# LECTURE NOTES

ON

# FLEXIBLE AC TRANSMISSION

**2019 – 2020**

**IV B. Tech II Semester (R16)**

ATTI V V SRINIVAS **, Assistant Professor**

**VSM COLLEGE OF ENGINEERING**

**Department of Electrical and Electronics Engineering**

# FLEXIBLE AC TRANSMISSION SYSTEM

## UNIT–I:

### Introduction to FACTS

Power flow in an AC System – Loading capability limits – Dynamic stability considerations – Importance of controllable parameters – Basic types of FACTS controllers – Benefits from FACTS controllers – Requirements and characteristics of high power devices – Voltage and current rating – Losses and speed of switching – Parameter trade–off devices.

## UNIT–II:

### Voltage source and Current source converters

Concept of voltage source converter(VSC) – Single phase bridge converter – Square–wave voltage harmonics for a single–phase bridge converter – Three–phase full wave bridge converte r– Three–phase current source

converter – Comparison of current source converter with voltage source converter.

## UNIT–III:

### Shunt Compensators–1

Objectives of shunt compensation – Mid–point voltage regulation for line segmentation – End of line voltage support to prevent voltage instability – Improvement of transient stability – Power oscillation damping.

## UNIT–IV:

### Shunt Compensators–2

Thyristor Switched Capacitor(TSC)– Thyristor Switched Capacitor – Thyristor Switched Reactor (TSC–TCR). Static VAR compensator(SVC) and Static Compensator(STATCOM)**:** The regulation and slope transfer function and dynamic performance – Transient stability enhancement and power oscillation damping– Operating point control and summary of compensation control.

## UNIT V:

### Series Compensators

Static series compensators**:** Concept of series capacitive compensation – Improvement of transient stability – Power oscillation damping – Functional requirements. GTO thyristor controlled Series Capacitor (GSC) – Thyristor Switched Series Capacitor (TSSC) and Thyristor Controlled Series Capacitor (TCSC).

## UNIT–VI:

### Combined Controllers

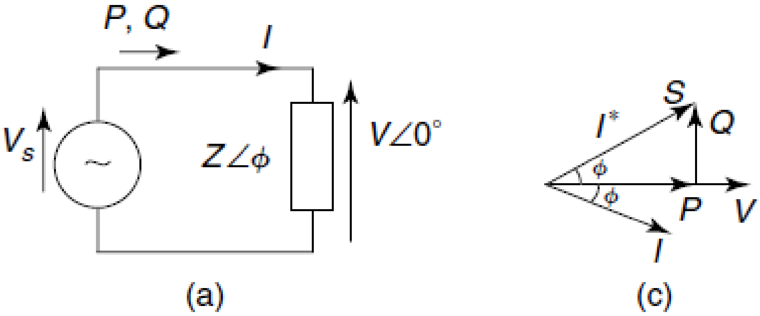
Schematic and basic operating principles of unified power flow controller(UPFC) and Interline power flow controller(IPFC) – Application of these controllers on transmission lines.

# UNIT I
# INTRODUCTION OF FACTS

- A Flexible Alternating Current Transmission System (FACTS) is a system composed of static equipment used for the AC transmission of electrical energy and it is meant to enhance controllability and increase power transfer capability of the network and it is generally a power electronics-based system.
- FACTS is defined by the IEEE as "a power electronics based system other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability".

## REACTIVE POWER CONTROL

- "To make transmission networks operate within desired voltage limits and methods of making up or taking away reactive power is called reactive-power control".
- The AC networks and the devices connected to them create associated time-varying electrical fields related to the applied voltage and as well as magnetic fields dependent on the current flow and they build up these fields store energy that is released when they collapse".

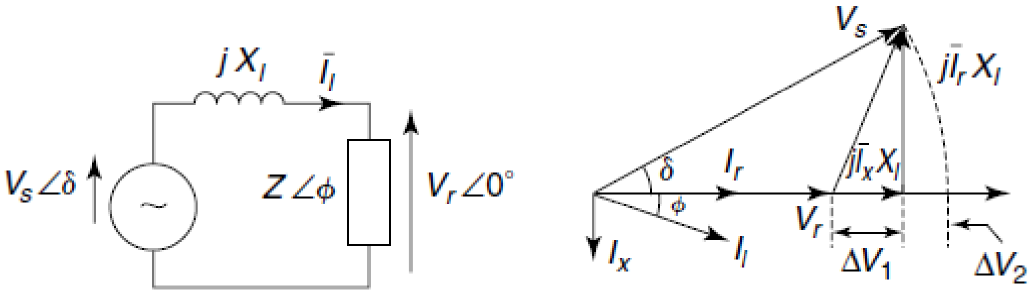


- Apart from the energy dissipation in resistive components, all energy-coupling devices (e.g: motors and generators) operate based on their capacity to store and release energy.
- While the major means of control of reactive power and voltage is via the excitation systems of synchronous generators and devices may be deployed in a transmission network to maintain a good voltage profile in the system.
- The shunt connected devices like shunt capacitors or inductors or synchronous inductors may be fixed or switched (using circuit breaker).
- The **Vernier** or smooth control of reactive power is also possible by varying effective susceptance characteristics by use of power electronic devices. Example: Static Var Componsator(SVC)" and a Thyristor Controlled Reactor (TCR).

# UNCOMPENSATED TRANSMISSION LINES

## Introduction

For simplicity let us consider only the inductive reactance



(a) (b)

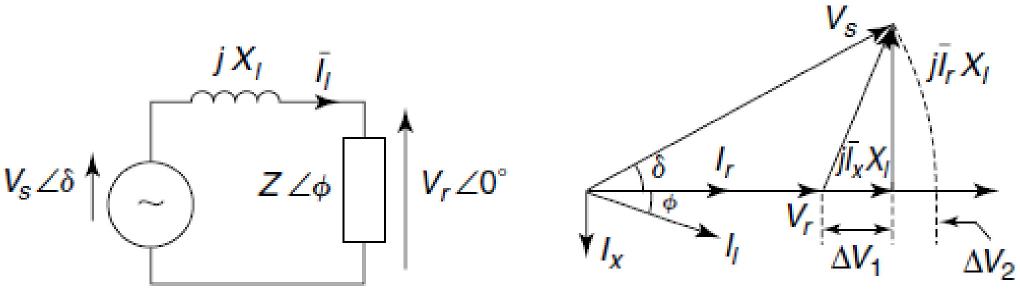
From the above figure it is clear that between he sending and the receiving end voltages and magnitude variation as well as a phase difference is created and the most significant part of the voltage drop in the line reactance is due to the reactive component of the load current and to keep the voltages in the network nearly at the rated value.

Two compensation methods are:

1. Load compensation
2. System compensation

## Load Compensation

- It is possible to compensate for the reactive current of the load by adding a parallel capacitive load so that $I_c = I_x$ and the effective power factor to become unity.
- In the figure the absence of $I_x$ eliminates the voltage drop $\Delta V_1$ bringing $V_r$ closer in magnitude to $V_s$, this condition is called load compensation and actually by charging extra for supplying the reactive power a power utility company makes it advantageous for customers to use load compensation on their premises.
- Loads compensated to the unity power factor reduce the line drop but do not eliminate it. They still experience a drop of $\Delta V_2$ from $j I_rX_1$.



(a) (b)

## System compensation

- To regulate the receiving-end voltage at the rated value a power utility may install a reactive-power compensator as shown in the figure and this compensator draws a reactive current to overcome both components of the voltage drop $\Delta V_1$ and $\Delta V_2$ as a consequence of the load current $I_1$ through the line reactance $X_1$.
- To compensate for $\Delta V_2$ an additional capacitive current $\Delta I_c$ over and above $I_c$ that compensates for $I_x$ is drawn by the compensator.
- When $\Delta I_c X_1 = \Delta V_2$ the receiving end voltage $V_r$ equals the sending end voltage $V_s$ and such compensators are employed by power utilities to ensure the quality of supply to their customers.

## Lossless Distributed Parameter Lines

- Most power transmission lines are characterized by distributed parameters: Series Resistance, Series Inductance, Shunt Conductance and Shunt Capacitance all per-unit length and these parameters all depend on the conductor size, spacing, and clearance above the ground, frequency and temperature of operation.
- In addition these parameters depend on the bundling arrangement of the line conductors and the nearness to other parallel lines.

## Symmetrical Lines

- When the voltage magnitudes at the two ends of a line are equal that is $V_s = V_r = V$ and the line is said to be symmetrical because power networks operate as voltage sources attempts are made to hold almost all node voltages at nearly rated values. Therefore a symmetrical line presents a realistic situation.
- Active and Reactive powers of a transmission line are frequently normalized by choosing the Surge-Impedance Load (SIL) as the base.

## Midpoint Conditions of a Symmetrical Line

- The magnitude of the midpoint voltage depends on the power transfer and this voltage influences the line insulation.
- For a symmetrical line where the end voltages are held at nominal values the midpoint voltage shows the highest magnitude variation.

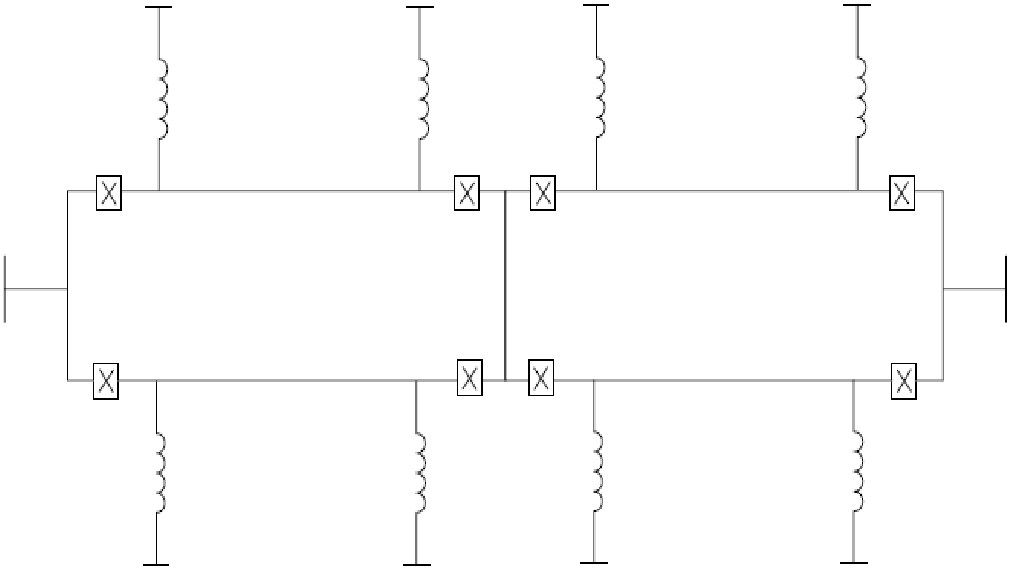
## PASSIVE COMPENSATION

The reactive-power control for a line is often called reactive-power compensation and external devices or subsystems that control reactive power on transmission lines are known as “compensators”.

A compensator mitigates the undesirable effects of the circuit parameters of a given line and the objectives of line compensation are invariably

1. To increase the power-transmission capacity of the line.

2. To keep the voltage profile of the line along its length within acceptable bounds to ensure the quality of supply to the connected customers, to minimize the line insulation costs.



**Types**

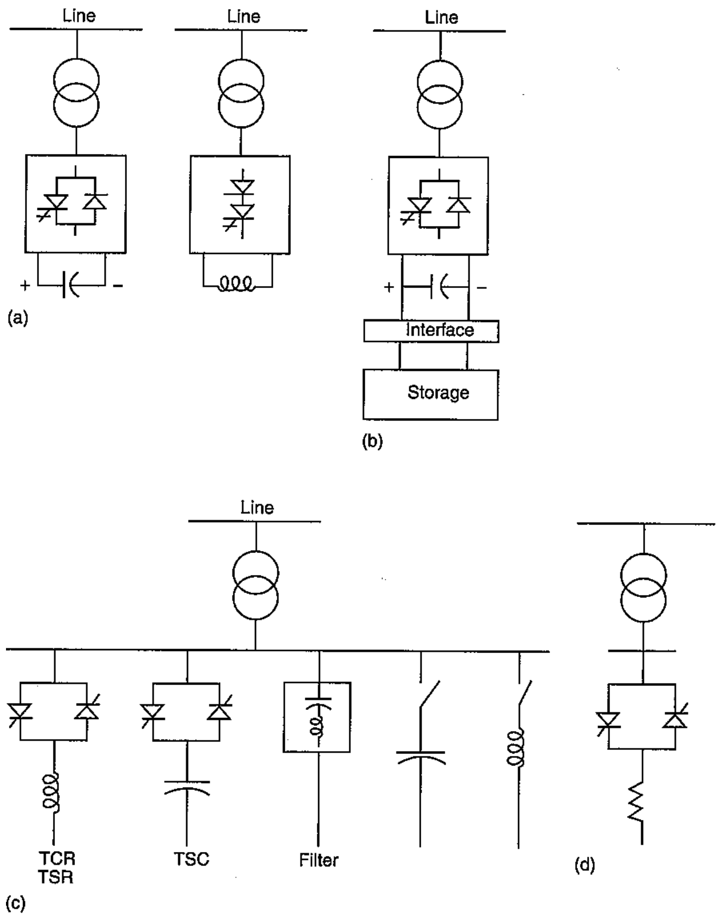
- Shunt Compensation
- Series Compensation

**Shunt Compensation**

- In a weak system voltage control by means of parallel compensation is applied to increase the power quality and improvement of the voltage profile for different system and load conditions when using a Static Var Compensator (SVC) for fast control of shunt connected capacitors and reactors.
- Shunt compensation can also be employed as a ‘local’ remedy against voltage collapse which can occur when large induction machines are connected to the system.
- After system faults the machines load the power system heavily with high reactive power consumption and the remedy for such fault is strong capacitive power injection for example by using an either SVC or STATCOM or just switched capacitors.
- The reactive current is injected into the line to maintain voltage magnitude and transmittable active power (P) is increased but more reactive power (Q) is to be provided.

$$P = (2V^2/X)\sin(\delta/2)\ Q$$

$$= (2V^2/X)[1-\cos(\delta/2)]$$



## Series Compensation

- The Series Compensation is a well established technology that primarily used to transfer reactances most notably in bulk transmission corridors.
- The result is a significant increase in the transmission system transient and voltage stability and Series Compensation is self regulating in the sense that its reactive power output follows the variations intransmission line current that makes the series compensation concept extremely straight forward and cost effective.
- The thyristor controlled series capacitors adds another controllability dimension as thyristor are used to dynamically modulate the ohms provided by the inserted capacitor and this is primarily used to provide inter-area damping of prospective low frequency electromechanical oscillations but it also makes the whole Series Compensation schama immune to Sub Synchronous Resonance (SSR).
- Series compensation is used to improve system stability and to increase the transmission capacity in radial or bulk power long istance AC systems and referring to below the equation and a series capacitor reduces the line impedance X hence the transmmission P will increase.

- This principle can also be applied in meshed systems for balancing the lods on parallel lines and the simplest form of series compensation is the fixed series compensator for reducing the transmission angle thus providing stability enhancement.
- FACTS for series compensation modify line impedance X is decreased so as to increase the transmittable active power (P), however more reactive power (Q) must be provided.

$$P = [V^2/(X - X_c)]\sin^{\delta}$$

$$Q = [V^2/(X - X_c)]\{1 - \cos^{\delta}\}$$

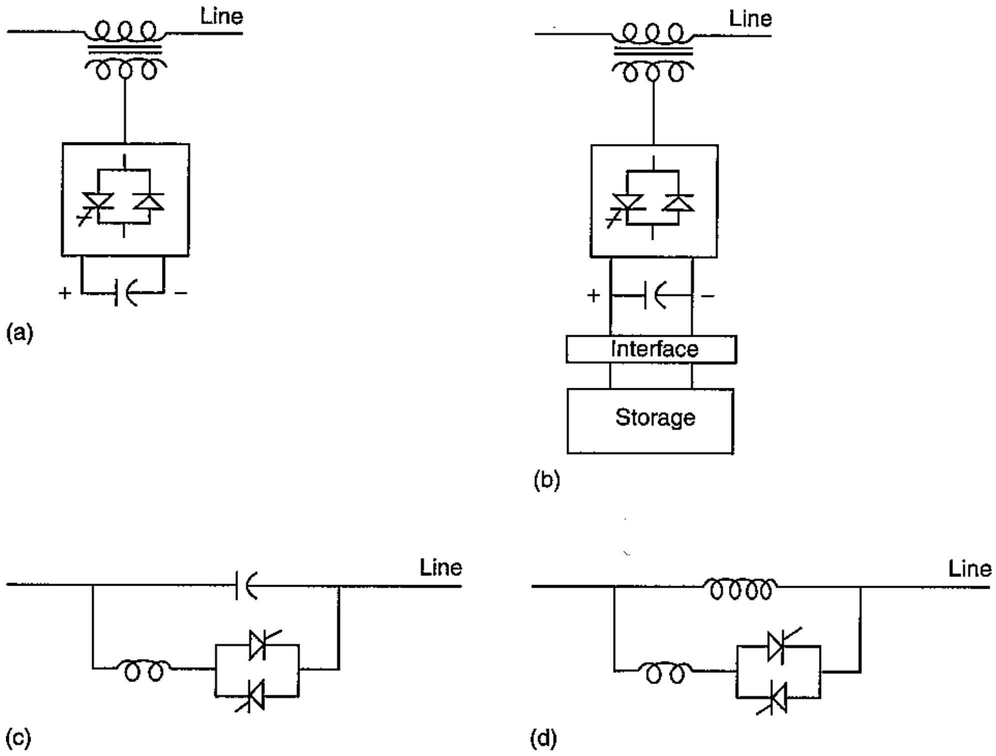


**Figure 1.6** (a) Static Synchronous Series Compensator (SSSC); (b) SSSC with storage; (c) Thyristor-Controlled Series Capacitor (TCSC) and Thyristor-Switched Series Capacitor (TSSC); (d) Thyristor-Controlled Series Reactor (TCSR) and Thyristor-Switched Series Reactor (TSSR).

## OVERVIEW OF FACTS DEVICES

### SVC – Static Var Compensator

- A SVC is an electrical device for providing fast acting reactive power on high-voltage electricity transmission networks.
- SVCs are part of the FACTS device family and regulating voltage and stabilizing the system.
- Unlike a synchronous condenser which is a rotating electrical machine a SVC has no significant moving parts and prior to the invention of the SVC power factor

compensation was the preserve of large rotating machines such as synchronous condensers or switched capacitor banks.

- The SVC is an automated impedance matching device designed to bring the system closer to unity power factor.
- SVCs are used in two main situations:
  - Connected to the power system, to regulate the transmission voltage.
  - Connected near large industrial loads, to improve power quality.
- In transmission applications the SVC is used to regulate the grid voltage.
- If the power system's reactive load is capacitive (leading) the SVC will use thyristor controlled reactors to consume vars from the system lowering the system voltage.
- Under inductive (lagging)conditions the capacitor banks are automatically switched on thus providing a higher system voltage and by connecting the thyristor-controlled reactor which is continuously variable along with a capacitor bank step and the net result is continuously-variable leading or lagging power.
- In industrial applications SVCs are typically placed near high and rapidly varying loads such as arc furnaces where they can smooth flicker voltage.

