~~Medium T.L.~~

Surge Impedance

Surge impedance (Z_0) of a line is defined as the square root of Z/Y

ie $Z_0 = \sqrt{\frac{Z}{Y}}$

where $Z = R + jX \rightarrow$ Series impedance

$Y = G + jB \rightarrow$ shunt admittance

For a line having negligible resistance (ie when the conductors are of large c-s.) and having no shunt leakage (ie when value of G will be zero), $Z = \sqrt{L/C}$ which is a pure resistance. It has a value of 400 to 600 Ω for an overhead line & 40 to 60 Ω for an underground cable.

The surge impedance of a line may be measured in terms of Z_{oc} & Z_{sc} where these are impedances measured at the sending end with receiving end open-circuited & short circuited resp.

We know, for a T.L.,

$$V_s = A \cdot V_R + B \cdot I_R$$

$$I_s = C \cdot V_R + D \cdot I_R$$

$\therefore$ When there is o.c. at R.E,

$$I_R = 0$$

$$\therefore V_s = A V_R$$

$$I_s = C V_R$$

$$\therefore Z_{oc} = \frac{V_s}{I_s} = A/C \quad \text{--- (1)}$$

When R.E is short circuited,

$V_R = 0$

$\therefore V_s = B \cdot I_R$

$I_s = D \cdot I_R$

$\therefore Z_{sc} = \frac{V_s}{I_s} = B/D. \quad — (2)$

Multiply (1) & (2),

$\therefore Z_{oc} \cdot Z_{sc} = \frac{A}{C} \cdot \frac{B}{D}$

As $A = D$ for a T.L;

$Z_{oc} \cdot Z_{sc} = B/C$

$\left.\begin{array}{l} B = \sqrt{Z/Y} \cdot \sinh\sqrt{YZ} \\ C = \sqrt{Y/Z} \ \sinh\sqrt{YZ} \end{array}\right\}$ for a long T.L.

$\therefore \frac{B}{C} = Z/Y$

But from definition of surge impedance,

$\frac{Z}{Y} = Z_c^2$

$\therefore Z_{oc} \cdot Z_{sc} = Z_c^2$

$\therefore$ ~~Z_{sc}~~

$\boxed{Z_0 = \sqrt{Z_{oc} \cdot Z_{sc}}}$

Surge impedance Loading (SIL)

SIL is a very imp. parameter in the study of power system as it is used in the prediction of max. loading capacity of T.L.s.

Before understanding SIL, we must know what is surge impedance (Zc) or (

We know that a long T.L. have distributed inductance & capacitance as its inherent property. When the line is charged, the capacitance component feeds reactive power to the line, while the inductance component absorbs the reactive power. If we take the balance of the two reactive powers, we get,

capacitive VAR = inductive VAR

$$\text{Capacitive VARs} = V \cdot I = V \cdot \frac{V}{X_c} = \frac{V^2}{X_c}$$

$$\text{inductive VARs} = V \cdot I = I \cdot X_L \cdot I = I^2 X_L$$

$$\therefore \frac{V^2}{X_c} = I^2 \cdot X_L$$

$$\therefore \frac{V}{I} = \sqrt{X_L X_C} = \sqrt{\frac{2\pi f L}{2\pi f C}}$$

$$\frac{V}{I} = \sqrt{\frac{L}{C}} = Z_c$$

This quantity having the dimensions of resistance (Ω) is called as surge impe

It can be considered as a purely resistive load which when connected at the receiving end of the line, the reactive power generated by capacitive reactance will be completely absorbed by inductive reactance. It is nothing but the characteristic impedance (Z_C) of a lossless line.

The surge impedance of a line may be measured in terms of Z_{oc} & Z_{sc} where these are impedances measured at the sending end with receiving end open-circuited & short circuited resp.

We know that,

$$V_S = A \cdot V_R + B I_R$$

$$I_S = C \cdot V_R + D \cdot I_R$$

When there is O.C. at R.E; $I_R = 0$

$$\therefore V_S = A \cdot V_R$$

$$I_S = C \cdot V_R$$

$$\therefore Z_{OC} = \frac{V_S}{I_S} = A/C \quad \text{--- (1)}$$

When there is S.C. at R.E; $V_R = 0$

$$\therefore V_S = B \cdot I_R$$

$$I_S = D \cdot I_R$$

$$\therefore Z_{SC} = \frac{V_S}{I_S} = B/D \quad \text{--- (2)}$$

Multiply ~~A~~ ① & ②,

$$Z_{oc} \cdot Z_{sc} = \frac{A}{C} \cdot \frac{B}{D}$$

$$= \frac{B}{C} \quad \ldots \text{as } A = D \text{ for T.L.}$$

$$\therefore Z_{oc} \cdot Z_{sc} = B/C$$

For a long T.L.,

$$B = \sqrt{Z/Y} \cdot \sinh\sqrt{YZ}$$
$$C = \sqrt{Y/Z} \, \sinh\sqrt{YZ}$$

$$\therefore \frac{B}{C} = Z/Y$$

But from definition of surge impedance,

$$\frac{Z}{Y} = Z_c^2$$

$$\therefore Z_{oc} \cdot Z_{sc} = Z_c^2$$

$$\therefore \boxed{Z_c = \sqrt{Z_{oc} \cdot Z_{sc}}} \longrightarrow \text{Surge impedance.}$$

Now let's define SIL.

