POWER SYSTEMS-II

UNIT-I I: REACTIVE POWER & VOLTAGE CONTROL

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REACTIVE POWER

- In an alternating current (AC) power system, Power comprises of two components, active power and reactive power.
- Useful work is accomplished by active power while reactive power improves voltage stability and avoids voltage collapse.
- By regulation of reactive power the parameters of a power system like utilisation of active power, Voltage stability, Power factor, System efficiency, Energy cost and Power quality can be controlled.

A physical analogy for reactive power

- A reasonably accurate analogy for reactive power is the process of filling a water tower tank with water – one bucket at a time.
- This analogy is based on the facts that, “In the power system useful work accomplishes by active power while reactive power supports the voltage.”

IMPORTANCE OF REACTIVE POWER

- Voltage control in an electrical power system is very important for proper operation for electrical power equipment to prevent damage
- Decreasing reactive power causing voltage to fall while increasing it causing voltage to rise
- Reactive power is essential to move active power through the transmission and distribution system to the consumer

Importance of Voltage and reactive power Control

both utility and customer equipment designed to operate at certain voltage rating, Long time operation outside allowable range could cause them damage

- the lamp characteristics are very sensitive to changes of voltage. the life of the lamp may be reduced by 50%
- Also the power load consisting of induction motors, the voltage variations may cause stray operation.
- Too wide variations of voltage cause excessive heating of electrical device such as distribution transformers

- **Reactive power formulas**

$$Q = \frac{V^2}{X} \text{ VAR} \qquad Q \,\alpha\, v^2$$

For heavy load condition s required

+ve var C- bank

For light load condition required

-ve var L –bank

Reactive power sources

- The reactive power compensation sources are classified as,
- **Static compensation** is ideal for a response within seconds and minutes like shunt capacitor, shunt reactor, and tap changer.
  - **Dynamic compensation** is ideal for an instantaneous response like Synchronous condenser, and OLTC(On Load Tap Changer).

  It is further classified as,
  - Dynamic shunt compensation
  - Dynamic series compensation

- So it is necessary to provide individual means of voltage control for each circuit or group of circuits.
- In practice, voltage control equipment is used at :
- (i) generating stations
- (ii) transformer stations
- (iii)the feeders if the drop exceeds the permissible limits

Methods of Voltage Control

- There are several methods of voltage control.
- The following are the methods of voltage control in an a.c. power system:
- (i) By excitation control
- (ii) **By using tap changing transformers**
- **(iii) Auto-transformer tap changing**
- **(iv) Booster transformers**
- (v) Induction regulators
- vi) **Sources or sinks of reactive power, such as shunt capacitors, shunt reactors, synchronous condensers and Static Var Compensators (SVCs).**
- **vii) Line reactance compensators , such as series capacitors.**

- Method(i) is used at the generating station only whereas methods (ii) to (vii) can be used for transmission as well as distribution systems.

Voltage control & line compensation methods

1.Tap-Changing Transformers :

- One important method is to use tap changing transformer and is commonly employed where main transformer is necessary.
- In this method, a number of tappings are provided on the secondary of the transformer.
- The voltage drop in the line is supplied by changing the secondary e.m.f. of the transformer through the adjustment of its number of turns.

- **(i) Off load tap-changing transformer**. Fig. 1 shows the arrangement where a number of tappings have been provided on the secondary.
- As the position of the tap is varied, the effective number of secondary turns is varied and hence the output voltage of the secondary can be changed.
- Thus referring to Fig. 1, when the movable arm makes contact with stud1, the secondary voltage is minimum and when with stud 5, it is maximum.

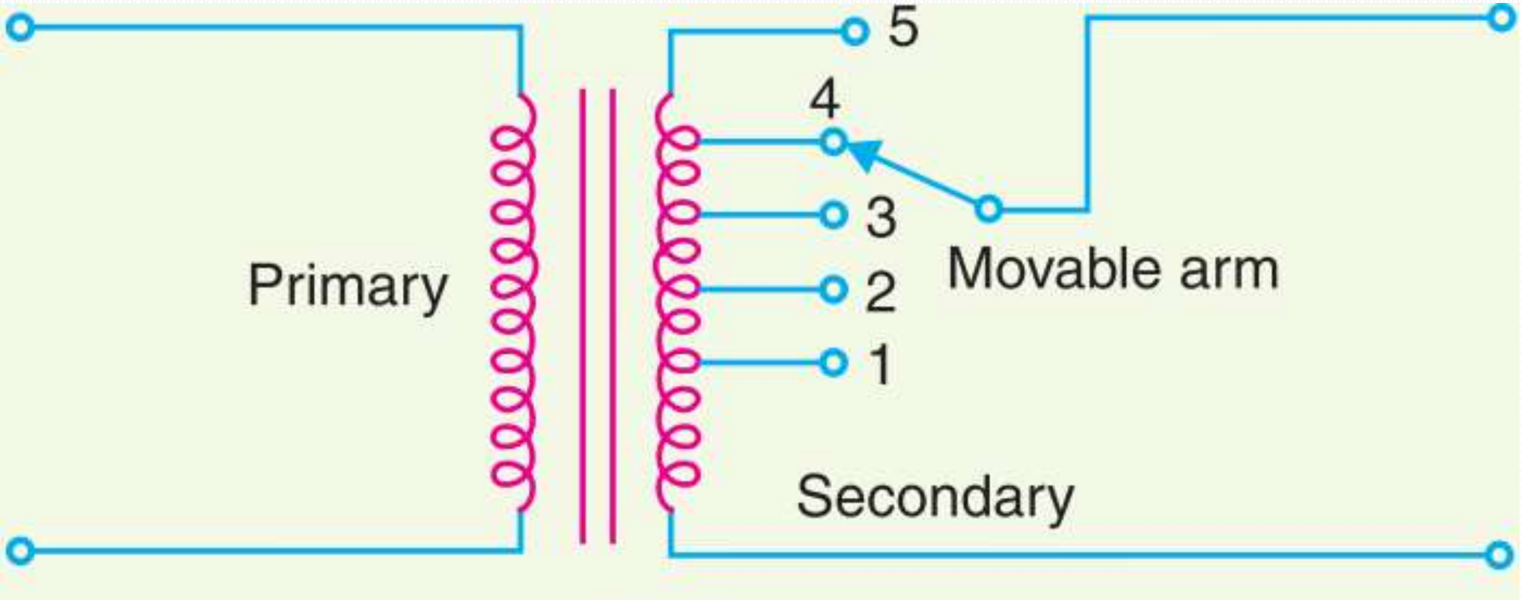


Fig. 1

- During the period of light load, the voltage across the primary is not much below the alternator voltage and the movable arm is placed on stud 1.
- When the load increases, the voltage across the primary drops, but the secondary voltage can be kept at the previous value by placing the movable arm on to a higher stud.
- Whenever a tapping is to be changed in this type of transformer, the load is kept off and hence the name off load tap-changing transformer.

- The principal disadvantage of this that it cannot be used for tap-changing on load.
- Suppose for a moment that tapping is changed from position 1 to position 2 when the transformer is supplying load.
- If contact with stud 1 is broken before contact with stud 2 is made, there is break in the circuit and arcing results.

- On the other hand, if contact with stud 2 is made before contact with stud 1 is broken, the coils connected between these two tappings are short circuited and carry damaging heavy currents.
- For this reason, the above circuit arrangement cannot be used for tap-changing on load.

(ii) On-load tap-changing transformer.

- The tapping is provided at the HV winding of the transformer because the HV winding is wound on the LV winding.
- Also, the current in the HV winding of the transformer is smaller due to which small contacts and leads are required for tapping connections

- **Needs For Tapping**
- Frequently change in load changes the voltage of the system. The tap changing in the power transformer is mainly done for keeping the output voltage within the prescribed limit.
- Nowadays almost all the large power transformer is provided with on-load tap changer.

- In supply system, tap-changing has normally to be performed on load so that there is no interruption to supply.
- Fig. 2 shows diagrammatically one type of on-load tap-changing transformer.
- The secondary consists of two equal parallel windings which have similar tappings 1a …… 5a and 1b ……… 5b.

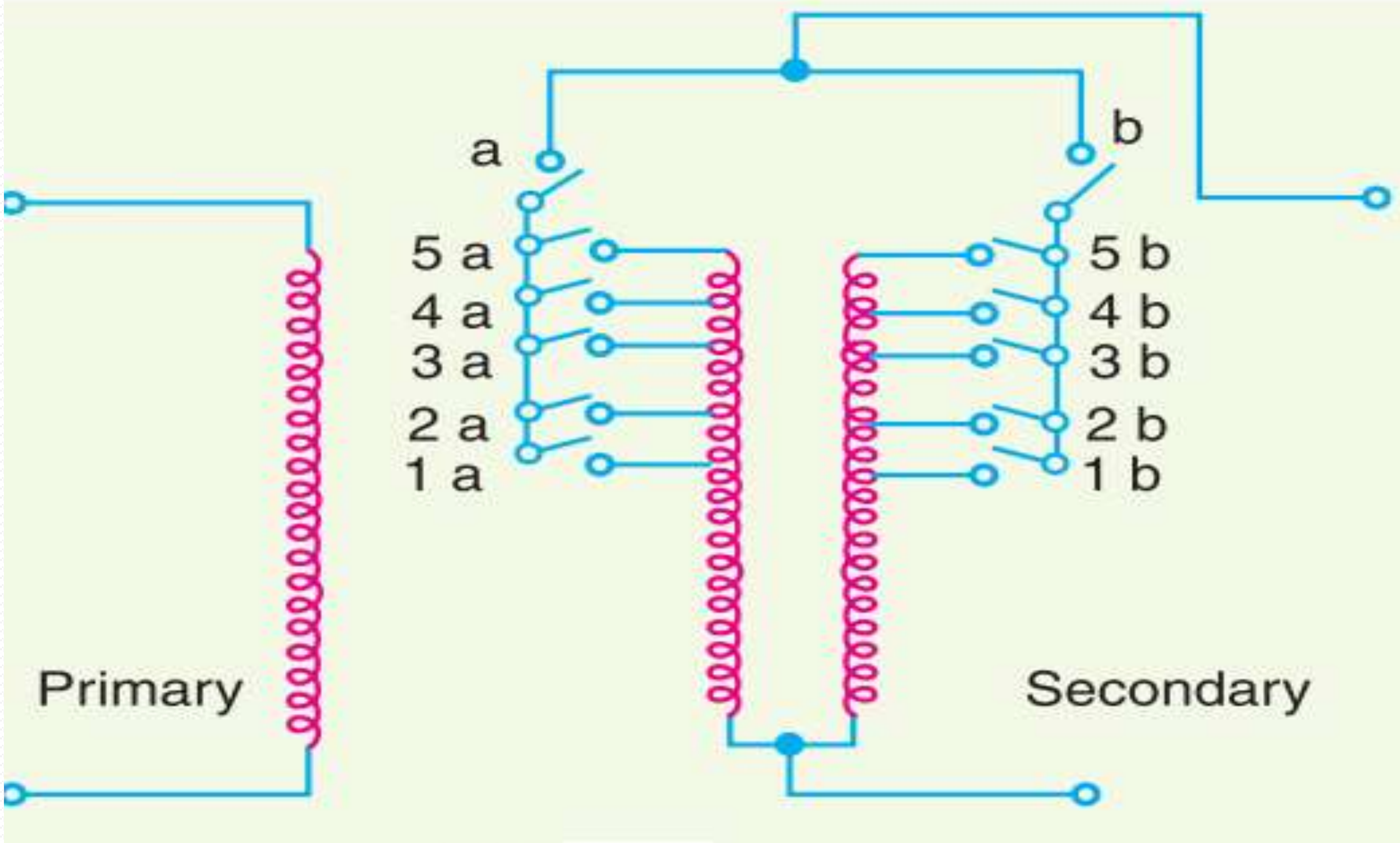


Fig. 2

- In the normal working conditions, switches a, b and tappings with the same number remain closed and each secondary winding carries one-half of the total current.
- Referring to Fig. 2, the secondary voltage will be maximum when switches a, b and 5a, 5b are closed.
- However, the secondary voltage will be minimum when switches a, b and 1a, 1b are closed.

- Suppose that the transformer is working with tapping position at 4a, 4b and it is desired to alter its position to 5a, 5b.
- For this purpose, one of the switches a and b, say a, is opened.
- This takes the secondary winding controlled by switch ‘a’ out of the circuit.

- Now, the secondary winding controlled by switch b carries the total current which is twice its rated capacity.
- Then the tapping on the disconnected winding is changed to 5a and switch a is closed.
- After this, switch b is opened to disconnect its winding, tapping position on this winding is changed to 5b and then switch b is closed.
- In this way, tapping position is changed without interrupting the supply.

- This method has the following disadvantages :
- (i) During switching, the impedance of transformer is increased and there will be a voltage surge.
- (ii) There are twice as many tappings as the voltage steps.

2. Auto-Transformer Tap-changing

- Fig. 3 shows diagrammatically auto-transformer tap changing.
- Here,a mid-tapped auto-transformer or reactor is used.
- One of the lines is connected to its mid-tapping.
- One end, say a of this transformer is connected to a series of switches across the odd tappings and the other end b is connected to switches across even tappings.

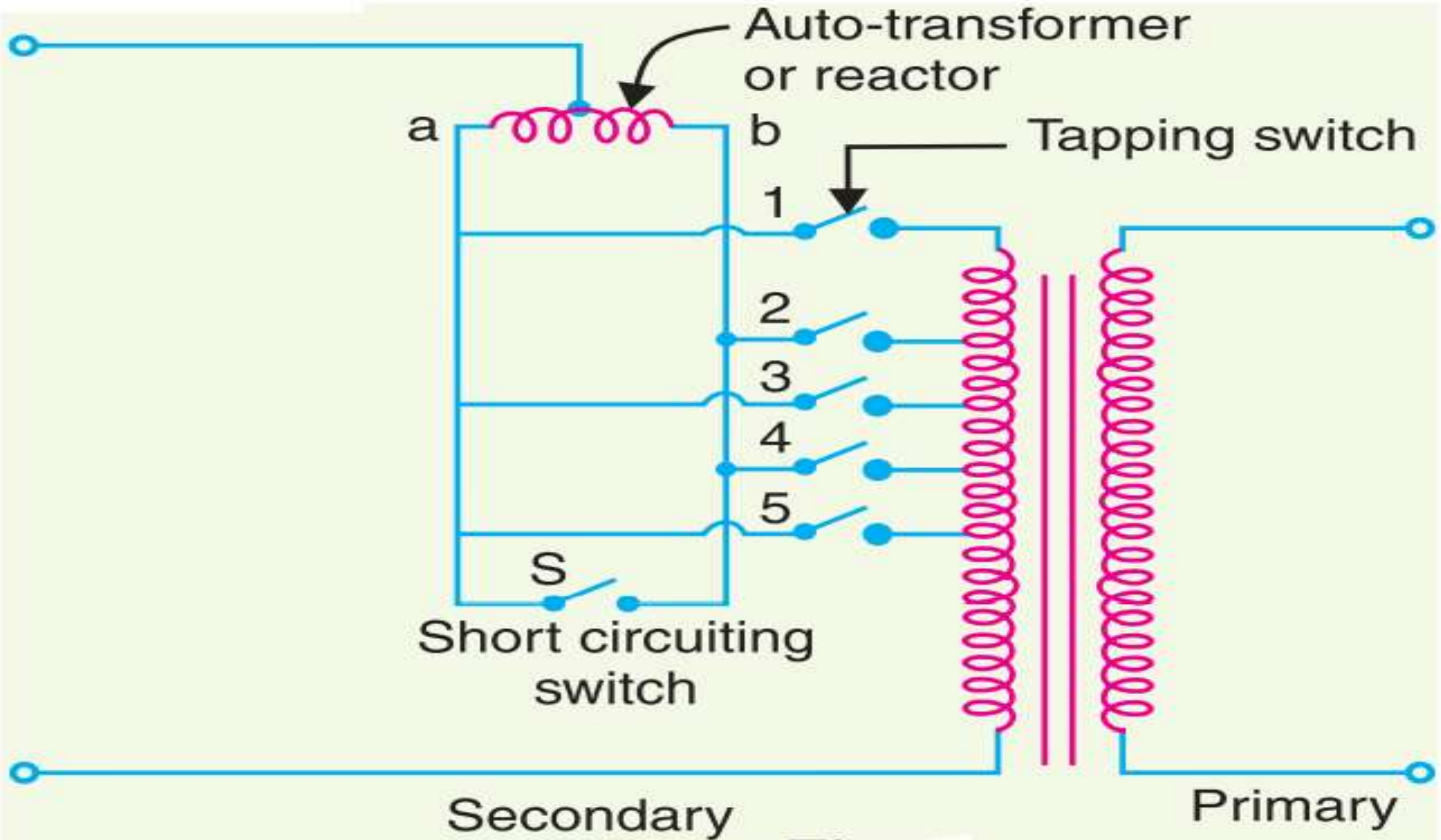

Auto-transformer
or reactor
a
b
Tapping switch
1
2
3
4
5
S
Short circuiting
switch
Secondary
Primary

Fig. 3

- A short-circuiting switch S is connected across the auto-transformer and remains in the closed position under normal operation.
- In the normal operation, there is no inductive voltage drop across the auto-transformer.
- Referring to Fig. 3, it is clear that with switch 5 closed, minimum secondary turns are in the circuit and hence the output voltage will be the lowest.

