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USN

Internal Assesment Test - II

Sub:	REACTIVE POWER MANAGEMENT							Code:	10EE831
Date:	16/04/2018	Duration:	90 mins	Max Marks:	50	Sem:	8th	Branch:	EEE
Answer Any FIVE FULL Questions									

		Marks	OBE	
			CO	RBT
1	Explain surge impedance and natural loading and their importance in reactive power management.	[10]	CO3	L4
2	With respect to uncompensated open circuit line on no load, derive the necessary equations and also draw voltage and current profile for a 200 mi line at 60Hz.	[10]	CO2	L1
3	Discuss the operation of symmetrical line at no load. Also draw the voltage and current profile for a 200 mi line.	[10]	CO2	L2
4	List out the objectives and limitations of series compensation.	[10]	CO3	L1
5	Explain the concept of symmetrical line with midpoint series capacitor and shunt reactor.	[10]	CO3	L4
6	Explain the concept of compensation by sectioning.	[10]	CO3	L4

******All the Best******

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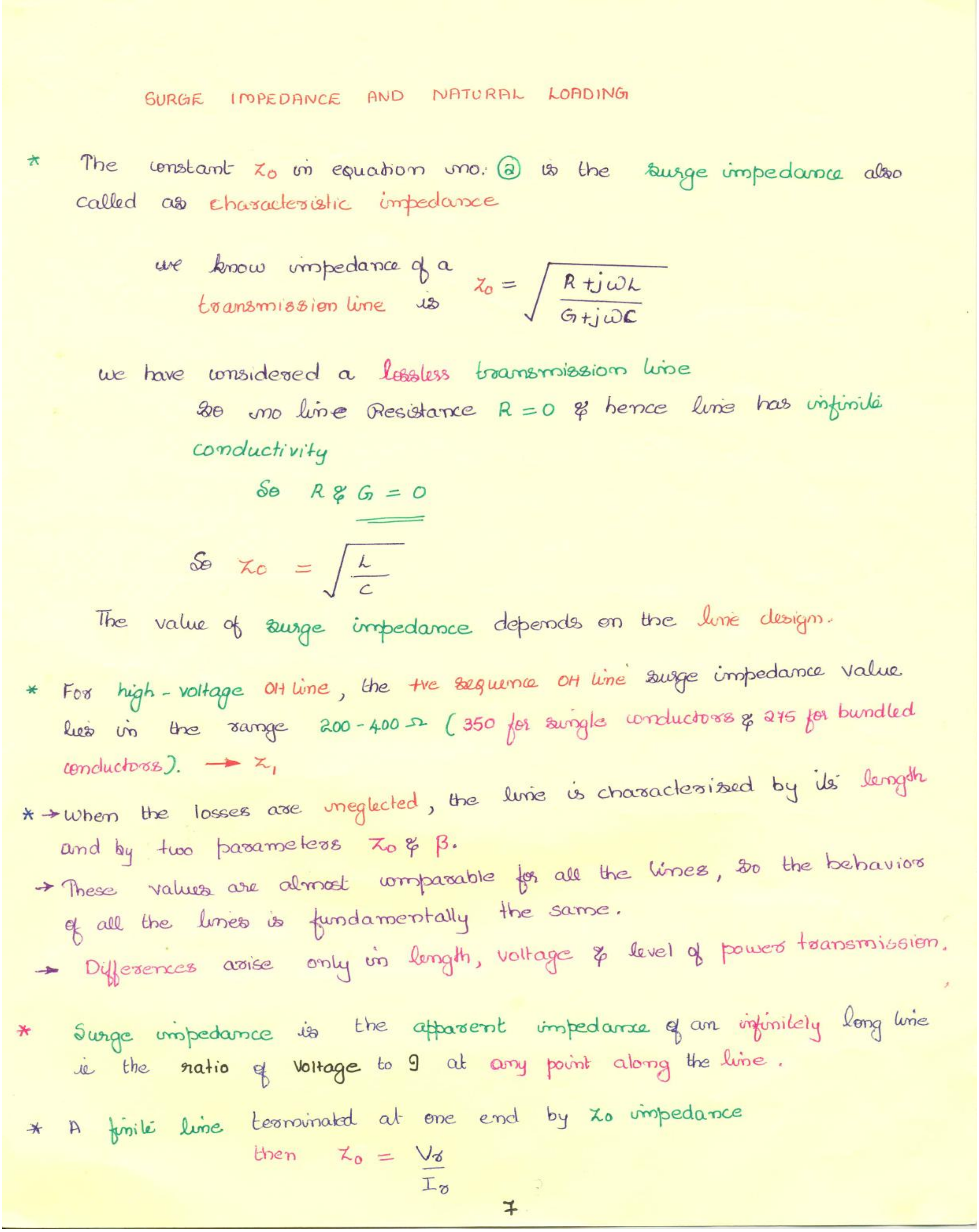
6	Explain the concept of compensation by sectioning.	[10]	CO3	L4

