

Voltage Control & Compensation

P.S

Methods of voltage control:

The methods for voltage control are the use of

- i) Shunt capacitors
- ii) Series capacitors
- iii) Synchronous capacitors
- iv) Tap changing transformers and
- v) Booster transformers.

Shunt Capacitors and Reactors

As is said earlier the shunt capacitors are used across an inductive load so as to supply part of the reactive vars required by the load so that the reactive vars transmitted over the line are reduced, thereby the voltage across the load is maintained within certain desirable limits. Similarly, the shunt reactors are used across capacitive loads or lightly loaded lines to absorb some of the leading vars again to control the voltage across the load to within certain desirable limits. capacitors are connected either directly to a bus bar or through a tertiary winding of the main transformer and are disposed along the

route to minimize the voltage drop and the losses. The disadvantage of the use of shunt capacitor or reactor is that with the fall of voltage at a particular node the correction vars are also reduced i.e., when it is most needed, its effectiveness fails. Similarly, on light loads when the corrective vars required are relatively less, the capacitor output is large.

Series capacitors:

If a static capacitor is connected in series with the line, it reduces the inductive reactance between the load and the supply point and the voltage drop is approximately

$$IR \cos \phi_r + I(X_L - X_C) \sin \phi_r$$

It is clear from the vector diagram that the voltage drop produced by an inductive load can be reduced particularly when the line has a high X/L ratio. In practice X_C may be chosen so that the factor $(X_L - X_C) \sin \phi_r$ becomes negative and numerically equal to $R \cos \phi_r$ so that the voltage drop becomes zero. The ratio X_C/X_L expressed as a percentage is usually referred to as the percentage compensation.

Comparision between series and shunt capacitors.

- i) The voltage boost due to a shunt capacitor is evenly distributed over the transmission line whereas the change in voltage between the two ends of the series capacitor where it is connected, is sudden. The voltage drop along the line is unaffected.
- ii) Let Q_c' be the reactive power of the shunt capacitor, E_r the receiving end voltage and X the reactance of the line; the current through the capacitor will be Q_c'/E_r and the drop due to this current in the line will be $(Q_c'/E_r) X$.

Similarly let Q_c be the rating of the series capacitor, the line current and $\sin \phi_r$ the sine of the power factor angle of the load; The drop across the series capacitor will be $(Q_c/I) \sin \phi_r$ since the magnitude of the voltage across the capacitor is Q_c/I .

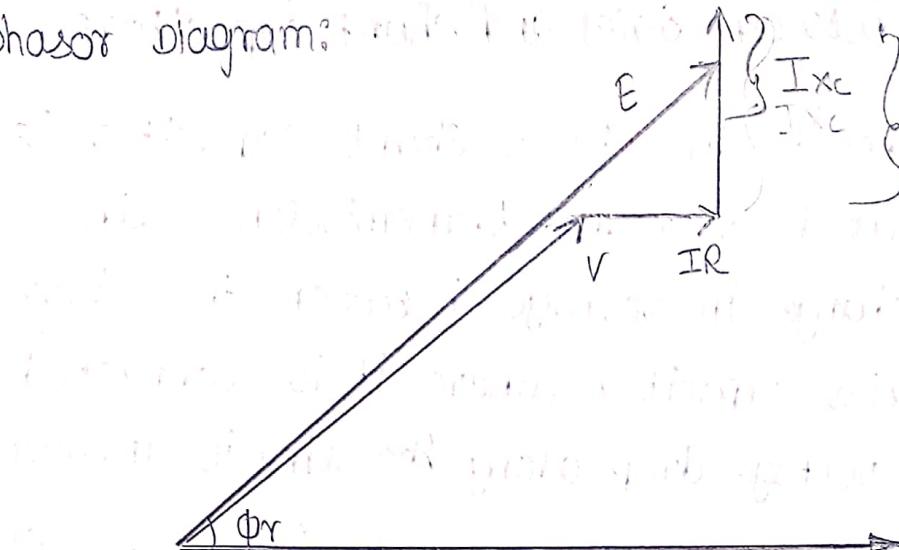
For a typical load with pf 0.8 lag, $\sin \phi_r = 0.6$ and assume $IX/E_r = 0.1$

for equality of voltage boost with the two applications

$$\frac{Q_c'X}{E_r} = \frac{Q_c \sin \phi_r}{I}$$

$$\frac{Q_c'}{Q_c} = \frac{\sin \phi_r}{IX/E_r} = \frac{0.6}{0.1} = 6$$

phasor diagram, which is given below:



phasor diagram, when series capacitor is connected on a line.

