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Internal Assesment Test - II

Sub:	REACTIVE POWER MANAGEMENT							Code:	10EE831
Date:	10 / 05 / 2017	Duration:	90 mins	Max Marks:	50	Sem:	8	Branch:	EEE

Answer Any **FIVE** FULL Questions

		Marks	OBE	
			CO	RBT
1	Discuss on surge impedance of a transmission line. Explain the condition of the line under surge impedance loading. Draw the phasor diagram of naturally loaded line for a = 200 mi & f = 60Hz	[10]	CO3	L2
2	Derive the necessary equations and also draw the voltage and current profiles with respect to uncompensated open circuit line on no load.	[10]	CO3	L2
3	Derive the expression for virtual natural load in terms of degree of series and shunt Compensation.	[10]	CO4	L2
4	Explain with the help of neat sketches, the control of open circuit voltage by shunt reactance.	[10]	CO4	L4
5	Discuss the objectives and limitations of series compensation.	[10]	CO5	L2
6	Explain the fundamental concepts of compensation by sectioning.	[10]	CO3	L4
7	Explain power transfer characteristics and maximum transmissible power for a general transmission line.	[10]	CO4	L4

SOLUTIONS IAT 2 - 2017

3ANS:

UNIFORMLY DISTRIBUTED FIXED COMPENSATION:

Modified Line Parameters: Virtual Z_0, θ & P_0

* Compensators are normally connected at the end of a line or at discreate points along it.
* They may be lumped or concentrated in nature
* It is easier & Simpler to derive the relationships for uniformly distributed compensation.

- The surge impedance of an uncompensated line can be written as

$$Z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{j\omega L}{j\omega C}} = \sqrt{x_c x_\ell} \longrightarrow (1)$$

CASE -1

If a uniformly distributed shunt compensating inductance $L_{\gamma sh}$ (H/mile) is introduced, then the effective value of shunt capacitive admittance per mile is

$$(j\omega c)' = j\omega c + \frac{1}{j\omega L_{\gamma sh}} \qquad \left[\because j\omega c + \frac{1}{j\omega L_{\gamma sh}} \times \frac{j\omega c}{j\omega c}\right]$$

$$= j\omega c(1 - K_{sh}) \longrightarrow (2)$$

where K_{sh} is the degree of shunt compensation

$$K_{sh} = \frac{1}{\omega^2 L_{\gamma sh} C} = \frac{X_c}{X_{\gamma sh}} = \frac{b_{\gamma sh}}{b_c} \longrightarrow (3) \quad \left[\because x = \frac{1}{b}\right]$$

Here $X_{\gamma sh}$ & $b_{\gamma sh}$ are the reactance and the susceptance per mile of the shunt compensating inductance.

Now substitute for $(j\omega c)'$ from eqn no: (2) in equation (1)

$$Z_0' = \sqrt{\frac{j\omega L}{j\omega C(1-K_{sh})}} = \frac{Z_0}{\sqrt{1-K_{sh}}} \longrightarrow (4)$$

CASE - 2

* If a **shunt capacitance** $C_{\gamma sh}$ is added instead of shunt inductance, then K_{sh} is negative

$$(j\omega c)' = j\omega c + j\omega C_{\gamma sh}$$
$$= j\omega c\left[1 + \frac{C_{\gamma sh}}{c}\right] \longrightarrow (5)$$

So $$K_{sh} = \frac{C_{\gamma sh}}{C} = \frac{X_c}{X_{\gamma sh}} = \frac{b_{\gamma sh}}{b_c} \longrightarrow (6)$$

where again $X_{\gamma sh}$ and $b_{\gamma sh}$ are reactance and susceptance per mile of the shunt compensating capacitance.

CASE - 3

If in the same way, if a **uniformly distributed** series capacitance $C_{\gamma se}$ is connected on the line l with inductance then

$$Z_0' = Z_0\sqrt{1-K_{se}} \longrightarrow (7)$$

where K_{se} is the **degree of series compensation**

$$K_{se} = \frac{1}{\omega^2 L C_{\gamma se}} = \frac{X_{\gamma se}}{X_L} = \frac{b_l}{b_{\gamma se}} \longrightarrow (9)$$

$$\because (j\omega L)' = j\omega L + \frac{1}{j\omega C_{\gamma se}}$$
$$= j\omega L\left[1 + \frac{1}{j^2\omega^2 L C_{\gamma se}}\right]$$
$$j\omega L\left[1 - \frac{1}{\omega^2 L C_{\gamma se}}\right] \longrightarrow (8)$$

Where again $X_{\gamma se}$ & $b_{\gamma se}$ are the reactance and susceptance per mile of series compensating capacitance.

