right)} \times 100\%$$

Nominal π Model :



$$\begin{bmatrix} v_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1+\frac{YZ}{2} & Z \\ Y\left(1+\frac{YZ}{4}\right) & 1+\frac{YZ}{2} \end{bmatrix} \begin{bmatrix} v_r \\ I_r \end{bmatrix}$$

Voltage Regulation :

$$V.R = \frac{\frac{v_s}{1+\frac{YZ}{2}} - v_r}{v_r} \times 100\%$$

$$\text{Efficiency} \quad \eta = \frac{p_r}{p_r + 3I_l^2 R} \times 100\%$$

$$I_l = I_r + v_r \frac{Y}{2}$$

Long T.L

$$\begin{bmatrix} v_s \\ I_s \end{bmatrix} = \begin{bmatrix} \cosh rl & z_c \sinh rl \\ \frac{1}{z_\in} \sinh rl & \cosh rl \end{bmatrix} \begin{bmatrix} v_r \\ I_r \end{bmatrix}$$

$r = \sqrt{zy}$ is called propagation constant

$z_c = \sqrt{\frac{z}{y}}$ is called charactenstic Impedance.

z = per unit length line Impedance

y = per unit length line admittance.

$$r = \alpha + j\beta$$

α = attenuation constant

β = phase constant

$$\cosh rl = \cosh(\alpha l + jBl)$$
$$= \cosh \alpha l \cos \beta l + j \sinh \alpha l \sin \beta l$$
$$= \sinh rl = \sinh(\alpha l + jBl)$$
$$= \sinh \alpha l \cos \beta l + j \cosh \alpha l \sin \beta l$$

Approx value of

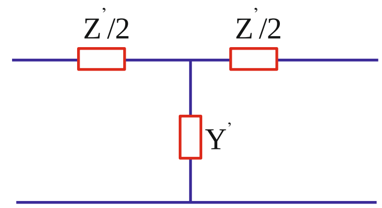
$$A = 1 + \frac{YZ}{2}$$

$$B = Z\left[1 + \frac{YZ}{6}\right]$$

$$C = Y\left[1 + \frac{YZ}{6}\right]$$

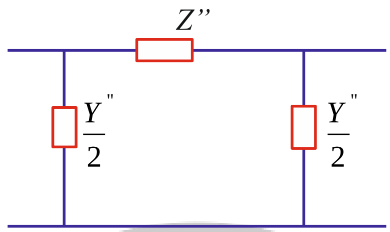
$$D = A$$

Equivalent T Model :



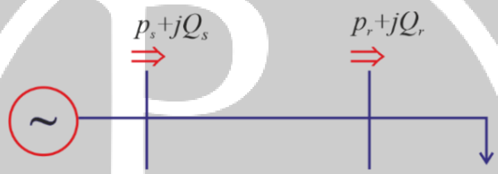
$$Y' = \frac{\sinh rl}{z_c} \qquad \frac{z'}{2} = z_c \tanh\frac{rl}{2}$$

Equivalent π Model :



$$z'' = z_c \sinh rl \qquad \frac{Y''}{2} = \frac{1}{z_c}\tanh\frac{rl}{2}$$

Power Formula



$$P_r = \frac{|v_s||v_r|}{|B|}\cos(\beta-\delta) - \frac{|A||v_r|^2}{|B|}\cos(\beta-\alpha)$$

$$Q_r = \frac{|v_s||v_r|}{|B|}\sin(\beta-\delta) - \frac{|A||v_r|^2}{|B|}sin(\beta-\alpha)$$

- If v_s & v_r are per phase voltage then it give per phase power. If v_s & v_r are line then it will be $3-\phi$ power.
- For maximum active power at receiving end

$$\boxed{\delta = B}$$

For stability $\frac{dP}{d\delta} > 0$

So if	B > δ	⇒	Stable
	B < δ	⇒	Unstable
	B = δ	⇒	Critically stable

Here $A = |A|\angle\alpha$ $\quad B = |B|\angle\beta$

$v_r = |v_r|\angle 0$ $\quad v_s = |v_s|\angle\delta$

For short T.L

$$\boxed{P_r = \frac{|v_s||v_r|}{|x|}\sin\delta}$$

In general if $v_s = |v_s| < \delta_1$ and $v_r = |v_r| < \delta_2$

$$\boxed{P_r = \frac{|v_s||v_r|}{|x|}\sin(\delta_1 - \delta_2)}$$

So active power flow from higher angle to lower angle if R < < X

$$\phi_r = \frac{|v_s||v_r|}{|x|}\cos\delta - \frac{|v_s|^2}{|x|}$$

Reactive power flow from higher voltage region to lower voltage region.

2.3.3. Sending end Power Formula

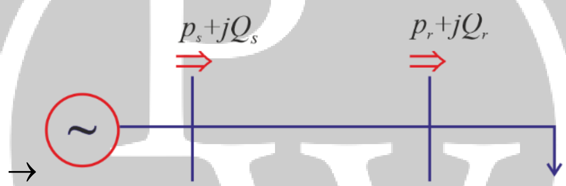
$$P_s = \frac{|A||v_s|^2}{|B|}\cos(\beta-\alpha) - \frac{|v_s||v_r|}{|B|}\cos(\beta+\delta)$$

$$Q_s = \frac{|A||v_s|^2}{|B|}\sin(\beta-\alpha) - \frac{|v_s||v_r|}{|B|}\sin(\beta+\delta)$$

- For maximum P_s $\boxed{\delta = 180-\beta}$
- For short transmission line

$$P_s \frac{|v_s||v_r|}{|x|}\sin\delta$$

$$Q_s = \frac{|v_s|^2}{|x|} - \frac{|v_s||v_r|}{|x|}\cos\delta$$



$$P_s + jQ_s = v_s I_s^*$$

$$P_r + jQ_r = v_r I_r^*$$

* P_s & Q_s is positive if it transfer power from source to line

* P_r & Q_r is positive if power transfer from line to load.

Ferranti effect – At no load & less load receiving end voltage is more than sending end voltage.

$$v_s - v_{ro} = -\frac{w^2 l^2}{18} v_{ro} \times 10^{-10} volt$$

v_s = sending end voltage at no load

v_{ro} = receiving end voltage at no load

$w = 2\pi f$

l = length of line.

2.4. Wave Nature

- Any function whose amplitude change w.r.t space as well as time is called wave.

$$F(x, t) = A\sin(wt - kx + \phi)$$

Is forward moving wave with constant amplitude.

& $f(x,t) = Ae^{-\alpha x}\sin(wt - kx + \phi_1)$ is forward moving wave whose amplitude attenuate while travelling.

- At any point in transmission line voltage is made from two wave form.

(i) Incident wave moving is forward direction

$$v(x,t)=\sqrt{2}\left|\frac{v_r+I_r z_c}{2}\right|e^{-\alpha x}\sin(wt-\beta x+\phi_1)$$

(ii) Reflected wave moving in backward direction.

$$v(x,t)=\sqrt{2}\left|\frac{v_r-I_r z_c}{2}\right|e^{\alpha x}\sin(wt+\beta x+\phi_2)$$

Similarly current at any point in T.L. is made from two wave form.

1. Incident current wave form moving in forward direction.

$$I(x,t)=\frac{1}{z_c}\sqrt{2}\left|\frac{v_r+I_r z_c}{2}\right|e^{-\alpha x}\sin(wt-\beta x+\phi_1)$$

2. Reflected current wave moving in back ward direction

$$I(x,t)=-\frac{1}{z_c}\sqrt{2}\left|\frac{v_r-I_r z_c}{2}\right|e^{\alpha x}\sin(wt+\beta x+\phi_2)$$

$$\frac{\text{Incident voltage wave}}{\text{Incident current wave}}=z_c$$

$$\frac{\text{Reflected voltage wave}}{\text{Reflected current wave}}=-z_c$$

Characteristic Impedance:

- Impedance offered by T.L. to travelling wave

$$Z_C=\sqrt{\frac{z}{y}}=\sqrt{\frac{Z}{Y}}=\sqrt{\frac{R+jwL}{G+jwc}}$$

- It does not depend on length and it is capacitive in nature.

Surge Impedance :

It is characteristic Impedance of a loss less line $Z_S=\sqrt{\frac{L}{C}}$

- T.L surge impedance = 400Ω
- U.G surge impedance = 40Ω
- X-mer surge impedance = 5000Ω
- Inductor surge impedance = ∞
- Capacitor surge impedance = 0

Infinite line/ Flat line :

If $Z_L=Z_C$

No reflected wave. The magnitude of voltage and current remain constant throughout line

Propogation Constant:

$$r=\alpha+j\beta$$

It tell about change in amplitude and phase when wave propogate in given direction.

α = attenuation constant, it is measure of change in amplitude of wave as wave propogate in given direction.

Unit = Neper /meter.

β = Phase constant, it is a measure of change of phase when it propogate in given direction

Unit = rad/meter

- wave length $X = \frac{2\pi}{\beta}$
- time period $T = \frac{2\pi}{w}$
- velocity $v = \frac{w}{\beta} = \frac{1}{\sqrt{l \cdot c}} = \frac{1}{\sqrt{\mu \in}}$

Distortion Less Line:

In this line wave propogate without changing its shape

$$\frac{L}{R} = \frac{C}{G}$$

$$\boxed{LG = RC}$$

Surge Impedance loading / Natural Loading:

A line operating at natural load if it is terminated by a resistance equal to its surge Impedance.

$$P = \frac{3v^2}{z_s}$$

- v = per phase voltage

or

$$\boxed{P = \frac{v_L^2}{z_s}} \qquad z_s = \sqrt{\frac{L}{C}}$$

- At this loading generation of reactive power by T.L is equal to consumption of reactive power
- Long line is loaded up to SIL by short line may be loaded several times of SIL.
- If line is terminated by surge Impedance then v(x) = $v_r \angle \beta x$ so voltage remain same but there will be phase difference.
- Similarly $I(x) = I_r \angle \beta x$ so current remain same but there may phase difference.
- But No phase difference between voltage and current.
- $P(x) + jQ(x) = \frac{{v_r}^2}{z_S} + j0$

So no reactive power flow and no power loss occur.

Case-I	if	loading = SIL $\lvert v_s \rvert = \lvert v_r \rvert$
Case-II	if	loading < SIL $\lvert v_R \rvert > \lvert v_s \rvert$
Case-III	if	loading > SIL $\lvert v_r \rvert < \lvert v_s \rvert$

SIL can be increased by

1. By increasing voltage
2. By reducing inductance (reducing GMD and increasing GMR) (using series capacitor)
3. By Increasing capacitance (using shunt capacitor)

❒❒❒

3 CORONA

3.1. Corona

- It is a ionization of air surrounding power conductor. It occur when E at surface of conductor is more than 30 kv/cm (Peak).
- A.C. (violet)
  D.C. (+ bluish white glow uniform
  – reddish tuffs and beads non uniform)
- Hissing sound & odour due to ozone

3.1.1. Critical Disruptive Voltage

$$v_d = 2rg_o\delta m_o \ln\frac{D}{r} \quad \text{For } 1\phi \text{ 2 wire line}$$

$$v_d = rg_o\delta m_o \ln\frac{D}{r} \quad \text{For } 3\phi \text{ line}$$

$$g_o = \frac{3\times10^6}{\sqrt{2}} v/m \text{ (RMS)}$$

$$\delta = \frac{3.92P}{273+Q} \quad P = \text{Pressure}, Q = \text{Temperature}$$

m_o = 1 for smooth conductor

= 0.92 – 0.98 (Rough conductor)

= 0.82 – 0.88 (stranded conductor)

3.1.2. Visual Critical Voltage

$$v_r = 2r\, g_o\delta m_v\left(1+\frac{0.03}{\sqrt{\delta r}}\right)\ln\frac{D}{r} \quad \text{for } 1\phi \text{ 2 wire line}$$

$$v_r = r\, \delta g_o\, m_v\left(1+\frac{0.03}{\sqrt{\delta r}}\right)\ln\frac{D}{r} \quad \text{for } 3\phi \text{ line}$$

m_v = 1 for smooth conductor

= 0.72 for stranded conductor

= 0.82 for decided conductor

Corona Loss:

As per peak formula

$$P = 241\times10^{-5}\,\frac{(f+25)}{\delta}\sqrt{\frac{r}{D}}(v_P - v_D)^2 \text{ kw/km/ph.}$$

v_P = actual per phase voltage

v_D = disruptive critical voltage per phase

δ = air density factor.

Generally this formula give more accurate result if $\frac{v_P}{v_D} > 1.8$

If $\frac{v_P}{v_D} < 1.8$ Peterson formula give more accurate result.

$$P_C = \frac{21\times10^{-6}\, f\, v^2}{\left(\log_{10} D/r\right)^2}\times F$$

F is a factor which will be given the equation.

- Untill, unless it as given in question. Use only peek formula.
- In foul weather condition we take v_D as a 80% of fair weather value.