- On the other hand, the output voltage will be maximum when switch 1 is closed.
- Suppose now it is desired to alter the tapping point from position 5 to position 4 in order to raise the output voltage.
- For this purpose, short-circuiting switch S is opened, switch 4 is closed, then switch 5 is opened and finally short-circuiting switch is closed.
- In this way, tapping can be changed without interrupting the supply

- It is worthwhile to describe the electrical phenomenon occurring during the tap changing.
- When the short-circuiting switch is opened, the load current flows through one-half of the reactor coil so that there is a voltage drop across the reactor.

- When switch 4 is closed, the turns between points 4 and 5 are connected through the whole reactor winding.
- A circulating current flows through this local circuit but it is limited to a low value due to high reactance of the reactor.

3.Booster Transformer

- Sometimes it is desired to control the voltage of a transmission line at a point far away from the main transformer.
- This can be conveniently achieved by the use of a booster transformer as shown in Fig. 4.
- The secondary of the booster transformer is connected in series with the line whose voltage is to be controlled.

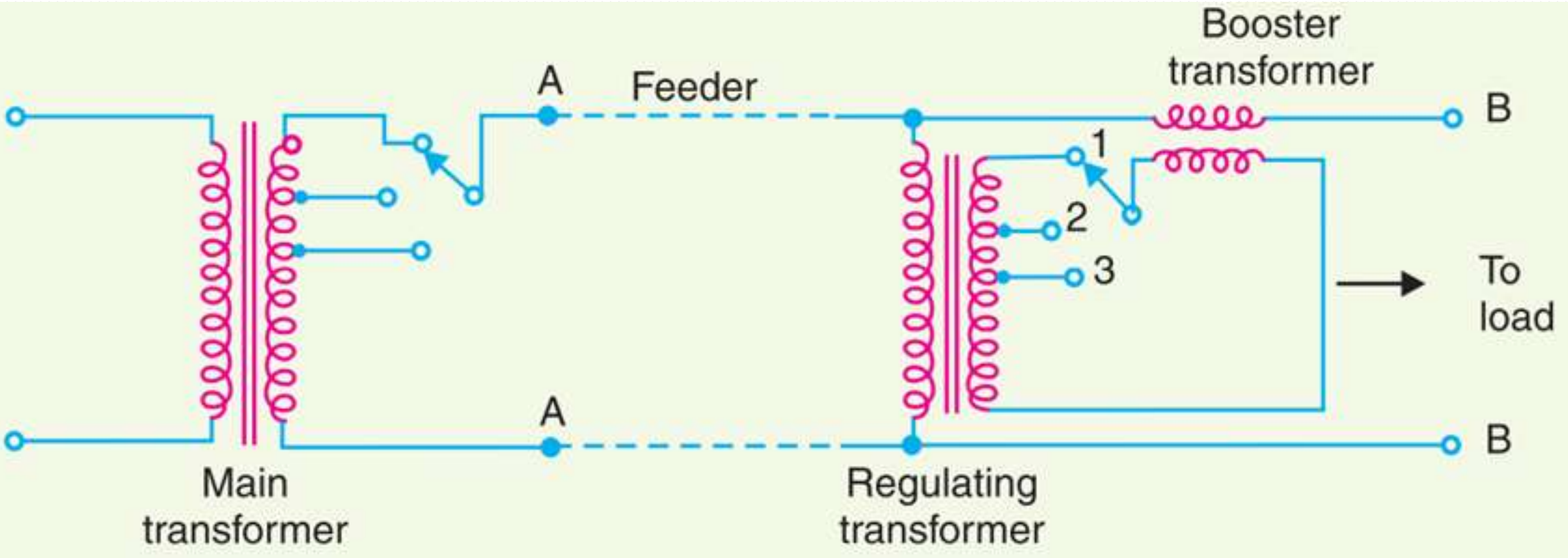

Booster transformer
A
Feeder
B
1
2
3
To load
A
B
Main transformer
Regulating transformer

Fig. 4

- The primary of this transformer is supplied from a regulating transformer fitted with on-load tap-changing gear.
- The booster transformer is connected in such a way that its secondary injects a voltage in phase with the line voltage.

- The voltage at AA is maintained constant by tap-changing gear in the main transformer.
- However, there may be considerable voltage drop between AA and BB due to fairly long feeder and tapping of loads.
- The voltage at BB is controlled by the use of regulating transformer and booster transformer.

- By changing the tapping on the regulating transformer, the magnitude of the voltage injected into the line can be varied.
- This permits to keep the voltage at BB to the desired value.
- This method of voltage control has three disadvantages.

- Firstly, it is more expensive than the on-load tap-changing transformer.
- Secondly, it is less efficient owing to losses in the booster and thirdly more floor space is required.
- Fig. 4 shows a three-phase booster transformer.

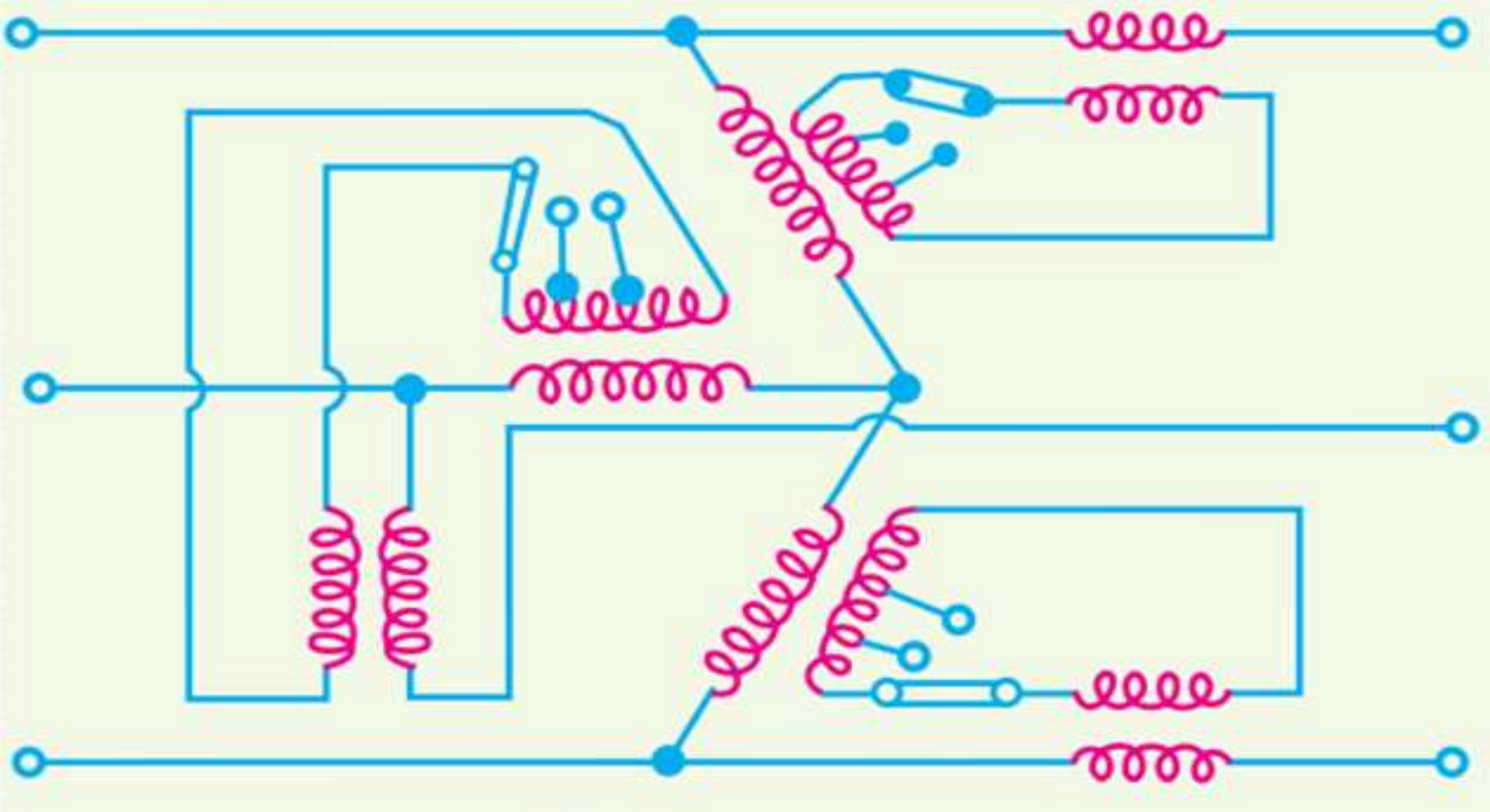


Fig. 5

Booster Transformer

4.Shunt Compensation

- For high voltage transmission line the line capacitance is high and plays a significant role in voltage conditions of the receiving end.
- When the line is loaded then the reactive power demand of the load is partially met by the reactive power generated by the line capacitance and the remaining reactive power demand is met by the reactive power flow through the line from sending end to the receiving end.

Shunt Compensation (continued…)

- The device that is connected in parallel with the transmission line is called the shunt compensator. A shunt compensator is always connected in the middle of the transmission line. It can be provided by either a current source, voltage source or a capacitor.
- An ideal shunt compensator provides the reactive power to the system.
- Shunt-connected reactors are used to reduce the line over-voltages by consuming the reactive power, while shunt-connected capacitors are used to maintain the voltage levels by compensating the reactive power to transmission line.

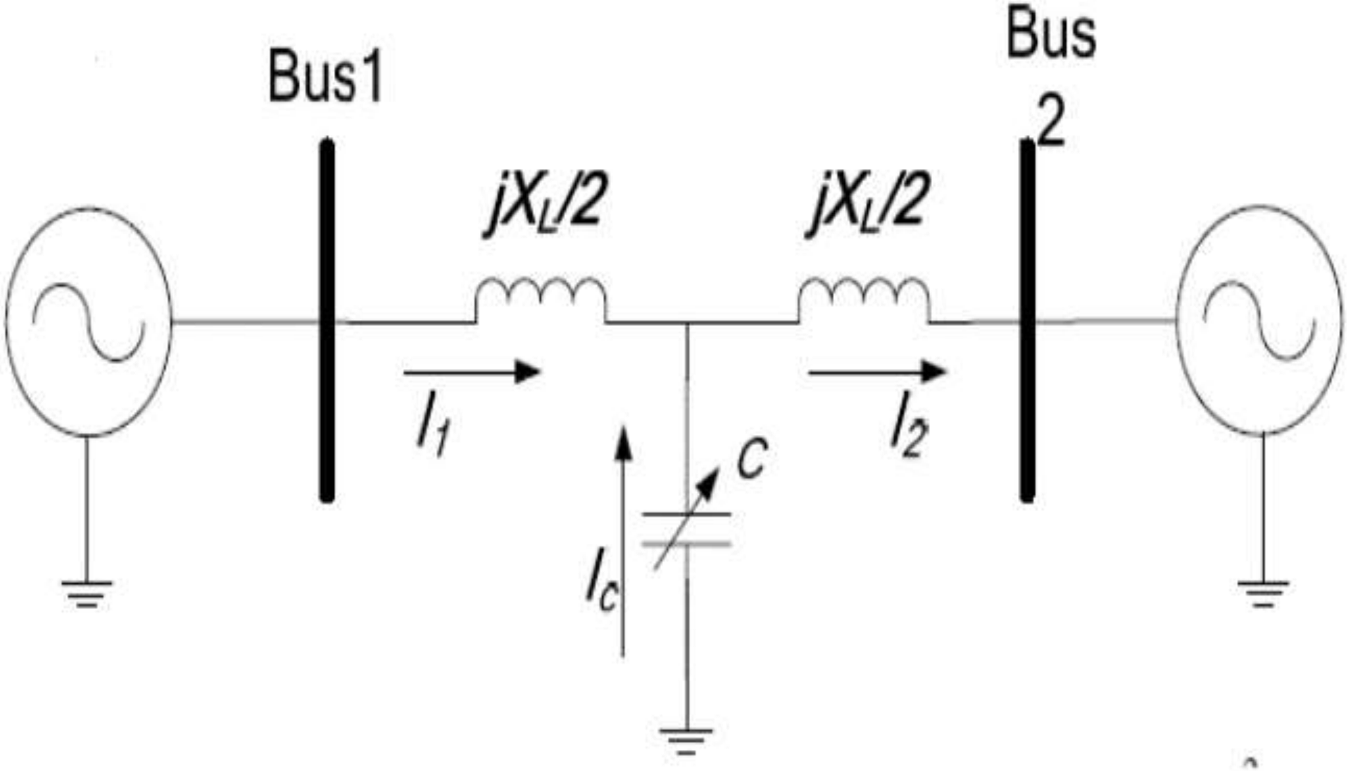
Shunt Compensation (continued…)

- If $X_C = 1/\omega C$ be the reactance of the shunt capacitor then the reactive power generated of leading VAr supplied by the capacitor:

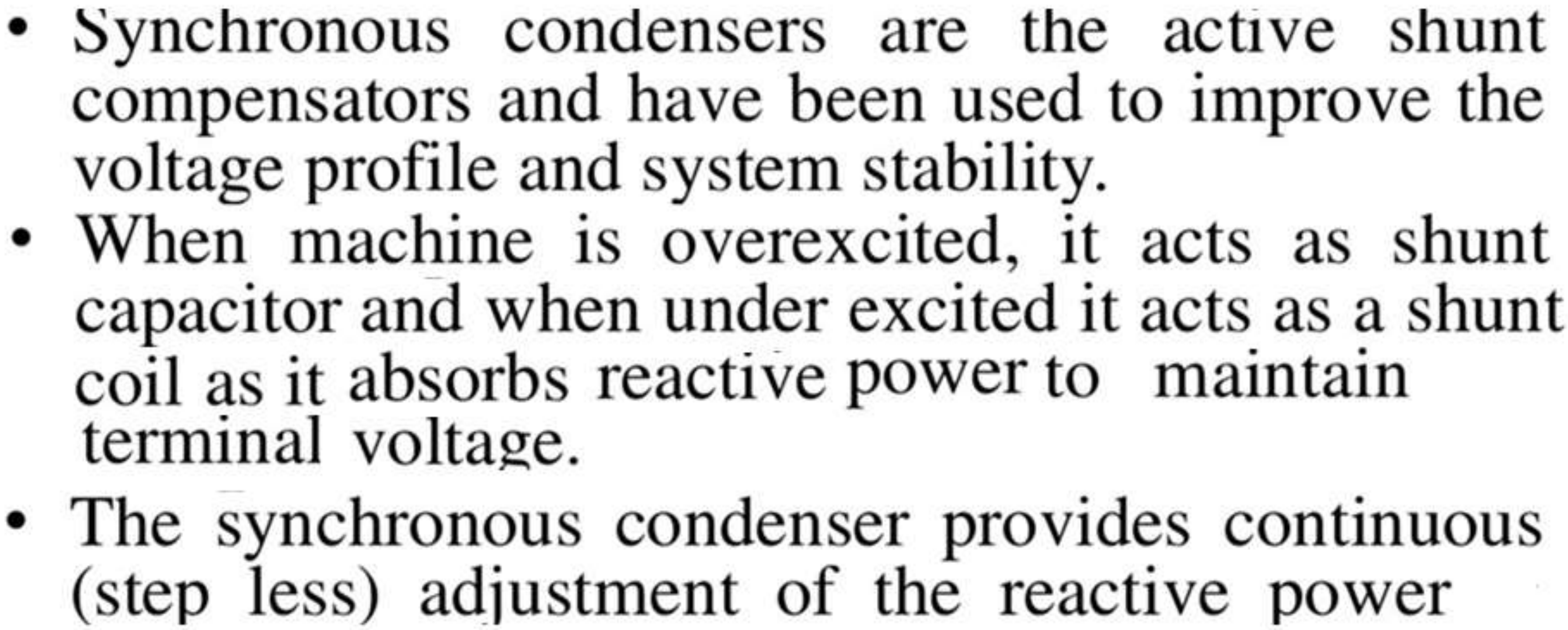
$$Q_C = \frac{|V_2|^2}{X_C} = |V_2|^2 \omega C$$

- where, $|V_2|$ is the magnitude of receiving end voltage.

Transmission line with shunt compensation



Active compensation(Synchronous condenser method)



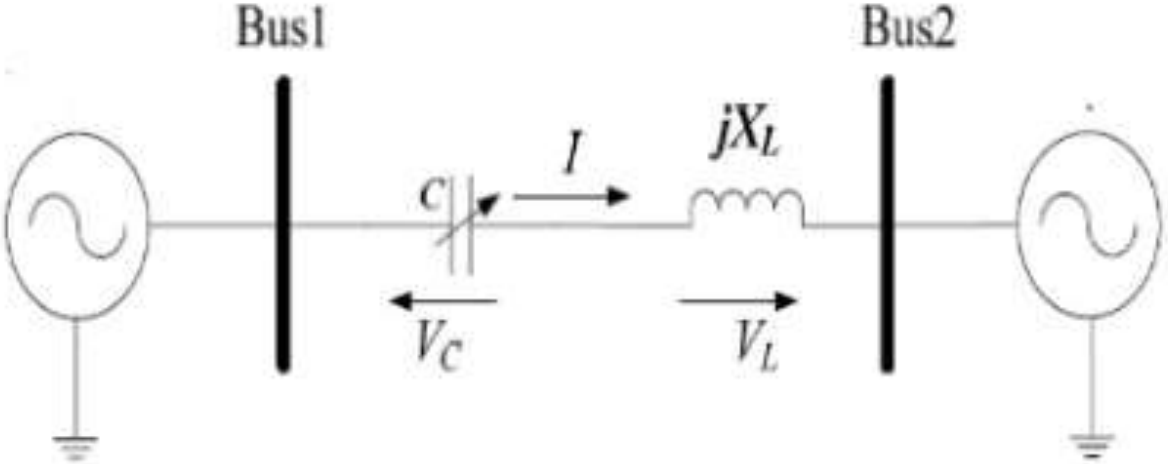
- Synchronous condensers are the active shunt compensators and have been used to improve the voltage profile and system stability.
- When machine is overexcited, it acts as shunt capacitor and when under excited it acts as a shunt coil as it absorbs reactive power to maintain terminal voltage.
- The synchronous condenser provides continuous (step less) adjustment of the reactive power

5. SERIES COMPENSATION

Series compensation is basically a powerful tool to improve the performance of EHV lines.