******All the Best******

Answer key

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 $Z_0 = \sqrt{\frac{R+j\omega L}{G+j\omega C}}$

we have considered a lossless transmission line

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

So R & $G = 0$

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

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 $Z_0 = \frac{V_r}{I_r}$

* 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

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

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

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

→ Then the line is said to have a flat voltage profile (ie 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 Ⓐ is $\theta = \beta a$ rad.

→ For a 200 mi line at 60 Hz, the angle is 0.405 rad or 23.2°.

*

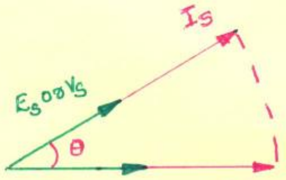


Fig 1. Phasor diagram of naturally loaded line

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

→ The natural load is (surge impedance load is)

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

where V_0 → nominal or rated V of line

* If V_0 is line to neutral voltage then eqn Ⓑ gives per-phase value of Surge-impedance power.

if V_0 is line to line voltage, then eqn Ⓑ 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 Ⓑ 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.

reactive power per unit length generated by shunt capacitance } $V^2\omega C$

reactive power per unit length absorbed by series inductor } $I^2\omega L$

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

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

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

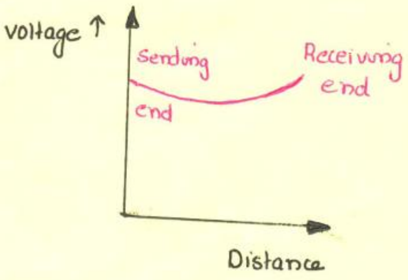
It gives FLAT VOLTAGE PROFILE & Unity P.f at both ends.

& P_0 is natural Power of line. Natural $Q_P = 0$.

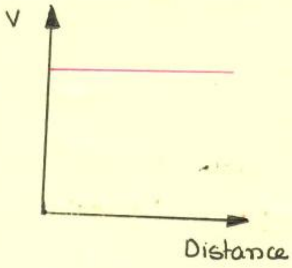
2ans: 10 marks

1. VOLTAGE & CURRENT PROFILE :

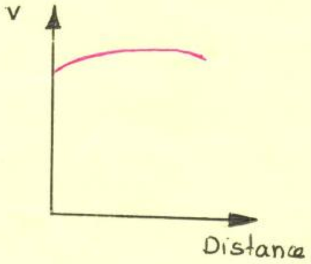
- Voltage profile along a long & lossless transmission line is as shown.



$P < P_o$



$P = P_o$



$P > P_o$

- 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 $$V(x) = V_r \cos\beta(a-x) \quad \& \qquad \longrightarrow \text{Ⓐ}$$
$$I(x) = j\left[\frac{V_r}{Z_o}\right]\sin\beta(a-x)$$

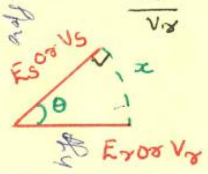
- Voltage & current at sending end are given by the equations with $x = 0$

$$V(x) = V(s) = E(s)$$
$$I(x) = I(s)$$
$$\theta = \beta a$$

So eqn Ⓐ is modified as

$$V(s) = V_r \cos\theta \quad \Rightarrow \quad E(s) = V_r\cos\theta \longrightarrow \text{Ⓑ}$$
$$I(s) = j\left[\frac{V_r}{Z_o}\right]\sin\theta = j\left[\frac{E(s)}{Z_o}\right]\tan\theta$$

$$\cos\theta = \frac{E_s}{V_r}$$



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

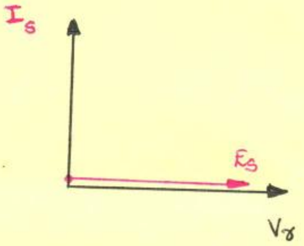


Fig2. Phasor diag of 200 mi line open ckted at receiving end.