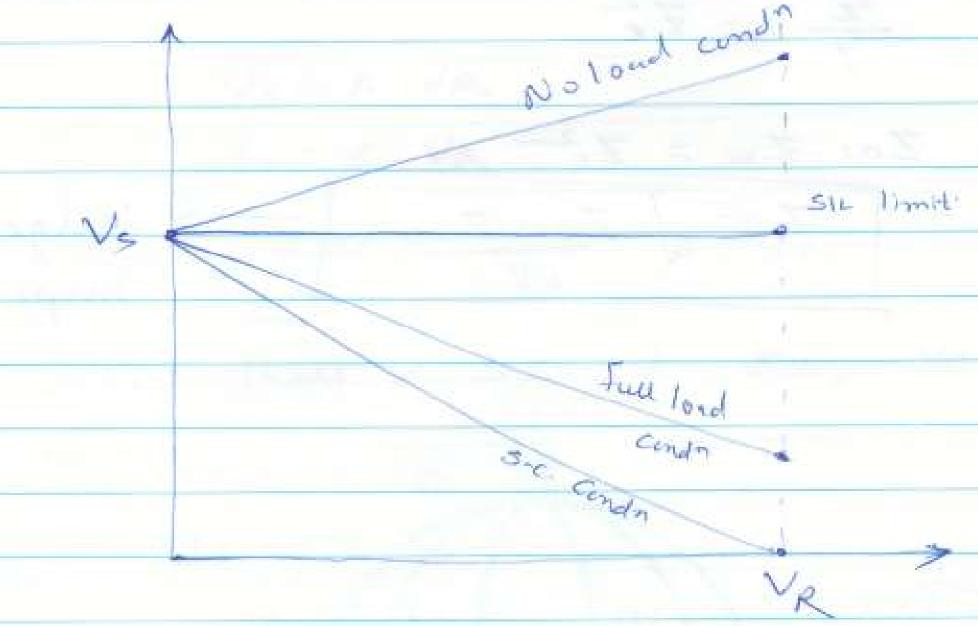
SIL is defined as the power delivered by a line to a purely resistive load equal in value to a surge impedance of that line.

The unit of SIL is watt.

When the line is terminated by surge impedance, the R.E. voltage is equal to S.E. voltage and this case is called as flat voltage profile.

* imp → surge impedance & hence SIL is independent of the length of the line. The value of surge impedance will be the same at all the points on the line & hence the voltage.

Voltage behavior of a long T.L. (without shunt reactor installed)



The power transmitted under SIL condn is

$$P_R = \frac{V_R^2}{Z_c}$$

$Z_c \rightarrow$ surge impedance.

$P_R \rightarrow$ surge impedance loading.

$\hookrightarrow$ is also called as natural power of the line.

Above eqn gives a limit to the max. power that can be delivered and is useful in the design of the T.L.

SIL can be used for the comparison of loads that can be carried on the lines at diff. voltages.

In order to increase the power transmitted through a long T.L., either value of RE voltage is to be increased or more than one T.L. can be run in parallel. But the 2nd method is costly.

$\therefore$ From above eqn, in order to increase P_R, either V_R is to be increased or Z_c is to be decreased.

Increase in V_R - now a days trend is for higher & higher voltages, so this is the most widely adopted method to increase the power limit.

Decrease in Z_c - Since spacing betn cond's cannot be decreased much, it being dependent on the line voltages & corona, etc, the value of

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<u>Decrease in Z_c</u> - Since spacing betn condrs cannot be decreased much, it being dependent on the line voltages & corona, etc, the value of

Z_c cannot be ~~vari~~ varied much.
$Z_c = \sqrt{L/C}$ for a lossless T.L. To decrease Z_c, either L is decreased using series capacitors or C is increased using shunt capacitors.

Surge Impedance Loading (SIL)

Surge impedance loading is defined as the load that can be delivered by the line having no resistance, the load being at unity p.f.

Surge impedance continued →

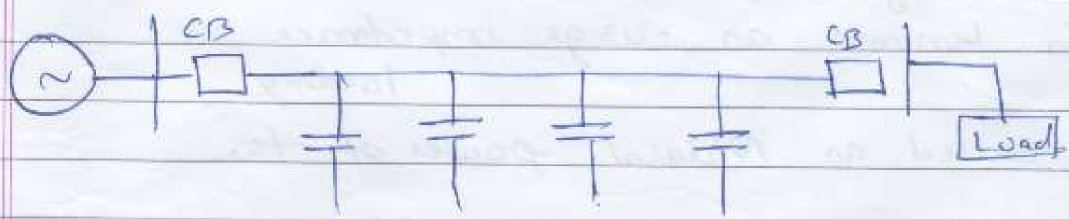
A long T.L. have distributed inductance & capacitance as its property. When the line is charged, the capacitance component feeds reactive power to the line while the inductance absorbs the reactive power.

At the balance of two reactive powers,

capacitive VAR = Inductive VAR

The load at which the inductive & capacitive VARs are equal & opposite, such load is called surge impedance load. In SIL, the voltage & current are in the same phase at all the points of the line.

Shunt capacitance charges the T.L. when the circuit breaker at the S.E is closed as shown below.



∴ Capacitive VARs generated in the line are,

$$= \frac{V^2}{X_c} = V^2 \omega C \quad \text{per ph.}$$

using $\left[V \cdot I = V \cdot \frac{V}{X_c} \right]$

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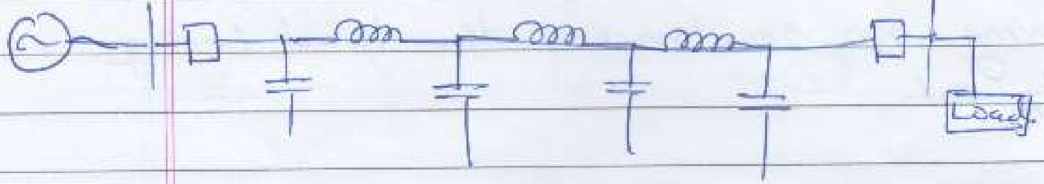
The series inductance of the line consumes the electrical energy when the S.E. & R.E. terminals are closed



∴ Inductive VARs absorbed by the line,

$$= I^2 X_L = I^2 \omega L. \qquad \left[\begin{aligned} P &= V.I = I.R.I \\ &= I^2 R \end{aligned}\right]$$

∴ Capacitive VARs = Inductive VARs

$$\frac{V^2}{X_c} = I^2 X_L$$

$$\therefore \frac{V}{I} = \sqrt{X_L \cdot X_c}$$

$$= \sqrt{\frac{L}{C}} = Z_0$$

The power transmitted under these conditions is,

$$P_R = \frac{V_R^2}{Z_0} \qquad \left(\text{using } P = \frac{V^2}{R}\right)$$

Z_0 is surge impedance
P_R is known as surge impedance loading
also called as Natural power of the line.