Factor Affecting Corona:

1. Increase with freq. $P_c \uparrow \alpha(f \uparrow +25)$
2. Increase with voltage $P_c \uparrow \alpha(V_P \uparrow - V_D)^2$
3. At hills $P \uparrow \Rightarrow \delta \downarrow \Rightarrow P_C \uparrow$ corona loss is more
4. With dust, rain and snow corona loss increase
5. With increase conductor diameter, corona loss decrease.
6. No of conductor per phase (Bundled conductor)

   $GMR \uparrow \Rightarrow v_d \uparrow \Rightarrow P_C \downarrow$
7. Heating decrease corona loss.

Advantage of Corona:

1. It dissipate voltage surge as a corona loss
2. It also reduce the steepness.

Disadvantage of Corona:

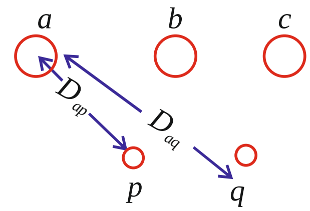
- Create energy loss
- Ozone create corrosion
- C Increase – charging current Increase.
- 3 harmonic current created – it create 3 harmonic voltage drop – create interference with communication line.

Interference in Communication Line

↙ Electromagnetic Induction ↘ Electrostatic Induction

Electromagnetic Induction:

Net flux linkage



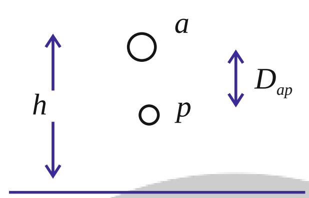
$$\psi = \psi_p - \psi_q = 2\times10^{-7}\left[\vec{I}_a \ln\frac{D_{aq}}{D_{ap}} + \vec{I}_b \ln\frac{D_{bq}}{D_{bp}} + \vec{I}_c \ln\frac{D_{cq}}{D_{cp}} + \right] wb\text{-T/m}$$

Induced EMF (RMS value)

$$E = 2\pi f \psi$$

- By transposition of power line, Induced EMF due to positive and negative current is eliminated.
- To eliminate the effect of zero sequence current the communication line should also be transposed.

Electrostatic Induction :



Voltage Induced in p conductor due to a phase voltage

$$v_{p(a)} = v_a \ln\frac{\frac{2h-D_{ap}}{D_{ap}}}{\frac{2h-r}{r}}$$

Similarly,

$$v_{p(b)} = v_b \ln\frac{\frac{2h-D_{bp}}{D_{bp}}}{\frac{2h-r}{r}}$$

$$v_{p(c)} = v_c \ln\frac{\frac{2h-D_{cp}}{D_{cp}}}{\frac{2h-r}{r}}$$

Total potential of p

$$v_p = v_{p(a)} + v_{p(b)} + v_{p(c)}$$

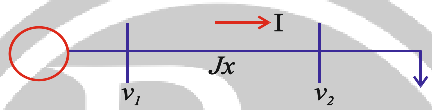
- When power line is transposed, there will be no induced emf between the line at end of barrel
- However a voltage due to electro static induction will still exist between communication line and ground.

4 VOLTAGE COMPENSATION TECHNIQUES & LOAD FREQUENCY CONTROL

4.1. Voltage Control

Voltage level of system should be within $\pm 5\%$ range. The voltage variation is maximum is

- Load is large
- P.f is low.

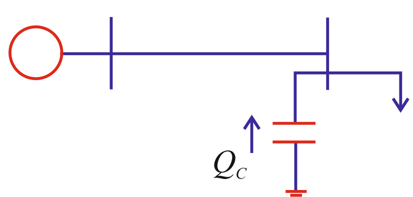


$$v_2 = \left[v_1 - \frac{QX}{v_1}\right] - j\left[\frac{PX}{v_1}\right]$$

$$\boxed{v_2 \simeq v_1 - \frac{QX}{V_1}}$$

Equipment	Source	Sink	None
Generator Syn.	✓ (over excited)	✓ (under excited)	✓ (Normally excited)
Transformer	×	✓	
Reactor	×	×	
Capacitor	✓	×	
Resistor	×	✓	✓
Induction Moter	×	✓	×
Induction Generator	×	✓	×

Shunt Capacitor:



$$v_r' = v_r + \frac{Q_C X}{v_s}$$

- Or increment of voltage $\Delta v = \frac{Q_C X}{v_s}$
- So rating of shunt capacitor for increment of Δv voltage $Q_C = \frac{v_s \Delta v}{X}$
- It also improve P.f rating of shunt capacitor to improve P.f angle brom ϕ_1 to ϕ_2

$$Q_C = P_1[\tan\phi_1 - \tan\phi_2]$$

$$\frac{3v_r^2}{X_C} = P_1[\tan\phi_1 - \tan\phi_2]$$

$$c_{pn} = \frac{P_1[\tan\phi_1 - \tan\phi_2]}{3wv_{r(ph)}^2}$$

4.1.1. Shunt Reactor

It reduce the voltage

$$v_r' = v_r - \frac{Q_C X}{v_s}$$

- Reduction in voltage $\Delta v = \frac{Q_C X}{v_s}$
- Rating of shunt reactor for decrement of Δv voltage $Q_C = \frac{\Delta v\, v_s}{X}$
- The value of shunt reactor to make sending end voltage equal to receiving end voltage $X_L = \frac{|B|}{1-|A|}$

Series Capacitor :

- It increase the voltage change in voltage $\Delta v = IX_C \sin\phi$
- Rating of series capacitor to change voltage Δv $Q_C = \frac{3\Delta v}{\sin\phi} \cdot I$
- Degree of series capacitor = $\frac{X_C}{x} \times 100\%$
- For same voltage boost up rating of shunt capacitor is more than rating of series capacitor.

4.1.2. Synchronous Condenser/Synchronous Coil

- Over excited syn. Motor at no load → Syn. Condenser (increase voltage)
- Under excited → Synchronous Coil (reduce voltage)

$$\phi_{sm} = p_1 \tan\phi_1 - (p_1 + p_{sm})\tan\phi_2$$

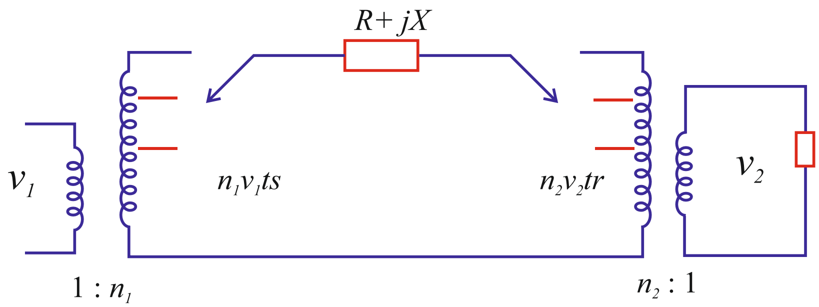
- Reactive power supplied by Synchronous Condenser for improvement of P.f from $\cos\phi_1$ to $\cos\phi_2$
- Here p_{sm} is active power taken by Synchronous Condenser to overcome loss.

4.1.3. Synchronous Phase Modifier

- Synchronous motor with load in over excited condition

$$Q_{sm} = p_1 \tan\phi_1 - (p_1 + p_{sm})\tan\phi_2$$

4.1.4. Tap Changing Transformer



$$ts^2\left[1-\frac{(RP+XQ)}{n_1 n_2 |v_1||v_2|}\right]=\frac{n_2|v_2|}{n_1|v_1|}$$

tap changing transformer → Transform voltage

tap changing transformer → Buck/boost voltage

Booster Transformer :

- It only Buck/Boost the voltage its rating is very low as compared to normal transformer.
- It is mainly used in distribution feeder.

Modification of SIL with Compensator :

With shunt capacitor $z_s' = \frac{z_s}{\sqrt{1+k_{sh}}}$

When $k_{sh} = \frac{B_C}{B_L} = \frac{C_C}{C_L}$ degree of shunt compensator

C_C = shunt capacitor of compensator

C_L = shunt capacitor of T.L.

So $SIL \uparrow = \frac{v^2}{z_s' \downarrow}$ is increased .

With shunt reactor

$$z_s' = \frac{z_s}{\sqrt{1-k_{sn}}}$$

$k_{sn} = \frac{B_C}{B_L}$

B_C = Suseptance of shunt reactor

B_L = Suseptance of T.L capacitor

$SIL \downarrow = \frac{v^2}{z_s'}$ is reduced.

With series capacitor

$$z_s' = z_s\sqrt{1-k_{sc}}$$

$$k_{sc} = \frac{X_C}{X_L}$$

X_C = reactance of series capacitor

X_L = reactance of T.L (series reactance)

$SIL \uparrow = \frac{v^2}{z_s'}$ is increased.

Series Reactor:

$$z_s' = z_s\sqrt{1+k_{sc}}$$

$$k_{sc} = \frac{X_C}{X_L}$$

X_C = reactance of series compensator

5 TRANSIENT

5.1. Introduction

Cause of transient

Internal cause | **External cause**

(I) Switching surge

(II) Insulator failure

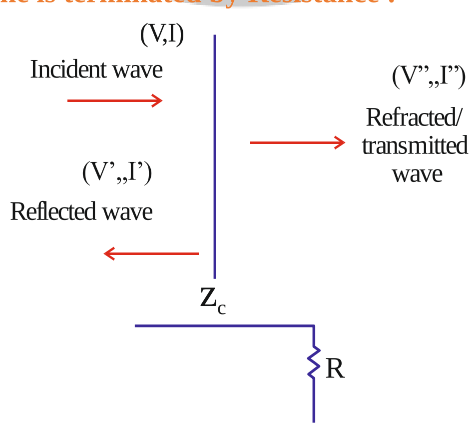
(III) Arching ground

(IV) Resonance

(V) Lightning stroke

- During transient these are two component of voltage.
  (I) Power frequency voltage (50Hz)
  (II) Natural frequency Voltage (for short duration)
- Change in voltage and current do not occur simultaneously in all parts but spread out in form of travelling wave & surges.
- Travelling wave is represented as a step wave for infinite time.

Reflection and refraction coefficient if line is terminated by Resistance :



Voltage refraction coefficient $\boxed{\frac{v''}{v} = \frac{2R}{R + Z_C}}$

Current refraction coefficient $\frac{I''}{I}=\frac{2Z_C}{R+Z_C}$

Voltage reflection coefficient $\frac{v'}{v}=\frac{R-Z_C}{R+Z_C}$

Current reflection coefficient $\frac{I'}{I}=-\left(\frac{R-Z_C}{R+Z_C}\right)$

- If line terminated by surge/characteristic

  Impedance $\begin{matrix} V'=0 \\ I'=0 \end{matrix}$ No reflection

  Occur and such line is called infinite line.

- If R> z_c then $v'' > v$

  (if surge enter into denser medium then transmitted wave > incident wave)

- If $R < Z_c$ then u" < v

  (If surge enter into lighter medium then transmitted wave < incident wave)

- If OH line is connected with cable magnitude of voltage and steepness is reduced.

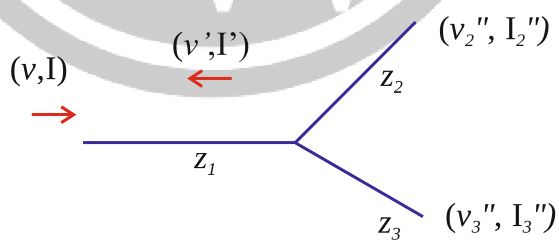
  Open-circuit line $\frac{v'}{v}=+1$ $\frac{I'}{I}=-1$

  $\frac{v''}{v}=2$ $\frac{I''}{I}=0$

  Short - circuit line $\frac{v'}{v}=-1$ $\frac{I'}{I}=+1$

  $\frac{v''}{v}=0$ $\frac{I''}{I}=2$

Reflection and refraction at T junction :



- Voltage refracted coefficient $\frac{v''}{v}=\frac{2\frac{1}{z_1}}{\frac{1}{z_1}+\frac{1}{z_2}+\frac{1}{z_3}}$

- Current refracted coefficient $\frac{I_2''}{I}=\frac{2\frac{1}{z_2}}{\frac{1}{z_1}+\frac{1}{z_2}+\frac{1}{z_3}}$

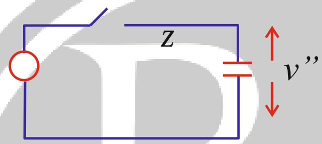
$$\frac{I_3''}{I} = \frac{2\frac{1}{z_3}}{\frac{1}{z_1}+\frac{1}{z_2}+\frac{1}{z_3}}$$

- Voltage reflection coefficient $\frac{v'}{v} = \frac{\frac{1}{z_1}-\frac{1}{z_2}-\frac{1}{z_3}}{\frac{1}{z_1}+\frac{1}{z_2}+\frac{1}{z_3}}$
- Current reflection coefficient $\frac{I'}{I} = \frac{\frac{1}{z_1}-\frac{1}{z_2}-\frac{1}{z_3}}{\frac{1}{z_1}+\frac{1}{z_2}+\frac{1}{z_3}}$

Incident wave + Reflected wave = Refracted wave :

$$1 + \text{Reflection cofficent} = \text{Refraction cofficent}$$

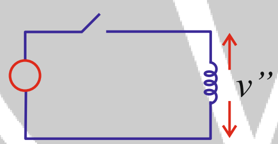
Line terminated by capacitor



$$v''(t) = 2v\left[1 - e^{-t/z_C}\right]$$

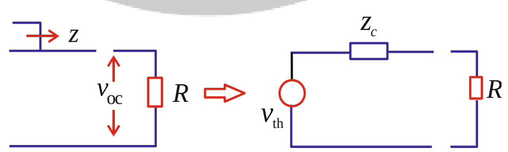
Capacitor reduce stepness of voltage

Line terminated by Inductor



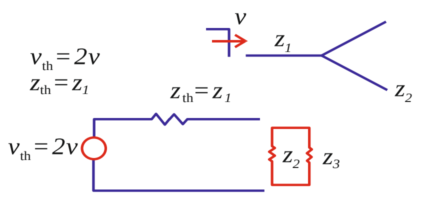
$$v''(t) = 2v\ e^{-\frac{Z}{L}t}$$

Thevenin equation Circuit: for travelling wave :



$$v_m = 2v$$
$$z_{th} = z_c$$

Thevenin ckt for T junction:



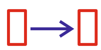
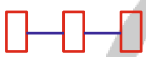
Ferranti absorber – It dissipate energy of surge as a eddy current loss.

