A Course Material on

# FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEM

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# UNIT I

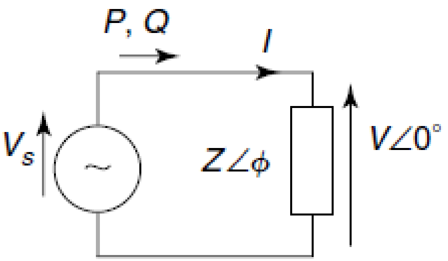
# INTRODUCTION

## 1.1 CONCEPT 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".

## 1.2 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".



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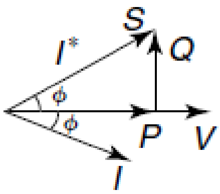


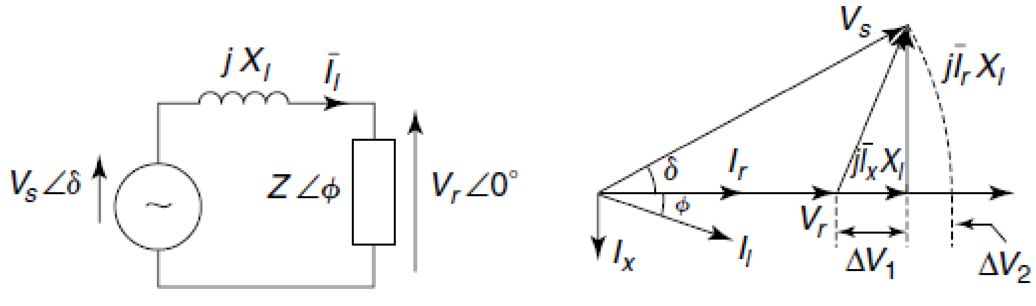
(c)

- 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).

## 1.3 UNCOMPENSATED TRANSMISSION LINES

### 1.3.1 Introduction

For simplicity let us consider only the inductive reactance



(a) (b)

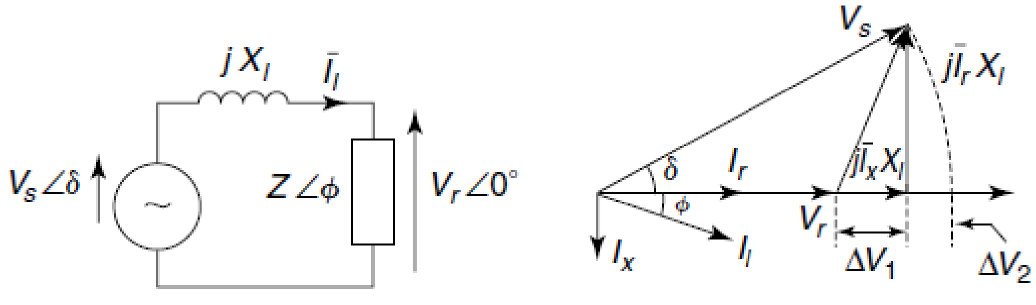
From the above figure it is clear that between he sending and the receiving end voltages and magnitude variation as well as a phase difference is created and the most significant part of the voltage drop in the line reactance is due to the reactive component of the load current and to keep the voltages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

Two compensation methods are:

1. Load compensation
2. System compensation

### 1.3.2 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 $I_r X_1$.



(a) (b)

### 1.3.3 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 $I_l$ 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.

### 1.3.4 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.

### 1.3.5 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.

### 1.3.6 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.

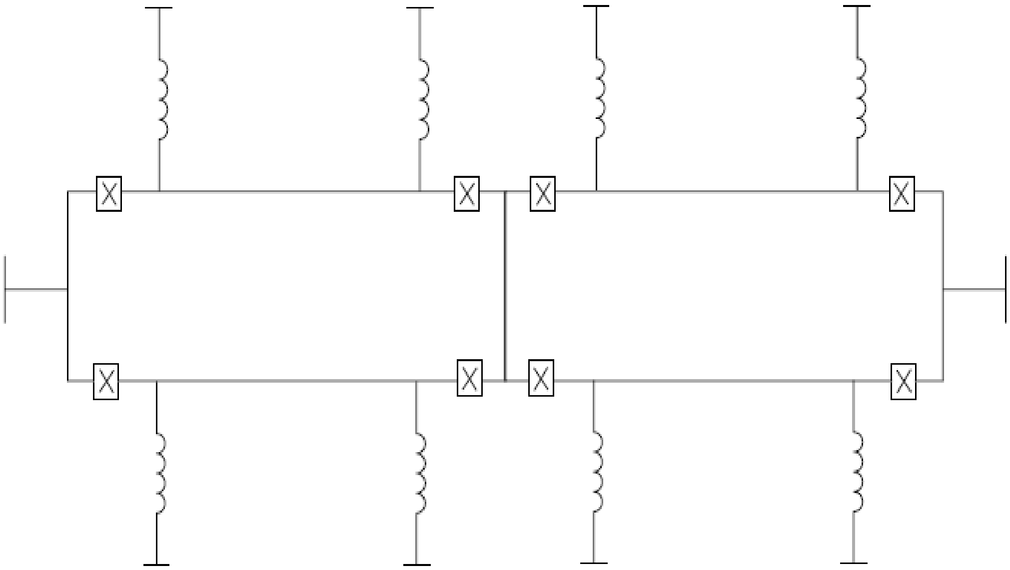
## 1.4 PASSIVE COMPENSATION

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**

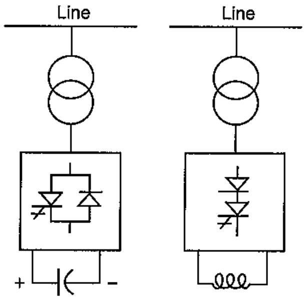
- Shunt Compensation
- Series Compensation

### 1.4.1 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.

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

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



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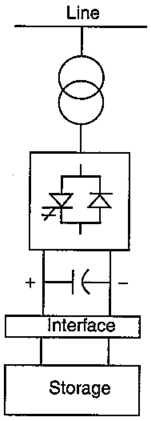

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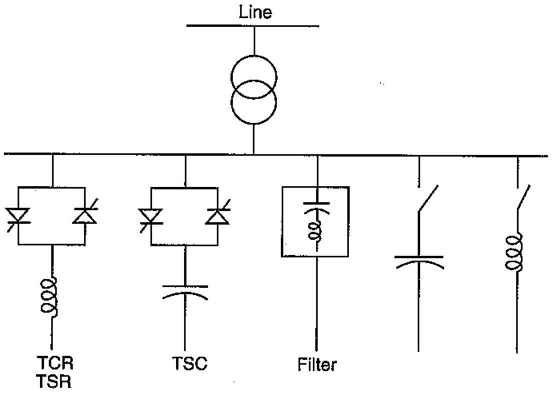

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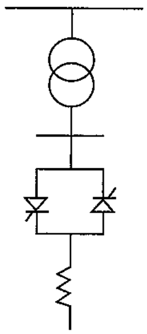


(d)

### 1.4.2 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.

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

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

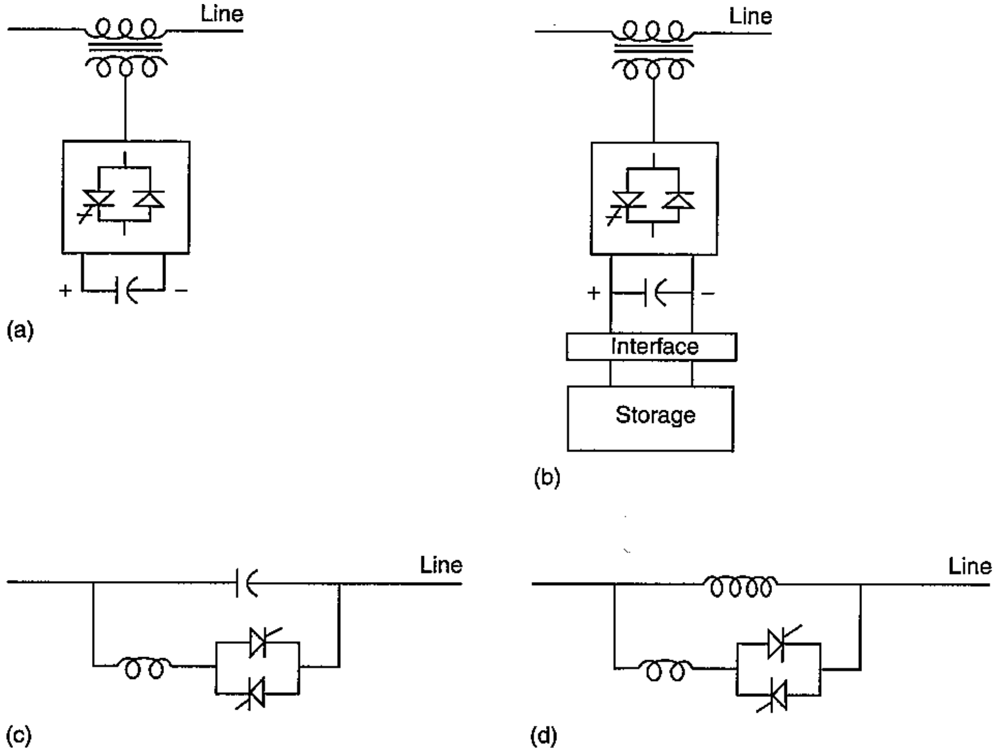


**Figure 1.6** (a) Static Synchronous Series Compensator (SSSC); (b) SSSC with storage; (c) Thyristor-Controlled Series Capacitor (TCSC) and Thyristor-Switched Series Capacitor (TSSC); (d) Thyristor-Controlled Series Reactor (TCSR) and Thyristor-Switched Series Reactor (TSSR).