If I is the full load current and X_c is the capacitive reactance of the series capacitor then the drop across the capacitor is IX_c and the VAR rating is I^2X_c . The voltage boost, produced by the series capacitor.

$$\Delta V = IX_c \sin \phi_r$$

one drawback of series capacitors is the high overvoltage produced across the capacitor terminals under short circuit conditions. The drop across the capacitor is If X_c , where If is the fault current which is of the order of 20 times the full load current under certain circuit condition. A spark gap with a high speed contactor is used to protect the capacitors under these conditions.

It is evident that for the same voltage boost, the reactive power capacity of a shunt capacitor is greater than that of a series capacitor.

- iii) The shunt capacitor improves the pif of the load whereas the series capacitor has little effect on the pif.
- iv) For long transmission lines where the total reactance is high, series capacitors are effective for improvement of system stability.

Synchronous capacitors:

A great advantage of the synchronous capacitor is its flexibility for use for all load conditions because it supplies vars when over-excited, i.e. during peak and load conditions and it consumes vars when under-excited during light load conditions.

There is smooth variation of reactive vars by synchronous capacitors as compared with step by step variation by the static capacitors.

Synchronous machines can be overloaded for short periods whereas static capacitors cannot. For large outputs the synchronous capacitors are much better than the static capacitors from economic

view point, because otherwise a combination of shunt capacitors and reactors is required which becomes costlier and also the control is not smooth as is achieved as is achieved with synchronous capacitors.

The main disadvantage of the synchronous capacitor is the possibility of its falling out of step which will thus produce a large sudden change in voltage. Also these machines add to the short circuit capacity of the system during fault condition.

A transmission line is said to be a constant voltage, or a regulated line if its receiving end voltage is controlled by varying the reactive power at the receiving end when the sending end voltage is kept constant.

Other systems where the reactive power available at the receiving end corresponds to the reactive power requirements of the load are termed as unregulated systems.

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Tap changing transformers

The main job of a transformer is to transform electrical energy from one voltage level to another. Almost all power transformers on transmission lines are provided with taps for ratio control i.e., control of secondary voltage. There are two types of tap changing transformers.

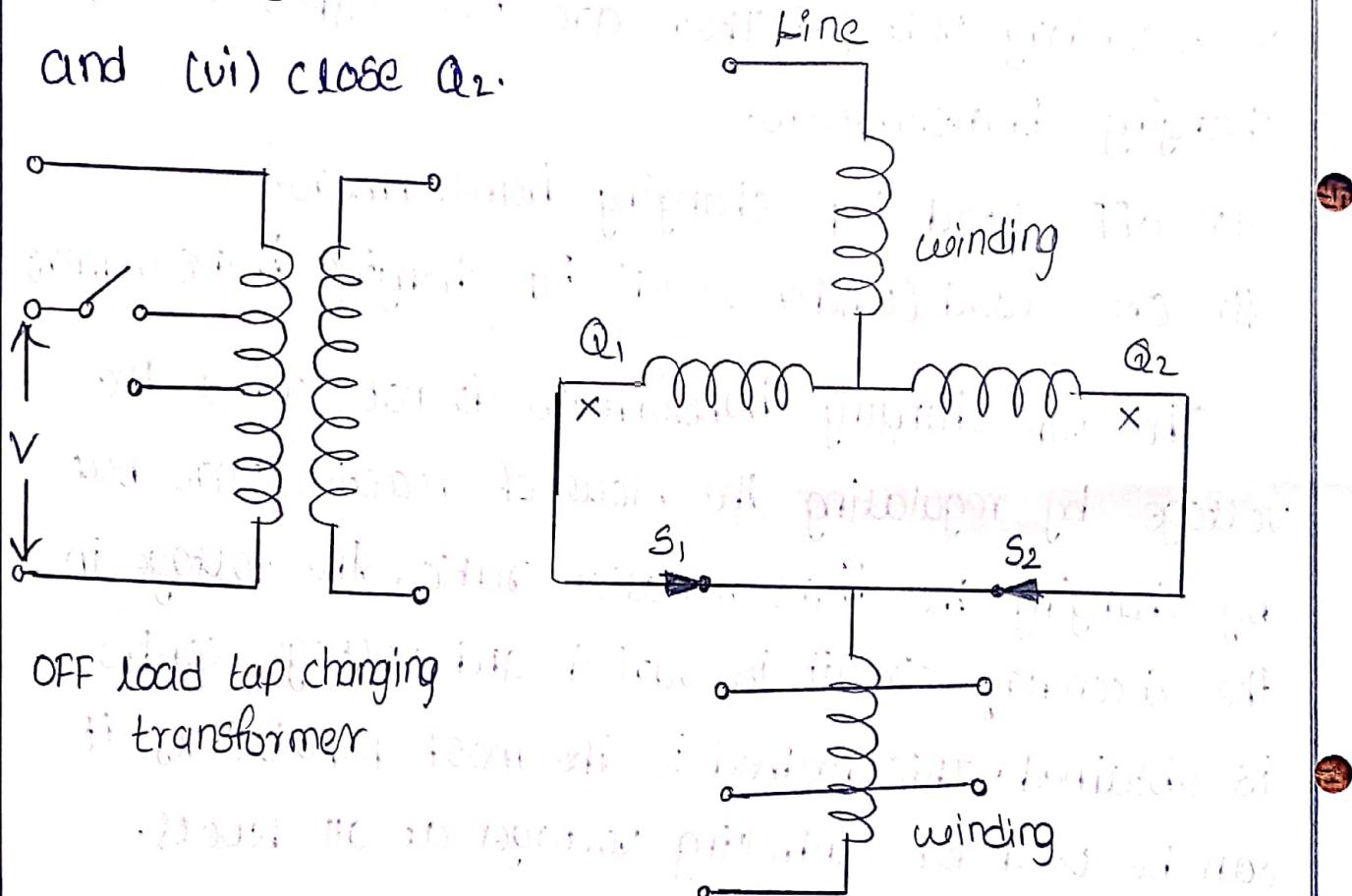
- (i) OFF-load tap changing transformers.
- (ii) ON-load (under-load) tap changing transformers.