* Now combining the effects of both shunt & series compensation

$$Z_0' = Z_0 \sqrt{\frac{1 - K_{se}}{1 - K_{sh}}}$$

So now considering virtual surge impedance Z_0' we can write the equation for virtual natural load P_0'

$$P_0' = P_0 \sqrt{\frac{1 - K_{sh}}{1 - K_{se}}}$$

* The wave no: β is also modified and the virtual value

$$\beta' = \beta \sqrt{(1-K_{sh})(1-K_{se})}$$

The electrical length θ is modified according to this equation

$$\theta' = \theta \sqrt{(1-K_{sh})(1-K_{se})}$$

where $\theta = \beta a$ & $\theta' = a\beta'$

These relations are shown graphically in figures in next page.

4.answer

CONTROL OF OPEN CIRCUIT VOLTAGE WITH SHUNT REACTORS :

* When $K_{sh} = 1$, the voltage profile is flat at no-load (or on open circuit).
* Shunt compensating reactors cannot be uniformly distributed, in practice.
* They are connected either at the ends of the line or at intermediate points - usually intermediate switching substations.
* The arrangement for a double-circuit line is shown in fig 3.

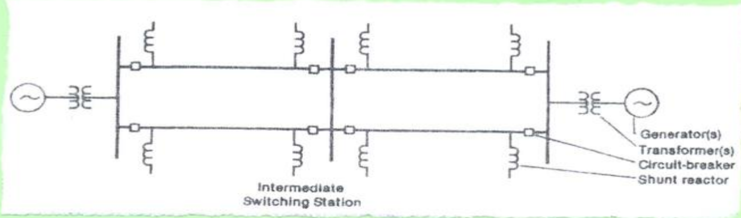


Fig 3. Arrangement of shunt reactors on a long-distance high voltage ac transmission line

- On a long radial line, the switching stations may occur at intervals of 50 & 250 mi.

In case of very long lines, at least few shunt reactors are permanently connected to the line to provide maximum security against overvoltage in the event of sudden open circuiting of the line.

On shorter lines, the overvoltage problem is less severe and so the reactors may be switched frequently to assist in hour-by-hour management of reactive power as load varies.

- Shunt capacitors are usually switched.

If there is sudden load rejection or open-circuiting of the line, it may be necessary to disconnect the compensator quickly so as to prevent them from increasing the voltage still further.

REQUIRED REACTANCE VALUES OF SHUNT REACTORS:

* Calculation of optimum ratings and the point of connection of Shunt reactors and capacitors is usually calculated by means of LOAD FLOW STUDIES.

Consider the simple circuit in fig 4, there is a simple Shunt reactor of inductance X at the receiving end and a pure voltage Source E_s at the sending end.

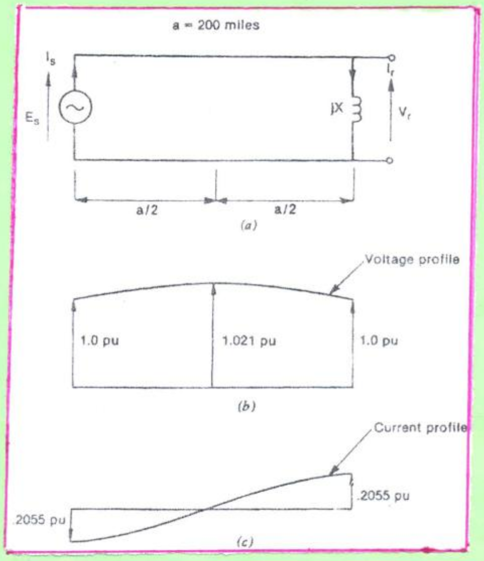


Fig4: Voltage & current profiles of a shunt compensated line at no-load ($a = 200$ mi).

The receiving end voltage is given by

$$V_r = jX\, I_r \longrightarrow ①$$

from transmission line equation we know

$$E_s = V_r \cos\beta a + j Z_0 I_r \sin\beta a$$

$$= V_r \left[\cos\theta + j\frac{Z_0}{X}\sin\theta\right] \longrightarrow ②$$

$\because \beta a = \theta$

$$I_r = \frac{V_r}{X}$$

From this equation it is clear that,

E_s & V_r are in phase.

So it is very well clear that no real Power is being transmitted.