**Description:**

Typically an SVC comprises one or more banks of fixed or switched shunt capacitors or reactors of which atleast one bank is switched by thyristors.

The elements which may be used to make an SVC typically include:

- Thyristor Controlled Reactor (TCR) where the reactor may be air or iron cored.
- Thyristor Switched Capacitor (TSC).
- Harmonic filter(s).
- Mechanically switched capacitors or reactors.

**Connection:**

- Generally SVC is not done at line voltage; a bank of transformers steps the transmission voltage down to a much lower level.
- This reduces the size and number of components needed in the SVC although the conductors must be very large to handle high currents associated with the lower voltage.
- In some SVC for industrial applications such as electric arc furnaces where there may be an existing medium-voltage bus bar present the SVC may be directly connected in order to save the cost of the transformer.
- The dynamic nature of the SVC lies in the use of thyristors connected in series and inverse-parallel forming “thyristor valves” and the disc-shaped semiconductors usually several inches in diameter are usually located indoors in a “valve house”.

**Advantages:**

- Near instantaneous response to changes in the system voltage. For this reason they are often operated at close to their zero-point in order to maximize the reactive power correction they can rapidly provide when required.

- In general, cheaper, higher-capacity, faster and more reliable than dynamic compensation schemes such as synchronous condensers.

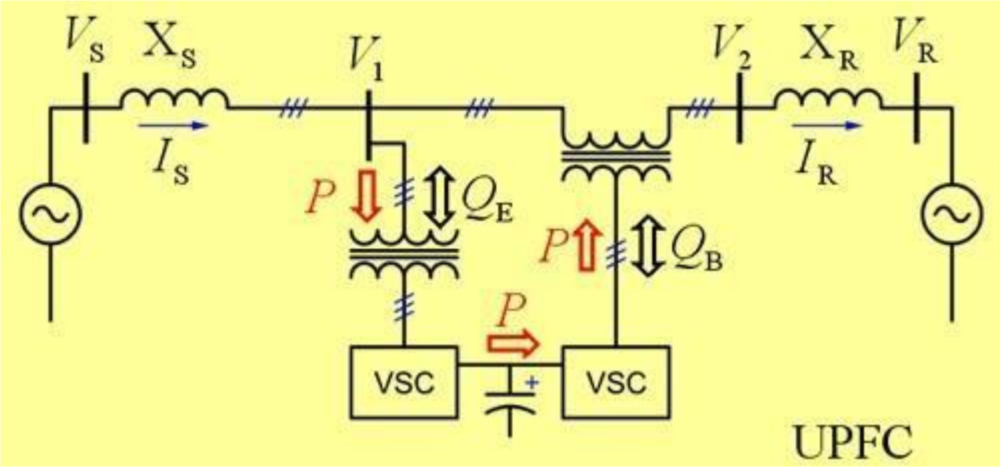
**Thyristor Controlled Series Capacitor (TCSC)**

- TCSC is a power electronic based system and Thyristor Switched Capacitor is connected in series with a bidirectional thyristor valve.
- The TCSC can control power flow, mitigate sub-synchronous resonance, improve transient stability, damp out power system oscillations resulting increase of power transfer capability.
- A single diagram of TCSC shows two modules connected in series and there can be one or more module depending on the requirement to reduce the costs and TCSC may be used in conjunction with fixed series capacitors.
- Nowadays TCSC is being included in some of the transmission systems and the basic circuit of a TCSC in one of the phase is shown in the fig.controls the current through the reactor.
- The forward-looking thyristor has firing angle $90^0 – 180^0$ and firing the thyristors at this time results in a current flow through the inductor that is opposite to the capacitor current and in this loop current increases the voltage across the capacitor.
- Further the loop current increases as firing angle decreases from $180^0$.
- The different compensation levels are obtained by varying the firing angle of the reactor-circuit-thyristor.

**UNIFIED POWER FLOW CONTROLLER (UPFC)**

- The UPFC is the most versatile member of FACTS family using power electronics to control power flow on power grids.
- The UPFC uses a combination of a shunt controller (STATCOM) and a series controller (SSSC) interconnected through a common DC bus.

  $P = (V_2V_3 \sin^{\delta})/X$ and $Q = (V_2(V_2 – V_3 \cos^{\delta}))/X$
- This FACTS topology provides much more flexibility than the SSSC for controlling the line active and reactive power because active power can now be transferred from the shunt converter to the series converter through the DC bus.



## INTEGRAL POWER FLOW CONTROLLER (IPFC)

- In other FACTS controllers there are two or more VSCs coupled together via a common DC bus which increases not only the controllability but also the complexity.
- For UPFC the connection between the shunt VSC and series VSC allows active power exchange of the two VSCs so the series VSC can control both the line active and reactive power flow.
- The shunt VSC regulates the bus voltage and satisfies the balance of power circulation through the DC capacitor.
- For IPFC two series VSCs connect to each other at the DC bus so one of them (assumed as the Master VSC) can control both line active and reactive power and the other one (assumed as Slave VSC) can only regulate line active power supporting sufficient active power to the Master VSC through the DC tie.

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UNIT-II

## Basic concept of voltage, sourced converter:

→ The converters applicable to FACTS controllers would be of the self commutating type. They are two basic categiories of self commutating devices.

① current sourced converter :- In which (Direct current) DC current has one polarity and the power reversal takes place through reversal of DC voltage polarity

② voltage sourced converter :- In which dc voltage has one polarity and the power reversal takes place through reversal of DC current polarity

Note :- conventional thyristor based converters, being without turnoff capability can only be current sourced converters.
whereas turn off device based converters can be of either type

→ In economic and performance point of view, vsc's are often preffered over CSC's for FACTS applica

## voltage sourced converter

→ Basically, a vsc generates ac voltage from a DC voltage. It is for historical reasons, often reffered to as an inverter even though it has the capability to transfer power in either direction.

→ with a vsc, the magnitude, phase angle and frequency of the o/p voltage can be controlled.

→ The dc current in a VSC flows in either direction, the converter values has to be bidirectional, and also since the dc voltage does not reverse.

→ The off devices has need not have reverse voltage capability.

→ such turn off device are known as "asymmetric turn off devices".

## ⓐ Value for a VSC :-

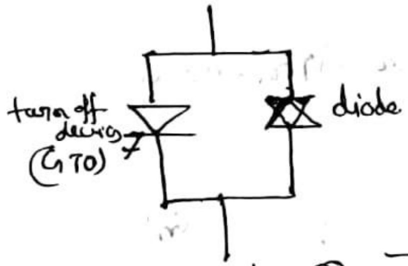


fig ⓐ

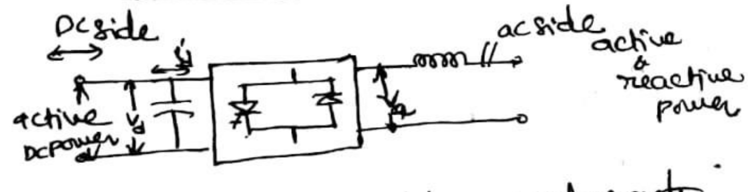
→ The VSC value is made up of an asymmetric turnoff device called GTO with parallel diode connected in reverse.

→ Some of the turnoff devices such as IGBTS and IGCTS may have a parallel / reverse diode built in as part of a complete integrated device suitable for VSC's.

→ However for high power converters, provision of seperate diodes is advantageous.

→ In general, the symbol of the turn off device with on parallel diode will represents a value of appropriate voltage and current rating required for the converter shown in fig ⓐ.

## ⓑ Voltage sourced converter concept :-



The above ckt represents basic concept of VSC.

→ The internal topology of converter valves is represented as a box with a value symbol inside.

→ on DC side, voltage is unipolar and is supported by a capacitor, This capacitor is large enough to atleast handle a sustained charge/discharge current

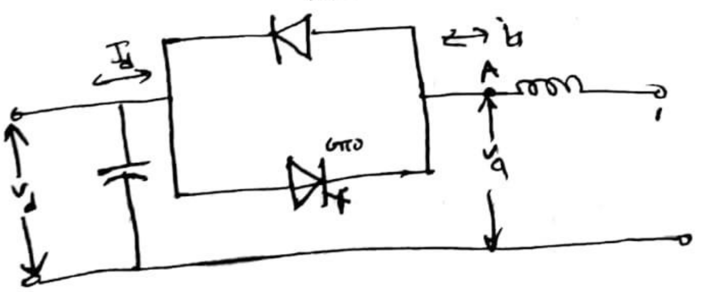
⇒ The DC capacitor voltage will be kept const.

→ It is also shown on DC side of the Ckt, that DC current can flow in either direction and that it can exchange dc power with the connected dc system in either direction shown on ac side.

⇒ Being an ac voltage source with low internal impedance, a series inductive interface with the ac system is essentially ensure that the dc capacitor ~~component~~ is not short circuited and discharged rapidly into a capacitive load such as transmission line.

→ also An ac filter also required to limit the consequent current harmonic entering the sym side, because of series inductance

## ⓒ Single value Operation.



In figure, DC voltage $V_d$ is assumed to be const, supported by large capacitor, with +ve polarity side connected to the anode side of the turn off devices

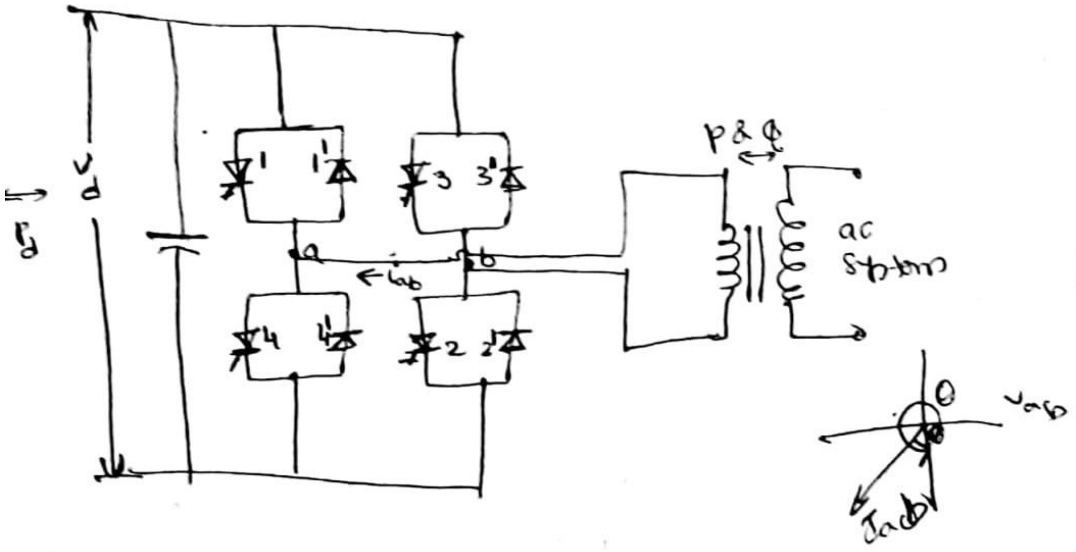
⇒ when turn off device is turn on, the $+V_d$ dc terminal is connected to the ac terminal 'A' and AC voltage would jump to $V_d$.

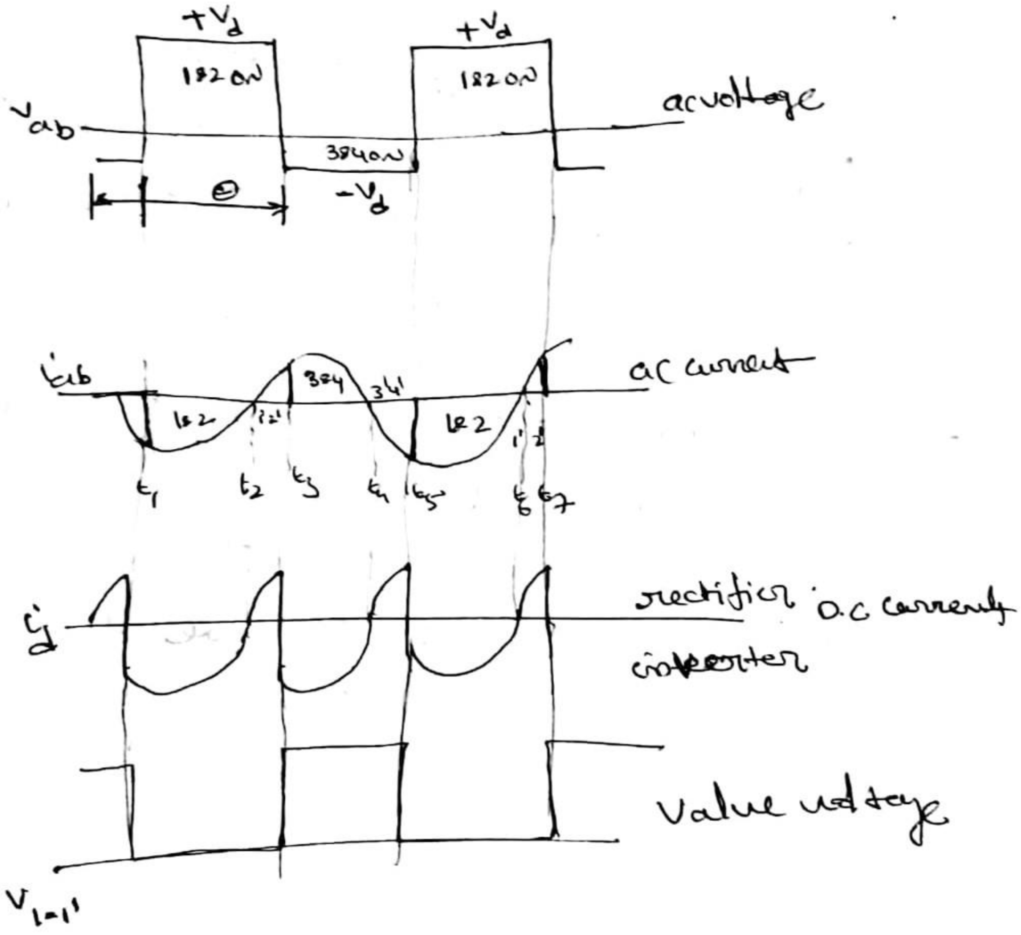
⇒ If the current happens to flow from $+V_d$ to 'A', the power would flow from ~~A~~ dc to ~~$+V_d$~~ AC (inverter operation) ~~it will flow through diode 1~~,

⇒ If the current happen to flow from A to $+V_d$ the power flow from A.C to d.c $(+V_d)$, i.e from A to $+V_d$. This called rectifier operation Even if device 1 is ~~called~~ so turned on.

→ The value combination and its capability to act as a rectifier or as an inverter with the instantaneous current flowing in +ve (ac to dc side) or -ve direction, respectively, is basic to VSC concept.

## * 1ϕ Full wave bridge V.S. converter operation:-





→ 1ϕ full wave bridge voltage sourced converter circu consists of four values i.e., from (1-1') to (4-4')

→ A DC capacitor is used to provide the dc voltage and two ac voltage connection points a&b.

→ The designated value numbers represent their sequence of turn on and turn off. The DC voltage is converted to ac voltage with the appropriate value turn on and turn off sequence as explained below.

→ As shown by the first waveform of figure ⓑ, with turnoff devices 1&2 turned on, voltage $V_{ab}$ becomes $+V_d$ for one half cycle. and with 3&4 turned on when devices 1&2 turned off, $V_{ab}$ becomes $-V_d$ for another half cycle.

→ The operation of the ckt from instants $t_1$ to $t_5$

| instant | Devices | $V_{ab}$ | Current flow | conducting devices | conversion |
|---|---|---|---|---|---|
| from $t_1$ to $t_2$ | 1&2 ON, 3&4 OFF | +ve | Negative | 1&2 | inverter |
| from $t_2$ to $t_3$ | 1&2 ON, 3&4 OFF | positive | positive | 1'&2' | rectifier |
| from $t_3$ to $t_4$ | 1&2 OFF, 3&4 ON | −ve | positive | 3&4 | inverter |
| from $t_4$ to $t_5$ | 1&2 OFF, 3&4 ON | −ve | negative | 3'&4' | rectifier |

→ from instant $t_5$, the cycle starts again as from as $t_1$ with devices 1&2 turned on & 3&4 turned off.

→ from fig ⓑ also shows the waveform of current flow $i_d$ in dc bus with the +ve side flowing from ac to dc i.e., rectifier action

→ and −ve side ~~from~~ flowing from Ac to ac i.e., inverter operation, clearly the avg dc current is −ve

The current $i_d$ containing the dc current and the harmonics.

The dC current must flows into dc system, and for a large dc capacitor.

→ For a large d.c capacitor, being a 1φ full wave bridge, the dc harmonics have an order of 2k, where 'k' is an integer i.e 2nd, 4th, 6th all of even harmonics.

→ The fourth waveform of fig ⓑ represents the voltage wave across Valve 1-1'.

→ fig ⓒ represents phase relationship between voltage & current phasors, showing power flow from ac to dc with a lagging p.f.