6 HVDC

6.1. HVDC

Generation and distribution are done in A.C. only transmission is done on D.C. because it has several advantage if Bulk power is transmitted over a long distance.

Type of link :

1. Point to point connection 
2. Back to back connection (Both rectifier and Inverter at same station)
3. Maltiterminal D.C 

Point to point connection:

1. Monopolar link - One conductor of negative polarity is used, ground is use as a return path. Direction of power flow is opposite to direction of current.
2. Bipolar link – it has one positive and one negative conductor. If fault develop in one conductor, one conductor can supply ray of power, the return current will flow through ground.

   $\pm 500kv \qquad \pm 800kv$

   Mono polar link – It has two negative conductor and ground is use as a return path.

   (B/B) Back to back connection - This connection is used to connect two A.C. system operating at difference frequency. The effective length of B/B connection is zero.

   Multiterminal D.C – It is D.C link which is connecting more than 2 transformer through HVDC.

Converter Station (S/S) equipment :

1. Thyristor value: Two 6 pulse converter is used in series one is feed from Y – Y transformer and another is feed from Y – Δ transformer. So overall it become 12 pulse converter

   Converter is which $\alpha < 90 \Rightarrow$ Rectifier

   $\alpha > 90 \Rightarrow$ Inverter
2. Converter Transformer : It convert A.C voltage into suitable voltage to feed into thyristor value it handle high harmonic.
3. Smoothing reactor : It make D.C. current almost ripple free and also limit magnitude of current.
4. AC & DC filter :

   A.C side harmonic = $(2n \pm 1)$

   Or

   $(n \pm 1)$

DC side harmonic = (2n)
or
(n)

A.C filter reduce harmonic it also provide reactive power to converter but D.C filter only reduce harmonic.

5. Reactive power compensator : it is supplied by A.C filter, shunt capacitor, synchronous condenser, static VAR compensator (TSC, TSR).

   The reactive power drawn by converter depend on firing angle & active power

   $$Q = P \tan\alpha$$

6. Ground return : Earth electrode is used (straight, ring and radial) graphite electrode is used which is buried in pit filled

Advantage of HVDC :

- No skin effect
- Corona loss is less $P_c \propto (f + 25)$
- With DC inter connection, fault level does not increase
- No continuous charging current occur
- Less conductor and "Right of way" is required.
- For long distance bulk power transmission DC system is more economical.

Disadvantage:

- Cost of DC circuit breaker is high
- Thyristor value create harmonic both in AC and DC side.
- Over load capacity of converter is limited and huge power required at converter terminal.

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7 DISTRIBUTION SYSTEM

7.1. DISTRIBUTION

- In feeder current density remain same throughout the length. It is designed as per current carrying capacity.
- In distributor tapping are taken to supply consumer. It is designed as per voltage drop.
- "Service main" is small cable connecting distributor to consumer terminal
- Primary distribution is a 3 phase 3 wire and secondary distribution is 3 phase 4 wire system.

Classification of Feeder:

1. Radial feeder
2. Parallel feeder
3. Ring feeder
4. Inter connected system.

Compansion of volume of conductor in various distribution system. If power and voltage (maximum) are same.

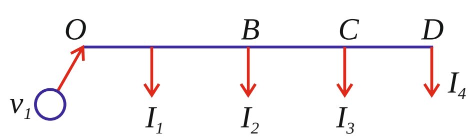
DC 2 wire system : DC 3 wire system : 1f AC system : 3 phase AC system

$$1 : \frac{1}{4} : \frac{2}{\cos^2\phi} : \frac{2}{2\cos^2\phi}$$

- So DC 3 wire system is more economical distribution system
- In AC, 3 phase 4 wire distribution is more economical.

Radial Distributor Feed from One End:

DC

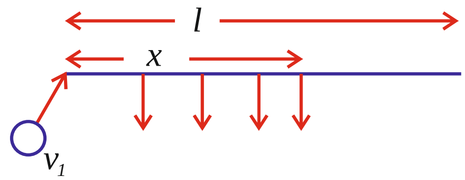


Total voltage drop = $R_{OA}(I_1+I_2+I_3+I_4)+R_{AB}(I_2+I_3+I_4)+R_{BC}(I_3+I_4)+R_{CD}I_4$

or $I_1R_{OA}+I_2(R_{OA}+R_{AB})+I_3(R_{OA}+R_{AB}+R_{BC})+I_4(R_{OA}+R_{AB}+R_{BC}+R_{CD})$

$$v_{\min} = v_1 \text{ - Total voltage drop.}$$

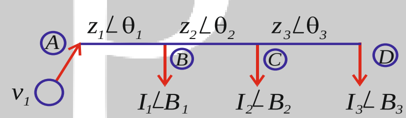
- Radial distribution with uniform loading feeding from one ends.



Voltage drop up to x distance

$$v = Ir\left[lx - \frac{x^2}{2}\right]$$

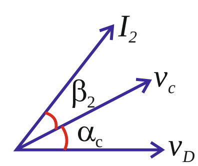
- Total voltage drop $\boxed{v = \frac{IR}{2}}$
- Minimum voltage $\boxed{v_{mn} = v_1 - \frac{IR}{2}}$
- Total loss up to x distance $i^2r\left[l^2x + \frac{x^3}{3} - 2l\frac{x^2}{2}\right]$
- Total power loss = $\frac{I^2R}{3}$
- Radial distribution fed from one end (A.C)



1. take v_D as a refrence and find out value of v_C

$$\vec{v}_c = (v_D\angle 0) + (I_3\angle\beta_3)(z_3\angle\theta_3)$$

$$\vec{v}_c = v_c\angle\alpha_c$$

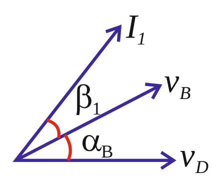


So, $\vec{I}_2 = I_2\angle(\alpha_c + \beta_2)$

2. Find out current in BC

$$\vec{I}_{BC} = I_2\angle(\alpha_c + \beta_2) + I_3\angle\beta_3$$

3. Find out v_B



$$\vec{v}_B = \vec{v}_c + \vec{I}_{BC}(z_2\angle\beta_2)$$
$$= v_B\angle\alpha_B$$

4. $\vec{I}_1 = I_1\angle(\alpha_B + \beta_1)$
5. Find out current in AB

$$\vec{I}_{AB} = \vec{I}_1 + \vec{I}_{BC}$$

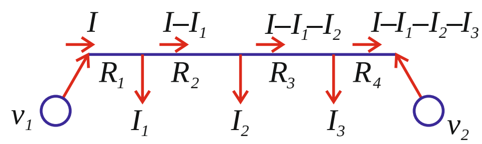
6. Finally find out $\bar{v}_A = \bar{v}_B + I_{AB}(z_1 < \theta_1)$

- Normally if we take same angle for all voltage

Then total voltage drop.

$$= (\bar{I}_1 + \bar{I}_2 + \bar{I}_3)(z_1\angle\theta_1) + (\bar{I}_2 + \bar{I}_3)(z_2 < \theta_2) + \bar{I}_3(z_3\angle\theta_3)$$

7.2. Radial Distributor Feeding from both Ends

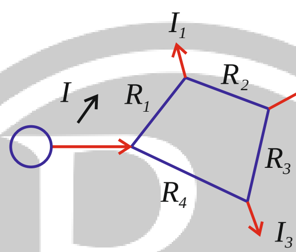


1. Assume total current = I
2. From total voltage drop find out value of I

$$(v_1 - v_2) = I(R_1 + R_2 + R_3 + R_4) - I_1(R_2 + R_3 + R_4) - I_2(R_3 + R_4) - I_3 R_4$$

3. Find out current in all section
4. Minimum voltage occur at a point where current direction reverse (it is become negative).

Ring Distributor :

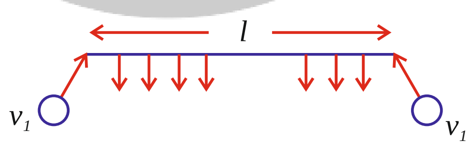


1. Convert ring distributor into radial distributor
2. Now find out I

$$I = \frac{I_1(R_2 + R_3 + R_4) + I_2(R_3 + R_4) + I_3 R_4}{R_1 + R_2 + R_3 + R_4}$$

3. Find out current in all section
4. Where direction of current reverse we will get minimum voltage

7.3. Radial Distributor Uniform Loading Feeding from both Ends



- Minimum voltage occur at $x = \frac{l}{2}$
- Maximum voltage drop = $\frac{IR}{8}$

$$\boxed{v_{mn} = v_1 - \frac{IR}{8}}$$

- Total Power loss = $\frac{I^2 R}{12}$

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8 CABLES AND INSULATOR

8.1. Cables

- The main component of underground cable is

  (1) Conductor (II) Insulation

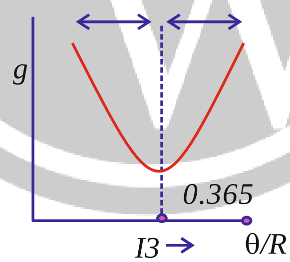
  (III) Metallic Sheath (IV) Bedding

  (V) Armouring (VI) Serving

- Electric field at conductor(core) and sheath is zero but insulation has to bear electrical stress(E)
- The electrical stress on insulation from *x* distance from center

$$g = E = \frac{v}{x \ln R / r}$$

- 1n 1ϕ cable use RMS value of voltage and for 3ϕ cable use per phase voltage
- But to find out peak value of electrical stress use peek value of voltage $\left(\sqrt{2} \times RMS\right)$
- since v is alternating, the E is also alternating.