The tap changing transformers do not control the voltage by regulating the flow of reactive vars but by changing the transformation ratio, the voltage in the secondary circuit is varied and voltage control is obtained. This method is the most popular as it can be used for controlling voltages at all levels.

Refers to the off-load tap changing transformer which requires the disconnection of the transformer when the tap setting is to be changed. The modern practice is to use on-load tap changing transformer which is shown in figure. In the position shown the voltage is a maximum and since the currents divide equally and flow in opposition through the coil

between Q_1 and Q_2 , the resultant flux is zero and hence minimum impedance. To reduce the voltage, the following operations are required in sequence

- (i) open Q_1
- (ii) move sector selector switch S_1 to the next contact
- (iii) close Q_1
- (iv) open Q_2 (in open Q_1)
- (v) move selector switch S_2 to the next contact;
- and (vi) close Q_2 .



OFF-load tap changing
transformer from off to on-load
adjust the no. of turns per phase
connected with a resistive load
on-load tap changing
transformer

Thus six operations are required for one change in tap position. The voltage change between taps is often per cent of the nominal voltage where nominal voltages are the voltages at the ends of the transmission

line and the actual voltages are $t_s V_1$ and $t_r V_2$ where t_s and t_r are the fractions of the nominal transformation ratios i.e., the tap ratio/nominal ratio.

Consider the operation of a radial transmission line with tap changing transformers at both the ends as shown in fig. It is desired to find out the tap changing ratios required to completely compensate for the voltage drop in the line. We assume here that the product of t_s and t_r is unity as this ensures that the overall voltage level remains of the same order and that the minimum range of taps on both transformers is used.