# UNIT III

# SHUNT COMENSATORS-1

## Shunt Compensation

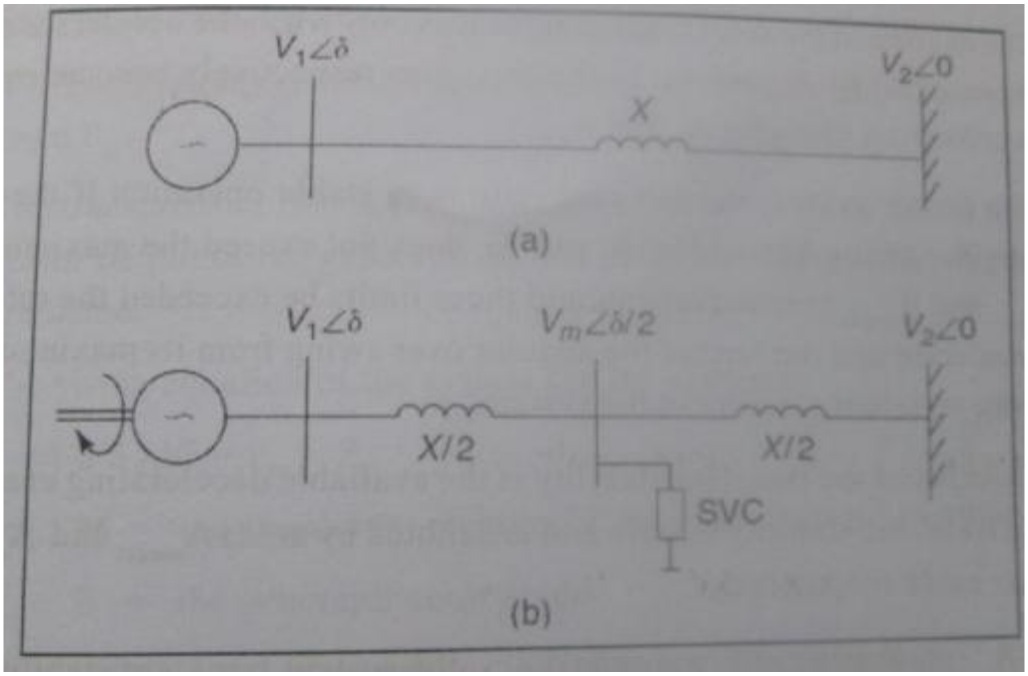
- In a weak system voltage control by means of parallel compensation is applied to increase the power quality and improvement of the voltage profile for different system and load conditions when using a Static Var Compensator (SVC) for fast control of shunt connected capacitors and reactors.
- Shunt compensation can also be employed as a ‘local’ remedy against voltage collapse which can occur when large induction machines are connected to the system.
- After system faults the machines load the power system heavily with high reactive power consumption and the remedy for such fault is strong capacitive power injection for example by using an either SVC or STATCOM or just switched capacitors.
- The reactive current is injected into the line to maintain voltage magnitude and transmittable active power (P) is increased but more reactive power (Q) is to be provided.

$$P = (2V^2/X)\sin(\delta/2)\ Q$$

$$= (2V^2/X)[1-\cos(\delta/2)]$$

## Enhancement of Transient Stability

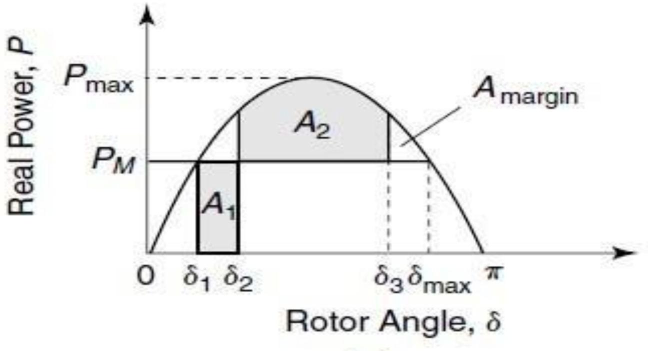
### 2.4.2.1Power-angle curves



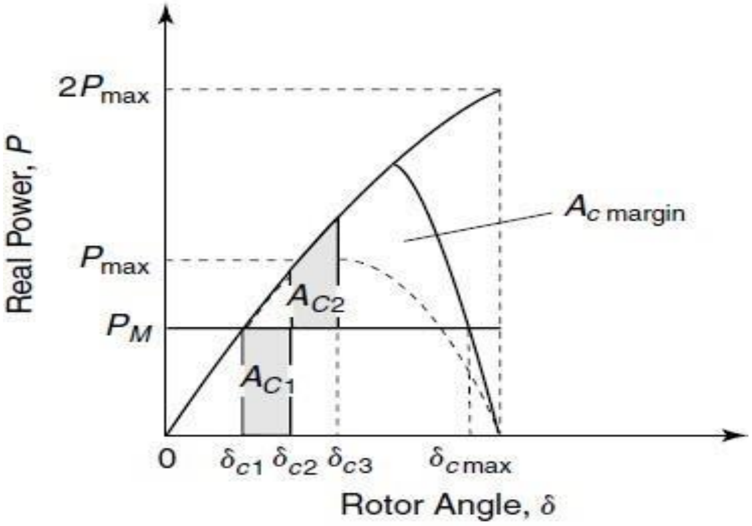
The SMIB system: (a) an uncompensated system (b) an SVC-compensated system

- An enhancement in transient stability is achieved primarily through voltage control exercised by the SVC at the interconnected bus.
- A simple understanding of this aspect can be obtained from the power-angle curves, of the uncompensated and midpoint SVC–compensated SMIB system.
- Consider both the uncompensated and SVC-compensated power system depicted in Fig.
- Assume that both systems are transmitting the same level of power and are subject to an identical fault at the generator terminals for an equal length of time.
- The power-angle curves for both systems are depicted in Fig.
- The initial operating point in the uncompensated and compensated systems are indicated by rotor angles $d_1$ and $d_{c1}$. These points correspond to the intersection between the respective power-angle curves with the mechanical input line $P_M$, which is same for both the cases.

- In the event of a 3-phase-to-ground fault at the generator terminals, even though the short-circuit current increases enormously, the active-power output from the generator reduces to zero. Because the mechanical input remains unchanged, the generator accelerates until fault clearing, by which time the rotor angle has reached values $d_2$ and $d_{C2}$ and the accelerating energy, $A_1$ and $A_{C1}$, has been accumulated in the uncompensated and compensated system, respectively.
- When the fault is isolated, the electrical power exceeds the mechanical input power, and the generator starts decelerating.
- The rotor angle, however, continues to increase until $\delta_3$ and $\delta c3$ from the stored kinetic energy in the rotor.
- The decline in the rotor angle commences only when the decelerating energies represented by $A_2$ and $A_{C2}$ in the two cases, respectively, become equal to the accelerating energies $A_1$ and $A_{C1}$.
- The power system in each case returns to stable operation if the post-fault angular swing, denoted by $d_3$ and $d_{C3}$, does not exceed the maximum limit of $d_{\max}$ and $dc$ max, respectively. Should these limits be exceeded, the rotor will not decelerate.
- The farther the angular overswing from its maximum limit, the more transient stability in the system.
- An index of the transient stability is the available decelerating energy, termed the *transient-stability margin*, and is denoted by areas $A_{\text{margin}}$ and $A_c$ margin in the two cases, respectively. Clearly, as $Ac$ margin significantly exceeds $A_{\text{margin}}$, the system-transient stability is greatly enhanced by the installation of an SVC. The increase in transient stability is thus obtained by the enhancement of the steady-state power-transfer limit provided by the voltage-control operation of the midline SVC.



(a)



(b)

### 2.4.2.2 Synchronizing Torque

A mathematical insight into the increase in transient stability can be obtained through the analysis presented in the text that follows. The synchronous generator is assumed to be driven with a mechanical-power input, *PM*. The transmission line is further assumed to be lossless; hence the electrical power output of the generator, *PE*, and the power received by the infinite bus are same. The swing equation of the system can be written as

$$M\,\frac{d^2\delta}{dt^2} = P_M - P_E$$

Where M = angular momentum of the synchronous generator

For small signal analysis,the equation is linearized as,

$$M\,\frac{d^2\Delta\delta}{dt^2} = \Delta P_M - \Delta P_E$$

The mechanical-input power is assumed to be constant during the time of analysis; hence

$\Delta PM = 0$. The linearized-swing equation then becomes

$$M \frac{d^2 \Delta\delta}{dt^2} = -\Delta P_E$$ (or)

The characteristic equation of the differential equation provides two roots:

On the other hand, if the synchronizing torque $K_S$ is negative, the roots are real. A positive real root characterizes instability. The synchronizing-torque coefficient is now determined for both the uncompensated and SVC-compensated systems.

$$\frac{d^2 \Delta\delta}{dt^2} = -\frac{1}{M}\left(\frac{\partial P_E}{\partial \delta}\right)\Delta\delta = -\frac{K_S}{M}\Delta\delta$$

where $K_S$ = the synchronizing power coefficient
= the slope of the power-angle curve
= $\partial P_E / \partial \delta$

or

$$\frac{d^2 \Delta\delta}{dt^2} + \frac{K_s}{M}\Delta\delta = 0$$

## Steady State Power Transfer Capacity

- An SVC can be used to enhance the power-transfer capacity of a transmission line, which is also characterized as the steady-state power limit.
- Consider a single-machine infinite-bus (SMIB) system with an interconnecting lossless tie line having reactance *X* shown in Fig.
- Let the voltages of the synchronous generator and infinite bus be $V_1$/–δ and $V_2$/–δ, respectively. The power transferred from the synchronous machine to the infinite bus is expressed as

$$P = \frac{V_1 V_2}{X} \sin \delta$$

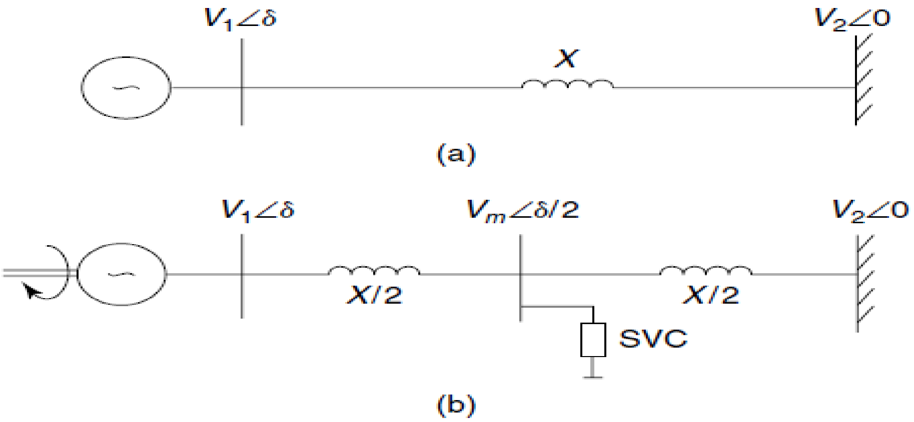
- For simplicity, if $V_1 = V_2 = V$, then

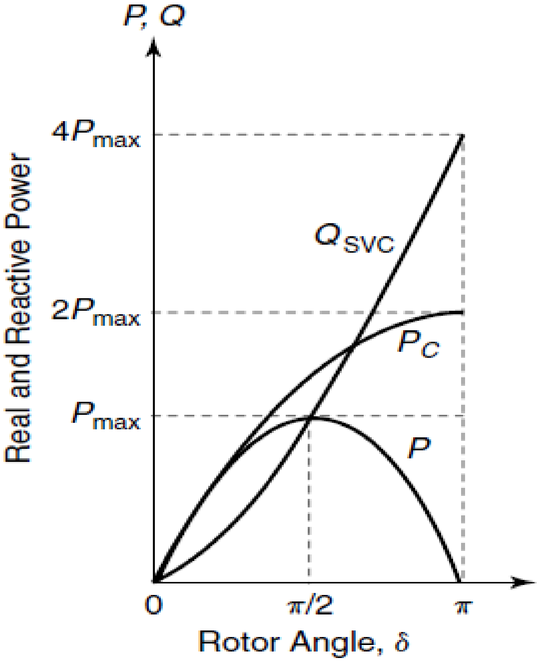
$$P = \frac{V^2}{X} \sin \delta$$

The SMIB system: (a) an uncompensated system (b) an SVC-compensated system

- The power thus varies as a sinusoidal function of the angular difference of the voltages at the synchronous machine and infinite bus, as depicted in Fig.
- The maximum steady-state power that can be transferred across the uncompensated line without SVC corresponds to $\delta = 90^0$; it is given by

$$P_{\max} = \frac{V^2}{X}$$





The variation of linear real-power flow and SVC reactive-power flow in a SMIB system

- Let the transmission line be compensated at its midpoint by an ideal SVC.
- The term *ideal* corresponds to an SVC with an unlimited reactive-power rating that can maintain the magnitude of the midpoint voltage constant for all real power flows across the transmission line.
- The SVC bus voltage is then given by $V_m$/–δ/ 2.The electrical power flow across the half-line section connecting the generator and the SVC is expressed as
- The maximum transmittable power across the line is then given by

$$P_{C\max} = \frac{2V^2}{X}$$

which is twice the maximum power transmitted in the uncompensated case and occurs at δ/ 2 =90$^0$.

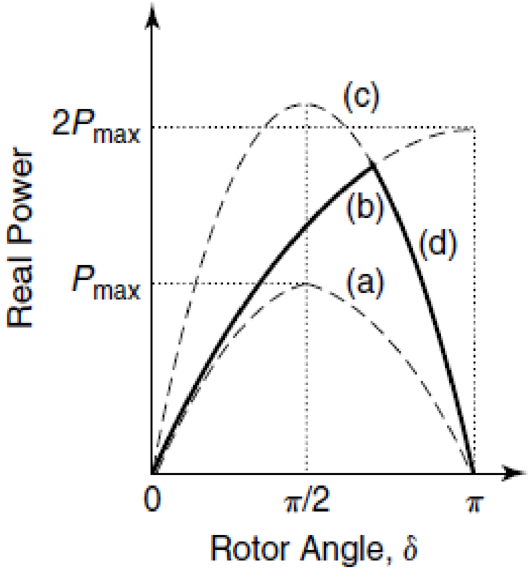
$$P_C = \frac{V_1 V_2}{X/2} \sin \frac{\delta}{2}$$

- If the transmission line is divided into $n$ equal sections, with an ideal SVC at each junction of these sections maintaining a constant-voltage magnitude ($V$), then the power transfer ($P'_c$) of this line can be expressed theoretically by

$$P'_c = \frac{V^2}{X/n} \sin \frac{\delta}{n}$$

- The maximum power, $P'c$ max, that can be transmitted along this line is $nV2/ X$. In other words, with $n$ sections the power transfer can be increased $n$ times that of the uncompensated line.
- It may be understood that this is only a theoretical limit, as the actual maximum power flow is restricted by the thermal limit of the transmission line.
- It can be shown that the reactive-power requirement, $Q_{SVC}$, of the midpoint SVC for the voltage stabilization is given by

$$Q_{SVC} = \frac{4V^2}{X}\left(1 - \cos\frac{\delta}{2}\right)$$



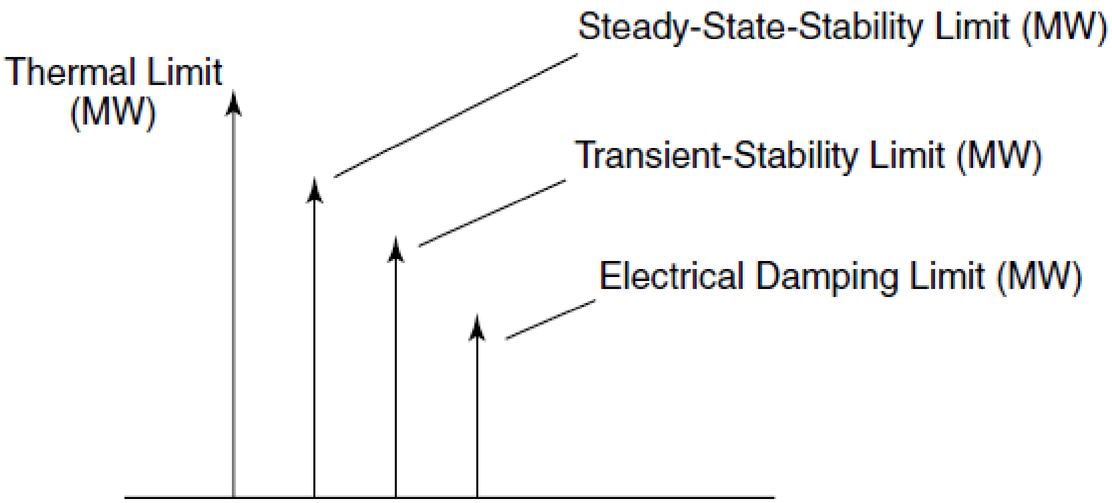
Power angle curve of a SMIB system☹a) uncompensated (b) ideal midpoint SVC unlimited rating curve (c) fixed capacitor connected at its midpoint (d) midpoint SVC limited rating curve

- This curve is based on the corresponding equivalent reactance between the synchronous generator and the infinite bus.
- If an SVC incorporating a limited-rating capacitor as in the preceding text ($Q$SVC _ 2$P$max) is connected at the line midpoint, it ensures voltage regulation until its capacitive output reaches its limit.
- In case the system voltage declines further, the SVC cannot provide any voltage support, and behaves as a fixed capacitor.

- Curve (d) represents the power-angle curve that shows this fixed-capacitor behavior and demonstrates that the realistic maximum power transfer will be much lower than the theoretical limit of 2*P*max if the SVC has a limited reactive-power rating.

## Enhancement of Power System Damping

- The power-transfer capacity along a transmission corridor is limited by several factors; for example, the thermal limit, the steady-state stability limit, the transient-stability limit, and system damping.
- In certain situations, a power system may have inadequate—even negative—damping; therefore, a strong need arises to enhance the electrical damping of power systems to ensure stable, oscillation-free power transfer.
- A typical scenario of the magnitude of various limits, especially where damping plays a determining role , is depicted graphically in Fig. Oscillations in power systems are caused by various disturbances.
- If the system is not series-compensated, the typical range of oscillation frequencies extends from several tenths of 1 Hz to nearly 2 Hz.
- Several modes of oscillation may exist in a complex, interconnected power system.
- The behavior of generator oscillations is determined by the two torque components: the ***synchronizing torque*** and ***damping torque***.
- The synchronizing torque ensures that the rotor angles of different generators do not drift away following a large disturbance.
- In addition, the magnitude of the synchronizing torque determines the frequency of oscillation. Meanwhile, damping torque influences the decay time of oscillations.
- Even if a power system is stable, the oscillations may be sustained for a long period without adequate damping torque.



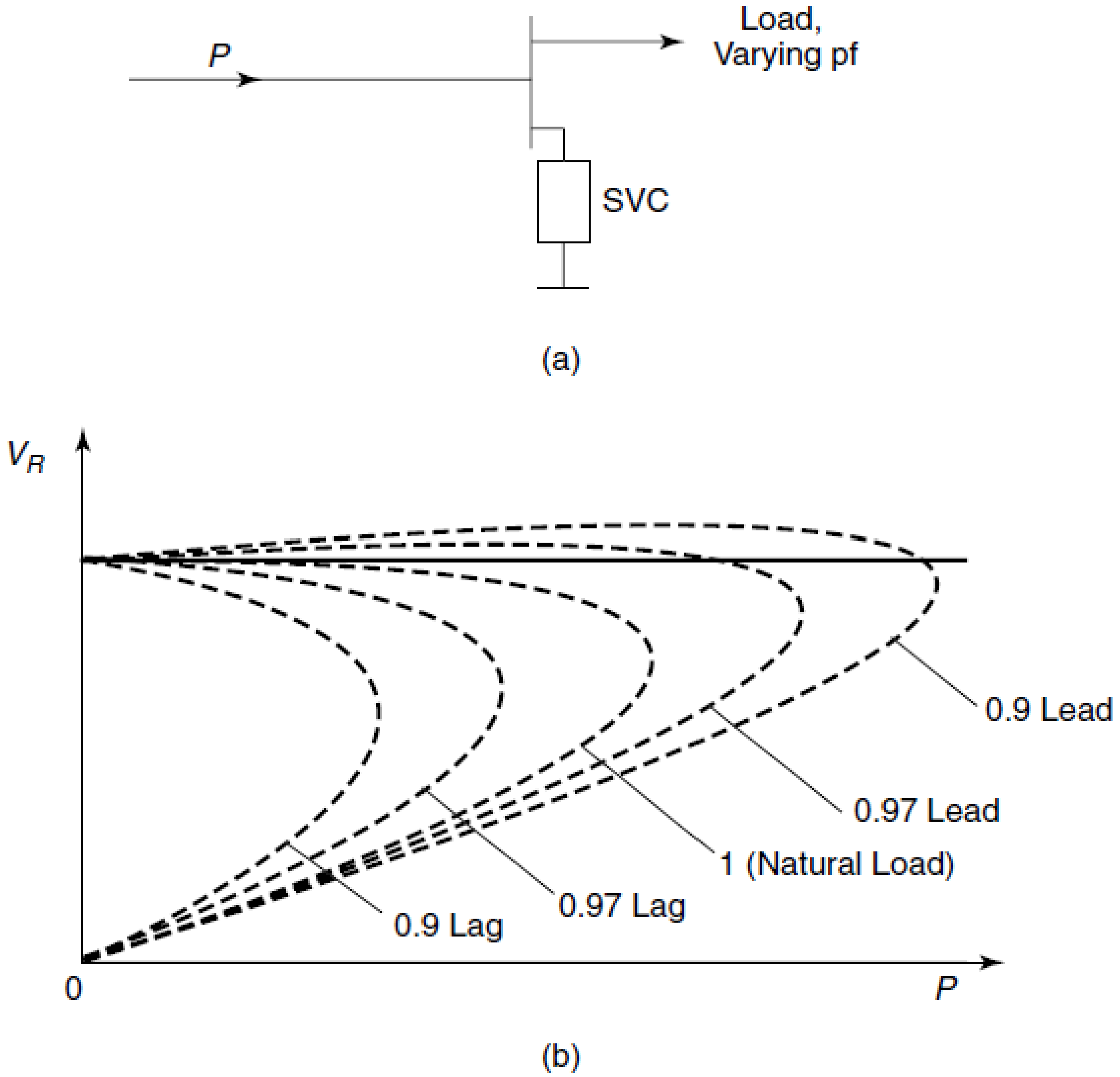
Comparison of different limits on the Power Flow

## Prevention of Voltage Stability

- Voltage instability is caused by the inadequacy of the power system to supply the reactive-power demand of certain loads, such as induction motors.
- A drop in the load voltage leads to an increased demand for reactive power that, if not met by the power system, leads to a further decline in the bus voltage. This decline eventually leads to a progressive yet rapid decline of voltage at that location, which may have a cascading effect on neighboring regions that causes a system voltage collapse.