- Min electrical stress occur at inner surface of sheath at x = R

$$E_{mn} = \frac{v}{R \ln \frac{R}{r}}$$

- Maximum electrical stress occur at surface of conductor at $x = r$

$$E_{(mn)} = \frac{v}{r \ln \frac{R}{r}}$$

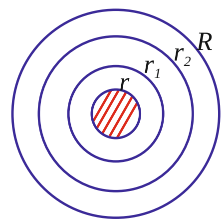
- For same value of cable size R & operating voltage the economical radius of conductor (it give minimum value of stress on conductor)

$$\frac{r}{R} = \frac{1}{e} \qquad \boxed{r = 0.365R}$$

- To make electrical stress in almost uniform throughout Insulation grading is used
- By effective grading same size cable is used for higher operating voltage or for some operating voltage smaller size cable can be used

Grading → Capacitance grading
Grading → Inter sheath grading

- In capacitance grading two or 3 material are used for insulation



(i) If "factor of safety" are same in all insulation material

$$\in_1 r G_1 = \in_2 r_1 G_2 = \in_3 r_2 G_3$$

$$r < r_1 < r_2$$

$$\boxed{\in_1 G_1 > \in_2 G_2 > \in_3 G_3}$$

G_1, G_2, G_3 is dielectric strength of insulating material

Total operating voltage = $\boxed{g_{1nx} r \ln\frac{r_1}{r} + g_{2nx} r_1 \ln\frac{r_2}{r_1} + g_{3nx} r_2 \ln\frac{R}{r_2}}$

(ii) All insulation is subjected to same maximum stress

$$\in_1 r = \in_2 r_2 = \in_3 r_3$$

$$r < r_1 < r_2$$

$$\boxed{\in_1 > \in_2 > \in_3}$$

So material with highest permittivity should be placed near to conductor

$$v = g_{nx} r \ln\frac{r_1}{r} + g_{nx} r_1 \ln\frac{r_2}{r_1} + g_{nx} r_2 \ln\frac{R}{r_2}$$

* This v will be per phase

- In inter sheath grading same insulation is used but by use of auto X-mer potential is maintain

$$\frac{g_{mx}\text{(with inter sheath)}}{g_{nx}\text{(without inter sheath)}} = \frac{3}{1+\alpha+\alpha^2}$$

$$\alpha = \frac{r_1}{r} = \frac{r_2}{r_1} = \frac{R}{r_2}$$

$$v = g_{mx}\left[r \ln\frac{r_1}{r} + r_1 \ln\frac{r_2}{r_1} + r_2 \ln\frac{R}{r_2}\right]$$

$$v = g_{nx} \ln\alpha\left[r + r_1 + r_2\right]$$

- Insulation resistance

$$R(I_m) = \frac{\rho}{2\pi l} \ln\frac{R}{r}$$

$$\boxed{R \propto \frac{1}{l}}$$

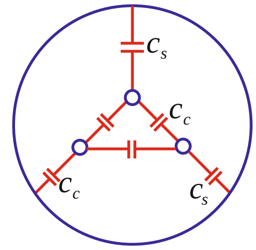
- Capacitance of single core cable

$$c = \frac{2\pi \in}{\ln R/r} \qquad \in = \text{permittivity of insulation}$$

- Capacitance of 3 core cable

Per phase capacitance

$$\boxed{C_{ph} = 3c_c + c_s}$$



Capacitance between two conductor = 1.5 c_c + 0.5 c_s

- Bunch all conductors the capacitance between bunched conductor & sheath

$$c_x = 3c_s$$

- Connect any two conductor with sheath, the capacitance between remaining conductor & sheath is

$$c_y = 2c_c + c_s$$

$$\boxed{c_{ph} = \frac{3}{2}c_y - \frac{c_x}{6}}$$

- Losses
  - core loss $\left(I^2r \quad or \quad 3I^2r\right)$
  - Insulation loss
  - Sheath loss
  - Armour loss
- Dielectric loss = $v^2 wc\tan\delta$
  - * In this formula if per phase voltage is used it give per phase loss
  - * If 3 phase line voltage is used it give 3 phase loss.

$\boxed{\delta = 90 - \theta}$ θ = No load P.f angle **

- Sheath loss = $\dfrac{I^2 W^2 M^2 R_S}{R_s^2 + (WM)^2}$

M = $2\times10^{-7}\ln\dfrac{d}{r_m}$ R_S = sheath Resistance

d = distance between two cable

r_m = Radius of one cable

- $\dfrac{\text{Sheath loss}}{\text{core (conductor loss)}} = \dfrac{R_S (WM)^2}{R\left(R_S^2 + (WM)^2\right)}$

8.2. Overhead Insulator

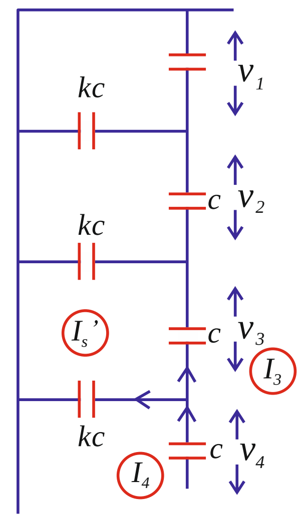
Material → Toughened glass (Dielectric Strength 35 kv/inch)
Material → Glazed porcelain

Type of Insulator:

1. Pin insulator – up to 33 *kv*.
2. String/Disc/Suspension insulator – each disc is designed for 11*kv*, string are at vertical plane.
3. Strain Insulator – String are at horizontal plane, used at line terminal, at angle tower and road/river crossing

Voltage	132	220	400
No. of Disc in suspension	9-10	15-16	22-23
No of Disc in strain Insulator	11-12	17-18	24-25

4. Shakle Insulator – used in distribution line
5. Post Insulator – it is used to support Bus bar



String Efficiency:

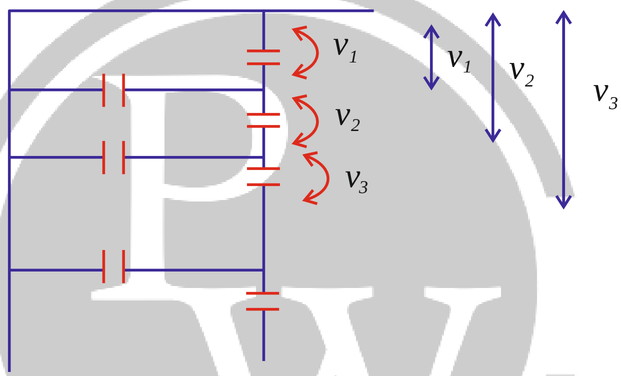
- Each disc of Insulator is act as a capacitor and each metal joint with tower formed a capacitor. Which is called stray capacitance. Due to this stray capacitance voltage distribution is become non uniform.

$$\eta = \frac{\text{voltage across whole string}}{\text{No. of Dics} \times \text{voltage across lower most unit}}$$

$$I_4 = I_3 + I_3'$$

$$jwcv_4 = jwcv_3 + jw(kc)(v_1 + v_2 + v_3)$$

Find out v_2, v_3 and v_4 is term of v_1 to find out string efficiency.
or you can use this formula directly



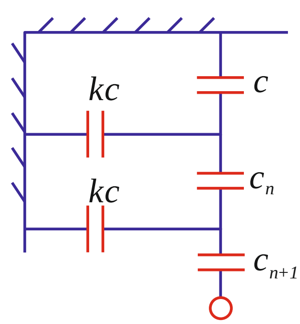
$$v_{n+1} = \frac{v_n}{m} + v_n$$

m = number of Disc

- By using this formula we can directly find out $v_1, v_2, v_3 .....$ For determination of string efficiency.

Improvement of String Efficiency:

1. By capacitance grading (capacitance of each unit should increase from tower end to conductor end.)



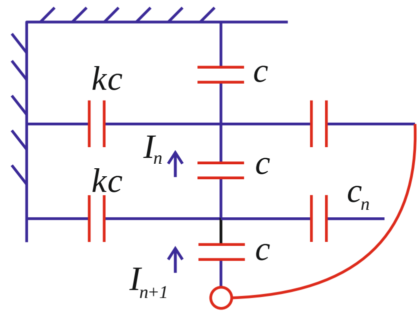
$$c_{n+1} = c_n + n(kc)$$

e.g $\quad c_2 = c_1 + kc$

$\quad c_3 = c_2 + 2kc$

$c_4 = c_3 + 3kc$

2. Static shielding :



$$\boxed{c_n = \frac{n}{m-n}kc}$$

Total capacitance – m

Insulator failure :

1. Mechanical stress
2. Cracking
3. Porosity
4. Flashover – Arc occur between conductor and Insulator.
5. Puncture – Permanent damage

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9 SYMMETRICAL COMPONENT & FAULT ANALYSIS

9.1. Symmetrical Component

3 phase unbalance phasor = 2 set of symmetrical phasor (positive & negative) +1 co phasal phasor (zero).

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} v_{a0} \\ v_{a1} \\ v_{a2} \end{bmatrix}$$

$$\boxed{[v_{abc}] = [A][v_{012}]}$$

or

$$\begin{bmatrix} v_{a0} \\ v_{a1} \\ v_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\boxed{[v_{012}] = [A]^{-1}[v_{abc}]}$$

$$a = 1\angle 120° = \frac{-1}{2} + j\frac{\sqrt{3}}{2}$$

$$a^2 = 1\angle 240° = \frac{-1}{2} - j\frac{\sqrt{3}}{2}$$

$$\boxed{1 + a + a^2 = 0}$$

$$a^3 = 1$$

$$a^* = a^2$$

$$1 - a = \sqrt{3}\angle -30°$$

$$I - a^2 = \sqrt{3}\angle 30°$$

Power :

$$B = v_a I_a^* + v_b I_b^* + v_c I_c^*$$

$$= \begin{bmatrix} v_a & v_b & c_c \end{bmatrix} \begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix}$$

$$B=[v_{abc}]^T[I_{abc}]^*$$

or $$s=3[v_{a0}\ \ v_{a1}\ \ v_{a2}]\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}^*$$

$$s=3[v_{012}]^T[I_{012}]^*$$

- The equations does not have any cross term like ($v_{a0}\,I_{a1}^*$) so these sequence network does not have any mutual coupling.

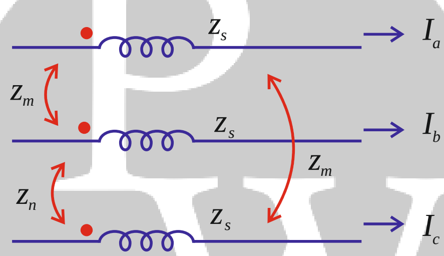
Sequance Impedance:

$$[v_{abc}]=[z_{abc}][I_{abc}]$$

$$[v_{012}]=[z_{012}][I_{012}]$$

$$\boxed{[z_{012}]=[A]^{-1}[z_{abc}][A]}$$

z_{abc} is 3 × 3 matrix which have both self & mutual impedance



$$[z_{abc}]=\begin{bmatrix} z_s & z_m & z_m \\ z_m & z_s & z_m \\ z_m & z_m & z_s \end{bmatrix}$$

$$[z_{012}]=\begin{bmatrix} z_s+2z_m & 0 & 0 \\ 0 & z_s-z_m & 0 \\ 0 & 0 & z_s-z_m \end{bmatrix}$$

$[z_{abc}]$ has mutual element but $[z_{012}]$ does not have any mutual term.

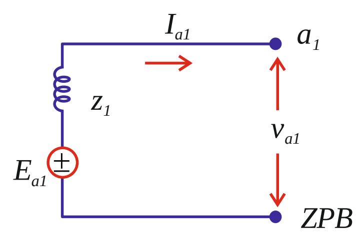
9.2. Sequence Network of Generator

Positive Sequence Network:

$z_1 = jX_d$ (steady state)

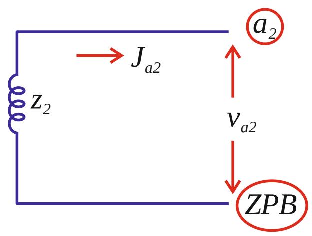
$z_1 = jX_d'$ (transient)

$z_1 = jX_d''$ (sub transient)



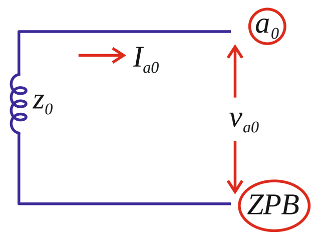
Negative Sequence Network:

$$z_2 = \frac{j(X_d + X_q)}{2}$$



Zero Sequence Network :

$$\boxed{\begin{aligned} z_o &= z_{go} + 3z_n \\ z_{go} &= j\,x_{al} \end{aligned}}$$



In alternator $\boxed{z_1 > z_2 > z_{go}}$

Sequence Network of T. L :

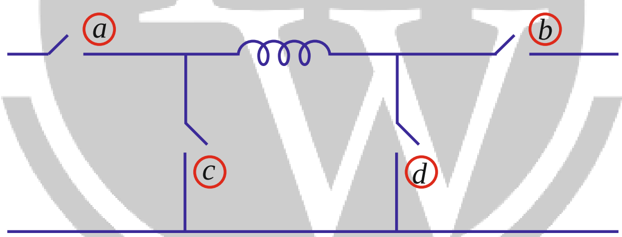
$$z_0 > z_1 = z_2$$

$$\boxed{\begin{aligned} z_1 = z_2 &= z_s - z_m \\ z_0 &= z_s + 2z_m \end{aligned}}$$

z_0 is 3 to 4 times of positive and negative sequence

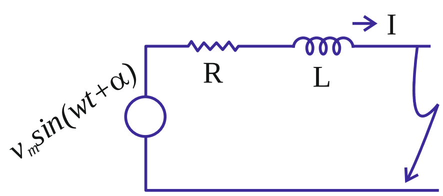
Sequence Network for Transformer:

$$z_1 = z_2 \simeq z_0$$



- Close $a \Rightarrow$ if primary star with neutral grounded.
- Close $b \Rightarrow$ if secondary star with neutral grounded.
- Close $c \Rightarrow$ if primary delta connected
- Close $d \Rightarrow$ if secondary delta connected

s/c in Transmission line :

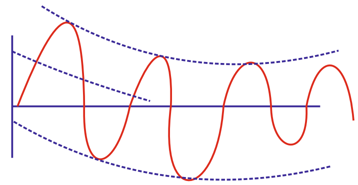


$$\theta = \tan^{-1}\frac{wL}{R}$$

$$i = \frac{v_m}{z}\sin(wt + \alpha - \theta) + \frac{v_m}{z}\sin(\theta - \alpha)e^{-t/T}$$