For the receiving end voltage to be **equal to** sending end voltage

$$X = Z_0\frac{\sin\theta}{1-\cos\theta} \longrightarrow ③$$

must be

$$\because E_s = V_r\left[\cos\theta + \frac{Z_0 \sin\theta}{Z_0\sin\theta}[1-\cos\theta]\right]$$

$$E_s = V_r$$

* From transmission line equation, we can write the expression for sending end current as

$$I_s = j\frac{E_s}{Z_0}\sin\theta + I_r\cos\theta \longrightarrow (4)$$

but $I_r = \frac{V_r}{jX} = -j\frac{V_r}{X}$

so $$I_s = j\frac{E_s}{Z_0}\sin\theta - j\frac{V_r}{X}\cos\theta$$

we know $E_s = V_r$ So substituting this in above equation

$$I_s = j\frac{E_s}{Z_0}\sin\theta - j\frac{E_s}{X}\cos\theta$$

we know $X = Z_0\frac{\sin\theta}{1-\cos\theta}$

$$= j\frac{E_s}{Z_0}\left[\sin\theta - \frac{(1-\cos\theta)}{\sin\theta}\cos\theta\right]$$

$$= j\frac{E_s}{Z_0}\left[\frac{\sin^2\theta - \cos\theta + \cos^2\theta}{\sin\theta}\right] = j\frac{E_s}{Z_0}\left[\frac{1-\cos\theta}{\sin\theta}\right]$$

$$= j\frac{E_s}{X} = -I_r \longrightarrow (5) \qquad (\because E_s = V_r)$$

This means that generator at the sending end behaves exactly like the shunt reactor at the receiving end.

Both absorb same amount of Reactive power

$$Q_s = -Q_r = \frac{E_s^2}{X} = \frac{E_s^2}{Z_0}\left[\frac{1-\cos\theta}{\sin\theta}\right] \longrightarrow (6)$$

The charging current divides equally between two halves of the line.

* The voltage profile is symmetrical about the midpoint and is shown earlier in fig 4. togather with line current profile

* In the left half of the line, the charging current is negative, at the midpoint it is zero & in the right half it is +ve.

* The maximum voltage is at midpoint and is given by the equation

$$V_m = V_r\left[\cos\frac{\theta}{2} + \frac{Z_0}{X}\sin\frac{\theta}{2}\right] = \frac{E_s}{\cos(\theta/2)} \longrightarrow (7)$$

* V_m is in phase with E_s & V_r, as is the voltage at all points along the line.

* For a 200 mi line, $E_S = V_0 = 1.0\,p.u$, the midpoint voltage is 1.021 p.u. and the reactive power absorbed at each end will be $0.2055\,P_0$.

* When compensating reactor was absent,
  $V_m = 1.088\,p.u$ & $Q_s = 0.429\,P_0$.

* For a continuous duty at no load, with a line voltage of 500 kV & $Z_0 = 250\,\Omega$, the rating of shunt reactor will be 68.5 MVAR

* With shunt reactor, the line behaves as at no-load where 2 separate open-circuited lines are connected back to back.

5.answer

OBJECTIVES AND PRACTICAL LIMITATIONS

* Series compensation consist of capacitors connected in series with the line at suitable location.

* Their main aim is to cancel part of the reactance of the line.

* By doing so the maximum power transfer increases, it reduces the transmission angle and increases the virtual natural load.

The line reactance is being effectively reduced, so there is less absorbtion of line charging reactive power, so at times Shunt inductive compensation is needed.

Application of series capacitors:

1. It is used to increase the power transfer on a line of any length

$$P = \frac{E \cdot V}{X} \sin\delta$$

$E \rightarrow$ sending end V
$V \rightarrow$ receiving end V
$X \rightarrow$ reactance of line
$\delta \rightarrow$ phase $\angle$ b/w E & V

2. Series capacitor can be used to increase the load share on one of two or more parallel lines especially in the case where there is a high voltage line near a low voltage line in same corridor.

3. Improvement of system Stability
For same amount of Power transfer and same value of E & V, δ in case of series compensated line is less than uncompensated line

$$P = \frac{EV}{X} \sin \delta$$

A lower value of δ means better system stability.

4. less installation time – Installation time of series capacitor is smaller (2 years approx) as compared to installation of parallel circuit lines.

Life of transmission line & capacitor is 20 - 25 years.

LIMITATIONS

* The upper limit to the degree of series compensation is of the order of 0.8.

∵ if $K_{se} = 1$, effective line reactance will be zero,

→ so even if there is a smallest disturbance in the rotor angle of synchronous machines, it will result in the flow of large currents.