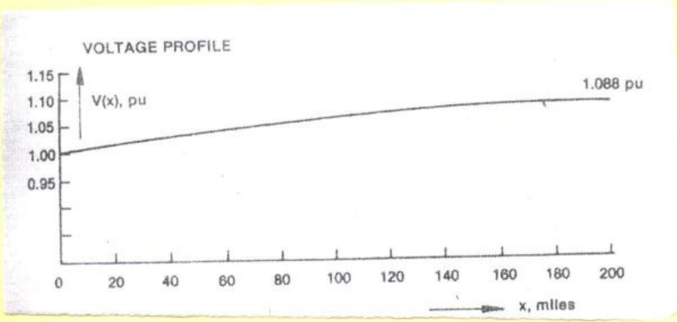
* The line voltage profile can be written more conveniently in terms of E_s

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

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

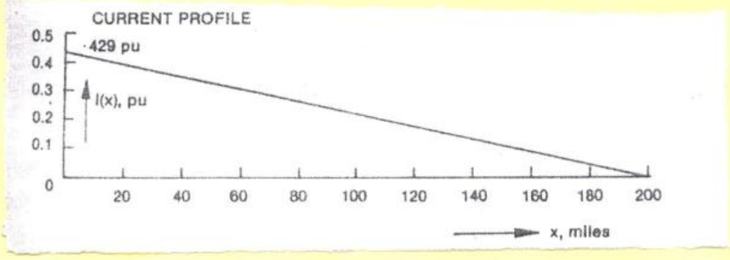
$$I(x) = j\frac{E_s}{Z_0}\frac{\sin\beta(a-x)}{\cos\theta}$$

* Fig 2. (below) shows the profile for a 200 miles transmission line with 60Hz. $\theta = 0.405$ radian $= 23.2°$. 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.



3ans: **10 marks**

2. The Symmetrical Line at No load :

* This is similar to open circuit line energized at one end.
* The line has identical synchronous machines at both ends. So there is no Power transfer.

* We know the solution of transmission line equation

$$V(x) = V_r \cos\beta(a-x) + jZ_0 I_r \sin\beta(a-x)$$

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

So by changing $V_r \rightarrow E_r$ & $\theta = \beta a$

$V(x) \rightarrow E_s$ $x = 0$

$I(x) \rightarrow I_s$

we can write the same equation as,

$$E_s = E_r\cos\theta + jZ_0 I_r \sin\theta \qquad \longrightarrow ⓒ$$

$$I_s = j\left[\frac{E_r}{Z_0}\right]\sin\theta + I_r\cos\theta$$

* Suppose terminal voltages are maintained ie, $E_s = E_r$

* with no Power transfer, electrical conditions are same at both the ends.

$$I_s = -I_r \longrightarrow \textcircled{D}$$

→ -ve sign is because we have taken the convention that +ve current flows away from sending end, so at receiving end is this taken as -ve.

* Now substituting Ⓓ in eqn Ⓒ,

$$-I_r = j\left[\frac{E_r}{Z_0}\right]\sin\theta + I_r\cos\theta$$

$$-I_r\,(1+\cos\theta) = j\left[\frac{E_r}{Z_0}\right]\sin\theta$$

$$-I_r = j\left[\frac{E_r}{Z_0}\right]\frac{\sin\theta}{1+\cos\theta}$$

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

$$= j\left[\frac{E_r}{Z_0}\right]\frac{2\cos\frac{\theta}{2}\sin\frac{\theta}{2}}{2\cos^2\frac{\theta}{2}} = \underline{\underline{j\left[\frac{E_r}{Z_0}\right]\tan\frac{\theta}{2}}} \longrightarrow \textcircled{E}$$

& $\underline{\underline{E_s = E_r}}$ (already discussed).

* So equation no: Ⓔ can be modified as

$$\therefore \quad \underline{\underline{I_s = j\left[\frac{E_s}{Z_0}\right]\tan\frac{\theta}{2}}}$$

* Since $E_s = E_r$

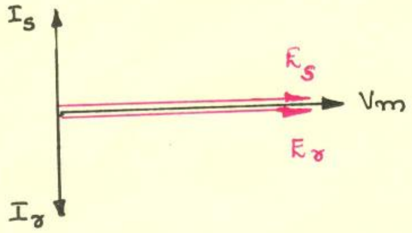
→ we know both are in phase

→ So again it is the fact that there is no power factor.

→ The current at each end is line charging current.

→ So the line is equivalent to two equal halves connected to back to back.