Above eqn gives a limit to the max. power that can be delivered & is useful in the design of T.Ls.

SIL can be used for the comparison

of loads that can be carried on the lines at different voltages.

In order to increase the power transmitted through a long T.L; either value of R.E. Vltg. is to be increased or more than one T.L. can be run in parallel. But the 2nd method is costly. From the above eqn, in order to increase P_R, either V_R is to be increased or Z_0 is to be decreased.

Increase in V_R – Now a days the trend is for higher & higher voltages, so this is the most widely adopted method to increase the power limit.

Decrease in Z_0 – Since spacing betn conductors cannot be decreased much, it being dependent on the line voltages & corona, etc., the value of Z_0 cannot be varied much. $Z_0 = \sqrt{L/C}$ for a lossless T.L. To decrease Z_0 either L is decreased using series capacitors or C is increased using shunt capacitors.

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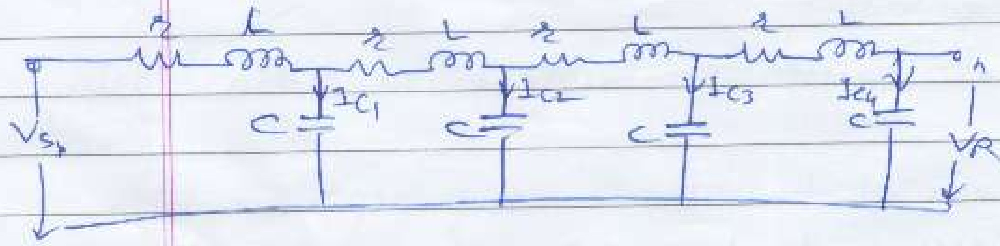
Ferranti Effect

In general, we know that for all electrical systems, current flows from region of higher potential to the region of lower potential. In all practical cases, the S.E. voltage is higher than the R.E. voltage due to line losses, so current flow from supply end to the load.

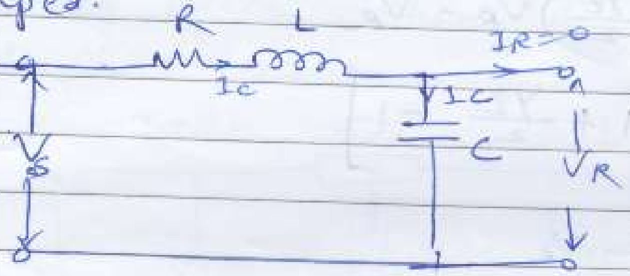
But Sir S.Z. Ferranti, in the year 1890, came up with an astonishing theory about medium & long T.L. suggesting that in case of light loading or no load operation, the R.E. Vltg increases beyond S.E voltage. This pheonomena is called as Ferranti effect in P.S.

A long T.L. can be considered to be composed of a considerably high amount of capacitance & inductance distributed across the entire length of the line. Ferranti effect occurs when the current drawn by the distributed capacitance of the line itself is greater than the current associated with the load at the R.E. of the line (during light load or no load).

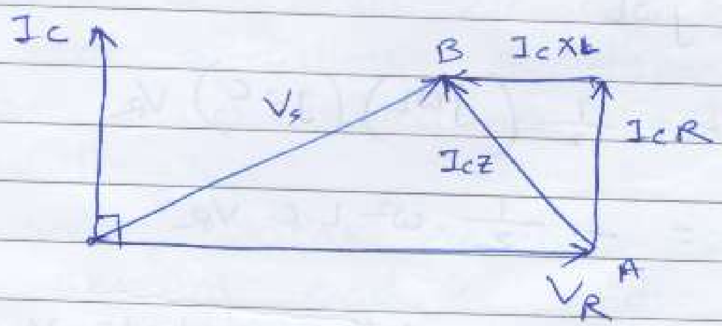


This capacitor charging current leads to a Vltg. drop across the inductor which is in phase with the S.E vltg. This vltg. drop keeps on increasing additively as we move towards the load end of the line and subsequently, the R.E vltg. tends to get larger than applied vltg leading to phenomena of Ferranti effect

The above fig. can be replaced by the new one shown below (for approximate analysis) where, distributed parameters are shown lumped.



~~etc~~ V_R is drawn as ref phasor.



Charging current I_C is 90° ahead of V_R. This current causes vltg. drop AB which is equal to $I_C(R + j\omega L)$ in the line.

It can be seen that V_s is lower than V_R.

Ferranti effect can also be explained with the help of nominal π ckt.

In nominal π model,

$$V_S = \left(1 + \frac{YZ}{2}\right) V_R + Z I_R$$

at no load, $I_R = 0$

$$\therefore \quad V_S = \left(1 + \frac{YZ}{2}\right) V_R$$

Now,
$$V_S - V_R = \left(1 + \frac{YZ}{2}\right) V_R - V_R$$

$$= V_R \left[1 + \frac{YZ}{2} - 1\right]$$

$$V_S - V_R = \frac{YZ}{2} \cdot V_R$$

$Z = R + j\omega L$

$Y = j\omega C$

if R is neglected,

$Z = j\omega L$

$$\therefore \quad V_S - V_R = \frac{1}{2} (j\omega L)(j\omega C) V_R$$

$$= -\frac{1}{2} \omega^2 L \cdot C \cdot V_R$$

It shows that difference betn V_S & V_R is -ve, ie V_R is bigger than V_S.

To reduce Ferranti effect -

1. To reduce R.E Vltg, shunt reactors can be converted at receiving end of the line. It will compensate the capacitive current

$\cosh j\theta = \cos\theta$
$\sinh j\theta = j\sin\theta$

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Tuned Power Lines

When receiving end voltage & current are numerically equal to the corresponding sending end values, so that there is no voltage drop on load. Such a line is called a tuned line.