→ Also it will be difficult to control transient voltage and currents during disturbances.

* The capacitor reactance is determined by steady state & transient power transfer characteristics & also by the location of capacitors on the line.

* The voltage rating will depend on the worst anticipated fault current through the capacitor & any bypass equipment.

*. It is not practical to distribute capacitance in small units along the line.

* So in practice **lumped capacitors** are installed at different locations along the line. This will help in providing even voltage profile.

6. answer

FUNDAMENTAL CONCEPTS OF COMPENSATION BY SECTIONING :

OR

DYNAMIC SHUNT COMPENSATION

* If a synchronous machine is connected at an intermediate point along a transmission line, it can maintain constant voltage at that point.

* By doing so, it can divide the line into 2 sections which are apparently quite independent.

The voltage profile, maximum transmissible power and Reactive power requirements of each section can be determined separately.

The maximum transmissible power is now dependent on the weakest link in the chain.

Usually the weakest link will be the longest section.

Eg: if a line is sectioned into 2 equal halves, if shunt capacitance is neglected or totally compensated by shunt reactor, then the Power transmitted is shown by the equation,

replace $\delta \longrightarrow \delta/2$

$X_l \longrightarrow \frac{X_l}{2}$

$E_s = E_r = E$

$\therefore \quad P = 2\frac{E_m E}{X_l} \sin\frac{\delta}{2}$ where $E_m \rightarrow$ midpoint V

* From the above equation it is clear that the maximum transmissible power is doubled.

* This scheme of compensation by sectioning was proposed by F.G Baum in 1921.

* He suggested that by connecting synchronous condensers at intervals of 100 mi, a substantially flat voltage profile will be obtained.

* The condenser will adjust the virtual natural load P_o' to be equal to actual load at all the times.

* If losses are neglected, then the compensating current taken by the intermediate synchronous machine is purely reactive (ie current is in phase quadrature with the voltage) & the machine supplies or absorbs reactive power from the line.

* In steady state, the machine can maintain constant voltage at its point of connection without the help of a mechanical prime mover.

* In steady state, there is a ratio between compensating current I_r & voltage at the point of connection.

→ The susceptance will be capacitive if I_r leads V & will be inductive if V leads I_r.

⇒ Synchronous machine in steady state can be replaced by capacitor or reactor.

* If the Power transmitted along the line changed value then obviously the voltage will also change.

→ So inorder to restore the voltage to a constant value always the capacitive or inductive susceptance should change value

→ So we have to modulate or control the susceptance of a real inductor or capacitor so as to maintain constant voltage at its point of connection.

→ Fig 2 shows the principle of modulating susceptance.

→ We know that a shunt compensating device should maintain constant voltage magnitude at its point of connection.

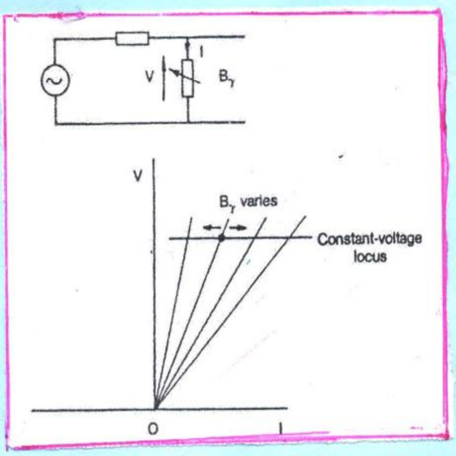


Fig 2. Principle of maintaining constant ac voltage at terminals of a controlled susceptance

→ Under steady state or slowly varying conditions, the Static compensator can be made functionally equivalent to an intermediate synchronous machine.

→ Under more rapidly varying conditions, the inertia of the synchronous machine rotor influences the phase of the Voltage at the point of connection.

→ This is because of the exchange of Kinetic Energy with the system as the rotor accelerates or decelerates.

→ So Purely static compensator cannot exchange Energy with the system.

→ So the theory of compensation by sectioning in the steady state and for very slowly varying conditions, it is so slow that the kinetic Energy of rotating machines to be negligible.