## Principle of SVC Control

- The voltage at a load bus supplied by a transmission line is dependent on the magnitude of the load, the load-power factor, and the impedance of the transmission line.
- Consider an SVC connected to a load bus, as shown in Fig. The load has a varying power factor and is fed by a lossless radial transmission line.
- The voltage profile at the load bus, which is situated at the receiver end of the transmission line, is depicted in Fig. For a given load-power factor, as the transmitted power is gradually increased, a maximum power limit is reached beyond which the voltage collapse takes place.
- In this typical system, if the combined power factor of the load and SVC is appropriately controlled through the reactive-power support from the SVC, a



constant voltage of the receiving-end bus can be maintained with increasing magnitude of transmitted power, and voltage instability can be avoided.

(a) An SVC connected at the load bus by a radial transmission line supplying a load and (b)the voltage profile at the receiving end of a loaded line with a varying power factor load.

  - 2–15 Hz for small-signal or control oscillations
  - 10–50/ 60 Hz for subsynchronous resonance (SSR) interactions
  - >15 Hz for electromagnetic transients, high-frequency resonance or harmonic resonance interactions, and network-resonance interactions

### Steady – State Interactions

- Steady-state interactions between different controllers (FACTS–FACTS or FACTS–HVDC) occur between their system-related controls.
- They are steady state in nature and do not involve any controller dynamics. These interactions are related to issues such as the stability limits of steady-state voltage and steady-state power; included are evaluations of the adequacy of reactive-power support at buses, system strength, and so on.
- An example of such control coordination may be that which occurs between the steady-state voltage control of FACTS equipment and the HVDC supplementary control for ac voltage regulation.

Load-flow and stability programs with appropriate models of FACTS equipment and HVDC links are

- HVDC links are generally employed to investigate the foregoing control interactions

## Enhancement of Power System Damping

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- In addition, the magnitude of the synchronizing torque determines the frequency of oscillation. Meanwhile, damping torque influences the decay time of oscillations.
- Even if a power system is stable, the oscillations may be sustained for a long period without adequate damping torque.

# UNIT-IV

## Methods of controllable var generation :-

They are mainly classified into ③ types.

① · Variable impedance type static var generat

They are further classified into ④

(i) Combination of TCR & TSR

(ii) Combination of ~~TSR~~ FC-TCR

(iii) Combination of TSC & TCR

(iv) T.SC.

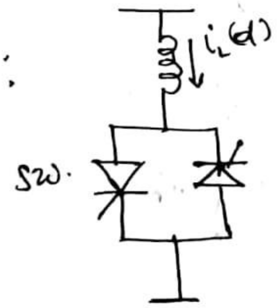
② Switching converter type var generator

③ Hybrid var generator.

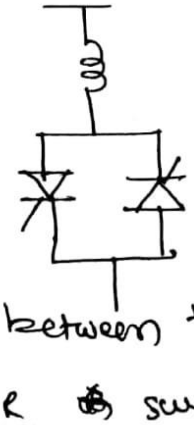
* TSR : Thyristor switched reactor
TSC : Thyristor switched capa.
TCR : Thyristor controlled reactor
FC-TCR : Fixed capacitor-thyristor controlled reac

## (i) Combination of TCR & TSR :-

Symbol of TCR :



Symbol of TSR :



Note :- The basic difference between the TCR & TSR is that, If TCR switching is restricted to a fixed delay angle usually $\alpha = 0°$, then it becomes TSR (thyristor switched reactor)

## Description of TCR & TSR :-

→ It consists of fixed reactance of inductance L, and bidirectional thyristor value or switch.

→ If it is large thyristor, the blocking voltage limits are 4000 to 9000V & conduction currents upto 3000 to 6000A.

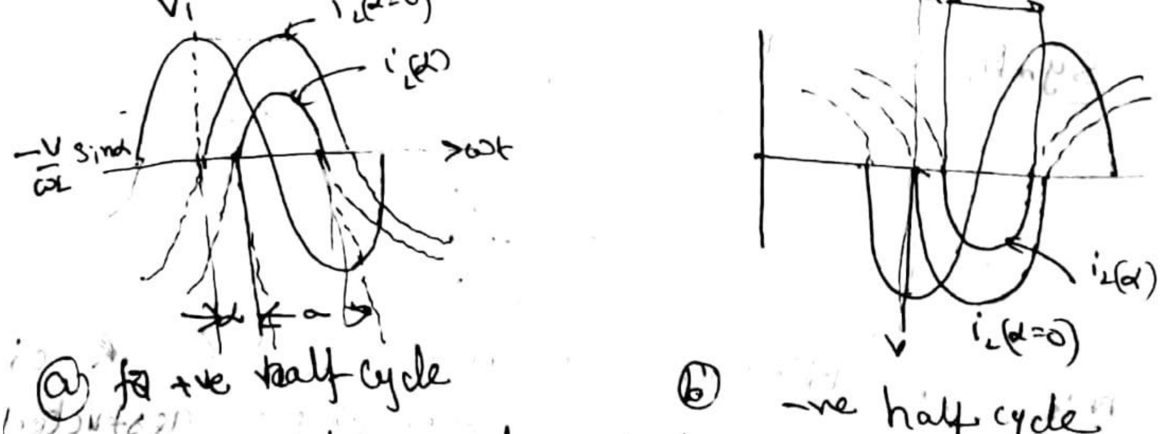
→ In practical, inorder to get ~~range~~ large blocking voltage, the thyristor must be connected in series

→ A thyristor values is brought into conduction by applying a gate pulse to all thyristors of same po

→ when ac current crosses zero, the value will automatically blocks.

→ The current in the reactor can be controlled from maximum to [illegible] by the method of <u>firing delay angle control</u>.

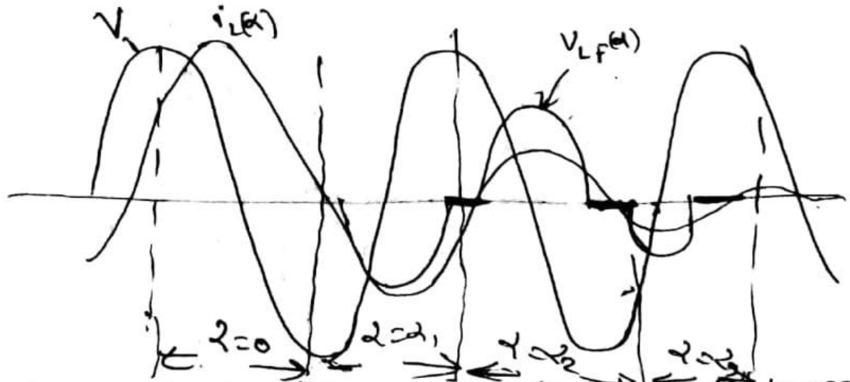
→ This method of current control is illustrated seperately for the +ve & -ve half cycles as shown fig.



ⓐ for +ve half cycle ⓑ -ve half cycle

fig: firing delay angle control of TCR & TSR for +ve & -ve half cy

# operating wave forms of TCR & TSR



→ The current in the reactor can be expressed with $v(t) = V\cos\omega t$ as follows.

$$i_L(t) = \frac{1}{L}\int_{\alpha}^{\omega t} v(t)\,dt$$

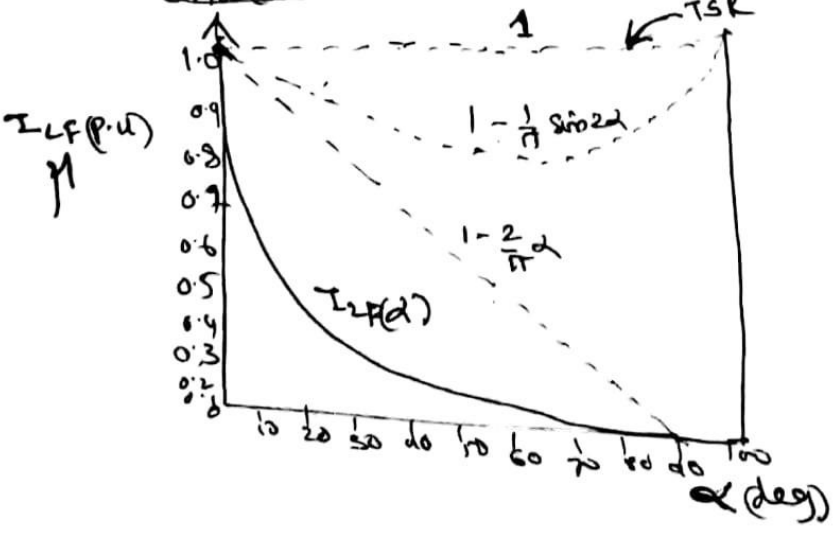
$$i_L(t) = \frac{V}{\omega L}(\sin\omega t - \sin\alpha)$$

→ The fundamental component of reactor current $I_{LF}(\alpha)$ can be expressed from the above Eqn.

$$I_{LF}(\alpha) = \frac{V}{\omega L}\left[1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right]$$

V → amplitude of applied a.c voltage
L → inductance of TCR
α → delay angle
ω → angular frequency

→ The fundamental TCR & TSR current with delay angle characteristics as shown in fig.



## ②(ii) Thyristor switched Capacitor (TSC) :-

symbol of TSC :-

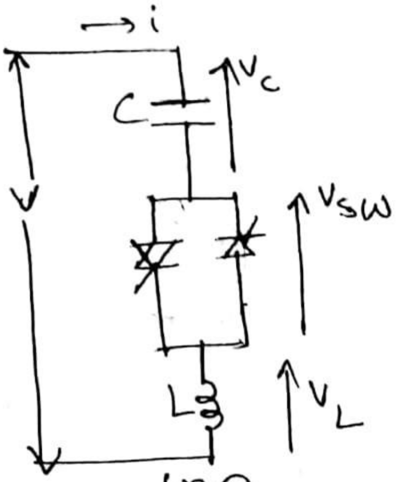


fig ⓐ

## Description of TSC :-

→ It consists of a capacitor, a bidirectional thyristor with and a reactor.

→ ⓐ The purpose of reactor is to limit the small surge currents under abnormal conditions.

→ ⓑ It may also be used to ~~reed~~ avoid resonances with the ac system impedance at particular frequency

⇒ The associated waveforms of TSC as shown in fig.

→ under steady state condition.

→ ~~and~~ when the thyristor value is closed, the current in the TSC branch is given by

$$i(\omega t) = \frac{Vn^2}{n^2-1}\,\omega C \cos\omega t \quad ①$$

where $n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_C}{X_L}}$ ②

→ The amplitude of the ~~[illegible]~~ voltage across the capacitor is given by, $V_C = \frac{n^2}{n^2-1} \times V.$

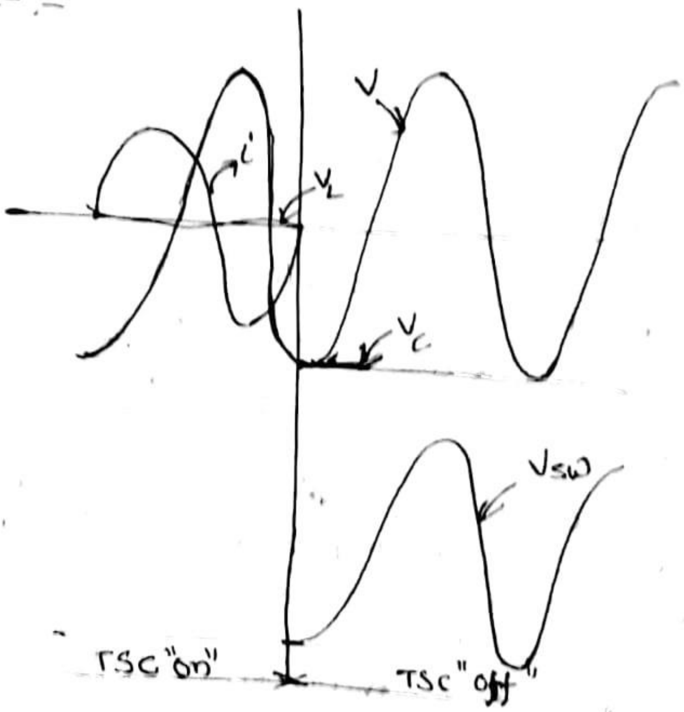
→ when the TSC branch is disconnected, at the voltage across capacitor at zero crossing is given by peak voltage ($\hat{V}_C$)

$$V_C\Big|_{i=0} = \frac{Vn^2}{n^2-1}$$

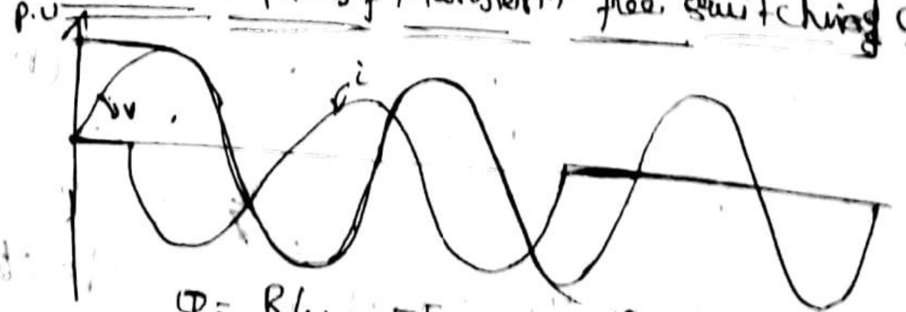
→ The disconnected capacitor stays charged to this voltage and consequently the voltage across the non conducting thyristor valve varies between 0 and the peak to peak va

→ when the disconnected TSC branch is connected in ckt, it will be switched on again due to the stored voltage of capacitor.

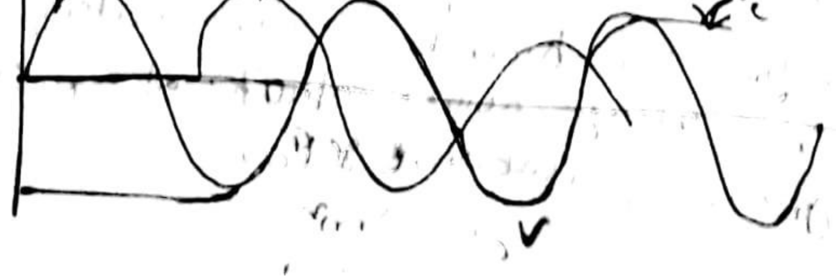
→ The characteristics of associated wave forms of TSC:-



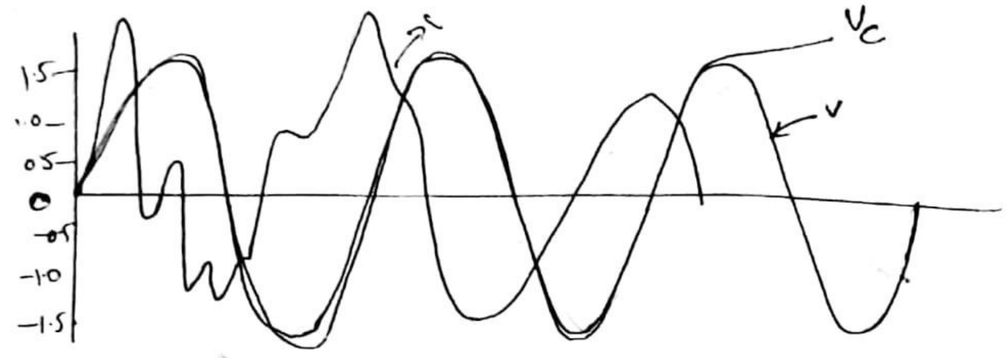
→ The wave forms of transient free switching capacitor:-



$Q = R/\omega_n L = 5$

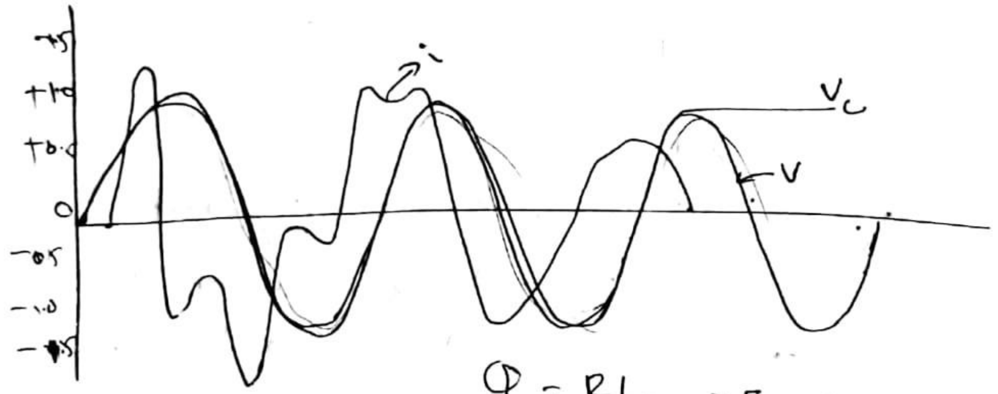


when capacitor fully discharged



$Q = R/\omega_n L = 5$

when capacitor partilly discharged.