we have

$$t_s V_1 = t_r V_2 + IZ$$

we know that the approximate line drop is given as

$$IZ = \Delta V = V_r \cos\phi + V_x \sin\phi$$

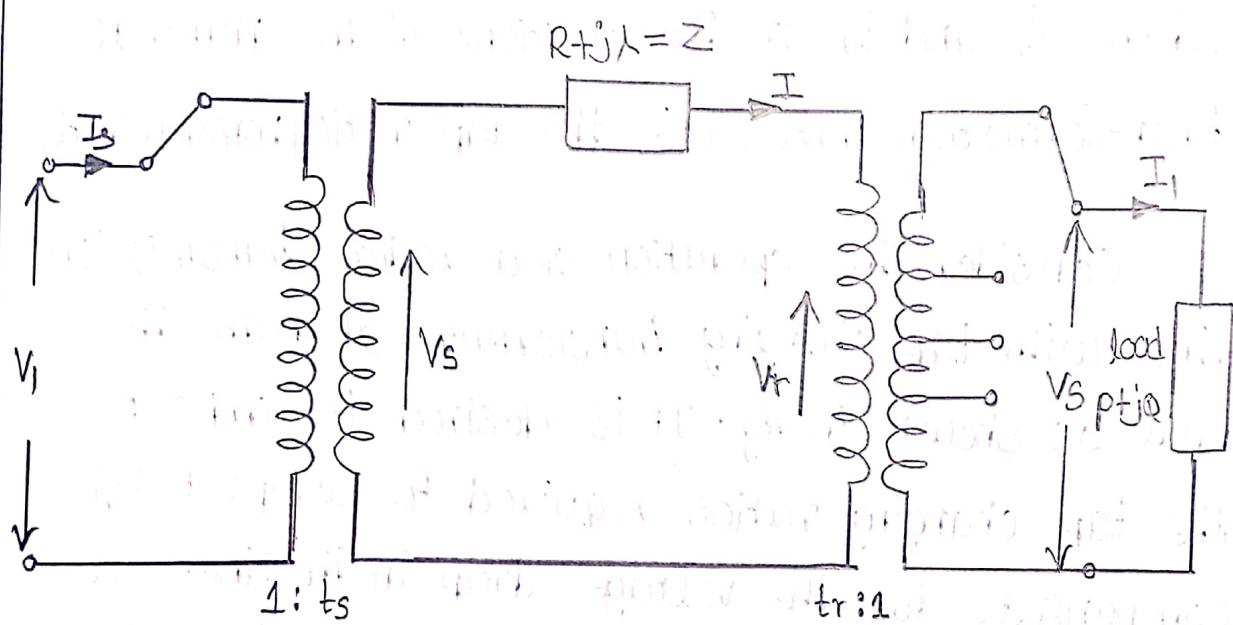
$$= IR \cos\phi + IX \sin\phi$$

$$= R \cdot I \cos\phi + X \cdot I \sin\phi$$

$$= \frac{R \cdot P}{V_r} + \frac{X \cdot Q}{V_r}$$

$$= \frac{RP + XQ}{tr V_2}$$

Radial transmission line with on-load tap changing



Radial transmission line with on-load tap changing

transformer at both the ends and so obtain

$$ts V_1 = tr V_2 + \frac{R_p + X_Q}{tr V_2}$$

$$ts = \frac{1}{V_1} \left[tr V_2 + \frac{R_p + X_Q}{tr V_2} \right]$$

now as $ts tr = 1$

$$so multiplying with $ts = \frac{1}{V_1} \left[\frac{V_2}{ts} + \frac{R_p + X_Q}{V_2 | ts} \right]$$$

$$ts^2 = \frac{V_2}{V_1} + \left[\frac{R_p + X_Q}{V_2 V_1} \right] ts^2$$

$$ts^2 \left[1 - \frac{R_p + X_Q}{V_1 V_2} \right] = \frac{V_2}{V_1}$$

$$\frac{R_p + X_Q}{V_1 V_2} = \frac{V_2}{V_1}$$

Load compensation:

Load compensation is the management of reactive power to improve the quality of supply especially the voltage and pf levels. Here the reactive power is adjusted with respect to an individual load and the compensating device is connected to the load itself. There are three main objectives in load compensation.

- i) Better voltage profile.
- ii) P.f correction
- iii) Load balancing

The voltage profile must remain within $\pm 5\%$ of the rated value for better and efficient operation of various electrical equipments. We know voltage variation is due to imbalance in the generation and consumption of reactive power in the system.

1. one of the obvious methods would be to have the system of large strength i.e., it interconnects large size machines and a large number of lines so that the effective impedance as seen from any point into the network is negligibly small and hence the voltage profile could be improved. However, this would result in high fault levels and would require switch-