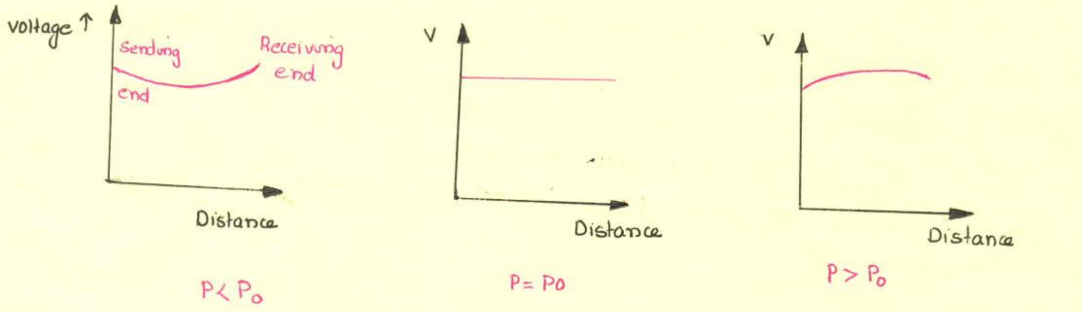
** —— **

2ANS:

VOLTAGE & CURRENT PROFILES OF UNCOMPENSATED RADIAL & SYMMETRICAL LINE ON OPEN CIRCUIT :

1. VOLTAGE & CURRENT PROFILE :

* Voltage profile along a long & lossless transmission line is as shown.



* A lossless line is energized by generators at the sending end and is open circuited at the receiving end.
* It can be described by **eqn no: 2** of the general solution for fundamental transmission line equation, by putting $I_r = 0$

So $V(x) = V_r \cos\beta(a-x)$ &

$I(x) = j\left[\frac{V_r}{Z_0}\right]\sin\beta(a-x)$ $\longrightarrow$ (A)

* Voltage & current at sending end are given by the equations with $x = 0$

$V(x) = V(s) = E(s)$

$I(x) = I(s)$

$\theta = \beta a$

So eqn (A) is modified as

$V(s) = V_r \cos\theta \Rightarrow E(s) = V_r \cos\theta \longrightarrow$ (B)

$I(s) = j\left[\frac{V_r}{Z_0}\right]\sin\theta = j\left[\frac{E(s)}{Z_0}\right]\tan\theta$

* If $E(s)$ & V_r are in phase, there is no power transfer. This phasor diagram is shown in figure below.

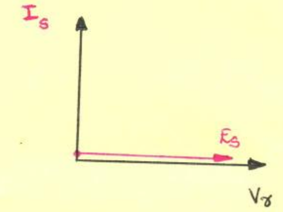


Fig 2. Phasor diag of 200 mi line open ckted at receiving end.

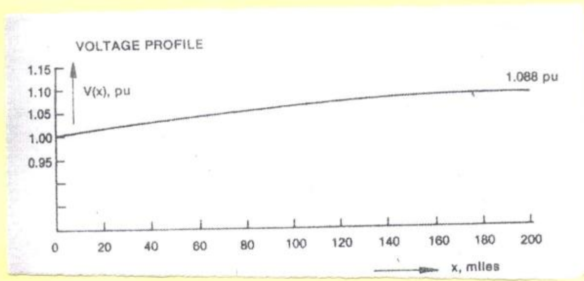
* The line voltage profile can be written more conveniently in terms of E_s

$$V(x) = \frac{E_s \cos\beta(a-x)}{\cos\theta}$$

$$I(x) = j\frac{E_s}{Z_0}\frac{\sin\beta(a-x)}{\cos\theta}$$

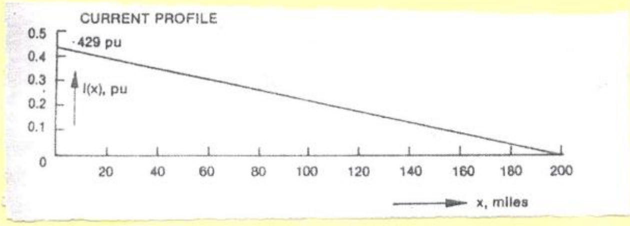
[∵ from (B)
$E_s = V_r \cos\theta$
$\frac{E_s}{\cos\theta} = V_r$]
So subt this in eqn (A)

* Fig 2. (below) shows the profile for a 200 miles transmission line with 60Hz. $\theta = 0.405$ radian $= 23.2^\circ$. with $E_s = 1.0$ pu & receiving end voltage $V_r = 1.088$ p.u, that is a rise of 8.8%, This rise is called Ferranti effect.



* A rise of 8.8% is not enough to cause severe problems for insulation. or voltage regulation equipment.
* At 400 mi transmission line, voltage will be 1.579 pu, it is unacceptable & dangerous.
* At 775 mi, the voltage rise will be infinite. So operation of such a line is impractical, without some means of compensation.