- When a device is connected in series with the transmission line it is called a series compensator. A series compensator can be connected anywhere in the line.
- There are two modes of operation – capacitive mode of operation and inductive mode of operation.
- A simplified model of a transmission system with series compensation is shown in Figure .

Transmission line with series compensation



Increase in transmission capacity

– The power transfer capacity of a line is given by

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

where, E is sending end voltage

V is receiving end voltage

X is reactance of line

δ is phase angle between E and V

Flexible AC Transmission System (FACTS)

- Using high speed thyristors for switching in or out transmission line components such as capacitors, reactors or phase shifting transformer for desirable performance of the systems.
- Power transfer between two systems interconnected through a tie-line is given as

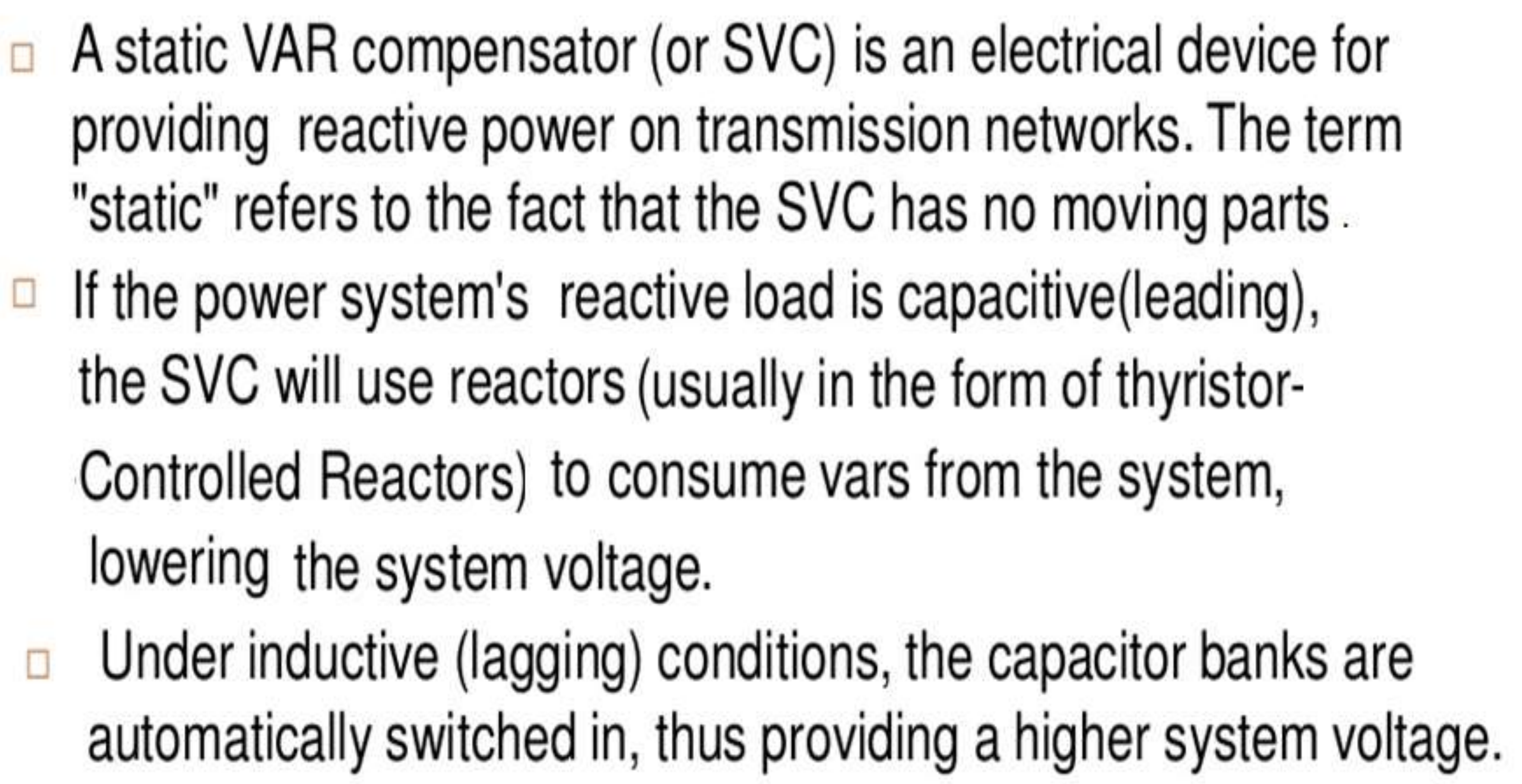
$$P = \frac{E.V}{X}\sin\delta$$

- The FACTS devices can be used to control one or more of voltages at the two ends, the reactance of the tie-line and the difference of the voltage angles at the two ends.

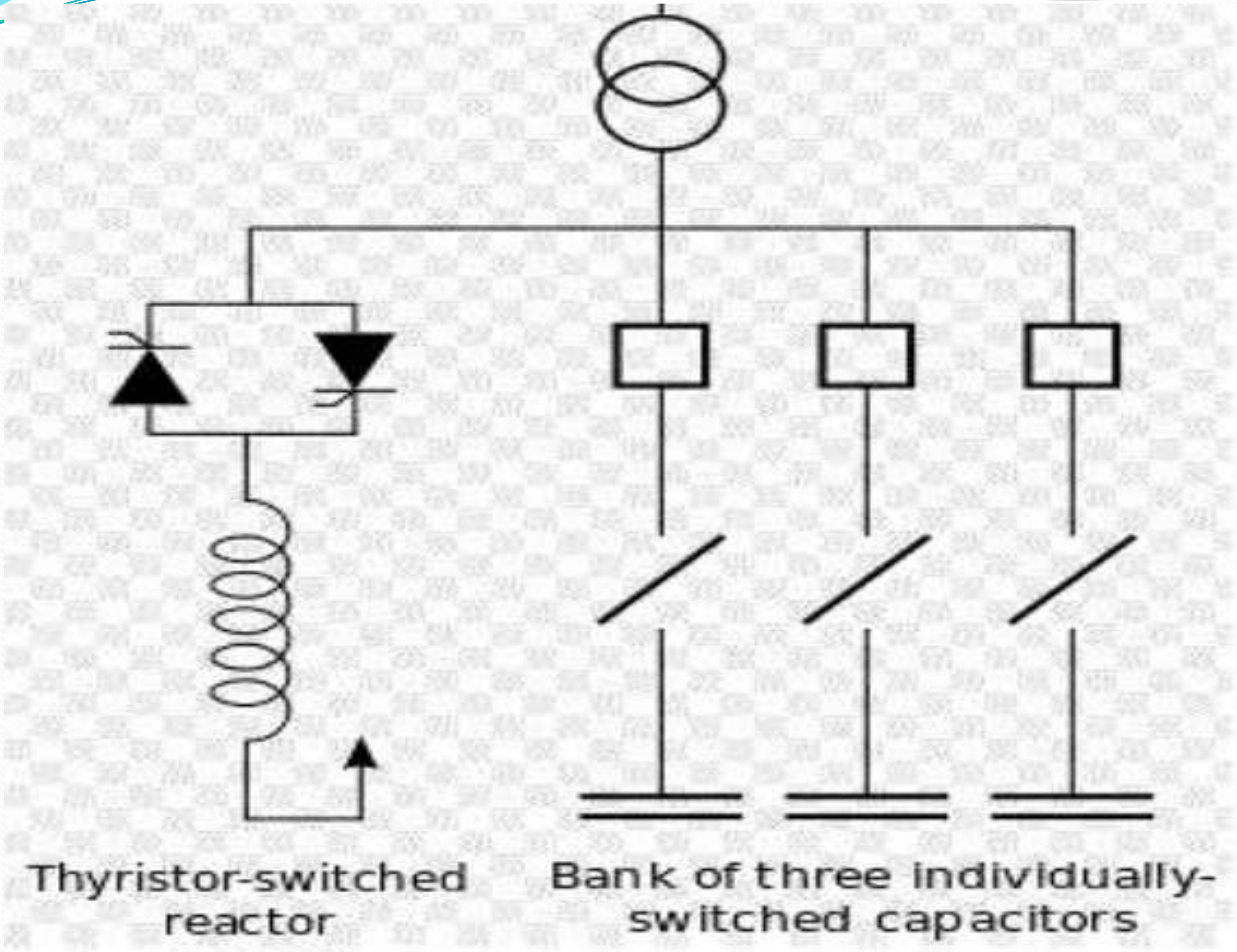
FACTS Devices

- The various devices used are
  - Static VAr compensator (SVC)
  - Static Condensors (STATCON)
  - Advanced Thyristor Controlled Series Compensation (ATCSC)
  - Thyristor Controlled Phase Shifting Transformer

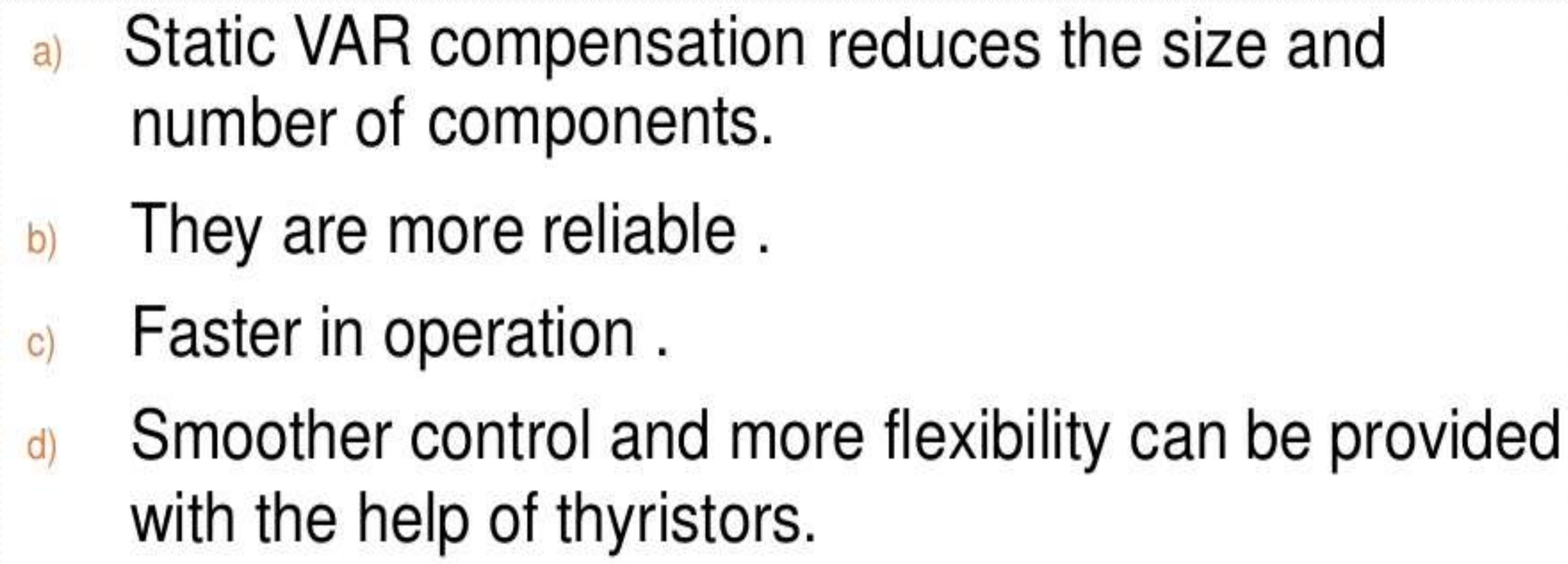
6. STATIC VAR COMPENSATOR(SVC)



- A static VAR compensator (or SVC) is an electrical device for providing reactive power on transmission networks. The term "static" refers to the fact that the SVC has no moving parts .
- If the power system's reactive load is capacitive(leading), the SVC will use reactors (usually in the form of thyristor-Controlled Reactors) to consume vars from the system, lowering the system voltage.
- Under inductive (lagging) conditions, the capacitor banks are automatically switched in, thus providing a higher system voltage.


Thyristor-switched reactor
Bank of three individually-switched capacitors

ADVANTAGES SVC



a) Static VAR compensation reduces the size and number of components.

b) They are more reliable .

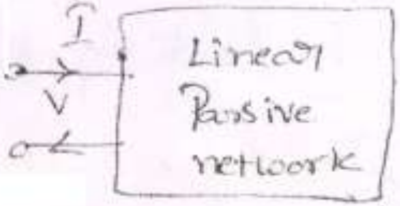
c) Faster in operation .

d) Smoother control and more flexibility can be provided with the help of thyristors.

Power in AC circuit

Consider the Single Phase ckt of fig.