The equation,

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & Z_0 \sinh \gamma l \\ \frac{1}{Z_0} \sinh \gamma l & \cosh \gamma l \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

characterises the performance of long T.L.

For a overhead line shunt conductance G is always negligible & it is sufficiently accurate to neglect the resistance R as well. With this assumption,

$\cancel{\gamma = j\omega}$

$$\gamma = \sqrt{yz} = j\omega\sqrt{LC}$$

$$\therefore \cosh \gamma l = \cosh j\omega l\sqrt{LC} = \cos \omega l\sqrt{LC}$$

$$\sinh \gamma l = \sinh j\omega l\sqrt{LC} = j\sin \omega l\sqrt{LC}$$

Hence above eqn is now,

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} \cos \omega l\sqrt{LC} & jZ_0 \sin \omega l\sqrt{LC} \\ \frac{j}{Z_0} \sin \omega l\sqrt{LC} & \cos \omega l\sqrt{LC} \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

Now if $\omega l\sqrt{LC} = n\pi$

where $n = 1, 2, 3, \ldots$

$$|V_s| = |V_R|$$
$$|I_s| = |I_R|$$

ie the R.E vltg. & current is numerically equal to corresponding S.E values.

For 50Hz, the length of the line for tuning is,

$$l = \frac{n\pi}{\omega\sqrt{LC}} = \frac{n\pi}{2\pi f\sqrt{LC}}$$

since $\frac{1}{\sqrt{LC}} \simeq v$, the velocity of light (3,00,000 km/sec)

$$l = \frac{1}{2}(n\lambda)$$

$\lambda = \frac{3,00,000}{\text{Freq}}$

$$= \frac{1}{2}\lambda, \lambda, \frac{3}{2}\lambda, \ldots$$ (Putting $n = 1, 2, 3 \ldots$)

$$= 3000\text{ km}, 6000\text{ km} \ldots$$

It is a too long a distance of transmission from the point of view of cost & efficiency. (here resistance was neglected).

For a given line length & frequency, tuning can be achieved by increasing L or C ie, by adding series inductances or shunt capacitances at several places along the line length. But this method is impractical & uneconomical for power frequency lines & is adopted for telephony (communication) where

The method presently experimented for tuning of lines is, using series capacitance to cancel the effect of line inductance & using shunt inductors to neutralise line capacitance. A long line is divided into several sections which are individually tuned.

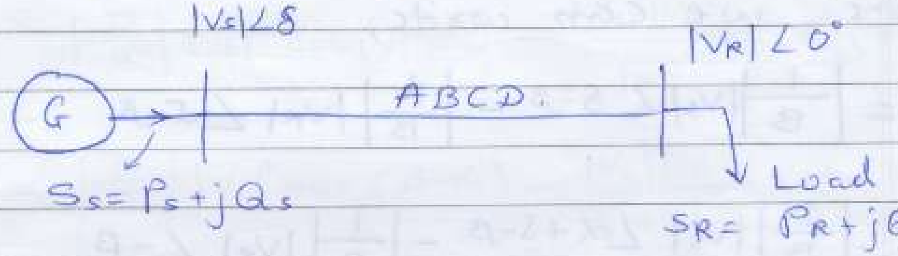
So far, the practical method of improving line regulation & power transfer capacity is to add series capacitors to reduce line inductance, shunt capacitors under heavy load conditions & shunt inductors under light or no-load conditions.

Power Flow through a T.L.

Till now T.L. performance eqns were in the form of vltg. & current relationships betn S.E. & R.E.

But since, loads are often expressed in terms of real & reactive powers, it is convenient to deal with T.L. eqns in the form of S.E and R.E. complex power & voltages.

Consider a single T.R. (2 node / 2 bus sys.)



. Consider a R.E vltg as reference phasor ($V_R = |V_R|\angle 0^\circ$) and let S.E. vltg. lead ~~by~~ it by an angle δ ($V_s = |V_s|\angle\delta$).

The angle δ is known as torque angle (torque angle is the angle by which rotating field lags the stator field in case of syn. motor).

The complex powers at S.E & R.E are,

$$S_R = P_R + jQ_R = V_R . I_R^* \quad \text{——— (1)}$$
$$S_S = P_S + jQ_S = V_S . I_S^* \quad \text{——— (2)}$$

From basic eqns of V_S & I_S ie

$$V_S = A V_R + B . I_R \longrightarrow B I_R = V_S - A V_R, \quad \therefore I_R = \frac{1}{B} V_S - \frac{A}{B} V_R$$
$$I_S = C V_R + D I_R \qquad I_S = C V_R + D\left[\frac{1}{B} V_S - \frac{A}{B} V_R\right]$$

I_S & I_R can be written as,

$$= C V_R + \frac{D}{B} V_S - \frac{DA}{B} V_R$$
$$= \frac{D}{B} V_S + V_R\left(C - \frac{DA}{B}\right)$$

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$$I_R = \frac{1}{B} \cdot V_s - \frac{A}{B} V_R \quad \text{--- (3)}$$

$$I_s = \frac{D}{B} V_s - \frac{1}{B} V_R \quad \text{--- (4)}$$

$\therefore I_s = \frac{D}{B} V_s + V_R \left(\frac{BC - AD}{B} \right)$

$= \frac{D}{B} V_s - \frac{1}{B} V_R$

$\because (BC - AD = -1)$

Where, A, B, D are T.L. constants as

$A = |A| \angle \alpha$

$B = \cancel{|B| \angle \delta}\ |B| \angle \beta$

$D = |D| \angle \alpha$ --- (as $A = D$).