* The magnitude of I_s in figure is 0.429 p.u. So it is clear from figure that the charging current flowing in sending end is 42.9% of the current corresponding to the natural load.



1ANS:

SURGE IMPEDANCE AND NATURAL LOADING

* The constant Z_0 in equation no. (2) is the surge impedance also called as characteristic impedance

we know impedance of a transmission line is $Z_0 = \sqrt{\dfrac{R + j\omega L}{G + j\omega C}}$

we have considered a lossless transmission line

so no line Resistance $R = 0$ & hence line has infinite conductivity

So R & $G = 0$

So $Z_0 = \sqrt{\dfrac{L}{C}}$

The value of surge impedance depends on the line design.

* For high-voltage OH line, the +ve sequence OH line surge impedance value lies in the range 200 - 400 Ω (350 for single conductors & 275 for bundled conductors). → Z_1

* → When the losses are neglected, the line is characterised by its length and by two parameters Z_0 & β.
  → These values are almost comparable for all the lines, so the behavior of all the lines is fundamentally the same.
  → Differences arise only in length, voltage & level of power transmission.

* Surge impedance is the apparent impedance of an infinitely long line ie the ratio of voltage to I at any point along the line.

* A finite line terminated at one end by Z_0 impedance then $Z_0 = \dfrac{V_r}{I_r}$

* then from eqn (2) of previous topic, the apparent impedance at any point is

$$Z(x) = \frac{V(x)}{I(x)} = \frac{Z_0 I_r [\cos\beta(a-x) + j\sin\beta(a-x)]}{I_r [\cos\beta(a-x) + j\sin\beta(a-x)]}$$

where

$$V(x) = V_r[\cos\beta(a-x) + j\sin\beta(a-x)] = V_r e^{j\beta(a-x)} \longrightarrow (A)$$
$$I(x) = I_r[\cos\beta(a-x) + j\sin\beta(a-x)] = I_r e^{j\beta(a-x)}$$

both V & I are assumed to have **constant amplitude** along the line.

→ Then the line is said to have a flat voltage profile (i.e all voltage angles are assumed zero eg: 1+j0)

It means that both V & I are inphase with each other all along the line

* The phase angle between the sending end & receiving end quantities as per equation (A) is $\theta = \beta a$ rad.
  → For a 200 mi line at 60 Hz, the angle is 0.405 rad or 23.2°

*

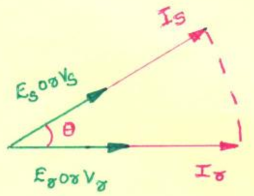


Fig 1. Phasor diagram of naturally loaded line

→ A line in this condition is said to be naturally loaded

→ The natural load is (surge impedance load is)

$$P_0 = \frac{V_0^2}{Z_0} \longrightarrow (B)$$

where V_0 → nominal or rated V of line

* If V_0 is line to neutral voltage then eqn (B) gives per-phase value of surge-impedance power.
  if V_0 is line to line voltage, then eqn (B) gives or P_0 is 3-Phase value.

* Natural load is an important reference quantity.
  - → Advantage of operating the line at natural load is that because of flat voltage profile, the insulation is uniformly stressed at all points.

* From eqn (B) it is clear that the natural load of an uncompensated line increases with square of voltage.
  That is the reason why transmission voltages has increased as the level of transmitted Power has grown.

* Surge impedance Z_0 is a real number.
  ∴ at Natural load, Power factor is cosine of angle between V & I.

  here angle = 0°

  $\cos 0 = 1$

  So Pf is Unity along the line including the ends.

* So it is clear that at natural load, no reactive power is needed to be absorbed or generated.

* So the reactive power generated in shunt capacitance of line is absorbed by series impedance.

$$\left.\begin{array}{r}\text{reactive power per unit}\\ \text{length generated by shunt}\\ \text{capacitance}\end{array}\right\} V^2\omega C$$

$$\left.\begin{array}{r}\text{reactive power per unit length absorbed}\\ \text{by series inductor}\end{array}\right\} I^2\omega L$$

$$V^2\omega C = I^2\omega L$$

ie, $$\frac{V}{I} = \sqrt{\frac{L}{C}} = Z_0$$

∴ reactive Power balance is achieved by natural loading with $P_0 = \frac{V^2}{Z_0}$.

It gives FLAT VOLTAGE PROFILE & Unity P.f at both ends.
& P_0 is natural Power of line. Natural $Q_P = 0$.

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