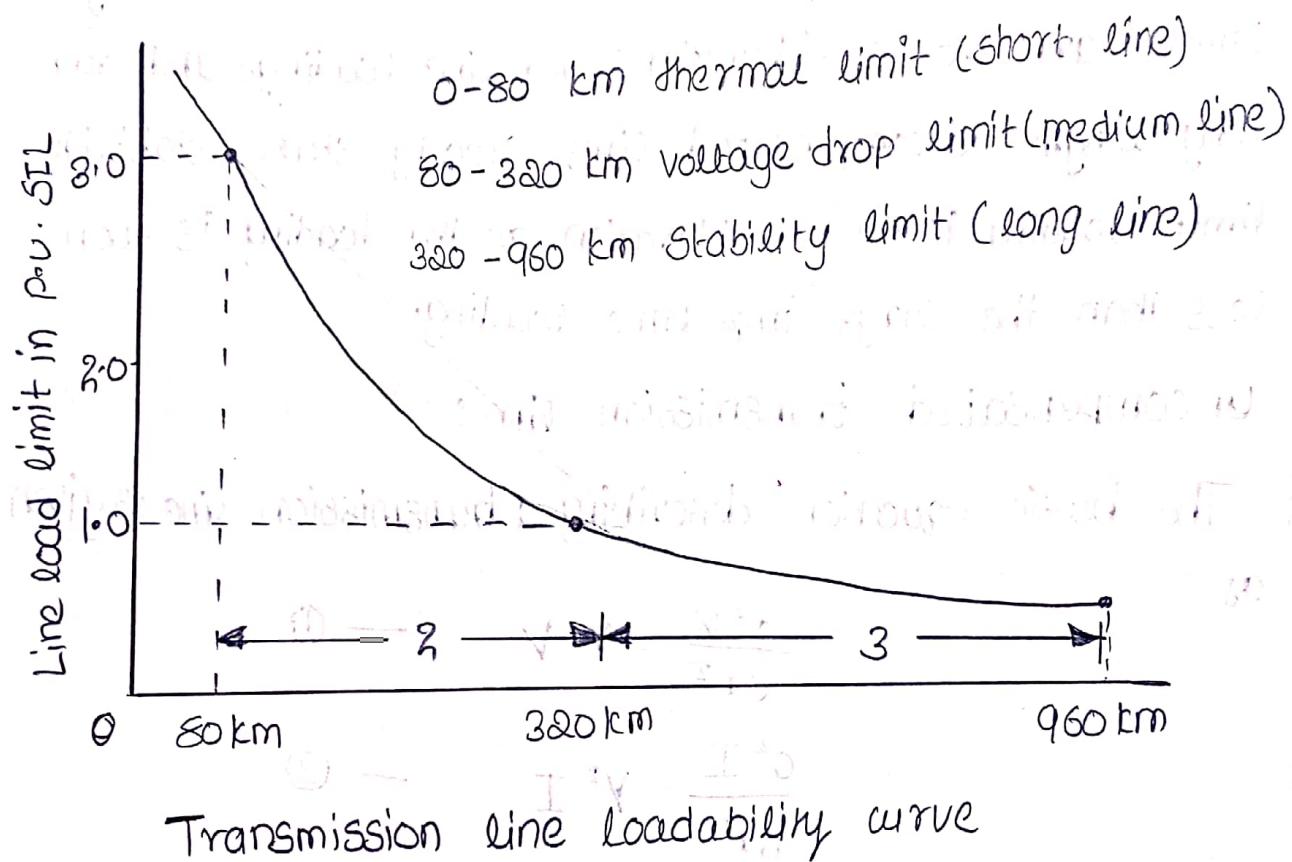
gears of relatively large capacity and hence is uneconomical from view point of improving voltage profile.

2. It is desirable both economically and technically to operate the system at near unity pf usually pf correction means to generate reactive power as close as possible to the load which requires it rather than generate it at a distance and transmit it to be load, as this results not only in large conductor size but also in increased losses. In fact,
3. A very important concept of load compensation is load balancing. It is desirable to operate the three phase system under balanced condition as unbalanced operation results in flow of negative sequence current in the system and is highly dangerous especially for the rotating machines.

Loadability characteristic of O/H Lines.

In order to have proper understanding of the power transfer capability of the lines which is the degree of line loading permissible expressed in per cent of SIL for a given thermal or voltage drop or S.S. stability limits.

This concept was first introduced by St. clair who developed transmission power transfer capability curves for voltages up to 330 kV and line lengths up to 600 kms. These curves have been useful to power system engineers for quickly estimating the maximum line loading limits.



The universal loadability curve for uncompensated line applicable to all voltage levels. The curve shows the limiting values for power that can be transmitted as a function (of) line length. The curve has been drawn taking into account the maximum allowable voltage drop along the line to be 5% and that the minimum allowable steady state stability margin is 30% for load angle 44°.

It is clear that for short length line, the steady state stability limit loading will be greater than the thermal loading and hence the loadability is determined by the thermal loading rather than steady state stability loading.

For medium length uncompensated lines voltage levels are the considerations for line loadings and for long length uncompensated lines steady state stability limit loading is the consideration as the loading is even less than the surge impedance loading.