$\downarrow$ Symmetrical Steady State A.C. current

$\downarrow$ DC offset current



- Sub transient – 1 to 2 cycle
- Transient – 2 to 5 cycle
- Steady state – After 5 cycle

Asymmetrical Current:

$$I_{asy}(RMS) = \frac{v_m}{\sqrt{2}z}\left[1 + 2\sin^2(\theta - \alpha)e^{-2t/T}\right]^{1/2}$$

$$\boxed{I_{asy} > I_{syn}}$$

Maximum Momentarily s/c Currnet:

$$i = \frac{v_m}{z} + \frac{v_m}{z}\cos\alpha \qquad \text{(for phase angle of } \alpha\text{)}$$

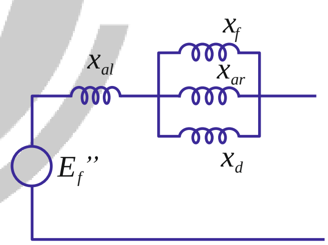
$$i \text{ (maximum possible)} = \frac{2v_m}{z}$$

S/C in alternator:

Sub transient time

Sub transient reactance

$$X_d'' = x_{al} + (x_{ar} \parallel x_f \parallel x_d)$$

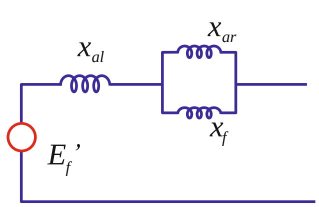


X_{ar} = A.R reactance

x_f = field winding reactance (due to field winding flux)

x_d = damping winding reactance (due to damping winding flux)

Transient time :



Transient reactance, $X_d' = x_{al} + \left(x_{ar} \parallel x_f\right)$

Steady State :

Steady state reactance

$$X_d = x_{al} + x_{ar}$$

$$\boxed{X_d'' < X_d' < X_d}$$

$$\boxed{I_f'' > I_f' > I_f} \leftarrow \text{fault current}$$

9.3. Symmetrical Fault

- Fault
  - Open circuit fault (Series fault)
  - Short circuit fault (shunt fault)
    - Symmetrical
    - Unsymmetrical

In shunt fault

1. Current increase
2. Voltage decrease
3. Frequency decreases

In series fault

1. Current decrease
2. Voltage increase
3. Frequency increase

Symmetrical Fault:

- All 3 phases are involved eg $\begin{pmatrix} L-L-L \\ L-L-L-G \end{pmatrix}$
- It is most severe fault
- Least occur fault (only 5% of total fault

Unsymmetrical Fault:

- Only one or two phase are involved

L-G	(70%)
L-L	(15%)
L-L-G	(10%)

- LG fault is least severe fault
- Relay is designed as per minimum fault current
- Circuit breaker is designed based on maximum fault current

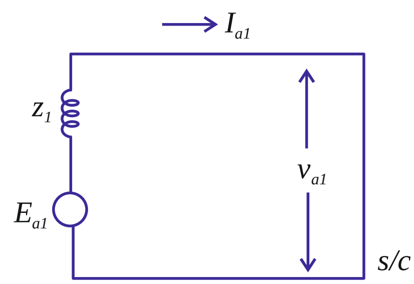
Assumption in Fault Analysis:

- The EMF of all generator is $1 \angle 0°$
- Shunt branch of transformer and shunt capacitance of TL is neglected
- System resistance is neglected
- Current carried by load under faulty condition is ignored.
- During fault synchronize motor act as a synchronize generator so it supply fault current.
- Speed and frequency variation of alternator is ignored.

Symmetrical Fault Analysis:

$$I_{a0} = I_{a2} = 0 \qquad I_{a1} = I_a$$

$$v_{a1} = v_{a2} = 0 \qquad v_{a0} = v_a$$



So $$\boxed{I_f - I_a = I_{a1} = \frac{E_{a1}}{z_1} = \frac{E}{z_1}}$$

- If fault impedance is given $\boxed{I_f = \dfrac{E}{z_1 + z_f}}$
- If fault occur at no. load condition or load current is neglected during fault) $\boxed{I_f = \dfrac{1\angle 0^\circ}{z_1 + z_f}}$

Step to find out Fault Current:

- Draw single line diagram
- Select a common base find p.u reactance of all generator, TL and x-mers.
- Now draw reactance diagram showing one phase and ZPB (ground).
- Short circuit through fault impedance where fault occur.
- Find out equations reactance seen from fault point (thevenin equivalent)
- Find out fault current $I_f = \dfrac{1\angle 0}{z_f + z_{\text{th}}}$

Symmetrical fault current if pre fault load current is given:

I Method :

- Find out value of E_g" and E_m"

$$Eg" = v_f + jI_L(x_d" + \ldots \text{any extra reactance between fault point \& generator terminal)}$$

$$E_m" = v_f - jI_L(x_d" + \ldots \text{ any extra reactance between fault point \& motor terminal)}$$

v_f = pre fault voltage at fault point.

- Replace synchronize motor & generator emf by Eg" and E_m" and find out fault current by usual method.

II Method :

- From load current find out pre fault voltage at the fault point.
- Now find out fault current using pre fault current $I_f = \dfrac{v_f}{z_{th} + z_f}$
- $\vec{I}_g = \vec{I}_L + \vec{I}_f$

  $\vec{I}_m = \vec{I}_f + \vec{I}_m$

Fault MVA (Fault Level)

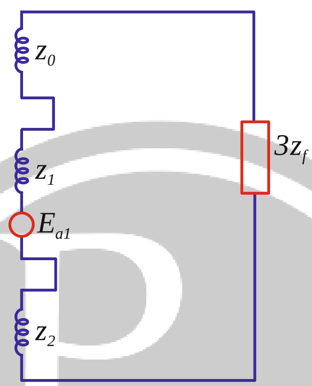
SC (MVA) = $\sqrt{3}$ × prefault voltage × s/c current if voltage and current are in p.u.

$$s.c(p.u) = v(p.u) \times I_f(p.u)$$

$$\boxed{s.c(p.u) = 1 \times \frac{1}{z_f + z_{th}}}$$

9.4. Unsymmetrical fault

L-G Fault



$$I_{a0} = I_{a1} = I_{a2} = \frac{1<0}{z_1 + z_2 + (z_0 + 3z_f)}$$

Fault current, $$\boxed{I_f = \frac{3<0}{z_1 + z_2 + (z_0 + 3z_f)}}$$

Actual fault MVA + $\dfrac{3 \times base\,MVA}{z_1 + z_2 + (z_0 + 3z_b)}$

Fault MVA = $\sqrt{3}$ pre fault voltage × post fault current

- If fault occur at alternator terminal $I_f(L-G) > I_f(3\phi)$
- If fault away from alternator $I_f(LG) < I_f(3\phi)$

L-L Fault

(b & c phase is s/c)

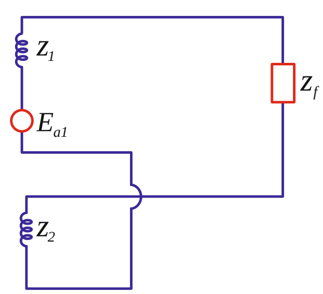
$$I_{a1} = \frac{Ea}{z_1 + z_2 + z_f}$$

$$\boxed{I_f = \frac{-j\sqrt{3}}{z_1 + z_2 + z_f}}$$

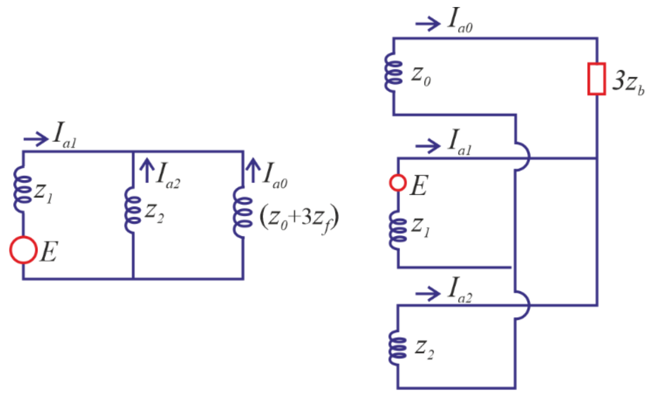
$$\boxed{\text{fault MVA} = I_f(p.u)}$$

$I_{a_o} = 0$ $\boxed{I_{a2} = -I_{a1}}$

$$\boxed{\begin{aligned} I_b &= -j\sqrt{3}I_{a1} \\ I_c &= -I_b \\ I_a &= 0 \end{aligned}}$$



L–L–G Fault :



$$I_{a1} = \frac{E}{z_1 + \dfrac{z_2(z_0+3z_f)}{z_2+z_0+3z_f}}$$

$$I_{a2} = -\frac{(z_0+3z_b)}{z_2+z_0+3z_f}\cdot I_{a1}$$

$$I_{a0} = -\frac{z_2}{(z_2+z_0+3z_f)}\cdot I_{a1}$$

$$\boxed{I_f = I_b + I_c}$$

If Prefault Current is given :

- First find out prefault voltage at fault point.
- Inter connect these network depending upon fault.
- Sequence component of fault current can be calculated.
- Sequence component of fault current are super imposed on sequence component of load current.
- Load current has positive sequence component.

Remember

- Positive sequence exist in all type of fault
- Negative sequence exist in all unsymmetrical fault
- Zero sequence exist in all ground fault.

$$\boxed{\text{Actual voltage (phase)} = I_f\,(p.u) \times \text{phase base voltage}}$$

- Always use phase voltage (not line voltage).

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10 Power System Stability

10.1. Power System Stability

Stability → Voltage stability/load stability

Stability → Synchronize stability/rotor angle stability

10.1.1. Steady State Stability

- Small and gradual change in load
- The maximum amount of power during this condition is called (SSSL)

Slow change means

If rate of change of load < rate of change of excitation

$$p_{mx} = \boxed{\text{SSSL} = \frac{v_1 v_2}{x}}$$

Is R is present

$$p_{nx} = \frac{|v_s||v_r|}{|z|} - \frac{|v_r|^2}{|z|} \cdot \frac{R}{|z|}$$

$\frac{dp_{mx}}{dx} = 0$ so is $\boxed{X = \sqrt{3}R}$

$$\tan\theta = \frac{X}{R} = \sqrt{3}$$

So for θ = 60 (line impedance angle)

Power will be maximum.

10.1.2. Dynamic of Synchronous Machine

$$w_{sm} = 2\pi n_s = 2\pi \frac{N}{60} \text{ mech rad/sec.}$$

$$w_s = 2\pi f \text{ elect rad/sec.}$$

$$W_{sm} = \frac{2}{p} W_s$$

$$\boxed{KE = \frac{1}{2} M w_s}$$

M = Inertia constant = $J\left(\frac{2}{p}\right)^2 ws \quad \frac{MJ - \sec}{elect\, rad.}$

H = Store energy = $\frac{K.E}{MVA \cdot (G)} \quad \frac{MJ}{MVA} \rightarrow \frac{M_0 - \sec}{MVA}$

$$GH = \frac{1}{2} MW_S$$

$M = \frac{GH}{\pi f}$ MJ–sec/elect rad.