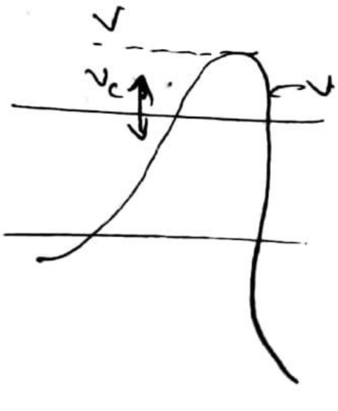
$Q = R/\omega_n L = 5$

→ ~~Thus~~ when reconnection of the capacitor may have ~~to~~ ~~be~~ residual capacitor voltage between 0 and $\frac{V_n^2}{n^2-1}$ .

which can explained by two cases.

Case(I) If the residual capacitor voltage is less than peak a.c voltage ($V_C << V$), ~~then~~ when switching occurs $\boxed{V_C = V.}$

→ The wave forms of above case is given by



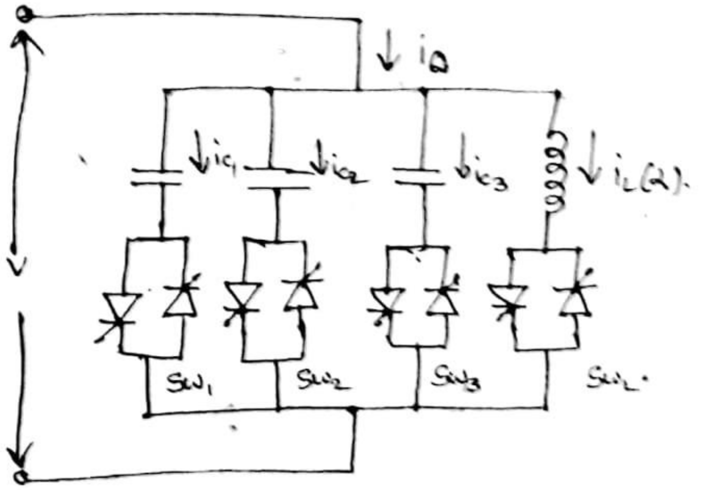
$V_C \leq V$

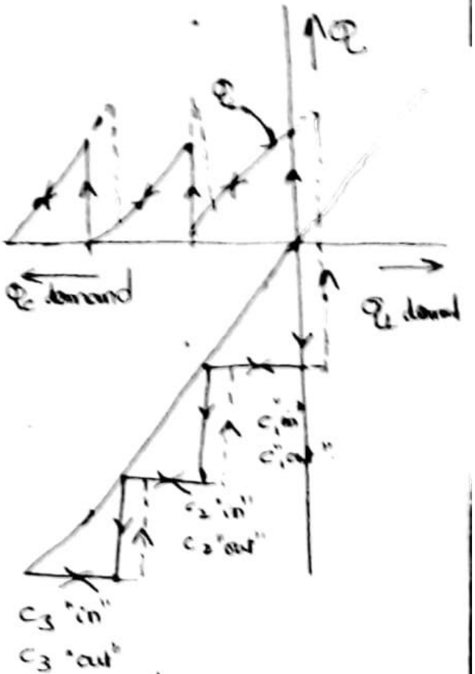
$V_C = V$

$ON_{SW} = 0$

(iv) Thyristor - Switched Capacitor (TSC), Thyristor - Controlled Reactor type var generator (TCR). (TSC - TCR) :-

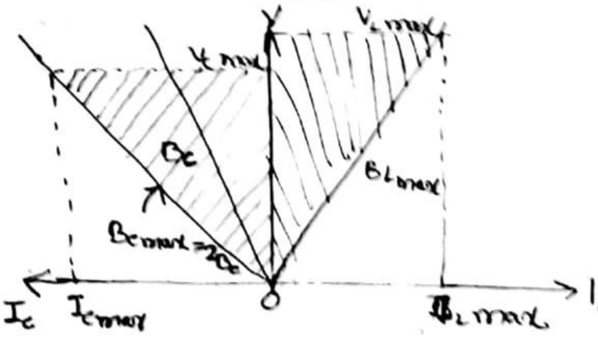
Basic Circuit diagram of TSC-TCR :-





var demand versus var output char.

VI characteristics of TSC-TCR



$V_{c\,max}$ = voltage limit for TSC

$V_{L\,max}$ = voltage limit for TC

$I_{c\,max}$ = capa. current limit

$I_{L\,max}$ = ind. current limit

$B_{L\,max}$ = Max. admi of TSC

$B_c$ = admi. of TSC

$B_{c\,max}$ = Max. cap. admitt

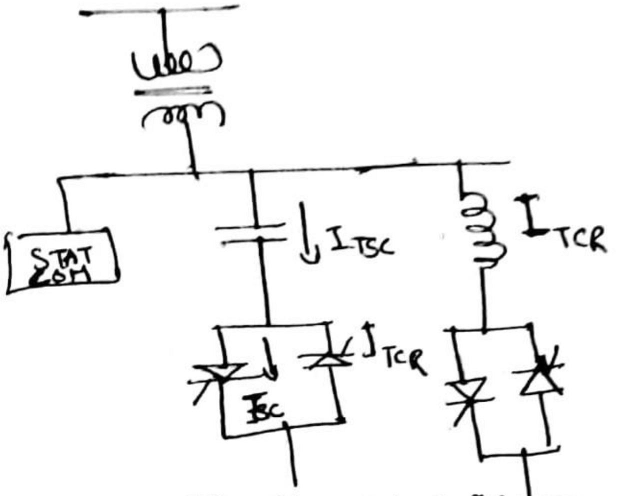
Functional Control scheme for the TSC - TCR type Static var generator :-

→ It provides (3) major function

1. Determines no: of TSC branches needed to be switched in to approximate required capacitive o/p current

2. It controls the switching of the TSC branches in a "transient free" manner.

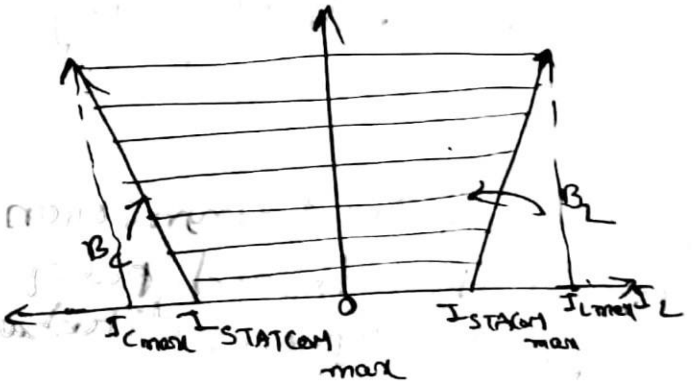
# STATIC VAR COMPENSATORS :-



→ Static Var ~~gender~~ compensator (SVC) and static synchr compensator (STAT-COM) are Static Var gen tory.

→ whose o/p is varied so as to maintain (or) cont specific parameter of the electric power sys.

→ The VI characteristics are as shown below.

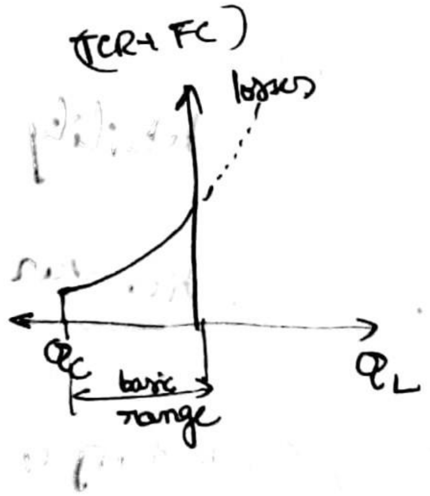


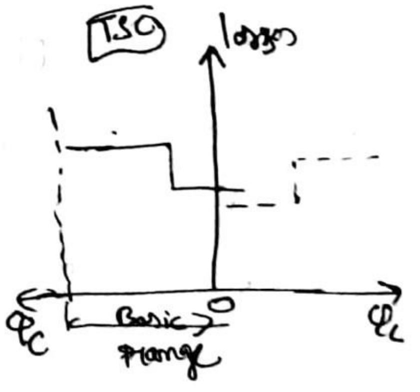
Vmax limit

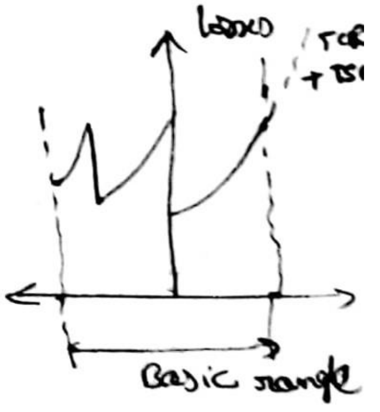
$I_L$ max = max. amount in indu

$I_C$ max. = max. Capaciti Current

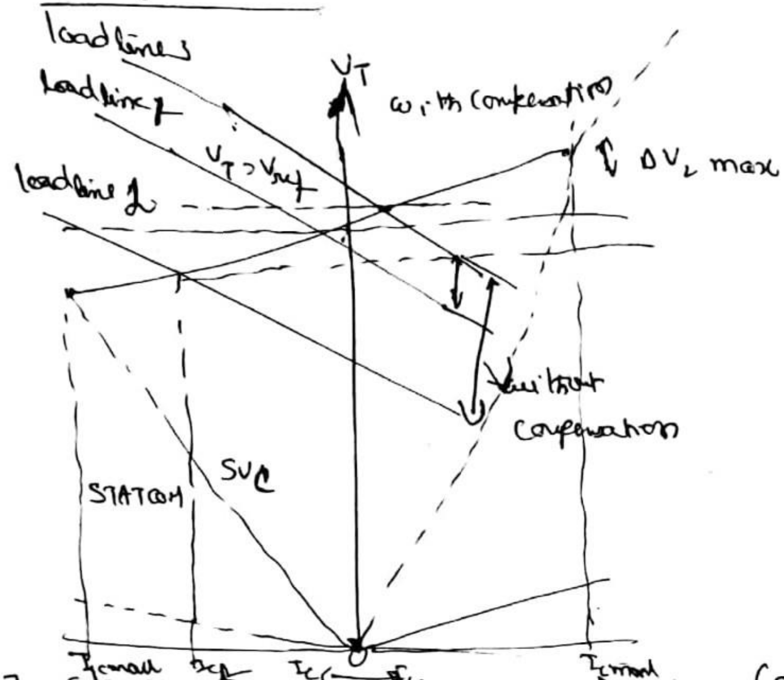
## loss Versus Var o/p characteristics :-





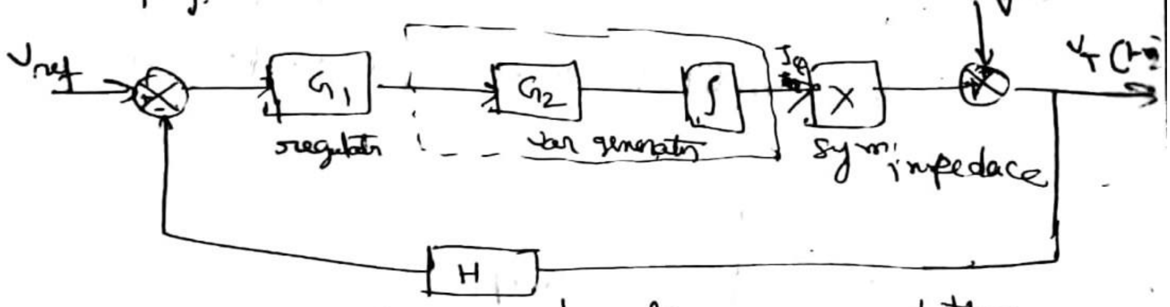


## Dynamic performance :-



→ The VI characteristic of the static compensator as shown in fig represents a steady state relationship

→ The dynamic behaviour of the compensator in the normal compensating range can be characterised by the basic transfer function block dig shown in fig.



→ In the linear operating range of the compensator, the terminal voltage $V_T$ can be expressed in terms of the internal voltage V and reference voltage $V_{ref}$ as follows

$$\boxed{V_T = V \times \frac{1}{1+G_1G_2HX} + V_{ref}\,\frac{G_1G_2X}{1+G_1G_2HX}}$$

→ Let $V_{ref} = 0$ and consider small variation only,

→ Then the variation of terminal voltage $\Delta V_T$ against the power system voltage $\Delta V$ can be expressed as

$$\frac{\Delta V_T}{\Delta V} = \frac{1}{1+G_1 G_2 HX} = \frac{1}{1+GHX}$$

where $G_1 = \frac{1/K}{1+T_1 s}$

& $G_2 = e^{-T_d s}$

$$G = G_1 G_2 = \frac{1/K}{1+T_1 s} e^{-T_d s}$$

$$H = \frac{1}{1+T_2 s}$$

where $T_1$ = main time const of the PI controller

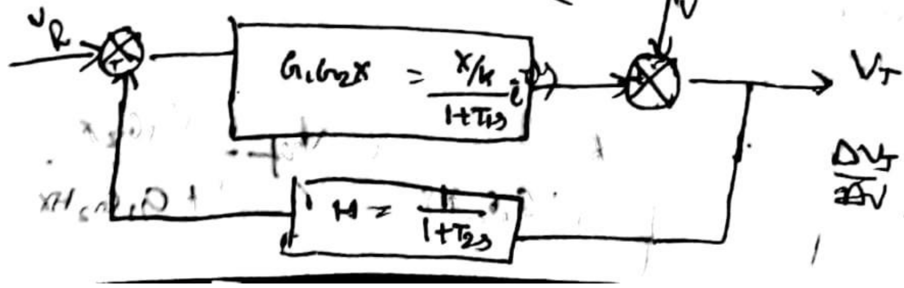
$T_2$ = Amplitude measuring ckt time const

$X = I_m Z$

$K$ = regulation slope

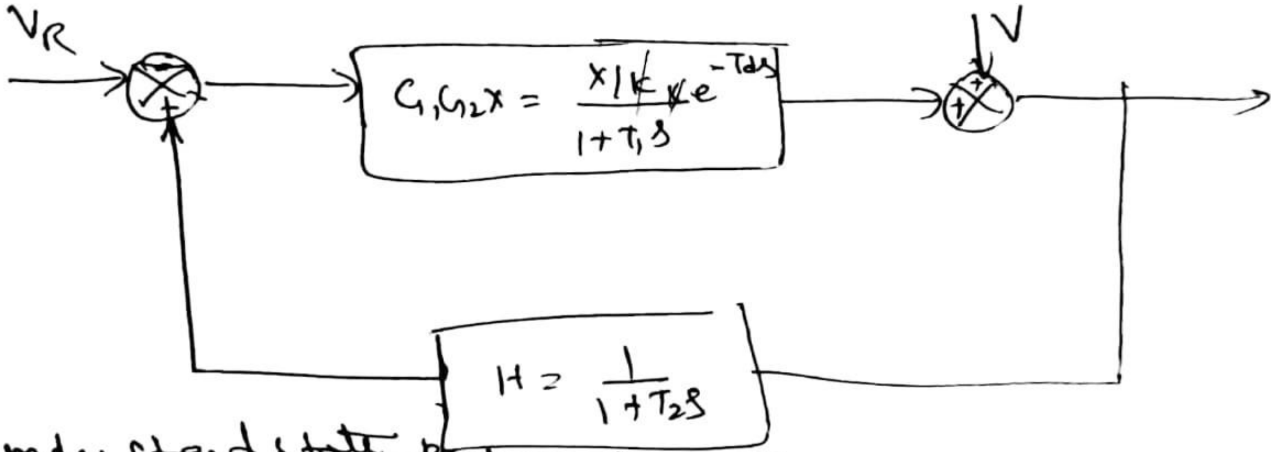
under steady state condition ($s \to 0$)

$$\frac{\Delta V_T}{\Delta V} = \frac{1}{1+X/K}$$



under steady state performance

$$\frac{\Delta V_T}{\Delta V}\Big|_{s=0} = \frac{1}{1+G_1 G_2 HX} = 0.15$$



under steady state performance :- $\Delta V_{ref} = 0$

$$\left.\frac{\Delta V_T}{\Delta V}\right|_{s=0} = \frac{1}{1+G_1G_2HX} = \underline{0.151}$$

## Transient Stability Enhancement :-

→ It is the ability of a system to reach the normal position after sudden and large disturbance

**for ex:** A severe fault on heavily loaded line.

In this condition [during above fault]. There is a steplike decrease in the transmitted electric power at const mech. i/p power.

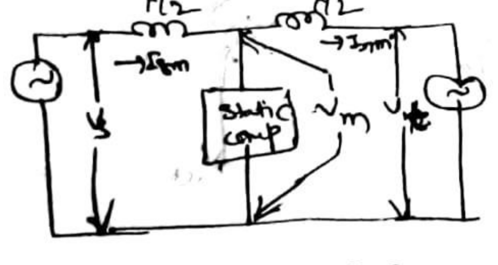
→ difference b/n mech i/p & elec. output causes the m/c to accelerate.

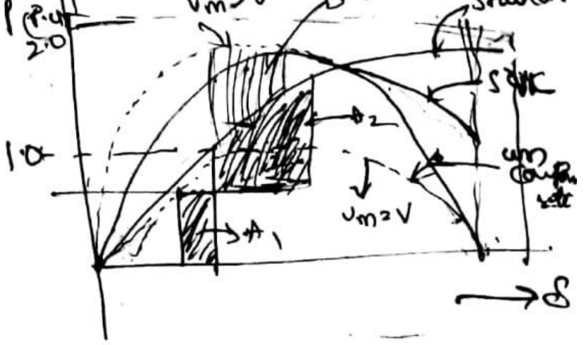
→ The transient stability concept can be easily explained by equal area criterion.