Uncompensated transmission line:

The basic equation describing a transmission line is given as

$$\frac{\partial^2 V}{\partial x^2} = \gamma^2 V \quad \text{--- (1)}$$

$$\frac{\partial^2 I}{\partial x^2} = \gamma^2 I \quad \text{--- (2)}$$

$$\frac{\partial V}{\partial x} = IZ \quad \text{--- (3)}$$

$$Y^2 = (r+j\omega L)(g+j\omega C)$$

$$Z = (r+j\omega L), Y = (g+j\omega C)$$

where x is the distance from the sending end. If l is the length of the line, the solution of the above equation lossless line.

where $r=0$ and $g=0$

$$V(x) = V_r \cos(l-x)\beta + j Z_c I_r \sin \beta(l-x) \quad (4)$$

where β is the phase constant i.e,

$$\gamma = \alpha + j\beta \text{ and for a lossless system}$$

$$\alpha = 0$$

$$\gamma^2 = (r+j\omega L)(g+j\omega C) = -\omega^2 LC$$

$$\gamma = j\beta$$

where

$$\beta = \omega \sqrt{LC} = \frac{2\pi f}{V} = \frac{2\pi}{h}$$

using equations (3) and (4) we get

$$I(x) = I_r \cos \beta(l-x) + j \frac{V_r}{Z_c} \sin \beta(l-x)$$

β is also known as wave number i.e, the number of complete wave per unit of line length.

At 50 Hz the wave length $\lambda = \frac{3 \times 10^8}{50} = 6000 \text{ kms}$ and β can be expressed as one wave length per 6000 kms i.e, 360° per

6000 kms or $= \frac{360}{6000} = 0.06^\circ$ per km or $1.0466 \times 10^{-3} \text{ rad}$

per km. The quantity βl is the electrical length in radians.

Symmetrical line:

A symmetrical line is one with identical synchronous machines at both the ends and $|V_s| = |V_r|$ and under no load condition there are in phase also indicating that there is no transfer of power (no load condition) otherwise V_s shall lead V_r , phase lead depending upon the loading with regard to such a line following observations are made.

- (i) If the loading is less than the surge impedance loading of the line, the mid point voltage is higher than the terminal voltage as there is a net of excess reactive power generated by the line.
- (ii) However, if the loading is greater than the SIL of the line, due to deficit reactive power on the line the mid-point voltage is lower than the terminal voltages.
- (iii) If the loading equals SIL of the line, the line has flat voltage profile. The corrective measures in cases (i) and (ii) above can be taken up by connecting suitable compensating network at suitable locations.

Assuming the line to be lossless, let us analyse the system when a load of $P_L + jQ_L$ is connected, using

$$V_s = V_r \cos \beta l + j Z_c \frac{P_L - j Q_L}{V_r} \sin \beta l \quad \text{--- (1)}$$

The above equation holds good irrespective of whether the load is synchronous or asynchronous. Let us assume that the load is synchronous and taking V_r as reference, say V_s leads V_r by an angle δ known as load angle therefore.

$$V_s = |V_s| (\cos \delta + j \sin \delta) \quad \text{--- (2)}$$

Substituting for V_s in (1), we have

$$|V_s| [\cos \delta + j \sin \delta] = V_r \cos \beta l + j Z_c \frac{P_L - j Q_L}{V_r} \sin \beta l$$

$$= V_r \cos \beta l + Z_c \frac{Q_L}{V_r} \sin \beta l + j Z_c \frac{P_L}{V_r} \sin \beta l \quad \text{--- (3)}$$

Equating the real and imaginary parts on the two sides,

$$V_s \cos \delta = V_r \cos \beta l + Z_c \frac{Q_L}{V_r} \sin \beta l \quad \text{--- (4)}$$

$$V_s \sin \delta = Z_c \frac{P_L}{V_r} \sin \beta l$$

$$PL = \frac{V_s V_r}{Z_c \sin \beta l} \sin \delta \quad \text{--- (5)}$$

If the length of the line is short $\sin \beta l \approx \beta l = \omega \sqrt{L C} \cdot l$.

and $Z_c \sin \beta l = \sqrt{\frac{L}{C}} \omega \sqrt{L C} \cdot l = IL \omega = X = \text{Total reactance}$ of the line. equation (5), therefore, reduces to a very well known equation.

$$PL = \frac{V_s V_r}{X} \sin \delta \quad \text{--- (6)}$$

Let $V_S = V_r$, then equation (5) becomes

$$P_L = \frac{V_r^2}{Z_0 \sin \beta l} \cdot \sin \delta$$

$$= \frac{P_c}{\sin \beta l} \cdot \sin \delta$$

For certain geometry and operating voltage of the line P_L is maximum where $\delta = 90^\circ$ and this maximum depends upon the length of the line, the longer the length the smaller is the maximum value of P_L .

The ratio $\frac{P_{L\max}}{P_c}$ for a few lengths is tabulated here.

Radial line with Asynchronous load:

Even when the load is asynchronous, there is a maximum power that can be transmitted over a line. This can be calculated as follows for a unity p.f. load. Let us consider that sending end source and line form a voltage source with open circuit voltage V_o and impedance $(R+jX)$ and at the receiving end a variable resistive load (unity p.f.) R_L is connected. Our objective is to find out value of R_L for which the power transfer is maximum.