$M = \frac{GH}{180 f}$ MJ–sec/elect degree.

$$\boxed{\begin{aligned} M_{P.u} &= \frac{H}{\pi f} \sec^2/\text{elect rad} \\ M_{P.u} &= \frac{H}{180 f} \sec^2/\text{elect degree} \end{aligned}}$$

$$\boxed{\begin{aligned} (M_{P \cdot u})_{new} &= (M_{Pu})_{old} \times \frac{(MVA)_{old}}{(MVA)_{new}} \\ (H_{P \cdot u})_{new} &= (H_{Pu})_{old} \times \frac{(MVA)_{old}}{(MVA)_{new}} \end{aligned}}$$

Swing Equation:

$$\boxed{\begin{aligned} &\frac{Md^2\delta}{dt^2} = p_s - p_e \\ &\frac{GH}{180 f} \cdot \frac{d^2\delta}{at^2} = p_s - p_e \\ &\frac{H}{180 f} \cdot \frac{d^2\delta}{dt^2} = (p_s - p_s) \end{aligned}}$$

δ = load angle/power angle

p_s = shaft I/P

p_e = electrical o/p

For Motor swing equation is $\boxed{\frac{Md^2\delta}{dt^2} = p_e - p_s = p_a}$

p_e = electrical I/P

p_s = shaft o/p

Since rotor is rotating part so law of mechanics applied here.

$$\omega = \omega_0 + \alpha t$$
$$2\pi f = 2\pi f_0 + \alpha t$$
$$\delta = \delta_0 + \frac{1}{2}\alpha t^2$$
$$f = f_o + \frac{\alpha}{2\pi} t$$

w_o = Initial angular velocity

w = find angular velocity

α = angular acceleration.

$$\boxed{2\pi\frac{N}{60} = 2\pi\frac{N_o}{60} + \alpha t}$$ → unit = mech rad/sec^2

f = final frequency

f_o = Initial frequency

N_o = Initial speed in RPM

N = Final speed in RPM

(I) Two machine swinging coherently

$$M_{eq} = M_1 + M_2$$
$$H_{eq} = \frac{G_1H_1 + G_2H_2}{G_{eq}}$$

(II) It two machine are swinging together.

$$M_{eq} = \frac{d^2\delta}{dt^2} = p_s - p_e$$
$$M_{eq} = \frac{M_1M_2}{M_1 + M_2} \qquad P_s = \frac{P_{s1}M_2 - P_{s2}M_1}{M_1 + M_2}$$
$$P_e = \frac{P_{e1}M_2 - P_{e2}M_1}{M_1 + M_2}$$

10.1.3. Steady State Stability

Frequency of oscillation, $$f = \sqrt{\frac{\left.\frac{\partial P}{\partial \delta}\right|_{\text{at } \delta = \delta_0}}{M}}$$

Method to Improve Steady State Stability

- Operating System at high voltage level
- Increasing excitation of system
- By using series capacitor
- By using Bundled conductor
- By using double circuit line
- By static vAR compensator

Transient stability : It is ability of system to maintain stability during sudden and large disturbance

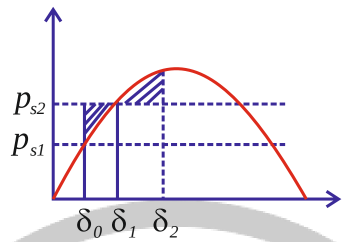
- To Determine transient stability, we use graphical method which is called “equal area criteria”
- “Equal area Criteria” method is used is single machine is connected with infinite bus

$$\int p_a d\delta = 0$$

If $p_s > p_e \Rightarrow$ Positive area

$p_s < p_e \Rightarrow$ Negative area

Case-I : Increasing steam I/P (Mechanical I/R) to alternator.



$$\boxed{p_{s2}(\delta_2 - \delta_0) = p_{mx}(\cos\delta_0 - \cos\delta_2)}$$

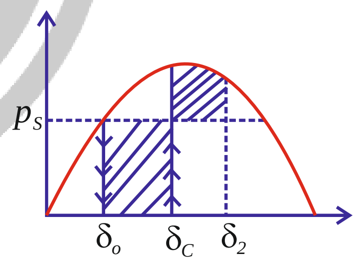
Maximum power angle $\boxed{\delta_m = 180 - \delta_1}$

$$\boxed{\delta_1 = \sin^{-1}\frac{p_{s2}}{p_{mx}}} \qquad \boxed{\delta_0 = \sin^{-1}\left(\frac{p_{s1}}{p_{mx}}\right)}$$

Case –II: Three phase fault occur near the bus.

$$p_s = p_m \sin\delta_0$$

$$\int_{\delta_o}^{\delta_C}(p_s - o)ds = \int_{\delta_C}^{\delta_2}(p_m \sin\delta - p_s)d\delta$$



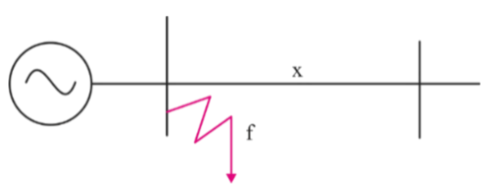
$$\boxed{\delta_C = \cos^{-1}\frac{p_s(\delta_2 - \delta_0) + p_m\cos\delta_2}{p_m}}$$

1fault clear angle

If $\delta_2 = (\pi - \delta_o)$ then $\delta_c = \delta_{cr}$

$$\boxed{\delta_{cr} = \cos^{-1}\frac{p_s(\pi - 2\delta_0) - p_m\cos\delta_0}{p_m}}$$

Critical clearing angle

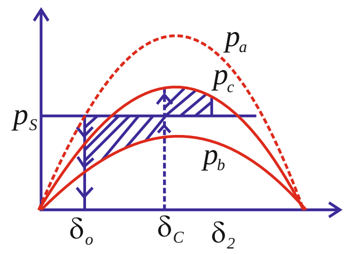


Critical Clearing Time :

$$\boxed{t_{cr} = \sqrt{\frac{2m(\delta_{cr} - \delta_o)}{p_s}}}$$

Case-III:

Fault occur at mid point of one of parallel path.



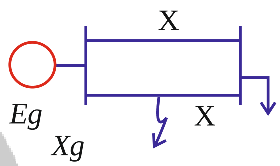
$$p_{am} = \frac{E_g V}{X_g + X/2} \qquad p_{cn} = \frac{E_g V}{X_g + X}$$

$$p_{bm} = \frac{E_g V}{X_g + X + \dfrac{X_g X}{X/2}}$$

$$\int_{\delta_o}^{\delta_C} (p_s - p_{bm}\sin\delta)ds = \int_{\delta_C}^{\delta_2} (p_{cm}\sin\delta - p_s)d\delta$$

$$\boxed{\delta_C = \cos^{-1}\frac{p_s(\delta_2-\delta_0)+p_{cm}\cos\delta_2 - p_{bm}\cos\delta_o}{p_{cm}-p_{bm}}}$$

For critical clearing angle $\delta_2 = (\pi - \delta_1)$



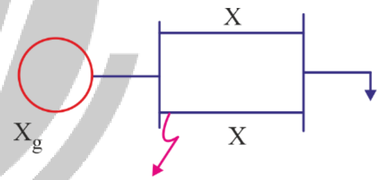
$$\delta_1 = \sin^{-1}\left(\frac{p_s}{p_{cm}}\right)$$

So, $\delta_c = \delta_{cr}$

Case-IV:

In parallel line fault recur near to bus.

$$p_{am} = \frac{E_g V}{X_g + X/2} \qquad p_{cn} = \frac{E_g V}{X_g + X}$$



$$\int_{\delta_o}^{\delta_C} (p_s - 0)ds = \int_{\delta_C}^{\delta_2} (p_{cm}\sin\delta - p_s)d\delta$$

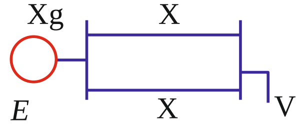
$$\boxed{\delta_C = \cos^{-1}\frac{p_s(\delta_2-\delta_0)+p_{cm}\cos\delta_2}{p_{cm}}}$$

For critical clearing angle $\delta_2 = (\pi - s_1)$

$$= \pi - \sin^{-1}\frac{p_s}{p_{cm}}$$

Case – V:

Removal of one line from two parallel line



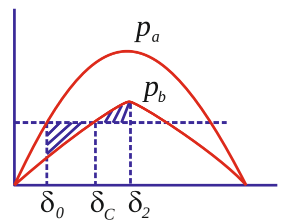
$$p_a = \frac{EV}{X_a}\sin\delta$$

$$X_a = X_g + X/2$$

After removal $p_b = \frac{EV}{X_b}\sin\delta$

$$X_b = X_g + X$$

$$\int_{\delta_0}^{\delta_1}(p_s - p_{bm}\sin\delta)ds = \int_{\delta_1}^{\delta_2}(p_{bm}\sin\delta - p_s)d\delta$$



Swing Equation of Motor:

$$p_e - p_s = \frac{Md^2\theta_e}{dt^2}$$

or

$$p_s - p_e = \frac{Md^2\delta}{dt^2}$$

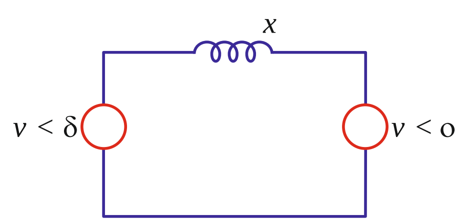
$\frac{d^2\delta}{dt^2}\downarrow = \frac{p_a\downarrow}{M\uparrow}$ $\Rightarrow$ less acceleration, more time for CB operation

Method for Improvement Transient Stability :

- Increasing moment of Inertia
- Using fly wheel, $p_a\downarrow = p_s - \frac{Ev}{x}\sin\delta\uparrow$
- Operating system at high voltage
- Reduction of reactance by using parallel line, bundled conductor, series compensator.
- Rapid fault clearing by auto reclose relay
- High speed CB
- Quick governor action
- Single pole switching of CB
- Fast acting AVR.
- So for stability point of view in alternator resistance grounding should be used and in motor reactance grounding should be used.

Static VAR Compensator :

- SVC is installed at middle point where voltage variation is more
- Without SVC, $P = \frac{V^2}{X}\sin\delta$
- With SVC $P = \frac{2V^2}{X}\sin\delta/2$



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11 BUS IMPEDANCE MATRIX

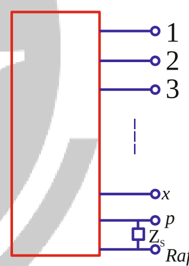
11.1. Bus Impedance Matrix

- Z_{Bus} is mainly used for fault analysis
- It is symmetrical about principle diagonal it diagonal element is called driving point impedance and off diagonal element is called transfer impedance.
- $[Z_{Bus}] = \frac{1}{[Y_{Bus}]^{-1}}$ But $Z_{ii} \neq \frac{1}{Y_{ii}}$

Modification in Existing Z_{Bus} :

- Suppose original system has n Bus so Z_{Bus} has ($n \times n$) order matrix.

(1) Addition of new element Z_S between new P and reference.

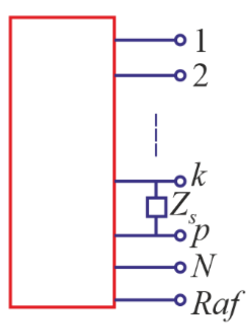


$$\begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \\ v_p \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} & 0 \\ Z_{21} & Z_{12} & \cdots & Z_{1n} & 0 \\ \vdots & & & & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} & 0 \\ o & o & & o & Z_s \end{bmatrix}$$

$$[Z_{Bus}]_{new} = \left[\begin{array}{c|c} [Z_{Bus}]_{old} & 0 \\ & \vdots \\ \hline O & z_s \end{array}\right]$$

(2) Addition of new element Z_S between new bus P and existing bus K

$$\begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_k \\ \vdots \\ v_n \\ v_p \end{bmatrix} = \begin{bmatrix} z_{11} & \cdots & z_{1k} & z_{1n} & z_{1k} \\ z_{21} & \cdots & z_{2k} & z_{2n} & z_{2k} \\ \vdots & \cdots & & & \\ z_{k1} & \cdots & z_{kk} & z_{kn} & z_{kk} \\ z_{n1} & \cdots & z_{nk} & z_{nn} & z_{nk} \\ z_{k1} & \cdots & z_{kk} & z_{kn} & z_{kk} + z_s \end{bmatrix}$$



$$[Z_{Bus}]_{new} = \begin{bmatrix} (Z_{Bus})_{old} & column\,k \\ Row\,k & z_{kk} + z_s \end{bmatrix}$$

- Node elimination in matrix (kron reduction)
  Suppose to elimination ($n+1$) row

$$[z_{new}] = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ z_{21} & \cdots & z_{2n} \\ z_{n1} & \cdots & z_{nn} \end{bmatrix} - \frac{1}{z_{(n+1)(n+1)}} \begin{bmatrix} z_{1(n+1)} \\ \vdots \\ z_{n(n+1)} \end{bmatrix} \begin{bmatrix} z_{1(n+1)} \cdots & z_{n(n+1)} \end{bmatrix}$$

(3) Addition of new element between old bus K and refrence.

(i) First add element between old Bus K and new bus P

(ii) Now eliminate new bus P

(a)
$$\begin{bmatrix} (z_{Bus})_{old} & z_{1k} \\ & z_{2k} \\ & \vdots \\ & z_{nk} \\ z_{k1} --- & z_{kk} + z_s \end{bmatrix}$$

k column element ↓

(b)
$$[z_{Bus}]_{new} = [z_{Bus}]_{old} - \frac{1}{z_{kk} + z_s} \begin{bmatrix} z_{1k} \\ \vdots \\ \vdots \end{bmatrix}$$

$Z_{kk} = K_{row}\, K_{column}$ element K row $[Z_{k_1} \ldots]$ element $[z_{k1} \ldots]$

(4) New element Z_S is added between bus i & k (i column - k column)

$$[z_{Bus}]_{new} = [z_{Bus}]_{old} - \frac{1}{z_{ii} + z_{kk} - 2z_{ik} + z_s} \begin{bmatrix} z_{1i} - z_{1k} \\ \vdots \\ z_{ni} - z_{nk} \end{bmatrix} [z_{i1} - z_{k1} \ldots]$$

↑ (i Row – k Row)

$$[z_{Bus}]_{new} = [z_{Bus}]_{old} - \frac{1}{z_{ii} + z_{kk} - 2z_{ik} + z_s}$$ [i column element – k column element]

[i Row element – k Row element]

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12 LOAD FLOW STUDIES

12.1. Load Flow Studies

Y matrix is used in load flow studies.

Y_{ii} = Sum of all admittance connected with i^{th} Bus.