Let $V = |V| \angle \theta_1$ and $I = |I| \angle \theta_2$

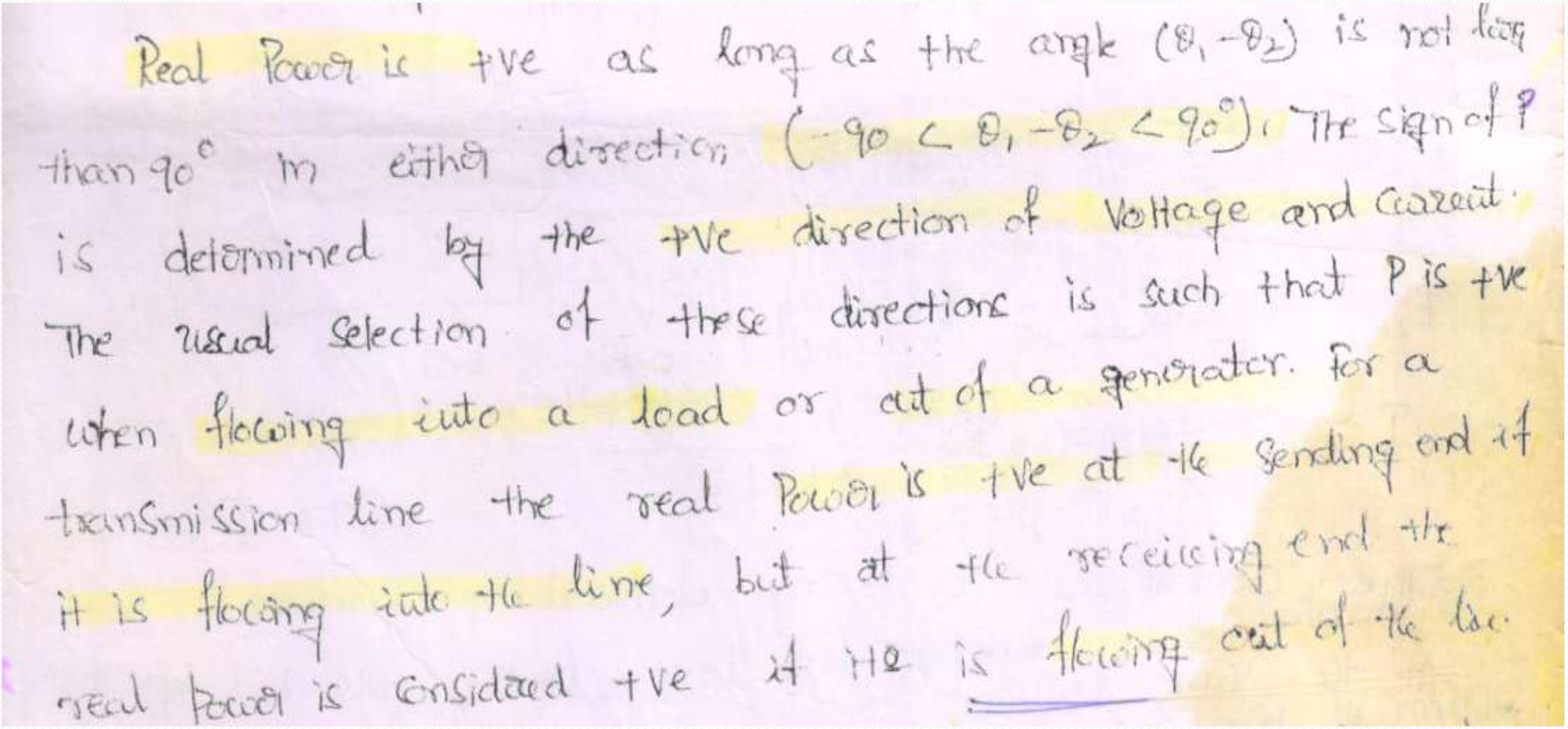


The complex Power S flowing into the network is defined as

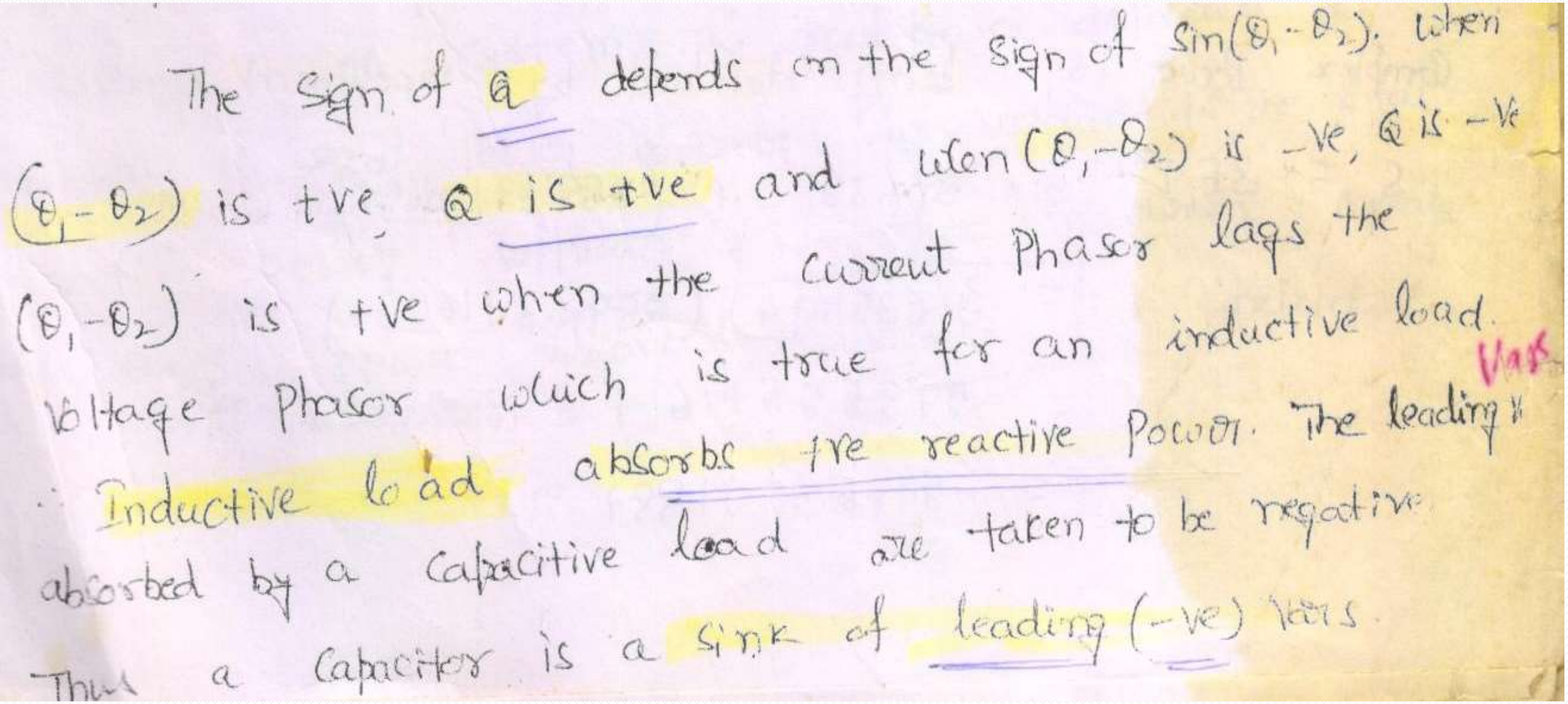
$$S = VI^* = |V|\,|I| \angle \theta_1 - \theta_2$$

$$= |V|\,|I| \cos(\theta_1 - \theta_2) + j\,|V|\,|I| \sin(\theta_1 - \theta_2)$$

The Complex Power S has two Components. The first component $|V|\,|I| \cos(\theta_1 - \theta_2)$ is known as real (active) Power P and is measu in watts. The Second component $|V|\,|I| \sin(\theta_1 - \theta_2)$ is known as reactive Power Q and is measured in vars. The angle $\angle \theta_1 - \theta_2$ is the Phase angle between Voltage and curt.



Real Power is +ve as long as the angle $(\theta_1 - \theta_2)$ is not larg than 90° in either direction $(-90 < \theta_1 - \theta_2 < 90°)$. The sign of P is determined by the +ve direction of Voltage and current. The usual selection of these directions is such that P is +ve when flowing into a load or out of a generator. For a transmission line the real Power is +ve at the sending end if it is flowing into the line, but at the receiving end the real Power is considered +ve if it is flowing out of the line.

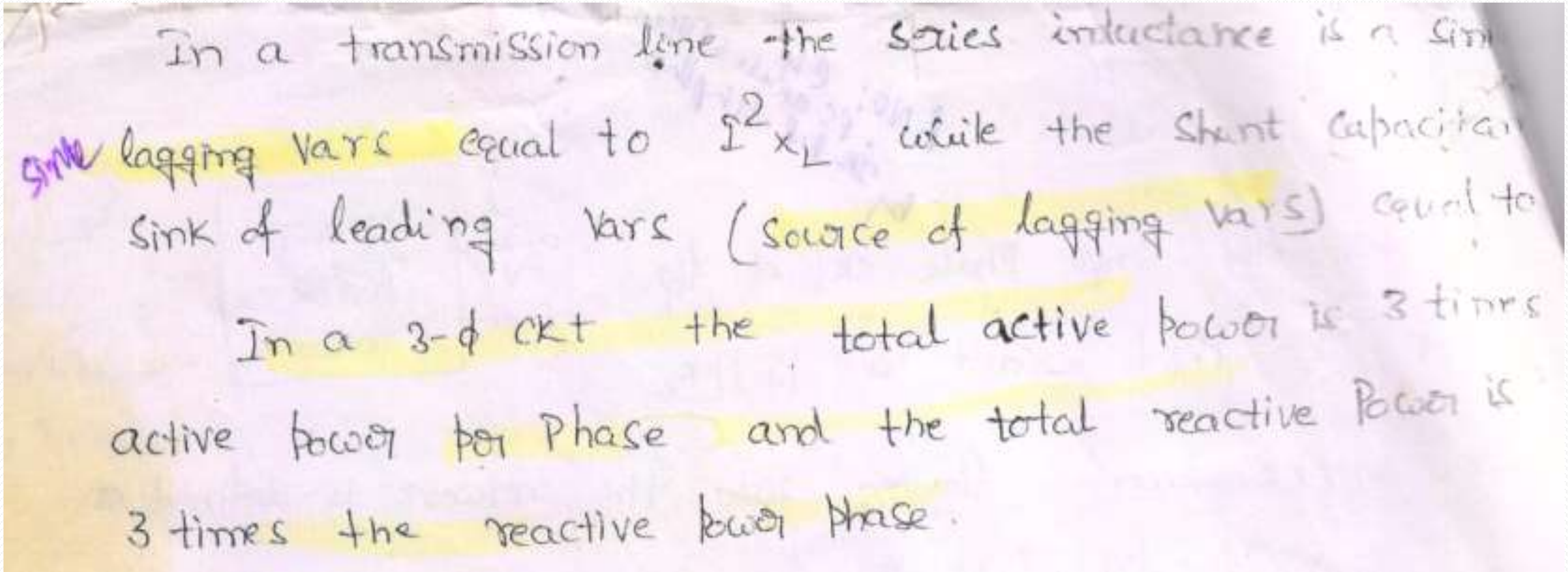


The Sign of Q depends on the sign of $\sin(\theta_1 - \theta_2)$. When $(\theta_1 - \theta_2)$ is +ve Q is +ve and when $(\theta_1 - \theta_2)$ is -ve, Q is -ve

$(\theta_1 - \theta_2)$ is +ve when the current Phasor lags the Voltage phasor which is true for an inductive load.

∴ Inductive load absorbs +ve reactive Power. The leading Vars absorbed by a Capacitive load are taken to be negative

Thus a Capacitor is a sink of leading (-ve) Vars.



In a transmission line the series inductance is a Sin

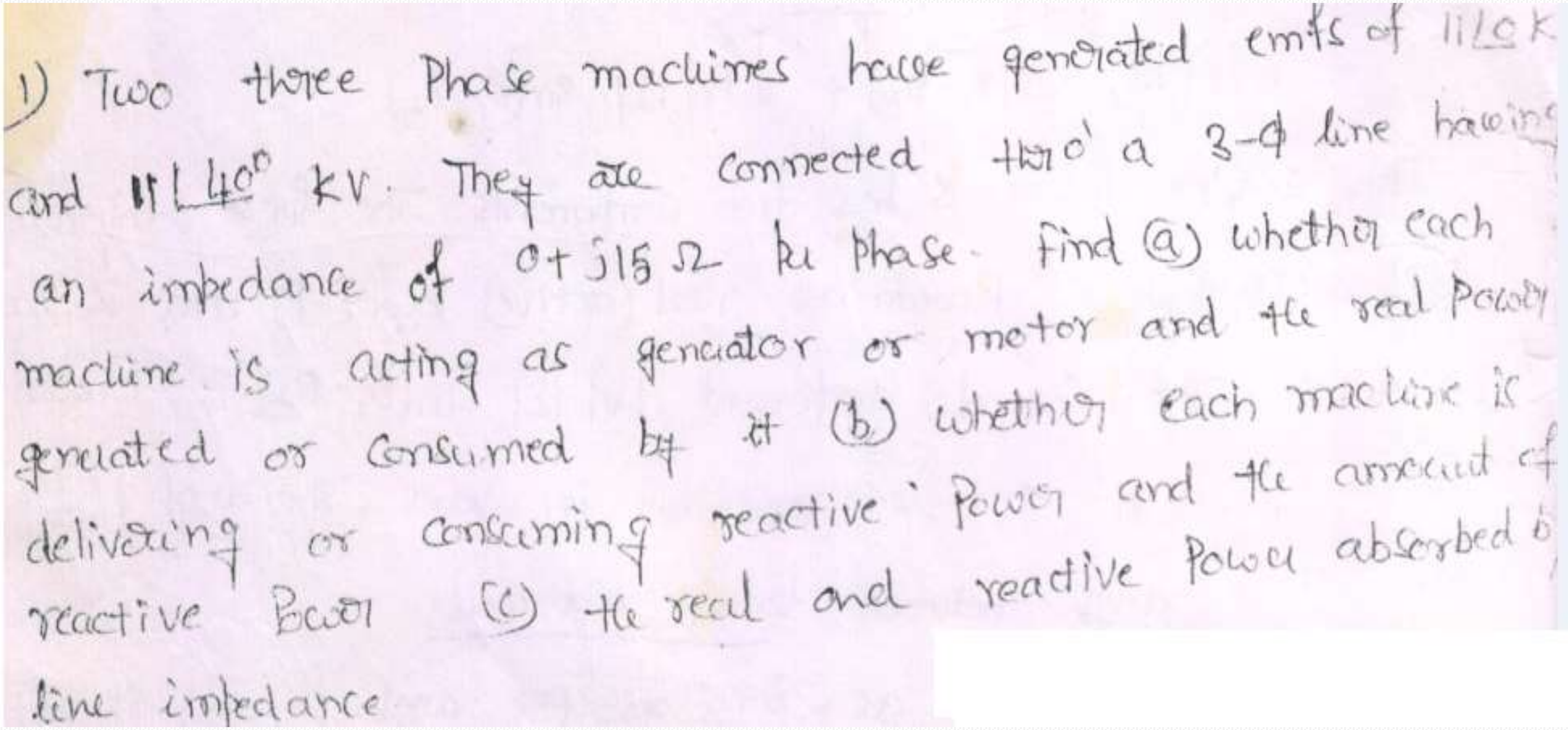
Sink lagging vars equal to $I^2 X_L$ while the Shunt Capacita

sink of leading vars (source of lagging vars) equal to

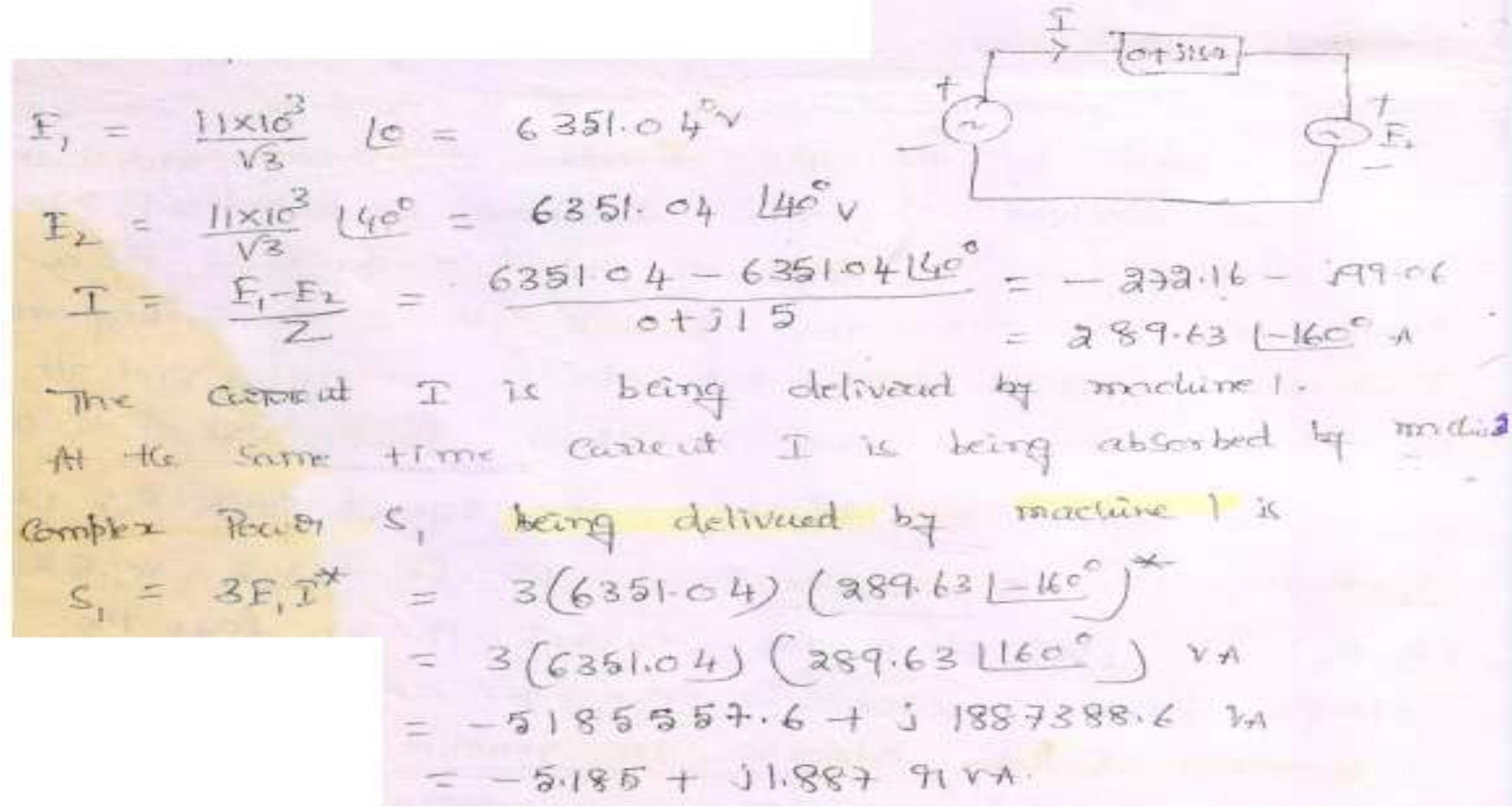
In a 3-ϕ ckt the total active power is 3 times

active power per Phase and the total reactive Power is

3 times the reactive power phase.



1) Two three Phase machines have generated emfs of $11\angle 0$ kV and $11\angle 40^\circ$ kV. They are connected thro' a 3-ϕ line having an impedance of $0+j15\ \Omega$ per Phase. Find (a) whether each machine is acting as generator or motor and the real Power generated or consumed by it (b) whether each machine is delivering or consuming reactive Power and the amount of reactive Power (c) the real and reactive Power absorbed by line impedance



$E_1 = \frac{11\times10^3}{\sqrt{3}} \angle 0 = 6351.04 \, V$

$E_2 = \frac{11\times10^3}{\sqrt{3}} \angle 40^\circ = 6351.04 \angle 40^\circ \, V$

$I = \frac{E_1 - E_2}{Z} = \frac{6351.04 - 6351.04\angle 40^\circ}{0+j15} = -272.16 - j99.06$

$= 289.63 \angle -160^\circ \, A$

The current I is being delivered by machine 1.