Now short circuit current $I_{SC} = \frac{V_o}{Z} = \frac{V_o}{R+jX}$ and in case

short circuit p.f. $\cos \phi_{SC} = \frac{R}{Z}$

$$\text{The load current } I = \frac{V_o}{(R+R_l) + jX}$$

$$\text{The power delivered} = \frac{V_o^2}{(R+R_l)^2 + X^2} \cdot R_l = P$$

The power delivered is maximum when $\frac{dP}{dR_l} = 0$

$$[(R+R_l)^2 + X^2] - R_l \cdot 2(R+R_l) = 0$$

$$R_l^2 + R^2 - 2RR_l + X^2 - 2RR_l - 2R_l^2 = 0$$

$$R_l = Z$$

$$\text{Therefore } P_{\max} = \frac{V_o^2 Z}{(R+Z)^2 + X^2} = \frac{V_o I_{sc} Z^2}{R^2 + Z^2 + 2RZ + X^2}$$

$$= \frac{V_o I_{sc} Z^2}{2Z^2 + 2RZ + X^2}$$

$$= \frac{V_o I_{sc} Z}{2(Z+R)}$$

$$= \frac{V_o I_s}{2(1+\cos\phi_{sc})} \quad \text{--- (1)}$$

Now V_o is the open circuit voltage i.e., V_r when $I_r = 0$

Therefore, from equation

$$V_s = V_o \cos \beta L$$

$$V_o = \frac{V_s}{\cos \beta L} \quad \text{--- (2)}$$

Similarly, short circuit current I_{sc} is the value of I_r when $V_r = 0$

using equations again, we have

$$V_S = j I_{SC} Z_C \sin \beta L$$

$$I_{SC} = \frac{V_S}{j Z_C \sin \beta L} \quad (3)$$

Assuming the line to be lossless $\cos \phi_{SC} = 0$

$$\therefore P_{max} = \frac{V_0 I_{SC}}{2} = \frac{V_S}{2 \cos \beta L} \cdot \frac{V_S}{Z_C \sin \beta L} = \frac{V_S^2}{Z_C \sin 2 \beta L} \quad (4)$$

Equation (4) represents loci of maximum power for different length of lines at unity p.f.

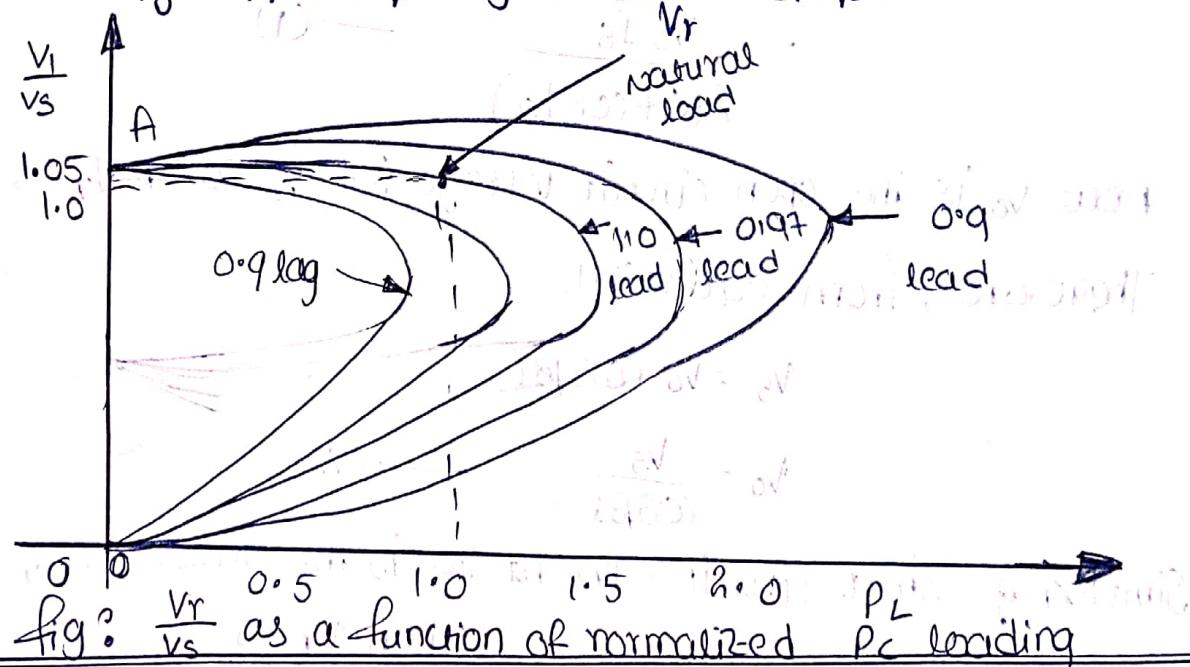
Let us consider a general load $P_L + j Q_L$ at the receiving end keeping the sending end voltage fixed.