→ The stability & fault clearing time determined by the P & δ characteristics of post fault sys. in equal area criterion

→ By using STATCOM, which can control terminal voltage, can in~~sta~~crease transient stability by maintaining transmission voltage in the of the increased power flow. after the fault clearing

## Enhancement ~~by~~ of transient stability by the SVC & STATCOM





$V_s = V\sin(\omega t + \delta/2)$

$V_t = V\sin(\omega t + \delta/2)$

$V_m = V_m \sin\omega t$

for $V_s = V$; $\boxed{P = 2 \cdot \frac{V^2}{X}\sin\frac{\delta}{2}}$

for uncompensated line $P = \frac{V^2}{X} \sin\delta$

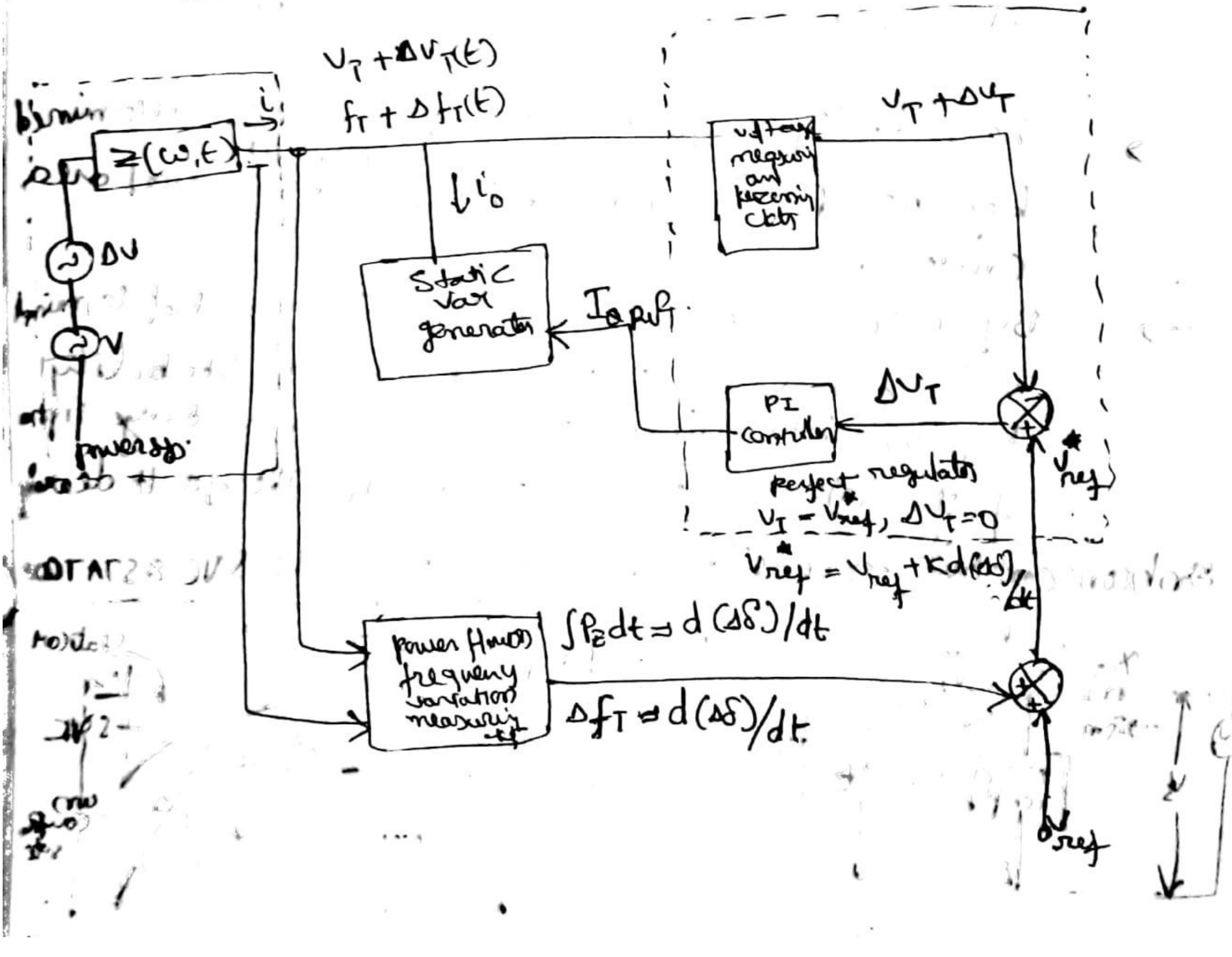
## power oscillation damping :-

→ In case of an undamped power system, any minor disturbance can cause the m/c angle to oscillate around its steady state value.

→ But whereas in compensated power system i.e by the STATCOM, the power oscillation dampings are approximatelly reduced.

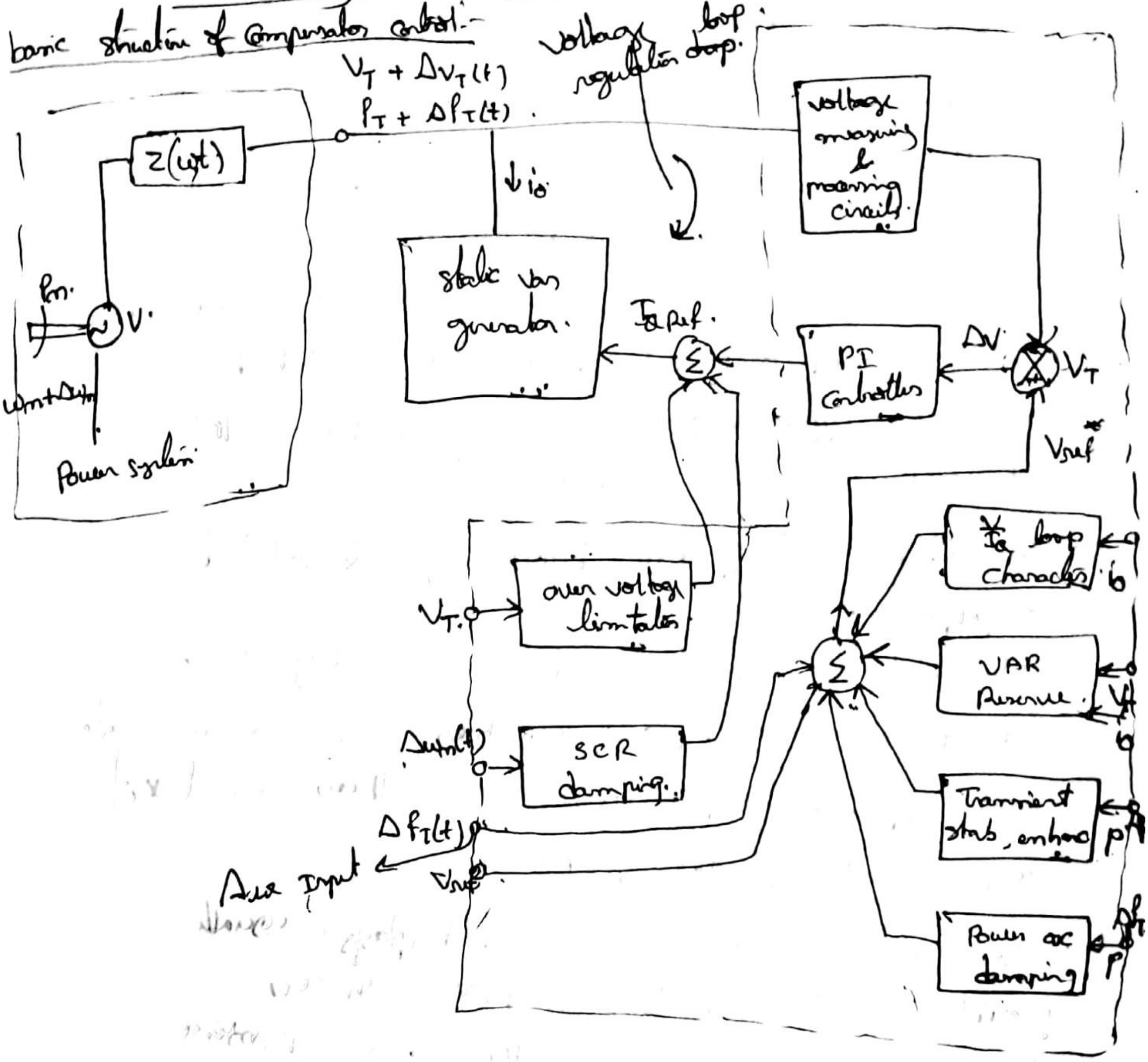
→ The effective power oscillation damping achieved by ② control schemes.

1. power oscillation damping by modulating ref volt.

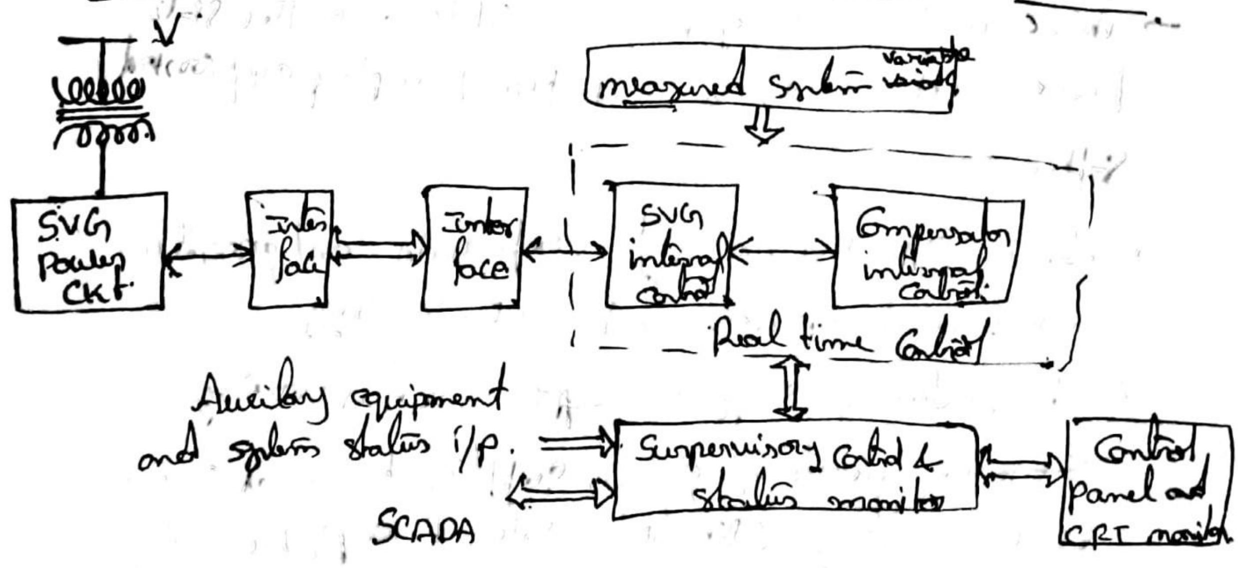


# Summary of Compensator Control:-

## basic structure of compensator control:-



## Main elements of the Complete Compensator Control:-

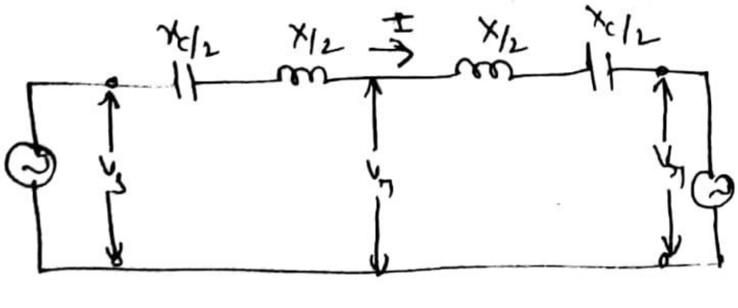


# UNIT - IV

## Objectives of Series Compensation.

- → Shunt Compensation is ineffective in controlling the actual transmitted power which, at a defined transmission voltage, is ultimately determined by the series line impedance & angle between end voltages of line
- → Series line compensation is a corner stone of facts technology
- → Series capacitive compensation increase the transmittable power
- → To achieve full utilization of transmission assets by controlling power flow in the lines
- → To prevent loop flows.
- → To minimise the effect of system disturbances.
- → The basic approach of reactive series compensation is to provide necessary foundations for the treatment of power electronics based Compensator
- → To determine maximum power transmission
- → To determine transient Stability, voltage Stability and power oscillations damping

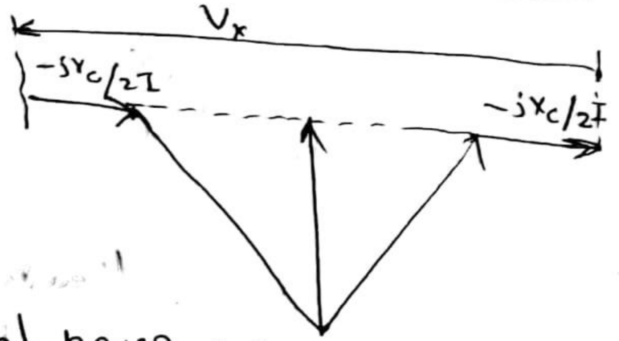
## Series Capacitive Compensation



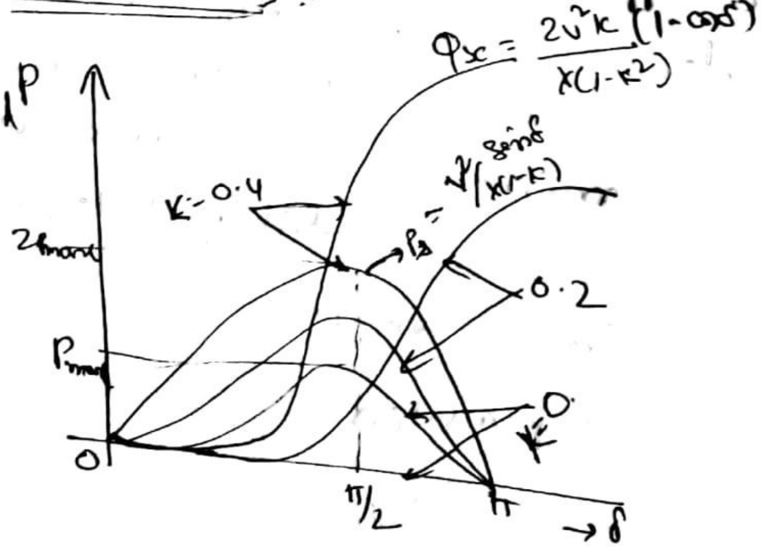
→ The basic idea behind series capacitive compensation is to decrease the overall effective series transmission impedance, from sending end to the receiving end.

→ consider the simple two-m/c model, which is analogous to that the shunt compensation but with a series capacitor compensated line, is assumed to be composed of two identical segments

## Voltage and current Phasor :-



## Real power & Series capacitor reactive power versus δ Characteristics :-



→ The same send voltages and magnitude of the total voltage a/c the series line inductance, $V_X = 2V_x/2$ is increased by the magnitude of the approximate voltage,

→ The effective transmission impedance $X_{eff}$ with the series capacitive compensation is given by,

$$X_{eff} = X - X_C$$

(or)

$$X_{eff} = (1-k)X$$

where 'k' is the degree of series compensation.

$$k = X_C/X \qquad 0 \leq k \leq 1$$

Assuming, $V_s = V_r = V$, the current in the compensated line, and the corresponding real power transmitted are

$$I = \frac{2V}{(1-k)X} \sin\delta/2$$

$$\boxed{P = V_m I = \frac{V^2}{(1-k)X} \sin\delta}$$

$$\boxed{2\sin^2\delta/2 = 1-\cos\delta}$$

$$\Rightarrow \sin^2\delta/2 = \frac{1-\cos\delta}{2}$$

The reactive power supplied by the series capacitor can be expressed as:

$$\boxed{Q_C = I^2 X_C = \frac{2V^2}{X} \cdot \frac{k}{(1-k^2)} (1-\cos\delta)}$$

$$\left[\because \begin{array}{l} 1+\cos 2\theta = 2\cos^2\theta \\ 1-\cos 2\theta = 2\sin^2\theta \end{array}\right]$$

$$1-\cos\delta = 2\sin^2(\theta/2)$$

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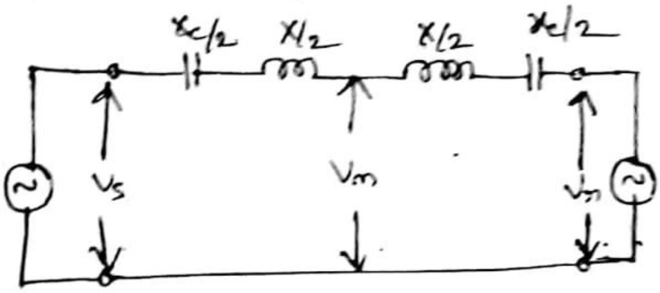
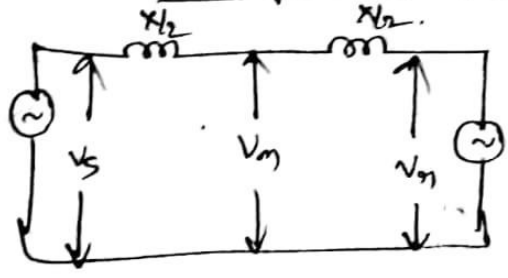
# Improvement of Transient stability :-

→ As in case of shunt compensation for improving transient stability analysis by equal area criterion is less effective than the series compensation by equal area criterion for improving transient stability

→ Consider simple series compensation system as shown in fig.



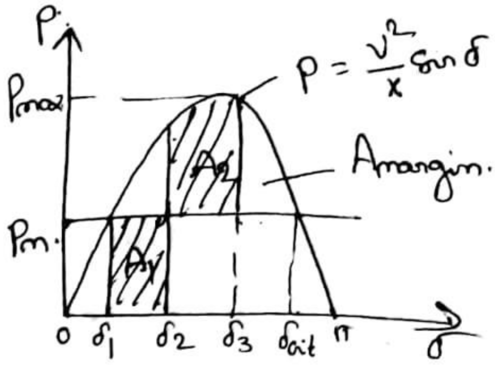
un compensated system



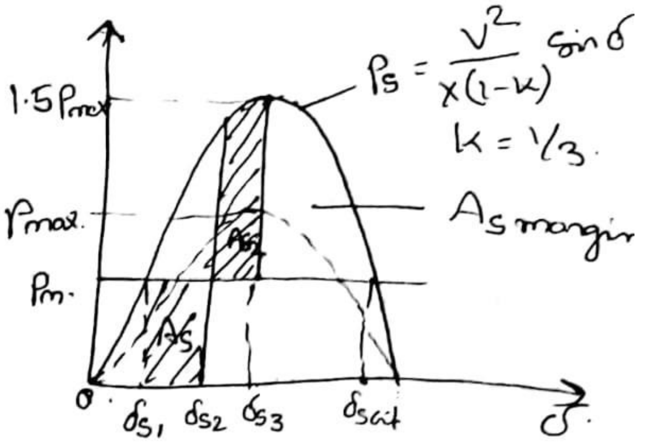
→ Assume that both the uncompensated and series compensated systems are subjected to same fault for the same period of time.

→. The dynamic behaviour of the above systems are illustrated as below.

without Compensation



with Compensation



⇒ Both the circuits transmits same mechanical power ~~after the~~ at the line of faults.

⇒ During the faults, the transmitted electric power becomes zero. while the mechanical i/p power to the generator remains constant Pm.

⇒ The accelerating areas are $A_1$ & $A_{S1}$

⇒ After fault clearing, the transmitted electric power exceeds the mechanical i/p power and machine decelerates.