Therefore, we can write,

$$I_R = \left|\frac{1}{B}\right| |V_s| \angle \delta - \beta - \left|\frac{A}{B}\right| |V_R| \angle \alpha - \beta \quad \text{--- (5)}$$

$$I_s = \left|\frac{D}{B}\right| |V_s| \angle \alpha + \delta - \beta - \left|\frac{1}{B}\right| |V_R| \angle -\beta \quad \text{--- (6)}$$

Substituting for I_R in eqn (1) & I_s in eqn (2)

$$S_R = |V_R| \angle 0 \left[\left|\frac{1}{B}\right| |V_s| \angle \cancel{\delta - \beta}\ \beta - \delta - \left|\frac{A}{B}\right| |V_R| \angle \cancel{\alpha - \beta}\ \beta - \alpha \right]$$

$$= \frac{|V_R||V_s|}{|B|} \angle (\beta - \delta) - \frac{|A|}{|B|} |V_R|^2 \angle (\beta - \alpha) \quad \text{--- (7)}$$

Similarly,

$$S_s = \left|\frac{D}{B}\right| |V_s|^2 \angle (\beta - \alpha) - \frac{|V_s||V_R|}{|B|} \angle (\beta + \delta) \quad \text{--- (8)}$$

Eqns (7) & (8) gives 3 ph. MVA if V_s & V_R are expressed in kV line.

If eqns (7) & (8) expressed in real & imaginary parts, we can write ~~rea~~ real & reactive powers at R.E & S.E as,

$$P_R = \frac{|V_s||V_R|}{|B|} \cos(\beta - \delta) - \left|\frac{A}{B}\right| |V_R|^2 \cos(\beta - \alpha) \quad \text{--- (9)}$$

$$Q_R = \frac{|V_s||V_R|}{|B|} \sin(\beta - \delta) - \left|\frac{A}{B}\right| |V_R|^2 \sin(\beta - \alpha) \quad \text{--- (10)}$$

Similarly,

$$P_s = \left|\frac{D}{B}\right| |V_s|^2 \cos(\beta - \alpha) - \frac{|V_s||V_R|}{|B|} \cos(\beta + \delta) \quad \text{--- (11)}$$

$$Q_s = \left|\frac{D}{B}\right| |V_s|^2 \cos(\beta - \alpha) - \frac{|V_s||V_R|}{|B|} \cos(\beta + \delta) \quad \text{--- (12)}$$

From eqn (9),

P_R will be max. when $\delta = \beta$

$$\therefore P_{R(max)} = \frac{|V_s||V_R|}{B} - \left|\frac{A}{B}\right| |V_R|^2 \cos(\beta - \alpha) \quad \text{--- (13)}$$

and corresponding Q_R will be,

$$Q_R = -\left|\frac{A}{B}\right| |V_R|^2 \sin(\beta - \alpha) \quad \text{--- (14)}$$

Thus load must draw this much leading reactive power (MVAR) in order to receive maximum real power.

Consider now a special case of short T.L with series impedance z, so

$$A = D = 1\angle 0°$$

$$B = Z = |Z| \angle \theta$$

substituting these values in eqⁿs (9), (10), (11) & (12) we get simplified results for short line as,

$$P_R = \frac{|V_S||V_R|}{|Z|}\cos(\theta - \delta) - \frac{|V_R|^2}{|Z|}\cos\theta \quad \text{— (15)}$$

$$Q_R = \frac{|V_S||V_R|}{|Z|}\sin(\theta - \delta) - \frac{|V_R|^2}{|Z|}\sin\theta \quad \text{— (16)}$$

$$P_S = \frac{|V_S|^2}{|Z|}\cos\theta - \frac{|V_S||V_R|}{|Z|}\cos(\theta + \delta) \quad \text{— (17)}$$

$$Q_S = \frac{|V_S|^2}{|Z|}\sin\theta - \frac{|V_S||V_R|}{|Z|}\sin(\theta + \delta) \quad \text{— (18)}$$

- Above short line eqⁿ will also be applicable for a long line when the line is replaced by its equivalent π or nominal π. This technique is always used to treat the load flow problem.

From eqⁿ (15), max. R.E power is when $\delta = \theta$, so that

$$\therefore P_{R(max)} = \frac{|V_s||V_R|}{|Z|} - \frac{|V_R|^2}{|Z|} \cos\theta$$

$$\cos\theta = R/|Z|$$

$$\therefore P_{R(max)} = \frac{|V_s||V_R|}{|Z|} - \frac{|V_R|^2}{|Z|^2} \cdot R \quad \text{—— (19)}$$

Normally the resis. of T.L. is small as compared to its reactance, so that,

$$\theta = \tan^{-1}\frac{X}{R} \simeq 90^\circ \quad \text{where } Z = R + jX$$

$\therefore$ Eq^n (15) & (16) at R.E can be approximated as,

$$P_R = \frac{|V_s||V_R|}{X} \sin\delta \quad \text{—— (20)}$$

$$Q_R = \frac{|V_s||V_R|}{X} \cos\delta - \frac{|V_R|^2}{X} \quad \text{—— (21)}$$

Eq^n (21) can be further simplified by assuming $\cos\delta \simeq 1$ since δ is normally small,

$$\therefore Q_R = \frac{|V_R|}{X}\left(|V_s| - |V_R|\right) \quad \text{—— (22)}$$

Let $|V_s| - |V_R| = |\Delta V|$ drop in vltg. along the T.L.,

$$Q_R = \frac{|V_R|}{X}|\Delta V| \quad \text{—— (23)}$$

Conclusions from eq^n (20) to (23) –

1. For a valid approximation of $R \simeq 0$, the real power transferred to R.E. is proportional to $\sin\delta$ while reactive power is proportional to magnitude of vltg. drop across the line.
2. Real power received is max. for $\delta = 90^\circ$ & the value $\frac{|V_s||V_R|}{X}$