At the same time current I is being absorbed by machi 2

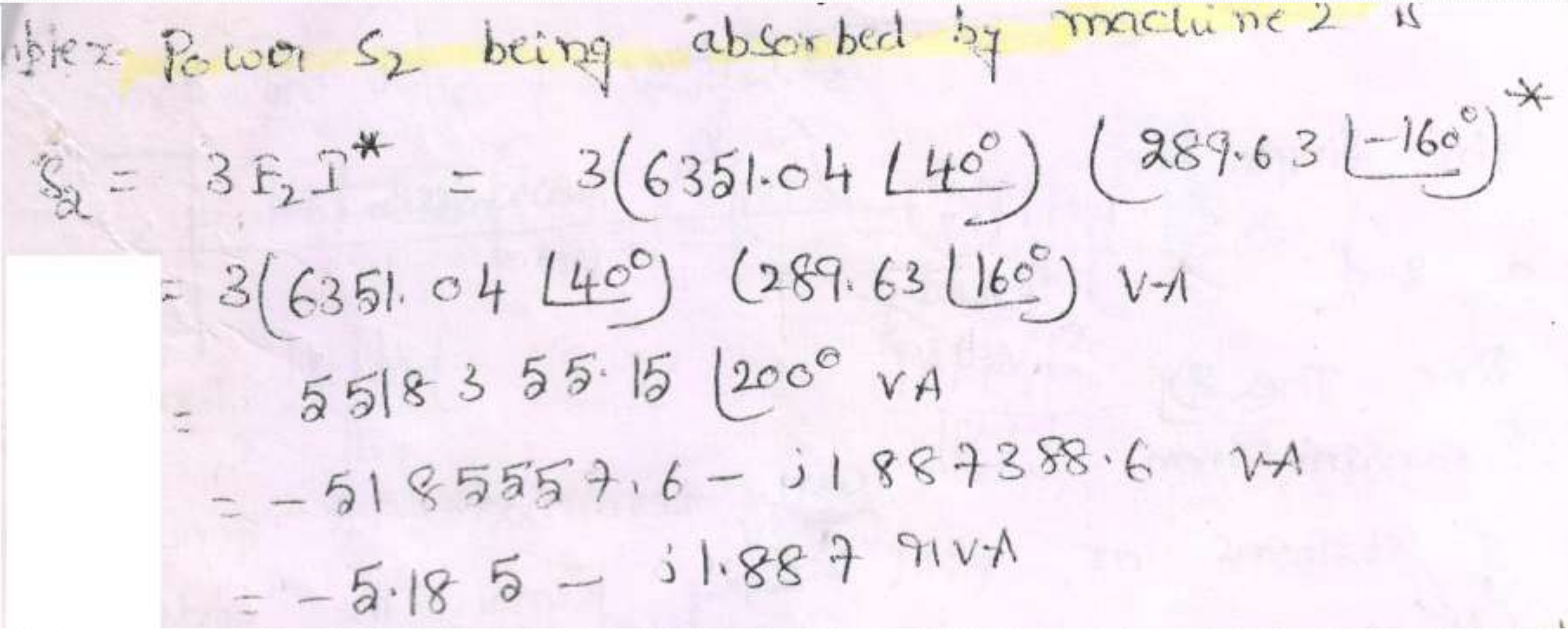
Complex Power S_1 being delivered by machine 1 is

$S_1 = 3E_1 I^* = 3(6351.04)(289.63 \angle -160^\circ)^*$

$= 3(6351.04)(289.63 \angle 160^\circ) \, VA$

$= -5185557.6 + j1887388.6 \, VA$

$= -5.185 + j1.887 \, MVA$



ple x: Power S_2 being absorbed by machine 2 is

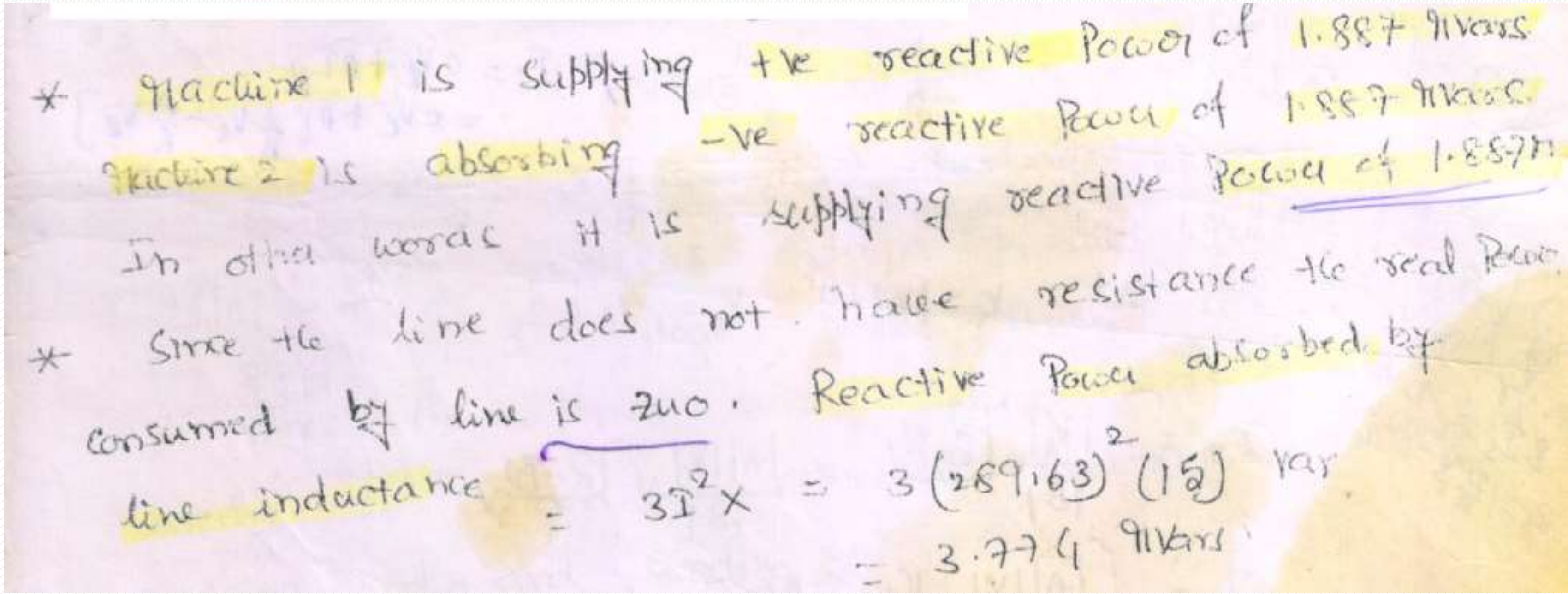
$$S_2 = 3E_2I^* = 3(6351.04\angle 40^\circ)(289.63\angle -160^\circ)^*$$

$$= 3(6351.04\angle 40^\circ)(289.63\angle 160^\circ) \text{ V-A}$$

$$= 5518355.15\angle 200^\circ \text{ VA}$$

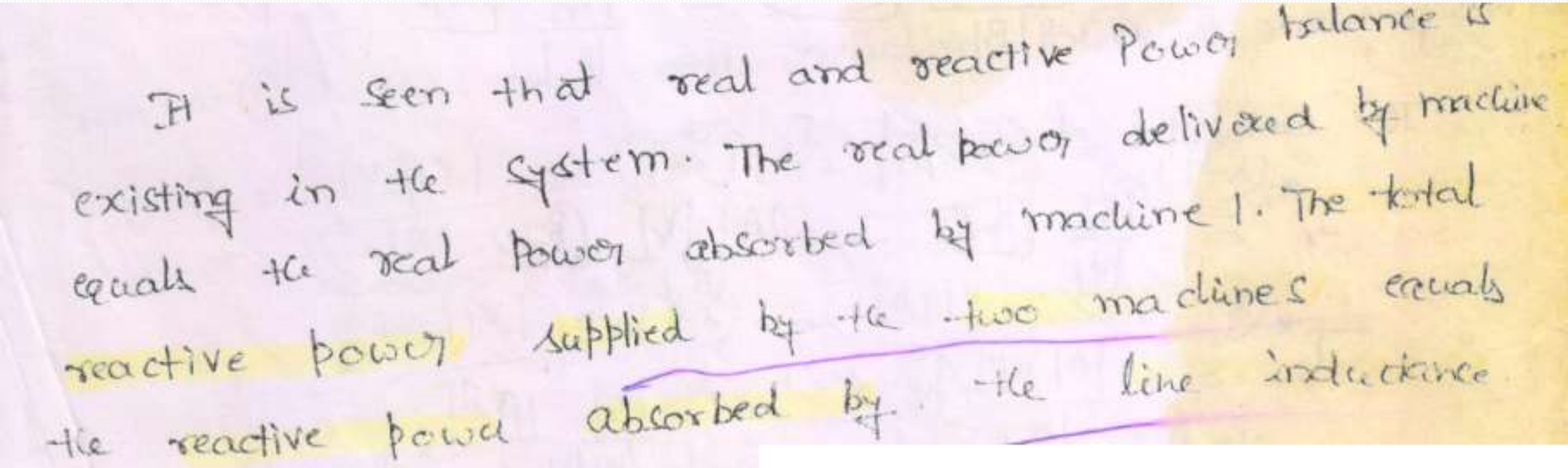
$$= -5185557.6 - j1887388.6 \text{ V-A}$$

$$= -5.185 - j1.887 \text{ MV-A}$$



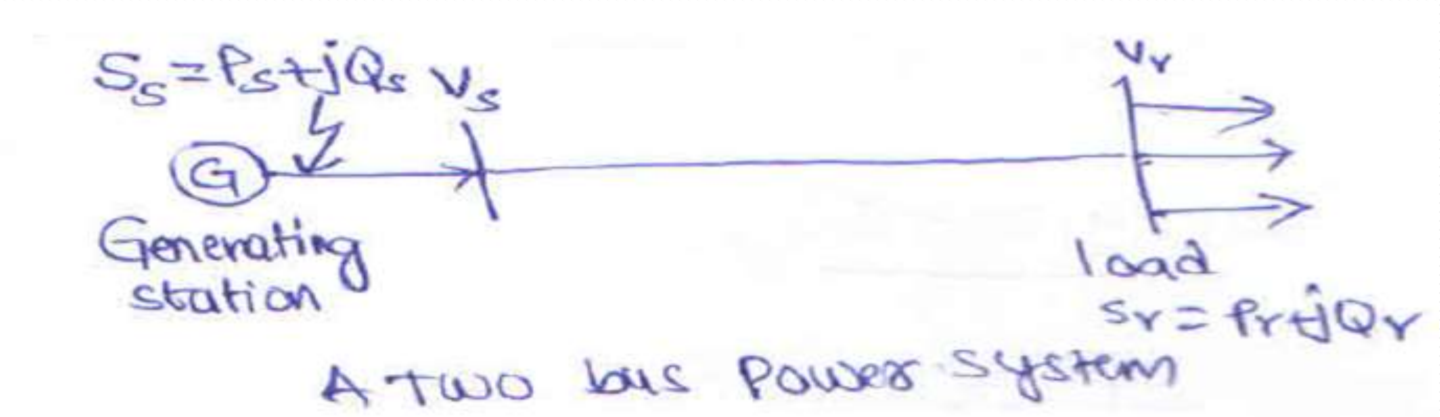
* Machine 1 is supplying +ve reactive Power of 1.887 Mvars.
Machine 2 is absorbing −ve reactive Power of 1.887 Mvars.
In other words it is supplying reactive Power of 1.887M

* Since the line does not have resistance the real Power
consumed by line is zero. Reactive Power absorbed by
line inductance $= 3I^2X = 3(289.63)^2(15)$ var
$= 3.774$ Mvars



It is seen that real and reactive Power balance is existing in the system. The real power delivered by machine equals the real power absorbed by machine 1. The total reactive power supplied by the two machines equals the reactive power absorbed by the line inductance

Power formulae for transmission line



A two bus Power System

Figure shows the single line diagram of a 3-phase transmission line. The ends of a transmission line can terminate at generating stations, grid stations or grid supply points. The ends of transmission lines are designated as busses. The concept of a bus in a one line diagram is essentially the same as that of a node in a circuit diagram. The system in Fig. is a two bus system having the sending end bus which is fed by the generator and receiving end bus which feeds the load.

$$V_S = AV_R + BI_R \quad \text{--}(1)$$

$$I_S = CV_R + DI_R \quad \text{--}(2)$$

$I_r = \frac{1}{B}V_S - \frac{A}{B}V_r$ (from eq1)

$I_S = \frac{D}{B}V_S - \frac{1}{B}V_r = \frac{A}{B}V_S - \frac{1}{B}V_r$ (Sub I_r in eq2)

Let $V_r = |V_r|\angle 0$; $V_s = V_s\angle\delta$, $D = A = |A|\angle\alpha$, $B = |B|\angle\beta$

then $I_r = \frac{|V_s|}{B}\angle(\delta-\beta) - \frac{|A||V_r|}{|B|}\angle(\alpha-\beta)$

$$I_s = \frac{|A|\,|V_s|}{|B|}\angle(\alpha+\delta-\beta) - \frac{|V_r|}{|B|}\angle-\beta$$

consugate of I_r & I_s

$$I_r^* = \frac{|V_s|}{|B|}\angle(\beta-\delta) - \frac{|A||V_r|}{|B|}\angle(\beta-\alpha)$$ --(3)

$$I_s^* = \frac{|A|\,|V_s|}{|B|}\angle\beta-\alpha-\delta - \frac{|V_r|}{|B|}\angle\beta$$ --(4)

The complex power per phase at the receiving end and sending end are

$$S_r = P_r + jQ_r = V_r I_r^*$$ (sub. eq3)

$$= |V_r|\angle 0\left[\frac{|V_s|}{|B|}\angle(\beta-\delta) - \frac{|A|\,|V_r|}{|B|}\angle(\beta-\alpha)\right]$$

$$S_r = \frac{|V_s|\,|V_r|}{|B|}\angle(\beta-\delta) - \frac{|A||V_r|^2}{|B|}\angle(\beta-\alpha)$$

The real and reactive power at receiving end are

$$\therefore P_R = \frac{V_S V_R}{B}\cos(\beta-\delta) - \frac{AV_R^2}{B}\cos(\beta-\alpha)$$

$$\therefore Q_R = \frac{V_S V_R}{B}\sin(\beta-\delta) - \frac{AV_R^2}{B}\sin(\beta-\alpha)$$

$$S_S = P_S + jQ_S = V_S I_S^* \quad \text{(sub eq4)}$$

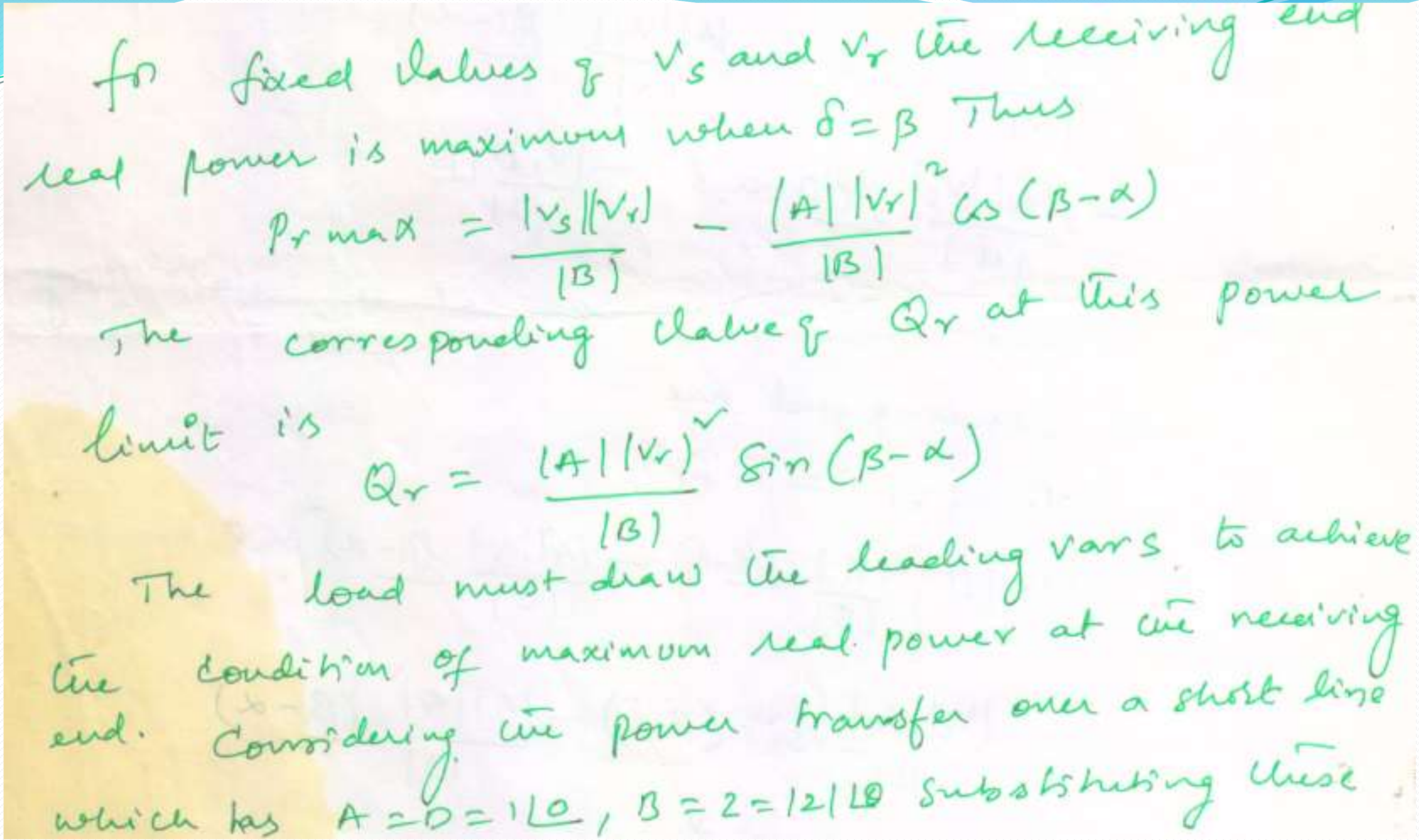
$$= |V_S| \angle \delta \left[\frac{|A|\,|V_S|}{|B|} \angle(\beta - \alpha - \delta) - \frac{|V_r|}{|B|} \angle \beta \right]$$

$$= \frac{|A|\,|V_S|^2}{|B|} \angle(\beta - \alpha) - \frac{|V_r|\,|V_S|}{|B|} \angle(\beta + \delta)$$

The real and reactive power at sending end are

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

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



for fixed values of V_s and V_r the receiving end real power is maximum when $\delta = \beta$ Thus

$$P_{r\,max} = \frac{|V_s||V_r|}{|B|} - \frac{|A||V_r|^2}{|B|}\cos(\beta-\alpha)$$

The corresponding value of Q_r at this power limit is

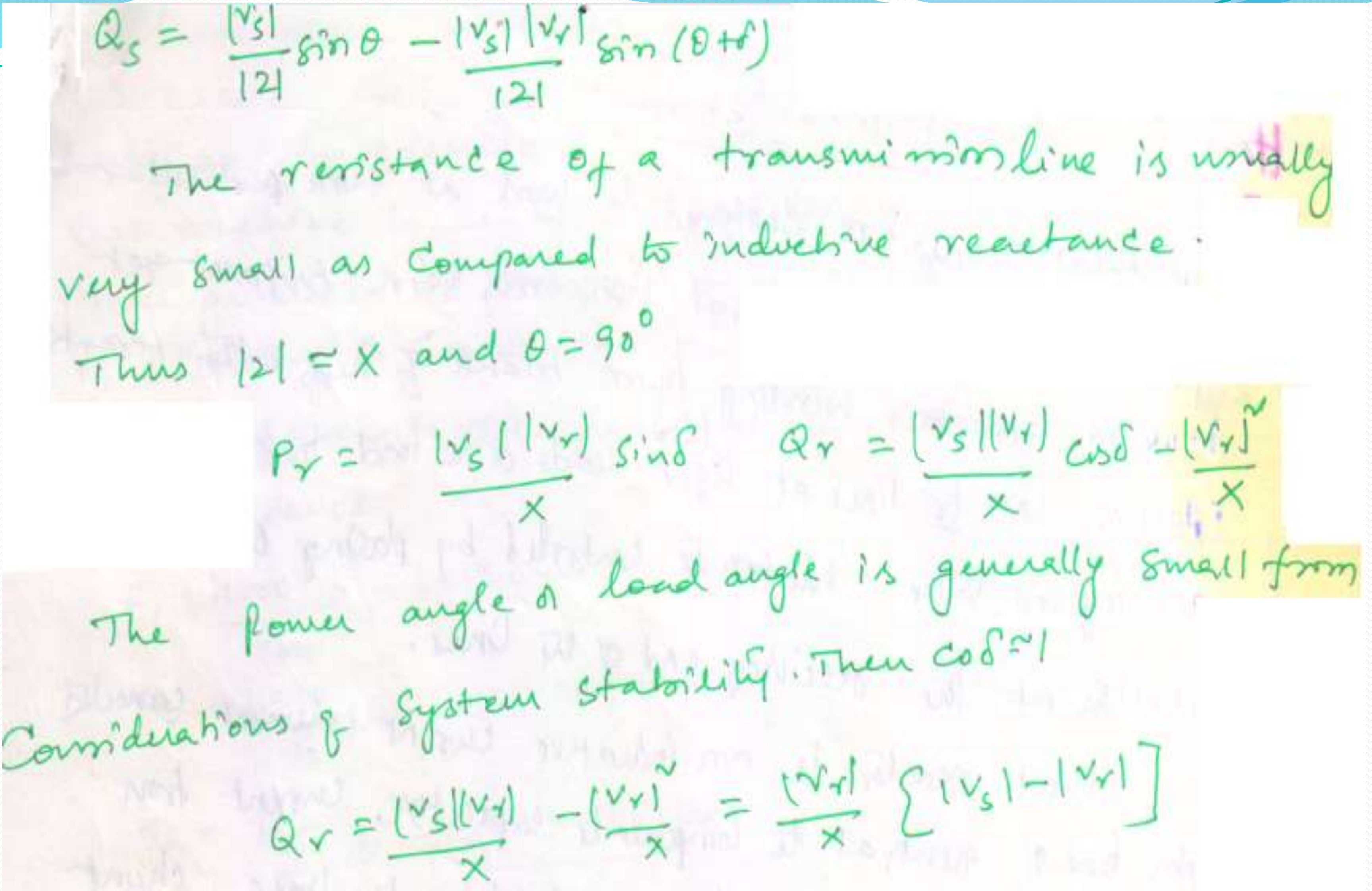
$$Q_r = \frac{|A||V_r|^2}{|B|}\sin(\beta-\alpha)$$

The load must draw the leading vars to achieve the condition of maximum real power at the receiving end. Considering the power transfer over a short line which has $A = D = 1\angle 0$, $B = Z = |Z|\angle\theta$ substituting these

$$P_r = \frac{|V_s||V_r|}{|Z|}\cos(\theta-\delta) - \frac{|V_r|^2}{|Z|}\cos\theta$$

$$Q_r = \frac{|V_s||V_r|}{|Z|}\sin(\theta-\delta) - \frac{|V_r|^2}{|Z|}\sin\theta$$

$$P_s = \frac{|V_s|^2}{|Z|}\cos\theta - \frac{|V_s||V_r|}{Z}\cos(\theta+\delta)$$



$$Q_s = \frac{|V_s|}{|Z|}\sin\theta - \frac{|V_s||V_r|}{|Z|}\sin(\theta+\delta)$$

The resistance of a transmission line is usually very small as compared to inductive reactance.

Thus $|Z| \approx X$ and $\theta = 90^\circ$

$$P_r = \frac{|V_s||V_r|}{X}\sin\delta \qquad Q_r = \frac{|V_s||V_r|}{X}\cos\delta - \frac{|V_r|^2}{X}$$

The power angle or load angle is generally small from considerations of system stability. Then $\cos\delta \approx 1$

$$Q_r = \frac{|V_s||V_r|}{X} - \frac{|V_r|^2}{X} = \frac{|V_r|}{X}\left[|V_s| - |V_r|\right]$$

POWER SYSTEMS-II

UNIT-I I: REACTIVE POWER & VOLTAGE CONTROL

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Power circle diagram

- The performance of transmission lines can be studied either by analytical methods or by graphical methods.
- Purely analytical methods sometimes involve tedious calculations.
- Power circle diagram provide a convenient graphical method for studying the performance of transmission line under the condition of varying load.
- Circle diagrams are easy to construct and use
- Their accuracy is fairly high .

Receiving end Power circle diagram

- 1.For determining the capacitance of phase modifier for certain system conditions
- 2.Given P_R , Q_R , V_R and line constants sending end voltage can be calculated.
- 3.Maximum receiving end power can be calculated.

Receiving end Power circle diagram

The complex power at the receiving and sending ends of a line are given by Eqs. (1&2) which can be re-written as

$$S_r = P_r + j\,Q_r$$

$$= \frac{-|A||V_r|^2}{|B|}\angle(\beta-\alpha) + \frac{|V_s||V_r|}{|B|}\angle(\beta-\delta) \quad \text{--- (1)}$$

$$S_s = P_s + j\,Q_s = \frac{|A||V_s|^2}{|B|}\angle(\beta-\alpha) - \frac{|V_r||V_s|}{|B|}\angle(\beta+\delta) \quad \text{---(2)}$$

Each of the powers is the sum of two phasors. Since the real parts of these phasors represent real power P and the imaginary part represents reactive power Q, it is possible to plot S_r and S_s in the $x-y$ plane whose horizontal and vertical coordinates represent the real and reactive powers respectively.

The transmission lines are usually operated with constant sending and receiving end voltages. Then one component of each power is a constant phasor (i.e., phasor of constant magnitude and phase) while the second component is a phasor of constant magnitude but variable angle. The loci of S_r and S_s are, therefore, circles drawn from the tip of constant phasors as centres.

The centre of the receiving end circle is located at the tip of the phasor $\frac{-|A||V_r|^2}{|B|}\angle(\beta-\alpha)$.

Thus the x-coordinate of the centre is $\frac{-|A||V_r|^2}{|B|}\cos(\beta-\alpha)$. MW and the y-coordinate is $\frac{-|A||V_r|^2}{|B|}\sin(\beta-\alpha)$ Mvar. The radius of the receiving end circle is $\frac{|V_s||V_r|}{|B|}$ MVA.

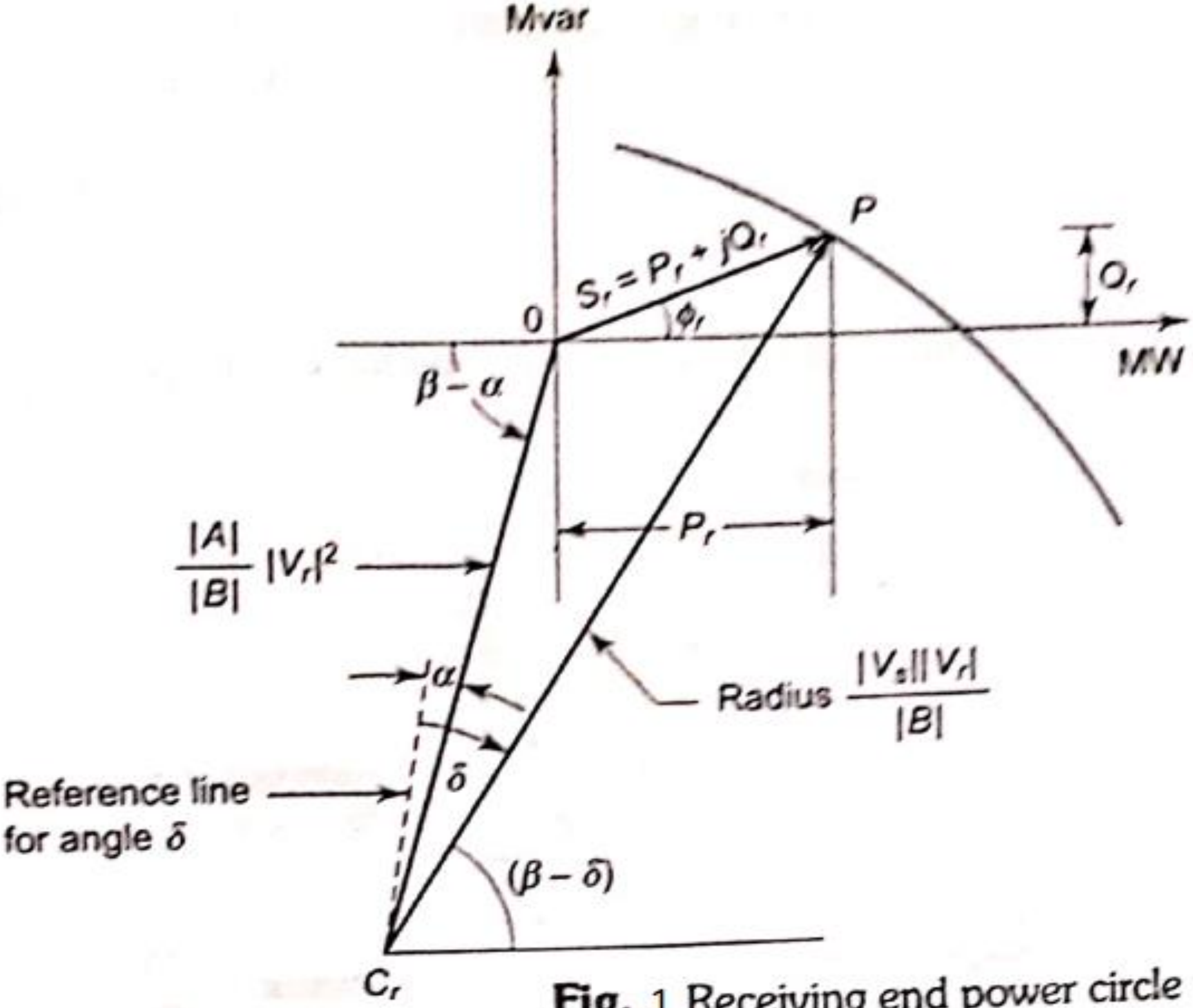
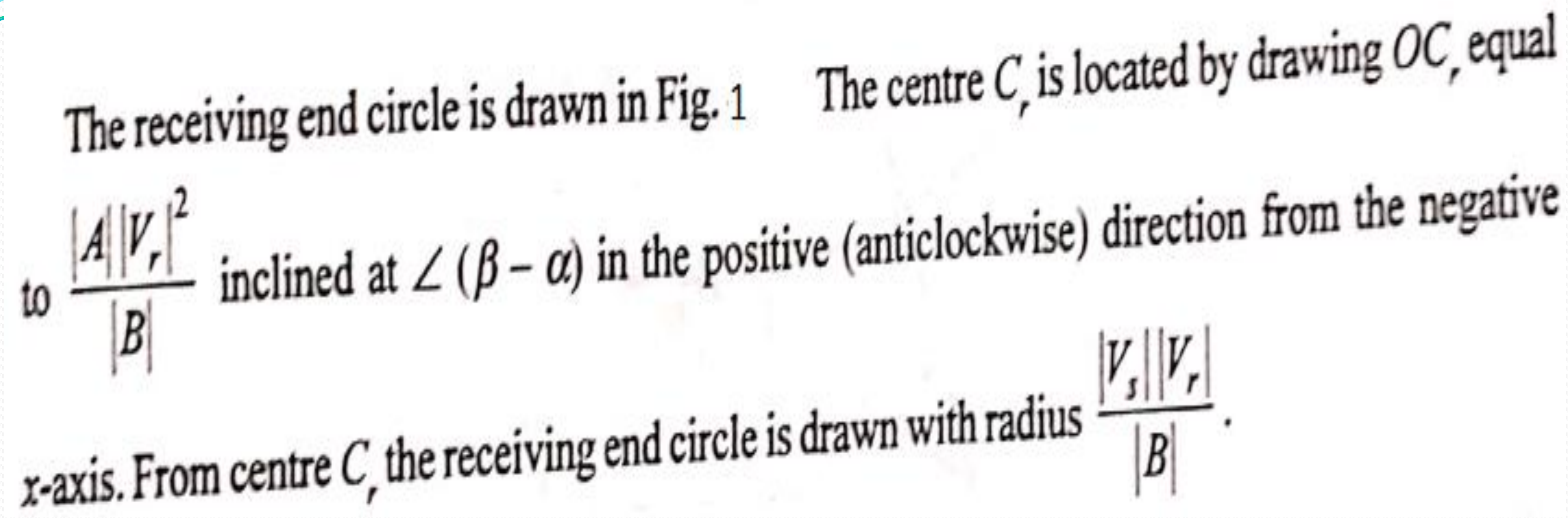


Fig. 1 Receiving end power circle diagram



The receiving end circle is drawn in Fig. 1 The centre C_r is located by drawing OC_r equal to $\dfrac{|A||V_r|^2}{|B|}$ inclined at $\angle(\beta - \alpha)$ in the positive (anticlockwise) direction from the negative x-axis. From centre C_r the receiving end circle is drawn with radius $\dfrac{|V_s||V_r|}{|B|}$.

The operating point P on the circle is located by the amount of real power delivered to the load, i.e., P_r. The corresponding value of Q_r can be read from the diagram. The power angle is the angle between the reference line shown and phasor C_rP. Many other useful information, e.g., capacity of compensation equipment, maximum receiving end power, etc., can also be obtained from the power circle diagram.

The receiving end power circles for constant V_r but varying V_s are concentric circles with C_r as centre and $\frac{|V_r||V_s|}{|B|}$ as radii.

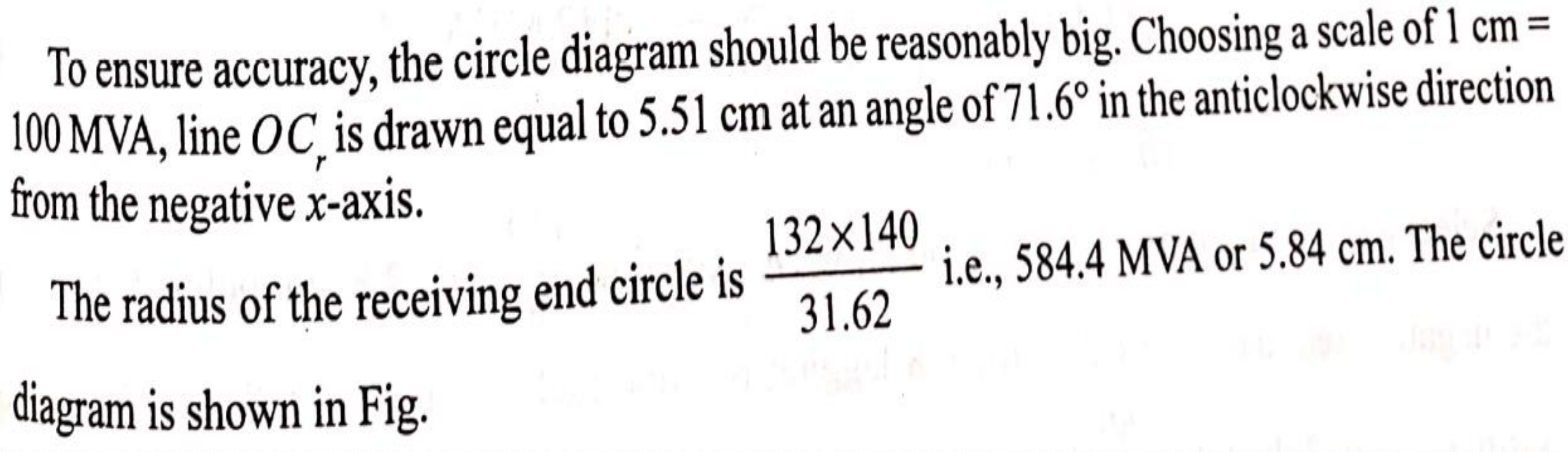
EXAMPLE1

A 3-phase overhead line has a series impedance of $10 + j\,30$ ohms per phase. For receiving and sending end voltages of 132 kV and 140 kV respectively draw the receiving end power circle and determine (a) the maximum real power which the line can supply and the load power factor for drawing this maximum power (b) the capacity of shunt compensation equipment for supplying a load of 150 MVA at 0.8 p.f lagging and power angle for this load condition (c) the capacity of shunt compensation equipment needed to maintain the above voltages under no load condition (d) the unity p.f. load which the line can supply with voltages at above values.

Solution

$$Z = 10 + j\,30 = 31.62 \angle 71.6° \text{ ohms}$$

$$\frac{|V_r|^2}{|Z|} = \frac{132 \times 132}{31.62} = 551 \text{ MVA}$$



To ensure accuracy, the circle diagram should be reasonably big. Choosing a scale of 1 cm = 100 MVA, line OC_r is drawn equal to 5.51 cm at an angle of 71.6° in the anticlockwise direction from the negative x-axis.

The radius of the receiving end circle is $\dfrac{132\times140}{31.62}$ i.e., 584.4 MVA or 5.84 cm. The circle diagram is shown in Fig.

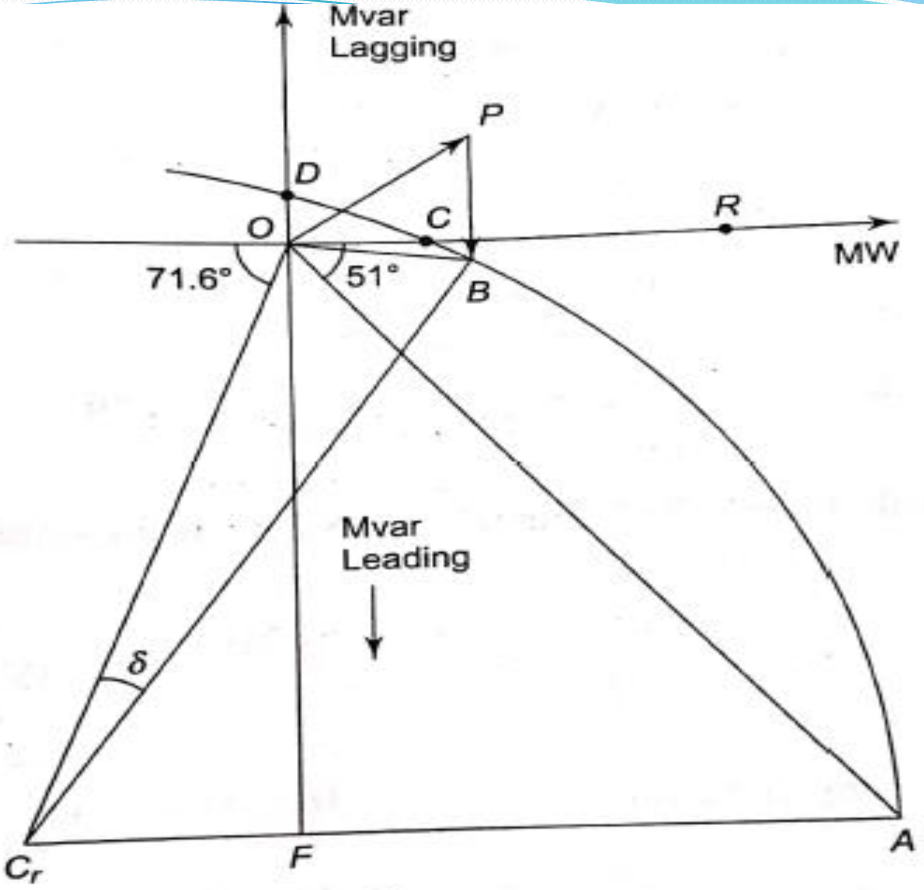
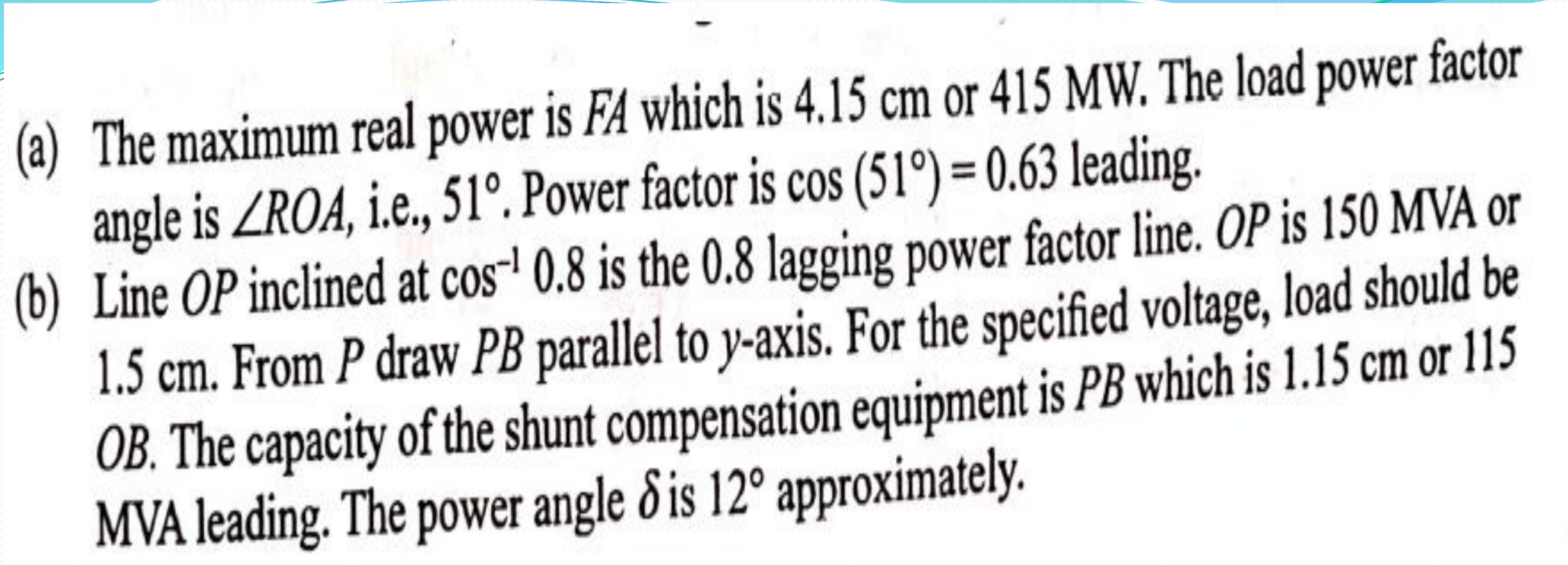
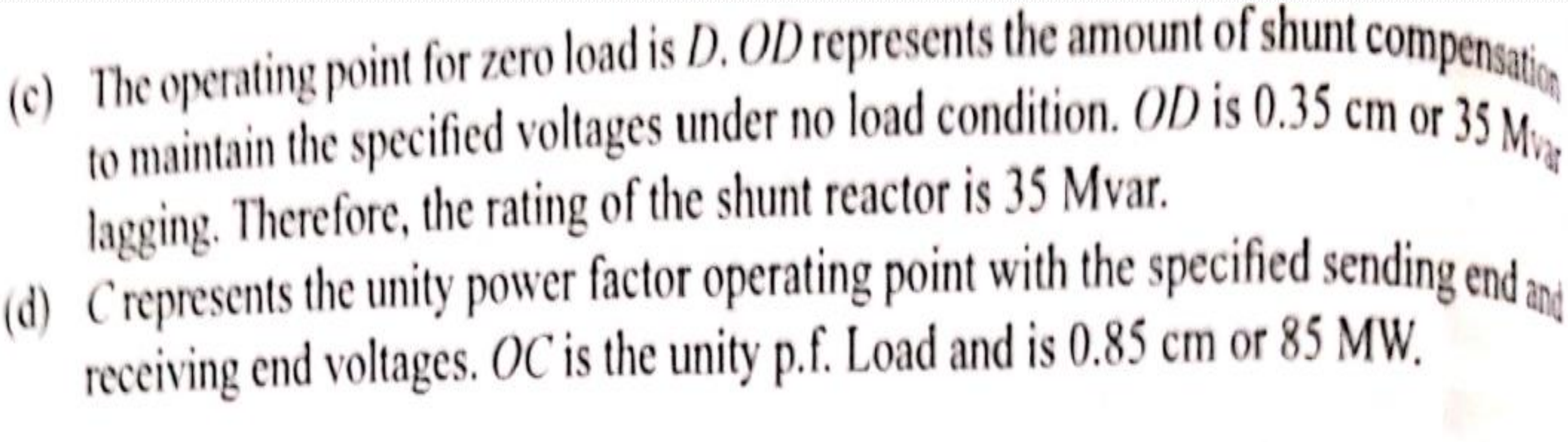


Fig.



(a) The maximum real power is *FA* which is 4.15 cm or 415 MW. The load power factor angle is $\angle ROA$, i.e., 51°. Power factor is $\cos(51°) = 0.63$ leading.

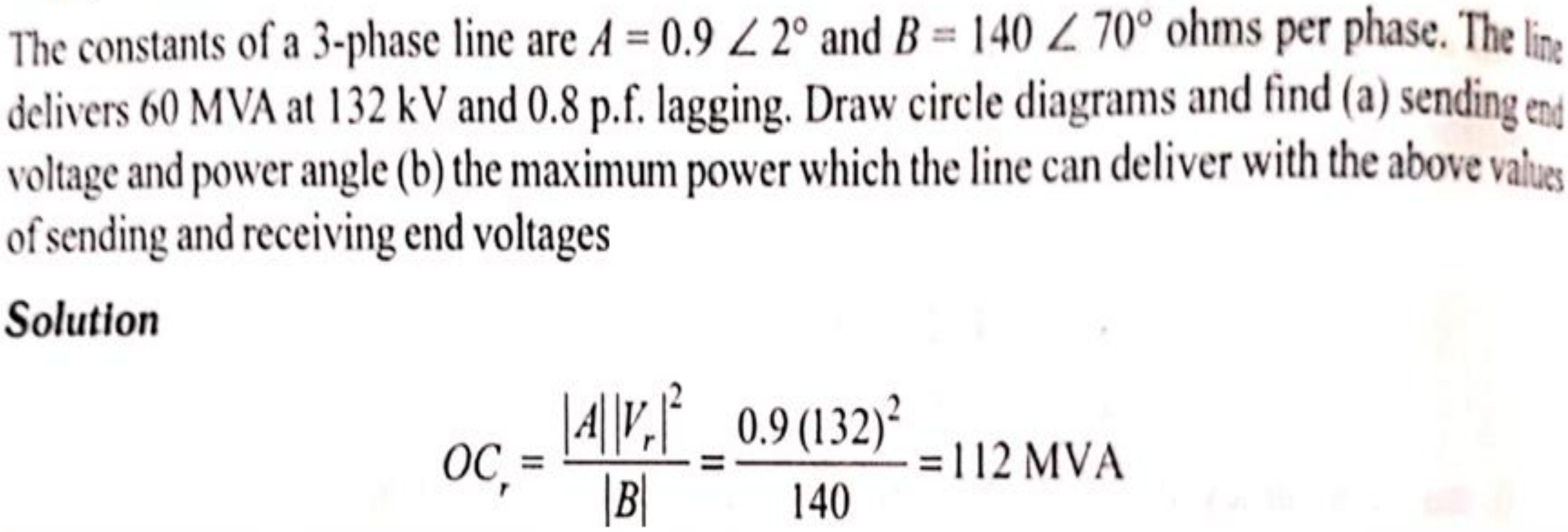
(b) Line *OP* inclined at $\cos^{-1} 0.8$ is the 0.8 lagging power factor line. *OP* is 150 MVA or 1.5 cm. From *P* draw *PB* parallel to *y*-axis. For the specified voltage, load should be *OB*. The capacity of the shunt compensation equipment is *PB* which is 1.15 cm or 115 MVA leading. The power angle δ is 12° approximately.



(c) The operating point for zero load is *D*. *OD* represents the amount of shunt compensation to maintain the specified voltages under no load condition. *OD* is 0.35 cm or 35 Mvar lagging. Therefore, the rating of the shunt reactor is 35 Mvar.

(d) *C* represents the unity power factor operating point with the specified sending end and receiving end voltages. *OC* is the unity p.f. Load and is 0.85 cm or 85 MW.

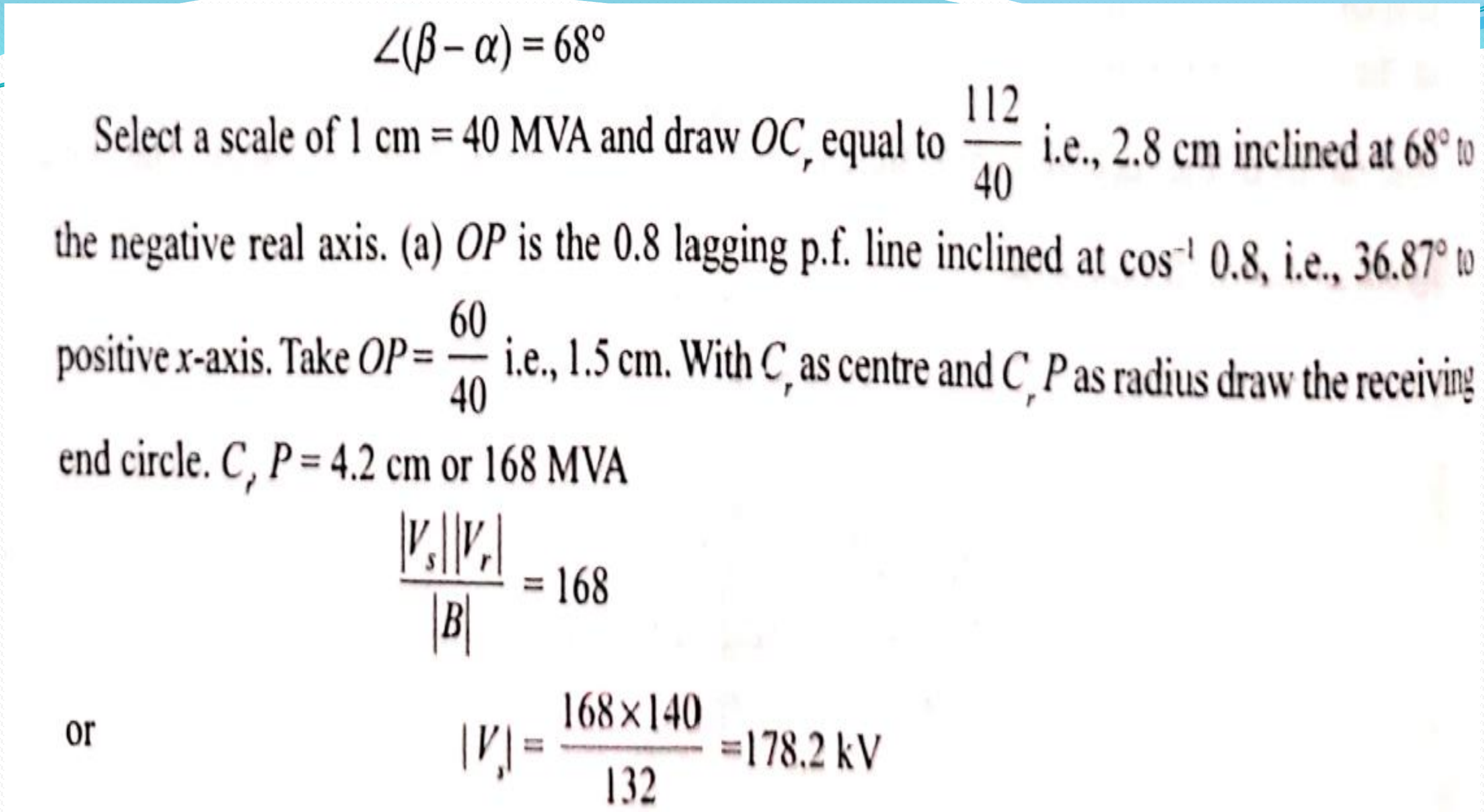
Example2



The constants of a 3-phase line are $A = 0.9 \angle 2°$ and $B = 140 \angle 70°$ ohms per phase. The line delivers 60 MVA at 132 kV and 0.8 p.f. lagging. Draw circle diagrams and find (a) sending end voltage and power angle (b) the maximum power which the line can deliver with the above values of sending and receiving end voltages