⇒ The decelerating areas are $A_2$ & $A_{S2}$

⇒ The areas b/w P versus δ curve and the Pm' line over the intervals defined by angle $\delta_3$ & $\delta_{crit}$, and $\delta_{S2}$ and $\delta_{Scrit}$ respectively determine the margin of stability. represent by area $A_{margin}$ & $A_{Smarg}$

› By comparing there is a substantial increase in the transient stability margin ~~of~~ the system compensated system with without

# Power oscillation damping

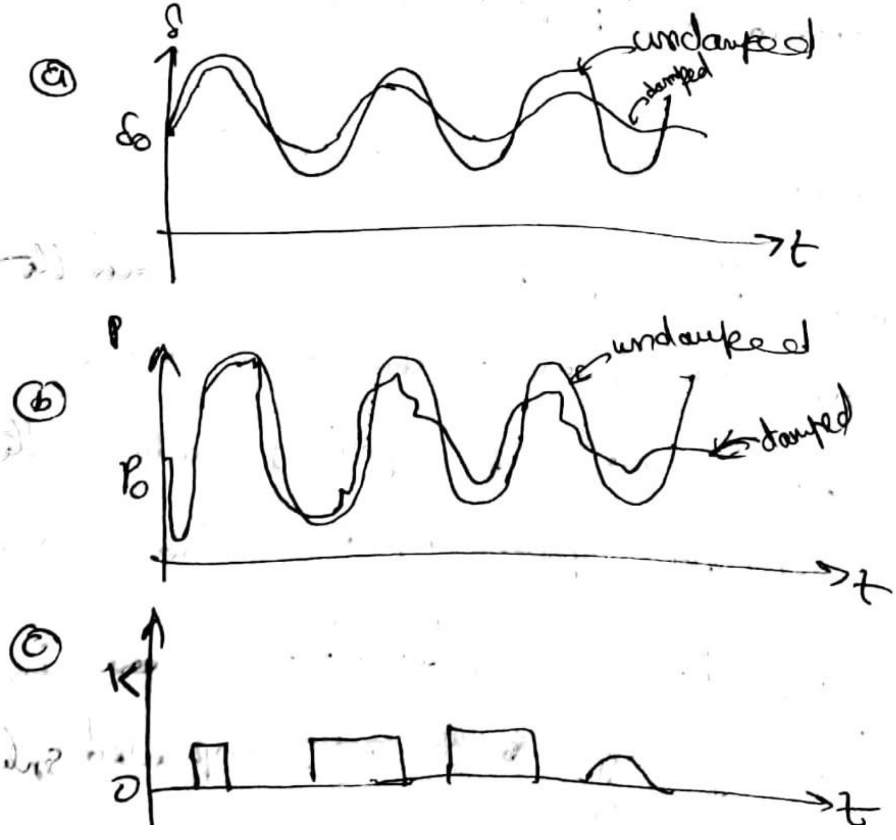
→ Controlled series compensation can be applied effectively to damp power oscillations.

→ For power oscillation damping it is necessary to vary the applied compensation so as to contract the accelerating decelerating swings of the disturbed mach

→ when the rotationally oscillating generator accelerates and angle δ increases, the electric power transmitte must be increased to compensate for the excess mechanical i/p power.

wave forms illustrating power oscillation damping by Controllable Series Compensation.

ⓐ Generator ⓑ transmitted power ⓒ degree of series compens



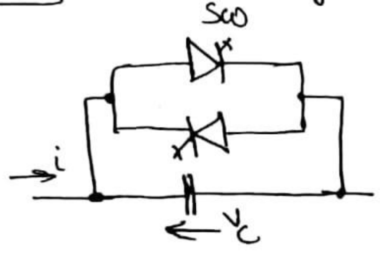
variable impedance type Series compensatory.

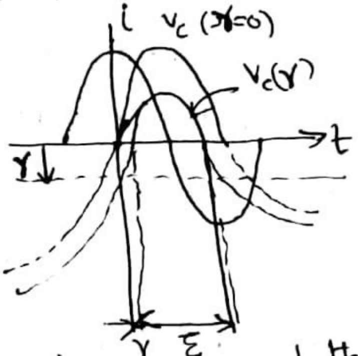
① GCSC [GTO thyristor controlled series capacitor]

② TSSC [thyristor switched series capacitor (TSSC)]

③ TCSC [thyristor controlled series capacitor]

**GCSC:-** Basic symbol of GCSC





(TSR - TCR) characteristics [Instead of we put γ]

→ The objective of GCSC is to control the ac voltage ($v_c$) across the capacitor, at a given line current i.

→ Operation :-

when GTO valve sw is closed, the voltage across the capacitor is zero.

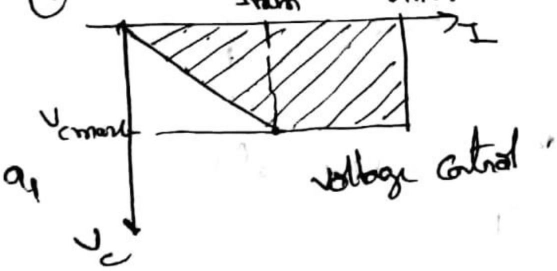
→ when valve is opened, it is maximum.

line current $i_t = I\cos\omega t$, ∴ $v_{ct} = \frac{1}{c}\int_{\gamma}^{\omega t} I(t)\,dt$

$= I/\omega c\,(\sin\omega t - \sin\gamma)$

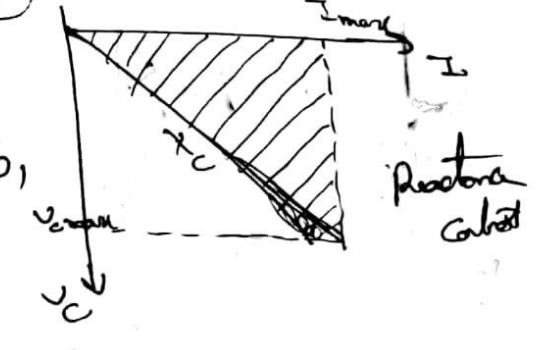
VI - Characteristics of GCSC :-

ⓐ



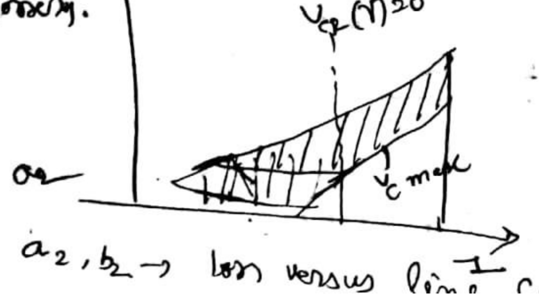
$a_1$ voltage control

ⓑ

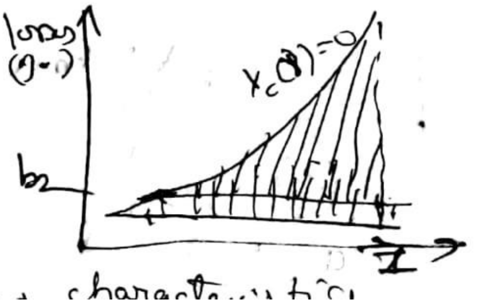


$b_1$ Reactance control

ⓒ



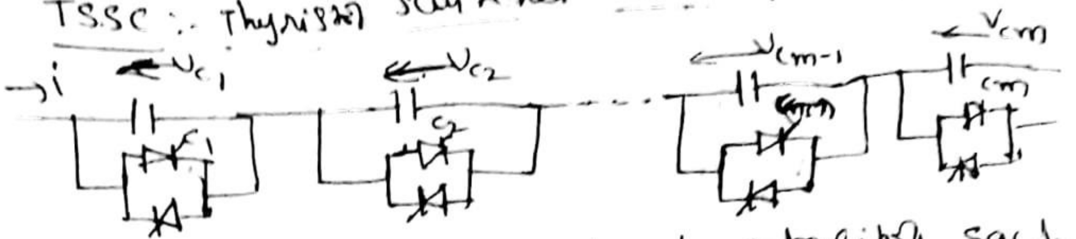
$a_2$



$b_2$

$a_2, b_2$ → loss versus line current characteristics

TSSC :- Thyristor switched series capaci



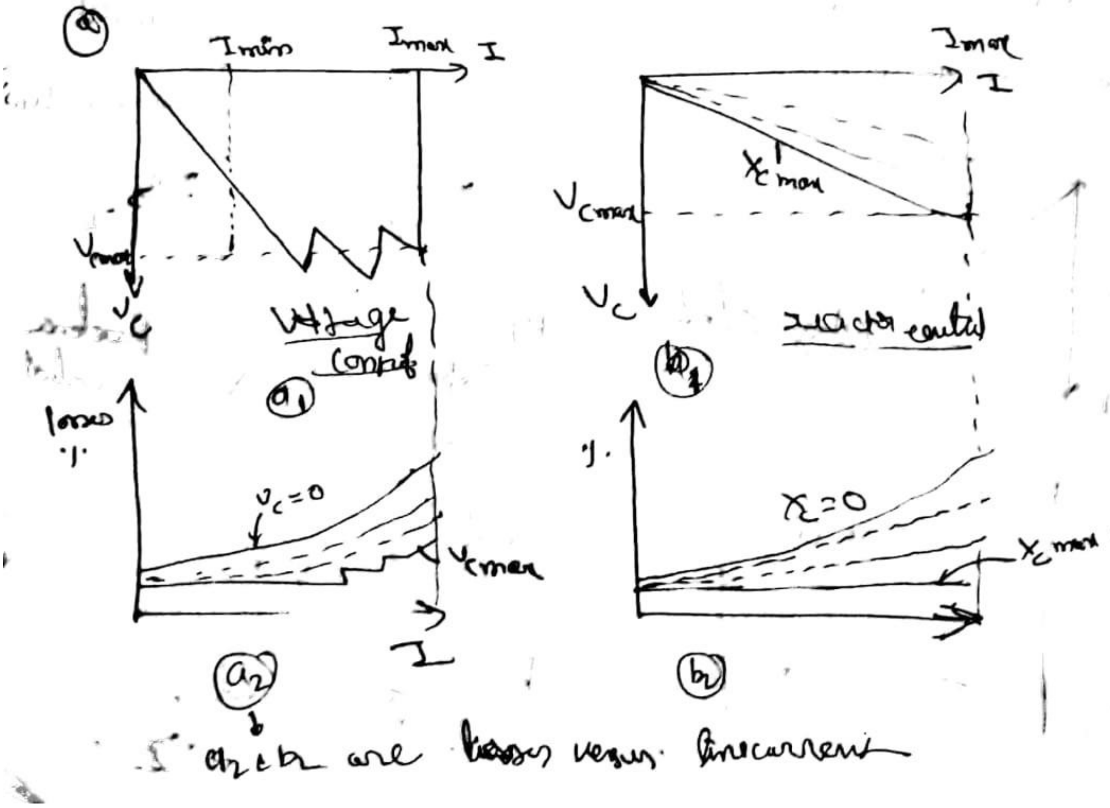
→ It consists of a number of capacitors. Each shunted by an rated bypass valve composed of a string of reverse parallel connected thyristor in series.

→ It is similar to the ckt structure of the sequentially operated GCSC. but its operation is different

→ The operating principle of the TSSC is straight forward.

→ The degree of series compensation is controlled in a step like manner by increasing or decreasing the number of series capacitor inserted.

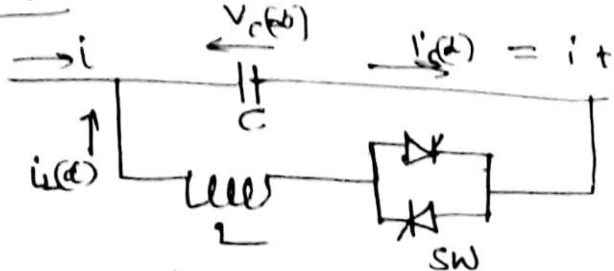
→ A capacitor is inserted by turning off, & it is bypassed by turning on.



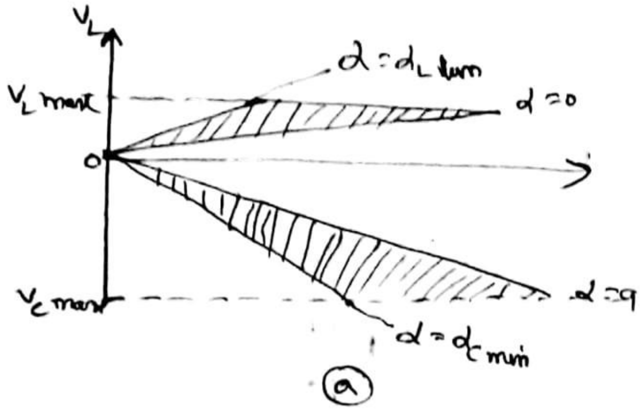
$a_2$ & $b_2$ are losses versus line current

## TCSC:

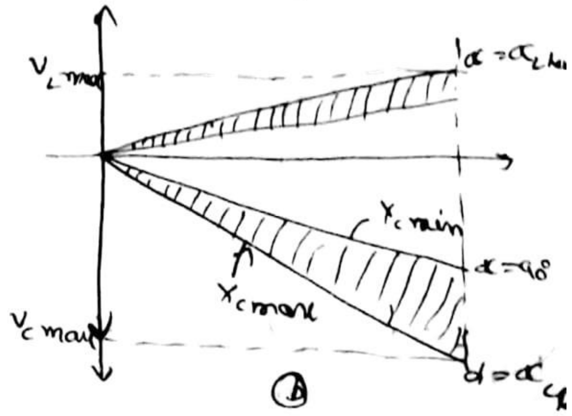
Basic thyristor controlled series capacitor scheme.



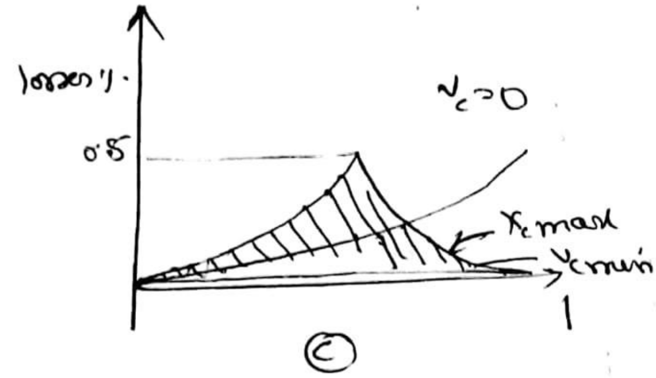
## VI-Characteristics of TCSC:



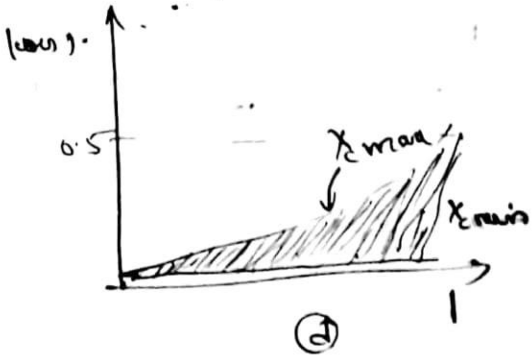
(a)



(b)



(c)



(d)

→ It is a method rapid adjustment of network impedance which is shown in fig.

→ It consists of series compensating capacitor shunted by TCR.

→ Inorder to get the desired voltage rating and operating characteristics several TCSC's connected in series

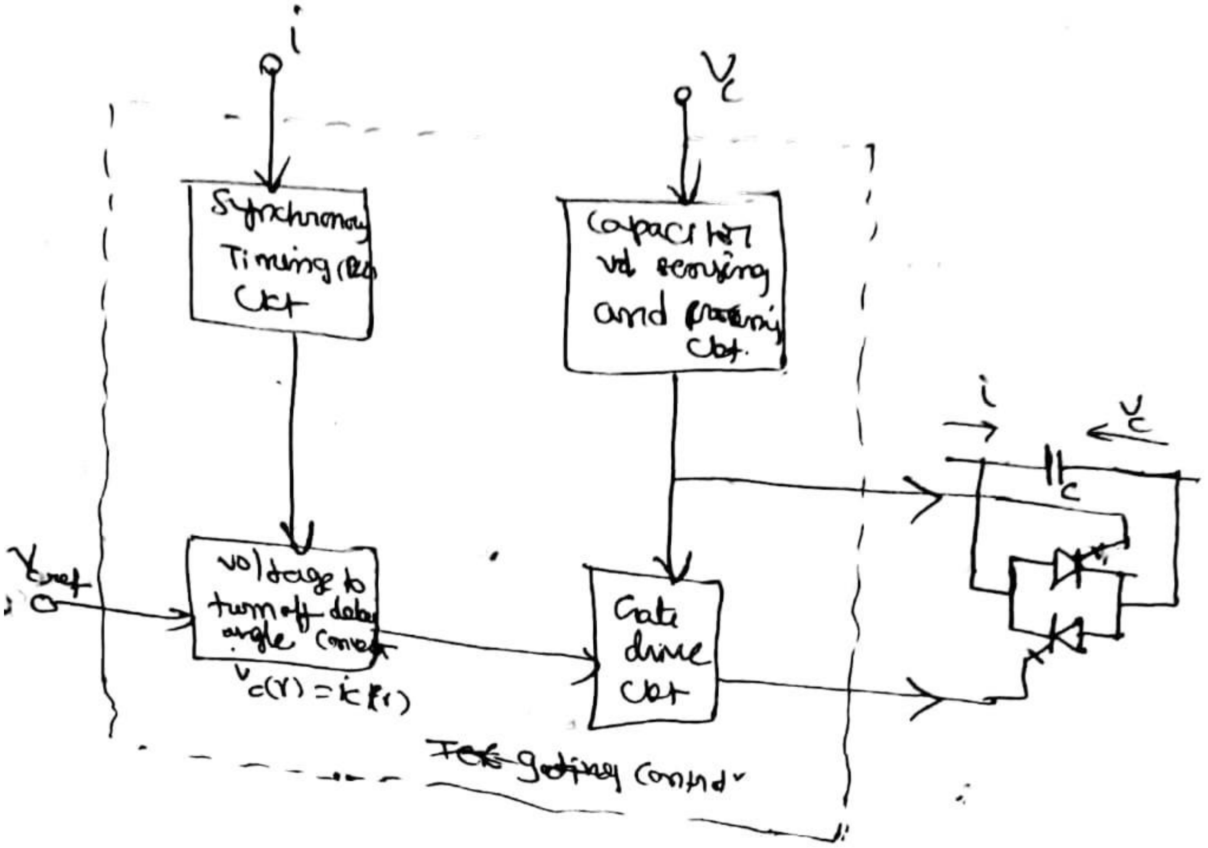
→ Total reactance of TCSC is given by

$$\boxed{X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C}}$$

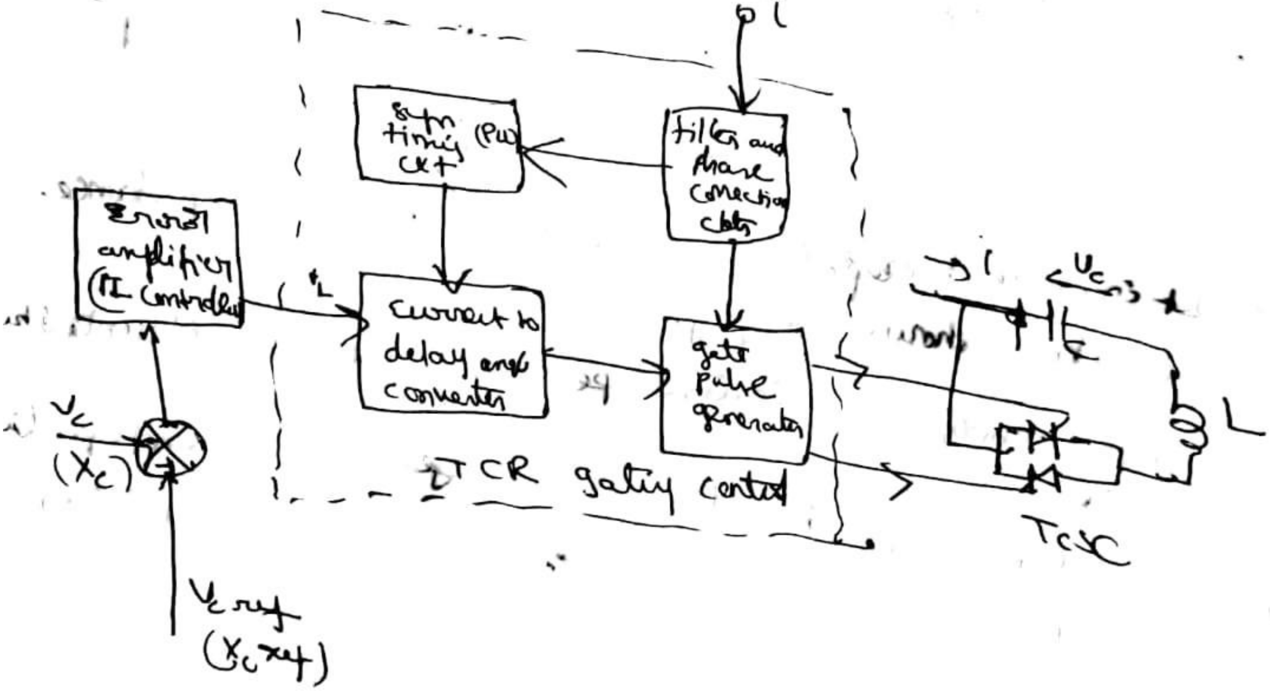
$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha}, \quad X_L \le X_L(\alpha) \le \infty,$$