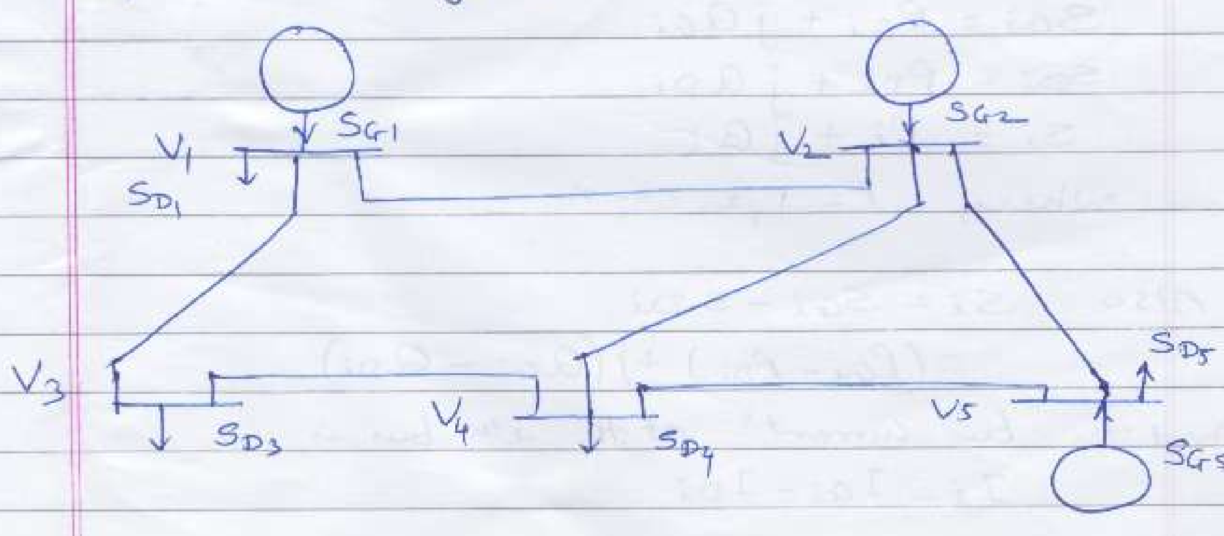
3. The VARs (lagging) delivered by a line is proportional to the line voltage drop & is independent of δ.

~~Power system stability~~

Q. Bus Admittance Matrix.

Load flow study in power system is the steady state solution of the power system network. The P.S. is modelled by an electric network & solved for the steady state powers & voltages at various buses. The main information obtained from the load flow study comprises of magnitudes & phase angles of load bus voltages, reactive powers and voltage phase angles at generator buses, real & reactive power flow on T.L. together with powers at reference buses, etc. This information is essential for continuous monitoring of the current state of the sys. and for analysing the effectiveness of alternate plans for the future such as adding new generator sites, meeting increased load demand & locating new transmission sites.

Fig. below shows one line diagram of P.S. having five buses.



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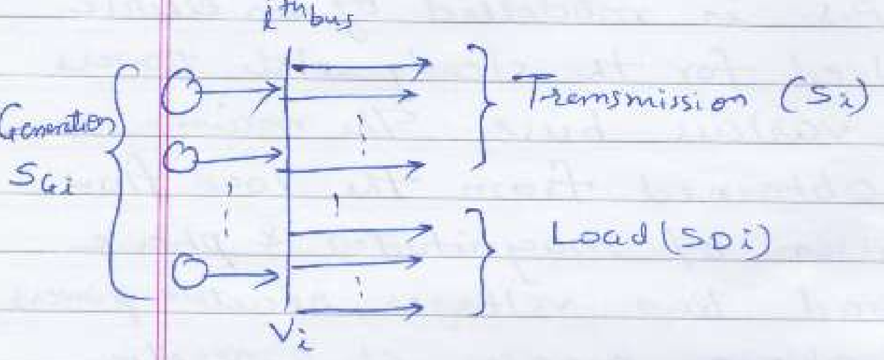
$S_{G}s$ & $S_{D}s$ represent the complex power injected by the generators & complex powers drawn by the loads. Vs represents complex voltages at various buses.

In practical sys. there can be thousands of buses & transmission links.



Consider an ith bus of an 'n' bus power system

It is convenient to work with power at each bus injected into the transmission sys., called the "bus power".

The ith bus power is,

$$S_i = S_{Gi} - S_{Di}$$

writing the complex powers interms of real & reactive powers,

$$S_{Gi} = P_{Gi} + jQ_{Gi}$$

$$S_{Di} = P_{Di} + jQ_{Di}$$

$$S_i = P_i + jQ_i$$

where, $i = 1, 2, \dots n$

Also $S_i = S_{Gi} - S_{Di}$

$$= (P_{Gi} - P_{Di}) + j(Q_{Gi} - Q_{Di})$$

And the "bus current" at the ith bus is,

$$I_i = I_{Gi} - I_{Di}$$

Next step is to develop relation between bus currents & bus voltages with following assumptions,

i) there is no coupling betn the T.L.s &

ii) there is an absence of regulating transformers.

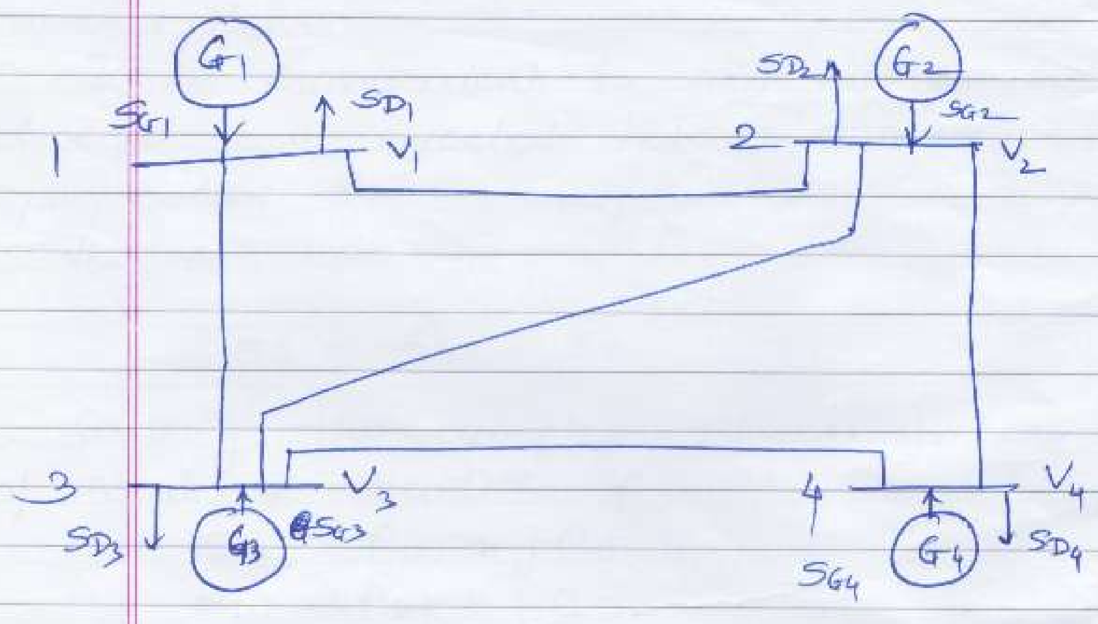
Let y_{ik} $(i \neq k)$ be the total admittance between the i^{th} & k^{th} buses.