## 1.5 OVERVIEW OF FACTS DEVICES

### 1.5.1 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.

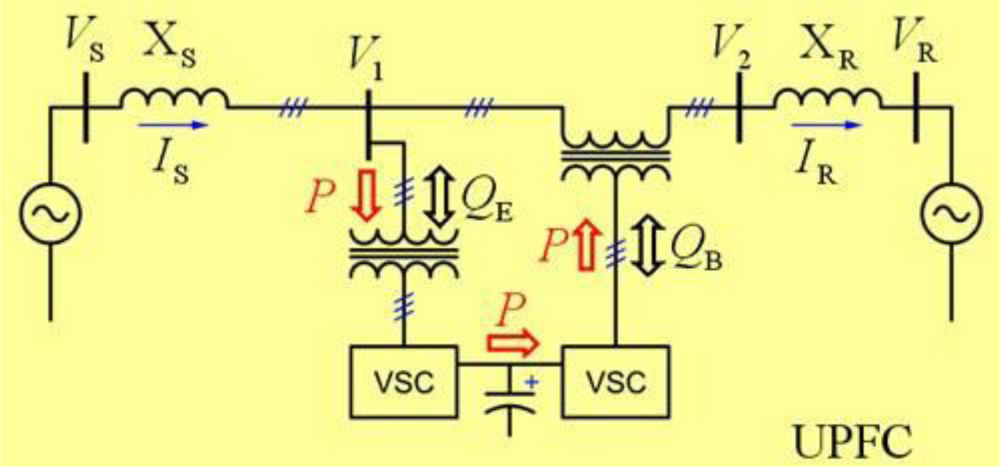
### 1.5.2 Thyristor Controlled Series Capacitor (TCSC)

- 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.

### 1.5.3 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.



### 1.5.4 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.

# UNIT II

# STATIC VAR COMPENSATOR (SVC) AND APPLICATION

## 2.1 VOLTAGE CONTROL BY SVC

- The voltage-control action can be explained through a simplified block representation of the SVC and power system shown below. The power system is modeled as an equivalent voltage source $V_s$ behind equivalent system impedance $X_s$ as viewed from the SVC terminals.
- The system impedance $X_s$ indeed corresponds to the short circuit MVA at the SVC bus and is obtained as

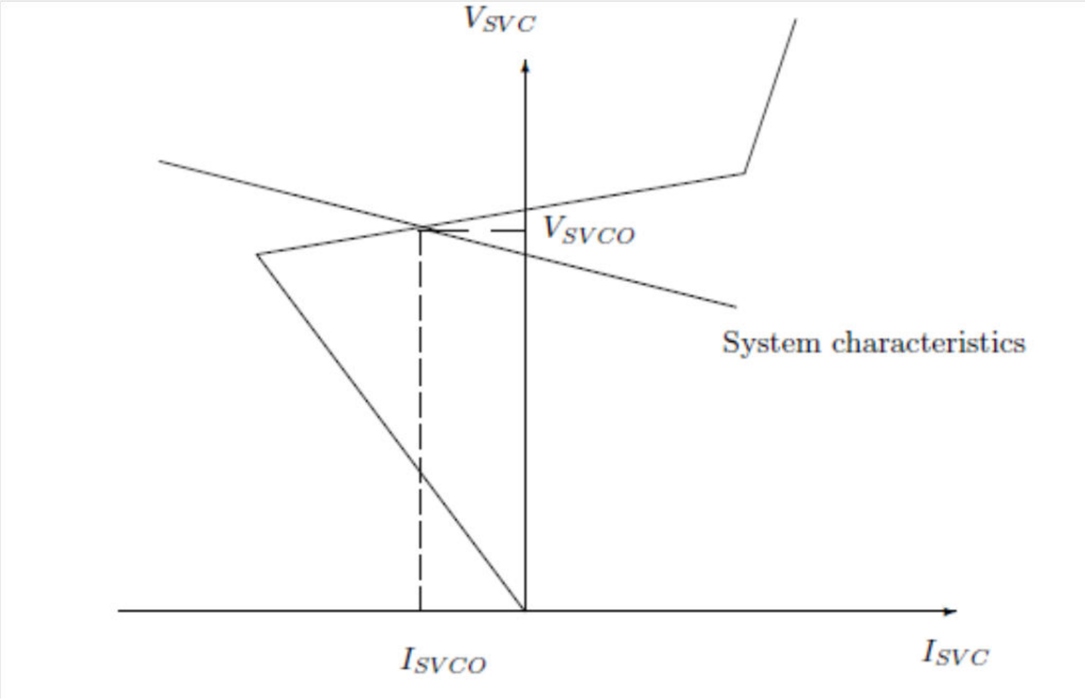
$$X_s = (V_b / S_c). MVA_b \text{ in p.u.}$$

Where, $S_c$ = the 3 phase short circuit MVA at the SVC bus
$V_b$ = the base line-line voltage
$MVA_b$ = base MVA

The SVC bus voltage is given by

$$V_s = V_{SVC} + I_{SVC} X_s$$

- The SVC current thus results in a voltage drop of $I_{SVC} X_s$ in phase with the system voltage $V_s$.
- The SVC bus voltage decreases with the inductive SVC current and increases with the capacitive current.
- The intersection of the SVC dynamic characteristic and the system load line provides the quiescent operating of the SVC as illustrated in the below figure.



Characteristics of the simplified power system and the SVC

- The voltage control action in the linear range is described as

$$V_{SVC} = V_{ref} + X_s I_{SVC}$$

Where $I_{SVC}$ is positive if inductive and $I_{SVC}$ is negative if capacitive.

- It is emphasized that the V-I characteristics described here relate SVC current or reactive power to the voltage on the high-voltage side of the coupling transformer.

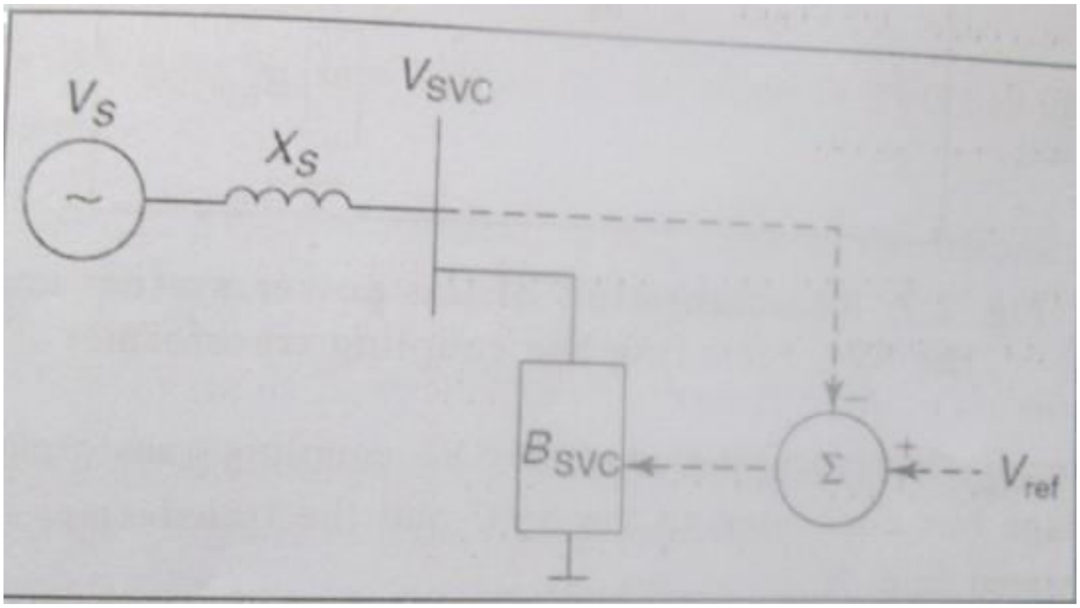
## 2.2 ADVANTAGES OF THE SLOPE IN THE SVC DYNAMIC CHARACTERISTICS

1. Substantially reduces the reactive-power rating of the SVC for achieving nearly the same control objectives.
2. Prevents the SVC from reaching its reactive-power limits too frequently.
3. Facilitates the sharing of reactive power among multiple compensators operating in parallel.