Y_{ij} = Negative of sum of all admittance connected with i^{th} Bus and j^{th} Bus.

Load flow Studies → Network Modelling
Load flow Studies → Mathematical Modelling
Load flow Studies → Solution Stage

Network Modelling

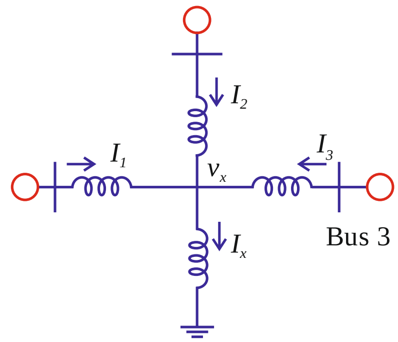
- Generator represent as a source of complex power $S_{Gi} = P_{Gi} + jQ_{Gi}$ and load is represented as demand of complex power $S_{Di} = P_{pi} + jQ_{Di}$
- TL is modelled on a short TL or Medium T.L. with π model

$$[I_{Bus}] = [Y_{Bus}][V_{Bus}]$$

- Y_{Bus} matrix is sparse matrix. As no of Bus increases in power system sparsity increase.
- If shunt admittance is neglected, then sum of elements of each row/column will be zero. So it is singular matrix so we choose one Bus as a reference Bus (Slack Bus) and corresponding row and column is deleted. Now matrix is become non singular.
- If shunt admittance is not neglected the sum of any row/column is equal to total shunt admittance connected to that Bus.
- If additional shunt admittance is added or change it only change diagonal element.
- For convergence of load flow. The diagonal element must be dominating over off diagonal element.

Special Case :

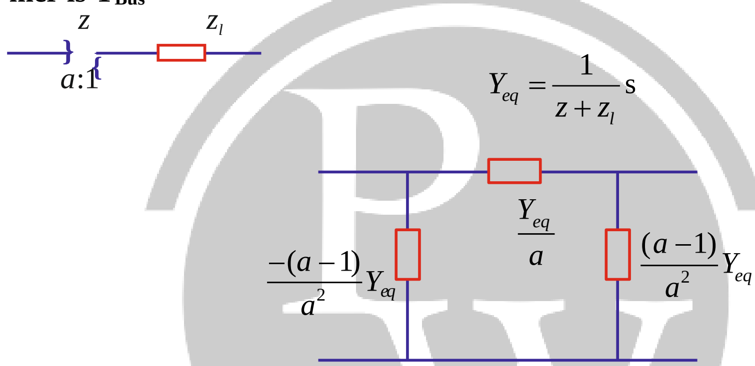
- Bus 1



For this type of system use formula $I_1 + I_2 + I_3 = I_x$

Then find out v_x and then from $I_1 + I_2 + I_3$ find out Y matrix element

- **The effect of x-mer is Y_{Bus} -**



Load Flow Equations:

$$p_i - j\theta_i = V_i^* I_i \quad \text{and} \quad I_i = \sum_{k=1} Y_{ik} v_k$$

$$p_i = \sum_{k=1}^{n} |v_i||v_k||y_{ik}|\cos(\delta_i - \delta_k - \theta_{ck})$$

$$\theta_i = \sum |v_i||v_k||y_{ik}|\sin(\delta_i - \delta_k - \theta_{ck})$$

Where $v_i = |v_i|\angle\delta_i$ $\qquad Y_{ik} = |Y_{ik}|\angle\theta_{ik}$

- For n Bus system we have $2n$ equation but we have y_n variable (P,θ, |v|, δ) so we spicily 2 variables in each Bus.

  1. Load Bus or PQ Bus.

$$\begin{cases} \text{Specified quantity} = p_i, \theta_i \\ \text{Unknown quantity} = |v|, \delta \end{cases}$$

  – 85% bus are load bus.

  – If it violate voltage limit then its treated like PV Bus.

Where = |v| = violated limit

2. Generator Bus / PV Bus.

$$\begin{cases}\text{Specified quantity} = p_i, |v| \\ \text{Unknown quantity} = \theta_i, \delta_i\end{cases}$$

– 15% buses are generator Bus.

Slack Bus:

Specified quantity = $|v_i|, \delta_i$

$$|v_i| = 1 \qquad \delta_i = 0$$

Unknown quantity = p_i, θ_i

- Generally we choose bus of largest generating station as slack bus. It has zero droop (constant frequency).
- Total slack bus - 1

GS Method :

It PV bus is absent–

$$v_j = \frac{1}{Y_{ii}}\left[\frac{p_i - jQ_i}{v_i^*} - \sum_{\substack{k=1 \\ k\neq c}}^{k=n} Y_{ik} v_k\right]$$

The $(r+1)^{th}$ iteration of vi

$$v_j^{r+1} = \frac{1}{Y_{ii}}\left[\frac{p_i - jQ_i}{\left(v_j^{r}\right)^*} - \sum_{k=1}^{k=i-1} Y_{ik} v_k^{r+1} - \sum_{k=i+1}^{n} Y_{ik} v_k^{r}\right]$$

Let $\frac{p_i - jQ_i}{Y_{ii}} = k_i \qquad \frac{Y_{ji}}{Y_{ii}} = L_{ik}$

$$v_i^{r+1} = \frac{k_j}{\left(v_j^{r}\right)^*} - \sum_{k=1}^{i-1} L_{ik} v_k^{r+1} - \sum_{i+1}^{n} L_{ik} v_k^{r}$$

Total Bus = n

Slack bus = 1

PQ Bus = 2,3,4, ----n [Total (n-1)]

Step – 1 Construct Y_{Bus} matrix and assume $|v_s|$= 1 and δ_i = 0. The v and δ of slack bus is already known.

Step – 2 Set iteration count $r = 0$

Tolerance of convergence E = 10^{-4}

Step – 3 Compute voltage of each bus.

$$v_i^{(r+1)} = \frac{k_i}{\left(v_j^{r}\right)^*} - \sum_{k=1}^{i-1} L_{ik} v_k^{r+1} - \sum_{i+1}^{n} L_{ik} v_k^{r}$$

i = 2,3,4,----n

Step – 4 Find error $|v_j^{r+1} - v_j^r|$

If error $\leq \in$ load flow solution converge

If error $> \in$ Then repeat step 3.

(No of iteration to converge = r +1)

GS method is PV Bus is also given -

Total Bus = N

Slack Bus = 1

PV Bus = 2,3,4,----- m = (m –1) Bus

PQ Bus = (m +1) ----- n = (n – m) Bus

Step -1 : Construct Y_{Bus} matrix for network assume $|v|=1, \delta=0$ for all PQ bus and $\delta=0$ for PV Bus.

Step -2 : Set iteration count r = 0 find out Q and δ for each PV Bus and v and δ for each PQ Bus One by one. Every time use updated quantities.

$$Q_i = \sum_{k=1}^{n} |v_i||v_k||Y_{ik}|\sin(\delta_i - \delta_k - Q_{ik})$$

$$v_i = \frac{1}{Y_{ii}}\left[\frac{p_i - jQ_i}{v_j^*} - \sum_{\substack{k=1 \\ k\neq i}}^{n} Y_{ik} v_k\right]$$

Step -3 : It limit of Q is violated in step 3 then fixed $Q = Q_{min}$ if $Q < Q_{min}$

$Q = Q_{max}$ if $Q > Q_{max}$

And treat it like PQ bus and find v & δ of this quantity.

Repeat step 3 and 4 for each iteration till error are within tolerance limit

** In PV bus we will keep |v| as a specified but modify δ in each iteration

Advantage :

- It is a simple method
- Time required for one iteration is less
- Less computer memory is required.

Disadvantage :

- Slow rate of convergence more no of convergence
- No of iteration depend on number of bus and selection of slack bus.

In GS method to speed up convergence procen acceleration factor is used.

$$v_i^{r+1} = v_i^r + \alpha\left(v_i^{r+1} - v_i^r\right)$$

Generally we use α = 1.6

N.R Method using Polar Co-ordination :

$$P = f(\delta, |v|)$$

$$Q = f(\delta, |v|)$$

$$\begin{bmatrix} P_{(sp)} - P_{(cal)} \\ Q_{(sp)} - Q_{(cal)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P|v|}{\partial |v|} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q|v|}{\partial |v|} \end{bmatrix} \begin{bmatrix} \partial\delta \\ \frac{\partial |v|}{|v|} \end{bmatrix}$$

Case-I : If PV bus does not exist

$$[\ ]_{2pq\times 1} = [2pq \times 2pq][\ ]_{2pq\times 1}$$

Case –II : If PV bus exist

$$[\ ]_{(2pq+pv)\times 1} = \left[\overbrace{(2pq+pv)\times(2pq+pv)}^{Jacobian\,Matrix}\right][\ ]_{(2pq+pv)\times 1}$$

- Order of H Matrix

$$H = \frac{\partial p}{\partial \delta} = (pq+pv)\times(pq+pv)$$

$$\underset{\substack{\text{Total known} \\ P}}{\downarrow} \qquad \underset{\substack{\text{Total unknown} \\ Q}}{\downarrow}$$

- Order of N Matrix $N = \frac{\partial p|v|}{\partial |v|} = (pq+pv)\times(pq)$
- Order of *J* matrix $J = \frac{\partial Q_1}{\partial \delta} = [pq \times (pq+pv)]$
- Order of L matrix $L = \frac{\partial Q_i|v|}{\partial |v|} = [pq \times (pq)]$

Element of Jacobian Matrix :

Diagonal Element

$$H_{ii} = -Q_j - |V_i|^2 B_{ii}$$

$$N_{ii} = P_i + |V_i|^2 G_{ii}$$

$$J_{ii} = P_i - |V_i|^2 G_{ii}$$

$$L_{ii} = Q_i - |V_i|^2 B_{ii}$$

Off Diagonal Element

$$H_{ij} = L_{ij} = |v_i||v_j||v_{ij}|\sin(\delta_i - \delta_j - Q_{ij})$$

$$N_{ij} = -J_{ij} = |v_i||v_j||v_{ij}|\cos(\delta_i - \delta_j - Q_{ij})$$

Step of NR Method:

1. First formed Y_{Bus}, Set iteration count $r = 0$ and set tolerance for convergence $\in$

   Total Bus = n

   But 1 = slack bus

   Bus 2,3,4, - -- - n = PV bus (m–1)

   Bus (m+1) - - - n = PQ Bus (n–m)

2. Calculate P_i and Q_i

$$P_i = P_{Gi} - P_{\Delta i} \text{ [for } PQ \text{ and } PV \text{ bus]}$$

$$Q_i = Q_{Gi} - Q_{\Delta i} \text{ [for } PQ \text{ bus]}$$

3. Assume $|v_i|$ and δ_i for all PQ bus and δ_i for all PV bus.

4. Calculate P_i and Q_i using load flow equation.

$$P_{i(cal)} = \sum_{k=1}^{n} |v_i||v_k||Y_{ik}|\cos(\delta_i - \delta_k - Q_{ik})$$

$$Q_{i(cal)} = \sum_{k=1}^{n} |v_i||v_k||y_{ik}|\sin(\delta_i - \delta_k - Q_{ik})$$

5. Calculate mismatch vector $\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}_{[(2pq+pv)\times 1]}$

$$\Delta P_i = P_{i(sp)} - P_{i(cal)}$$

$$\Delta Q_i = Q_{i(sp)} - Q_{i(cal)}$$

6. Calculate the element of Jacobian matrix

7. Now find out $\Delta\delta_i$ and $\frac{\Delta|v_i|}{|v_s|}$ by using.

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \frac{\Delta|v|}{|v|} \end{bmatrix}$$

8. Update the voltage Mog and δ for all PQ and PV bus.

$$\delta_i^{r+1} = \delta_i^r + \Delta\delta_i^r$$

$$|v_i|^{r+1} = |v_i|^r + \Delta|v_i|^r$$

9. Compute $P_{i(cal)}$ & $Q_{i(cal)}$ with updated value of $|v|$ and δ.

10. If $Q_{i(cal)}$ of PV bus violate the limit of reactive power then treat it as a PQ Bus. By keeping Q = violated limit

11. Continue same procedure till ΔP_i and ΔQ_i of all PQ bus and ΔP_i of all PV bus are within tolerance limit.

Fast Decoupled Method

It is a modification of NR method in which Jacobian matrix has only suseptance B of Y matrix

$$\begin{bmatrix} \Delta P_i / |v_i| \\ \Delta Q_s / |v_i| \end{bmatrix} = \begin{bmatrix} {}^{\ominus}B\,Matrix \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \Delta v_i \end{bmatrix}$$

Method:

- Form Y_{Bus} Matrix
- Find out $P_{i(sp)}$ and $Q_{i(sp)}$
- Now calculate P_i and Q_s for all PQ buses and P_i for all PV bus.

$$P_{i(cal)} = \sum |v_i||v_k||Y_{ik}|\cos(\delta_i - \delta_k - Q_{ik})$$

$$Q_{i(cal)} = \sum |v_i||v_k||Y_{ik}|\sin(\delta_i - \delta_k - Q_{ik})$$

- Find out mismatch vector. $\frac{\Delta P_i}{|v_i|}$ and $\frac{\Delta Q_i}{|v_s|}$
- Solve equations to find out $\Delta\delta_i$; and $|V_i|$
- Update δ and use then to find out mismatch vector.