The receiving end current

$$I_r = \frac{P_L - j Q_L}{V_r}$$

using equation and assuming line to be lossless, we have

$$V_S = V_r \cos \beta L + j Z_C \frac{P_L - j Q_L}{V_r} \sin \beta L \quad (5)$$



Compensation of lines:

By compensation of lines is meant the use of electrical circuits to modify the electrical characteristics of the lines such that the compensated lines will achieve the following objectives.

- i) Ferranti effect is minimized so that a flat voltage profile will exist on the line for all loading condition.
- ii) Underexcited operation of alternator will be avoided and an economical means of reactive power management will be achieved.
- iii) The power transfer capability of the system will be enhanced and hence stability margins increase.

$$P_{C1}^1 = \frac{V_r^2}{Z_{C1}} = P_L$$

Even though compensators are used at discrete locations along the line, it is useful to obtain certain relation assuming the effect of compensators as uniformly distributed. The relations so desired are more or less true for practical system.

We know that,

$$Z_C = \sqrt{\frac{L}{C}} = \sqrt{\frac{j\omega L}{j\omega C}} = \sqrt{X_L X_C} \quad \text{--- (1)}$$

Suppose shunt inductance L_{sh} per unit is used as a compensator, the net shunt susceptance will be

$$\begin{aligned} j\omega c' &= j\omega c + \frac{1}{j\omega L_{sh}} = j\omega c - \frac{j}{\omega L_{sh}} \cdot \frac{\omega c}{c} \\ &= j\omega c \left(1 - \frac{1}{\omega^2 C L_{sh}} \right) \\ &= j\omega c (1 - r_{sh}) \quad - (2) \end{aligned}$$

$$r_{sh} = \frac{1}{\omega^2 C L_{sh}} = \frac{x_c}{x_{Lsh}}$$

where r_{sh} is known as the degree of shunt compensation.

The modified value of surge impedance will be

$$Z_c' = \sqrt{\frac{j\omega L}{j\omega c(1-r_{sh})}} = \frac{Z_c}{\sqrt{1-r_{sh}}} \quad - (3)$$

However, if shunt capacitance is added, the r_{sh} will be negative and hence it can be concluded that shunt inductance increases the virtual surge impedance of the line and hence reduces the virtual surge impedance loading of the line and shunt capacitance reduces the virtual surge impedance.

Let us consider the effect of series compensation on the surge impedance loading. Suppose C_{se} is the series capacitance per unit length for series compensation. Therefore, the series reactance will be,

$$j\omega L - \frac{j}{\omega C_{se}} = j\omega L - \frac{j}{\omega C_{se}} \cdot \frac{j\omega L}{j\omega L} \\ = j\omega L \left[1 - \frac{1}{\omega^2 L C_{se}} \right]$$

$$= j\omega L \left[1 - \frac{X_{cse}}{X_L} \right]$$

$$\text{Therefore, } Z_{c'} = j\omega L (1 - \gamma_{se}) \quad \rightarrow (4)$$

where γ_{se} is known as degree of series compensation. Therefore, virtual surge impedance.

$$Z_c' = \sqrt{\frac{j\omega L (1 - \gamma_{se})}{j\omega C}} \\ = Z_c \sqrt{(1 - \gamma_{se})} \quad \rightarrow (5)$$

Taking into consideration both shunt and series compensation simultaneously, we have

$$Z_0' = \sqrt{\frac{j\omega L'}{j\omega C}} = Z_c \sqrt{\frac{1 - \gamma_{se}}{1 - \gamma_{sh}}} \quad \rightarrow (6)$$

Therefore, the virtual surge impedance loading

$$P_c' = P_c \sqrt{\frac{1 - \gamma_{sh}}{1 - \gamma_{se}}} \rightarrow (7)$$

The wave number β is also modified to

$$\beta' = \beta \sqrt{(1 - \gamma_{se})(1 - \gamma_{sh})} \rightarrow (8)$$

The equation derived earlier for uncompensated lines are valid for compensated lines except the equivalent parameters (e.g., inductance, capacitance etc.) are to be substituted as obtained in this section.

$$(8) \rightarrow (8' + 1) \text{ or } (8')$$