y_{io} be the admittance between i^{th} bus & the ground

In a power system, power is injected into a bus from generators, while the loads are tapped from it. There may be some buses with only generators & there may be other only with loads. Some buses may have both, while some other may have static capacitors for reactive power compensation.

The surplus power at some of the buses is transported through T.L. to the bus deficient in power.

Single line diag. of a 4-bus sys. with generators & load at each bus is shown below.



Let $S_{Gi} \rightarrow$ 3 ph. complex power generated

$S_{Di} \rightarrow$ 3 ph. complex power demand

These are represented as,

$$S_{Gi} = P_{Gi} + jQ_{Gi}$$

$$S_{Di} = P_{Di} + jQ_{Di}$$

∴ Net complex power injected into the bus is difference of S_{Gi} & S_{Di}

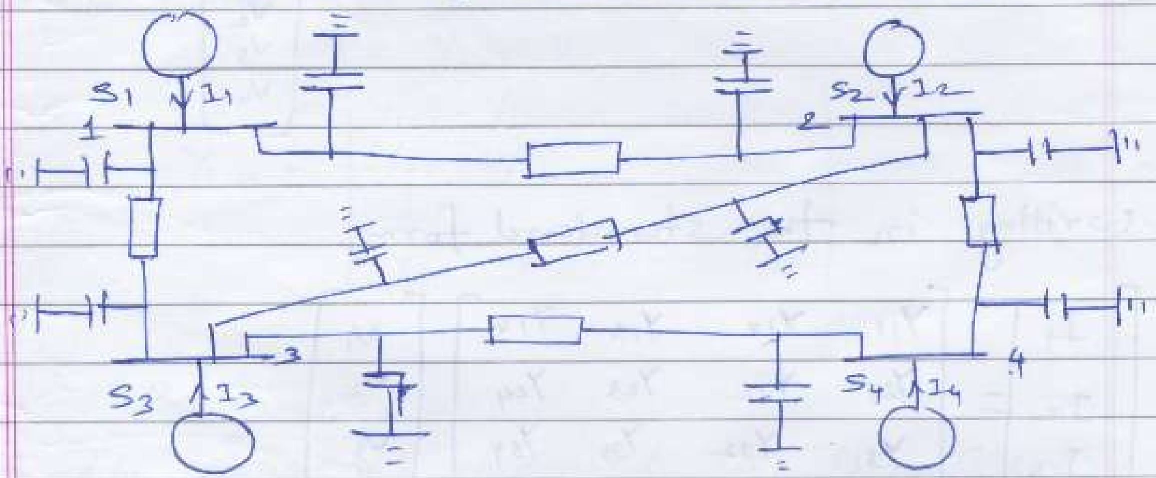
$$S_i = P_i + jQ_i = (P_{Gi} - P_{Di}) + j(Q_{Gi} - Q_{Di})$$

where, $P_i = P_{Gi} - P_{Di}$

$Q_i = Q_{Gi} - Q_{Di}$

where $i = 1, 2, 3, \ldots n$.

The one line diagram above is replaced by its equivalent circuit & shown below, where, the equivalent power source at i^{th} bus injects current I_i into the bus. The structure is such that all the sources are always connected to a common ground node. T.L. are replaced by their nominal π equivalent.



The line admittance betn nodes i & k is represented by $Y_{ik} = Y_{ki}$. Further the mutual admittances betn the lines is assumed to be zero.

In above figure, there are five nodes ie, 4 nodes corresponding to 4 buses and one ground node

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Applying KCL to the four nodes gives ~~the~~ following eqns.

$$I_1 = V_1 \cdot y_{10} + (V_1 - V_2) y_{12} + (V_1 - V_3) y_{13}$$
$$I_2 = V_2 \cdot y_{20} + (V_2 - V_1) y_{21} + (V_2 - V_3) y_{23} + (V_2 - V_4) y_{24}$$
$$I_3 = V_3 y_{30} + (V_3 - V_1) y_{31} + (V_3 - V_2) y_{23} + (V_3 - V_4) y_{34}$$
$$I_4 = V_4 y_{40} + (V_4 - V_2) y_{24} + (V_4 - V_3) y_{34}$$

Rearranging above eqns, we get

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} y_{10}+y_{12}+y_{13} & -y_{12} & -y_{13} & 0 \\ -y_{12} & y_{20}+y_{21}+y_{23}+y_{24} & -y_{23} & -y_{24} \\ -y_{13} & -y_{23} & y_{30}+y_{13}+y_{23}+y_{34} & -y_{34} \\ 0 & -y_{24} & -y_{34} & y_{40}+y_{24}+y_{34} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$

Writing in the standard form,

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$

OR. $I_{bus} = Y_{bus} \cdot V_{bus}$

~~The~~ ~~As~~ It can be observed that, the diagonal elements of the Y_{bus} are self admittances and are given by, sparse.