# Control Schemes of (GCSC, TSSC, TCSC).

## GCSC :-



## TSSC :-



# UNIT – VI COMBINED CONTROLLERS

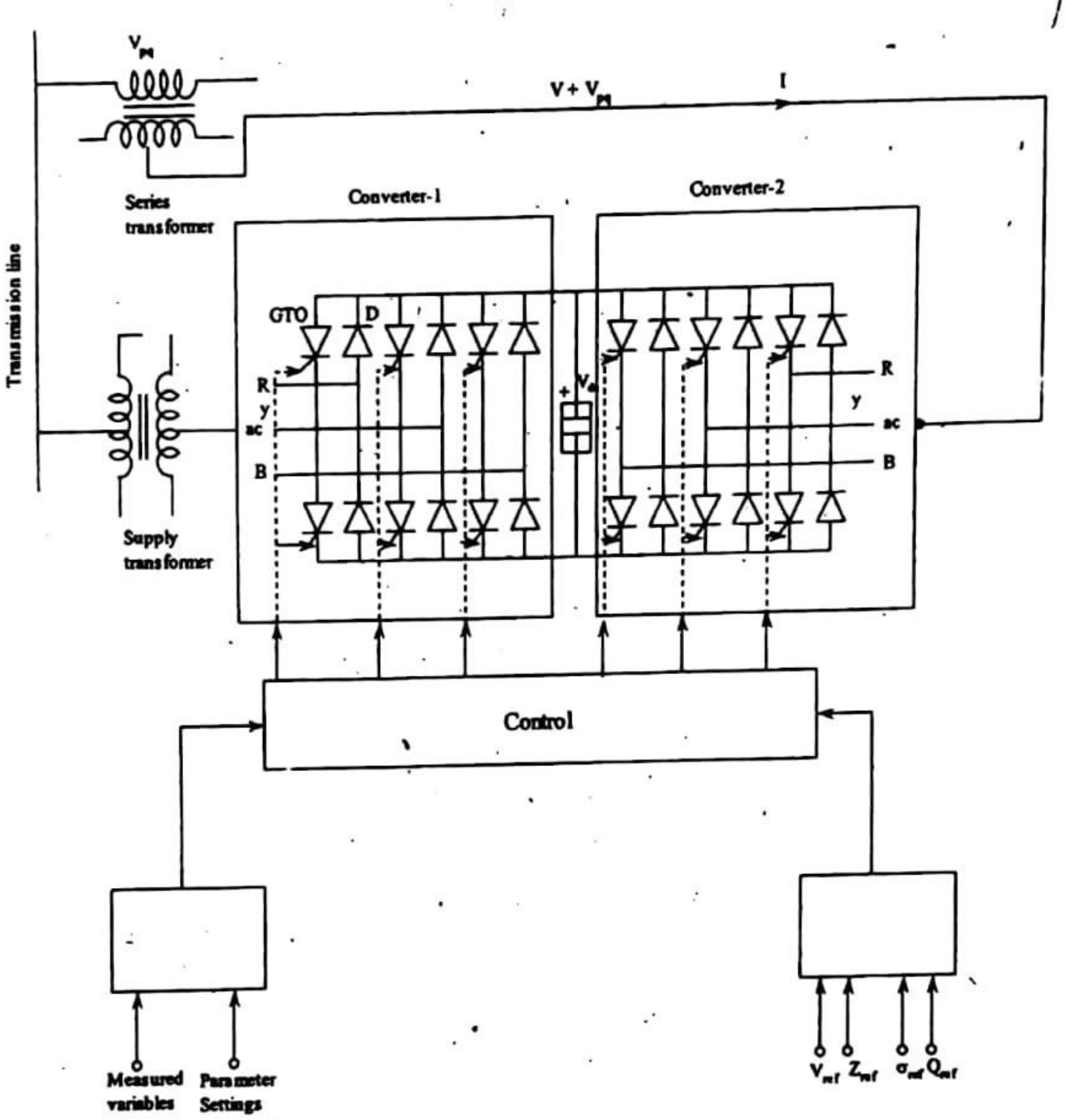
UPFC is basically the combination of the static synchronous compensator (STATCOM) and static series compensator (SSSC) which are coupled by a common D.C link. This combined system allows the bidirectional flow of active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. The UPFC is then controlled so that active and reactive series line compensation can be achieved without an external electric energy source.

It is a device which is designed for the real-time control of A.C transmission network. It acts as a dynamic compensator in the A.C transmission system and also controls the real and reactive power individually in transmission lines. It provides multifunctional flexibility that is necessary for solving number of problems faced by the power transmission sector.

UPFC controls either simultaneously or selectively, all the parameters which affect the flow of power in transmission lines. These controlled parameters include voltage impedance, phase angle etc. This unique property of controlling the parameters governing the power flow has earned the name "Unified" for this controller.

## Implementation of the UPFC:

A Unified Power Flow Controller (UPFC) consisting of two voltage sourced converters connected back to back is sho in figure.



Figure

Where,

$V_{pq}$ = Injected voltage

$GTO$ = Gate turn-off thyristor

$D$ = Diode

$V_{ref}$ = Reference voltage

$Z_{ref}$ = Reference value of impedance

$\sigma_{ref}$ = Reference value of the angular phase shift

$Q_{ref}$ = Reference value of reactive power.

The two converters operates from a common D.C link which is provided with a D.C storage capacitor. The arrangeme represents an ideal A.C to A.C power converter wherein the real power can freely flow in either direction between the A terminals of the two converters. Each of the converters can either generate or absorb the reactive power independently at its o A.C output level.

The main operation of UPFC is done by converter-2 which injects a controllable voltage of magnitude $V_{pq}$ and a pha angle of ρ in series with the line. This voltage injection is accomplished by a series insertion transformer. The voltage bei

A real and reactive power exchange occurs whenever the transmission line current flows through the voltage source. The converter-2 generates reactive power internally which gets exchanged at the A.C terminals. The real power exchanged at the AC terminal is now converted into D.C power that appears at the D.C terminals as a positive or negative real power demand.

The primary function of converter-1 is to either supply or absorb the real power which is demanded by converter-2. at the common D.C link. The converter-1 converts the D.C link power demand of converter-2 back to the A.C power and is coupled to the transmission line bus through a shunt connected transformer. It also generates or absorbs controllable reactive power when desired so that shunt reactive compensation for the line can,be achieved independently.

It should be observed that the real power has a closed direct path which is negotiated by the action of series voltage injection through converters 1 and 2 back to the line. But the corresponding reactive power exchanged (generation or absorption) by the converter-2 occurs locally and hence does not need to be transmitted by the line.

Thus, the operation of converter-1 occurs at unity power factor or it can be controlled in order to have a reactive power exchange with the line independent of the reactive power, exchanged by converter-2. As a result the UPFC D.C link does not carry any reactive power.

# OPERATING PRINCIPLE of IPFC :

The basic operating principle of interline power flow controller is illustrated by considering a basic two-converter IPFC, employing two back-to-back DC to AC converters. Each converter compensates a transmission line by injecting a series voltage as shown in figure (1).

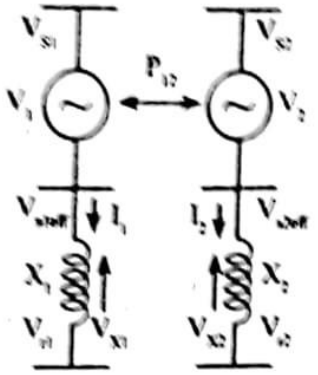


Figure Basic Two Converter Interline Power Flow Scheme

Where,

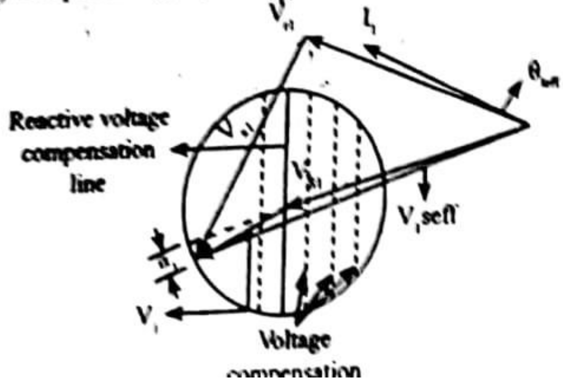
$V_{S1}, V_{S2}$ = Sending end bus voltage phasor of line 1 and line 2.

$V_{r1}, V_{r2}$ = Receiving end bus voltage phasor of line 1 and line 2.

$V_1, V_2$ = Voltage sources in series with line 1 and line 2 representing the two back-to-back D.C to A.C converters.

$X_1 X_2$ = Reactance of line 1 and line 2.

For analysis, the equivalent sending end and receiving end sources in both systems are assumed as stiff A.C sources. It is also assumed that both the systems have identical line parameters. Under IPFC scheme, system-1 is termed as primary system and system-2 is termed as secondary system. In this configuration, the series voltage injected into each line can be controlled in both its magnitude ($0 \leq V_{pq1} \leq V_{pq1max}$) and phase angle ($0 \leq \alpha_{pq1} \leq 360°$) as shown in figure (2).



The variation of real power $P_{r1}$ and reactive power $Q_{r1}$ with $V_{Pq1max}$ can be represented in($Q_{r1}$, $P_{r1}$) plane along with its vector diagram. The compensation of line '1' explained above is similar to the operation of UPFC except that, in UPFC the real power exchange occurs from the sending bus by means of the shunt converters. In case of IPFC, the real power is obtained from other system through series-connected compensating converter of that line. To compensate secondary system under the primary system, disintegrate the total power provided for line 1 into active and reactive power. The inserted voltage phasor $V_{1Pq}$ is divided into two components $V_{1q}$ and $V_{1p}$. The characteristics of IPFC is shown in figure (3).

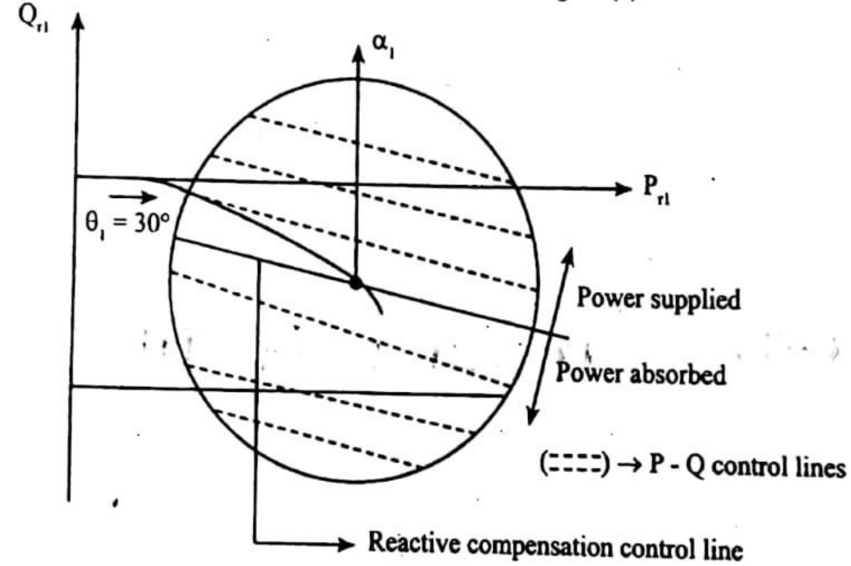


**Figure : Characteristics of IPFC Scheme**

The operating region on injected voltage phasor, magnitude of $V_{1Pq}$ is controlled by a range of angle α and the ends of the system lies on voltage compensation line parallel to reactive voltage compensation lines. The circular operating region of IPFC scheme is divided into two equal halves. The real power $P_r$, supplied to system 1 as the compensation line shifts higher than reactive compensation line whereas real power consumed by the system shifts lower below reactive compensation control line.

Code No:**R164202B** **R16** **Set No. 1**

**IV B.Tech II Semester Regular Examinations, September - 2020**

# FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS

**(Electrical and Electronics Engineering)**

**Time: 3 hours** **Max. Marks: 70**

***Question paper consists of Part-A and Part-B***
***Answer ALL sub questions from Part-A***
***Answer any FOUR questions from Part-B***

*****

## PART–A*(14 Marks)*

1. a) List out the importance of controllable parameters. [3]
   b) What are the principal types of current sourced converters? [2]
   c) How do you improve the transient stability using shunt compensation? [3]
   d) What are the methods of controlling the reactive power? [2]
   e) What are the various types of variable impedance type series compensators? [2]
   f) Why you need UPFC. [2]

## PART–B*(4x14 = 56 Marks)*

2. a) Explain the dynamic stability considerations of a transmission interconnections. [7]
   b) Describe the possible benefits from FACTS technology. [7]

3. a) Discuss the basic concept of voltage source converter. [7]
   b) Explain the operation of three phase bridge converter with diagrams. [7]

4. Explain the mid–point voltage regulation for line segmentation with necessary diagrams and expressions. [14]

5. a) Explain the regulation slope of static VAr generator with block diagram. [7]
   b) Describe the VAr reserve control of static compensator. [7]

6. a) Discuss the concept of series capacitive compensation with necessary expressions. [7]
   b) What is the summary of functional requirements of series compensation? [7]

7. Explain the basic operating principle of UPFC with diagrams. [14]

Code No:**R164202B**

# R16

**Set No. 2**

**IV B.Tech II Semester Regular Examinations, September - 2020**

## FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS

**(Electrical and Electronics Engineering)**

**Time: 3 hours** **Max. Marks: 70**

***Question paper consists of Part-A and Part-B***
***Answer ALL sub questions from Part-A***
***Answer any FOUR questions from Part-B***

*****

## PART–A*(14 Marks)*

1. a) What are the basic types of FACTS controllers? [2]
   b) What is the basic concept of voltage source converter? [3]
   c) What is the need ofend of line voltage support to prevent voltage instability? [3]
   d) What is meant by thyristor switched capacitor? [2]
   e) What is meant by thyristor controlled series capacitor? [2]
   f) What is meant by UPFC?Draw its diagram. [2]

## PART–B*(4x14 = 56 Marks)*

2. a) What limits loading capability in AC power transmission system. Discuss them. [7]
   b) Explain the losses and speed of switching of high power devices. [7]

3. a) Discuss the operation of single phase full wave bridge converter. [7]
   b) Derive the expressions for fundamental and harmonic voltages for a three phase bridge converter. [7]

4. Describe the improvement of transient stability using shunt compensation with necessary diagrams. [14]

5. a) Compare the different types of static VAr generators. [7]
   b) Derive the transfer function of SVC and STATCOM. [7]

6. Describe the thyristor switched series capacitor with neat diagrams and expressions. [14]

7. Explain the conventional transmission control capabilities of UPFC with diagrams and expressions. [14]

Code No:**R164202B** **R16** **Set No. 3**

**IV B.Tech II Semester Regular Examinations, September - 2020**

## FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS

**(Electrical and Electronics Engineering)**

**Time: 3 hours** **Max. Marks: 70**

***Question paper consists of Part-A and Part-B***
***Answer ALL sub questions from Part-A***
***Answer any FOUR questions from Part-B***

*****

### PART–A*(14 Marks)*

1\. a) What are the benefits fromFACTS controllers? [3]
   b) What are the basic categories of self-commutating converters? [2]
   c) What are the objectives of shunt compensation? [3]
   d) What are the functions provided by the control scheme of TSC-TCR type VAr generator? [2]
   e) What is meant by thyristor switched series capacitor? Draw its diagram. [2]
   f) What is the need of UPFC? [2]

### PART–B*(4x14 = 56 Marks)*

2\. a) What are the opportunities of FACTS? How they are fulfilled in AC power transmission? [7]
   b) What are the basic types of FACTS controllers? Discuss them with neat diagrams. [7]

3\. a) How do you determine dominant harmonics in the square wave output voltage of a single phase inverter? [7]
   b) What are the merits and demerits of current source verses voltage source converters? [7]

4\. a) Explain the power oscillation damping with shunt compensation. [7]
   b) What is the summary of shunt compensator requirements? [7]

5\. Describe the TSC–TCR type VAr generator with necessary diagrams. [14]

6\. a) Explain the improvement oftransient stability using static series compensator. [7]
   b) Briefly discuss the GTO thyristors controlled series capacitor. [7]

7\. Explain the independent real and reactive power flow control of UPFC with diagrams. [14]

Code No:**R164202**B **R16** **Set No. 4**

**IV B.Tech II Semester Regular Examinations, September - 2020**

## FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS

**(Electrical and Electronics Engineering)**

**Time: 3 hours** **Max. Marks: 70**

***Question paper consists of Part-A and Part-B***
***Answer ALL sub questions from Part-A***
***Answer any FOUR questions from Part-B***

*****

### PART–A*(14 Marks)*

1. a) What are the various types of high power thyristor devices? [2]
   b) What is the primary difference between current source converterand voltage source converter? [3]
   c) What is the need of mid–point voltage regulation for line segmentation? [3]
   d) What is meant by STATCOM? Draw its diagram. [2]
   e) What are the objectives of series compensation? [2]
   f) Draw the circuit diagram of UPFC. [2]

### PART–B*(4x14 = 56 Marks)*

2. a) Why we need transmission interconnections? [5]
   b) Illustrate the power flow in an AC System. [9]

3. a) Derive the expression for square wave voltage harmonics for single phase bridge. [7]
   b) Explain the operation of threephase current source converter. [7]

4. a) What are the objectives of shunt compensation? [5]
   b) Explain how you prevent voltage instability using end of line voltage support. [9]

5. a) Describe the thyristor switched capacitor with neat diagrams. [9]
   b) Compare SVC and STATCOM type of VAr generators. [5]

6. Describe the thyristor controlled series capacitor with neat diagrams and expressions. [14]

7. Compare the UPFC to controlled series compensators with necessary diagrams [14]