→ Half line charging current is supplied from each end.



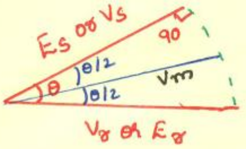
* Phasor diagram for $a = 200$ mi with
$E_s = E_r = V_0 = 1.0$ p.u

Fig: Phasor diagram of 200 mi Symmetrical line

* By symmetry the midpoint current is zero.

* Mid point voltage is equal to open circuit voltage, having half the total length

$$V_m = \frac{E_s}{\cos(\theta/2)}$$



$$\because \cos\frac{\theta}{2} = \frac{E_s}{V_m}$$

* The voltage & current profile for symmetrical line at no load can be derived from eqn Ⓐ

$$V(x) = E_s \frac{\cos\beta(a/2 - x)}{\cos(\theta/2)} \longrightarrow Ⓕ$$

&

$$I(x) = \frac{j\left[\frac{E_s}{Z_0}\right]\sin\beta(a/2 - x)}{\cos(\theta/2)}$$

* for $x \le \frac{a}{2}$ we got $V(x)$ & $I(x)$ as eqn Ⓕ.

* Now for other half of the line $\frac{a}{2} \le x \le a$

$$V(x) = V(a-x)$$
$$I(x) = -I(a-x)$$

* The profiles are shown in figure below.