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$$Y_{11} = y_{10} + y_{12} + y_{13}$$
$$Y_{22} = y_{20} + y_{21} + y_{23} + y_{24}$$
$$Y_{33} = y_{30} + y_{31} + y_{32} + y_{34}$$
$$Y_{44} = y_{40} + y_{42} + y_{43}$$

The off-diagonal elements are the transfer (or mutual admittances) admittances and are given by

$$Y_{12} = Y_{21} = -y_{12}$$
$$Y_{13} = Y_{31} = -y_{13}$$
$$Y_{14} = Y_{41} = 0$$
$$Y_{23} = Y_{32} = -y_{23}$$
$$Y_{24} = Y_{42} = -y_{24}$$
$$Y_{34} = Y_{43} = -y_{34}$$

Similarly, general eqn for n-bus network based on KCL & admittance form is,

$$I = Y_{bus} \cdot V$$

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & & & \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix}$$

Properties:-

1. The diagonal elements of Y_{bus} are the self admittances
2. Off-diagonal elements are the transfer admittances
3. Y_{bus} is $n \times n$ matrix where n is no. of buses.
4. Y_{bus} is a symmetric matrix
5. Y_{ik} $(i \neq k) = 0$ if i^{th} & k^{th} buses are not connected.

Corona

In overhead T.L., when the electric gradient is set up betn two parallel conductors, electrons & ions are set in motion by the electric field resulting in a small current betn the conductors. This phenomenon undergoes a radical change when the electric field intensity reaches a value of 30kV/cm.

At this stage, the moving ions attain a high velocity and strike the adjacent molecule dislodging electron from it. This dislodged electron further collide with other molecules producing more ions. This ultimately results in a complete electric breakdown of the dielectric medium betn the conductors establishing an arc between these two conductors.

This phenomenon is further prominent as the electric field intensity goes up. It is maximum on the surface of the conductors and decreases in inverse proportion to the distance from centre of the conductors. The ionisation is generally accompanied by a violet luminous glow around the conductor. The glow is brightest near the rough surface of the conductor. It is also associated with a hissing sound.

This phenomenon is designated as <u>Corona</u> & is very much evident in power lines of 100kV. & above.

Corona also produces power loss

and depends on weather conditions. During humid & moist climate corona loss is higher.

In EHV AC transmission lines the visible glow of corona is mostly uniform about both the conductors. Whereas in HVDC sys. the glow is uniform about the positive wire but spotty about the negative wire.

Factors affecting corona loss

1. Frequency - Corona loss is directly prop. to supply freq.
2. Sys. vltage - As electric field increases with greater potential difference, Corona loss increases
3. Conductivity of air - During rain & thunderstorms, ion content in air increases & thus corona loss becomes high.
4. Conductor diameter - With greater conductor diameter, electric field intensity reduces resulting in low corona loss.
5. Load current - Flow of load current increases temperature of conductor. Thus it prevents deposition of dew or ~~ice~~ snow on conductor surface & thus reduces corona loss.
6. Conductor surface - Roughness of conductor surface results in field distortion & gives rise to high potential gradient causing higher Corona loss.

Wireless signals are adversely affected by corona discharges. Corona discharge may create interference to communication line within even few kilometers.

Methods of reducing corona-

Intense corona effects are observed at a working voltage of 33kV or above. Therefore, careful design should be made to avoid corona on substations or bus-bars rated for 33kV. & higher voltage. Corona effects can be reduced by following methods.-

i) **By increasing conductor size** - by this method, the voltage at which corona occurs is raised & hence corona effects are considerably reduced. For this reason only, ACSR conductors ~~be~~ those used in T.L.s have large c.s. area.

ii) **By increasing conductor spacing**- because of this, the voltage at which corona occurs is raised & hence corona effects can be eliminated.

Power system stability

Society today need an ever-increasing supply of electric power & the demand is increasing every year. Successful operation of P.S. depends largely on the ability to provide reliable & uninterrupted service to the loads. Ideally, the loads must be fed at constant voltage & frequency at all times. In any case, all interconnected synchronous machines should remain in synchronism if the sys. is stable, ie, they should all remain operating in parallel & at the same speed.

If the Oscillatory response of a P.S. during the transient period following a disturbance is damped & the sys. settles in a finite time to a new steady operating condition, ~~it is~~ the sys. is said to be stable.

P.S. stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire sys. remains intact.

Classification of P.S. stability

- Rotor angle stability
  - Small disturbance angle stability
  - Transient stability
- Frequency stability
- Voltage stability
  - Large disturbance Vltg. stability
  - Small disturbance Vltg. stability

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Rotor angle stability -

Rotor angle stability refers to the ability of syn. machines of an interconnected p.s. to remain in synchronism after being subjected to disturbance. It depends on the ability to restore equilibrium betn electromagnetic torque & mechanical torque of each syn. machine in the sys. Instability that may result occurs in the form of increasing angular swings of some generators leading to their loss of synchronism with other generators.

Small disturbance rotor angle stability is concerned with the ability of the p.s. to maintain synchronism under small disturbances.

Transient stability is concerned with the ability of the p.s. to maintain synchronism when subjected to a severe disturbance, such as a s.c. on a T.L. Transient stability depends on both the initial operating state of the sys. & severity of disturbance. Instability is usually in the form of periodic angular separation due to insufficient synchronising torque, first swing instability, etc.

Voltage stability -

Voltage stability refers to the ability of the p.s. to maintain steady voltages at all buses in the sys. after being subjected to a disturbance from a given initial operating condition. It depends on

the ability to restore equilibrium betn load demand & load supply from the P.S.
Instability that may result occurs in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of T.Ls and other elements by their protective systems leading to cascading outages. Loss of synchronism of some generators may result from these outages.

Large disturbance vltg. stability refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, etc.

small disturbance voltage stability is sys.'s ability to maintain steady vltg. when subjected to small disturbances such as incremental changes in sys. load.

Frequency stability.

It refers to ability of the P.S. to maintain steady freq. following a severe system problem resulting in significant imbalance betn generation & load. The instability occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads.