EE 3004

# HVDC AND FACTS

## UNIT-I INTRODUCTION

Reactive power control in electrical power transmission Lines - Load and System compensation, Uncompensated transmission Line - Shunt and Series compensation. Need for HVDC transmission, Comparison between AC and DC transmission, types of HVDC transmission system.

### Objective:

Students will able to study basic idea about HVDC (high voltage DC Transmission) and FACTS (Flexibl AC Transmission)

### What is HVDC Transmission?

HVDC (high Voltage Direct Current transmission is a technology used to transmit electrical power over Long distances. It involves the conversion of alternating Current (AC) to direct current (DC).

### What is FACTS?

- FACTS Stands for flexible Alternating current Transmission System. It refers to a collection of Power electronic-based devices and Systems that are used to enhance the controllability and stability of AC Power systems.

## Why we need study HVDC Transmission ?

HVDC transmission is more efficient than traditional AC (Alternating Current) transmission over Long distances. It incurs Lower energy Losses and allows for the transmission of Large amounts of Power over thousands of kilometers.

## why we need study FACTS ?

As power systems become more complex and Interconnected Maintaining Stability and reliability becomes increasingly challenging. FACTS Technologies provide tools to control Powerflow.

## TECHNICAL TERMS

HVDC → High voltage Direct current transmission

FACTS → Flexible AC Transmission.

1. Rectifier → A device that converts AC Power to DC power
2. Inverter → A device that converts DC power to AC Power
3. Thyristor → A type of semiconductor device used in HVDC converters
4. converters Station → A facility that houses the equipment for converting AC to DC and vice versa in HVDC Systems.
5. Bipolar transmission → HVDC transmission using both Positive and negative polarity of DC Voltage.

## Reactive power control in electrical power transmission Lines

→ we always in practice to reduce reactive power to improve System efficiency.

→ If system is purely resistively (or) capacitance it make cause some problem in electrical system.

→ Alternating system supply two kind of power
(1) Real power (2) Reactive power.

→ Real power → Real power accomplishes useful work

Real power is the power actually consumed due to the resistive Load. real power also called as true power (or) active power.

UNIT of Real Power - KW

→ Reactive power:→ Reactive power is the power, measured in VAR or KVAR, released and stored by capacitors and inductors.

→ useless power is called reactive power.

Power factor cos ø

$$\cos\phi = \frac{\text{Real power (KW)}}{\text{Apparent power (KVA)}}$$

## Necessary to control of Voltage and Reactive power

→ Voltage control and reactive power management are two aspects of a single activity that both supports reliability and facilitates commercial transactions across transmission network.

→ on an alternating current (AC) Power system, Voltage is controlled by managing production and obsorption of reactive power.

→ There are three reasons why it is necessary to manage reactive power and control Voltage.

→ First both customer and power system equipments are designed to operate with in a range of voltages, usually within 5% of the nominal voltage.

At Low voltage → Equipment perform Poorly, Light bulbs Less illumination, induction motors can overheat and be damaged.

At high voltage → High voltages can damage equipment and Shorten their Life times.

→ Second. reactive Power consumes transmission and generation resources. To maximize the amount of real Power that can be transferred across a congested transmission interface. reactive Power flows must be minimized. Similarly, reactive Power Production can limit a generator's real Power capability.

→ Third. Moving reactive Power on the transmission System incurs real Power losses. Both capacity and energy Must be supplied to replace these losses.

## Basic concept of Reactive Power

→ Active power is the energy supplied to run a motor, heat a home, or illuminate an electric Light bulb. Reactive power provides the important function of regulating voltage.

→ If voltage on the system is not high enough, active power cannot be supplied.

→ Reactive power is used to provide the voltage Levels necessary for active power to do useful work.

1. Why we need Reactive power.

→ Reactive power is essential to move active Power through the transmission and distribution System to the Customer Reactive Power is required to Maintain the voltage to deliver active Power (Watts) through transmission Lines.

→ Motor loads and other loads require reactive Power to convert the flow of electrons into useful work.

→ When there is not enough reactive Power, the voltage Sags down and it is not possible to push the power demanded by Loads through the Lines.

2. Reactive power is a Byproduct of Ac systems
   - → Transformers, transmission Lines, and motors require reactive power. Electric motors need reactive power to produce magnetic fields for their operation.
   - → Transformers and transmission Lines introduce inductance as well as resistance.
     - → Both Oppose the flow of current.
     - → Must raise the voltage higher to push the power through the inductance of the Lines.
     - → unless capacitance is introduced to offset inductance.

3. How Voltages controlled by Reactive power.
   - → Voltages are controlled by providing sufficient reactive power control margin supply needs through
     1. Shunt Capacitor and reactor compensations
     2. Dynamic compensation.
     3. Proper voltage schedule of generation.
   - → voltages are controlled by predicting and correcting reactive power demand from Loads.

4. Reactive power and power factor.
   - → Reactive power is present when the voltage and current are not in phase
     - * one waveform Leads the other
     - * Phase angle not equal to $0^{\circ}$
     - * Power factor Less than unity

→ Measured in volt-ampere reactive (VAR).

→ Produced when the current waveform leads voltage waveform (Leading power factor).

→ Vice verse, consumed when the current waveform lags voltage (Lagging power factor).

5. Reactive power Limitations.

→ Reactive power does not travel very far.

→ Usually necessary to produce it close to the location where it is needed.

→ A supplier / source close to the location of the need is in a much better position to provide reactive power versus one that is located far from the location of the need.

→ Reactive power supplies are closely tied to the ability to deliver real (or) active power.

## Importance of Reactive Power

→ Has a strong effect on system voltages

→ It must balance in the grid to prevent voltage problems

→ Reactive power levels have an effect on voltage collapse. Due to deficiency of reactive power in the grid the blackout occurse.

## Effects of Reactive power in Various elements of Power Syste:

1. Generation
2. Synchronous condenser
3. Capacitor and inductors
4. SVC
5. STATCOM
6. Distribution.
7. Transmission.

Important generators of reactive power are

- ✓ overexcited Synchronous Machines
- ✓ capacitor banks
- ✓ The capacitance of overhead Lines and cables
- ✓ FACTS devices

Important consumers of reactive power are.

- ✓ Inductive Static loads
- ✓ under excited Synchronous machines
- ✓ Induction motors
- ✓ shunt reactors
- ✓ The inductance of overhead Lines and cables
- ✓ Transformer inductances
- ✓ FACTS devices.

## UNCOMPENSATED TRANSMISSION LINES

→ The need of reactive power control, let us consider a lossless short transmission line consists of a Source $E_s$ with angle $\delta$ connected to a Load impedance $Z$ with angle $\phi$.

→ Assume the Line is represented only by its inductive reactance $X_L$.

→ phasor diagram showing the relationship between voltages and Currents.

→ The most significant part of the voltage drop in the line reactance $(\Delta E_1 = jI_x X_L)$ is due to the reactive component of the load current $I_x$.

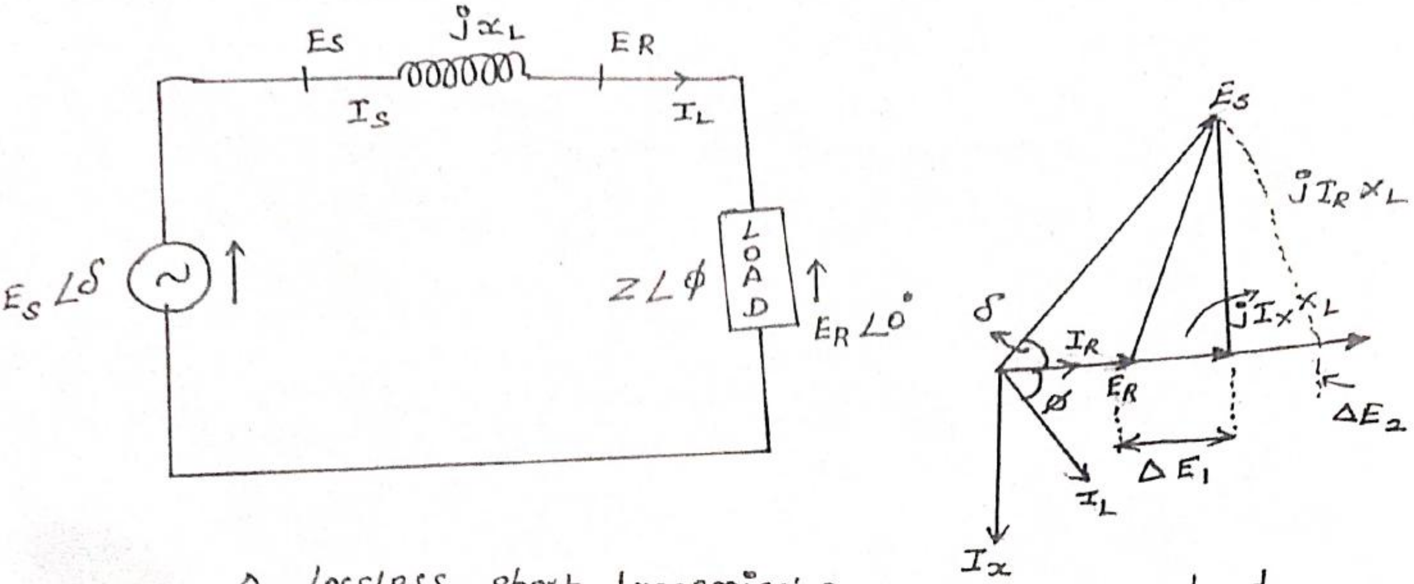
To keep the voltages in the power network at nearly the rated value, two control actions have been employed.

(1) Load Level compensation

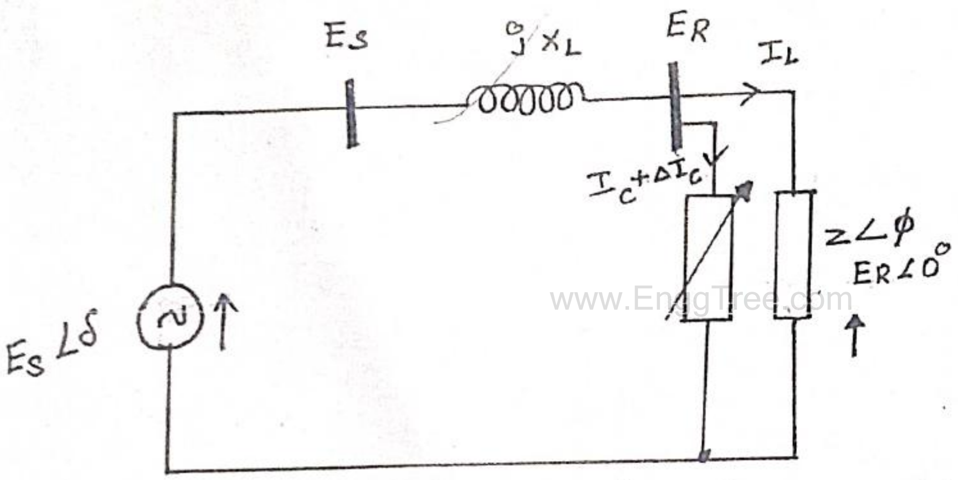
(2) System Level compensation.

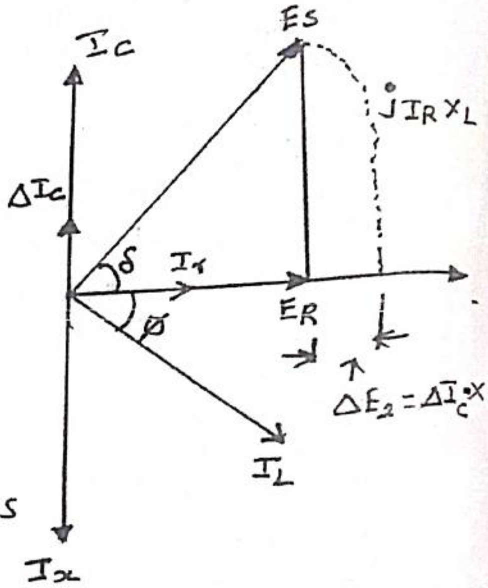
### (1) Load Level Compensation

→ compensation of reactive current $I_x$ of the load can be obtained by adding a parallel capacitive Load so that $I_c = -I_x$ Doing in this way causes the effective power factor of the combination to become unity.



A Lossless short transmission line fed with load.





Reactive power controls for Voltage regulations

→ The absence of reactive current $I_x$ eliminates the Voltage drop $\Delta E_1$, bringing receiving end Voltage $E_R$ closer in magnitude to sending end Voltage $E_s$ this condition is called Load compensation.

✓ charging extra for supplying the reactive power, a power ~~unity~~ utility company makes it advantageas for customers to use load compensation on their location.

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- ✓ Due to unity power factor redue the line drop but do not eliminate completely, they still experience a drop of $\Delta E_2$ from $jI_R X_L$.

## SYSTEM LEVEL COMPENSATION:

→ This compensator draws a reactive current to overcome both components of the voltage drop $\Delta E_1$ and $\Delta E_2$ as a consequence of the load current $I_L$ through the transmission line reactance $X_L$.

→ To compensate for drop $\Delta E_2$, an additional capacitive reactive current, $\Delta I_c$, over and above $I_c$ that compensates for $I_x$, is drawn by the compensator.

→ when $\Delta I_c X_L = \Delta E_2$ the receiving end voltage, ER, equals the sending end voltage, Es. Such compensators are used by power utilites to ensure the quality of supply to their customers.

## PRINCIPLE OF REACTIVE POWER COMPENSATION

→ The reactive power is defined as the AC component of the instantaneous power, with a frequency equal to 100/120 Hz in a 50 (or) 60 HZ system.

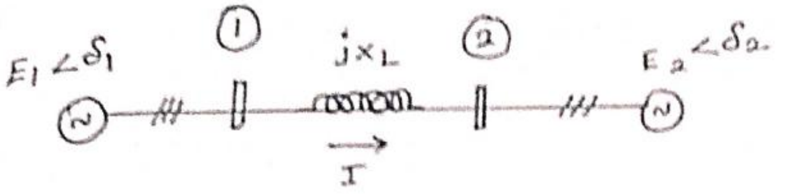
→ The reactive power generated by the AC power source is stored in a capacitor (or) a reactor during a quarters of a cycle, and in the next quarter cycle is sent back to the power source.

→ The reactive power oscillates between the AC source and the capacitor or reactor, and also between them, at a frequency equals to two times the rated value (50 or 60 HZ).

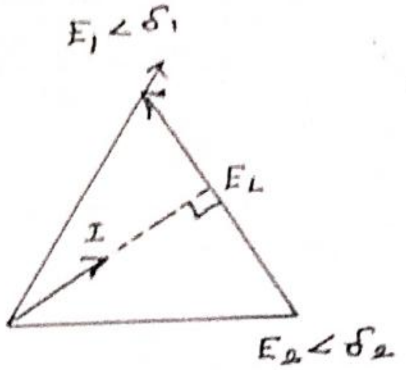
→ For this reason it can be compensated using VAR generators, avoiding its circulation between the load (inductive or capacitive) and the source, and therefore improving voltage stability of the power system.

→ Reactive power compensation can be implemented with VAR generators connected in parallel (or) in series. the principles of both shunt and series reactive power compensation alternatives

## Simplified model



Simplified model



Phase diagram.

→ Two power grids are connected by a transmission line which is assumed lossless and represented by the reactance $X_L$, $E_1$ and $E_2$ represent the voltage phasors of the two power grid buses with angle $\delta = \delta_1 - \delta_2$ between them.

The magnitude of the current in the transmission line is

$$I = \frac{E_L}{X_L} = \frac{|E_1\angle\delta_1 - E_2\angle\delta_2|}{X_L} \quad \ldots\ldots(1)$$

The active and reactive components of the current flow at bus 1,

$$I_{d1} = \frac{E_2 \sin\delta}{X_L}, \quad I_{q1} = \frac{E_1 - E_2\cos\delta}{X_L} \quad \ldots\ldots(2)$$

The active power and reactive power at bus 1

$$P_1 = \frac{E_1 E_2 \sin\delta}{X_L}, \quad Q_1 = \frac{E_1(E_1 - E_2\cos\delta)}{X_L} \quad \ldots(3)$$

The active and reactive components of the current flow at bus 2.

$$I_{d2} = \frac{E_1 \sin\delta}{X_L}, \quad I_{q2} = \frac{E_2 - E_1\cos\delta}{X_L} \quad \ldots\ldots(4)$$

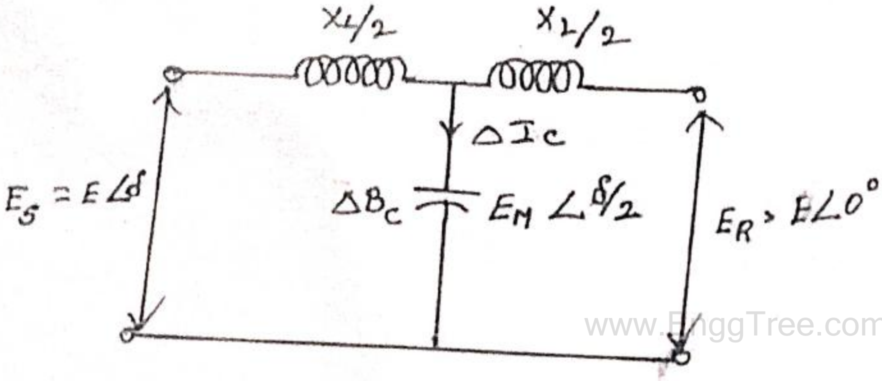
The active power and reactive power at bus 2.

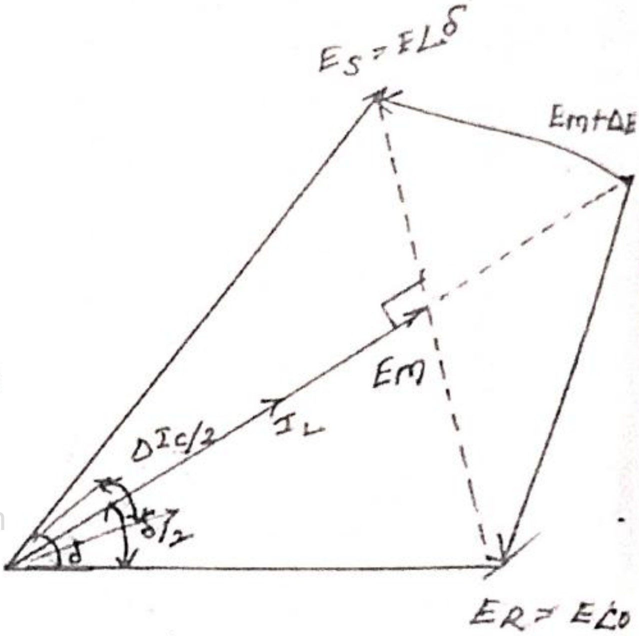
$$P_2 = \frac{E_1 E_2 \sin\delta}{X_L}, \quad Q_2 = \frac{E_2 (E_2 - E_1 \cos\delta)}{X_L} \quad \text{---} (5)$$

The compensation of transmission systems can be divided into two main groups

(1) shunt compensation.
(2) Series compensation.

## ① SHUNT COMPENSATION





→ For the symmetrical short transmission line a shunt capacitor at the midpoint of the line gives shunt susceptance ($\Delta B_c$), is incrementally added. The net power transfer in terms of the midpoint voltage on the line is given by

$$P = E \frac{E_M}{\frac{X_L}{2}} \sin\delta/2 \quad \text{------} (1)$$

$$P = \frac{2E \cdot E_M}{X_L} \sin\delta/2 \quad \text{-----} (2)$$

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The differential change in Power, $\Delta p$ causes a differential change in, $\Delta E_m$, is given as.

$$\Delta_p = \frac{2E}{X_L} \sin \delta/_2 \, \Delta E_M \quad \text{----} ③$$

$$\Delta I_c = E_M \Delta B_C \quad \text{-----} ④$$

The shunt capacitor current $(\Delta I_c)$ in the middle lines Modifies the Line Current is the sending and receiving ends of the line which is given by

$$I_{LS} = I_L - \frac{\Delta I_c}{2} \quad \text{and}$$

$$I_{LR} = I_L + \frac{\Delta I_c}{2}$$

$$E_m = E_R + \frac{j I_L X_L}{2}$$

$$\Delta E_m = \frac{\Delta I_c X_L}{4} \quad \text{------} ⑤$$

sub ③ in ⑤ gives

$$\Delta E_m = \frac{V_m \Delta B_c X_L}{4} \quad \text{--------} ⑥$$

sub ⑥ in ③

$$\Delta_p = \frac{2E}{X_L} \sin \delta/_2 \frac{E_m \Delta B_c X_L}{4} \quad \text{——} ⑦$$

$$\Delta_p = \frac{E E_m}{2} \sin \delta/_2 \, \Delta B_c \quad \text{——} ⑧$$

since

$$E_m \simeq E \cos \delta/_2$$

$$\Delta p = \frac{E_m}{\cos \delta/2} \cdot \frac{E_m}{2} \sin \delta/2 \, \Delta B_c$$

$$= \frac{E_m^2}{2} \frac{\sin \delta/2}{\cos \delta/2} \Delta B_c$$

$$\Delta p = \frac{E_m^2}{2} \tan \delta/2 \, \Delta B_c$$

$$\Delta p = \frac{\Delta Q_{sh}}{2} \tan \delta/2 \quad \text{—⑨} \quad \left[ \frac{\sin \theta}{\cos \theta} = \tan \theta \right]$$

If the midpoint voltage of the line is approximately equal to $E \cos \delta/2$, then the incremental rating of the shunt capacitor compensation will be $\Delta Q_{sh} = E_m^2 \Delta B_c$

$$\frac{\Delta P}{\Delta Q_{sh}} = \frac{1}{2} \tan \delta/2 \quad \text{—⑩}$$

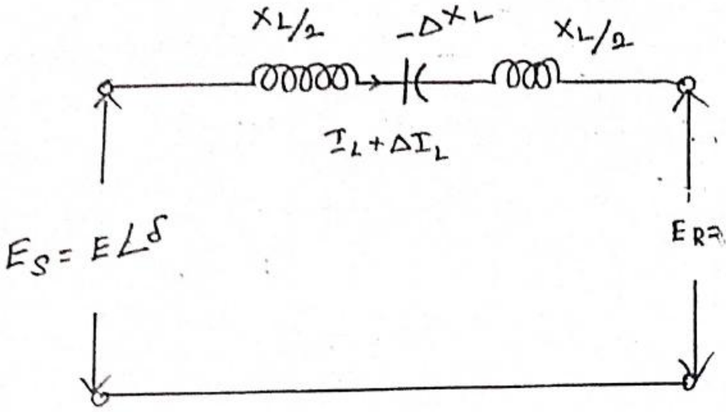
$$\frac{Q_{se}}{2 \tan \delta/2} = \frac{Q_{sh} \tan \delta/2}{2} \quad \text{—⑪}$$

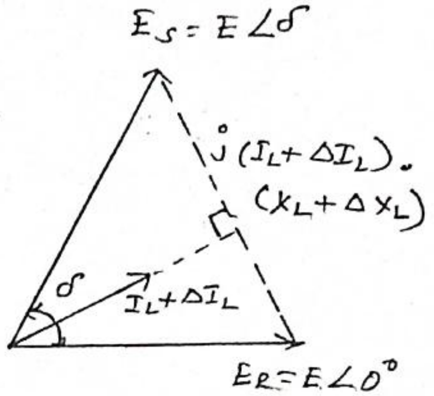
By comparing equ $\left[ \frac{\Delta P}{\Delta Q_{se}} = \frac{1}{2 \tan \delta/2} \right]$ series compensation

and equ ⑨ in both series and shunt compensation an equivalent power trasfer on a short transmission line is given by

$$\frac{\Delta Q_{se}}{\Delta Q_{sh}} = \left( \tan \delta/2 \right)^2 \quad \text{—⑫}$$

## (2) SERIES COMPENSATION





In series compensation the effective reactance of a transmission line is controlled by inserting a series capacitor. Then a change in the line reactance $(\Delta X_L)$ will result in a change in the current $\Delta I_L$, where the line terminal voltage remain unchanged.

$$\Delta I_L = \frac{-2E}{X_L} \sin \delta/2 \, \frac{\Delta X_L}{X_L} \quad \text{——— ①}$$

$$I_L = \frac{2E}{X_L} \cdot \sin \delta/2 \quad \text{——— ②}$$

$$\Delta I_L = \frac{-2E}{X_L} \sin \delta/2 \, \frac{\Delta X_L}{X_L} \quad \text{——— ③}$$

From ① and ② $\Delta I_L = -I_L \frac{\Delta X_L}{X_L}$ ——— ④

Power transfer is given by $P = \frac{E^2}{X_L} \sin\delta$ ——— ⑤

Also

$$P = \frac{E^2}{X_L} 2 \sin \delta/2 \cos \delta/2 \quad \text{——— ⑥}$$

Therefore, from equ ⑥, the corresponding change in the power transfer will be

$$\Delta p = -\frac{E^2}{X_L^2} 2 \sin \delta/2 \cos \delta/2 \, \Delta X_L \quad \text{——— ⑦}$$

$$= -\frac{2E}{X_L} \sin \delta/2 \; E \cos \delta/2 \frac{\Delta X_L}{X_L} \quad \text{——— ⑧}$$

Substitute ② in ⑧

$$\Delta p = -I_L E \cos \delta/2 \frac{\Delta X_L}{X_L} \quad \text{——— ⑨}$$

Multiply and divide by $\cos \delta/2$ in ③

$$\Delta I_L = \frac{-2E \sin \delta/2 \cos \delta/2}{X_L \cos \delta/2} \cdot \frac{\Delta X_L}{X_L} \quad \text{——— ⑩}$$

$$-\frac{\Delta I_L \cdot X_L}{2 \tan \delta/2} = E \cos \delta/2 \frac{\Delta X_L}{X_L} \quad \text{——— ⑪}$$

comparing ⑨ and ⑪

$$\Delta p = -I_L \left[ \frac{-\Delta I_L \cdot X_L}{2 \tan \delta/2} \right] \quad \text{——— ⑫}$$

Sub ④ in ⑫

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$$= \frac{I_L}{2\tan\delta/2} \cdot X_L \left[ -I_L \frac{\Delta X_L}{X_L} \right] \quad \text{——} \; ⑬$$

$$\Delta p = \frac{1}{2\tan\delta/2} \left( -\Delta X_L I_L^2 \right) \quad \text{——} \; ⑭$$

From equation ⑭ $(-\Delta X_L I_L^2) = \Delta Q_{se}$ represents the incremental Var rating of the series capacitor, therefore

$$\frac{\Delta p}{\Delta Q_{se}} = \frac{1}{2\tan\delta/2}$$

## Need for HVDC Transmission

- Long distance bulk power transmission.
- underground (or) Underwater cables
- Asynchronous interconnection of AC system operating at different frequencies (or) where independent control of system is desired.
- Control and Stabilization of power flows in AC ties in an integrated power system.
- In AC systems there arises some technical problems in long distances.

* For efficient power transmission for Long distance HVDC over HVAC

* Improving the reliability of transmission.

* A DC Line has less corona Loss and reduced interference.

* Fast control to limit current in DC Lines

* Reduced transmission Lines

* Inter connection of systems operating at different frequencies.

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## Comparison between AC and DC Transmission.

The electric power can be transmitted either by means of D.C (or) A.C. Each system has its own merits and demerits.

The following factors are

1) Economics of Power transmission
2) Technical Performance
3) Reliability.

This implies that the established of a Particular line must be considered as a Part of an overall Long-term System planning.

1) Economics of power Transmission.

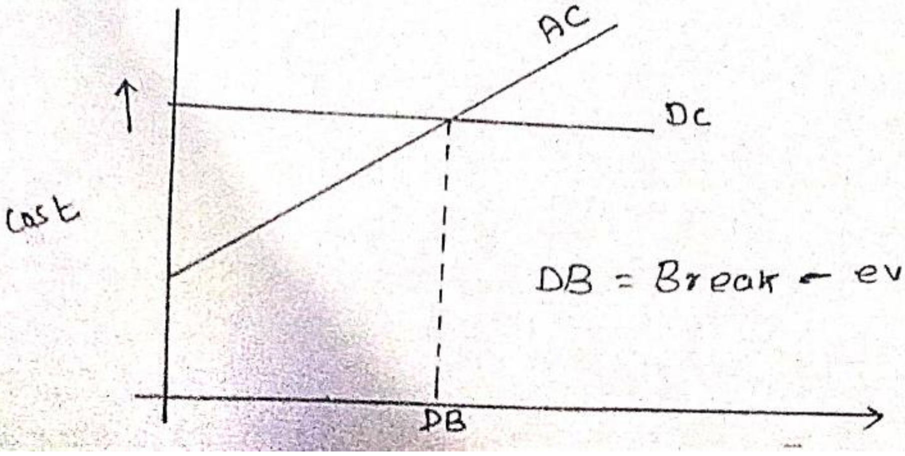
→ The cost of a transmission line includes the investment and operational costs.

→ The investment includes costs of Right of way (Row transmission towers, conductors, insulators and terminal equipment. the operational costs include mainly the cost of losses.

→ The DC Line requires Less ROW. Simpler and cheaper towers and reduced conductor and insulator costs. The power losses are also reduced with DC as there are only two conductors [about 67% of that for AC with same current carrying capacity of conductors].

→ The absence of Skin effect with DC is also beneficial in reducing power loss marginally.

→ The dielectric losses in case of power cables is also very loss for DC transmission.



DB = Break - even distance

→ Dc lines do not require compensation but the terminal equipment costs are increased due to the presence of converters and small filters.

→ The variation of costs of transmission with distance for Ac and Dc transmission. For distance less than "Break even" distance, Ac tends to be economical than Dc and costlier for longer distances.

→ The break even distances can vary from 500 to 800 km in overhead lines depending on the per unit line costs.

## 2) Technical performance

The Dc transmission has some positive features which are lacking in Ac transmission. These are mainly due to the fast controllability of power in Dc link through converters control.

Advantages

(i) Full control over power transmitted.

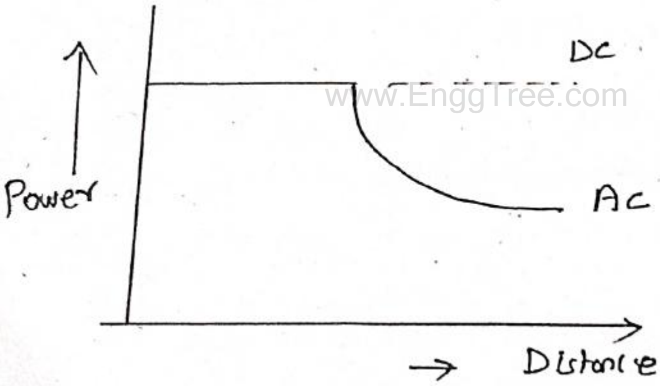
(ii) The ability to enhance transient and small signal stability in associated Ac networks.

(iii) Fast control to limit fault currents in Dc lines, avoid Dc breakers in two terminal Dc links.

## (a) stability limits

The power transfer in AC Lines is dependent on the angle difference between the voltage phasors at the two ends. this angle increases with distance.

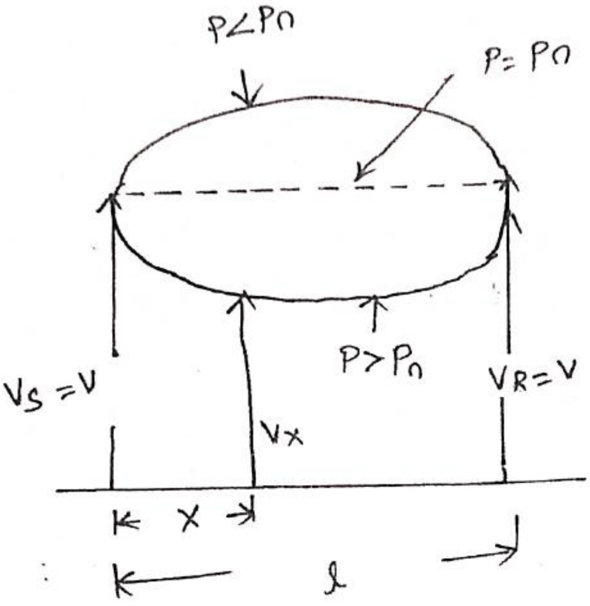
The power carrying capability of DC Lines which is unaffected by the distance of transmission and is limited only by the current carrying capacity of the conductors.



## (b) Voltage control

→ The voltage control in AC Lines is complicated by The Line charging and inductive voltage drops. The voltage profile in a AC Line is relatively flat only for a fixed Level of power transfer corresponding to surge impedance loading (SIL).

→ The voltage profile varies with the Line Loading for constant voltage at the Line terminals, the Midpoint voltage is reduced for Line loading higher than SIL and increased for loadings less than SIL



x = distance from the sending end

l = Length of the line

→ The maintenance of constant Voltages at the two ends requires reactive power control from inductive to capacitive as the line loading is increased.

→ The reactive power requirements increase with the increase in line lengths.

→ Although DC converter stations with line commutatec converters require reactive power related to the line loadings, the line itself does not require reactive Power.

→ The steady state charging currents in AC lines pose serious problems in cables.

Line compensation

For reasons mentioned earlier, AC Lines require shunt and series compensation in Long distance transmission, Mainly to over come the problems of line charging and stability limitations.

Series capacitors and shunt inductors are used for this purpose

→ The increase in power transfer and voltage control is also possible through the use of shunt connected static var compensator (SVC).

→ In AC cable transmission, it is necessary to provide, shunt compensation at regular intervals. This is a serious problem in underwater cables.

Problems of AC Interconnected

→ when two power systems are connected through AC ties, the automatic generation control of both system have to be coordinated using tie. line power and frequency signals.

→ Presence of Large power oscillations which can lead to frequent tripping

→ Increase in fault Levels.

→ Transmission of disturbances from one system to the other.

## Grounding

→ In AC transmission, the existence of ground currents cannot be permitted in steady - state due to high magnitudes of ground impedance which will not only affect efficient power tranfer, but also result in telephone interference.

→ The ground impedance is negligible for DC currents and a DC link can operate using one conductor with ground return.

## Disadvantages of DC Transmission

DC transmission is limited by the following factors

(a) The difficulty of breaking DC currents which results in high cost of DC Breakers

(b) Inability to use transformers to change voltage Levels

(c) High cost of conversion equipment

(d) Generation of harmonics which require AC and DC filters, adding to cost of converter stations

(e) Complexity of control.

## Reliablity

→ The reliability of DC transmission is best comparable to that of AC systems, An exhaustive, record of existing. HVDC links in the world is available from which the reliability statistics can be computed.

→ It must be remembered that the performance of thyristor values is much more reliable than mercury arc values and further developments in devices. control and protection have improved the reliability Level.

There are two measures of overall system reliability.

Energy Availability

$$\text{Energy availability} = 100\left(1 - \frac{\text{equivolent outage time}}{\text{total time}}\right).$$

where equivalent outage time is the product of the actual outage time and the fraction of system capacity lost due to outage.

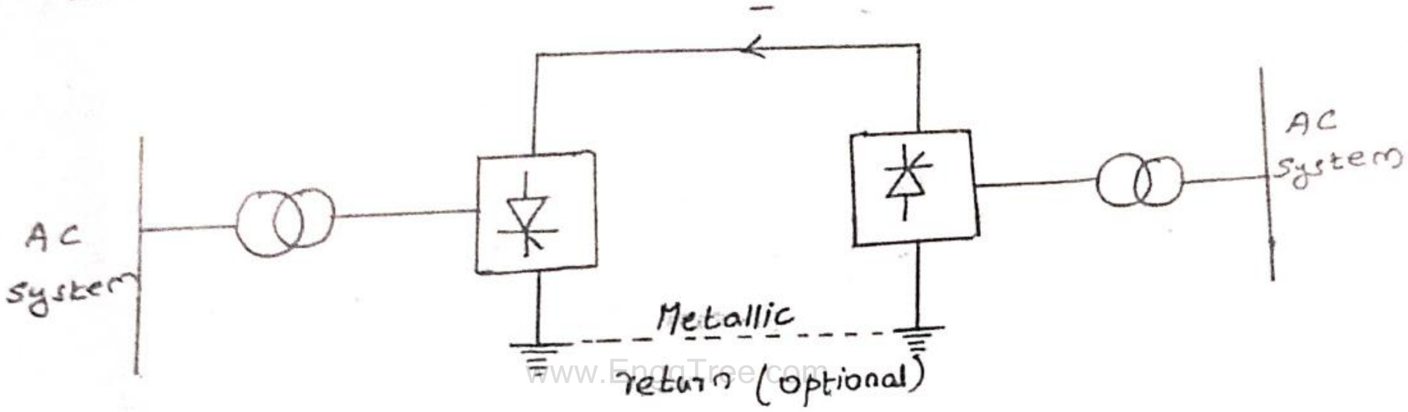
Transient reliability:

$$\text{Transient reliability} = \frac{100 \times \text{No. of times HVDC System Perfromed as designed}}{\text{No. of recordable AC faults.}}$$

# TYPES OF HVDC TRANSMISSION SYSTEM.

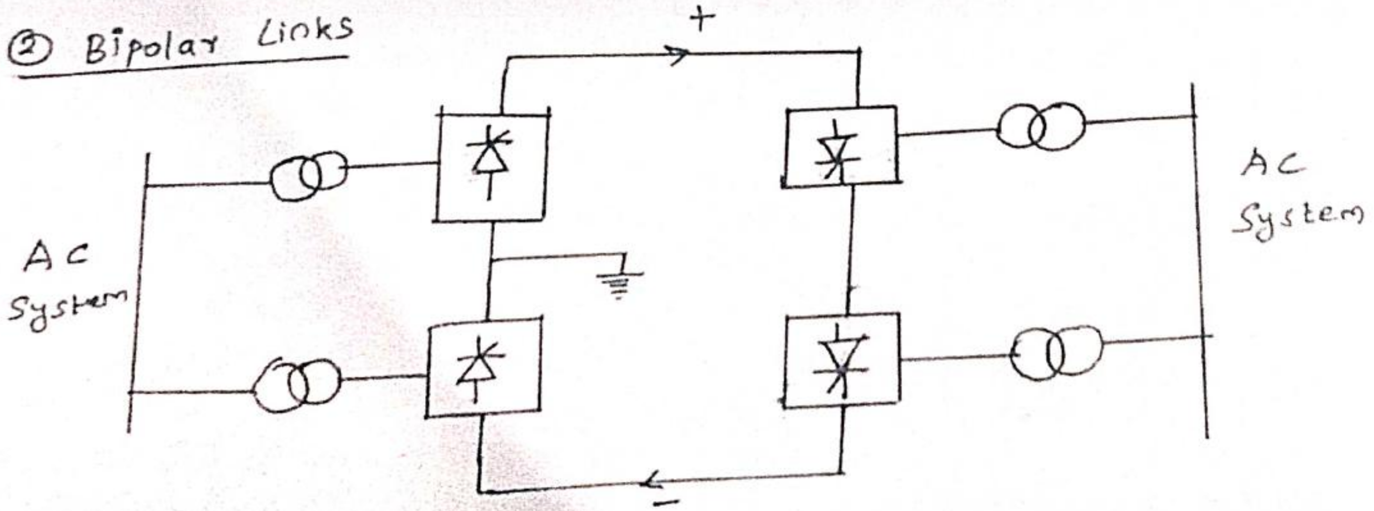
1) Monopolar links
2) Bipolar links
3) Homopolar links
4) Back-to-back links.

## ① Monopolar Links.



→ It uses one conductor
→ The return path is provided by ground (or) water
→ use of this system is mainly due to cost considerations
→ A metallic return may be used where earth resistivity is too high.

## ② Bipolar Links



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→ It uses two conductors, one positive and the other negative.

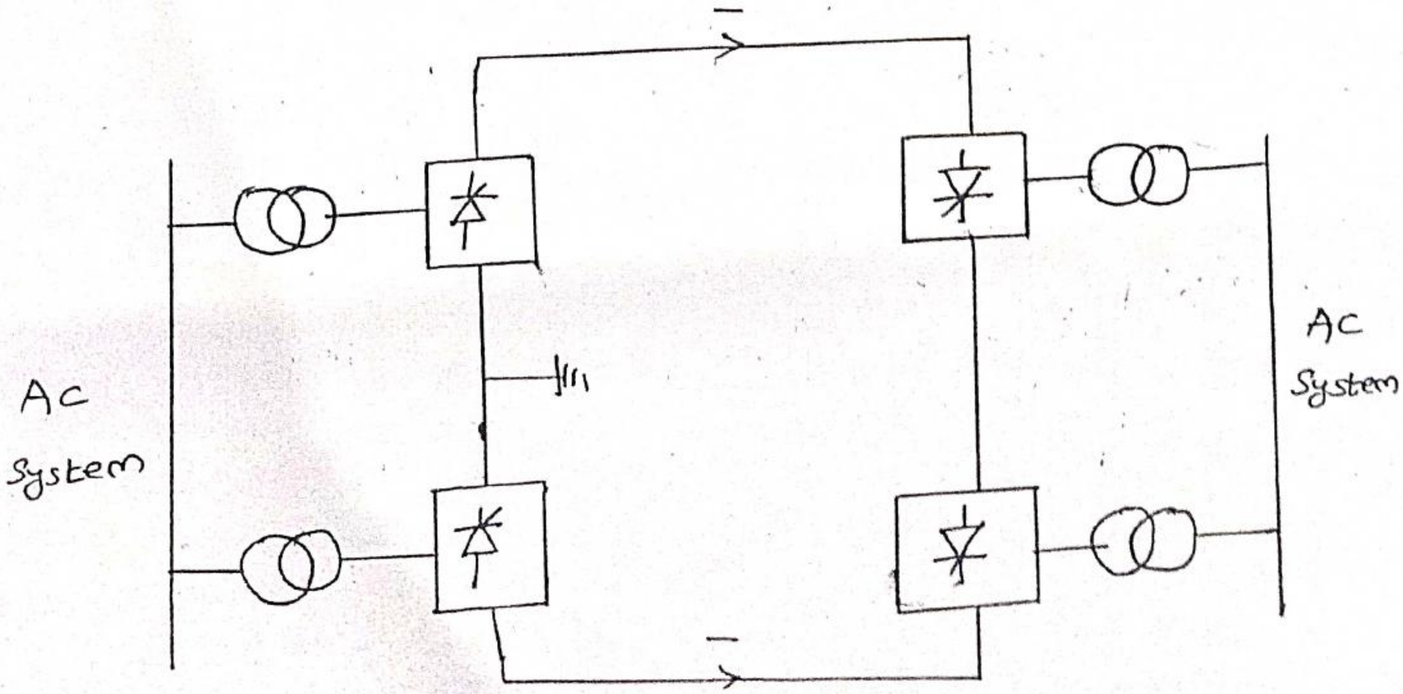
→ Each terminal has two converters of equal rated Voltage, connected in Series on the DC side.

→ The junctions between the converters is grounded.

→ Currents in the two poles are equal and there is no ground current.

→ If one pole is isolated due to fault, the other pole can operate with ground and carry half the rated Load (or more using overload capabilities of its converter line).

③ Homopolar Links

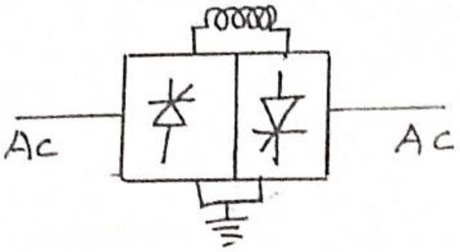


→ It has two (or) More conductors having the same Polarity, usually negative.

→ Since the corona effect in DC transmission lines is less for negative polarity, homopolar link is usually operated with negative polarity

→ The return path for such a system is through ground.

## ④ Back to Back HVDC coupling system.



→ It is used for interconnection between geographically adjacent Ac network for the purpose of frequency conversion (or) for an asynchronous interconnection.

→ Ac network coupled by a back to back converter.

→ The direction of power flow and amount of power flow through the coupling system can be controlled in magnitude and direction irrespective of the conditions in the connected Ac network.

→ A Smoothing Reactor is connected in the dc loop.

→ The rectifier and inverter are connected to form a Dc loop. there is no Dc transmission line.

→ Dc loop is earthed at a single point between the rectifier and inverter to provide a reference earth on Dc side. It provides asynchronous tie between two independently controlled Ac ~~Networks~~. network.

1:16

## Multiterminal Direct current (MTDC) system.

Types

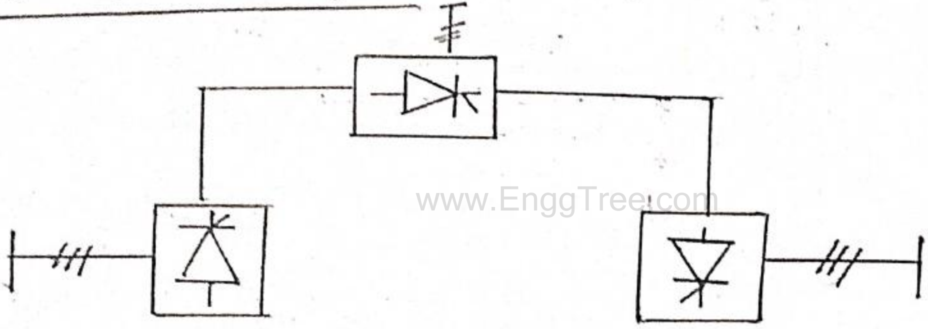
→ There are two possible types of MTDC systems

(i) Series
(ii) Parallel

→ Parallel MTDC systems can be further subdivided into

(a) Radial
(b) Mesh.

### ① Series MTDC system.



→ This is natural extension of Two terminal system which is a series connected system.

→ In a series connected system the current is set by one converter station and is common for all the stations. The remaining stations operate at constant angle (or) voltage control.

→ In order to minimize the reactive power requirements and the losses in value damper circuits, the normal operating values of firing angles may be adjusted using tap changer control.

→ At all times, the sum of the voltage across the rectifier stations must be larger than the sum of the voltage across the inverter station. In case of a dr drop in the voltage at the current controlling rectifier station; the inverter with the larger current referen takes over the current control.

→ The switching in (or) out of a bridge is accomplished by deblocking / block and by pass in a manner similar to that in a two terminal system. the clearing of a fault in the DC line is also similar.

→ [The power reversal at a station is also done as in a two terminal system, by reversing the DC voltage by converter control. The power control in a two terminal system is accomplished by adjusting the current] while trying to maintain a constant voltage in the system. this is done to minimize the losses.

→ However, in a MTDC series system / central control would be required to adjust the current in response to changing loading conditions.

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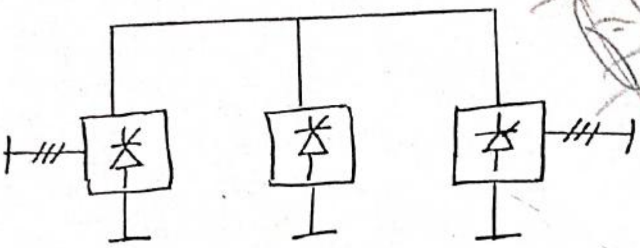
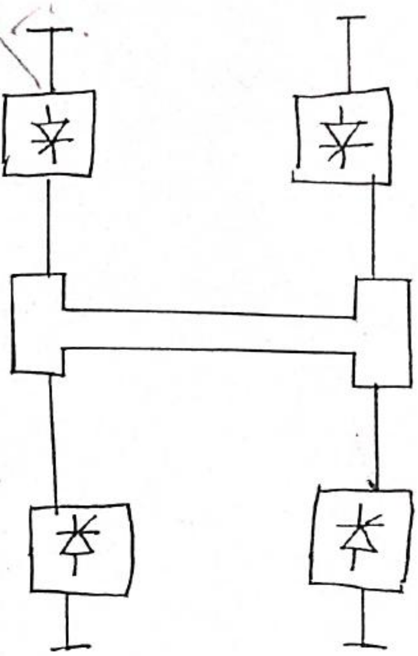
## ② Parallel MTDC System



Parallel connected radial MTDC



Parallel mesh system.

→ The operating philosophy of constant voltage AC system is extended to DC system. the current in all the converter stations except one are adjusted according to the power requirement one of the terminals operates as a Voltage setting terminal at constant angle (or) voltage.

→ An example of 3 terminal radial system is one in which the disconnection of one Segment of transmission would result in interruption of power from one (or) more converters station.

→ In a mesh system, the removal of one link would not result in a ~~dist~~ disruption, Provided the remaining Links are capable of carrying

The required power (with increased losses). Evidently a mesh system can be more reliable than a radial system.

→ The power reversal in parallel MTDC system would involve mechanical switching as the voltage cannot be reversed. Also, loss of bridge in one converter station would require the either the disconnection of a bridge in all the stations (or) disconnection of the affected station.

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OUTCOME

The outcome of HVDC and FACTS, includes improved power transmission efficiency, increased grid stability, better voltage control, and enhanced power quality.

Reference Books.

1. HVDC Power Transmission System
K.R Padiyar

2. FACTS
e. RAVICHNDRAN.
T.A. RAGHAVENDIRAN

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Part-A

① List out two Merits of AC and DC transmission

② what are the types of DC link ?

③ Define Reliability.

④ Define Availability

⑤ List the types of Power devices for HVDC transmission.

⑥ Define Real Power.

⑦ Define Reactive Power

⑧ Define Apparent Power

⑨ Draw the Power Triangle.

⑩ write down any two application of DC Transmission ?

⑪ what are the Factors to be considered for Planning HVDC Transmission ?

⑫ Difference between AC and DC Transmission.

⑬ Mention the some HVDC Projects from abroad ?

Part-B

① Explain basic concept of reactive power.

② Explain ~~Power~~ reactive power control in electrical Power transmission Lines.

③ Explain (i) Load Level compensation (ii) System Level compensation.

④ Explain Series and Shunt compensation

⑤ Comparison between AC and DC Transmission.

⑥ Explain Types of HVDC Transmission system

# UNIT-II

## STATIC VAR COMPENSATOR (SVC) AND THYRISTOR CONTROLLED SERIES COMPENSATOR (TCSC)

VI characteristics of FC + TSR, TSC + TSR, Voltage control by SVC - Advantages of Slope in dynamic characteristics - Influence of SVC on System Voltage - Design of SVC voltage regulator, Thyristor controlled Series compensator (TCSC), Concept of TCSC, operation of the TCSC - Different modes of operation, Applications.

Objective:

students will able to study basic idea about Static Var compensator (SVC) and Thyristor controlled Series compensator (TCSC)

### What is static Var compensator (SVC) ?

A static Var compensator (SVC) is a type of power electronics device used in electrical power systems to provide dynamic reactive power compensation.

### what is TCSC ?

TCSC stands for thyristor - controlled Series capacitor. It is a type of power electronics device used in electrical power systems to provide dynamic Impedance control.

## TECHNICAL TERMS

1. Reactive Power compensation:- SVCs are used to provide reactive Power Support to the Power system by dynamically adjusting the reactive Power output to help regulate voltage Levels and improve power factor.

2) TCR ⇒ Thyristor controlled Reactor

3) TCSC → Thyristor - controlled Series capacitor

4) SSSC ⇒ Static Synchronous Series compensator

5) TSSC → Thyristor Switched Series capacitor.

## Reference Books

1) Flexible AC Transmission systems

C. RAVICHANDRAN
T.A. RAGHAVENDIRAN

2. Flexible AC Transmission System (FACTS)

R. UMA MAHESHWARI

2:2

## VI characteristics of FC+TSR [Fixed capacitor + Thyristor Switched Reactor]

The Static Var compensator (SVC) provides an excellent source of rapidly controllable reactive shunt compensation for dynamic voltage control through its utilization of high speed thyristor switching | controlled reactive devices.

An SVC is typically made up of the following major components

→ coupling transformer

→ Thyristor valves

→ Reactors

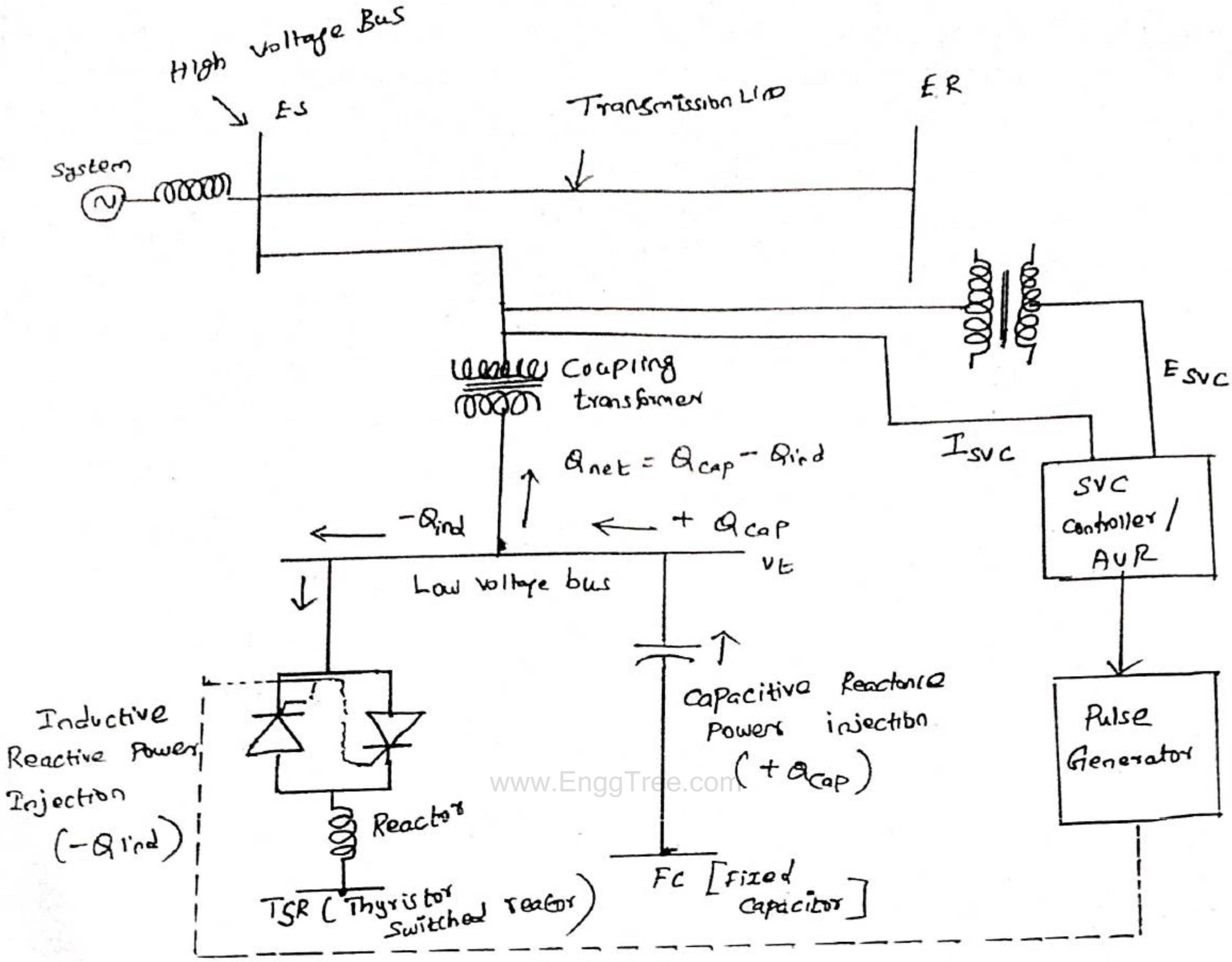
→ capacitor (often tuned for harmonic filtering)

→ In general, the two thyristor valve controlled/switched concepts used with SVC's are the thyristor - controlled Reactor (TCR) and the thyristor - switched capacitor (TSC).

→ The TSC provides a "stepped" response and the TCR provides a "smooth" or continuously variable. susceptance.

→ The control objective of SVC is to Maintain the desired Voltage at a high voltage bus.

→ In steady state, the SVC will provide some Steady State control of the Voltage to Maintain it in the highest voltage bus at the predefined Level.



→ If the voltage at bus begins fall below its set point range, the SVC will inject reactive power (Qnet) into the system (within its control limits), thereby increasing the bus voltage back to its desired voltage level.

→ If bus voltage increase, the SVC will inject less (or TCR will absorb more) reactive power (within its control limits), and the result will be to achieve the desired bus voltage.

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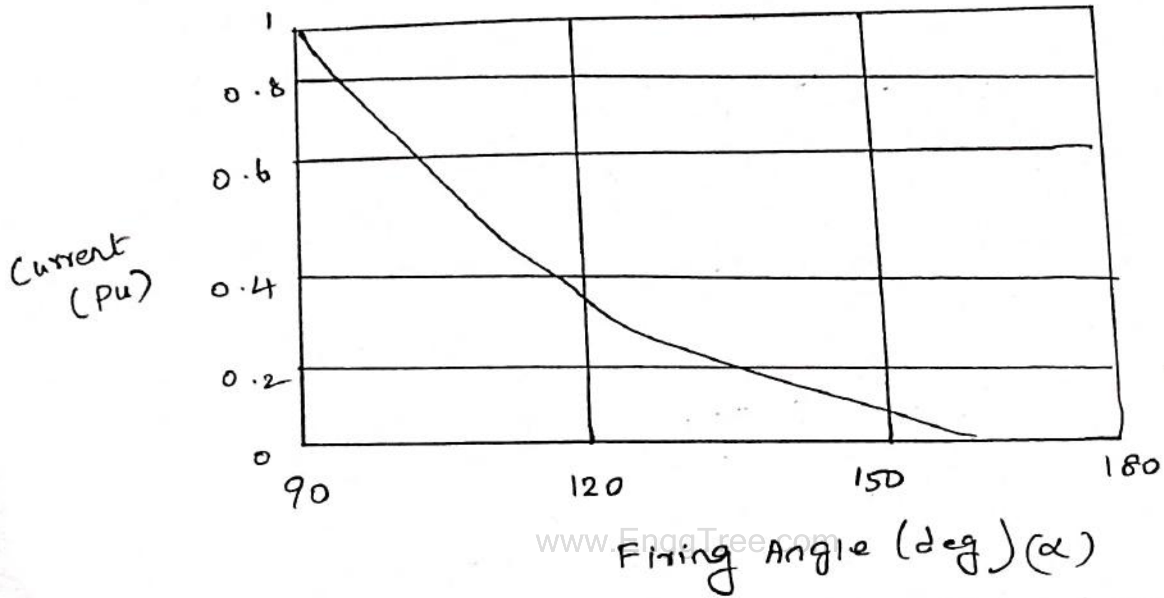
→ $+Q_{cap}$ is a fixed value, therefore the magnitudes of reactive power injected into the system. $Q_{net}$ is controlled by the magnitudes of reactive power $(-Q_{ind})$ absorbed by the TCR.



→ Above the graph describes the relationship between the fundamental frepuencies TCR current and firing angle.

→ The firing pulses are on the order of 10 μs. so it is concluded that as the firing angle increases above 90 degrees, the current in the TCR is reduced.

→ The pulse generator block after the AVR block utilizes the concepts discussed here and is used to determine the firing angle for the thyristor valve controlling the reactor.

→ The susceptance of the TCR, as seen by the grid, can be determined as a function of firing angle α.

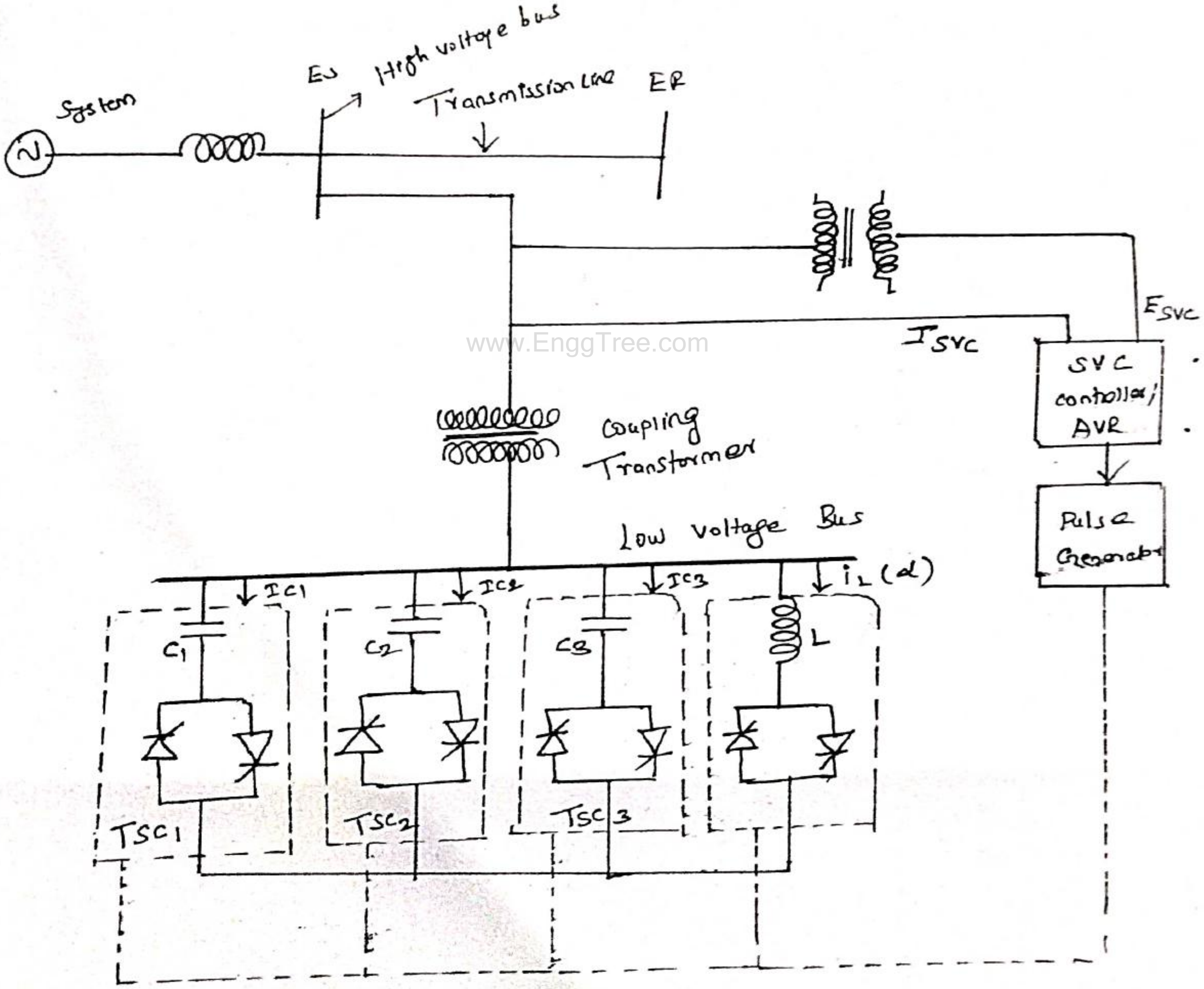
$$B_{TCR}(\alpha) = \frac{1}{\omega_0 L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin(2\alpha)\right]$$

## ② TSC – TSR Type SVC.

TSC → Thyristor Switched Capacitor

TSR → Thyristor Switched Reactor.

→ The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer.



→ Each capacitor bank is switched on and off by three thyristor switches (Thyristor switched capacitor (or) TSC).

→ Reactors are either switched on-off (Thyristor Switched Reactor or TSR) or phase-controlled (Thyristor controlled Reactor (or) TCR).

→ The thyristor-switched capacitor, thyristor-controlled reactor (TSC-TCR) type Var generator was developed primarily for dynamic compensation of power transmission systems with the intention of minimizing standby losses and providing increased operating flexibility.

→ A Basic TSC-TCR consists of n TSC branches and one TCR.

→ The numbers of branches n is determined by practical considerations that include the operating voltage level, maximum VAR output, current rating of the thyristor valves, bus work, and installation cost, etc.. Of course, the inductive range also can be expanded to any maximum rating by employing additional TCR branches.

## V-I CHARACTERISTIC OF SVC

→ The SVC can be operated in two different modes: one is voltage regulation mode and another is VAR control mode (The SVC susceptance is kept constant).

→ when the SVC is operated in voltage regulation mode: it implements the following V-I characteristics.

→ As long as the SVC susceptance B stays within the maximum and minimum susceptance values imposed by the total reactive power of capacitor banks ($B_{Cmax}$) and reactor banks ($B_{Lmax}$), the Voltage is regulated at the reference voltage $E_{ref}$.

→ However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristics has the slope indicated in the V-I characteristics is described by the following three equations.

SVC is in regulation range $(-B_{Cmax} < B < B_{Lmax})$ —①

$$E = E_{ref} + X_c I .$$

If SVC is fully capacitive $(B = B_{Cmax})$

$$E = \frac{1}{B_{Cmax}} \quad \text{——— ②}$$

If SVC is fully inductive $(B = B_{Lmax})$

$$E = \frac{1}{B_{Lmax}} . \quad \text{——— ③}$$

where

E = Positive sequence voltage (P.u)

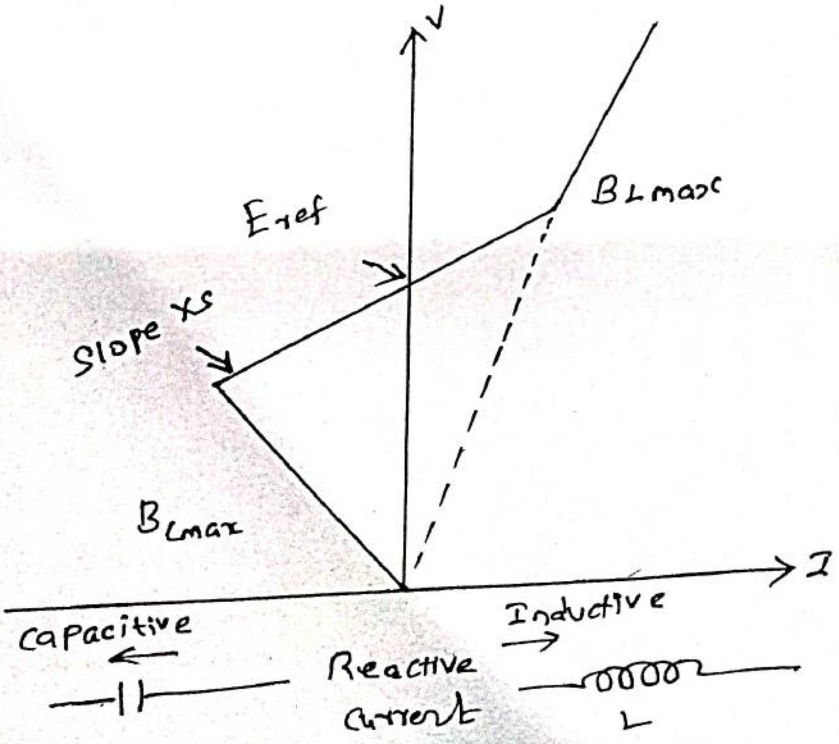
I = Reactive Current (P.u / $P_{base}$) (I > 0 indicates an inductive current)

$X_s$ = slope or droop reactance (P.u / Pbase)

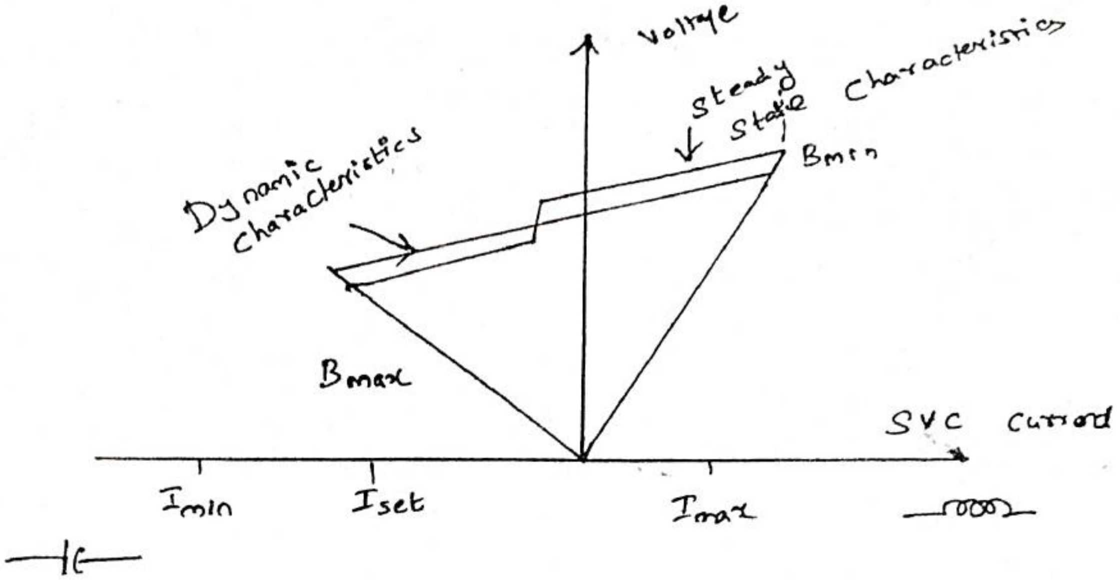
$B_{Cmax}$ = Maximum capacitive susceptance (P.u / Pbase) with all TCSs in service, no TSR (or) TCR.

$B_{Lmax}$ = Maximum inductive susceptance (P.u / Pbase) with all TSRs in service or TCRs at full condition. no TSC

Pbase = Three - phase base power.



# STEADY STATE AND DYNAMIC VI CHARATERISTICS OF SVC



→ In the active control range, current / susceptance and reactive power is varied regulate voltage according to a slope (droop) characteristics.

→ The slope value depends on the desired voltage regulation, the desired sharing of reactive power production between various sources, and other needs of the system.

→ The slope is typically 1-5 %. At the capacitive limit, the SVC becomes a shunt capacitor.

→ At the inductive limit, the SVC becomes a shunt reactor (the current (or) reactive power may also be limited).

The different operating region of SVC Voltage / current characteristics are given by

(i) Reference voltage, $E_{ref}$
(ii) Linear control Range
(iii) Slope or current Droop
(iv) Overload Range
(v) Overcurrent Limit

## (i) Reference voltage, $E_{ref}$

→ This is the voltage at the terminals of the SVC during the floating condition, that is, when the SVC is neither nor generating any reactive power.

→ The reference voltage can be varied between the maximum and minimum limits which is set either by the SVC control system or by the taps of the coupling transformer.

## (ii) Linear control Range.

→ In this control range SVC terminal voltage varies Linearly with SVC current or reactive power, In which the reactive power is varied over its entire capacitive to Inductive range

## (iii) Slope (or) current Droop

$$K_s = \frac{\Delta V}{\Delta I} \text{ ohm}$$

$\Delta V$ = the change in voltage magnitude (V)

$\Delta I$ = the change in current magnitude (A)

### (iv) overload Range

when the SVC cross outside the Linear controllable range on the inductive side, the SVC enters the overload region, in this condition it behaves like a fixed inductor.

### (v) over current limit

The maximum inductive current in the overload range is controlled to a constant value by an additional control action in order to prevent the thyristor valves from being subjected to excessive thermal stresses

### SVC Dynamic Response

$$T_c = \frac{1}{K_i (X_s + X_n)}$$

$T_c$ = closed loop time constant

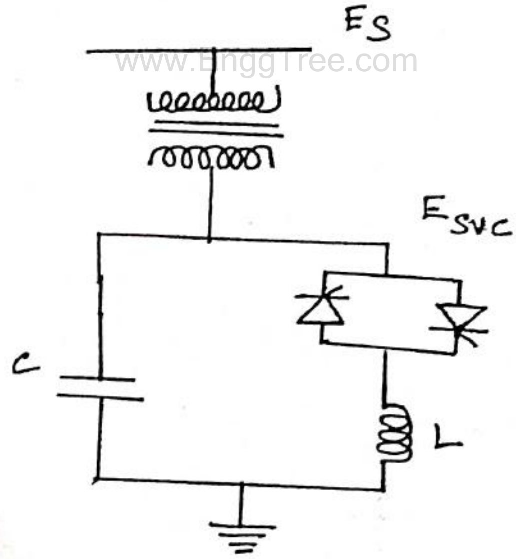
$K_i$ = Proportional gain of the voltage regulator

$X_s$ = slope reactance P.u./Pbase

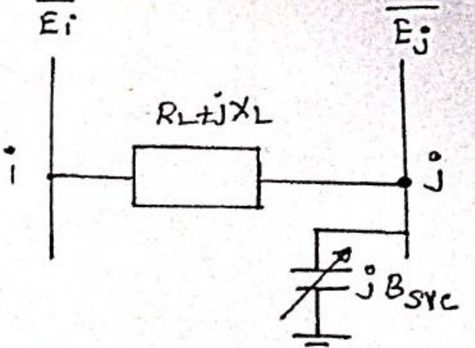
$X_n$ = Equivalent power system reactance (P.u/P.base)

## VOLTAGE CONTROL BY SVC

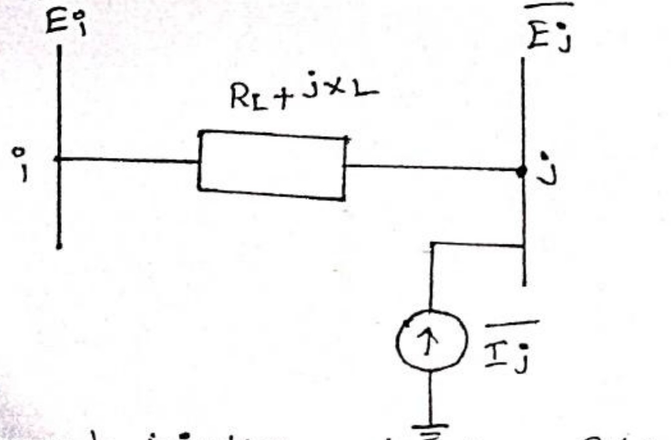
- → The static VAR compensator (SVC) is shunt connected device whose main functionality is to regulate the voltage at a chosen bus by suitable control of its equivalent reactance.
- → A basic topology consists of a series capacitor bank, C, in parallel with a thyristor controlled reactor, L.
- → In practice the SVC can be seen as an adjustable reactance that can perform both inductive and capacitive compensation.



Basic SVC Topology



Representation of a SVC



Current injection model of a SVC

→ where $I_{jsvc}$ is the complex svc injected Current at node j, $E_i$ and $E_j$ are the complex Voltages at nodes i and j.

→ The reactive power injection in node j is given by

$$Q_j = -E_j^2 B_{svc} \text{ ——— } ①$$

where, $B_{svc} = B_C - B_L$, $B_C$ and $B_L$ are the susceptance of the fixed capacitor and thyristor controlled reactor, respectively. The reactive power can be transferred into injected current at bus 'j' given by:

$$Q_{jsvc} = j E_j B_{svc} \text{ ——— } ②$$

→ The injected SVC current thus results in a voltage drop of which is in phase with the system voltage $E_s$.

→ The SVC bus voltage increases with the capacitive SVC current and decreases with the inductive SVC current.

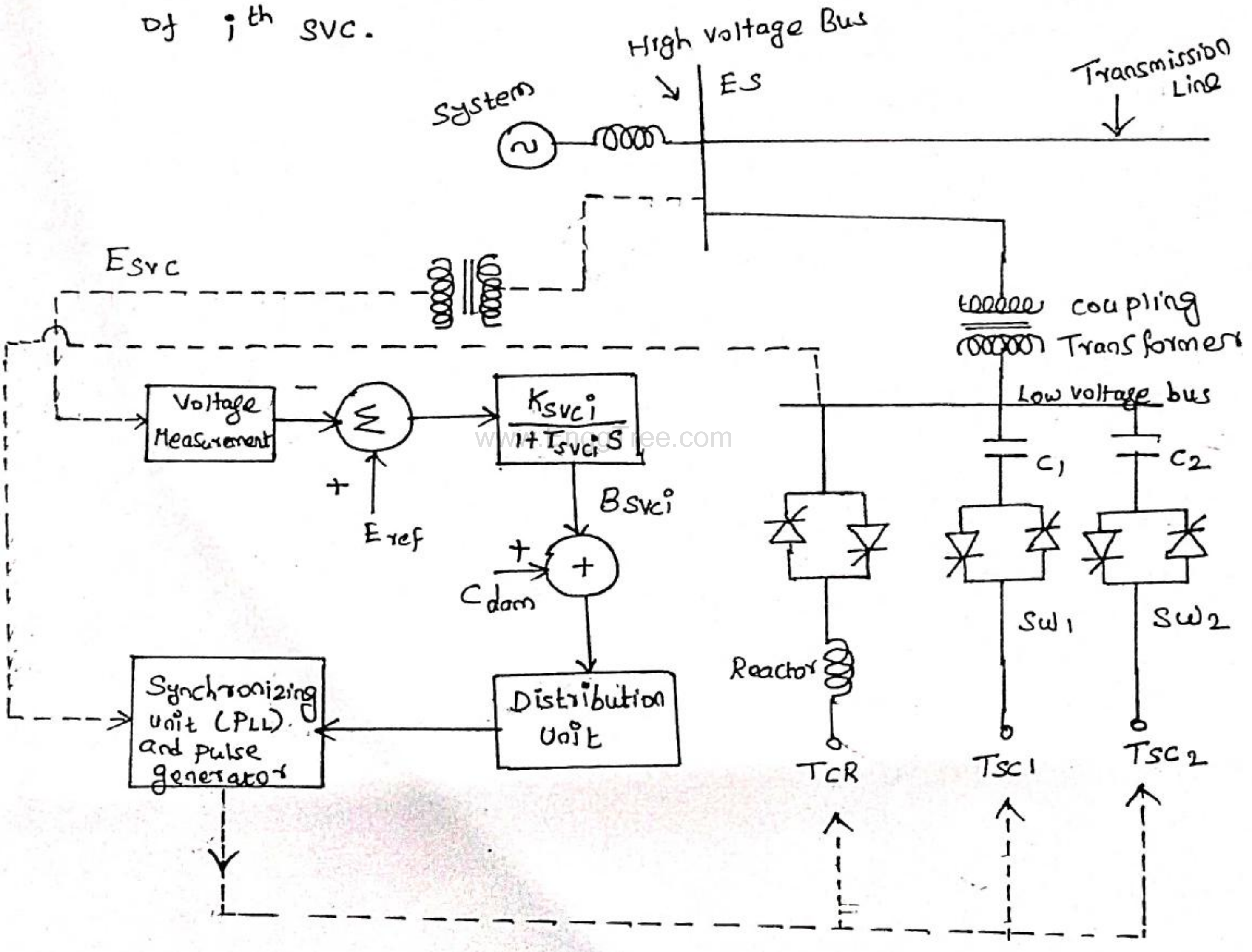
→ Also the SVC is more efficient in controlling voltage in weak AC systems and less efficient in strong AC systems.

→ SVC is basically represented by a variable reactance with maximum inductive and capacitive limits to control the bus voltage.

→ A total reactance Bsvc is assumed and the differential equation can be expressed.

$$B_{svci} = \frac{1}{T_{svci}}\left[-B_{svc} + K_{svci}\left(E_{ref} - E_{svc}\right)\right] \quad ③$$

Where $K_{svci}$ and $T_{svci}$ are the gain and time constant of $i^{th}$ SVC.



The SVC control system consists of the following four Main Modules.

(1) Measurement System

→ The measurement system measures the Positive sequence primary voltage.

→ This system uses discrete Fourier computation technique to evaluate fundamental Voltage over a one cycle.

→ The voltage measurement unit is driven by a Phase locked loop (PLL) to take into account Variations of System frequency.

## (2) Voltage Regulator

→ The voltage Regulator uses a PI regulator to regulate primary voltage at the reference voltage.

→ A voltage drop is incorporated in the voltage regulation to obtain a V-I characteristics with a slope.

→ SVC operating point changes from fully capacitive to fully inductive.

## (3) Distribution unit.

→ The Distribution unit uses the primary susceptance Bsvc computed by the voltage regulator to determine the TCR firing angle $\alpha$ and the Status (on/off) of the three TSC branches

$$B_{TCR} = \frac{2(\pi-\alpha)+\sin(2\alpha)}{\pi}$$

## (4) Firing unit

→ Firing unit consists of a PLL Synchronized on Line-to-Line Secondary voltage and a pulse generator for each of the TCR and TSC branches.

→ The pulse generator uses the firing angle $\alpha$ and the TSC status coming from the Distribution Unit to generate pulses.

## Advantages of slope in dynamic characteristics

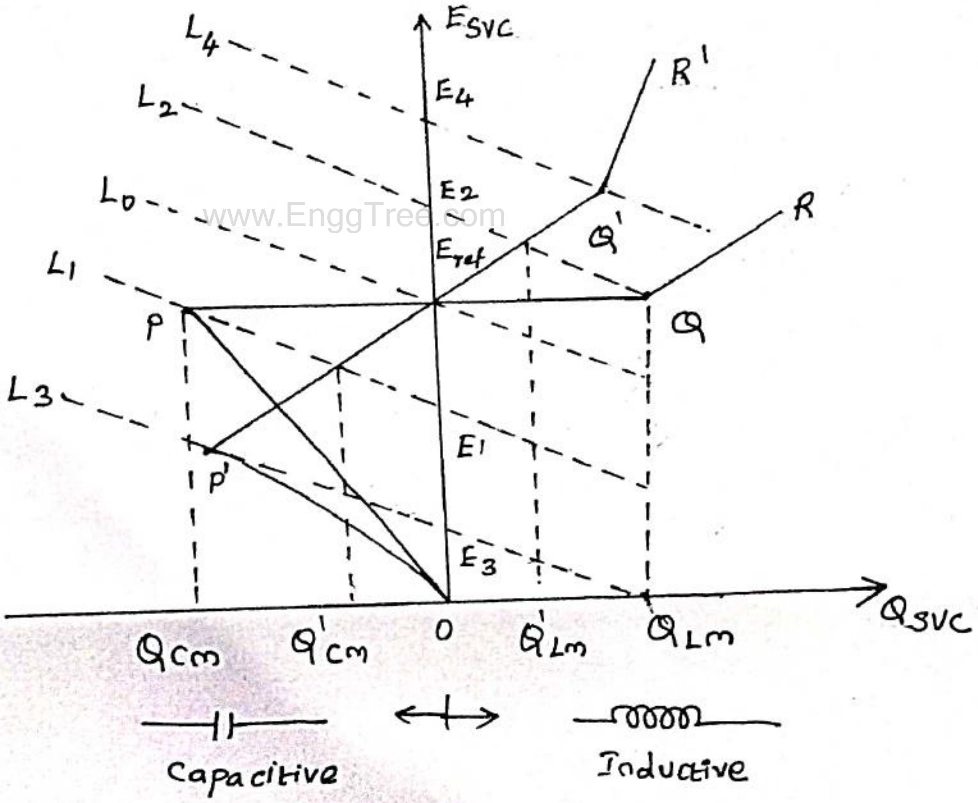
→ significance reduction of the reactive power rating of the SVC for achieving same control objectives.

→ Prevention of reaching reactive power too frequently.

→ Sharing of reactive power during operation of Multiple compensators in parallel.

### (a) Significance reduction of the reactive power rating of the SVC for achieving same control objectives

→



→ Finite slop is introduced only in QP'Q'R' characteristics, but not in characteristics OPQR. It is assumed that the system load line varies between $L_1$ and $L_2$.

→ From the characteristics OPQR required maximum reactive power rating of the SVC for providing

Smooth voltage regulation is $Q_{cm}$ capacitive to $Q_{Lm}$ inductive was determined.

→ If a slight deregulation in the SVC bus voltage is considered and is demonstrated by the characteristics $OP'Q'R'$.

→ From the characteristics $OP'Q'R'$ required maximum reactive power rating of the SVC for performing the voltage control corresponding to the same same variation in the system load line is $Q'_{cm}$ capacitive to $Q'_{Lm}$ inductive.

→ clearly shows $Q'_{cm} < Q_{cm}$ and $Q'_{Lm} < Q_{Lm}$.

(b) prevention of reaching reactive power to frequently

→ If there is no slope in the dynamic characteristics, even a small change in the system load line from a small variation, $E_2 - E_1$, in the no-load equivalent system voltage, as viewed from the SVC bus may cause the SVC to traverse from one end of the reactive-power range to the other end to maintain constant voltage.

→ If the AC system tends to be strong then the reactive power limits of the SVC are reached more frequently. under this condition the slop of the system load line is quite small. Therefore the effectiveness of the SVC as a voltage control device becomes limited.

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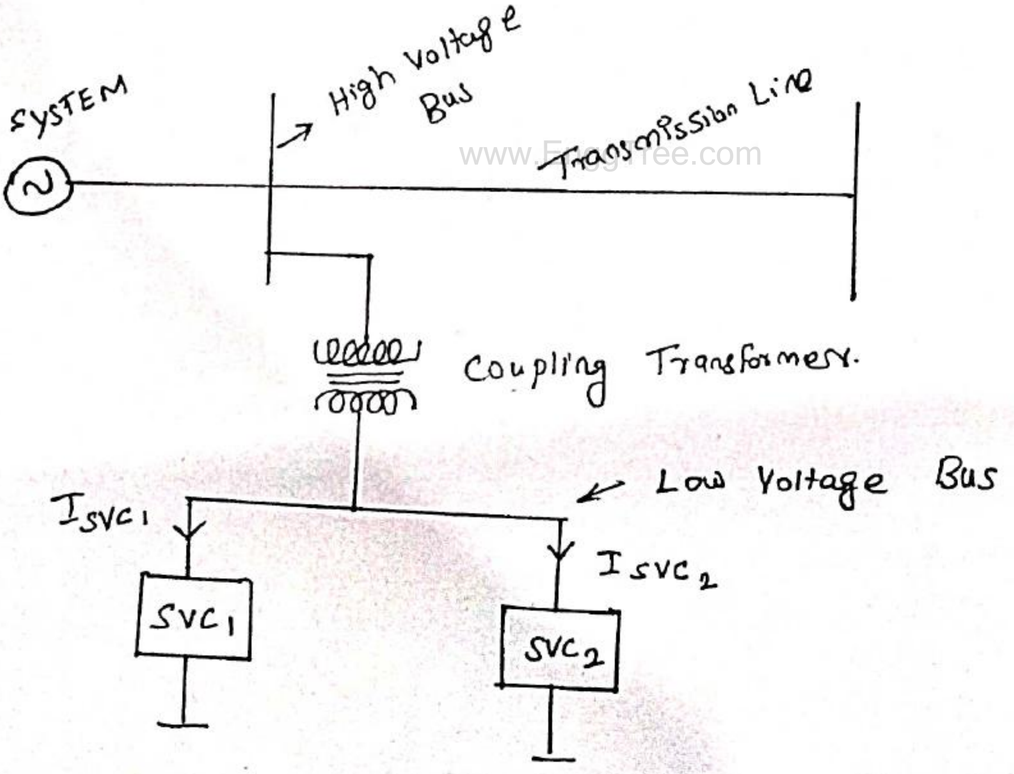
→ An introduction of finite slop in the V-I characteristics the svc operates continuously in the linear controllable range for a much larger variation in the load line of the external AC system.

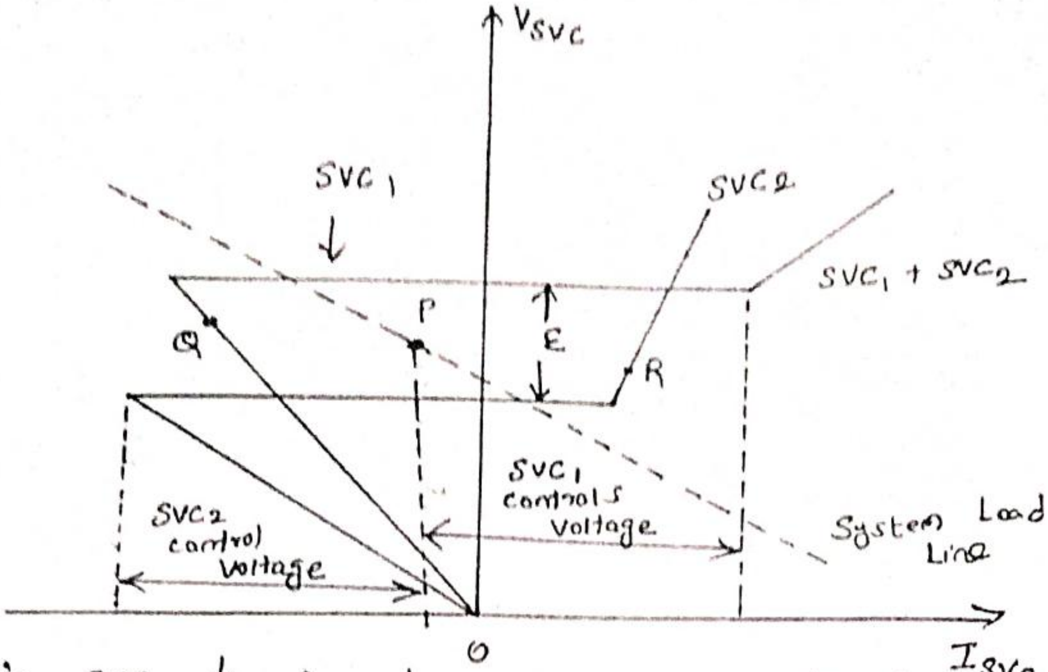
→ For instance E$_4$-E$_3$ in the equivalent AC system no load voltage, the SVC can exercise voltage control for a significantly larger variation.

(c) Sharing of reactive power during operation of multiple compensators in parallel.



Two SVCs connected in Parallel at a System bus.

→ The control action must be coordinated when more than one compensator is used at one location in order to obtain reliability and for minimizing the net harmonics generation.



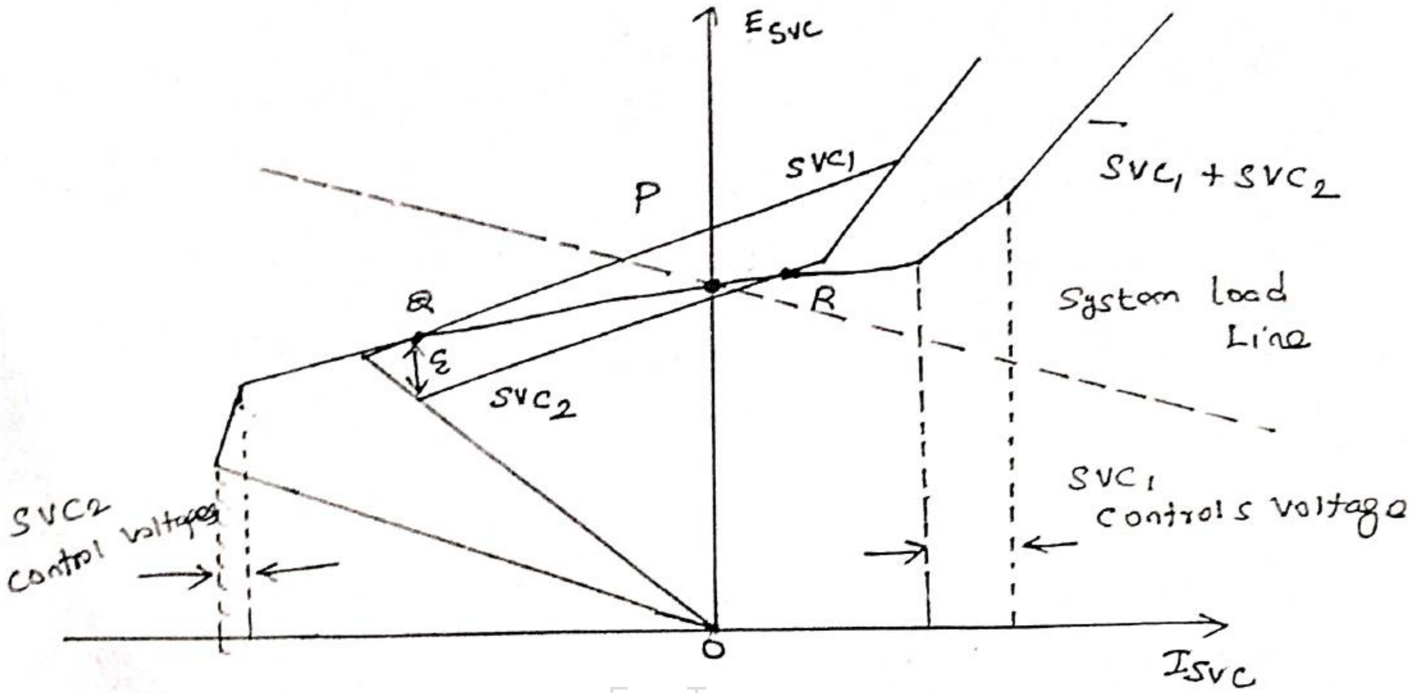
Slop in svc dynamic characteristics with out difference in the reference - voltage set points.

→ The ratings of two SVCs are same but the reference voltages ($E_{ref}$) of the two control characteristics differs by a small amount although it is not almost zero.

→ The combined V-I control characteristics of the two SVCs is derived by summing up the individual currents of both SVCs for the same bus voltage magnitude.

→ The combined operating characteristis in the case of zero current slopes is set with a discontinuity in point P.

→ Full reactive power production on svc, (point Q) and full inductive - reactive power absorption on SVC$_2$ (point R) is obtained at quiescent operating Point P, which is obtained at intersection of V-I characteristics by System Load Line.



→ SVC$_2$ controls the bus voltage at the Left side of Point P, whereas SVC$_1$ remains in full production. However, on the right side of point P, SVC$_1$ controls the bus voltage and SVC$_2$ is at full absorption.

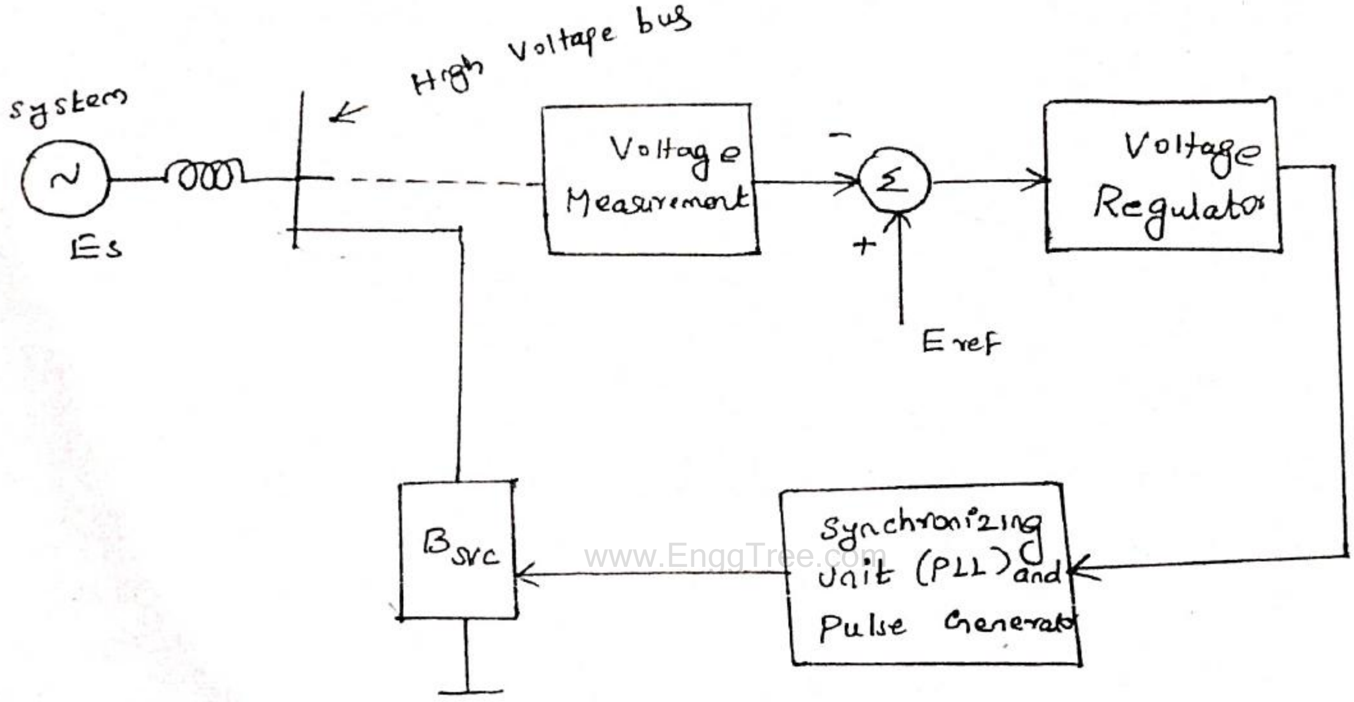
→ The combined operating characteristic of both SVCs is continuous regardless of the difference in the voltage reference set points in current drop region.

→ If the two SVCs and the power System achieve a Stable-operating Point P, SVC$_1$ operates at Q and SVC$_2$ at R.

## INFLUENCE OF THE SVC ON THE SYSTEM VOLTAGE

### (1) without considering coupling Transformers

→ The efficient use of SVC in regulating the System Voltage is dependent on the relative strength of the connected AC System.



→ The effect of the coupling transformer is not considered and the SVC is modeled as a controlled susceptance at the high voltage bus.

→ The SVC is considered absorbing reactive power from the AC System while it operates in the inductive mode and supplying reactive powers to the AC System while it operates in the capacitive mode.

The SVC bus Voltage, Esvc, is given by

$$E_{SVC} = E_{ref} + X_s I_{SVC} \quad \text{——} ①$$

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Linearizing equation ① gives the Variation in the $E_{SVC}$ as a function of change in the SVC current, $I_{svc}$. Thus for the constant - ephuivalent - source voltage $E_s$,

$$\Delta E_{svc} = -X_s \Delta I_{svc} \quad \text{—— ②}$$

The $E_{SVC}$ is also related to $I_{SVC}$ through the SVC reactance, $B_{SVC}$ as follows.

$$I_{svc} = B_{svc} \cdot E_{svc} \quad \text{—— ③}$$

For incremental charges Equaton ③ is Linearized to give

$$\Delta I_{svc} = B_{svc_0} \Delta E_{svc} + \Delta B_{svc} E_{svc_0} \quad \text{—— ④}$$

Substituting $\Delta I_{svc}$ from epuation ④ in epuaton ②

$$\Delta E_{svc} = -X_s [B_{svc_0} \Delta E_{svc} + \Delta B_{svc} \cdot E_{svc_0}]$$

$$\Delta E_{svc} = -X_s B_{svc_0} \Delta E_{svc} - X_s \Delta B_{svc} E_{svc_0}$$

$$\Delta E_{svc} + X_s B_{svc_0} \Delta E_{svc} = -X_s \Delta B_{svc} E_{svc_0}$$

$$\Delta E_{svc} [1 + X_s B_{svc_0}] = -X_s \Delta B_{svc} E_{svc_0}$$

$$\frac{\Delta E_{svc}}{\Delta B_{svc}} = \frac{-X_s E_{svc_0}}{[1 + X_s B_{svc_0}]}$$

$$= \frac{-E_{svc_0}}{\left[\frac{1}{X_s} + \frac{X_s B_{svc_0}}{X_s}\right]}$$

$$\frac{\Delta E_{svc}}{\Delta B_{svc}} = \frac{-E_{svc_0}}{\left[\frac{1}{X_s} + B_{svc_0}\right]} \quad \text{——} ⑤$$

where the effective short-circuit ratio (ESCR) is defined as

$$\cancel{ESCR = \left[\frac{1}{X_s} + B_{svc_0}\right]}$$

$$\cancel{ESCR =} \qquad ESCR = \frac{1}{(-\Delta E_{svc} / \Delta I_{svc})}$$

From equation ②

$$\frac{-\Delta E_{svc}}{\Delta I_{svc}} = X_S$$

So $$\frac{1}{X_s} = \frac{-\Delta I_{svc}}{\Delta E_{svc}} \quad (\text{or}) \quad \frac{1}{X_s} = \frac{1}{\left(\frac{-\Delta E_{svc}}{\Delta I_{svc}}\right)}$$

So $$\frac{1}{X_s} = ESCR \quad \text{——} ⑥$$

Sub ⑥ in ⑤

$$\frac{\Delta E_{svc}}{\Delta B_{svc}} = \frac{-E_{svc_0}}{ESCR + B_{svc_0}} \quad \text{——} ⑦$$

$$= \frac{1}{X_s} = B_S \quad \text{——} ⑧$$

where $B_S$ is the equivalent system susceptance.

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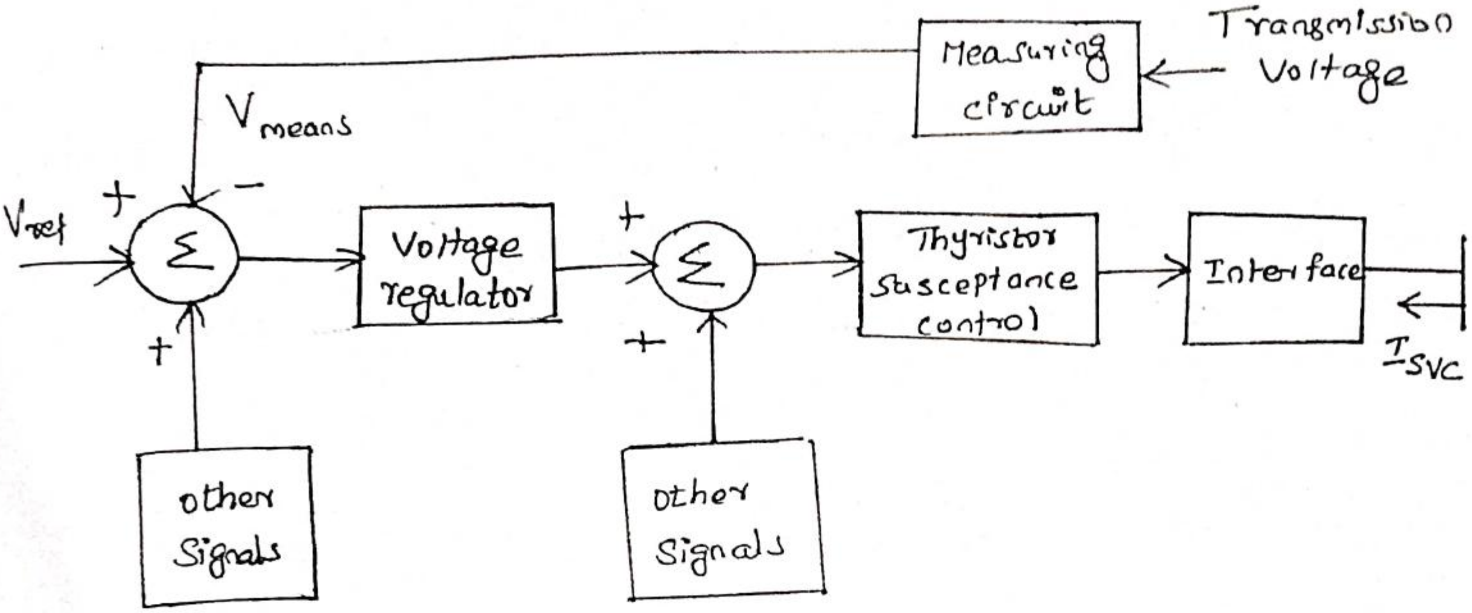
## SVC Voltage Regulator Design



→ SVC is basically a shunt connected static VAR generator/Load whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variables; typically, the controlled variable is the SVC bus voltage.

→ One of the major reasons for installing a SVC is to improve dynamic voltage control, and this, increase system Load ability.

→ An additional Stabilizing signal, and supplementary control, superimposed on the voltage control loop of a SVC can provide damping of system oscillation.

→ The SVC is basically represented by a variable reactance with maximum inductive and capacitive limits to control the SVC bus voltage, with an additional control block and signals to damp-out electromechanical oscillations.

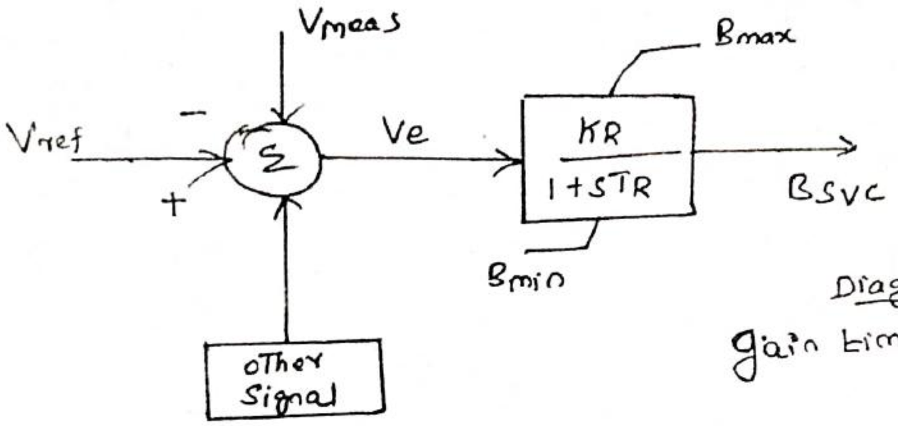


Diagram (1)
gain time constant

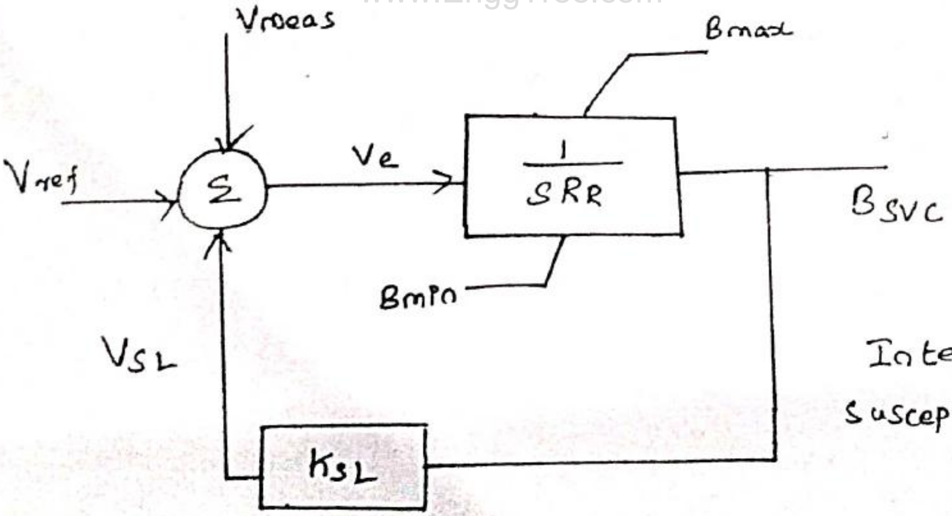


Diagram (2)
Integrator with susceptance drop feedbac

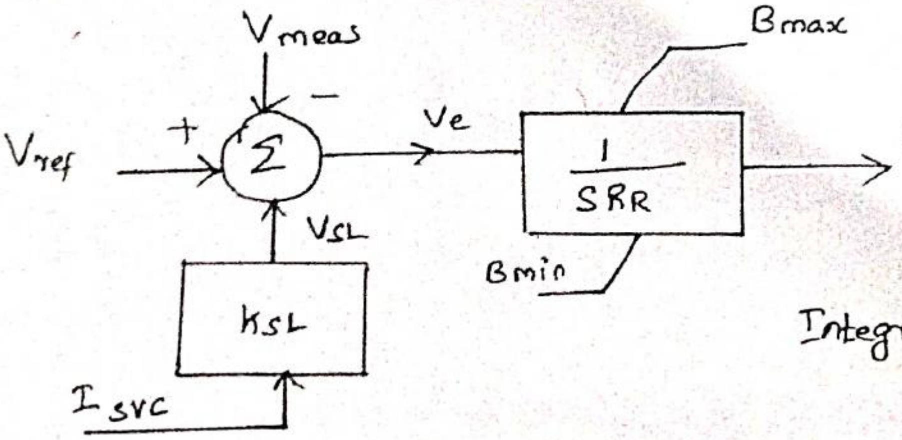


Diagram (3)

Integrator with current drop feedback.

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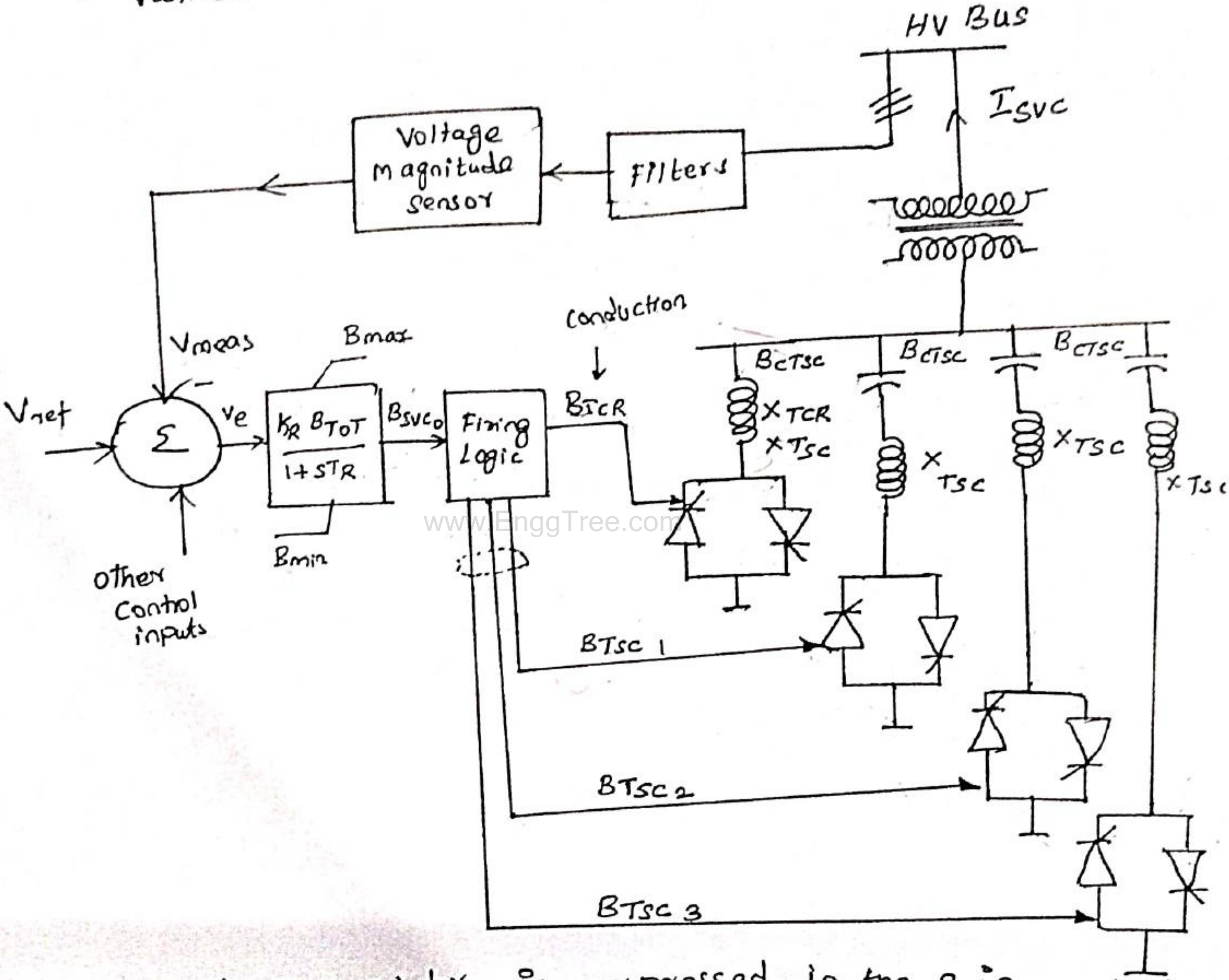
## Design

→ change in system voltage caused by the SVC is small.

→ SVC bus voltage is very close to the nominal rated voltage

→ Variations in the SVC reference voltage are also quite small.



→ The voltage regulator is expressed in the gain constant format. In the gain time constant representation, the voltage regulator is expressed by the following transfer function

$$G_R(s) = \frac{K_R}{1+sT_R}$$

where

$K_R$ = the static gain = $1/K_{SL}$ (PU)

$K_R$ : The static gain.

$T_R$ = Time constant of regulator

$B_{SVC0}$ = resultant susceptance

$B_{min}$ = $B_{SVC}$ at the TCR only

$B_{max}$ = $B_{SVC}$ at all TSCs only

$K_{SL}$ = the current droop

$T_R$ = the regulator time con.

An aditional transient gain, $K_T$ is defined as

$$K_T = K_R / T_R$$

In the integrator current droop model, the voltage regulator is represented as an integrator $G_R(s)$ with the explicit current feed back loop

$$G_R(s) = \frac{1}{S R_P}$$

where $R_R$ = the response rate (ms/pu)

The relationship between the regulator time constant $T_R$ and the response rate $R_R$ as given as

$$T_R = \frac{R_R}{K_{SL}}$$

The thyristor phase control is indicated by $G_y$ and is given by

$$G_y(s) = \frac{e^{-sT_d}}{1+sT_y}$$

where $T_d$ = The thyristor dead line

$T_y$ = firing delay time of thyristor caused by the switching sequence

A PI controller with fastest stable response for the weakest system configuration having gain $K_{N\,max}$ is determined as

$$G_R(s) = K_P\left[1+\frac{1}{ST_Y}\right]$$

$$= -\frac{1}{2(K_{SL}+K_{N\,max})}\left[1+\frac{1}{ST_Y}\right]$$

The overall closed loop trasfer function, $G_w(s)$, of the control system for incremental variation is given by

$$G_w(s) = \frac{\Delta V(s)}{\Delta V_{ref}(s)} = \frac{K_N G_R G_y}{1+(K_{SL}+K_N)G_R G_y H_M}$$

$H_m$ - is the transfer function of the measurement system

## Thyristor controlled series compensator (TCSC).

→ Thyristor controlled series capacitor is a series FACTS device.

→ TCSC is a capacitive reactance compensator which consists of a series capacitor bank shunted by a Thyristor controlled reactor (TCR).

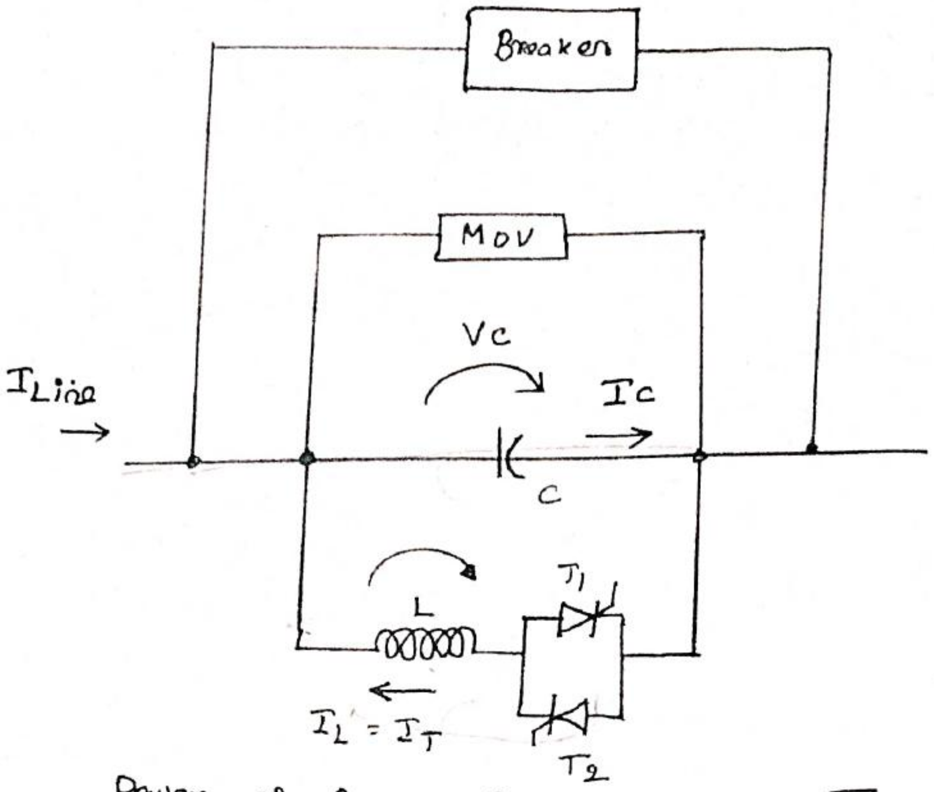
→ TCSC is more effective and provides distinct solutions due to flexible control of thyristor.

→ TCSC is connected in series with the transmission line conductors in order to offset the inductive reactance of the line.

→ TCSC plays vital roles in the operation and control of power systems such as enhancing power flow, limiting fault current, enhancing transient and dynamic stability.

Advantages of TCSC

→ Increase power transmission capability
→ Improve system stability
→ Reduce system losses
→ Improve voltage profile of the lines
→ optimize power flow between parallel lines
→ Damping of the power swings from local and inter area oscillations
→ Suppression of sub-synchronous oscillations
→ Enhanced level of protection for series capacitors
→ In the events of high short-circuit current.



Power circuit configuration of a TCSC Module.

→ A TCSC module consists of a Series and a Parallel Path ~~fadu~~ including a thyristor switch and a Series inductor.

→ Metal - oxide Varistor (MOV) for overvoltage protection and a bypass breaker.

→ A complete TCSC System may consist of several such modules and conventional Series capacitor Part in series to improve the over all power System efficiency.

→ TCSC is a controllable power electronic element in the whole power circuit, and line impedance Can be adjusted by the phase control of its thyristor switches.

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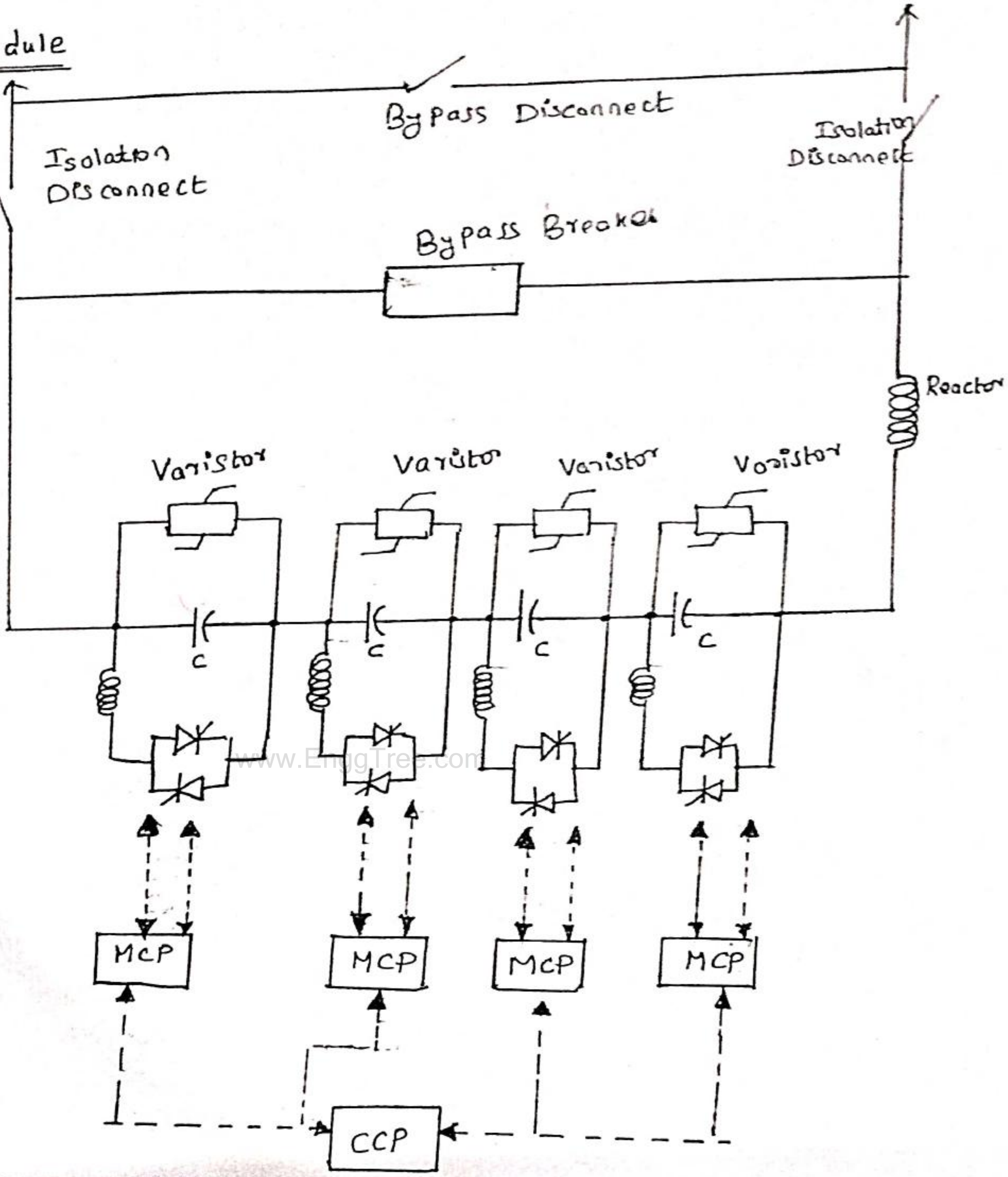
## TCSC Module



→ The TCSC basically comprises a capacitor bank inserted in series with the transmission line. a parallel metal oxide Varistor (MOV) to protect the capacitor against over voltage and a TCR branch, with a thyristor value in series with reactor, in parallel with the capacitor.

- → Mechanically bypass breakers are provided in Parallel with the capacitor bank and in Parallel with the thyristor valve.
- → During normal operation, the bypass switch is open, the bank disconnect switches (1 and 2) are closed and the circuit breaker is open.
- → when it is required to disconnected the TCSC, the bypass circuit breaker is switched on first, and then the bypass switch is switched on.
- → The damping circuit is used to limit the current when the capacitor is switched on (or) when the bypass circuit breaker is switched on.

- → Minimum series compensation is achieved when the TCR is off.
- → The TCR can be selected to achieve the ability to restrict the voltage at the capacitor at faults and other system contingencies of similar effect.
- → The control and Protection of TCSC are partitioned in two Levels; common and module. commands for both control and protective operations flow from the common Level to the module Levels.

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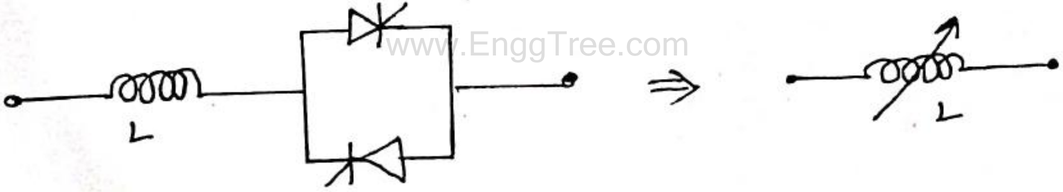
## PRINCIPLE OF OPERATION

→ The basic operation of TCSC can be easily explained from circuit analysis.

→ It consists of a series compensating capacitor shunted by a thyristor controlled reactor (TCR).

→ TCR is a variable inductive reactor ($X_L$) is controlled by firing angle $\alpha$. Here variation of $X_L$ with respect to $\alpha$ is given by

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin 2\alpha} \quad \text{—①}$$



→ For the range of 0 to 90 of $\alpha$, $X_L(\alpha)$ start very from actual reactance $X_L$ to infinity.

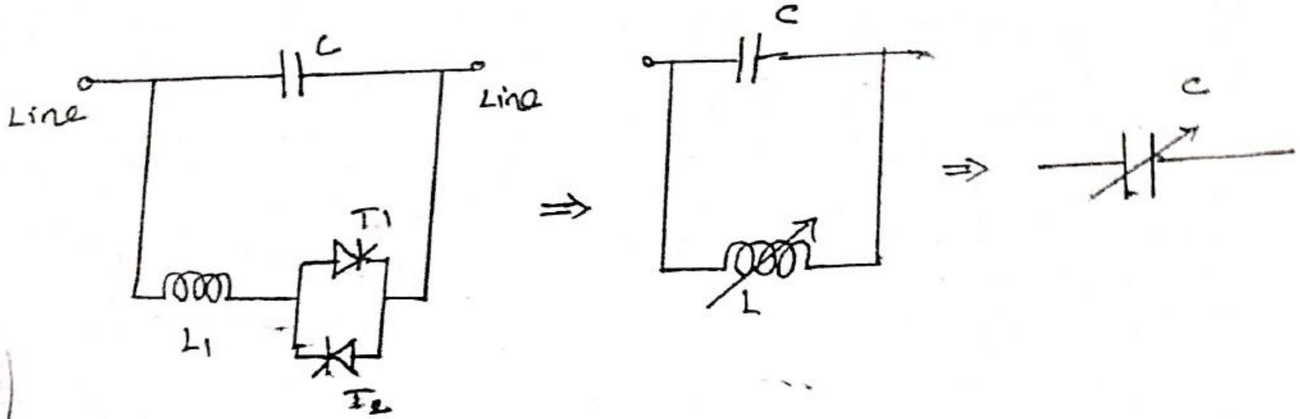
→ This controlled reactor is connected across the series capacitor, so that the variable capacitive reactance is possible across the TCSC to modify the transmission line impedance.

→ The fundamental effective TCSC reactance $X_{TCSC}$ with respect to the firing angle $\alpha$ of the thyristor is given as.

$$x_{Tcsc}(\alpha) = -x_c + c_1((2(\pi-\alpha)+\sin(2(\pi-\alpha))) - c_2 \cos^2 \cdot (\pi-\alpha)(\overline{\omega}\tan(\overline{\omega}(\pi-\alpha)) - \tan(\pi-\alpha) \quad \text{②}$$

where

$$X_{LC} = \frac{X_C X_L}{X_C - X_L}, \quad C_1 = \frac{X_C + X_L}{\pi}, \quad C_2 = \frac{4X_{LC}^2}{X_L \pi} \quad \text{③}$$



$x_L$ is the inductive reactance of TCSC in ohms, $x_c$ is the capacitive reactance of TCSC in ohms, $\omega$ is the Parameters which determines the operating Performance of TCSC and is given as

$$\overline{\omega} = \sqrt{\frac{x_c}{X_L}} = \frac{\omega_0}{\omega} \quad \text{④}$$

where $\omega$ is the network frequency while $\omega_0$ is the resonant frequency which occurs in a high Power electronic circuit such as TCSC when the inductive reactance $X_L = \omega_L$ and the capacitive reactance $X_c = 1/\omega c$. In addition, it is expressed as

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad \text{⑤}$$

From equation ②, it shows the relation between $\overline{\omega}$ and $X_{TCSC}(\alpha)$. The effective reactance $X_{TCSC}(\alpha)$ would be infinity, when

$$\overline{\omega}(\pi-\alpha) = (2m \pm 1)\frac{\pi}{2}; \quad (m = 1,2,3....) \qquad ⑥$$

(or)

$$\alpha_{crt} = \pi - \frac{(2m \pm 1)}{2\overline{\omega}}\pi \qquad ⑦$$

equation ⑦ showed that between $90^\circ$ and $180^\circ$ of firing angle $\alpha$, a Multiple TCSC resonant point may occur.

- → A proper operating performance of TCSC, only one resonant point, namely one capacitive range and one inductive range, is allowable.
- → Multiple resonant points will reduce the operating range of the TCSC. Thus, some measure as to be taken to ensure only one resonant point between $90^\circ$ to $180^\circ$ of $\alpha$.
- → one evident way to achieve a single TCSC resonant point is to restrict the value of $\overline{\omega}$ factor by

$$\overline{\omega} = \sqrt{\frac{X_C}{X_L}} = \frac{\omega_0}{\omega} < 3 \qquad ⑧$$

## Operating modes of TCSC

→ TCSC canbe classified four operating modes

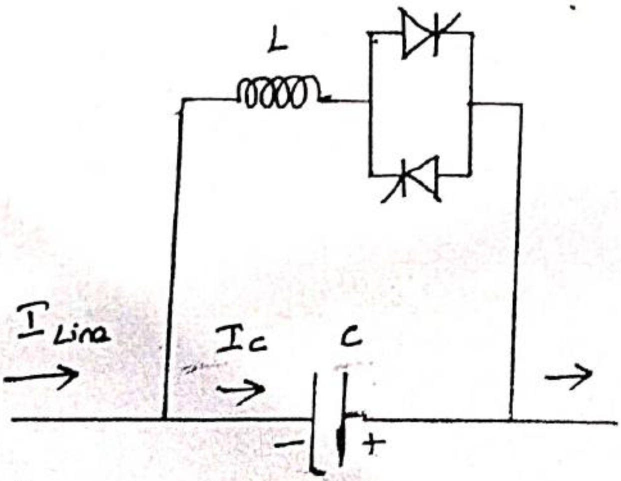
(1) Blocking mode (waiting mode)
(2) Bypass mode
(3) Capacitive boost mode (Capacitive Vernier mode)
(4) Inductive boost mode (Inductive Vernier mode)

### ① Blocking mode (waiting Mode)

→ In this mode the thyristor value is not triggered and the thyristors are kept in non-conducting state.

→ If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing.

→ The Line Current passes only through the capacitor bank ($X_{TCSC} = X_C$). Thus, the boost factor is equal to one.



→ In this mode the TCSC Performs Like a fixed series capacitor and the net TCSC reactance is capacitive.

→ The DC offset voltages of the capacitors are monitored continuously and quickly discharged using suitable control strategy without causing any harm to the

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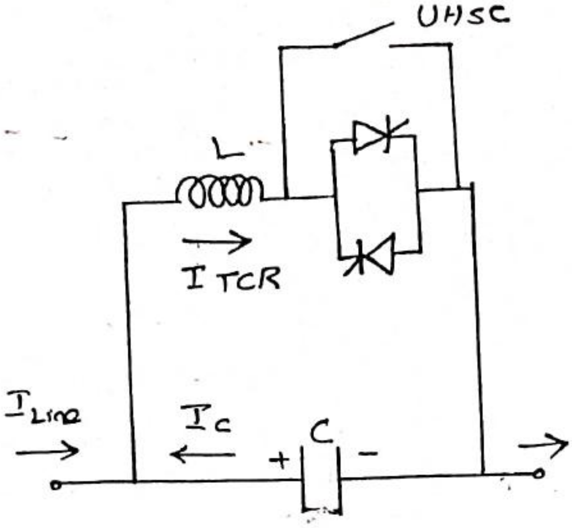
Transmission System transformers.

## (2) Bypass Mode.



→ In bypass mode the thyristor valve is triggered continuously and Therefore the valve stays conducting all the time.

→ In this mode, the thyristors are made to fully conduct with a conduction angle of 180° Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous flow of current through the thyristor valves.

→ The TCSC behaves like a parallel connection of the series capacitor and the inductor which gives the equivalent reactance.

→ In this mode, the resulting voltage in the steady state across the TCSC is inductive and the valve current is somewhat bigger than the line current due to the generation in the capacitor bank.

→ For practical TCSCs with $X_L/X_C$ ratio between 0.1 to 0.3 ranges. the amplitude of capacitor

Voltage Vc is much lower in bypass than in blocking mode.

Therefore, the bypass mode is utilized to reduce the capacitor stress during faults.

$$X_{TCSC} = \frac{X_L X_C}{X_L + X_C}$$

Vernier control mode.

- → This mode is also called Partially conducting thyristor mode which allows the TCSC to behave either as a continuously controllable capacitive reactance (or) as a continuously controllable inductive reactance.
- → This mode is ~~ach~~ achieved by Changing the thyristor Pair firing angle in an appropriate range.

→ Due to resonant region between the two modes, a smooth transition from the Capacitive to inductive mode is not permitted.

To prevent resonance, the firing angle of the forward conducting thyristor, as measured from the positive reaching a zero crossing of the capacitor voltage, is constrained in the range $\alpha_{min} \leq \alpha \leq 180°$.

→ This constraint provides a continuous Verinier control of the TCSC module reactance.

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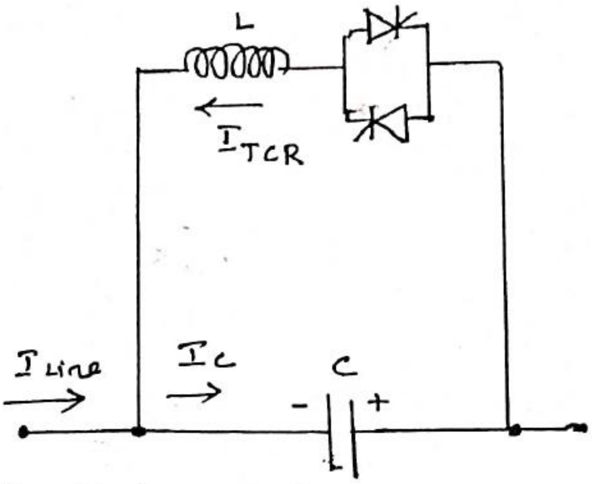
## (3) Vernier control mode (capacitive boost mode)



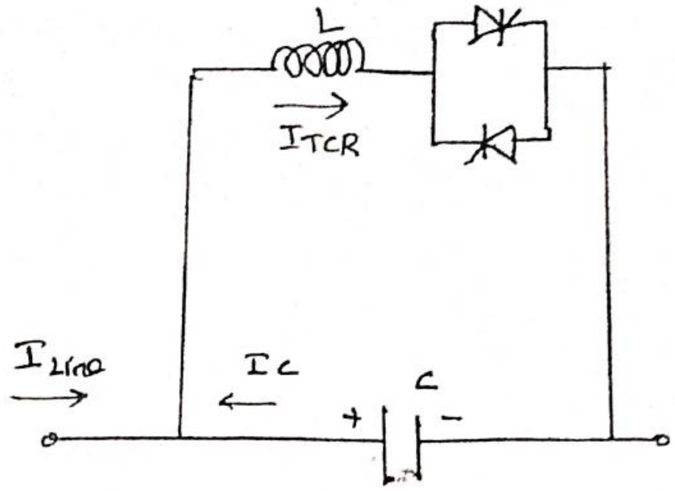
→ In capacitive boost mode a trigger pulse is supplied to the thyristor having forward voltage just before the capacitor voltage crosses the zero line, so a capacitor discharge current pulse will circulate through the parallel inductive branch.

→ The discharge current pulse adds to the line current through the capacitor and causes a capacitor voltage that adds to the voltage caused by the line current.

→ The capacitor peak voltage thus will be increased in proportion to the charge that passes through the thyristor branch.

→ The fundamental voltage also increases almost proportionally to the charge. From the system point of view, this mode inserts capacitors to the line up to nearly three times the fixed capacitor. this is the normal operating

## ④ Vernier control mode (Inductive boost mode)



- → Inductive boost mode the circulating current in the TCSC thyristor branch is bigger than the line current.
- → In this mode, Large thyristor currents result and further the Capacitor voltage waveform is very much distorted from its sinusoidal shape.
- → The Peak voltage appears close to the turn on.
- → The poor waveform and the high valve stress make the inductive boost mode less attractive for steady state operation
- → This mode increases the inductance of the Line, so it is in contrast to the advantages associated with the application of TCSC.

It is to be concluded based on the above operating modes of thyristor valve following variants of the TCSC occur.

→ Thyristor Switched Series capacitor (TSSC), which allows a discrete control of the capacitive reactance

→ Thyristor controlled Series capacitor (TCSC), which allows a continuous control of capacitive (or) Inductive reactance.

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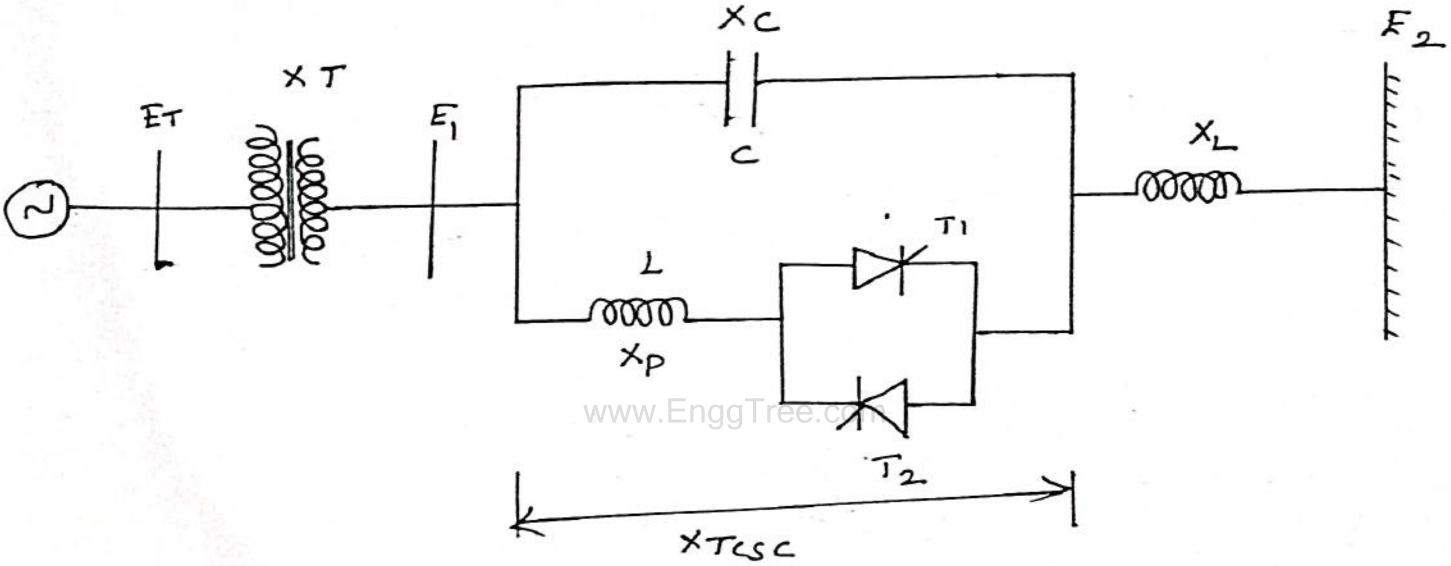
# APPLICATIONS OF TCSC

→ The TCSC device improves the power oscillation damping (POD), sub synchronous resonance (SSR) mitigation and transient stability.

## (i) Improvement of the System Stability Limit.



→ Bulk power cannot be transmitted over a long distance and line may become severely over loaded due to the outage of a critical line in a meshed system.

→ Under this condition provision of fixed series compensation on the parallel path is a feasible solution to expand the power transfer capability but it may increase the total system losses.

→ A qualitative analysis of the performance of the TCSC steady state stability control for both line power flow and line current magnitude input signals can be carried out on the simple single machine connected to an infinite bus (SMIB) system.

→ If the classical machine Model is used and the resistance on the network is neglected, the generator real powers can be expressed as

$$P_{12} = \frac{E_1 E_2}{(X_L - X_C)} \sin\delta = \frac{E_1 E_2}{(X_L - (X_{eo} + X_m))}$$

Where

$P_{12}$ = the power flow from bus 1 to bus 2

$E_1 E_2$ = The voltage magnitudes of buses 1 and 2, respectively.

$X_L$ = The equivalent reactance of the transmission link without the compensator (including the reactance of the transformer and the line as well as the generators's transient reactance)

$X_C$ = The controlled TCSC reactance combined with fixed series capacitor reactance

$X_{eo}$ = denotes the TCSC steady state reactance

$X_m$ = Modulation reactance obtained from stability contro

$\delta$ = The difference in the voltage angles of buses 1 and 2 (internal generator phase angle).

→ This change in transmitted power is further accomplishe with minimal influence on the voltage of interconnecting buses, as it introduces voltage in quadrature.

→ The freedom to locate a TCSC almost anywhere in a line is a significant advantage.

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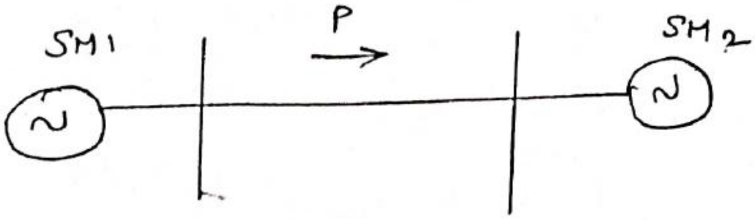
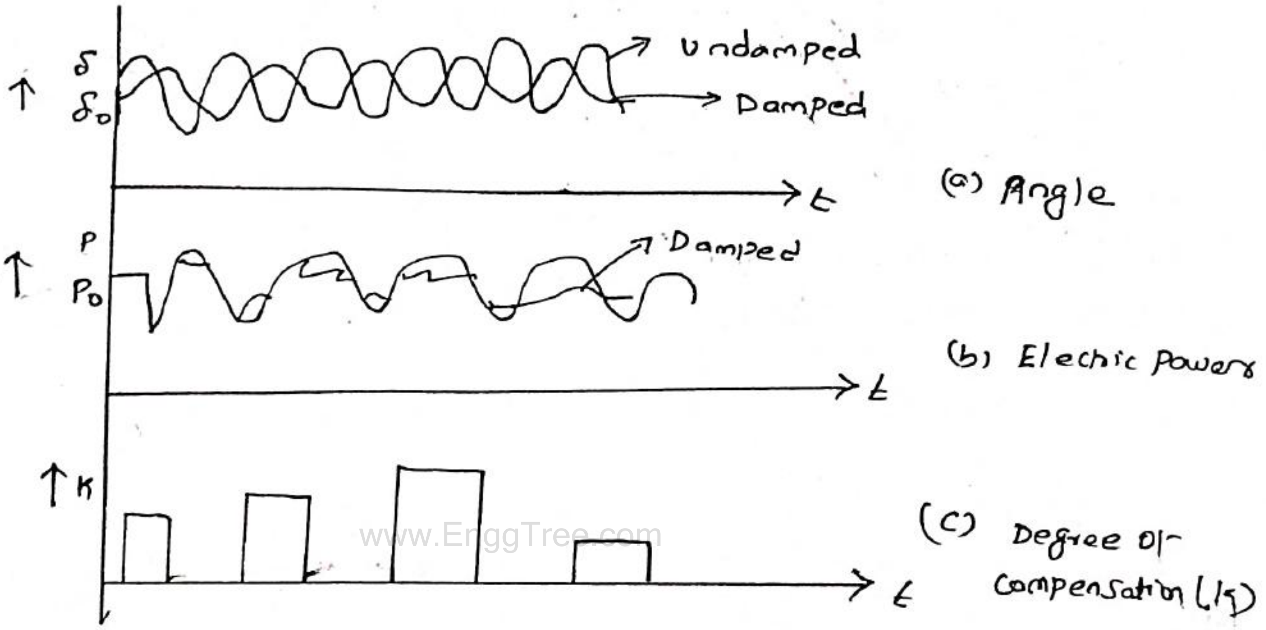
## (2) Damping of power oscillations using TCSC





(a) Angle

(b) Electric Power

(c) Degree of compensation (K)

PoD [Power oscillation damping] waveforms for TCSC

### Role of TCSC for damping control.

→ During normal operation stabilize both post disturbance oscillations and impulsively increasing oscillations

→ prevent the high frequency resonance network interaction

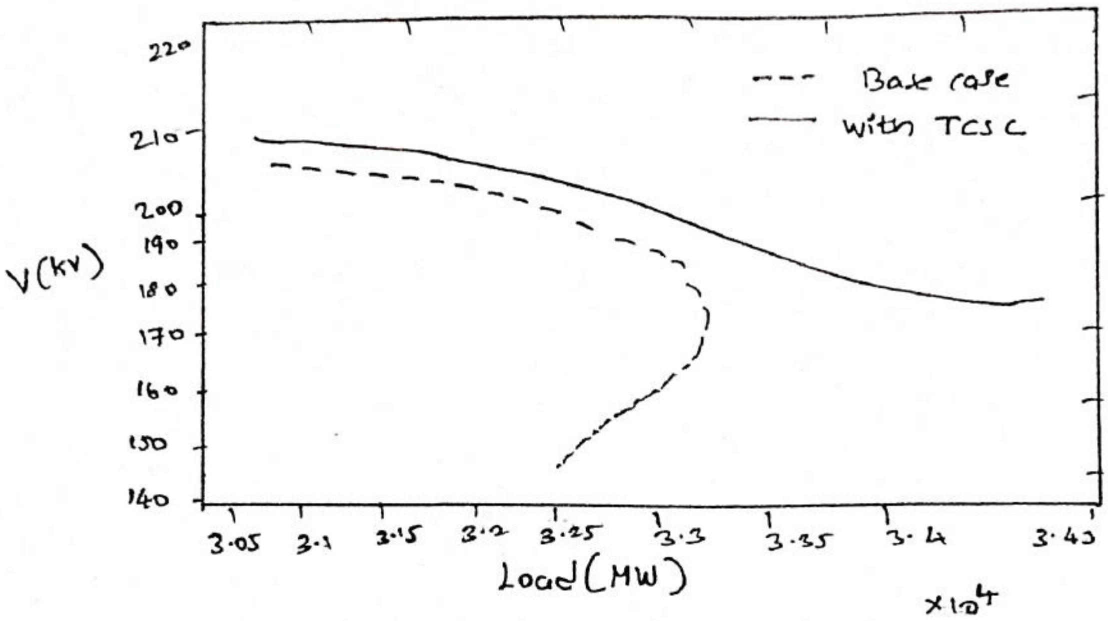
→ prevent local instabilities within the controller bandwidth

### Requirement of good damping control.

→ Should be robust in that it informs the desired damping over a wide range of system operating conditions

→ should be reliable.

## (3) Voltage collapse Prevention



→ Voltage collapse problems are a serious concern for power system engineers and planners. Voltage collapse is mathematically indicated when the system Jacobian becomes singular.

→ The collapse points are indicative of the maximum loadability of the transmission lines or the available transfer capability.

→ While the TCSC reduces the effective line reactance, thereby increasing the power flow, it generates reactive power with increasing through current, thus exercising a beneficial influence on the neighboring bus voltage.

→ Represents the voltage profile of the critical bus employing 50% TCSC compensation

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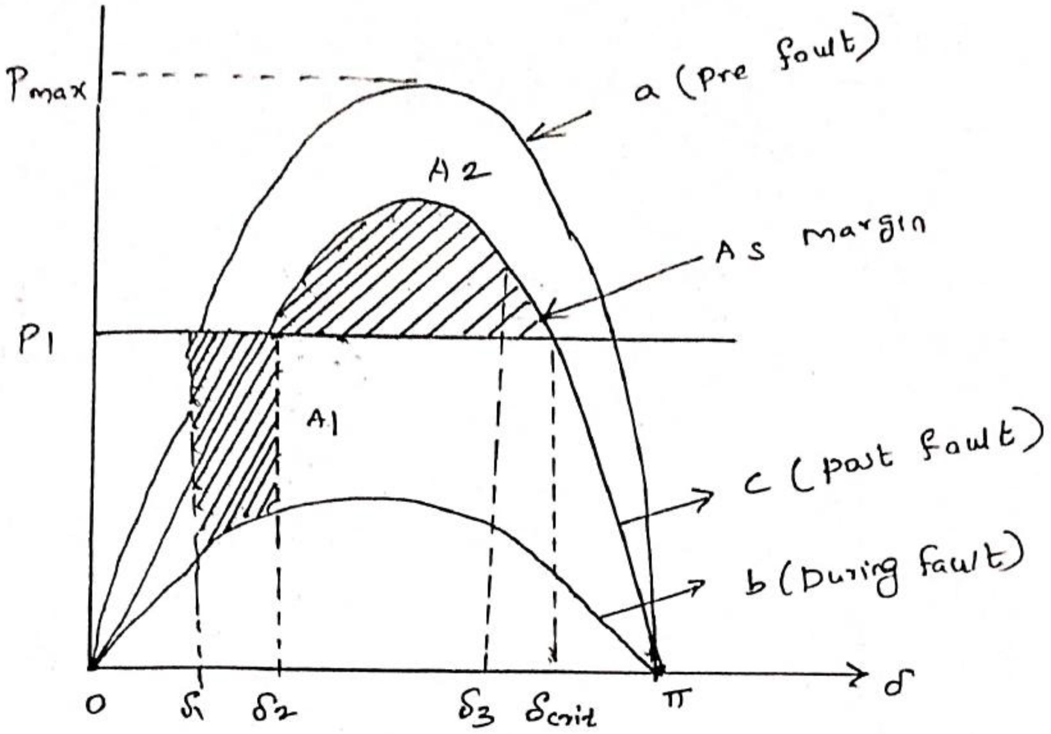
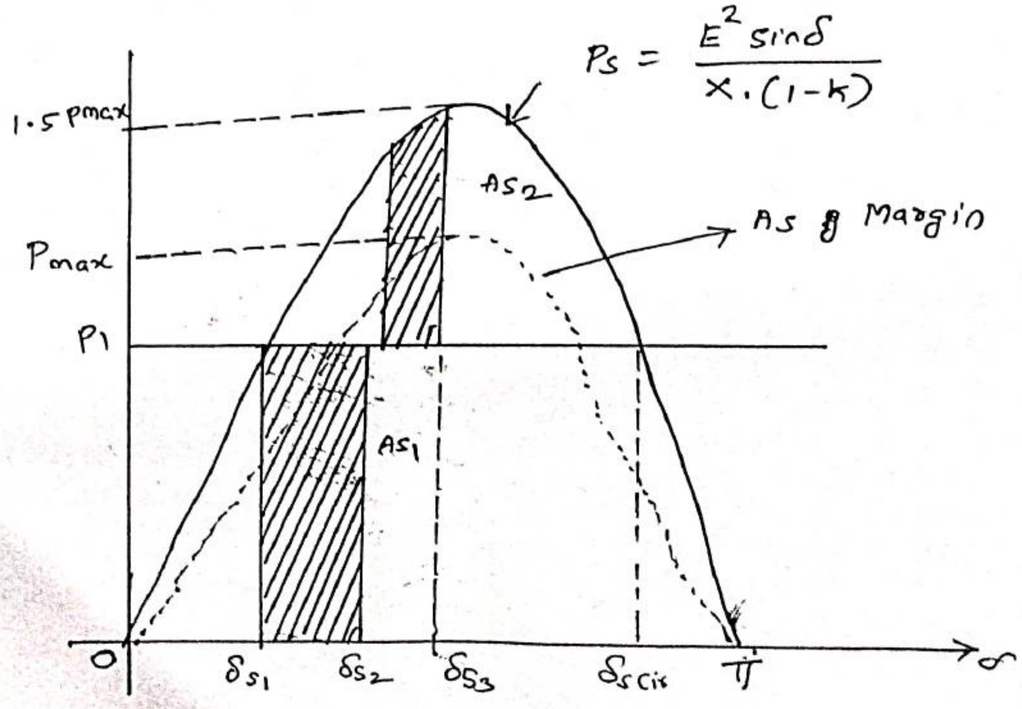
## (4) Improvement of Transient Stability



Power angle curve without Series compensation.



Power angle curve with Series compensation

→ The relay in the system detects the fault in the transmission system and cause circuit breaker to open at both ends of the line.

→ when the fault is cleared, the circuit breakers are set to reclose automatically after a preset interval of time thus restoring normal operating status of the original circuit.

→ This sequence of breaking/Making events constitutes a shock to the power system and is accompanied by transients.

→ During the period of transient, system may get unstable and loss its reliability, thus to improve the transient stability margin, the period of persistence of transient has to be minimized.

→ curve a, b, and c shows the pre fault, during fault and post fault condition of power angle curve. $A_1$ and $A_2$ are accelerating and decelerating energy area. The area $A_{smargin}$ between $\delta_3$ and $\delta_{crit}$ gives the transient stability margin of the syste

→ The margin of the transient stability is normally very small under without compensation system. It is possible to improve by either adding a shunt (or) series type of compensators on the transmission line.

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PART - A

1) Define Static VAR compensator ?

2) what are the different types of SVC ?

3) Define [illegible] Thyristor controlled Reactor (TCR) type SVC.

4) Define Fixed capacitor - Thyristor Controlled Reactor (FC-TCR)

5) Define Thyristor Switched Capacitor (TSC).

6) what are the main components of SVC ?

7) what are the advantages of SVC ?

8) what is the use of TSC - TCR type SVC ?

9) what are the advantages of the slope in SVC Dynamic characteristics ?

10) How the SVC is employed for prevention of Voltage instability ?

Part - B

1) Explain VI Characteristics of FC + TSR

2) Explain VI Characteristics of TSC + TSR

3) Draw and explain voltage control by SVC.

4) what are the advantages of slope in dynamic Characteristics ?

5) Design of SVC voltage regulator.
6) principle of operation of TCSC
7) Explain different modes of TCSC
8) write the applications of TCSC

## UNIT-III

# VOLTAGE SOURCE CONVERTER BASED FACTS CONTROLLERS

Static Synchronous compensator (STATCOM) - Principle of operation - V-I characteristics Applications: Steady state Power transfer - enhancement of transient stability - Prevention of voltage instability. SSSC - operation of SSSC VI characteristics, Enhancement in powers transfer capability - UPSC - Operation Principle Applications.

## Objective:

Students will able to study Voltage source Converter based FACTS controllers.

## What is FACTS Controller?

FACTS Stands for Flexible AC transmission System, and a FACTS controller is a device used in power Systems to control and optimize the flow of electrical power. It is typically used to enhance the controllability and stability of AC transmission Systems by adjusting parameters such as Voltage, Impedance, and phase angle.

## Technical Terms

1. Voltage Source converter (VSC)
2. Flexible Ac Transmission system (FACTS) controller
3. Static Synchronous compensator (STATCOM)
4. Static Var compensator (SVC)
5. Unified power flow controller (UPFC)
6. Interline power flow controller (IPFC)
7. Dynamic Voltage Restorer (DVR)

## Reference Books.

1. HVDC Power Transmission system

   K.R. Padiyar

2. FACTS

   C. RAVICHNDRAN

   T.A. RAGHAVENDIRAN.

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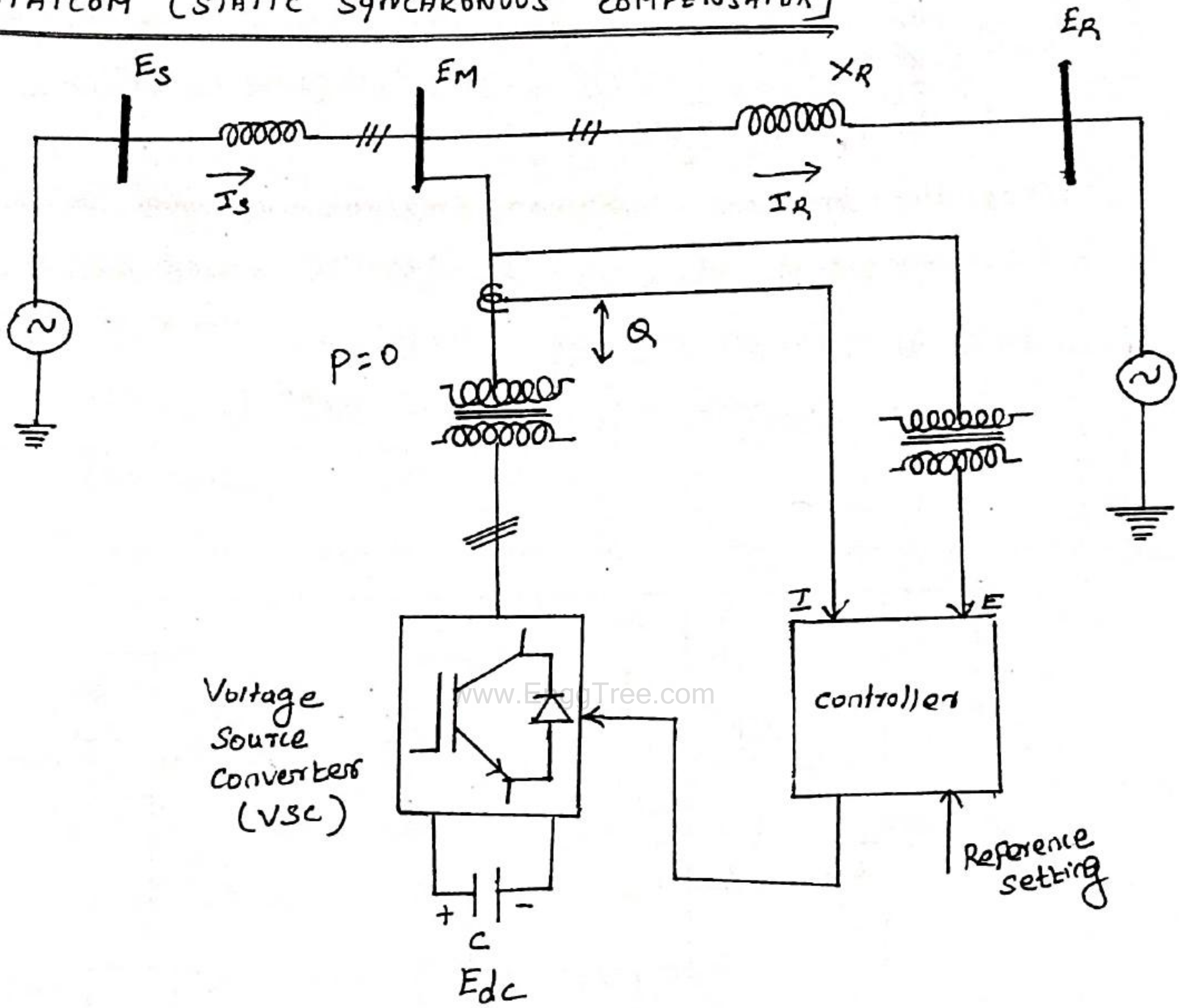
## STATCOM (STATIC SYNCHRONOUS COMPENSATOR)

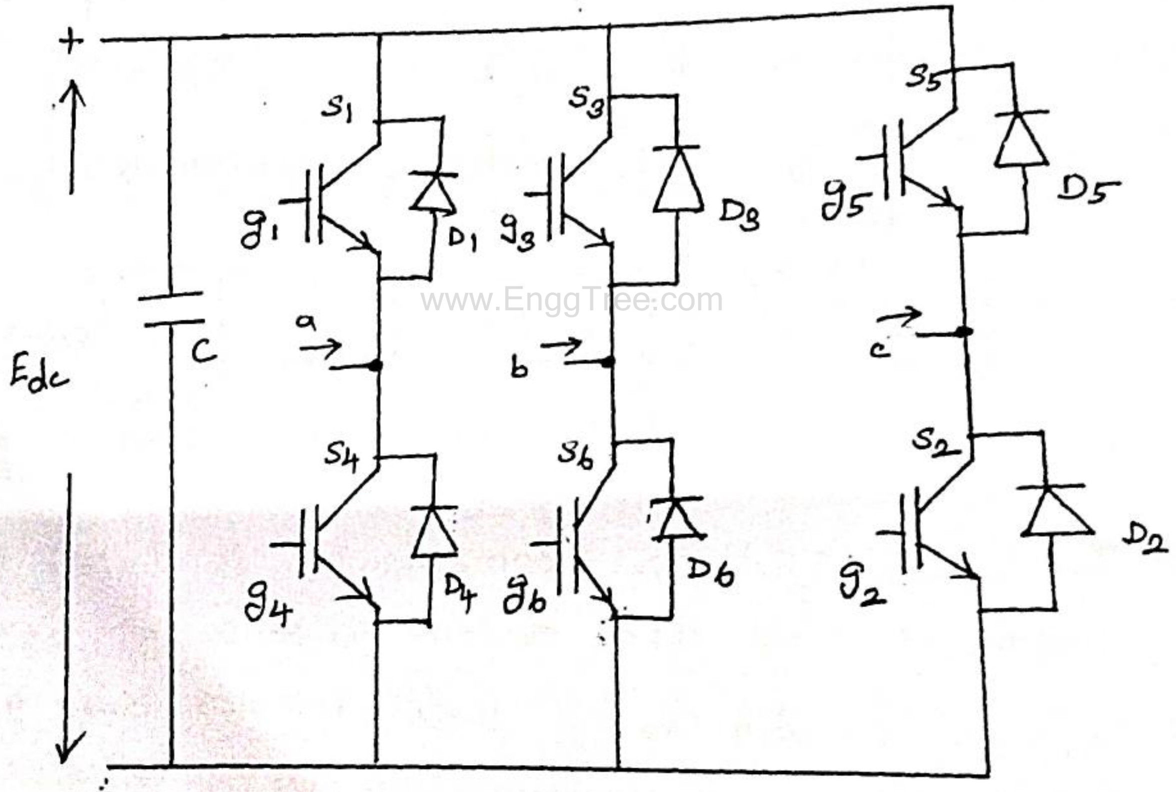


→ The static synchronous compensator is based on a shunt connected solid state reactive compensation device.

→ Implemented with Voltage Source converter that generates the voltage wave comparing it to the one of the electric system to realize the exchange of reactive power and connected in parallel to the power system through a coupling transformer (or) reactor, in analogy with a

→ Generating balanced sett of three sinusoidal voltages at the fundamental frequency, with controllable amplitude and phase shift angle.

→ Thus the STATCOM controller provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors (or) capacitor banks.



→ The control system of the STATCOM adjusts at each moment the inverse voltage so that the current injected in the network is in quadrature to the network voltage, in these conditions $P=0$ and $Q=0$.

3.3

→ The Voltage source - Converter or inverter (VSC or VSI) is the building block of a STATCOM and other FACTS devices.

→ A very simple inverter produces a Square voltage waveform as it switches the direct voltage source on and off.

→ The basic objective of a VSI is to produce a sinusoidal AC voltage with minimal harmonic distortion from a DC voltage.

→ Three basic techniques are used for reducing harmonics in the converter output voltage such as harmonic neutralization using magnetic coupling (Multi-pulse converter configurations), harmonic reduction using ~~Multi~~ Multilevel converter configurations and the Pulse width modulation (PWM) technique.

Typical applications of STATCOM are:-

→ Effective Voltage regulation and control.

→ Reduction of temporary over voltages

→ Improvement of steady state power transfer capacity.

→ Improvement of transient stability margin

→ Damping of power system oscillations

→ Damping of sub Synchronous power system oscillations

→ Flicker control

→ Power quality improvement

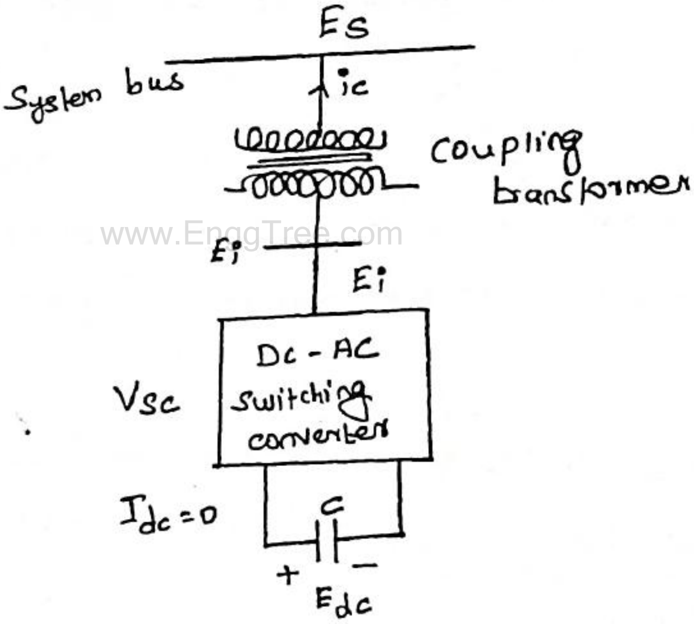
→ Distribution system applications.

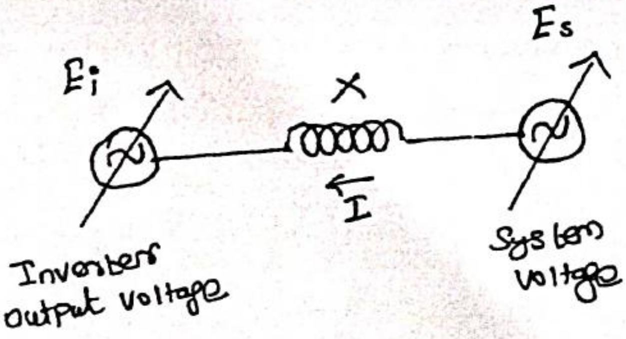
## STATCOM Principle of Operation.

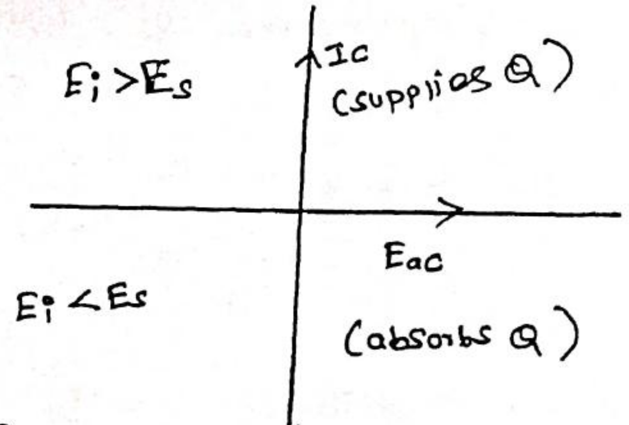
→ The operating principle of STATCOM is explained with help of one line diagram and its equivalent diagram.

→ The IGBTs converter with a DC Voltage Source and the Power system are illustrated as variable AC voltages in this system.

→ These two voltages are connected by a reactance representing the transformer Leakage inductance.







Es → utility voltage
Ei → station output voltage

3:4

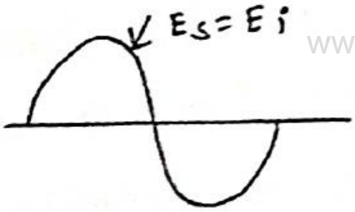
Using the conventional equations that describe the active and reactive power flow in a line in terms of converters voltage $E_i$ and supply voltage $E_s$, the transformers impedance $X$ (which can be assumed ideal) and the angle difference between both bus bars $\delta$, we can define $P$ and $Q$ as

$$P_i = \frac{E_s E_i}{X} \sin\delta \quad \text{——} ①$$

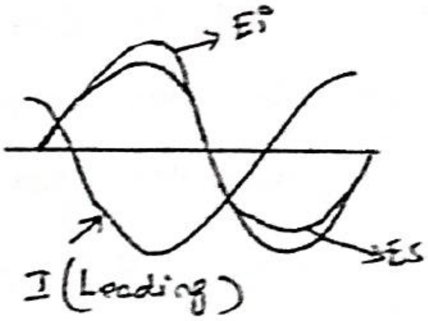
$$Q_i = \frac{E_i (E_i - E_s \cos\delta)}{X} \quad \text{——} ②$$

$$Q_s = \frac{E_s (E_s - E_i \cos\delta)}{X} \quad \text{——} ③$$

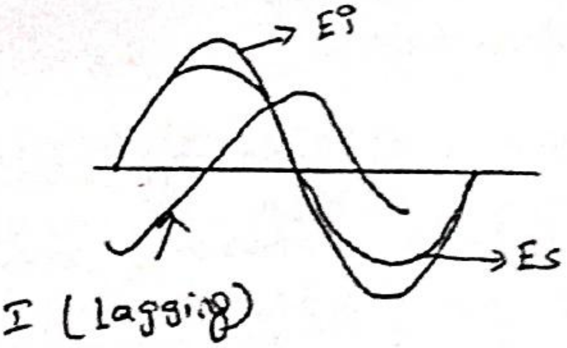
No Load



Capacitive operation



Inductive operation



→ The angle between the Es and Ei in the system is δ.

→ when the STATCOM operates with δ = 0 we can see how the active power send to the system device becomes Zero while the reactive power will Mainly depend on the voltage ~~do~~ Module.

→ This operation condition means that the current that goes through the transformer must have a +/- 90 Phase difference to Es.

→ In other words, if Ei is higher than Es, the reactive Power will be send to the STATCOM of the system (capacitive operation), originating a current flow in this ~~so~~ direction.

→ In the contrary case, if Es is higher than Ei the reactive power will be absorbed from the System through the STATCOM (inductive operation) and the current will flow in the opposite direction.

→ Finally if the modules of Es and Ei are equal, there won't be nor current nor reactive power flow in the system.

→ We can say that in a Stationary state Q only depends on the module difference between Es and Ei Voltages.

→ The amount of the reactive power is proportional to the voltage difference between Es and Ei.

3:5

## Active and Reactive power Exchange

→ It is to be noted that the reactive power exchange between the AC System and the compensator is controlled by Varying the magnitude of the fundamental component of the inverter voltage above and below that of the AC system.

→ The compensator control is achieved by small variations in the switching angle of the semiconductor devices, so that the fundamental component of the voltage Produced by the inverters is forced to lag or Lead by a few degrees. the AC system voltage

→ This causes active power to flow into or out of the inverter modifying the value of the DC capacitor voltage, and consequently the magnitude of the inverter terminal voltage and the resultant reactive power.

→ If the compensator supplies only reactive power, the active power provided by the DC capacitor is zero. Therefore, the capacitor does not change its voltage. one could say then that the capacitor plays not any role in the reactive power generation.

→ With the provision of DC source or energy storage device on its DC side, there can be a little active power exchange between the STATCOM and the electric power system.

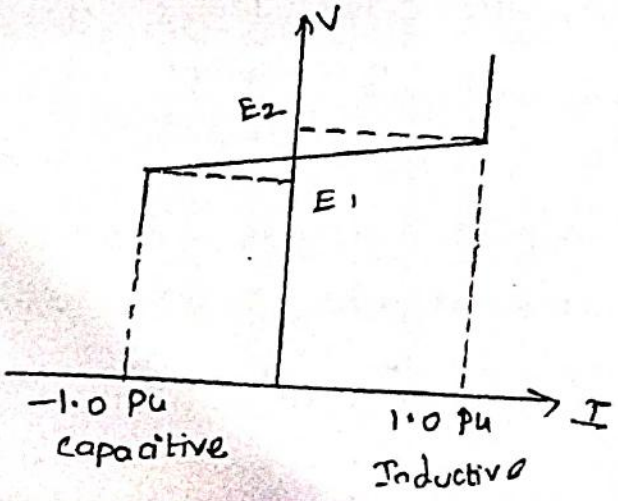
→ when the phase angle of the AC power system Leads the inverter phase angle, the STATCOM absorbs real power from the AC system; If the phase angle of the AC power system Lags the inverter phase angle, the STATCOM supplies real power to AC system.

## VI CHARACTERISTICS OF A STATCOM

→ The STATCOM smoothly and continuously controls voltage from $E_1$ to $E_2$.

→ If the system voltage exceeds a Low voltage ($E_1$) or high-voltage Limit ($E_2$), the STATCOM acts as a constant current source by controlling the converter Voltage ($E_i$) appropriately.

→ when operating at its voltage Limits, the amount of reactive power compensation Provided by the STATCOM is more than the Most common competing FACTS controllers, namely the Static Var Compensator (SVC).

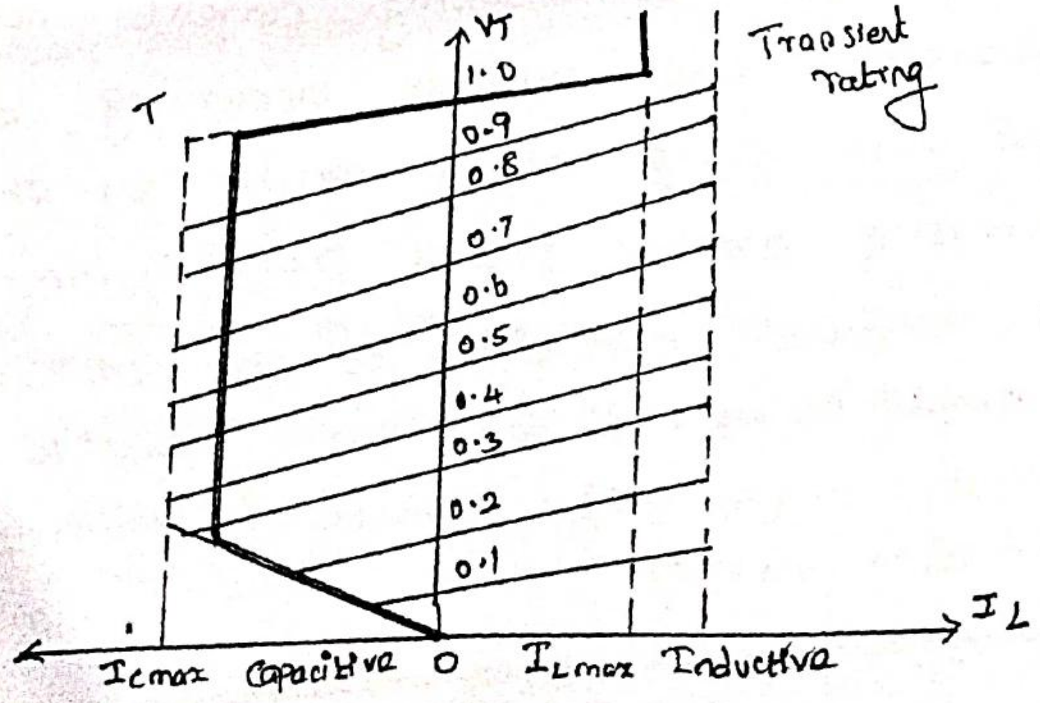


→ This is because at a low voltage limit, the reactive power drops off as the square of the voltage for the SVC, but drops off linearly with the STATCOM.

→ This makes the reactive power controllability of the STATCOM superior to that of the SVC, particularly during times of system suffering.

→ The STATCOM can provide both capacitive and inductive compensation and is able to control its output current over the rated maximum capacitive or inductive range independently of the AC system voltage.

→ The STATCOM can provide full capacitive output current at any system voltage, practically down to zero. (This is in contrast to the SVC which can supply only diminishing output current with decreasing system voltage as determined by its maximum equivalent capacitive admittance).



-> The STATCOM may have an increased transient rating in both the inductive and capacitive operating regions [The conventional SVC has no means to increase transiently the VAR generation since the maximum capaciti current it can draw is strictly determined by the size of the capacitor and the magnitude of the system voltage].

-> The available transient rating of the STATCOM is dependent on the characteristics of the power semiconductors used and the junction temperature at which the devices are operated.

-> The ability of the STATCOM to produce full capacitive output current at low system voltage also makes it more effective than the SVC in improving the transient (first swing) stability.

-> This is because the STATCOM is able to maintain full compensating current at depressed line voltage occurring during the first swing as a result of sharply increasing electric power transmission.

-> The inherent capability of the STATCOM to generate as well as to absorb reactive power makes it eminently suitable for power oscillation damping.

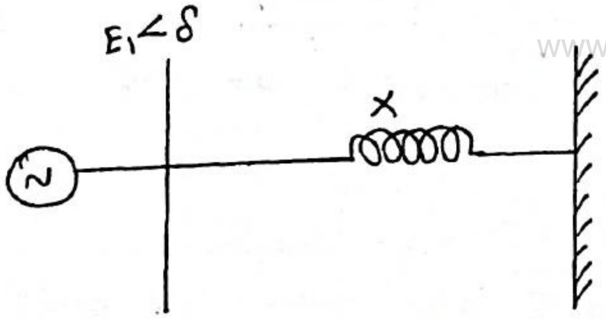
---

## APPLICATIONS OF STATCOM

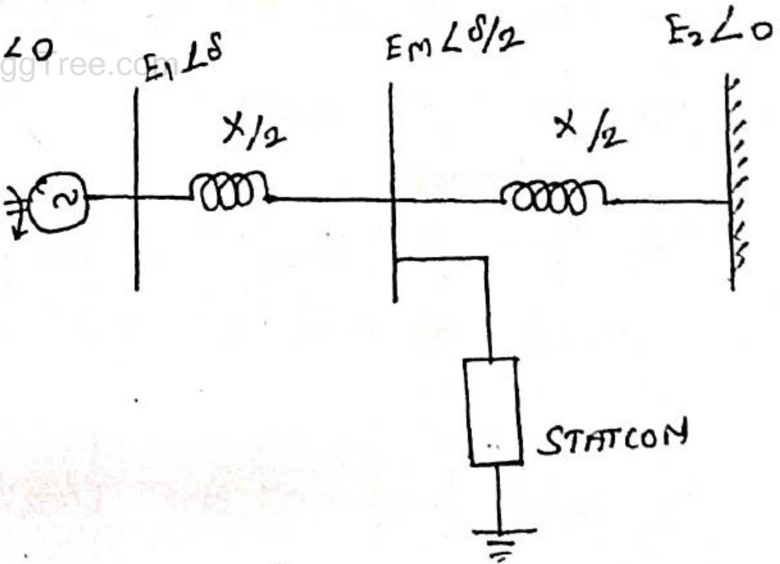
(1) increases in steady-state power transfer capacity
(2) Enhancement of transient stability.
(3) Prevention of voltage instability.

### (1) Increase in steady-state power transfer capacity

→ STATCOM can be used to improve the power-transfer capacity of a transmission line, which is also characterized as the steady state power transfer limit. Let us consider a single-machine connected to an infinite-bus system with a lossless transmission line having reactance X.



An uncompensated system



A STATCOM compensated system.

→ Let the voltage of the synchronous generator $E_1$ with displacement angle $\delta$ and infinite bus is $E_2$ with initial load angle 0, respectively.

In general the power transferred from the Synchronous machine to the infinite bus is given as

$$P = \frac{E_1 E_2}{X} \sin\delta \text{ ——— } ①$$

Assuming, if $E_1 = E_2 = E$, then

$$P = \frac{E^2}{X} \sin\delta \text{ ——— } ②$$

The maximum steady-state power than can be transferred across the uncompensated line without STATCOM corresponds to $\delta = 90^\circ$ is given by

$$P_{max} = \frac{E^2}{X} \text{ ——— } ③$$

## Steady State stability Improvement (Ideal compensator)

→ An ideal STATCOM is connected at the midpoint.

→ If the voltage at the midpoint is kept the same as that at the sending and receiving ends. The power flow equation can be applied for each half of the line.

$$P = \frac{E^2}{X/2} \sin \delta/2 \text{ ——— } ①$$

$$E_s = E \sin\omega t \text{ ——— } ②$$

$$E_M = E \sin(\omega t - \delta/2) \text{ ——— } ③$$

$$E_R = E \sin(\omega t - \delta) \text{ ——— } ④$$

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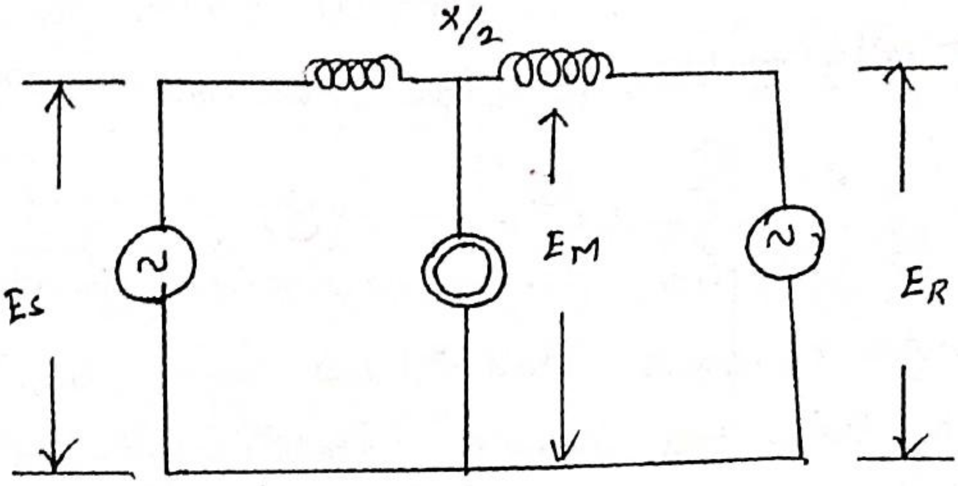
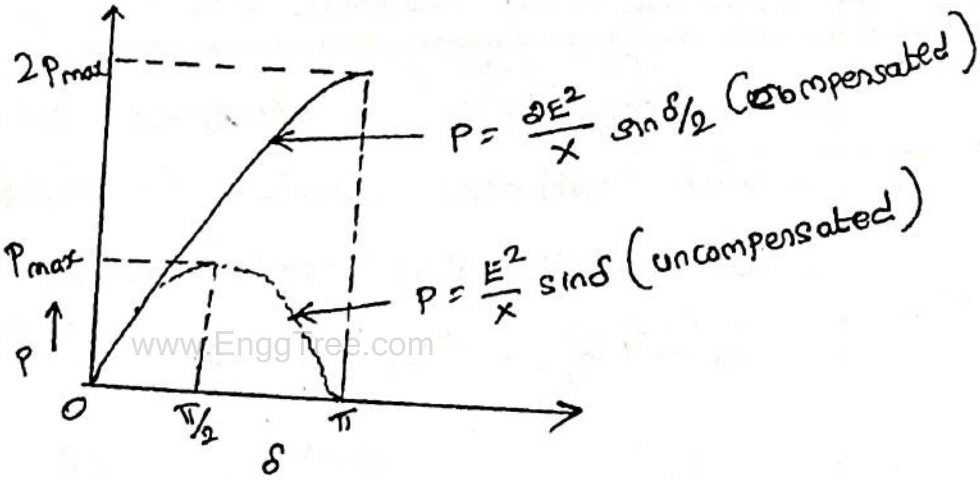




→ The power transmission relationship expressed in equation ⑤ is illustrated in above the characteristics.

Maximum transmittable power obtained at $\delta/2 = \pi/2$

$$P_{cmax} = 2\frac{E^2}{X} \quad \text{———} ⑤$$

which is twice the steady-state limit of the uncompensated case.

→ In general, the transmission reactance X can be divided into n equal sections with a perfect synchronous compensator at the joining points of the sections.

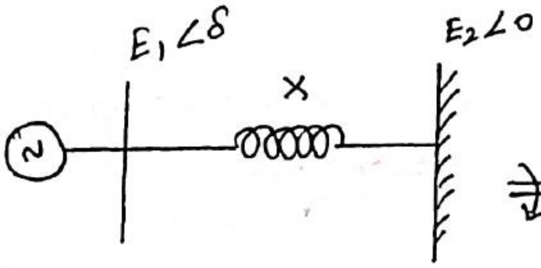
- In this case, the power transmission is characterized theoretically by the following equations.

$$P = \frac{\frac{E^2}{X}}{X/n} \sin \delta/n \quad \text{——} ⑤$$

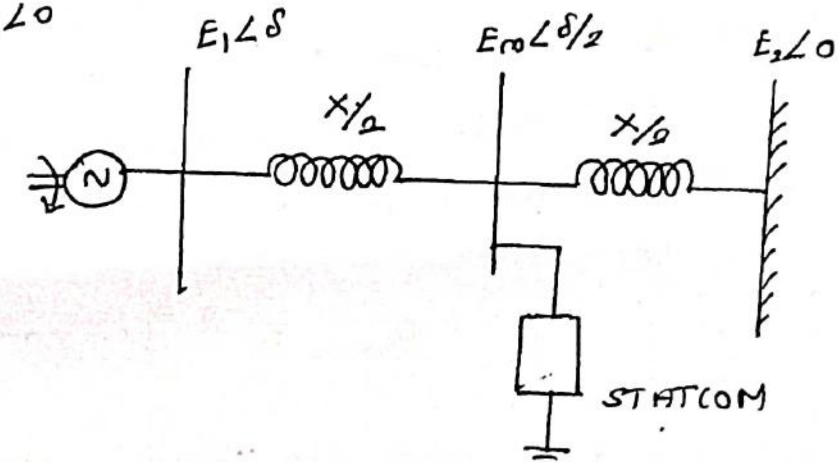
which gives a maximum transmittable power of $nE^2/x$, that is, n times the steady-state power limit of the uncompensated case.

## (2) Enhancement of Transient Stability.

→ The improvement in transient stability achievable with controlled shunt compensation is simply due to the significant increase in the steady-state stability limit obtained.



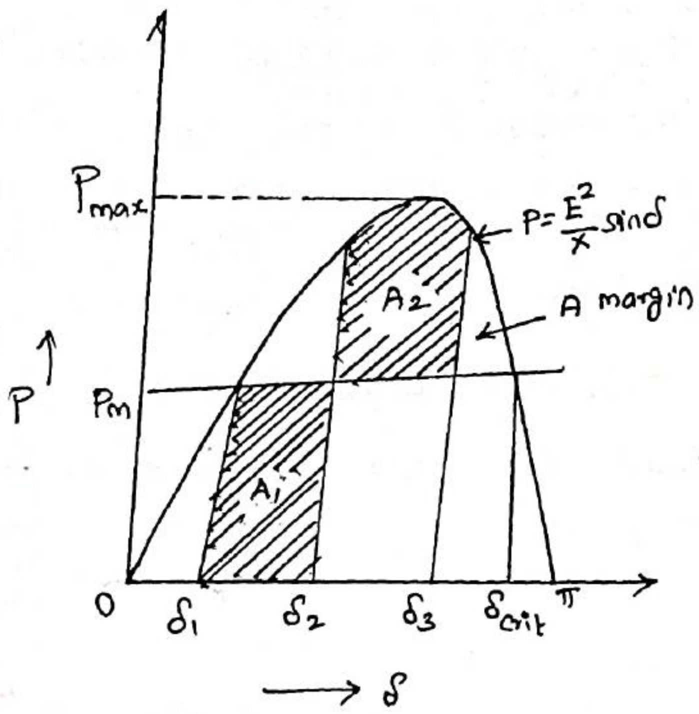
An uncompensated System



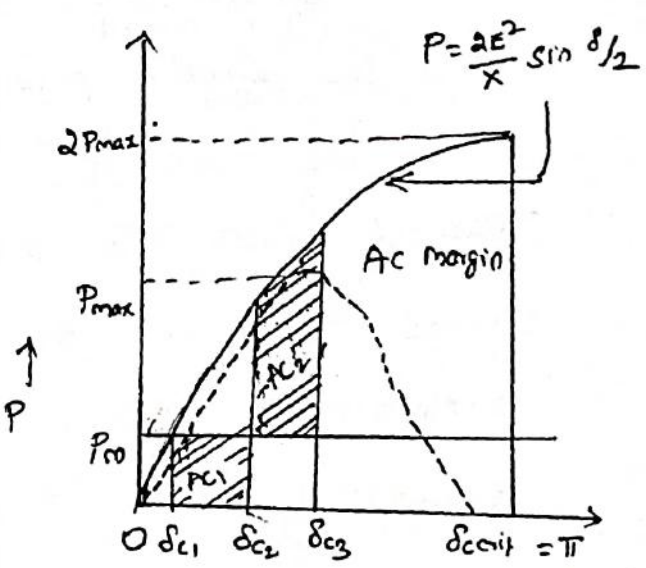
STATCOM - Compensated System.

→ Suppose that in both the compensated and uncompensat Systems the transmitted power is the same.

→ Assume that both systems are subjected to the same fault for the same period of time.



without compensation



with an ideal midpoint compensator.

prior to the fault:-

Each system transmits power Pm at angle δ and $\delta_{c1}$ respectively (subscript c stands for "compensated").

During the fault:-

The transmitted electric power becomes zero, while the mechanical input power to the generators remains constant (Pm). therefore, the generators accelerate from the steady state angles $\delta_1$ and $\delta_{c1}$ to angles $\delta_2$ and $\delta_{c2}$, at which the fault clears. The accelerating energies in the two systems are represented by areas $A_1$ and $A_{c2}$.

After fault :

→ After fault clearing, the transmitted electric power exceeds the mechanical input power and the machines decelerate, but their angle further increases due to the kinetic energies accumulated in the rotors.

→ The maximum rotor angles $\delta_3$ and $\delta_{c3}$ are reached when the ~~decele~~ decelerating energies defined by areas $A_2$ and $A_{c2}$ are equal to the accelerating energies defined by areas $A_1$ and $A_{C1}$, respectively.

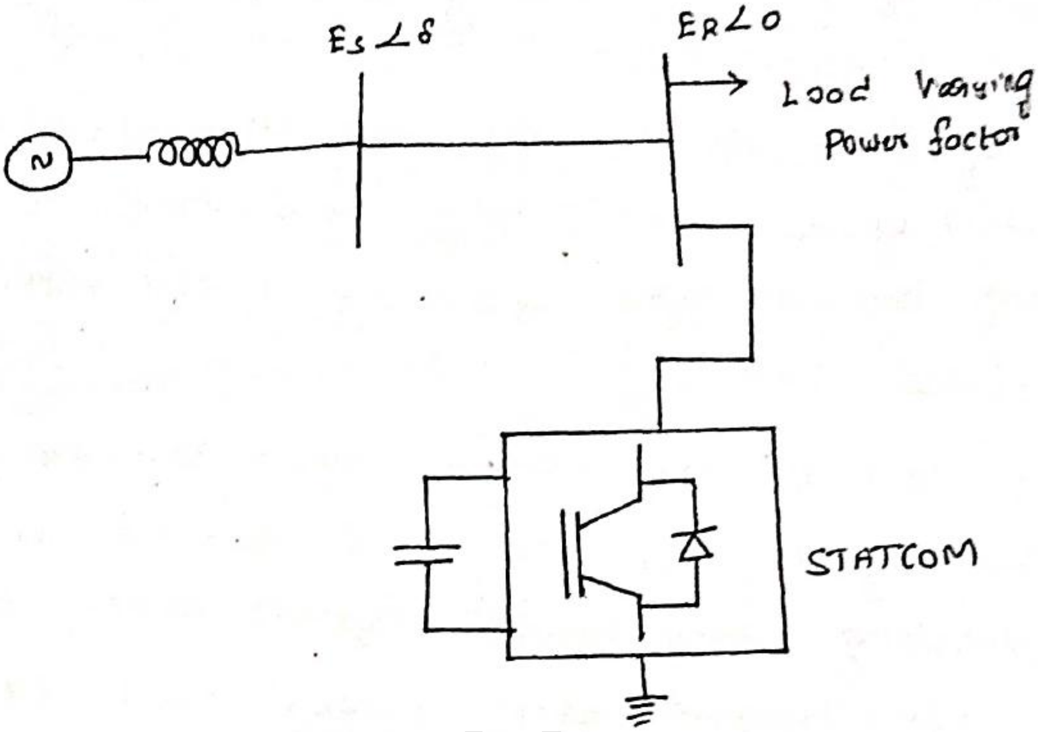
Post fault:-

→ Post fault system the maximum rotor ($\delta_3$ or $\delta_{c3}$) reached is below the critical rotor angle ($\delta_{crit}$ or $\delta_{ccrit}$ the system will remain transiently stable.

→ The critical rotor angle represents the rotor ~~angle ($\delta_3$ or $\delta_{c3}$)~~ angular swing beyond which rotor deceleration cannot be maintained.

## (3) Prevention of Voltage Instability

→ The STATCOM is frequently used to regulate the voltage at dynamic Loads.



→ It is used to provide a voltage support inside of a power system when it takes place small gradual system changes such as natural increase in system load. or Large sudden distrubance such as loss of a generating unit or a heavily loaded Line.

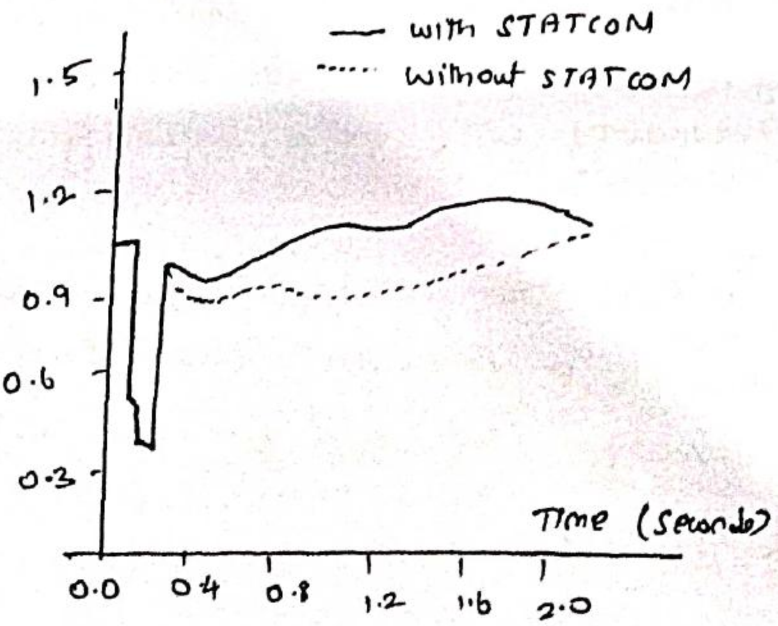
→ These events can alter the pattern of the voltage waveform in such a manner that it ~~Change~~ can damage or Lead to mal functio of the protection devices.

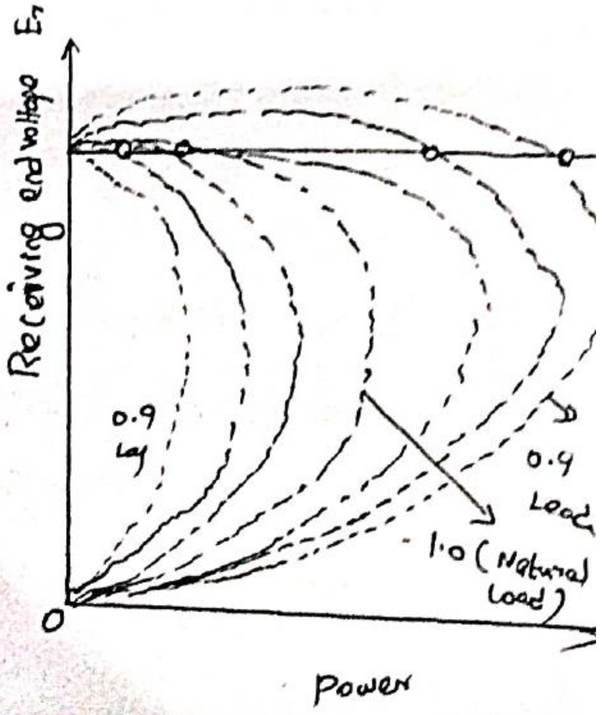
→ They are sufficient reserves and the systems settles to stable voltage level.

→ The additional reactive power demands may lead to voltage collapse. causing a major breakdown of part or all system.

→ A typical system configuration for potential voltage instability is when a large load area is supplied from two or more generator plants with independe transmission lines.

→ The loss of one of the power sources could suddenly increase the load demand on the remaining part of the system above the maximum transmittable power level. causing the receiving end voltage to collapse.



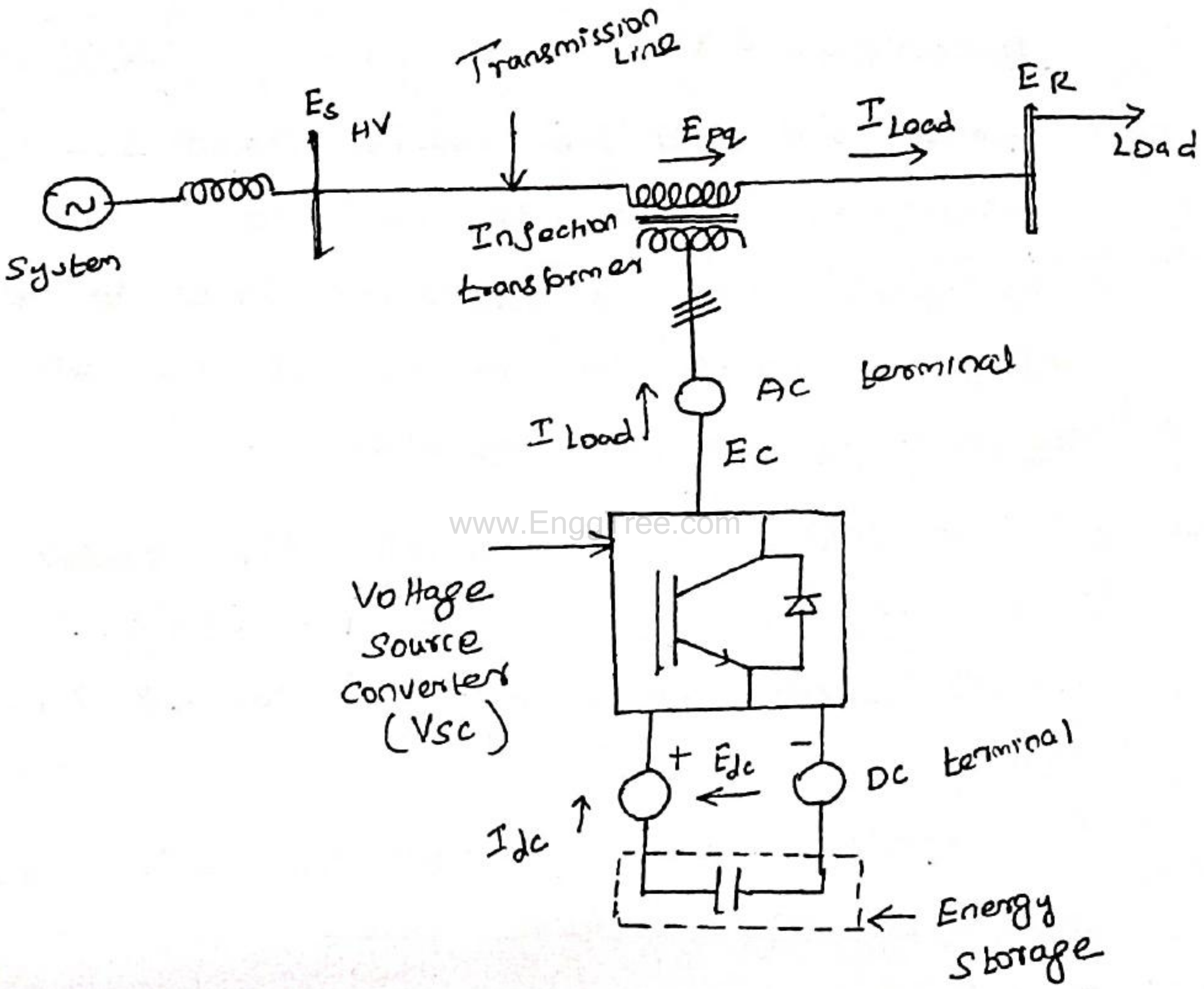


3.11

# STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

The SSSC is a device which can control simultaneously all three parameters of line power flow [Line impedance, voltage and phase angle].

## Principle of operation



→ A SSSC usually is comprised of a coupling transformers, an inverters and a capacitor. It is series connected with a transmission line through the coupling transformers.

→ It uses the voltage source converter with a capacitor in its DC terminal to replace the switched capacitors of the conventional series compensations.

→ In principle, the inserted series voltage Epq with SSSC canbe regulated such a way that change the impedance (more precisely reactance) of the transmission line.

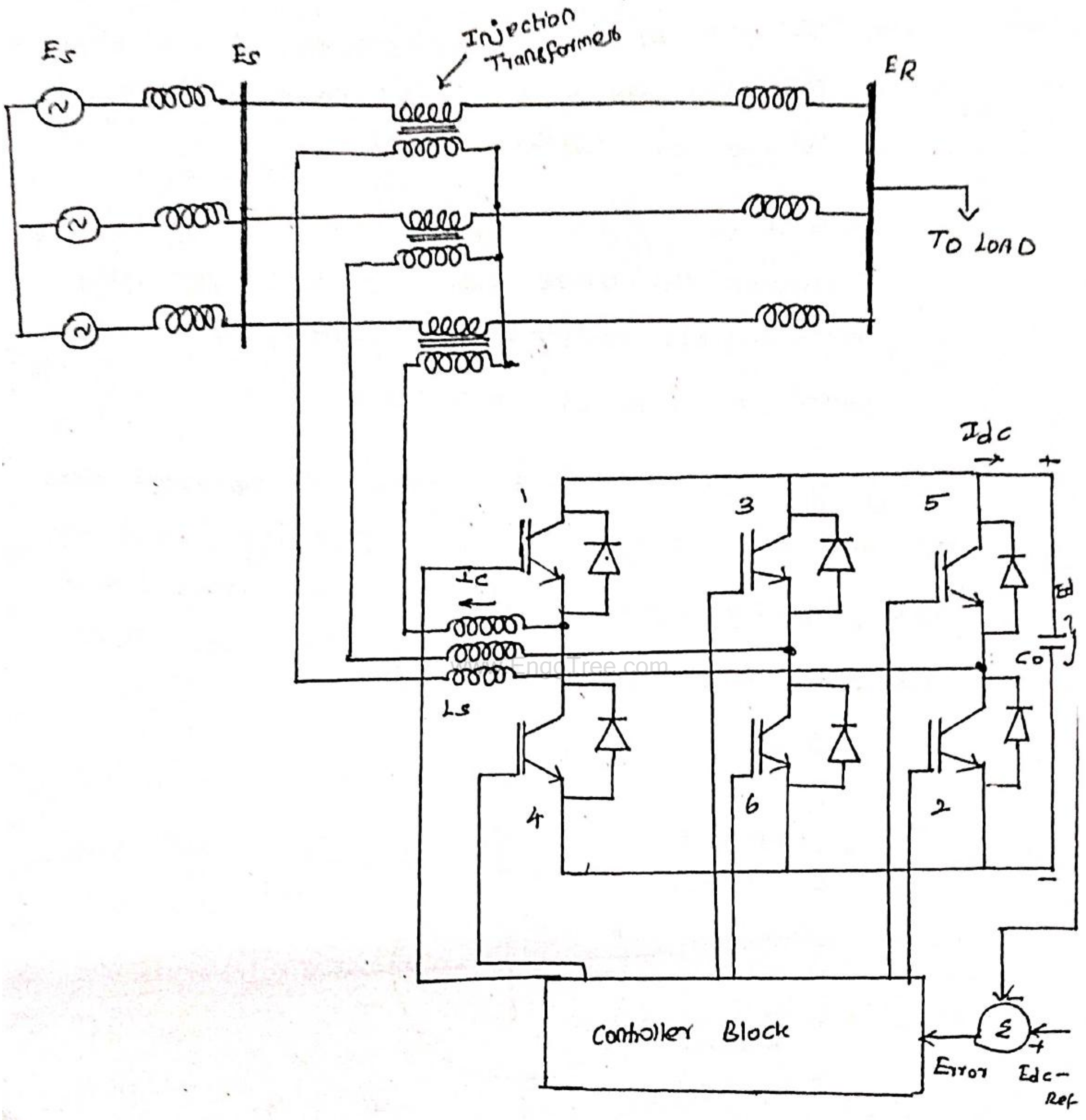
→ Therefore the real and reactive power flow of transmission line can be controlled.

→ The SSSC injects a voltage in series to the line, 90° phase shifted with the load current, operating as a controllable series capacitor.

→ The basic difference, as compared with series capacitor is that the voltage injected by an SSSC is not related to the line current and can be independently controlled.

→ The converter output voltage Ec, which can be set to any relative phase, and any magnitude within its operating limits, is adjusted to appear to load the line current by 90°, thus behaving as a capacitor.

→ If the angle between Ec and the line current was not 90°, then this would imply that the series compensator exchanges active power with the transmission line.



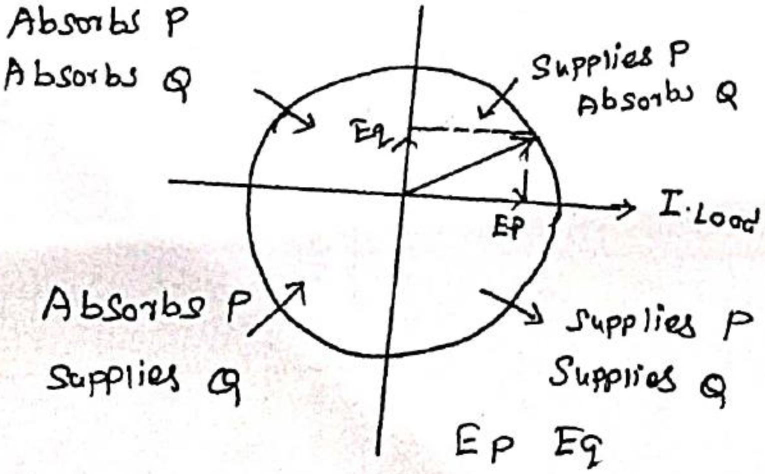
→ The SSSC can be gated to produce an output Voltage that Leads the Line current by 90°, which provides additional inductive reactance in the Line.

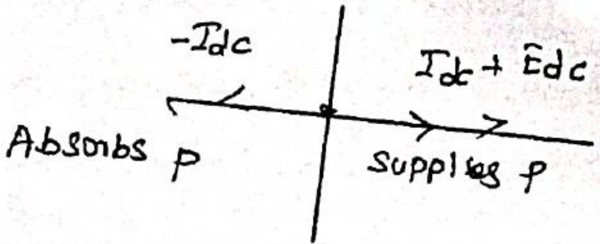
Features

→ This type of Series compensation can provide a continuous degree of series compensation by varying the magnitude of Ec.

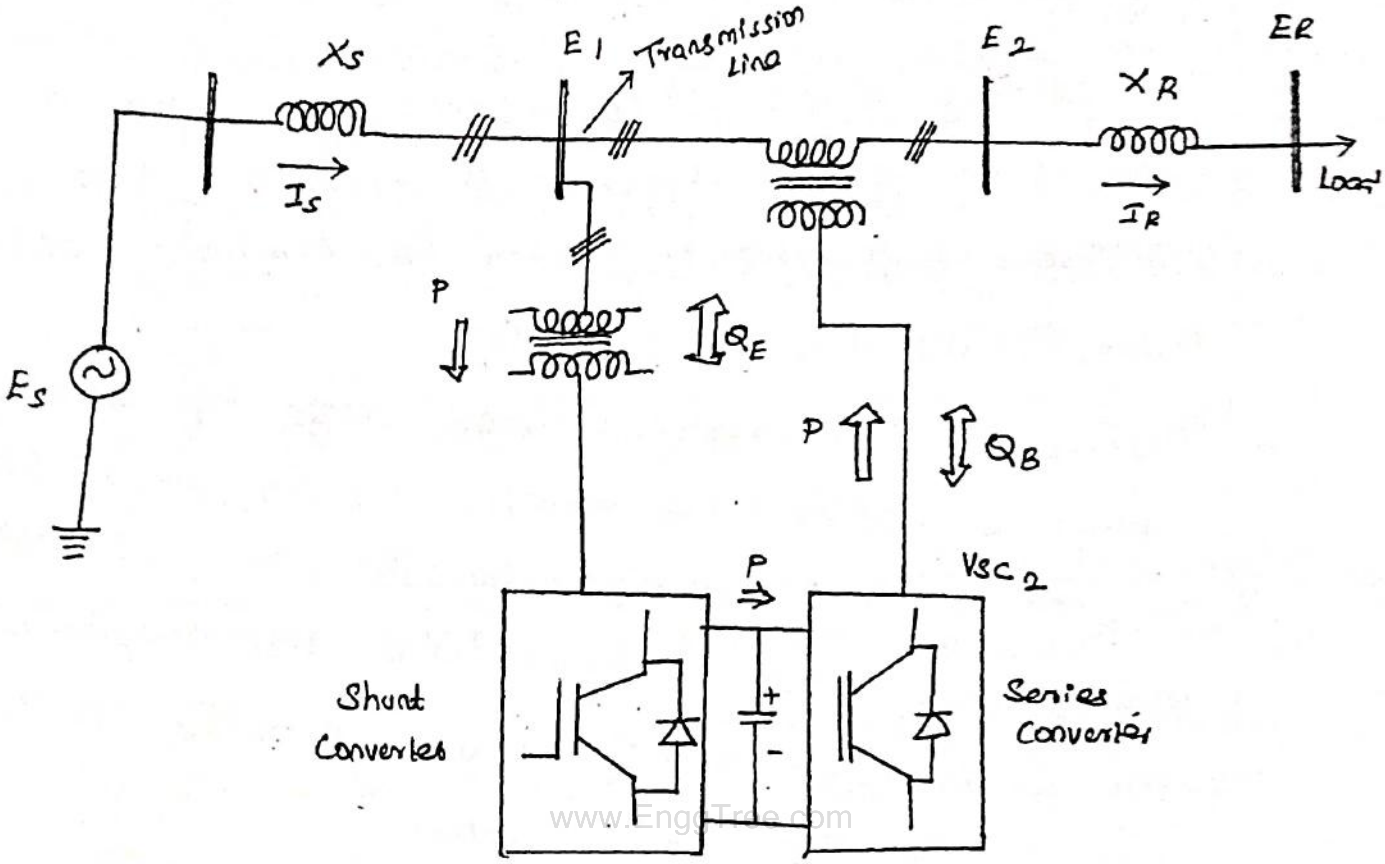
→ Also it can reverse the phase of Ec, thereby increasing the overall line reactance, this may be desirable to limit fault current, or to damp ~~Output~~ & out power oscillations.

In general, the controllable Series compensator can be used to increase transient stability, to damp out Sub-Synchronous resonance where other fixed capacitors are used, and to increase line power capability





## ○ UNIFIED POWER FLOW CONTROLLER (UPFC)



→ The UPFC is a representative of the last generation of FACTS devices which can control simultaneously all three parameters of line power flow (line impedance, Voltage and phase angle).

→ The UPFC combines together the features of the static Synchronous compensator (STATCOM) and the Static Synchronous series compensator (SSSC).

→ The DC terminals of the two underlying voltage source converters (VSCs) are now coupled, and this creates a path for active power exchange between the converters. Hence, the active power supplied to the line by the series converter can now be supplied by the shunt converter.

-> This topology offers three degrees of freedom or more precisely four degrees of freedom (two associated with each VSC) with one constraint (active powers of the VSCs must match).

-> Therefore, a fundamentally different range of control options is available compared to STATCOM or SSSC

-> The UPFC can be used to control the flow of active and reactive power through the line and to contro the amount of reactive power supplied to the line at the point of installation.

-> while operating both inverters as a UPFC, the exchaged power at the terminals of each inverte can be real as well as reactive.

## Principle of operation

-> In practice, these two devices (STATCOM & SSSC) are two voltage source Inverters (VSI's) connected respectively in shunt with the transmission line through a shunt transformer and in series with the transmission line through a series transformer,

3:14

Connected to each other by a common DC link including a storage capacitor (fundamental frequency mod

- The shunt inverter is used for voltage regulation at the point of connection injecting an appropriate reactive power flow into the line and to balance the real power flow exchanged between the series inverter and the transmission line.
- The series inverter can be used to control the real and reactive line power flow inserting an appropriate voltage with controllable magnitude and phase angle in series with the transmission line.
- The reactive power is electronically provided by the series inverter, and the active power ~~flow~~ is transmitted to the DC terminals.
- The shunt inverter is operated in such a way as to demand this DC terminal power (positive or negative) from the line keeping the voltage across the storage capacitor $E_{dc}$ constant.
- The net real power absorbed from the line by the UPFC is equal only to the losses of the two inverters and their transformers.
- The remaining capacity of the shunt inverter can be used to exchange reactive power with the line so to provide a voltage regulation at the connection point.

→ Applying the pulse width Modulation (PWM) technique to the two VSCs the following equations for magnitudes of Shunt and Series injected voltages are obtained

$$E_{sh} = M_{sh} \frac{E_{dc}}{2\sqrt{2 n_{sh} E_b}}$$

$$E_{se} = M_{se} \frac{E_{dc}}{2\sqrt{2 n_{se} E_b}}$$

where

$M_{sh}$ - amplitude modulation index of the shunt Vsc contro signal

$M_{se}$ → amplitude modulation index of the Series Vsc control sig

$n_{sh}$ → Shunt transformer turn ratio

$n_{se}$ → Series transformer turn ratio

$E_b$ → the system side base voltage in kV

$E_{dc}$ → DC link voltage in kV

the phase angles of $V_{sh}$ and $V_{se}$ are

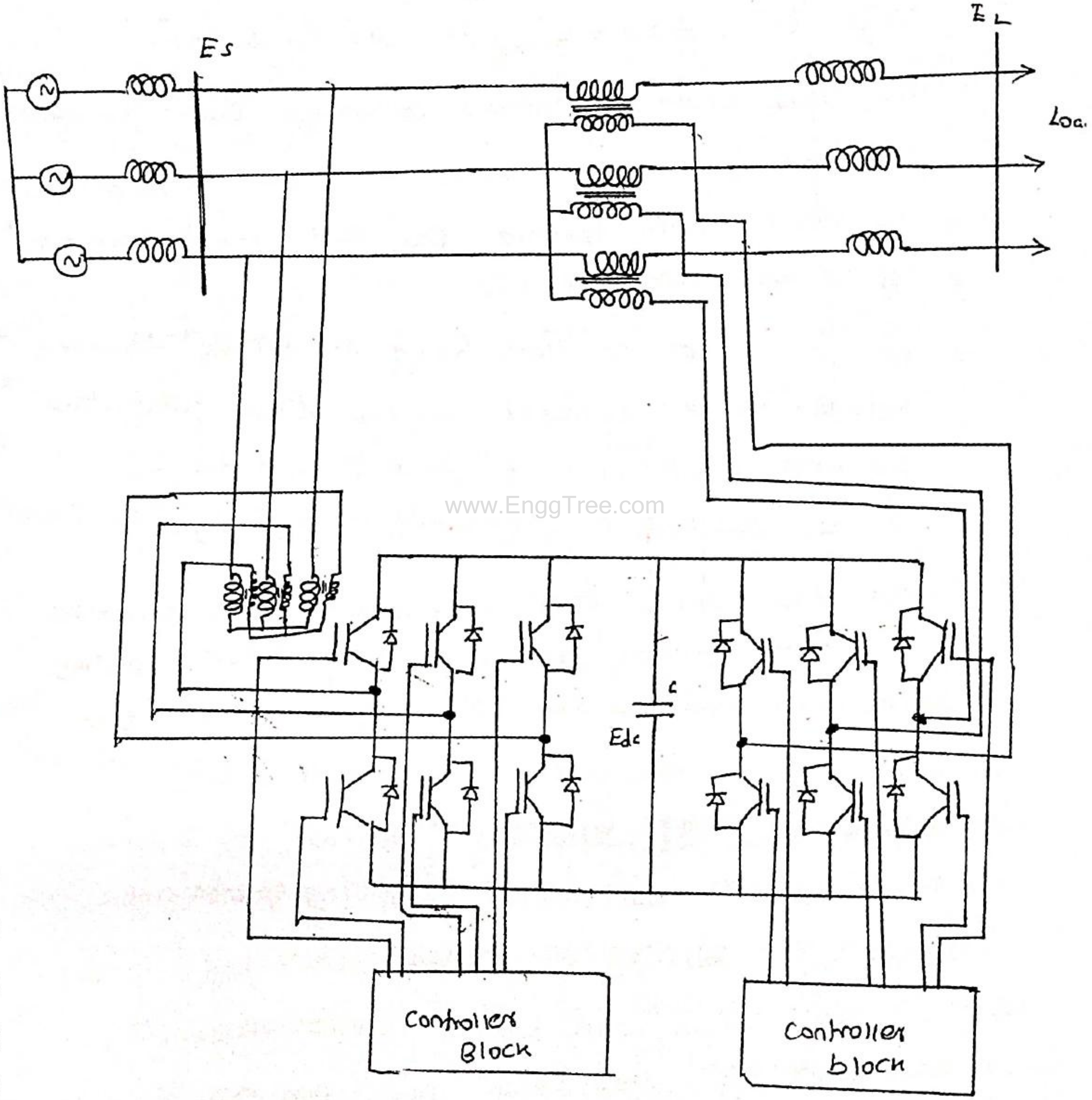
$$\delta_{sh} = \angle(\delta_s - \phi_{sh})$$

$$\delta_{se} = \angle(\delta_s - \phi_{se})$$

where

$\phi_{sh}$ - firing angle of the Shunt Vsc with respect to the phase angle of the sending bus voltage.

○ $\phi_{se}$ → firing angle of the series VSC with respect to the phase angle of the sending bus voltage.



→ The Series converter injects an AC voltage $E_{se} = E_{se} \angle(\delta_s - \phi_{se}$ in Series with the transmission line.

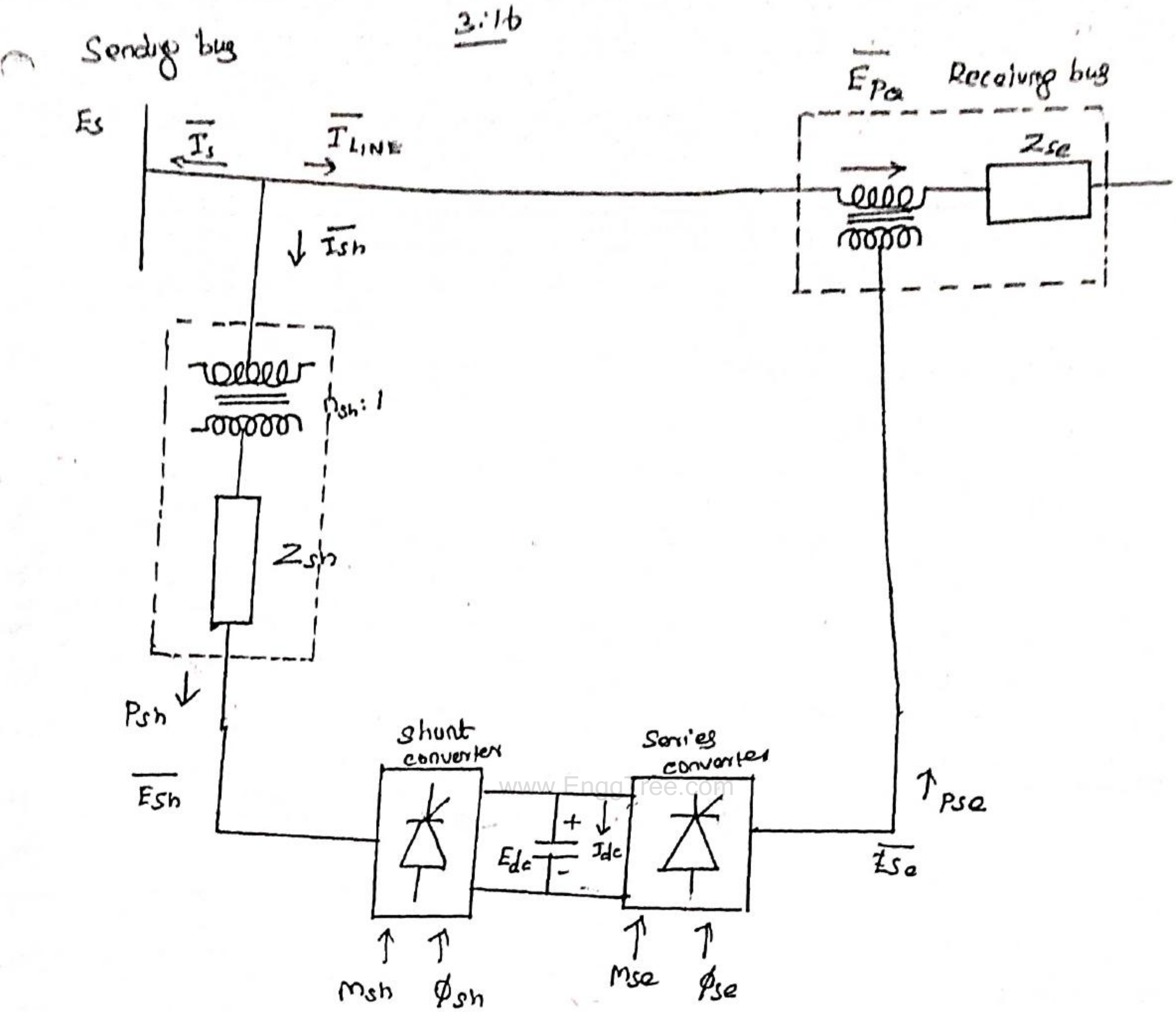
→ Series voltage magnitude $E_{se}$ and its phase angle $\phi_{se}$ with respect to the Sending bus are controllable in the range of $0 \le E_{se} \le E_{se\,max}$ and $0 \le \phi_{se} \le 360°$.

→ The shunt converter injects controllable Shunt Voltage Such that the real component of the current in the Shunt branch balance the real power demanded by the Series converter.

→ the real power can flow freely in either direction between the AC terminals. on the other hand the reactive power cannot flow through the DC Link. It is absorbed or generated locally by each converter.

→ Thereby, the UPFC can fulfill functions of reactive shunt compensation, active and reactive series compensation and phase shifting. Besides, the UPFC allows a secondary but important function such as stability control to suppress power system oscillations improving the transient stability of power system.

→ The two VSI's can work independently of each other by separating the DC side.



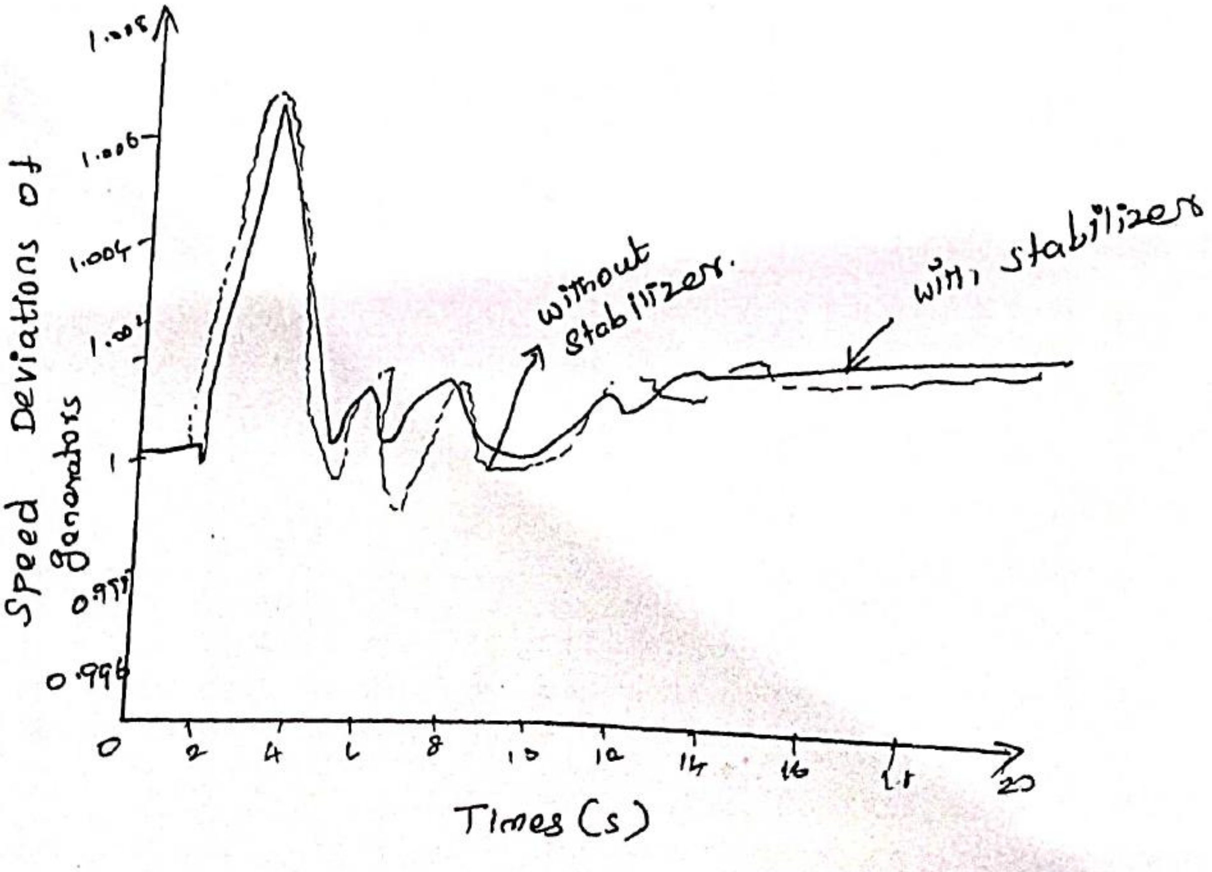
→ The shunt inverter is operating as a STATCOM that generates or absorbs reactive power to regulate the voltage magnitude at the connection point.

→ Instead, the series inverter is operating as SSSC that generates or absorbs reactive power to regulate the current flow, and hence the power flows on the transmission line.

## APPLICATIONS OF UPFC

→ UPFC is one of the most complex FACTS devices in a power system today. It is primarily used for independent control of real and reactive power in transmission lines for flexible, reliable and economic operation and Loading of power systems.

→ until recently all three parameters that affect real and reactive power flows on the Line, Line impedan Voltage magnitudes at the terminals of the Line, and power angle, were controlled separately using eithe mechanical or others FACTS devices. But UPFC allows simultaneous or independent control of all these three parameters, with possible switching from one control scheme to another in real time.



## (1) Improve Damping of Power System oscillations

→ The UPFC can be used for voltage support and transient stability improvement by damping of low frequency power system oscillations.

→ Low frequency oscillations in electric power system occur frequently due to disturbances such as changes in loading conditions or a loss of a transmission line or a generating unit.

→ These oscillations need to be controlled to Maintain system stability.

→ Many in the past have presented Lead - Lag type UPFC damping controllers.

→ The UPFC having the ability for dynamic stability enhancement via damping of low frequency oscillations at a Multi machine electric power system.

→ A stabilizer controller is provided to improve damping of power system oscillations.

→ This controller is considered as a lead lag compensator and provides an electrical torque in phase with the speed deviation in order to improve damping of power system oscillations.

→ Applying the supplementary stabilizer signal greatly enhance the damping of the generator angle oscillations and therefore the system become more stable. under this situation, while the performance of the system without stabilizer becomes poor, the stabilizer has a stable and robust performance

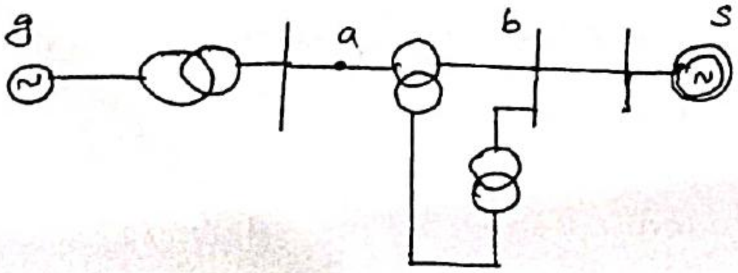
→ The system without stabilizer does not have enough damping and the responses fluctuate after disturbance.

## (2) Power System Stability Enhancement using PSS and UPFC

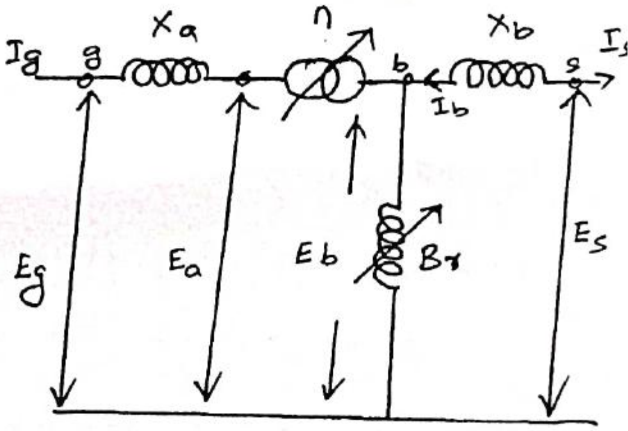
Effect of UPFC

→ The main task of UPFC device is the control of active and reactive power during steady state.

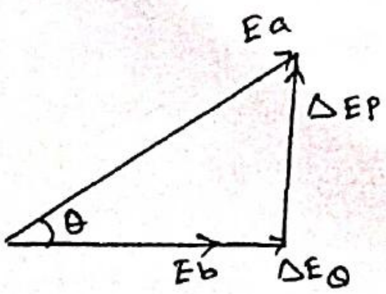
→ High speed and flexibility of switching Processes allow the use of UPFC during Post disturbance fast dynamics.



Schematic diagram



Single -Phase diagram



Phasor diagram.

$\eta$ → complex transformation ratio

$B_T$ → shunt susceptance

The ratio $\eta$ resolved into two orthogonal components

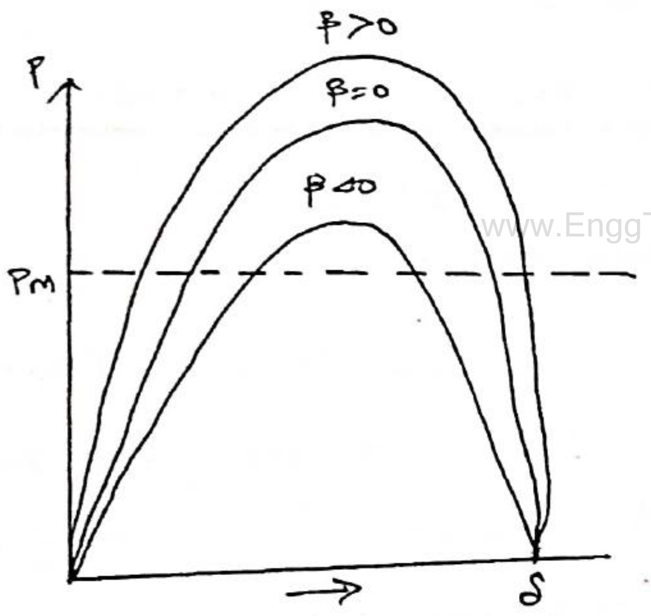
→ Direct - $\beta$ corresponding to the voltage increment $\Delta E_Q$ and

→ Quadrature $\gamma$ corresponding to voltage increment $\Delta E_P$.

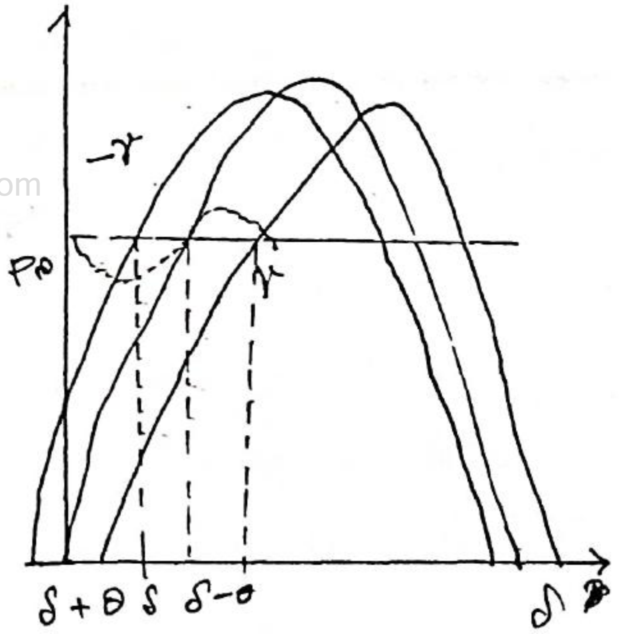
Using the previously defined components the ratio $\eta$ can be defined as follows

$$\eta = (1+\beta)+j\gamma$$

using the model presented, the influence of different UPFC voltage components on the power characteristics.



Direct control influence



Quadrature control influence

→ The regulation of quadrature component depending on the UPFC voltage sign makes the power characteristics move right (or) Left.

→ The direct component changes results in magnitude change of active power angle characteristics in a small range of Load angle change.

## Part-B

① Explain the block diagram of STATCOM.

② Explain the Principle and operation of STATCOM.

③ Explain V-I characteristics of STATCOM

④ Explain different applications of STATCOM.

⑤ Explain the Principle of operation of SSSC.

⑥ Explain the UPFC

⑦ Explain different applications of UPFC

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4.1 [UNIT-IV]

# LINE COMMUTATED HVDC TRANSMISSION

Operation of Gratz bridge - Effect of delay in Firing angle - Effect of commutation overlap - Equivalent circuit. Basic concept of HVDC transmission. Model of operations and control of power flow CC and CEA mode of operation.

**Objective :-**

Students will able to study basic idea about line commutated HVDC Transmission.

## what is meant by Line commutated HVDC Transmission ?

Line -commutated HVDC transmission refers to a type of high- voltage direct current (HVDC) transmission system where the conversion of AC to DC and vice versa is achieved through the use of thyristor - based converters. In line - commutated HVDC systems, the commutation process, which involves switching the direction of current flow, is performed by the AC system itself through the natural zero - crossing of the AC voltage waveform.

## Technical terms

**Two-terminal HVDC transmission System:**

HVDC transmission system consisting of two HVDC transmission substations and the connecting HVDC transmission Lines.

**Value:**

Complete operative controllable or non-controllable value device assembly normally conducting in only one direction, which can function as a converter arm in a converter bridge.

## Reference books.

1. Flexible AC Transmission Systems

C. RAVICHANDRAN

T.A. RAGHAVENDIRAN

2. HVDC Power Transmission system

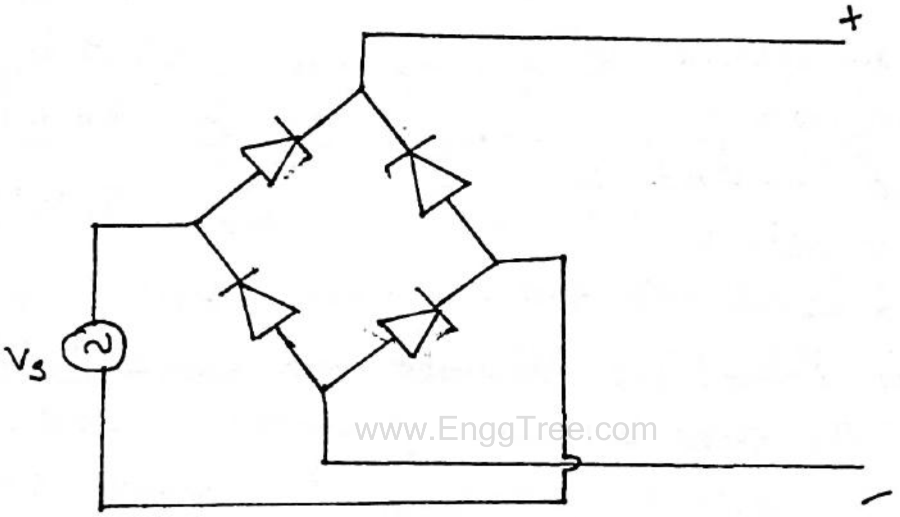
K.R. Padiyar

4.2

# Gratz Bridge

Definition of Graetz circuit :-

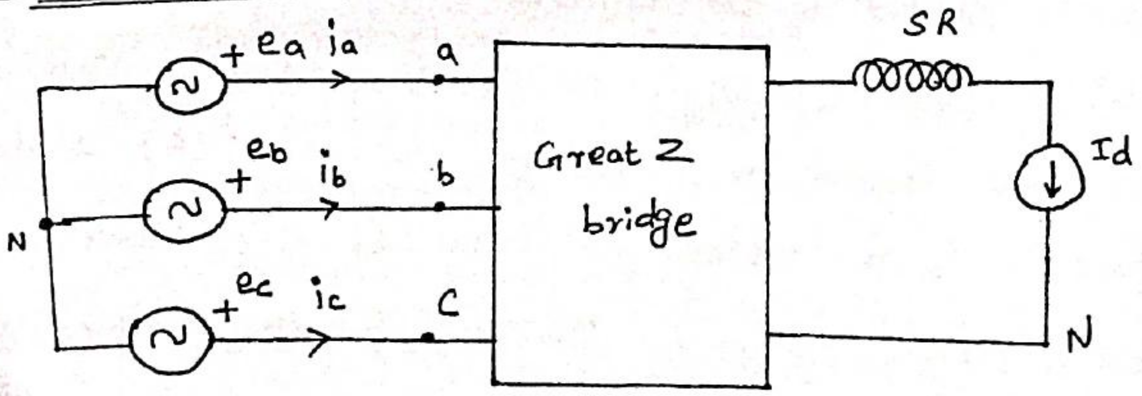
A hand mode diode bridge. A diode bridge is an arragement of four (or) more diodes in a bridges circuit configuration that provides the Same polarity of output (or) either polarity of inputs.

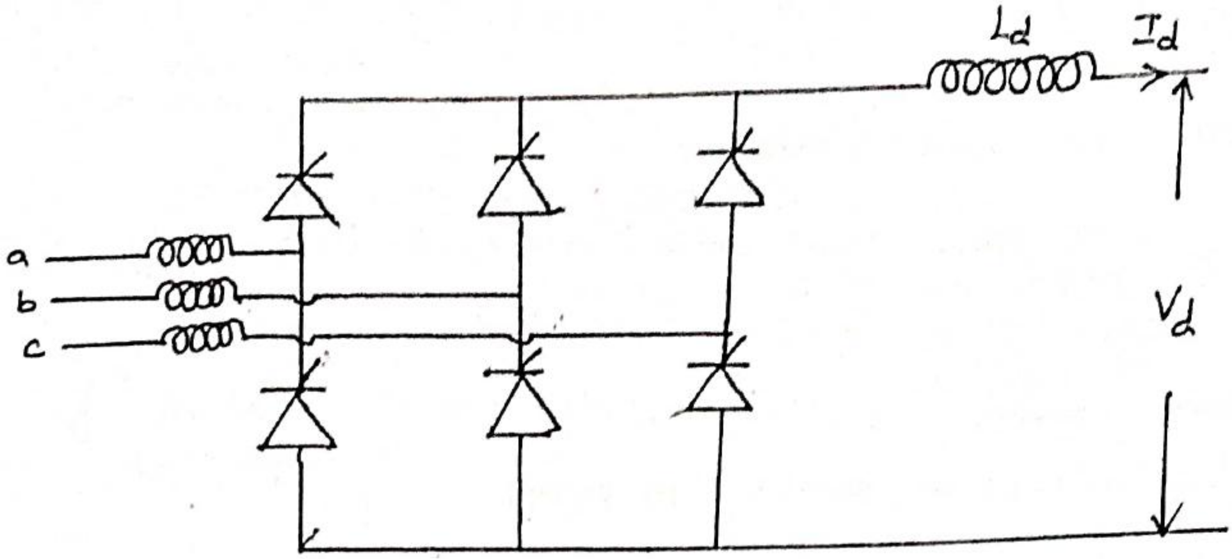


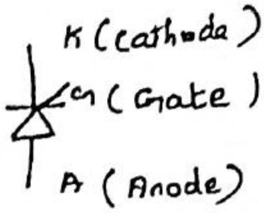
Simplify analysis of Graetz circuit have 2 methods

1. without overlap
2. with overlap

## ① without overlap







Valve 2 → fired 60° after Valve 1

Valve 3 → fired 60° after Valve 2

each conduct for 120°

→ In a Line commutated converter, Graetz bridge is connected to three balanced sinusoidal voltage source on the AC side and constant DC current source on the DC side as shown in the figure.

→ Each of the switches $S_1$ to $S_6$ in the Graetz bridge are made of series connected thyristor devices (to provide the required voltage ratings). The Value is denoted by the thyristor.

→ A Thyristor Value (ideally) can be viewed as a switch which can be turned on. when the terminal (A) anode is positive with respect to terminal K (cathode) an a gate (firing) signal is provided at the terminal ( Once the thyristor switch is turned on, it can be turned off only when the current through it goes to zero and there is a minimum commutation margin [when the voltage across the thyristor is reversed biased, The voltage at terminal A, is negative with respect to K). In modern high voltage thyristor device (rated at 8 kV and above) the margin required may be hundreds of Microseconds.

→ when no gate pulse is present, the switch should withstand both positive and negative voltages.

Neglecting losses in the thyristor valves the voltage across the device is zero when it is turned on and the current through the devices is zero when it is not conducting. In other words, the valves can be viewed as ideal switches subject to the constraints mentioned above.

Without overlap is defined as

* At any instant two valves are conducting in the bridge
* The following assumption are made to simplify the analysis

→ The DC current is constant.

→ The valves can be modeled as ideal switch with zero impedance when ON and with infinite impedance when OFF.

→ The AC Voltage at the converter bus are sinusoidal and remains constant.

→ one period of the AC supply voltage can be divided into 6 intervals each corresponding to the conduction of pair of valves.

→ The DC Voltage wave from repeats for each interval.

→ Thus for the calculation of the averaged DC voltage it is necessary to consider only one interval.

→ Note that the current can flow only in one direction through the thyristor switch (from anode to cathode) when it is on.

(2) with overlap

→ Due to Leakage inductance if the converter transformer and the impedance in the supply networks the current in a valve cannot change suddenly and the commutation from one valve to next cannot be instantaneous

→ For example, when valve 3 is fired.

→ The current transfer from valve 1 to valve 3 takes a finite period during which both valves are conducting. This is called overlap and its duration is measured by the overlap [Commutation] angle U.

4:4

⑦

## Effect of delay in Firing angle

→ Delay angle is the time required for firing the Pulses in a converter for its conduction.

→ It is generally expressed in electrical degrees

→ In other words, it is the time between zero crossing of commutation voltage and starting point of forward current conduction.

→ The mean value of DC voltage can be reduced by decreasing the conduction duration, which can be achieved by delaying the pulses i.e., by increasing the delay angle we can reduce the DC Voltage and also the power transmission form one valve to another valve can also be reduced.

→ when $\alpha = 0$, the commutation takes place naturally and the converter acts as a rectifier

→ when $\alpha > 60$ degree, the voltage with negative spikes appears and the direction of power flow is from AC to DC system without change in magnitude of current.

→ when $\alpha = 90°$, the negative and positive portions of the voltage are equal and because of above fact, the DC voltage per cycle is zero. Hence the energy transferred is zero.

→ when $\alpha > 90°$, the converter acts as an inverter and the flow of power is from DC system to AC system.

Let volve 3 is fired at an angle of $\alpha$.

The DC output voltage is given by

$$V_{dc} = V_{do} \cos\alpha$$

$$V_d = e_b - e_c = e_{bc}$$

$$e_{bc} = \sqrt{2}\, V_{LL} \sin(\omega t + 60°)$$

$$V_{dc} = \frac{6}{2\pi} \int_{\alpha}^{\alpha+60°} e_{bc}\, d\omega t$$

$$V_{dc} = \frac{3}{\pi} \int_{\alpha}^{\alpha+60°} \sqrt{2}\, V_{LL} \sin(\omega t + 60°) \cdot d\omega t$$

$$= \frac{3\sqrt{2}}{\pi} V_{LL} \left[ \cos(\alpha + 60°) - \cos(\alpha + 120°) \right)$$

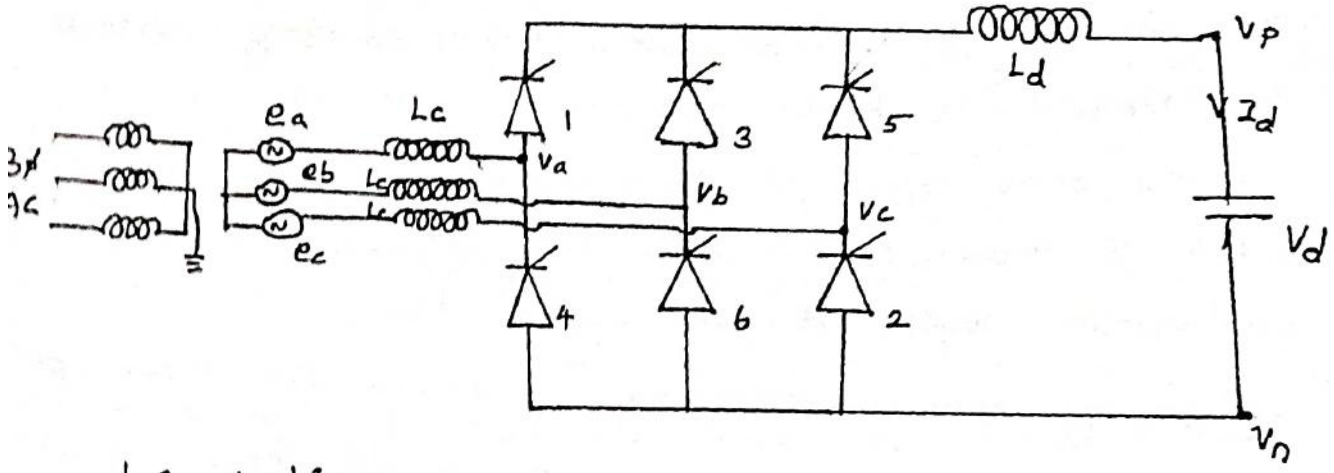
$$= \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha$$

$$= 1.35\, V_{LL} \cos\alpha$$

From above equation we can say that if firing angle varies, tho DC output voltage varies.

4.5

## Effect of commutation overlap



Lc indicates Leakage inductance of transformer

$V_d, I_d$ = Dc voltage and current flowing in the Line $L_d$ = Dc side reactance

$V_1$ = voltage across the thyristors

P, n = positive and negative pole on the Line

Due to the leakage inductance in the supply network, the current in a valve cannot change suddenly and thus commutation from one valve to the next cannot be instantaneous.

For example, when valve 3 is fired, the current transformer from valve 1 to valve 3, takes a finite period during which both valves are conducting. This is called overlap and its duration is measured by the overlap (commutation) angle $\mu$.

## Commutation delay:-

→ The process of transfer of current from one path to another path with both paths carrying current simultaneously is known overlap.

→ The time repuired for commutation or overlappi which is expressed in electrical degrees is done wi commutation angle, denoted by $\mu$.

→ During normal operating conditions the overlap angle is in the range of 0 to 60 degrees. in whic two (or) three valves are conducting.

→ However, if the overlap angle is the range of 60 to 120 degrees, then three to four valves are in conducting state which is known as abnormal operating mode.

→ During commutation period, the current increases from 0 to $I_d$ in the incoming valve and reduces to zero from $I_d$ in the outgoing valve.

→ The commutation process begins with delay angle and ends with extinction angle.

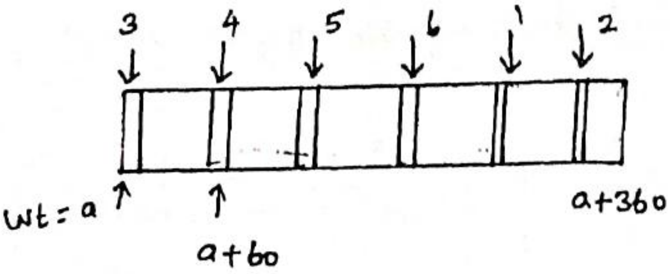
It starts when $\omega t = \alpha$ and ends when $\omega t = \alpha + \mu = \delta$, where $\delta$ is known as an extinction angle.

Three modes of the converter

1. Mode 1 → Two and three value conduction ($\mu < 60°$)
2. Mode 2 → Three valve conduction ( $\mu = 60°$)

3. Mode 3 → Three and four valve conduction ($\mu > 60°$)

Depending upon the delay angle $\alpha$, the mode 2 must be just a point on the boundary of modes 1 and 3.



→ Analysis of Two and three valve conduction mode.

generally overlap angle will be less than 60°, So let us analyse this mode.

→ In this mode each interval of the period of supply can be divided into two subintervals.

→ In the first subinterval, three valves are conducting and in the second subinterval, two values are conducting.

Let us assume the input voltages

$$e_a = E_m \cos |wt + 60°|$$

$$e_b = E_m \cos |wt - 60°|$$

$$e_c = E_m \cos |wt - 180°|$$

Corresponding line voltages are $e_{ac}$, $e_{ba}$, $e_{cb}$

$$e_{ac} = e_a - e_c$$

$$= E_m \cos(wt + 60) - E_m \cos(wt - 180°)$$

$$= E_m\left(\cos(\omega t+60^\circ) - \cos(\omega t-180^\circ)\right)$$

$$= E_m\left[\left[\cos\omega t\,\tfrac{1}{2} - \sin\omega t\cdot\frac{\sqrt{3}}{2} + \cos\omega t\right]\right]$$

$$= E_m\left[\frac{3}{2}\cos\omega t - \frac{\sqrt{3}}{2}\sin\omega t\right]$$

$$= \sqrt{3}\,E_m\left|\frac{\sqrt{3}}{2}\cos\omega t - \tfrac{1}{2}\sin\omega t\right|$$

$$= \sqrt{3}\,E_m\left[\cos 30^\circ\cos\omega t - \tfrac{1}{2}\sin\omega t\right]$$

$$\boxed{e_{ac} = \sqrt{3}\,E_m\cos(\omega t+30^\circ)}$$

$$e_{ba} = E_m\cos(\omega t-60^\circ) - E_m\cos(\omega t+60^\circ)$$

$$= E_m\left((\cos\omega t\cdot\cos 60^\circ + \sin\omega t\sin 60^\circ) - (\cos\omega t\cos 60^\circ . \sin\omega t\sin 60^\circ)\right.$$

$$= E_m\left[\cos\omega t\cdot\tfrac{1}{2} + \sin\omega t\,\frac{\sqrt{3}}{2} - \cos\omega t\,\tfrac{1}{2} + \sin\omega t\,\frac{\sqrt{3}}{2}\right]$$

$$= \sqrt{3}\,E_m(\sin\omega t)$$

$$\boxed{e_{ba} = \sqrt{3}\,E_m\sin\omega t}$$

$$e_{cb} = E_m\left(\cos(\omega t-180^\circ) - \cos(\omega t-60^\circ)\right)$$

$$= E_m\left(\cos\omega t\cdot\cos 180^\circ + \sin\omega t\sin 180^\circ - \cos\omega t\cos 60^\circ - \sin\omega\right.$$
$$\left.\sin 60^\circ\right)$$

$$= E_m\left[-\frac{3}{2}\cos\omega t - \frac{\sqrt{3}}{2}\sin\omega t\right]$$

$$= \sqrt{3}\,E_m\left[-\frac{\sqrt{3}}{2}\cos\omega t - \tfrac{1}{2}\sin\omega t\right]$$

$$\boxed{e_{cb} = \sqrt{3} E_m \cos(\omega t + 150^\circ)}$$

$$e_{cb} = E_m \left( \cos(\omega t - 180) - \cos(\omega t - 60^\circ) \right)$$

$$= E_m [\cos \omega t \cdot \cos 180^\circ + \sin \omega t \sin 180^\circ - \cos \omega t \cos 60^\circ - \sin \omega t \sin 60^\circ)$$

$$= E_m \left[ \frac{3}{2} \cos \omega t - \frac{\sqrt{3}}{2} \sin \omega t \right]$$

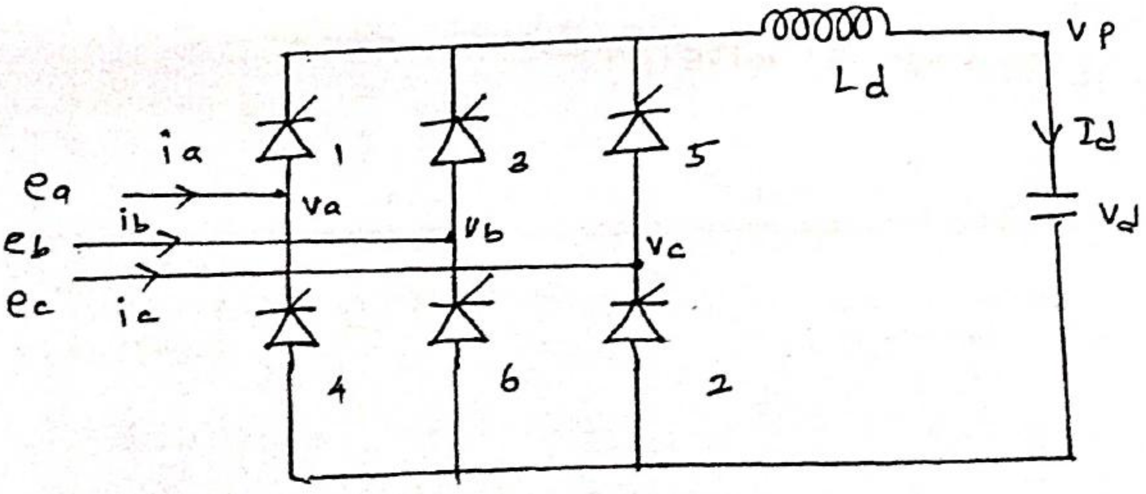
$$= \sqrt{3} E_{cb} \left| -\frac{\sqrt{3}}{2} \cos \omega t - \frac{1}{2} \sin \omega t \right|$$

$$\boxed{e_{cb} = \sqrt{3} E_m \cos(\omega t + 150^\circ)}$$

Each Valve will Conduct for 120° and each Pair will Conduct for 60° if there is no overlap.

Let us consider non-overlap of only valve 1, 2 conducting followed by overlap of 3 with 1 (i.e) 1, 2 and 3 conducting

when only valve 1 and 2 conducting



$i_a = -i_c = I_1 = I_2 = I_d$

$i_b = I_3 = I_4 = I_5 = I_6 = 0$

$V_a = V_p = e_a = E_m \cos(\omega t + 60^\circ)$

$V_b = e_b = E_m \cos(\omega t - 60^\circ)$

$V_c = V_n = e_c = E_m \cos(\omega t - 180^\circ)$

$V_d = V_p - V_n = e_a - e_c = e_{ac} = \sqrt{3} E_m \cos(\omega t + 30^\circ)$

$V_1 = V_2 = 0$

$V_3 = e_{ba} = \sqrt{3} E_m \sin \omega t$

$V_4 = V_n - V_p = -V_d$

$V_5 = V_n - V_p - V_d$

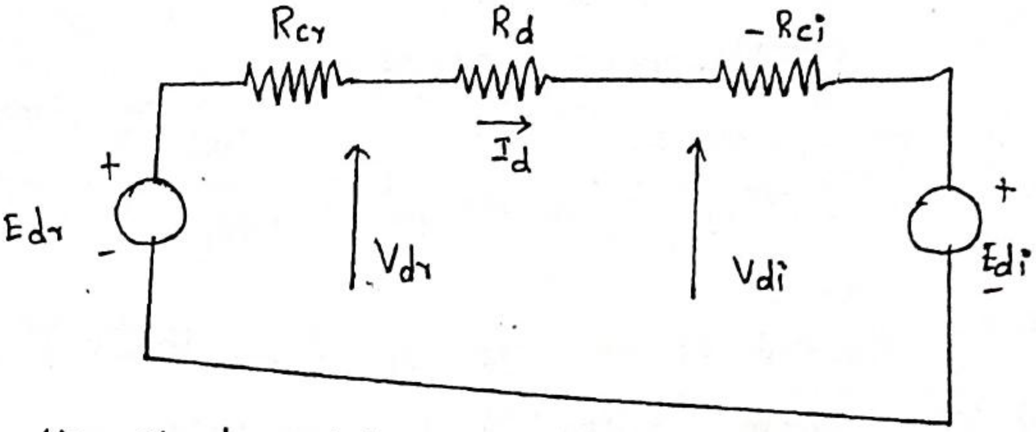
$V_6 = e_c - e_b = e_{cb} = \sqrt{3} E_m \cos(\omega t + 150^\circ)$

when valve 3 is fired then 3 will overlap with 1 and it will be 3 valve conduction periods (i.e) 1, 2 and 3.

## Equivalent circuit for HVDC Transmission.

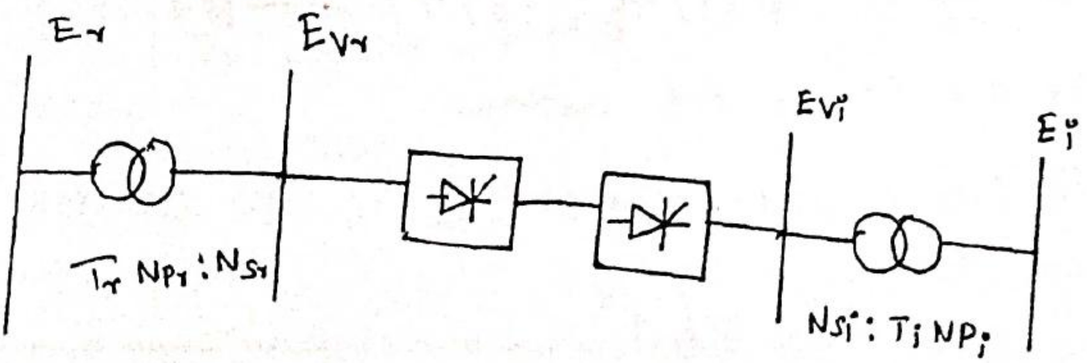
→ The control of power in a DC link can be achieved through the control of current or voltage.

→ From minimization of loss considerations, we need to maintain constant voltage in the link and adjust the current to meet the required power.



consider the steady state equivalent circuit of a two terminal DC link. This is based on the assumption that all the series connected bridges in both poles of a converter station are identical and have the same delay angle.

→ Also the number of series connected bridges ($n_b$) in both stations (rectifier and inverter) are the same.



The voltage sources $E_{dr}$ and $E_{di}$ are defined by

$$E_{dr} = (3\sqrt{2}/\pi)\, n_b E_{V_1} \cos\alpha_T \quad \text{--- ①}$$

$$E_{di} = (3\sqrt{3}/\pi)\, n_b E_{Vi} \cos\gamma_i \quad \text{--- ②}$$

where $E_{Vr}$ and $E_{Vi}$ are the line to line voltages in the value side windings of the rectifier and inverter transformer respectively.

Voltage can be obtained by

$$E_{Vr} = \frac{N_{sr} E_r}{N_{pr} T_r} \qquad E_{Vi} = \frac{N_{si} E_i}{N_{pi} T_i} \quad \text{--- ③}$$

where $E_r$ and $E_i$ are the AC (line to line) voltages of the converter buses on the rectifier and inverter side.

$T_r$ and $T_i$ are the OFF-nominal tap ratios, on the rectifier and inverter side.

Combining equations (1) (2) and (3)

$$E_{dr} = (A_r E_r / T_r) \cos\alpha_r \quad \text{--- ④}$$

$$E_{di} = (A_i E_i / T_i) \cos\gamma_i \quad \text{--- ⑤}$$

where $A_r$ and $A_i$ ~~are~~ are constants

The steady-state current $I_d$ in the DC link is obtained as

$$I_d = \frac{(E_{dr} - E_{di})}{R_{cr} + R_d - R_{ci}}$$

Substituting equations (4) and (5) in the above equation, we get

$$I_d = \frac{(A_r E_r / T_r) \cos \alpha_r - (A_i E_i / T_i) \cos \gamma_i}{R_{cr} + R_d - R_{ci}}$$

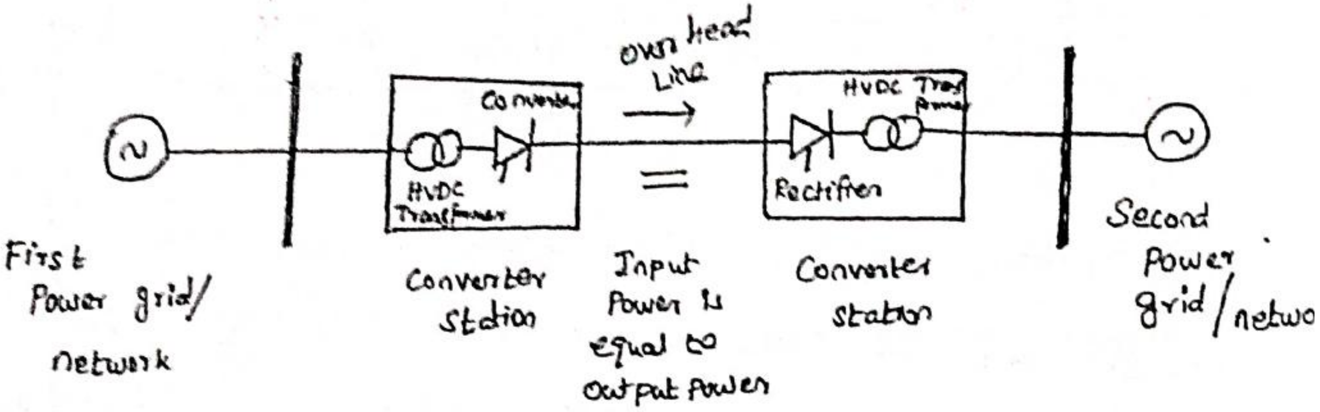
The control variables in the above equation are $T_r$, $T_i$ and $\alpha_r$, $\beta_i$. However, for maintaining safe commutation ~~at~~. margin, it is convenient to consider $\gamma_i$ as control variable instead of $\beta_i$

The feedback control of power in a DC link is not desirable because.

(1) At low DC voltages, the current required is excessive to maintain the required level of power. This can be counterproductive because of the excessive requirements of the reactive power, which depresses voltage further.

2) The constant power characteristic contributes to negative damping and degrades dynamic stability.

## Basic concept of HVDC Transmission lines



→ The High Voltage Direct current (HVDC) transmission system uses direct current for the transmission of power over Long distances.

→ The HVDC transmission system provides efficient and economic transmission of Power even to very Long distances that meet the requirements of growing ~~Long~~ Load demands.

→ Due to its simple Constructional feature and Less Complexity, ~~Yea~~ research and development authority discovered its usage in modern power transmission.

## Components of HVDC transmission

1. Converters
2. Smoothing reactors
3. Harmonic filters
4. Reactive power source
5. Electrodes
6. DC Lines
7. AC circuit breakers.

### 1. Converters

→ They perform AC/DC and DC/AC conversion

→ They consist of valve bridges and transformers

→ Valve bridge consists of high Voltage valves Connected in a 6-pulse (or) 12-pulse arrangement.

→ The transformers are ungrounded such that the DC System will be to establish its own reference to ground.

### 2. Smoothing reactors

→ They are high reactors with inductance as high as 1 H in Series with each pole.

→ They serve the following

  → They decrease harmonics in voltages and currents in DC Lines

  → They prevent commutation failures in inverters

  → Prevent current from being discontinuous for high Loads

### 3. Harmonic filters

→ Converters generate harmonics in voltages and currents. these harmonics may cause overheating of capacitors and nearby generators and interference with telecommunication systems

→ Harmonic filters are used to mitigate these harmonics.

## Technical advantages of HVDC

- → Lesser corona Loss and Radio interference.
- → The voltage regulation problem is much Less Serious for DC, since only the IR drop is involved. For the same reason Steady state Stability is no Longer a major problem.
- → No skin and proximity and Ferranti effect
- → Asynchronous operation possible between regions having different electrical parameters.

## Economical Advantages

- → Dc Lines and Cables are cheaper than Ac Lines or Cables.
- → The towers of the Dc lines are narrower simpler and cheaper compared to the towers of the Ac Lines.
- → Line Losses in a Dc Line are Lower than the losses in an AC Lines.

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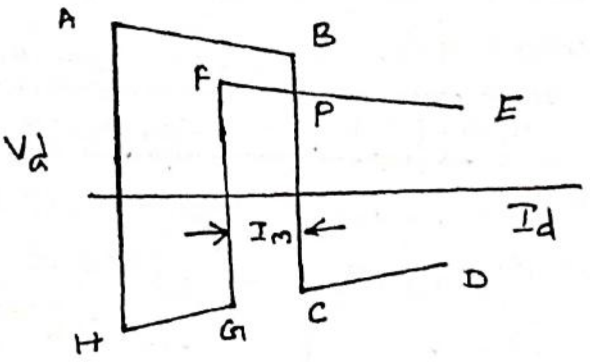
## Converters control characteristics Basic characteristics



Controllers characteristics

CC → constant current control

CEA → constant (minimum) extinction angle

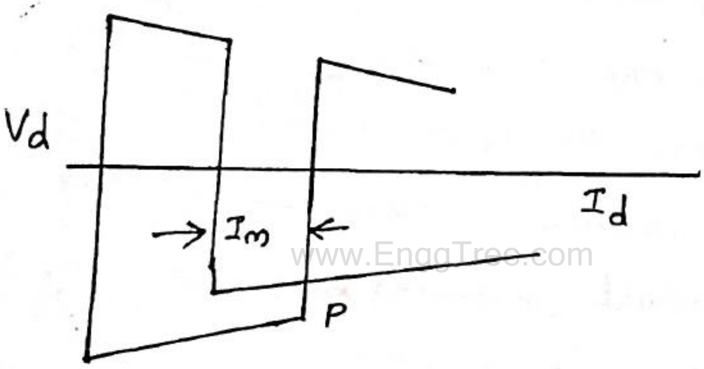
The intersection of the two characteristics (point A) determines the mode of operation - station I operating as rectifier with constant current control and station II operating at constant (minimum) extinction angle.

→ There can be three modes of operation of the link (for the same direction of power flow) depending on the ceiling voltage of the rectifier which determines the point of intersection of the two characteristics which are defined below.

1. CC at rectifier and CEA at inverter (operating point A) which is the normal mode of operation.
2. with slight dip in the AC voltage, the point of intersectio drifts to C which implies minimum α at rectifier and minimum γ at the inverter.

4) with lower AC voltage at the rectifier, the mode of operation shifts to point B which implies CC at the inverter with minimum $\alpha$ at the rectifier.

| Station - I | Station - II | controller type |
|---|---|---|
| AB | HG | minimum $\alpha$ |
| BC | GF | constant current |
| CD | EF | CEA (Minimum $\gamma$) |



power reversal controllers characteristics.

→ The characteristic AB has generally more negative slope than characteristic FE because the slope of AB is due to the combined resistance of $(R_d + R_{cr})$ while is the slope of FE is due to $R_{ci}$

→ The above figure shows the control characteristics for negative current margin Im (or where the current reference of station II is larger than that of station I). The operating point shifts now to D which implies power reversal with station I [now acting as inverter) operating with minimum CEA control while station II operating with CC control.

→ This shows the importance of Maintaining the correct sign of the current margin to avoid inadvertent power reversal. the maintenance of proper current margin repuires adequate telecommunication channel for rapid transmission of the current (or) power order.

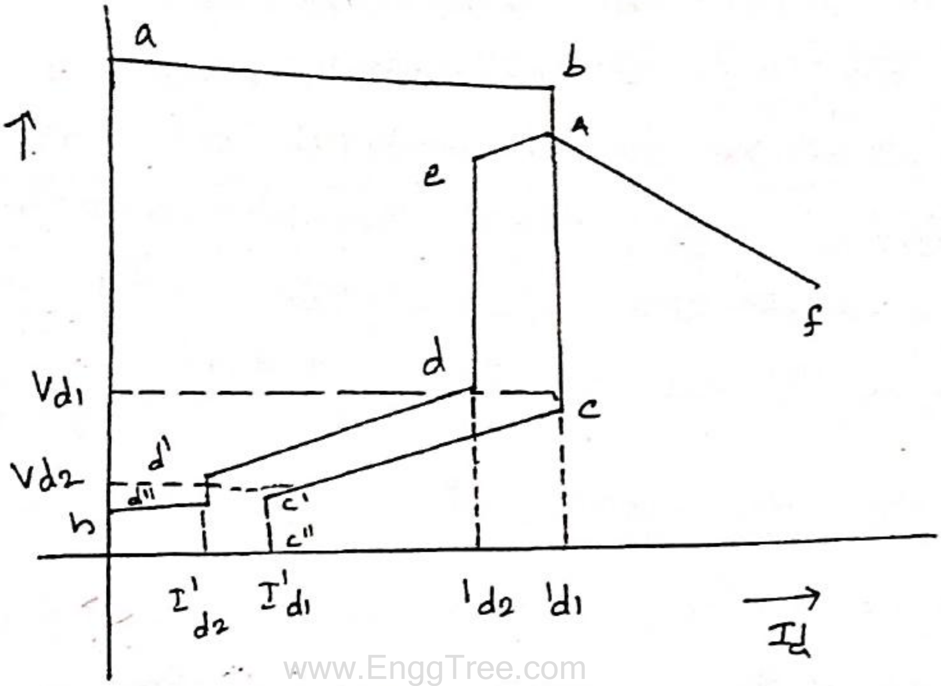
Voltage Dependent current Limit:-

→ The Low voltage in the DC Link is mainly due to the faults in the AC System on the rectifier (or) inverter side. The Low AC voltage due to faults on the Inverter side can result in persistent commutation failure because of the increase of the overlap angle.

→ In such cases, it is necessary to reduce the DC current in the Link until the conditions that Led to the reduced DC voltage are relieved.

→ Also the reduction of current relieves those valves in the inverter which are overstressed due to continuous current flow in them.

→ If the low voltage is due to faults on the rectifier side AC System, the Inverter has to operate at very Low Power factor causing excessive consumption of reactive power which is also undesirable.



Part-B

① Explain Graetz bridge circuit.

② Effect of delay in firing angle.

③ Explain effect of Commutation overlap.

④ Explain equivalent circuit for HVDC Transmission.

⑤ Explain basic concept of HVDC Transmission Lines.

⑥ Explain converter control characteristics.

## UNIT- V

# VSC BASED HVDC TRANSMISSION

Basic 2 Level IGBT Inverter operation - 4 Quadrant Operation - Phase angle control - dq control - control of power flow in Vsc based HVDC Transmission, Topologies of MTDC system.

## Objective

Students will able to Study Voltage Source converter (VSC) Based HVDC Transmission.

## What is Vsc based HVDC Transmission?

Transmission system that utilizes Voltage Source Converter (VSCs) as the Primary means of converting alternating current (AC) to direct current (DC) and vice versa.

## Why we need Study Vsc based HVDC Transmission?

Advancements in power System technology: VSC-based HVDC transmission systems represent a significant advancement in Power system technology, offering improved controllability, flexibility, and efficiency compared to traditional HVDC Systems based LCCs. Understanding the principles and operation of VSC-based HVDC Systems is essential for engineers and researchers working in the field of power system.

## Technical terms

1) Voltage Source converter (VSC):-

A power electronics device used in VSC-based HVDC Transmission Systems to convert AC power to DC power and vice versa.

2) Multilevel Converter:-

A type of VSC that uses multiple Levels of Voltage to achieve higher power quality and efficiency in HVDC transmission system.

3) Pulse width modulation (PWM):

A control technique used in VSC-based HVDC systems to generate switching signals for the power converters, enabling precise control of the output voltage and current.

## Reference Books

1. HVDC Power Transmission System
   K.R. Padiyar

2. FACTS
   C. RAVICHNDRAN
   T.A. RAGHAVENDIRAN

5:2

(ii)

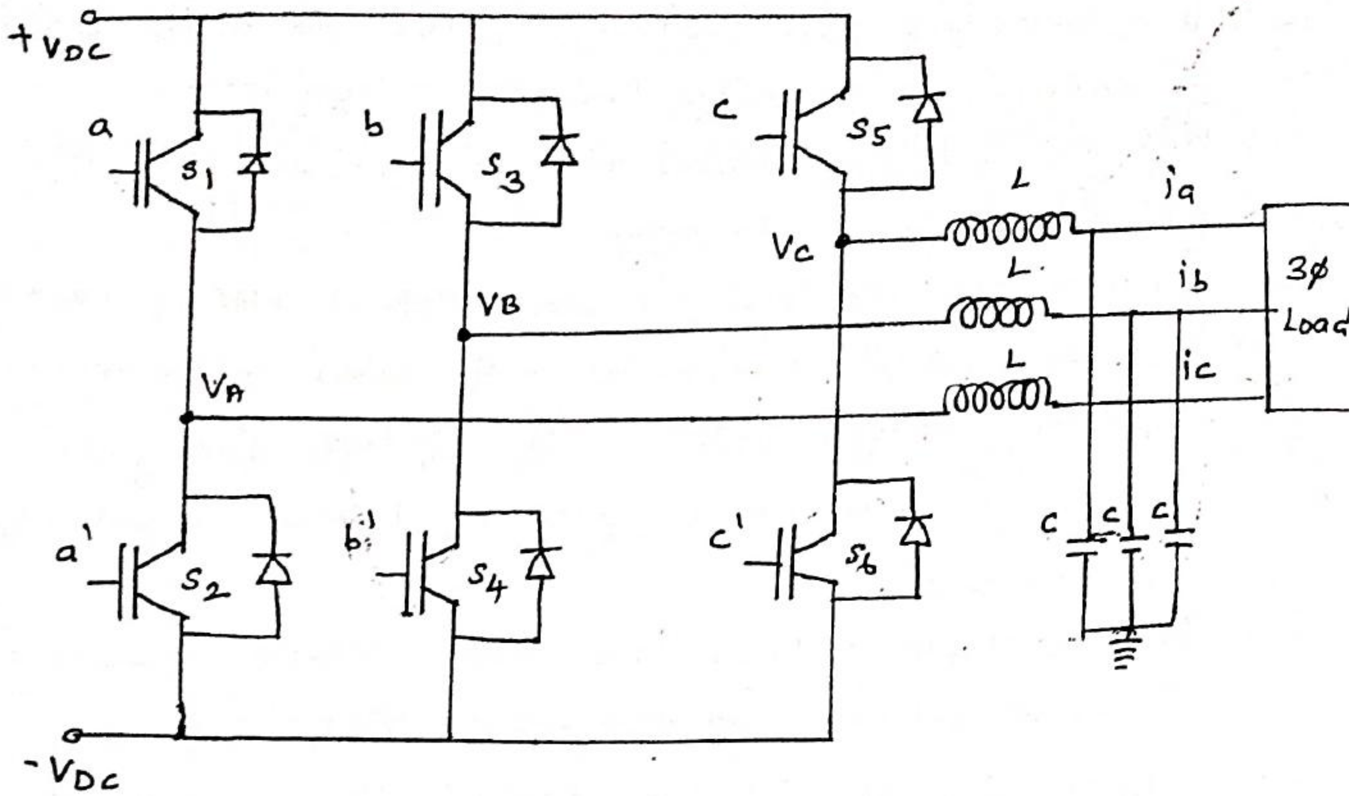
## Basic -2 Level IGBT Inverter operation

→ The IGBT is a well established device for power conversion applications as low and medium voltage drives. UPS and battery charges and is available in many different types of Packages.

→ Most of the standard pakages were developed mainly for Low voltage applications and when going to medium voltage systems one pakage family is becoming predominant and it is the Hipak-type of modules.

→ The available ratings are 1700 - 6500V enabling inverter ratings up to about 2400 Vrms. with devices current ratings up to 2400A, 1700 V and 750 A, 6500 V it is possible to accomplish converters with ratings beyond 500 KW even with forced air cooling. with out series (or) Parallel connection.

→ Although the devices due to the large size and high power ratings cannot be switched as fast as IGBT - modules for Lower power applications. It is still possible to reach switching frequencies of 2-4 KHZ for the 1700 V.



→ A basic 2-Level IGBT inverter is a type of Power electronic device used to convert DC power into AC power.

1. Input DC power:-

The inverter receives a fixed DC voltage from a DC power source, such as a battery or a rectifier.

2. Inverter circuit:

The basic 2-Level IGBT inverter consists of pairs of insulated Gate Bipolar Transistors (IGBTs) connected in an H-bridge configuration. Each pair of IGBTs forms a Leg of the inverter circuit.

## 3. PWM control :-

Pulse width Modulation (PWM) control is used to switch the IGBTs on and off rapidly to create an Ac output waveforms. By adjusting the width of the pulses, the amplitude and frequency of the output voltage can be controlled.

## 4. output AC Voltage:

→ The IGBTs are switched in a specific sequence to generate a quasi-sinusoidal Ac output voltage.

→ The output voltage waveform is characterized by two voltage levels (hence the name "2-Level") corresponding to the positive and negative peaks of the Ac waveform.

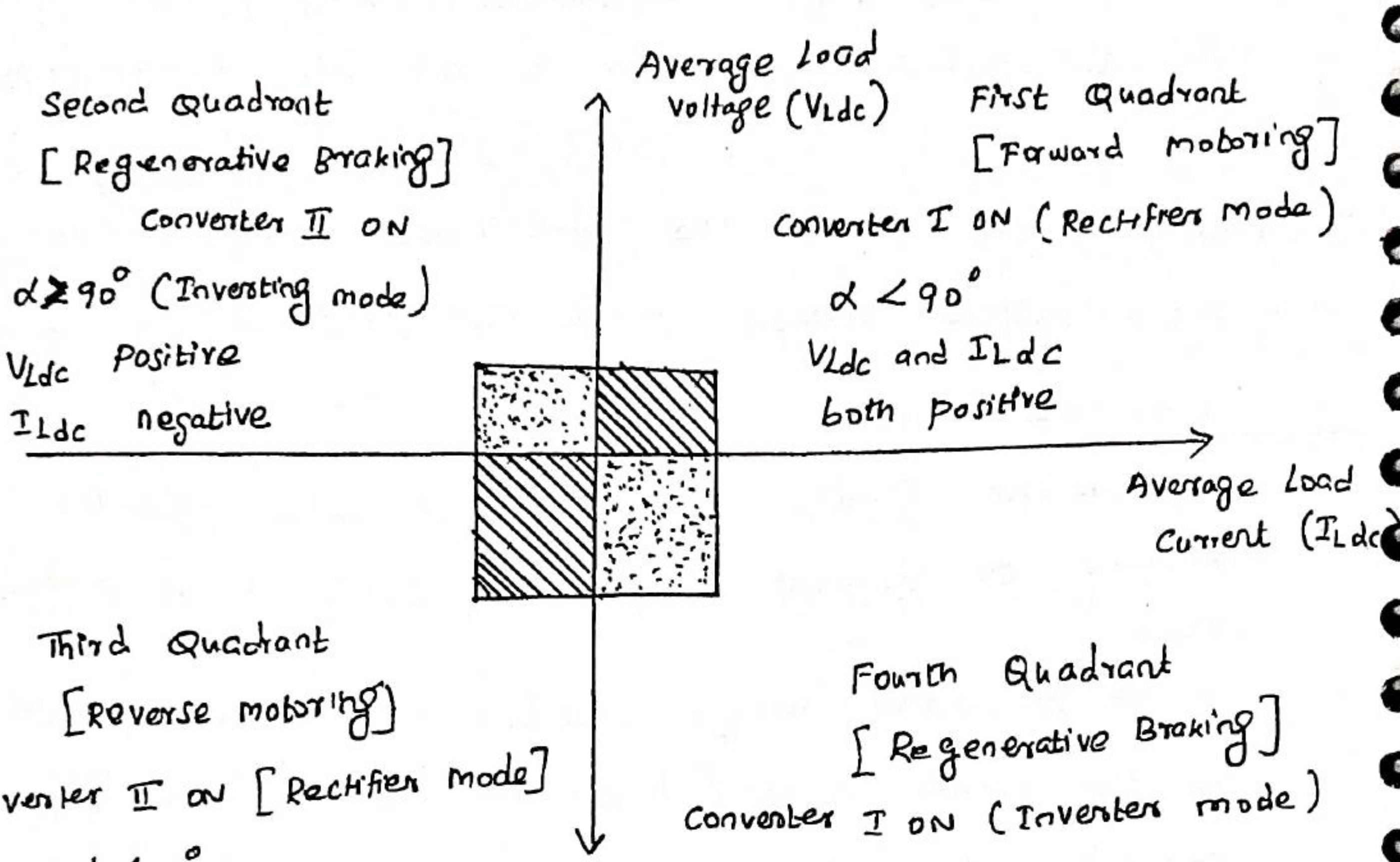
## 5. Filtering

In Some cases, Additional filtering components such as Lc fillers may be used to smooth out the output voltage waveform and reduce harmonics.

## 6. Applications:

2-Level IGBT inverters are commonly used in various applications such as motor drives, renewable energy system (Like Solar inverters), uninterruptible power supplies (UPS). and electric Vechicle inverters.

# 4 Quadrant operation of converter

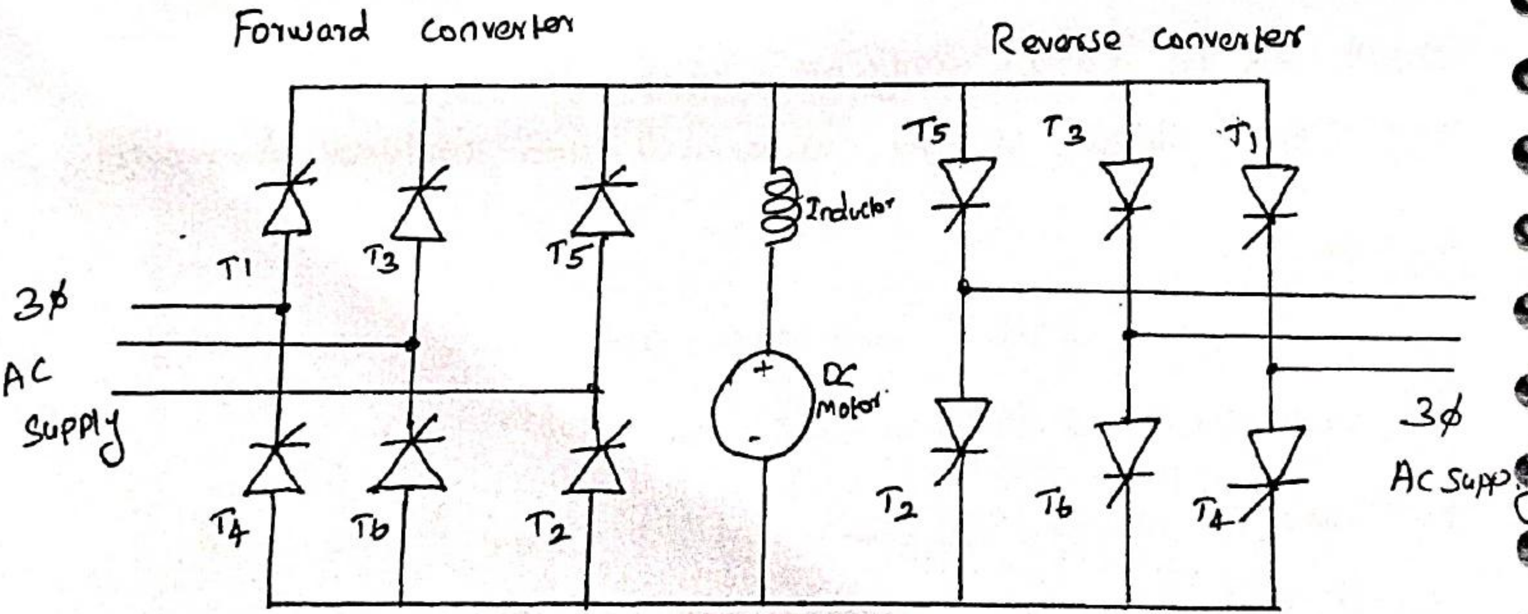


Second Quadrant
[Regenerative Braking]
Converter II ON
$\alpha > 90^\circ$ (Inverting mode)
$V_{Ldc}$ Positive
$I_{Ldc}$ negative

First Quadrant
[Forward motoring]
Converter I ON (Rectifier mode)
$\alpha < 90^\circ$
$V_{Ldc}$ and $I_{Ldc}$ both positive

Third Quadrant
[Reverse motoring]
Converter II ON [Rectifier mode]
$\alpha < 90^\circ$
$V_{Ldc}$ - negative
$I_{Ldc}$ - Negative.

Fourth Quadrant
[Regenerative Braking]
Converter I ON (Inverter mode)
$\alpha > 90^\circ$
$V_{Ldc}$ negative
$I_{Ldc}$ - positive



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→ In a four - quadrant operation of a converter, the converter is capable of operating in all four quadrants of the current - voltage plane. this means that it can both source and sink power in both positive and negative directions.

→ In practical terms, this means that the converter can both generate power (such as in motor drives) and absorb power (such as in ~~[illegible]~~ regenerative braking) in any direction. this flexibility allows for more efficient and versatile operation in a wide range of applications.

→ Four - quadrant converters are commonly used in applications where bidirectional power flow is required. such as in electric vehicles, renewable energy systems, and grid - tied inverters

they are typically implemented using power electronic devices such as power transistors or thyristors controlled by sophisticated control algorithms to achieve the desired power flow in all four quadrants.

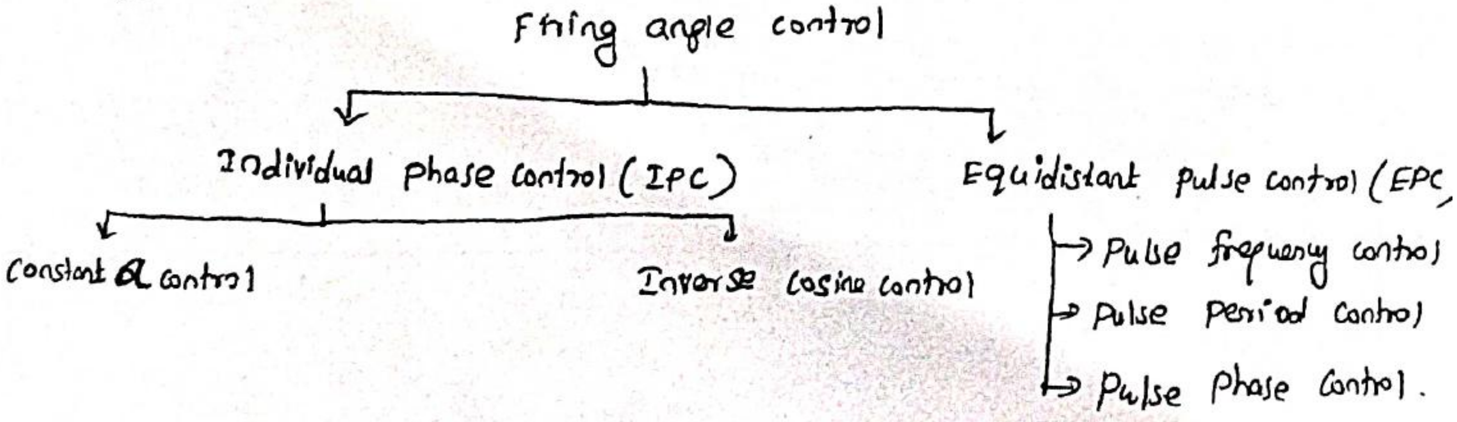
## Phase angle control

Basic Requirements for firing pulse generation.

- → The firing instant for all the valves are determined at ground potential the firing signals sent to individual thyristors by light signals through fiber-optical cables.
- → The required gate power is made available at the potential of individual thyristor for electrically triggered Thyristor (ETT) Valves.
- → For light triggered thyristor (LTT) valves, the light signal can be used to directly fire individual thyristor.
- → Gate pulse generator must send a pulse whenever required, if the particular valve is to be kept in a conducting state.

## Firing Angle control

The operation of CC (constant current) and CEA (constant extinction angle) controllers are closely linked with the Method of generation of gate pulses for the valves in a converter.



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## Individual phase control (IPC)

→ This was used in early HVDC projects

→ The main feature is that the firing pulse generation for each phase (or valve) is independent of each other and the firing pulses are rigidly synchronized with the commutation voltages

→ There are two ways in which this can be achieved

(1) constant a control
(2) Inverse cosine control

## 1) constant a control.

constant a control is a method used in phase angle control to regulate the power delivered to a load by maintaining a constant firing angle for a thyristor or other semiconductor device. In constant a control the firing angle of the thyristor is kept constant throughout the operation, regardless of changes in the load or input conditions.

## 2) Inverse cosine control.

→ Six timing voltages, are each phase shifted by 90° and added separately to a common control voltage V.

Of the sum of the two voltages.

→ The zero crossing of the sum of the two voltages initiates the firing pulse for the particular valve considered.

→ The delay angle a is proportional to the inverse cosine of the control voltage.

→ It also depends on the AC system voltage amplitude and shape.

→ The main advantage of this control scheme is that the average DC voltage across the bridge varies linearly with the control voltage $V_c$.

→ It is essential in this scheme to maintain the phase sint at 90 for variations in the supply frequency.

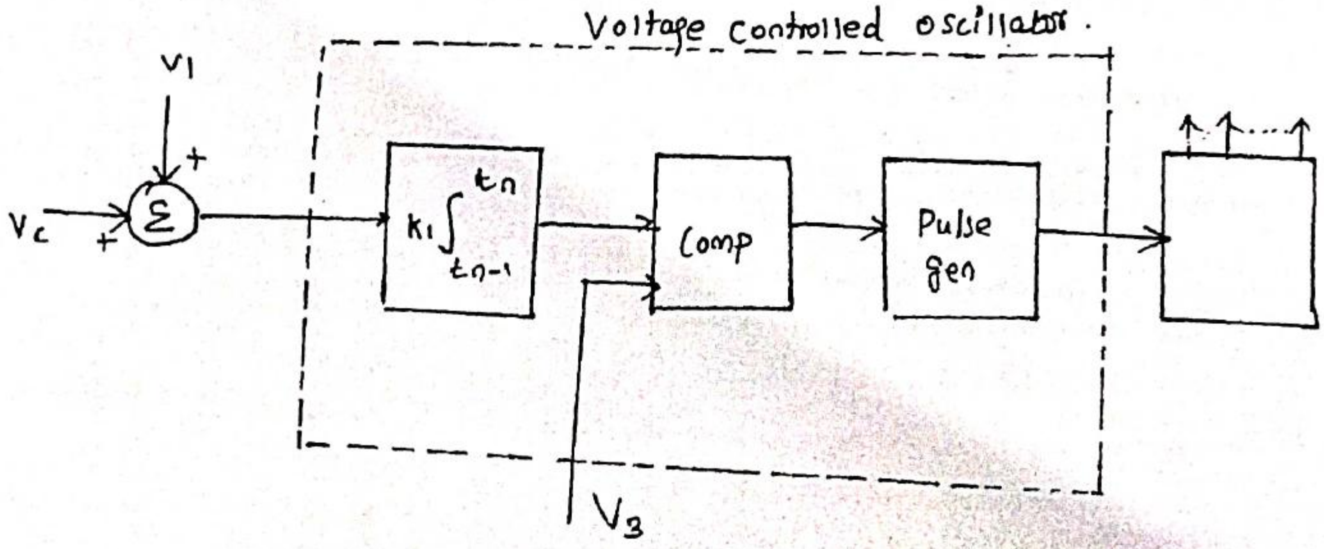
## Equidistant pulse control (EPC)

→ In this scheme, the firing pulses are generated in steady state at equal intervals of $1/pf$, through a ring counter.

→ There are three variations

(1) pulse Frequency control (PFC)
(2) pulse period control
(3) pulse phase control (PPC)

### (1) Pulse Frequency control (PFC)



- → A voltage controlled oscillator (VCO) is used
- → Frequency of VCO is determined by the control voltage V which depend on the error in the quantity being regulated.
- → Steady state operation frequency Pt, where f is the nominal frequency of the AC system.
- → PFC system has an integral characteristics.
- → It has to be used along with a feedback control system for stabilization.
- → V is a bias (constant voltage)
- → V is proportional to the system period.
- → V is control voltage which is related to the error in the quantity.

Pulse phase Control (PPC)

- → Analog circuit is configured to generate firing pulses according to the following equation.

$$\int_{t_{n-1}}^{t_n} K_1 V_1 \, dt = V_{cn} - V_{r(n-1)} + V_3$$

- → where V and V are the control voltages at the instants and respectively.
- → For proportional current control, the steady state can be reached when the error or is constant.

# dq control

- → In power electronics, dq control is a widely used techniq for controlling three-phase systems, such as inverters and converters, to achieve precise and efficient operat The dq control method involves transforming the three-Phas variables (such as voltages or currents) into a two-coordinate rotating reference frame known as the dq fra
- → By transforming the variables into the dq frame, the control of power electronic systems becomes easier and more effective.
- → The D-axis represents the direct component of the system, which is typically associated with the active power flow, while the Q-axis represents the quadrature component, often related to reactive power flow or others control objectives.

- → overall, DQ control is a powerful technique in power electronics that simplifies the control of three-phase systems and enables more efficient and accurate regulation of power flow, making it a key tool for optimizing the performance of various power electronic devices and systems

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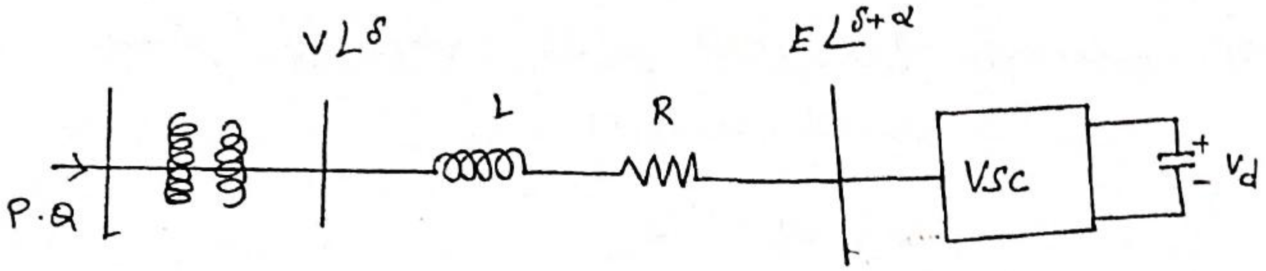
# POWER FLOW ANALYSIS WITH VSC BASED HVDC SYSTEM



→ above the diagram VSC connected to the AC network the Leakage reactance of the converter transformer is considered as part of the AC Network.

→ The interface bus with the AC network (where the power injection are considered) is the bus connected to the primary winding of the transformer.

→ The Control Variables for the VSC are the modulation index (m) and the control angle (α).

→ Line commutated converter the injected voltage $\bar{E} = km V_{dc} \angle \gamma + \alpha$, wher $k = \frac{\sqrt{3}}{\pi}$ for a two Level converter and $k = \frac{2\sqrt{6}}{\pi}$ for a three Level converter.

→ modulation index M lies in the range $0 < m \leq 1$

→ In a multiterminal System with 'n' terminals one of the terminal is selected as VST where $V_d$ is specified, $P_d$ specified.

-> The only difference is that in a VSC there is no commutation resistance to be modded.

-> The voltages at the DC buses of the VSC are unknown quantities to be computed from the following equations

$$[G] V_d = I_d.$$

$$I_{dj} = \frac{P^*_{dj}}{V_{dj}} \quad j = 1, 2, \dots (n-1)$$

$V_{dn} = V^*_{dn}$ there is no loss of generality in assumi VST as the $n^{th}$ terminal. $[G]$ is a $[n \times n]$ matrix whic is singular.

-> We can eliminate the row and column corresponding to VST and derive the following equation

$$[G] V_{dr} = I_{dr} - g_n V_{dn}.$$

Power Flow analysis under Dynamic conditions

-> AC-DC Systems in Steady state when the System is operating under equilibrium conditons which is represented by a point in the dyamic. State space in which all the system trajectories lie.

-> A disturbance followed by control actions results in the system Leaving a stable equilibrium point and entering another stable equilibrium point.

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→ The transition may be accompanied by oscillations that are damped as the system settles to a new steady state.

→ The transient (or) dynamic conditions may last for few seconds which is too short for the OLTC to act.

→ Hence the control variable at a converter is only the firing (or) extinction angle (θ) and the off-nominal tap ratio 'a' remains constant at the initial value.

→ In solving the DC network and control equations there are no major differences except the fact that we have now only one set of specifications.

→ $W_{dc}^{spec}$ as there is only one control variable per terminal.

→ At non VST terminals we can select $I_d$ (or) $P_d$ as specified variables.

→ However, at VST we can select one among $V_d$, $\theta$, $\theta_d$, $I_q$ (or) $V$.

Power balance equations at a converter bus

$$P_k(V,\delta) + P_{dk}(I, Q_k) = 0 \quad ①$$

$$Q_k(V,\delta) + Q_{dk}(I, Q_k) - Q_{ck}(V_k) = 0 \quad ②$$

→ First term in the above equation are obtained from the AC network.

→ Second term are computed from the converters equatio

→ $\Theta_k$ → Unknown and is linked to the AC voltage( $V_k$ )

## ON LINE POWER FLOW ANALYSIS FOR SECURITY CONTROL

→ During the operation of large power systems, several contingencies can occur – such as sudden tripping of a large generator (or) a AC transmission line due to a permanent fault.

→ While spinning reserve can take care of the first type contingency, the lose of a line can result in redistribution of power flow in the AC network, resulting in overloading of one (or) more lines.

→ To maintain static security it is necessary to alleviate the overloads in AC lines by control methods that act before the protection system trips the overloads in AC lines by control methods that act before the protection system trips the over loaded lines.

→ Contingency rescheduling is the prevalent control meth to alleviate AC line overloads.

④→ Contingency analysis can also be used to anticipate Potential Problems and maintain secure operation by Preventive control.

→ If phase shifting transformers are present in the System, they can also be used to redistribute Power flow.

→ However, generators are normally dispatched to minimize full costs and rescheduling will increase costs.

→ If HVDC links are present in the system, advantages can be takes of their fast controllability of Power to alleviate AC line overloads.

→ The control will be fast and the costs lowers than the costs involved in rescheduling generator output Power.

→ It reactive power constraints are not an issue, Linear AC power flow model can be used for contingency analysis and control.

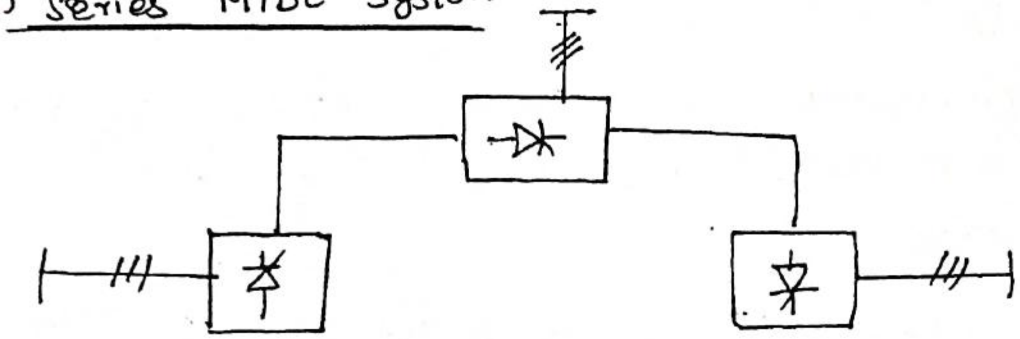
→ It is to be noted that Linear AC power flow Solution is equivalent to the solution available at the end of the first P-Q iteration of the fast decoupled Load flow.

→ Although the Linear AC power flow is approximate it is reliable and computationally efficient.

# MTDC [Multiterminal Direct current]

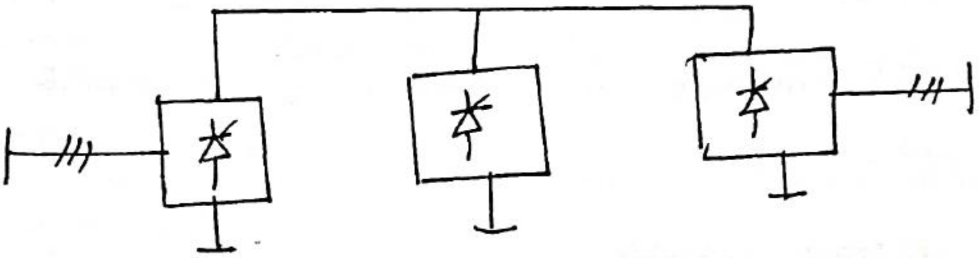
1) Series MTDC System
2) Parallel MTDC System
   - Radial
   - mesh.

## (1) Series MTDC System

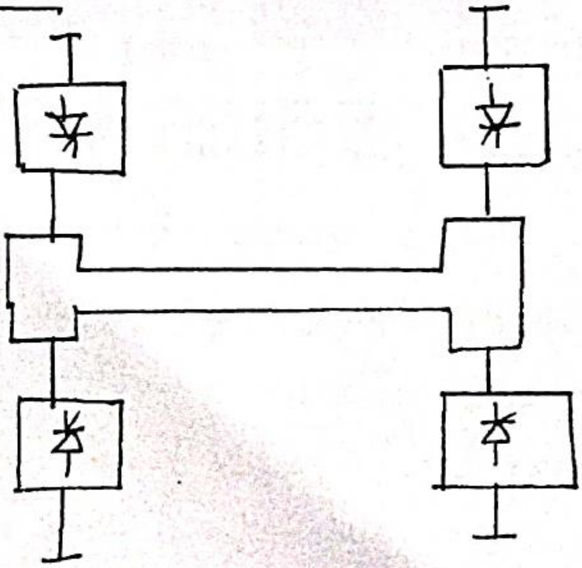


## 2) Parallel MTDC System.

### (a) Radial.



### (b) Parallel mesh



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## Part-B

① Explain the Basic - 2 Level IGBT inverter operation.

② Draw and explain 4-Quadrant operation of converter.

③ Explain different types of Phase angle control.

④ what is meant by dq control?

⑤ Explain power flow analysis with VSC based HVDC system.

⑥ Explain different types of MTDC.