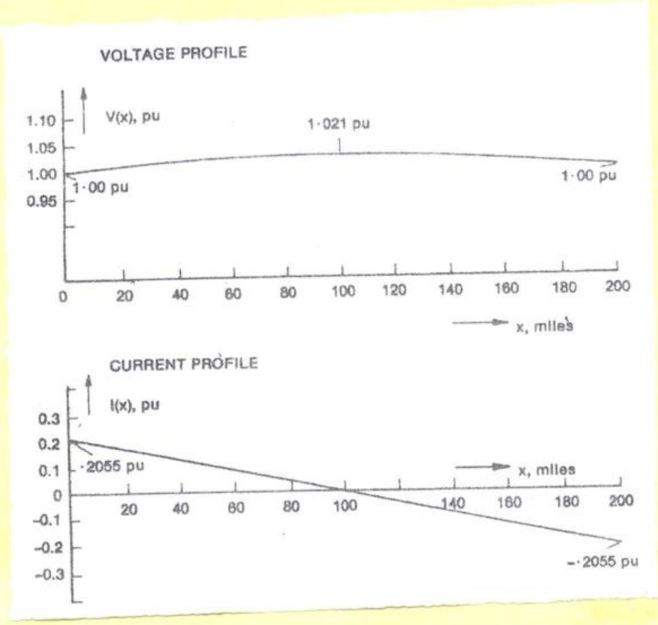


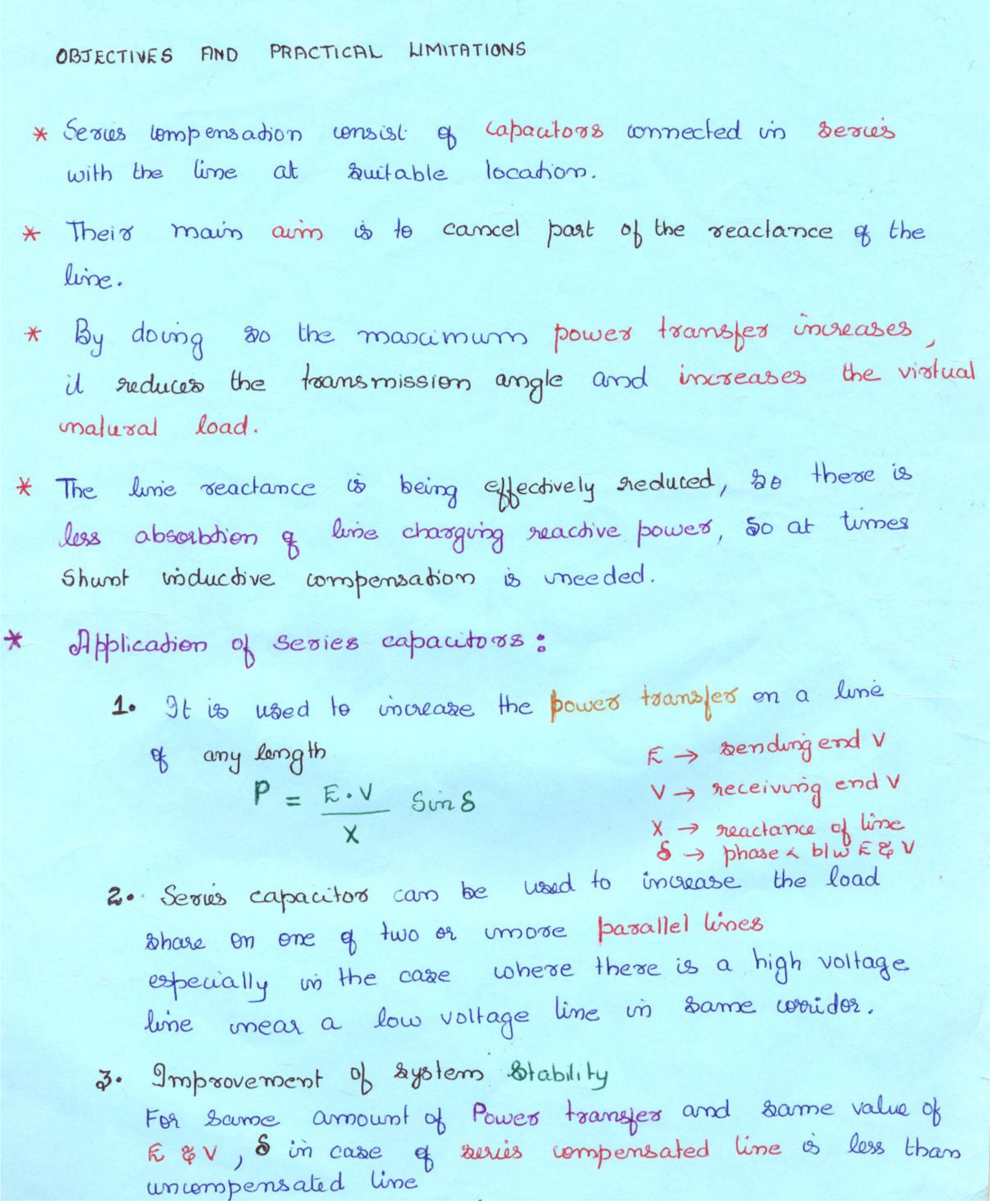
Fig: voltage & current profile for a 200mi symmetrical line

* If $E_s \ne E_r$, the current & voltage profile are no longer symmetrical & highest voltage is no longer midpoint.

→ But it will be nearer to the end of the line, which has highest terminal voltage.

→ The currents in synchronous machines are also unequal.

4ans: **10 marks**



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 → sending end V

V → receiving end V

X → reactance of line

δ → phase ∠ 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.

5ans: **10 marks**

SYMMETRICAL LINE WITH MIDPOINT SERIES CAPACITOR & SHUNT REACTORS :

- We are considering a lossless, symmetrical line with a midpoint series capacitor on either side connected to two equal shunt reactors as seen in fig 1.

- The capacitor is split into two equal series parts for the convenience in analysis.

- The shunt reactor is to control the line voltage.

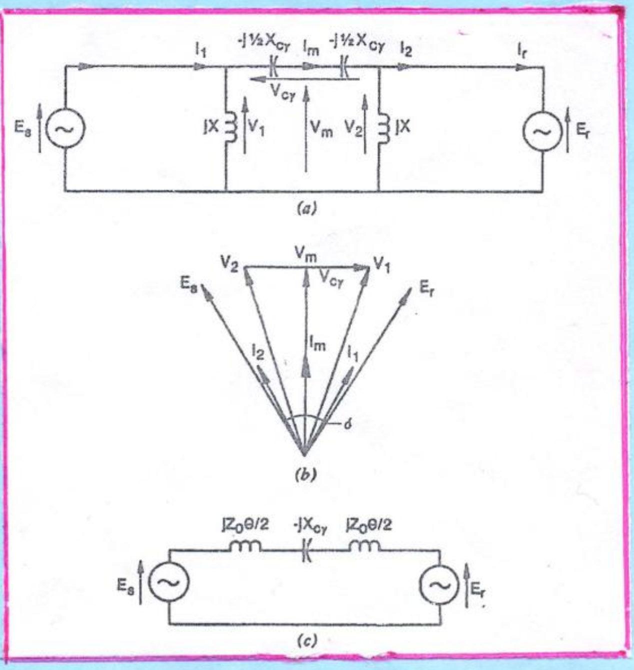


Fig 1 a) Symmetrical line with midpoint series capacitor & shunt reactors

1 b) general phasor diagram

1 c) Equivalent circuit with perfect shunt compensation.