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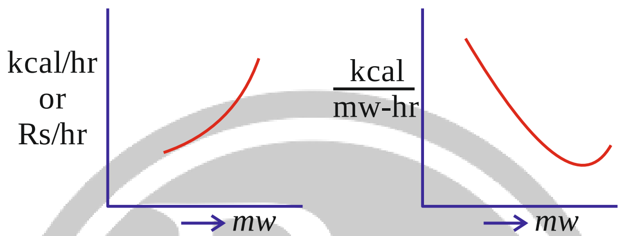
13 Economic Load Dispatch

13.1. Introduction



Input– Output Curve:

Economic load dispatch neglecting loss –

For optimal operation

$$\frac{df_1}{dP_1} = \frac{df_2}{dP_2} = \frac{df_3}{dP_3} ..... = \frac{df_n}{dP_n} = \lambda$$

- If power calculated by economic operation violate active power limit. We fixed power to that limit

$$P_1(cal) \geq P_1(\max)$$

$$P_1 = P_1(\max)$$

- If (max I.C) of unit 1 is less than (min I.C) of unit 2. Then we load unit 1 to its rated capacity first and remaining power will taken from unit
- If I.C of any unit is fixed and this cost is less than minimum I.C of others unit. Then we will load the unit up to its rated capacity and remaining power will be taken by other units.

Loss Equations :

$$P_L = \sum_n \sum_m P_m B_{mn} P_n$$

Or in matrix for *m* $\quad P_L = P^T BP$

i.e. in 2 Bus system = $\begin{bmatrix} P_1 & P_2 \end{bmatrix} \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \end{bmatrix}$

- In N bus system we have N^2 coefficient

Lagrangian Method (Including Losses):

$$\frac{df_1}{dP_1}L_1 = \frac{df_2}{dP_2}L_2 ---= \frac{df_n}{dP_n}L_n = \lambda$$

$$L_n = \text{Penalty factor} = \frac{1}{\left(1-\frac{\partial P_L}{\partial P_n}\right)}$$

If total load is connected with Bus 2 loss coefficient connected with B in 2 will be always zero.

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14 SWITCH GEAR AND PROTECTION

14.1. Introduction

Fault clear time = Relay time + CB time

- "Relay time" is time between instant of fault and instant of closure of relay.
- "CB time" is the time between closure of relay & instant of arc interruption.

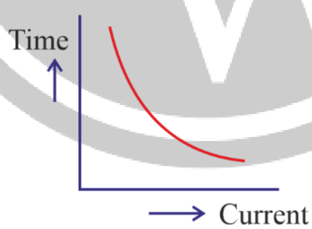
Desirable Feature of Relay:

1. Sensitivity and discrimination
2. Selectivity
3. Reliability
4. Speed

$$\frac{\text{Reset value}}{\text{Pickup value}} = 0.6 \text{ to } 0.99$$

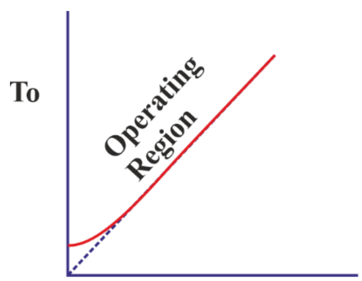
Attracted Armature type Relay:

$$I > \frac{\sqrt{k_2}}{\sqrt{k_1}}$$



Balance Bean Relay :

$$\frac{I_1}{I_2} > \sqrt{\frac{k_2}{k_1}}$$



Induction Disc Relay :

1. Shaded Pole Relay :

$$To \times \phi_{m1}\phi_{m2} \sin\theta$$

- Disc is spiral in nature
- Disc more from unshaded pole to shaded pole

2. Watthour meter type

- The AT require for operation of Relay is fixed. by using PSM, no of turn can be change.

$$\text{PSM} = \frac{\text{Secondary current in CT}}{\text{Relay current setting}}$$

- If Relay rating is not given we take secondary side ratio of CT as a relay pick up value.
- By changing TSM the distance between fixed and moving contact is charge.
- If operating time for TMS 1 is *s* then operating time for TMS = T is = S ×T

Induction Cup Type Relay:

- It has two, four or more electromagnet
- Router is a follow cylinder cup type
- This relay are more sensitive and use for high speed application.

PMMC Relay:

- Coil is rotate in magnetic field.
- $T \propto I$

Rectifier Relay : Measured quantity are rectified and then feed to moving coil unit.

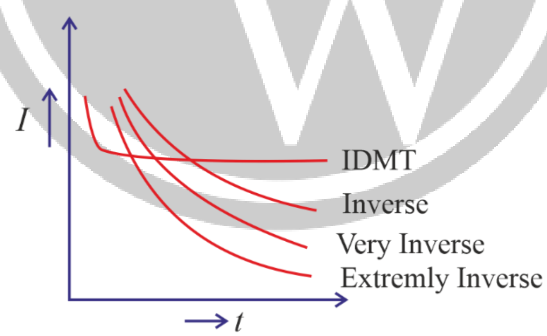
Thermal Relay : Used for over load protection

Under Frequency/Over Frequency Relay : Frequency change due to charge load

Under Voltage/Over Voltage Relay: If voltage change beyond ±5% variation then these relay operate

Directional Relay : It sense the power and respond only if power is positive.

Over Current Relays :



- In IDMT operating time is inversely proportional to current up to pick up value above pick up value operating time is constant
- Inverse time relay $t \propto \frac{1}{I}$
- Very inverse Relay $t = \frac{K}{I^n - n}$

  N = (1.02-2)
- Extreme inverse relay $I = \frac{K}{I^n}$

  $(n = 2-8)$

Earth Fault Protection:

- Residually connected earth fault relay.
- EF relay connected to neutral to earth.
- EF protection with core balance

Directional Over Current Protection:

It has two elements:

1. Directional element
2. Non directional O/C relay

Torque developed in directional unit.

$$T = KVI \cos(\theta - \tau)$$

θ = actual angle between V and I

τ = Maximum torque angle

Differential Protection :

- It is a unit protection used for protection of generator, transformer, Bus bar and T.L.
- Biased/percentage differential protection

$$\text{Operating torque} \propto N(I_1 - I_2)$$

$$\text{Restraining torque} \propto \left(\frac{I_1 + I_2}{2}\right)N$$

$$\%\text{ pickup value} = \frac{(I_1 + I_2)}{N\frac{(I_1 + I_2)}{2}} \times 100\%$$

- For feeder protection we generally used voltage balance differential relay.

Distance Relay :

Universal Relay equation

$$T = k_1 I^2 + k_2 v^2 + k_3 vI \cos(\theta - \tau) + k_4$$

Impedance Relay:

- Voltage restrain over current relay

$$k_1 I^2 > k_2 v^2 \text{ for Relay operation}$$

- It is non directional Relay

Reactance Relay:

- It is directional restrain over current Relay

$$T = k_1 I^2 - k_2 vI \cos(\theta - \tau)$$

- Relay operate when X seen by Relay is less than preset value.
- It is non directional relay

Mho Relay :

- It is voltage restrain directional Relay

$$T = k_3 vI \cos(\theta - \tau) - k_2 v^2$$

or $$Y \cos(\theta - \tau) > k_2 / k_3$$

- It has directional properties

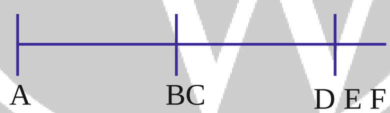
Arc resistance effect
→ Reactance Relay (unaffected)
→ Mho (maximum affected)
→ Impedance (Moderately affected)

Effect of power swing
→ Mho (least affected)
→ Reactance (maximum affected)
→ Impedance (Moderately affected)

- Long line – Mho Relay
- Medium – Impedance Relay
- Short line – Reactance Relay

Protection of T.L.:

- For Radial feeder time – current grading scheme is used.
- In parallel feeder relay near the source should be non-directional < Relay near load should be directional



- Distance protection is 3 step characteristic first zone – 80% of line AB

  Second zone – 20% of line AB + 20 to 50% of line CD

  Third zone – Remaining 50 of CD + 20% of EF
- Differential protection /Pilot relaying.
  (a) Wire pilot – 1 Hz to 1 kHz
  (b) Carrier pilot – 1 kHz to 100 kHz

Protection of Transformer :

overload
— o/c Relay
— Thermal Relay

Inter turn fault & oil leakage $\rightarrow$ Buchhloz relay

Phase fault & ground fault $\rightarrow$ Biased diff. relay(main protection)

Over current relay (back up protection)

- For Biased differential relay

$$\boxed{v_{ph1} \times (CT\ Ratio)_1 = v_{ph2} \times (CT\ Ratio)_2}$$

If main x-mer Y → CT side Δ

If main x-mer Δ → CT side Y

- Differential protection should not operate due to magnetizing inrush current we use “Harmonic restrain protection”

Operating coil ⟶ only fundamental component

Restraining coil ⟶ Rectified sum of fundamental component + harmonics.

Protection of Alternator:

- Unbalance loading – Negative sequence Relay
- Loss of excitation – offset Mho relay

Or

- Under current Relay in series of field winding.
- Modified differential protection

$$\%x = \frac{I_{\text{Pick}} \times R}{v} \times 100\%$$

x = Unprotected winding

v = per phase voltage

R = Neutral resistance

V = per phase voltage

- If winding reactance is also included then $I_{pick} = \dfrac{xv}{\sqrt{R^2 + X^2}}$

X = Reactance of only unprotected zone

- In restricted EP protection $I_{p/ck} = \dfrac{xv_{ph}}{\sqrt{R_n^2 + X^2}}$ (generally R_n >> X)

R_n = *Neutral resistance*

X = Reactance of unprotected winding.

Inter turn fault – split phase relaying

Over load protection – thermistor/thermocouple

Over voltage – over voltage Relay

Over speeding – watthour meter type of Relay

Failure of prime mover – Reverse power watt metric Relay.

Bus Bar Protection:

Main protection – Diff. protection

Back protection — o/c protection
Back protection — Distance protection

14.2. Circuit Breaker

- Arc is initiated by field emission and arc is maintained by thermal emission.
- Arc is resistive in nature

- Conductance of Arc $\propto \frac{\text{diameter of Arc}}{\text{length of Arc}}$

  So Arc can be interrupted by increasing length of Arc or decreasing diameter of Arc.

- Arc Interruption Method — High Resistance Method
  — Low Resistance method

- In high resistance method, resistance is increased by lengthening of Arc, splitting of Arc, Cooling of Arc. It is used in D.C ckt breaker and low and medium voltage CB
- Low resistance/current zero method is used for high voltage A.C circuit breaker.

Arc Interruption Theory:

- If RRRV > Build up of dielectric strength $\Rightarrow$ Arc restrike again
- If RRRV < Build up of dielectric strength $\Rightarrow$ Arc extinguished

Energy Balance Theory:

- If Rate of heat generated < rate of heat dissipated $\Rightarrow$ Arc extinguished
- **Recovery voltage :** it is power frequency (50Hz) RMS voltage between CB contact when arc is extinguished.
- **Active recovery voltage :** It is instantaneous voltage across CB contact at time of arc extinction

$$\text{ARV} = k_1 k_2 k_3 v_m \sin\phi$$

v_m = maximum phase voltage

k_3 = 1 for phase voltage

= $\sqrt{3}$ for line voltage

k_2 = one pole to clear factor

Restriking Voltage :

$$v_m\left[1-\cos\frac{t}{\sqrt{LC}}\right]$$

Rate of rise of recovery voltage, $RRRV = \frac{v_m}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}}$

Average value of RRRV = $\frac{2v_m}{\pi\sqrt{LC}}$

- **Current chopping :** When interrupting low magnitude of inductive current. The current is interrupted before current zero is called current chopping. It mainly occur in Air Blast CB.
- Resistance switching is used $R = \frac{1}{2}\sqrt{\frac{L}{C}}$

1. Bulk oil CB
   - Plain Break CB
   - Arc control CB
2. Minimum oil CB
3. Air Break CB
4. Air Blast CB
   - Axial Blast
   - Cross Blast
5. Vacuum CB
6. SF_6 CB

Symmetrical Breaking Current :

RMS value of AC component of fault current which CB is capable of breaking.

Asymmetrical Breaking Current :

$$I_{asy} = \sqrt{(I_{DC})^2 + \left(\frac{I_{AC}(mx)}{\sqrt{2}}\right)^2}$$

- Breaking capacity = $\sqrt{3} \times$ rated line voltage $\times$ I_{sym}
- Rated Making current = $1.8 \times \sqrt{2} \times$ rated s/c breaking current (RMS)