Solution

$$OC_r = \frac{|A||V_r|^2}{|B|} = \frac{0.9\,(132)^2}{140} = 112 \text{ MVA}$$



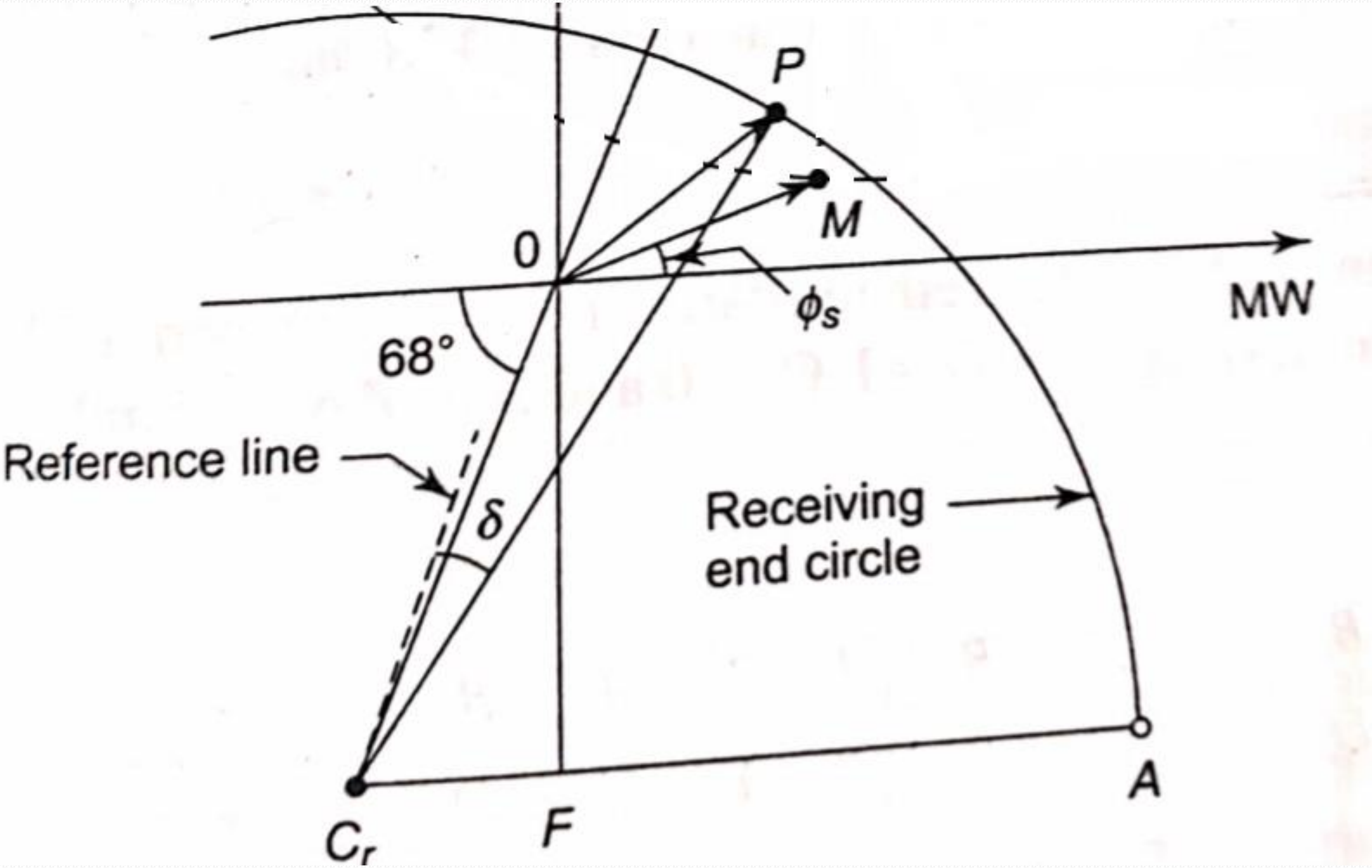
$$\angle(\beta - \alpha) = 68°$$

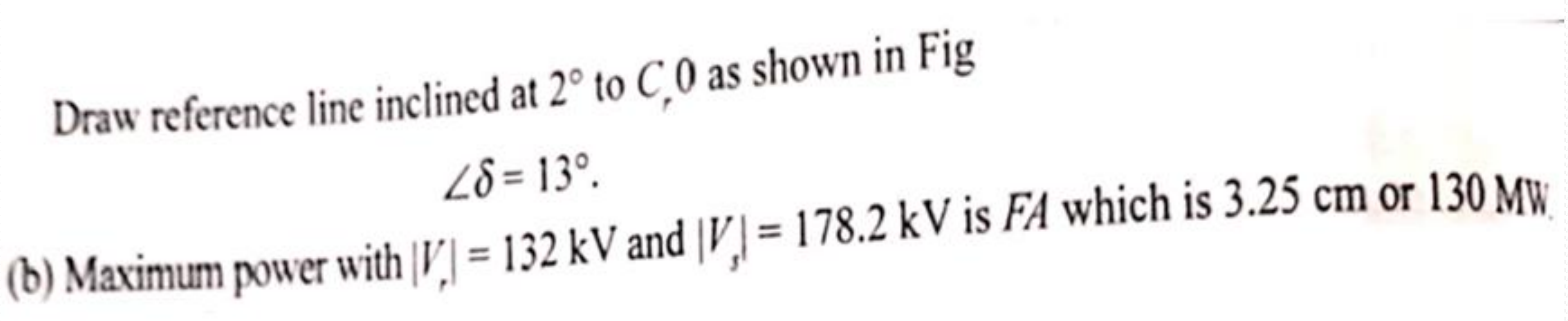
Select a scale of 1 cm = 40 MVA and draw OC_r equal to $\frac{112}{40}$ i.e., 2.8 cm inclined at 68° to the negative real axis. (a) OP is the 0.8 lagging p.f. line inclined at $\cos^{-1} 0.8$, i.e., 36.87° to positive x-axis. Take $OP = \frac{60}{40}$ i.e., 1.5 cm. With C_r as centre and $C_r P$ as radius draw the receiving end circle. $C_r P$ = 4.2 cm or 168 MVA

$$\frac{|V_s||V_r|}{|B|} = 168$$

or

$$|V_s| = \frac{168 \times 140}{132} = 178.2 \text{ kV}$$

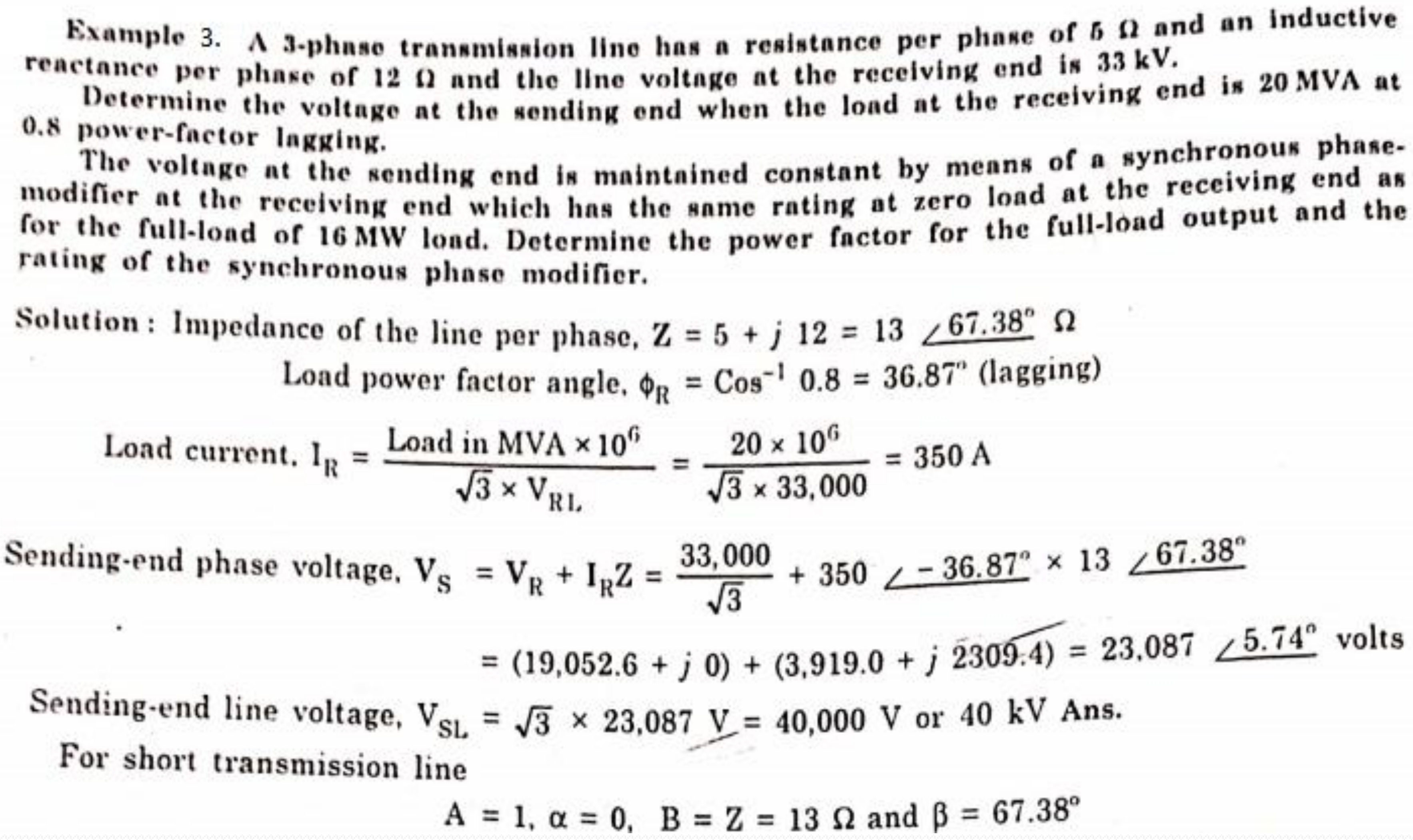

P
M
0
ϕ_s
MW
68°
Reference line
δ
Receiving end circle
A
C_r
F



Draw reference line inclined at 2° to C_r0 as shown in Fig

$\angle\delta = 13^\circ$.

(b) Maximum power with $|V_r| = 132$ kV and $|V_s| = 178.2$ kV is *FA* which is 3.25 cm or 130 MW.



Example 3. A 3-phase transmission line has a resistance per phase of 5 Ω and an inductive reactance per phase of 12 Ω and the line voltage at the receiving end is 33 kV.

Determine the voltage at the sending end when the load at the receiving end is 20 MVA at 0.8 power-factor lagging.

The voltage at the sending end is maintained constant by means of a synchronous phase-modifier at the receiving end which has the same rating at zero load at the receiving end as for the full-load of 16 MW load. Determine the power factor for the full-load output and the rating of the synchronous phase modifier.

Solution : Impedance of the line per phase, $Z = 5 + j\,12 = 13 \angle 67.38^\circ\ \Omega$

$$\text{Load power factor angle, } \phi_R = \text{Cos}^{-1}\, 0.8 = 36.87^\circ \text{ (lagging)}$$

$$\text{Load current, } I_R = \frac{\text{Load in MVA} \times 10^6}{\sqrt{3} \times V_{RL}} = \frac{20 \times 10^6}{\sqrt{3} \times 33{,}000} = 350 \text{ A}$$

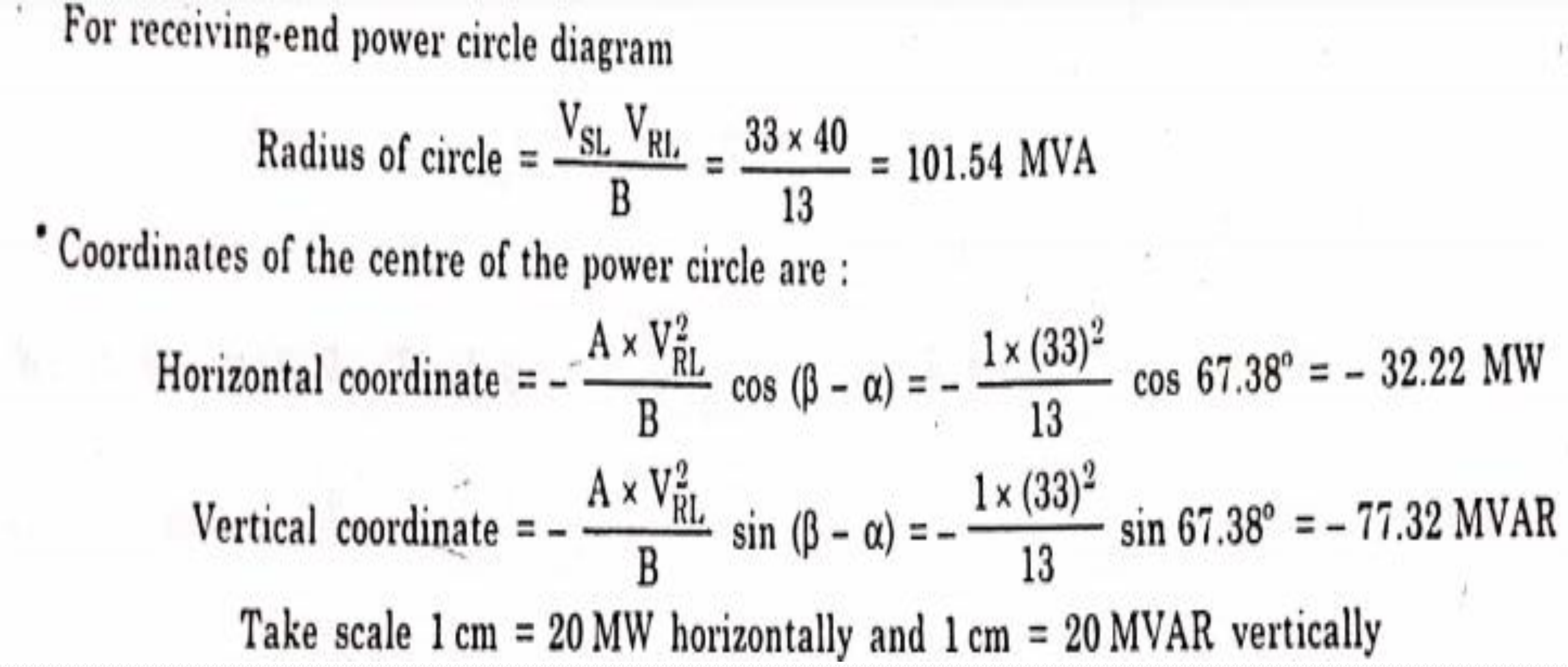
$$\text{Sending-end phase voltage, } V_S = V_R + I_R Z = \frac{33{,}000}{\sqrt{3}} + 350 \angle -36.87^\circ \times 13 \angle 67.38^\circ$$

$$= (19{,}052.6 + j\,0) + (3{,}919.0 + j\,2309.4) = 23{,}087 \angle 5.74^\circ \text{ volts}$$

Sending-end line voltage, $V_{SL} = \sqrt{3} \times 23{,}087 \text{ V} = 40{,}000$ V or 40 kV **Ans.**

For short transmission line

$$A = 1,\ \alpha = 0,\ \ B = Z = 13\ \Omega \text{ and } \beta = 67.38^\circ$$



For receiving-end power circle diagram

$$\text{Radius of circle} = \frac{V_{SL}\ V_{RL}}{B} = \frac{33 \times 40}{13} = 101.54 \text{ MVA}$$

- Coordinates of the centre of the power circle are :

$$\text{Horizontal coordinate} = -\frac{A \times V_{RL}^2}{B} \cos(\beta - \alpha) = -\frac{1 \times (33)^2}{13} \cos 67.38^\circ = -32.22 \text{ MW}$$

$$\text{Vertical coordinate} = -\frac{A \times V_{RL}^2}{B} \sin(\beta - \alpha) = -\frac{1 \times (33)^2}{13} \sin 67.38^\circ = -77.32 \text{ MVAR}$$

Take scale 1 cm = 20 MW horizontally and 1 cm = 20 MVAR vertically

$$\text{Radius of the circle} = -\frac{101.54}{20} = -5.1 \text{ cm}$$

$$\text{Horizontal coordinate} = -\frac{32.22}{20} = -1.6 \text{ cm}$$

$$\text{Vertical coordinate} = -\frac{77.32}{20} = -3.86 \text{ cm}$$

and draw circle diagram fig.

At no-load the synchronous phase modifier will be taking lagging MVAR given by

$Oa = 0.95$ cm $= 20 \times 0.95$ MVAR $= 19$ MVAR **Ans.**

Take O*b* = 16 MW, the full load supplied. At point *b* draw a perpendicular *bcd* cutting the arc of the circle at the point *c*. The MVAR supplied is given by the line *bc*. The synchronous phase modifier is supplying the same MVAR at full-load of 16 MW as at no-load *i.e.* 19 MVAR. Take *cd* = 19 MVAR. Join point O with the point *d* to give the load line.

The receiving-end power factor angle at full load = Cos ϕ_R = Cos 62.8° = 0.4586 (lagging) **Ans.**

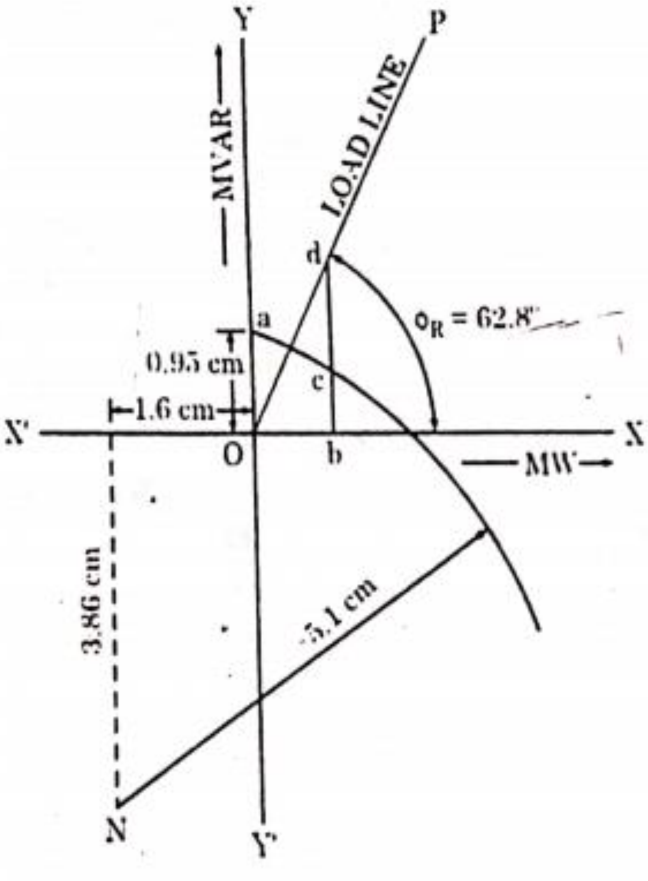


Fig.

Unit-II Assignment questions

- 1.(a)Draw the phasor diagram for the medium transmission line for nominal-T and nominal pi representation and derive necessary equations.
- (b)Derive the ABCD parameters of a long transmission line using rigorous method
- 2.Explain different methods of voltage control.
- 3.what is receiving end power circle diagram. How can it be drawn?