POWER TRANSFER CHARACTERISTICS AND MAXIMUM TRANSMISIBLE POWER :

- The general phasor diagram is shown in fig 1(b).

- First consider the left hand section (sending end)

$$E_s = V_1 \cos\frac{\theta}{2} + j Z_0 I_1 \sin\frac{\theta}{2} \longrightarrow ①$$

$$I_s = j\frac{V_1}{Z_0}\sin\frac{\theta}{2} + I_1 \cos\frac{\theta}{2} \longrightarrow ②$$

- The receiving end half of the line also behaves in same manner.

- The capacitor reactance $X_{cr} = \frac{1}{\omega C_r} \longrightarrow ③$

& the voltage across the capacitor is given by

$$V_{cr} = V_1 - V_2 = -j I_m X_{cr} \longrightarrow ④$$

* By Symmetry

$$P = V_m I_m \quad , \quad E_S = E_r \quad \&$$

$$V_m = V_1 - \tfrac{1}{2} V_{cr} = V_2 - \tfrac{1}{2} V_{cr} \longrightarrow ⑤$$

* The currents I_1 & I_2 are given by

$$I_m = I_1 + j\frac{V_1}{X} = I_2 - \frac{jV_2}{X} \longrightarrow ⑥$$

* Now using all these relations and taking V_m as reference phasor, it is possible to ~~show~~ derive the basic power transfer characteristics

$$P = \frac{E_s V_m}{Z_0 \sin\frac{\theta}{2} - \frac{X_{cr}}{2}\left[\cos\frac{\theta}{2} + \frac{Z_0}{X}\sin\frac{\theta}{2}\right]} \sin\frac{\delta}{2} \longrightarrow ⑦$$

$$\& \quad E_s \cos\frac{\delta}{2} = V_m\left[\cos\frac{\theta}{2} + \frac{Z_0}{X}\sin\frac{\theta}{2}\right] \longrightarrow ⑧$$

[discussed in previous chapter (4)th]

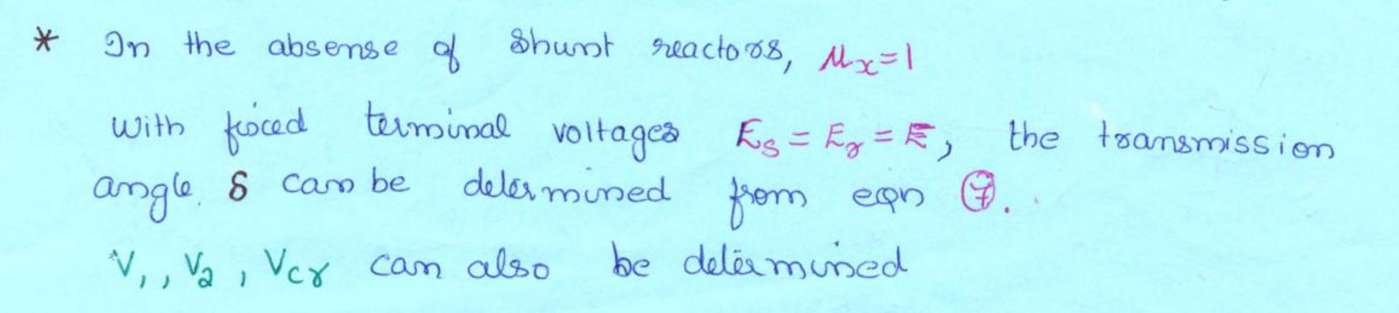
This itself is equal to

$$= E_r \cos\frac{\delta}{2}$$

* If V_m is substituted from eqn ⑧ to eqn ⑦ we get, & with $E_S = E_r$

$$P = \frac{E_s E_r}{\left[Z_0 \sin\theta - \frac{X_{cr}}{2}(1+\cos\theta)M_x\right] M_x} \sin\delta$$

$$\text{where } M_x = 1 + \frac{Z_0}{X}\frac{\sin\theta}{1+\cos\theta} = 1 + \frac{Z_0}{X}\tan\frac{\theta}{2}.$$

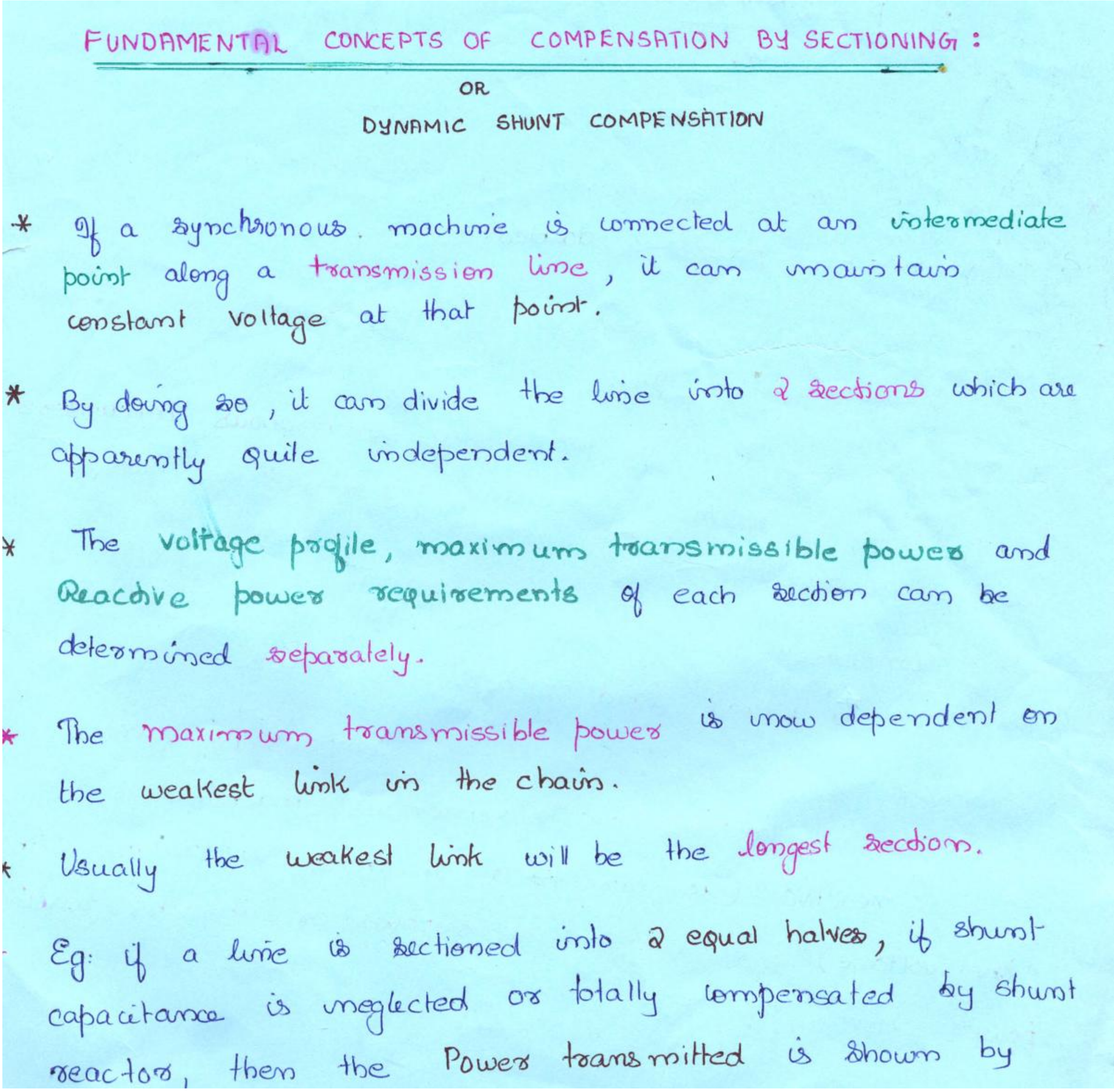


- * In the absense of shunt reactors, $\mu_x = 1$

  with fixed terminal voltages $E_s = E_r = E$, the transmission angle δ can be determined from eqn ⑦.

  V_1, V_2, V_{cr} can also be determined

6ans:**10 marks**



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_γ & voltage at the point of connection.

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

⇒ 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.

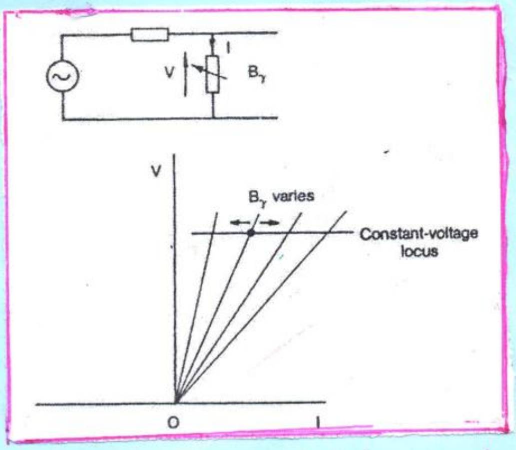
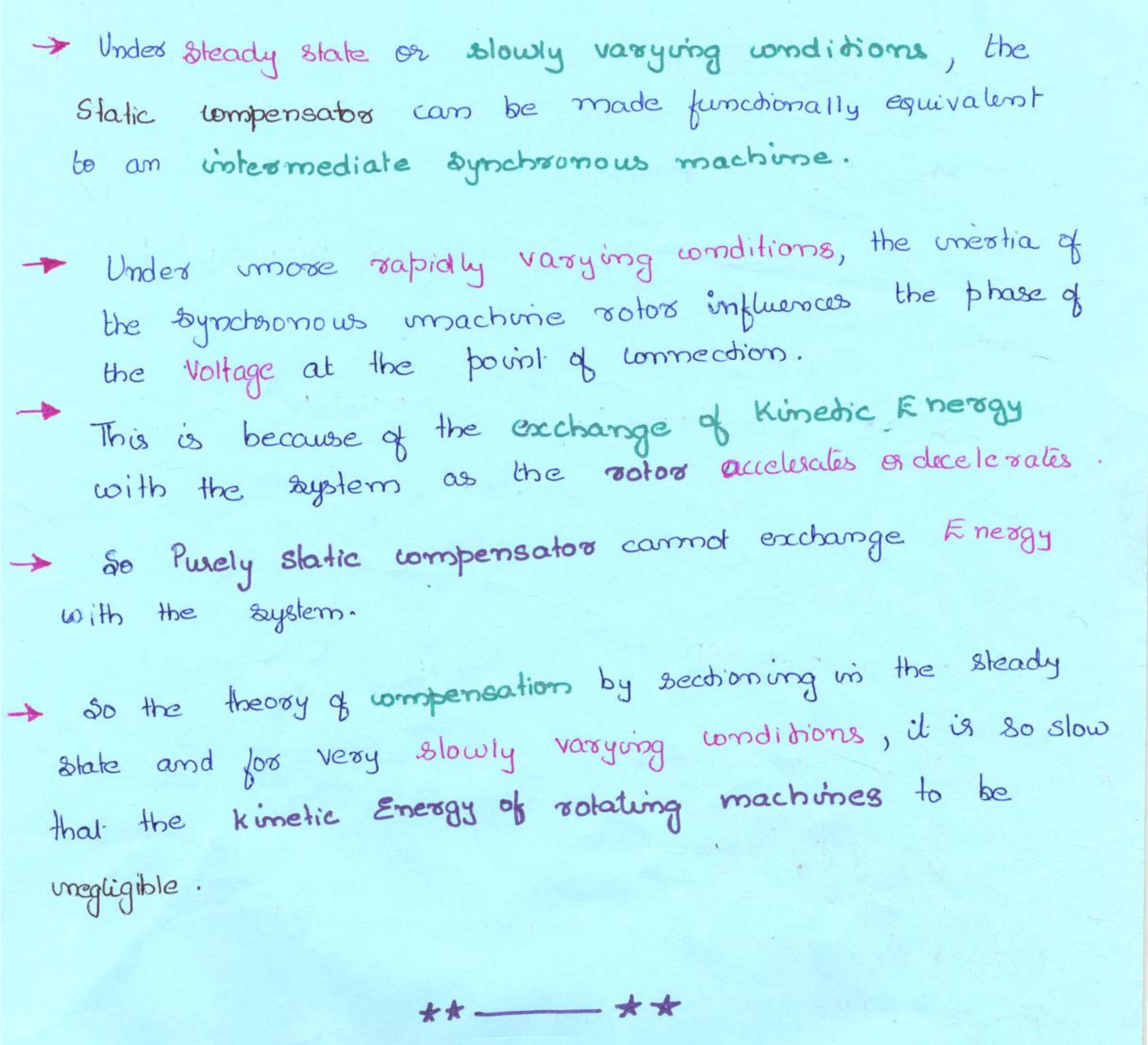


Fig2. Principle of maintaining constant ac voltage at terminals of a controlled susceptance



- 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.

** ——— **

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