## 2.3 INFLUENCE OF SVC ON THE SYSTEM VOLTAGE

### 2.3.1 Coupling Transformer Ignored

The SVC behaves like a controlled susceptance and its effectives in regulating the system voltage are dependent on the relative strength of the connected ac system. The system strength or equivalent system impedance, primarily determines the magnitude of voltage variation caused by the change in the SVC reactive current.



A simplified block diagram of the power system and SVC control system

- The variation in the $V_{SVC}$ as a function of change in the SVC current $I_{SVC}$. Thus for constant equivalent source voltage $V_s$,
  - $\Delta V_{SVC} = -X\, \Delta I_{SVC}$

  And also $\Delta V_{SVC} = I_{SVC}\, B_{SVC}$
- For incremental changes the equation is linearized to give

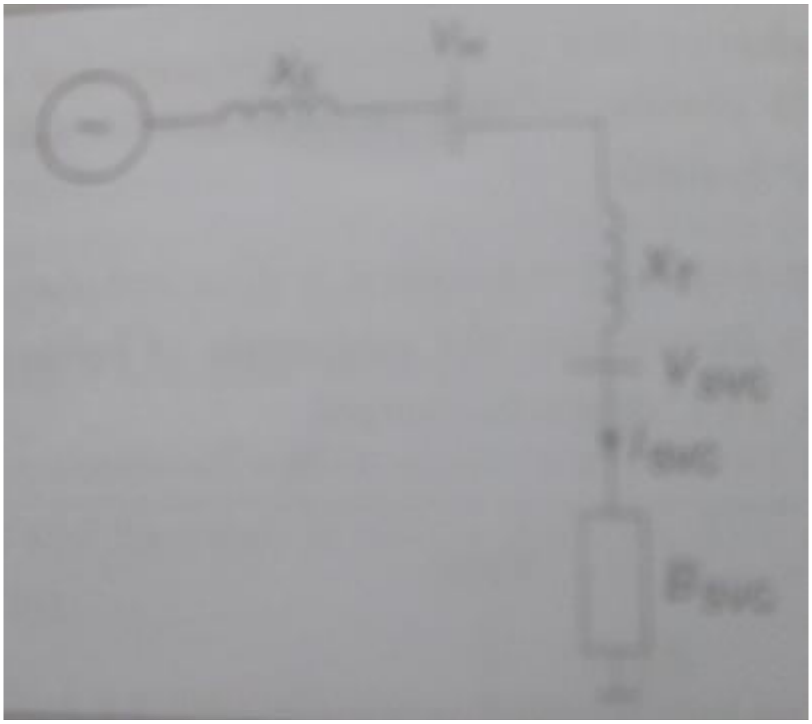
$$\Delta I_{SVC} = B_{SVCo}\, \Delta V_{SVC} + \Delta B_{SVC}\, V_{SVC0}$$

On substitution

$$\Delta V_{SVC} / \Delta B_{SVC} = -\, V_{SVC0} / (ESCR + B_{SVCo})$$

Where ESCR = Effective short circuit Ratio

### 2.3.2 Coupling Transformer Considered



Representation of power system and the SVC including the coupling transformer

- The representation of the SVC coupling transformer creates a low voltage bus connected to the SVC and the transformer reactance $X_T$ is separated from $X_s$.
- The high voltage $V_H$ is related to low voltage side $V_{SVC}$ as

$$V_{SVC} / V_H = 1 / 1 + X_T\, B_{SVC}$$

- Linearizing the above equation gives

$$\Delta V_{SVC}\, (1 + X_T\, B_{SVC0}) + V_{SVC0}\, X_T\, \Delta B_{SVC} = \Delta V_H$$

On substitution

$$\Delta V_H / \Delta B_{SVC} = - V_{H0} / (ESCR + B_{SVC0}) . (1 - X_T ESCR / 1 + B_{SVC0})$$

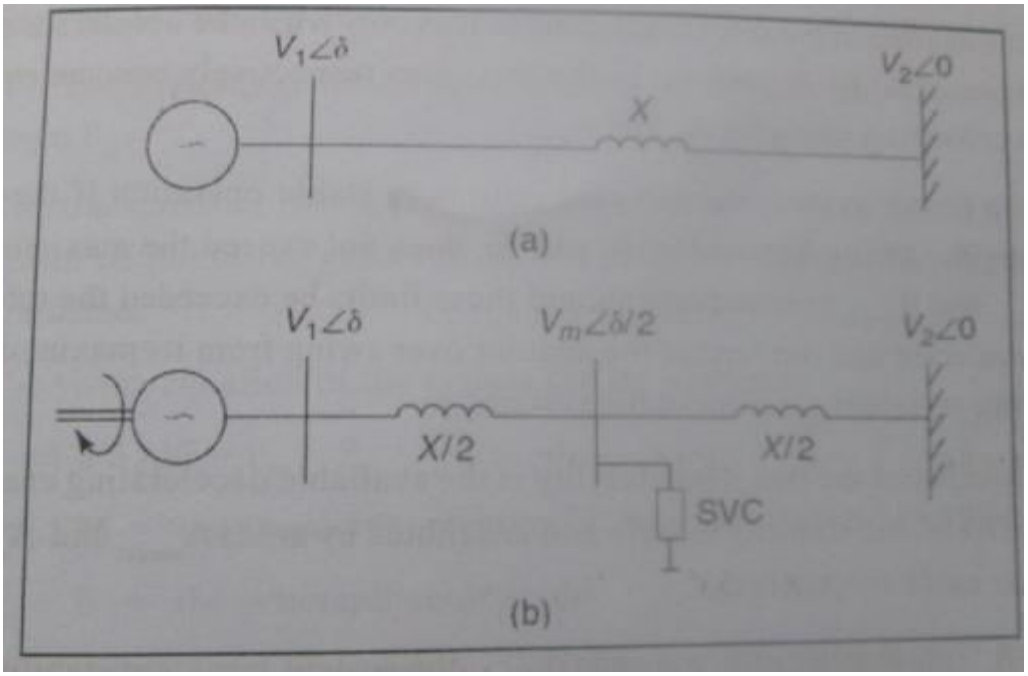
## 2.4 SVC APPLICATIONS

### 2.4.1 Introduction

Static var compensators (SVCs) constitute a mature technology that is finding widespread usage in modern power systems for load compensation as well as transmission-line applications. In high-power networks, SVCs are used for voltage control and for attaining several other objectives such as damping and stability control.

### 2.4.2 Enhancement of Transient Stability

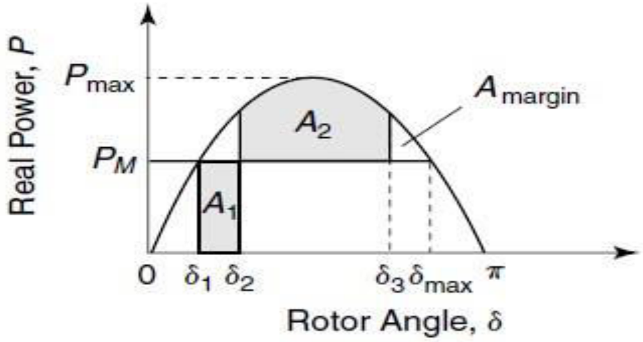
#### 2.4.2.1Power-angle curves



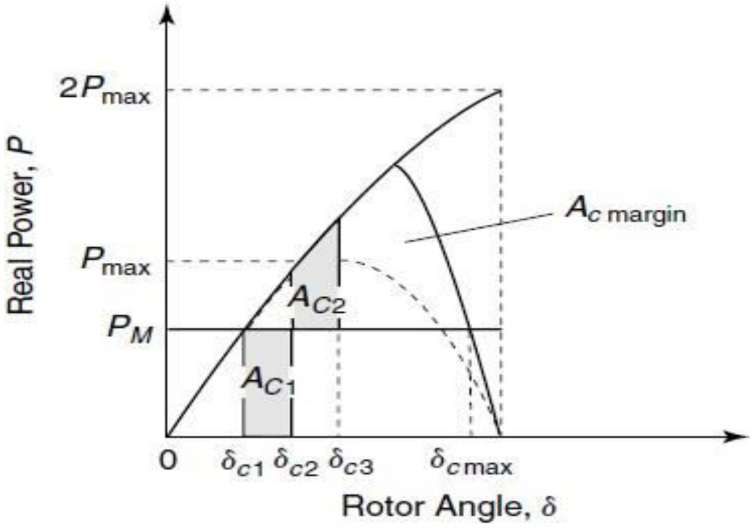
The SMIB system: (a) an uncompensated system (b) an SVC-compensated system

- 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 $d_{\text{max}}$ 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)

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

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

or

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

The characteristic equation of the differential equation provides two roots:

$$\lambda_1, \lambda_2 = \pm\sqrt{K_s/M}$$

If the synchronizing torque $K_s$ is positive, the resulting system is oscillatory with imaginary roots:

$$\lambda_1, \lambda_2 = \pm j\omega_s$$

where

$$\omega_s = \sqrt{K_S/M}$$

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.

### 2.4.3 Steady State Power Transfer Capacity

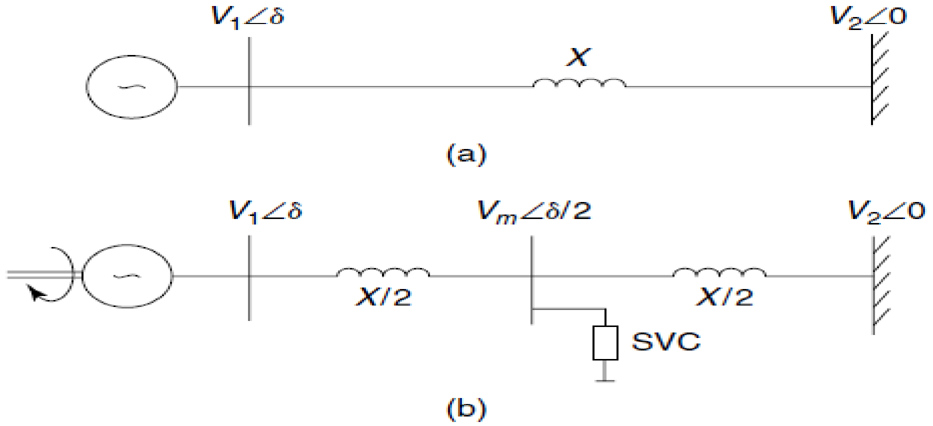
- An SVC can be used to enhance the power-transfer capacity of a transmission line, which is also characterized as the steady-state power limit.
- Consider a single-machine infinite-bus (SMIB) system with an interconnecting lossless tie line having reactance *X* shown in Fig.
- Let the voltages of the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

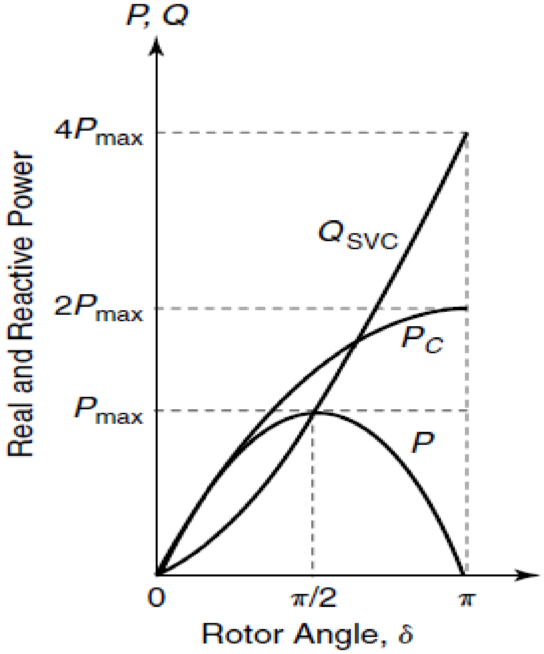
$$P = \frac{V^2}{X} \sin \delta$$

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 $V_m \angle -\delta/2$.The electrical power flow across the half-line section connecting the generator and the SVC is expressed as

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

- The maximum transmittable power across the line is then given by

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

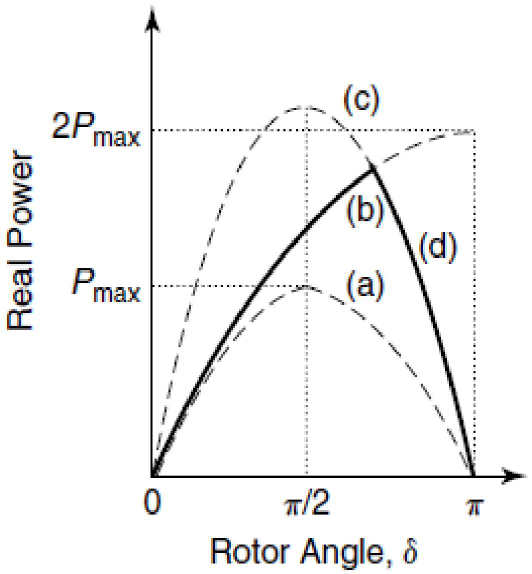
which is twice the maximum power transmitted in the uncompensated case and occurs at $\delta/2 = 90^0$.

- 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

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



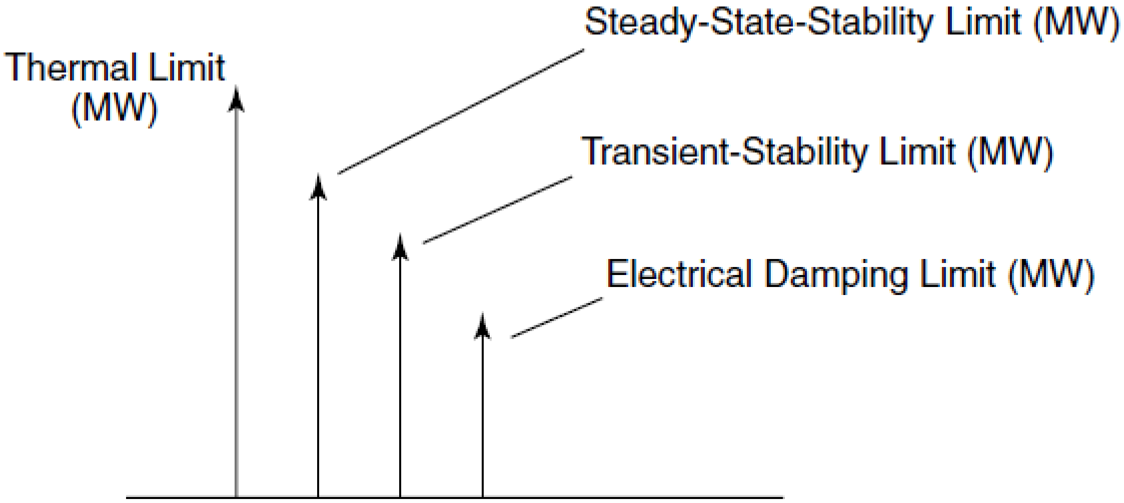
Power angle curve of a SMIB system☹a) uncompensated (b) ideal midpoint SVC unlimited rating curve (c) fixed capacitor connected at its midpoint (d) midpoint SVC limited rating curve

- 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.

### 2.4.4 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

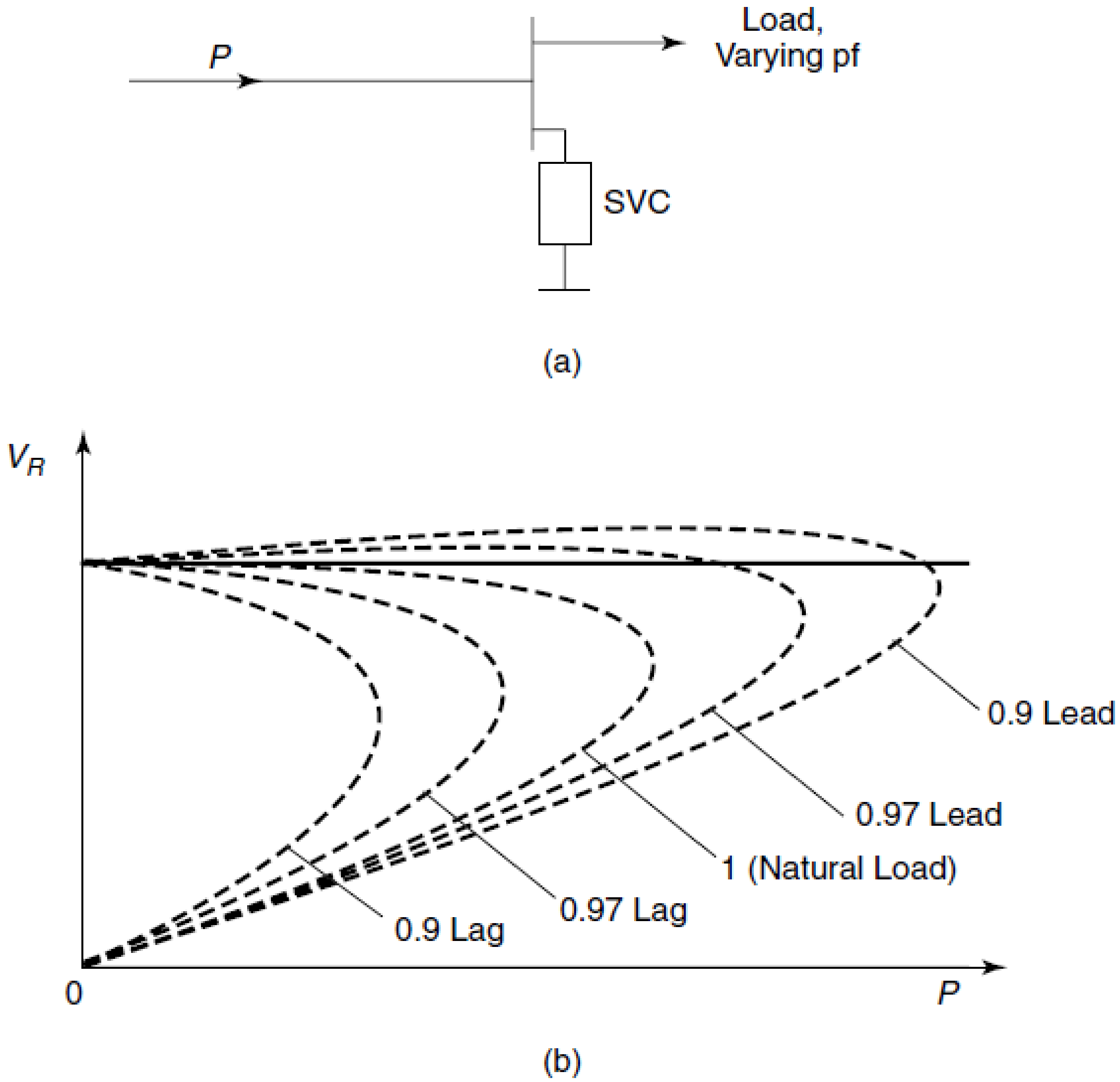
### 2.4.5 Prevention of Voltage Stability

- 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.

#### 2.4.5.1 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

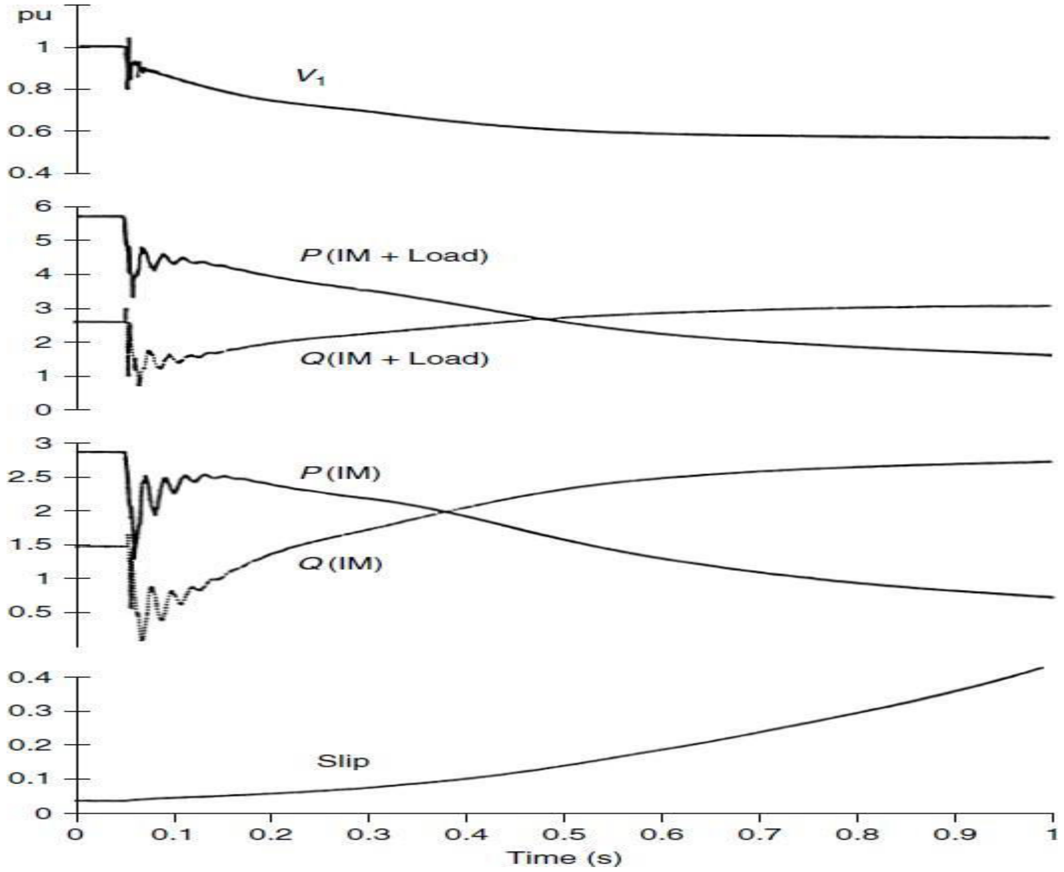
constant voltage of the receiving-end bus can be maintained with increasing magnitude of transmitted power, and voltage instability can be avoided.



(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.

### 2.4.5.2 Configuration and Design of the SVC Controller

- As the primary purpose of an SVC is voltage control, a PI-type voltage regulator is generally sufficient.
- The controller parameters are optimized using eigen value analysis to give fast, stable responses over the full range of expected network impedances and also without any adverse interactions with the power-system oscillation modes.
- In some situations, voltage dips may also be accompanied by system oscillations, as in the case of critical synchronous motor loads supplied by a distribution feeder.
- An auxiliary damping control may then need to be installed along with the voltage regulator.



System Transient Response

### 2.4.5.3 Rating of an SVC

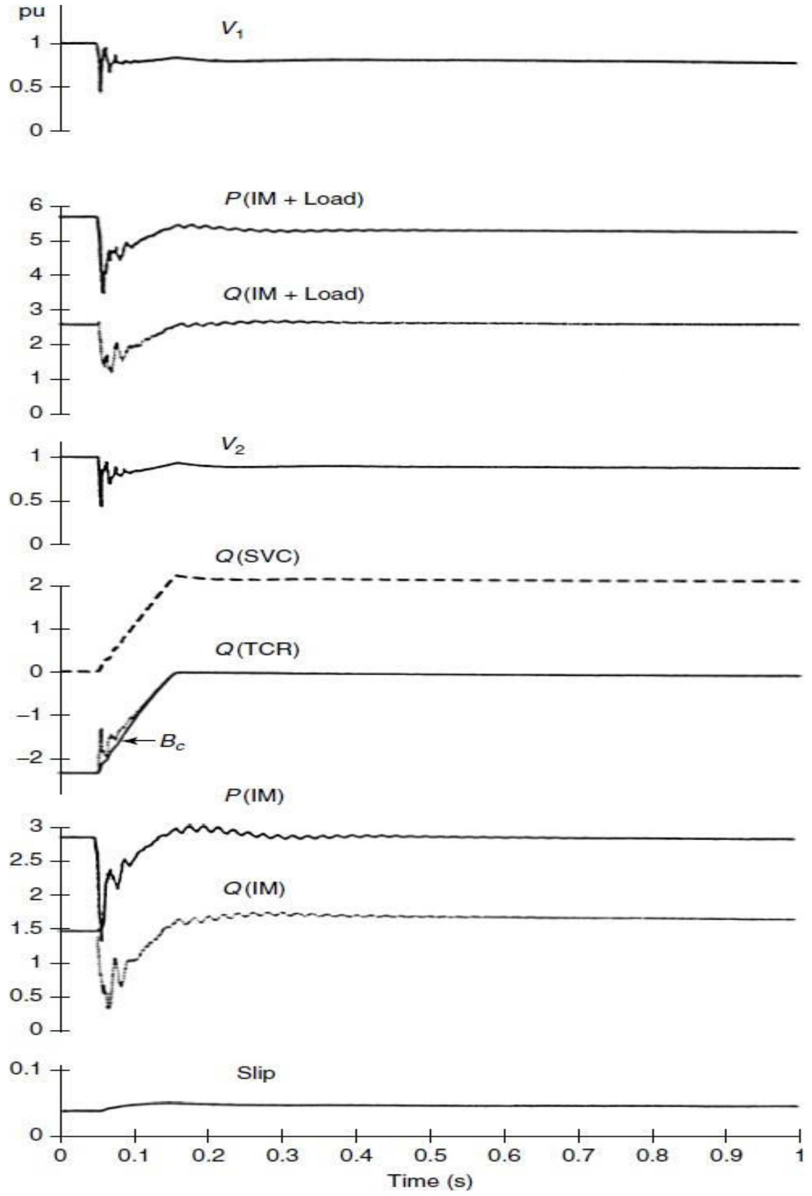
- Steady-state considerations determine the capacitive rating of an SVC. During a critical outage, the capacitive-reactive power needed to regulate the load voltage to a marginally stable level is selected as the capacitive range of SVC. Alternatively, once the critical bus that needs reactive-power support is identified, the SVC rating is chosen based on the capacitive-reactive power required to maintain the bus voltage at the minimum estimated SVC voltage-control range for the specified maximum loading condition or the voltage-collapse point .
- The collapse is indicated by the system Jacobian's increasing singularity at that loading point and is obtained through load-flow studies.
- The inductance rating is chosen to be that which can restrict the dynamic overvoltages at the SVC bus to 10%. This is determined from transient studies for critical-load rejections.
- It is shown that the system loading cannot be increased beyond a maixmum value, irrespective of the size of the SVC connected at the critical bus. One means of obtaining the optimal SVC rating is maximization of a performance index, $f\,p$, where

$$f_p = \frac{\lambda_0(\mathrm{MW})}{Q_{\mathrm{SVC}}(\mathrm{MVAR})}$$

where $\lambda_0$ = the maximum system loading

$Q_{\mathrm{SVC}}$ = the SVC MVAR rating

- The point of maximum $f\,p$ corresponds to the maximum load increase at the minimum MVAR compensation level. This reactive-power level is chosen to be the optimal SVC rating.



System Transient Response for open one circuit

# UNIT III

# THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC) AND APPLICATIONS

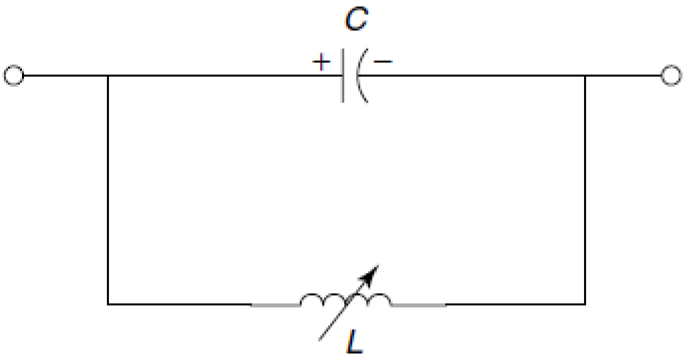
## 3.1 OPERATON OF TCSC

### 3.1.1 Basic Principle

- A TCSC is a series-controlled capacitive reactance that can provide continuous
- control of power on the ac line over a wide range.
- The principle of variable-series compensation is simply to increase the fundamental-frequency voltage across an fixed capacitor (FC) in a series compensated line through appropriate variation of the firing angle.
- This enhanced voltage changes the effective value of the series-capacitive reactance. A simple understanding of TCSC functioning can be obtained by analyzing the behavior of a variable inductor connected in parallel with an FC, as shown in Fig.
- The equivalent impedance, *Z*eq, of this *LC* combination is expressed as

$$Z_{eq} = \left(j\,\frac{1}{\omega c}\right) \Big\| \,(j\omega L) = -j\,\frac{1}{\omega C - \dfrac{1}{\omega L}}$$

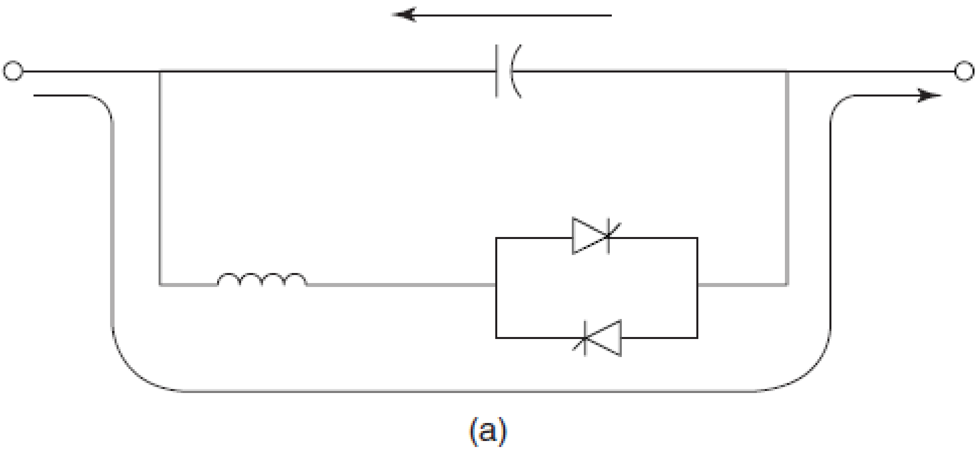
- The impedance of the FC alone, however, is given by $-j(1/\omega C)$.
- If $\omega C-(1/\omega L) > 0$ or, in other words, $\omega L > (1/\omega C)$, the reactance of the FC is less than that of the parallel-connected variable reactor and that this combination provides a variable-capacitive reactance are both implied. Moreover, this inductor increases the equivalent-capacitive reactance of the *LC* combination above that of the FC.
- If $\omega C - (1/\omega L)$ c 0, a resonance develops that results in an infinite-capacitive impedance is obviously unacceptable condition.
- If, however, $\omega C - (1/\omega L) < 0$, the *LC* combination provides inductance above the value of the fixed inductor. This situation corresponds to the inductive-vernier mode of the TCSC operation.
- In the variable-capacitance mode of the TCSC, as the inductive reactance of the variable inductor is increased, the equivalent-capacitive eactance is gradually decreased.
- The minimum equivalent-capacitive reactance is obtained for extremely large inductive reactance or when the variable inductor is open-circuited, in which the value is equal to the reactance of the FC itself.
- The behavior of the TCSC is similar to that of the parallel *LC* combination.
- The difference is that the *LC*-combination analysis is based on the presence of pure sinusoidal voltage and current in the circuit, whereas in the TCSC, because of the voltage and current in the FC and thyristor-controlled reactor (TCR) are not sinusoidal because of thyristor switchings.



A Variable inductor connected in shunt with an FC

### 3.1.2 DIFFERENT MODES OF OPERATION

#### 1. Bypassed Thyristor mode:

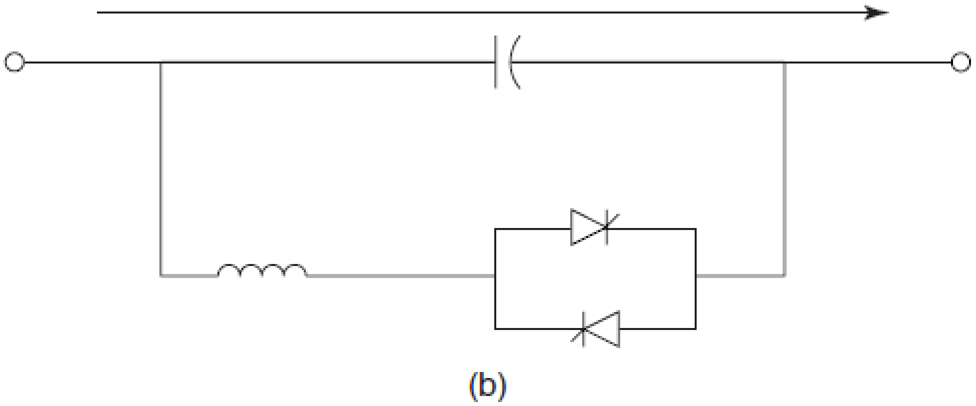


The bypassed thyristor mode

- In this bypassed mode, the thyristors are made to fully conduct with a conduction angle of $18^0$. Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous sinusoidal of flow current through the thyristor valves.
- The TCSC module behaves like a parallel capacitor–inductor combination. However, the net current through the module is inductive, for the susceptance of the reactor is chosen to be greater than that of the capacitor.
- Also known as the *thyristor-switched-reactor* (TSR) mode, the bypassed thyristor mode is distinct from the *bypassed-breaker* mode, in which the circuit breaker provided across the series capacitor is closed to remove the capacitor or the TCSC module in the event of TCSC faults or transient over voltages across the TCSC.

- This mode is employed for control purposes and also for initiating certain protective functions.
- Whenever a TCSC module is bypassed from the violation of the current limit, a finite-time delay, *T* delay, must elapse before the module can be reinserted after the line current falls below the specified limit.

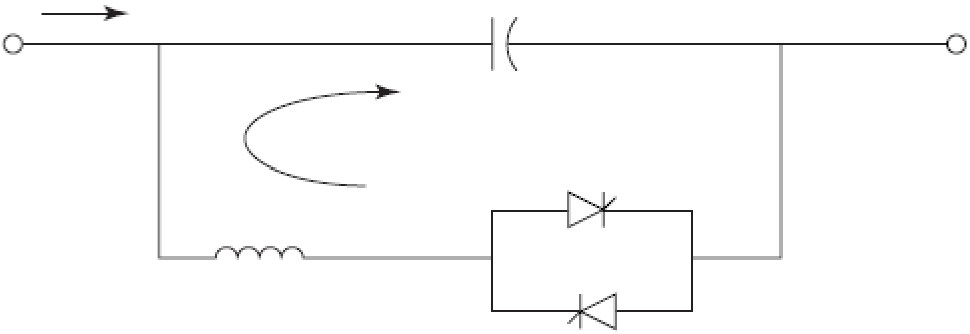
## 2.Blocked – Thyristor Mode:



The blocked thyristor mode

- In this mode, also known as the *waiting* mode, the firing pulses to the thyristor valves are blocked.
- 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 TCSC module is thus reduced to a fixed-series capacitor, and the net TCSC reactance is capacitive.
- In this mode, the dc-offset voltages of the capacitors are monitored and quickly discharged using a dc-offset control [9] without causing any harm to the transmission-system transformers.

## 3 Partially Conducting Thyristor Mode or Vernier Mode:



- This mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance.
- It is achieved by varying the thyristor-pair firing angle in an appropriate range. However, a smooth transition from the capacitive to inductive mode is not permitted because of the resonant region between the two modes.
- A variant of this mode is the *capacitive-vernier-control* mode, in which the thyristors are fired when the capacitor voltage and capacitor current have opposite polarity.
- This condition causes a TCR current that has a direction opposite that of the capacitor current, thereby resulting in a loop-current flow in the TCSC controller.
- The loop current increases the voltage across the FC, effectively enhancing the equivalent-capacitive reactance and the series-compensation level for the same value of line current.
- To preclude resonance, the firing angle α of the forward-facing thyristor, as measured from the positive reaching a zero crossing of the capacitor voltage, is constrained in the range $\alpha_{min} \leq \alpha \leq 180^0$.
- This constraint provides a continuous vernier control of the TCSC module reactance. The loop current increases as α is decreased from $180^0$ to $\alpha_{min}$.
- The maximum TCSC reactance permissible with a c α min is typically two-and-a-half to three times the capacitor reactance at fundamental frequency.
- Another variant is the *inductive-vernier mode*, in which the TCSC can be operated by having a high level of thyristor conduction.
- In this mode, the direction of the circulating current is reversed and the controller presents a net inductive impedance.
- Based on the three modes of thyristor-valve operation, two variants of the TCSC emerge:
  1. ***Thyristor-switched series capacitor*** (TSSC), which permits a discrete control of the capacitive reactance.
  2. ***Thyristor-controlled series capacitor*** (TCSC), which offers a continuous control of capacitive or inductive reactance.

## 3.2 MODELING OF TCSC

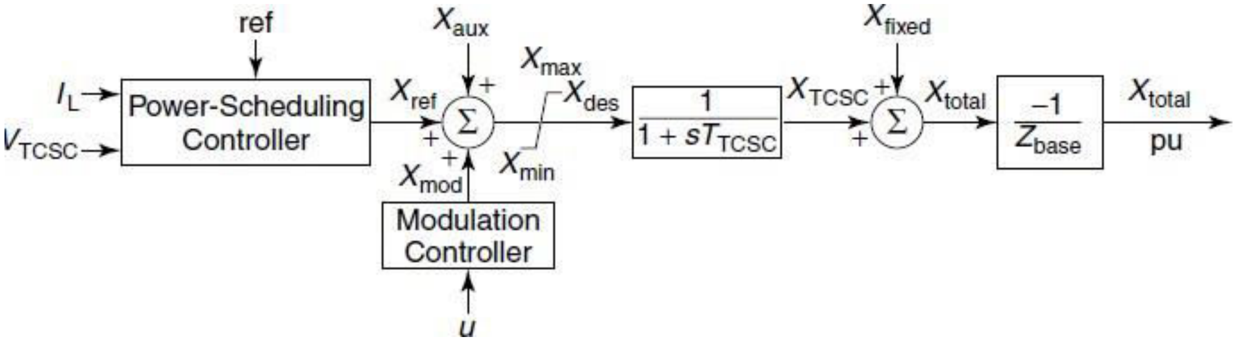
- A TCSC involves continuous-time dynamics, relating to voltages and currents in the capacitor and reactor, and nonlinear, discrete switching behavior of thyristors. Deriving an appropriate model for such a controller is an intricate task.

### 3.2.1 Variable-Reactance Model

#### 3.2.1.1 Introduction

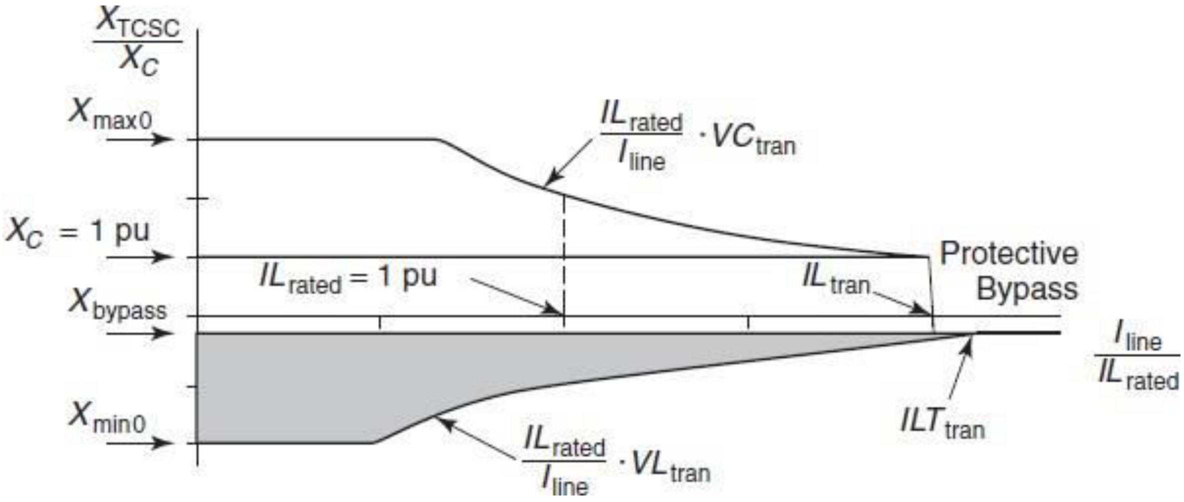
- A TCSC model for transient- and oscillatory-stability studies, used widely for its simplicity, is the variable-reactance model depicted in Fig.
- In this quasi-static approximation model, the TCSC dynamics during power-swing frequencies are modeled by a variable reactance at fundamental frequency.
- The other dynamics of the TCSC model—the variation of the TCSC response with different firing angles.
- It is assumed that the transmission system operates in a sinusoidal steady state, with the only dynamics associated with generators and PSS.

- This assumption is valid, because the line dynamics are much faster than the generator dynamics in the frequency range of 0.1–2 Hz that are associated with angular stability studies.
- As described previously, the reactance-capability curve of a single-module TCSC, as depicted in Fig. exhibits a discontinuity between the inductive and capacitive regions.
- However, this gap is lessened by using a multimode TCSC. The variable-reactance TCSC model assumes the availability of a continuous-reactance range and is therefore applicable for multi module TCSC configurations.
- This model is generally used for inter-area mode analysis, and it provides high accuracy when the reactance-boost factor (=*X*TCSC/ *XC*) is less than 1.5.



Block diagram of the variable reactance model of the TCSC

### 3.2.1.2 Transient – Stability Model



The X – I capability characteristic for a multi module TCSC

- In the variable-reactance model for stability studies, a reference value of TCSC reactance, $X_{ref}$, is generated from a power-scheduling controller based on the power-flow specification in the transmission line.
- The reference $X_{ref}$ value may also be set directly by manual control in response to an order from an energy-control center, and it essentially represents the initial operating point of the TCSC; it does not include the reactance of FCs (if any).
- The reference value is modified by an additional input, $X_{mod}$, from a modulation controller for such purposes as damping enhancement.
- Another input signal, this applied at the summing junction, is the open-loop auxiliary signal, $X_{aux}$, which can be obtained from an external power-flow controller.
- A desired magnitude of TCSC reactance, $X_{des}$, is obtained that is implemented after a finite delay caused by the firing controls and the natural response of the TCSC. This delay is modeled by a lag circuit having a time constant,$T_{TCSC}$, of typically 15–20 ms.
- The output of the lag block is subject to variable limits based on the TCSC reactance-capability curve shown in Fig.
- The resulting *X*TCSC is added to the $X_{fixed}$, which is the reactance of the TCSC installation's FC component.
- To obtain per-unit values, the TCSC reactance is divided by the TCSC base reactance, $Z_{base}$, given as

$$Z_{base} = \frac{(kV_{TCSC})^2}{MVA_{sys}}$$

where ,

$kV_{TCSC}$ = the rms line–line voltage of the TCSC in kilovolts (kV)

$\text{MVA}_{\text{sys}}$ = the 3-phase MVA base of the power system

- The TCSC model assigns a positive value to the capacitive reactance, so $X_{\text{total}}$ is multiplied by a negative sign to ensure consistency with the convention used in load-flow and stability studies.
- The TCSC initial operating point, $X_{\text{ref}}$, for the stability studies is chosen as

$$X_{\text{ref}} = X_{\text{total}} - X_{\text{fixed}}$$

- The reactance capability curve of the multimodal TCSC shown in Fig. can be simply approximated by the capability curve shown in Fig.
- This figure can be conveniently used for the variable-reactance model of TCSC, and the capability curve that the figure depicts includes the effect of TCSC transient overload levels.
- It should be noted that the reactance limit for high currents is depicted in Fig. as a group of discrete points for the different modules.
- During periods of over current, only some TCSC modules move into the bypassed mode, for the bypassing of a module causes the line current to decrease and thus reduces the need for the remaining TCSC modules to go into the bypass mode.
- However, for the case of modeling, only one continuous-reactance limit—denoted by a vertical line in Fig is considered for all TCSC modules.
- All reactance are expressed in per units on $XC$; all voltages, in per units on $IL_{\text{rated}}$. $X_C$ and all currents, in amps. In the capacitive region, the different TCSC reactance constraints are caused by the following:
    1. The limit on the TCSC firing angle, represented by constant reactance limit $X_{\text{max}}\,0$.
    2. The limit on the TCSC voltage $VC_{\text{tran}}$. The corresponding reactance constraint is give by

$$X_{\max VC} = (VC_{\text{tran}}) \frac{IL_{\text{rated}}}{I_{\text{line}}}$$

    3. The limit on the line current ($IL$tran) beyond which the TCSC transpires into the protective-bypass mode:

$$\begin{aligned} X_{\max I_{\text{line}}} &= \infty \qquad \text{for } I_{\text{line}} < IL_{\text{tran}} \cdot IL_{\text{rated}} \\ &= X_{\text{bypass}} \qquad \text{for } I_{\text{line}} > IL_{\text{tran}} \cdot IL_{\text{rated}} \end{aligned}$$

- The effective capacitive-reactance limit is finally obtained as a minimum of the following limits:

$$X_{\max\text{ limit}} = \min(X_{\max 0}, X_{\max VC}, X_{\max I_{\text{line}}})$$

- In the inductive region, the TCSC operation is restricted by the following limits:
    - The limit on the firing angle, represented by a constant-reactance limit $X$min 0.
    - The harmonics-imposed limit, represented by a constant-TCSC-voltage limit $VL_{\text{tran}}$. The equivalent-reactance constraint is given by

$$X_{\min VL} = (VL_{\text{tran}}) \frac{IL_{\text{rated}}}{I_{\text{line}}}$$

#### 3.2.1.3 Long - Term – Stability Model

- The capability curves of the TCSC depend on the duration for which the voltage- and current-operating conditions persist on the TCSC.
- In general, two time-limited regions of TCSC operation exist: the *transient-overload region*, lasting 3–10 s, and the *temporary-overload region*, lasting 30 min; both are followed by the *continuous region*. For long-term dynamic simulations, an overload-management function needs to be incorporated in the control system.
- This function keeps track of the TCSC variables and their duration of application, and it also determines the appropriate TCSC overload range, for which it modifies the $X_{\max}$ limit and $X_{\min}$ limit. It then applies the same modifications to the controller.
- The variable-reactance model does not account for the inherent dependence of TCSC response time on the operating conduction angle.
- Therefore, entirely incorrect results may be obtained for the high-conduction-angle operation of the TCSC or for whenever the power-swing frequency is high (>2 Hz) .
- However, the model is used widely in commercial stability programs because of its simplicity, and it is also used for system-planning studies as well as for initial investigations of the effects of the TCSC in damping-power oscillations.
- A reason for the model's widespread use lies in the assumption that controls designed to compensate the TCSC response delay are always embedded in the control system by the manufacturer and are therefore ideal.
- Hence the response predicted by the model is a true replica of actual performance.
- In situations where this assumption is not satisfied, a more detailed stability model is required that accurately represents the inherent slow response of the TCSC.

## 3.3 APPLICATIONS

### 3.3.1 Introduction

- Thyristor-controlled series capacitors (TCSCs) can be used for several power system performance enhancements, namely, the improvement in system stability, the damping of power oscillations, the alleviation of sub synchronous resonance (SSR), and the prevention of voltage collapse.
- The effectiveness of TCSC controllers is dependent largely on their proper placement within the carefully selected control signals for achieving different functions.
- Although TCSCs operate in highly nonlinear power-system environments, linear-control techniques are used extensively for the design of TCSC controllers.

### 3.3.2 Improvement of the System – Stability Limit

- During the outage of a critical line in a meshed system, a large volume of power tends to flow in parallel transmission paths, which may become severely overloaded.
- Providing fixed-series compensation on the parallel path to augment the power-transfer capability appears to be a feasible solution, but it may increase the total system losses.
- Therefore, it is advantageous to install a TCSC in key transmission paths, which can

adapt its series-compensation level to the instantaneous system requirements and provide a lower loss alternative to fixed-series compensation.

- The series compensation provided by the TCSC can be adjusted rapidly to ensure specified magnitudes of power flow along designated transmission lines.
- This condition is evident from the TCSC's efficiency, that is, ability to change its power flow as a function of its capacitive-reactance setting:

$$P_{12} = \frac{V_1 V_2}{(X_L - X_C)} \sin \delta$$

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

$V_1, V_2$ = the voltage magnitudes of buses 1 and 2, respectively

$X_L$ = the line-inductive reactance

$X_C$ = the controlled TCSC reactance combined with fixed-series-capacitor reactance

$\delta$ = the difference in the voltage angles of buses 1 and 2

- This change in transmitted power is further accomplished with minimal influence on the voltage of interconnecting buses, as it introduces voltage in quadrature.
- In contrast, the SVC improves power transfer by substantially modifying the interconnecting bus voltage, which may change the power into any connected passive loads.
- The freedom to locate a TCSC almost anywhere in a line is a significant advantage. Power-flow control does not necessitate the high-speed operation of power flow control devices and hence discrete control through a TSSC may also be adequate in certain situations.
- However, the TCSC cannot reverse the power flow in a line, unlike HVDC controllers and phase shifters.

### 3.3.3 Enhancement of System Damping

#### 3.3.3.1 Introduction

- The TCSC can be made to vary the series-compensation level dynamically in response to controller-input signals so that the resulting changes in the power flow enhance the system damping .The power modulation results in a corresponding variation in the torques of the connected synchronous generators particularly if the generators operate on constant torque and if passive bus loads are not installed.
- The damping control of a TCSC or any other FACTS controller should generally do the following:
    1. Stabilize both post disturbance oscillations and spontaneously growing oscillations during normal operation;
    2. Obviate the adverse interaction with high-frequency phenomena in power systems, such as network resonances; and
    3. Preclude local instabilities within the controller bandwidth.
- In addition, the damping control should

1. be robust in that it imparts the desired damping over a wide range of system operating conditions, and
2. be reliable.

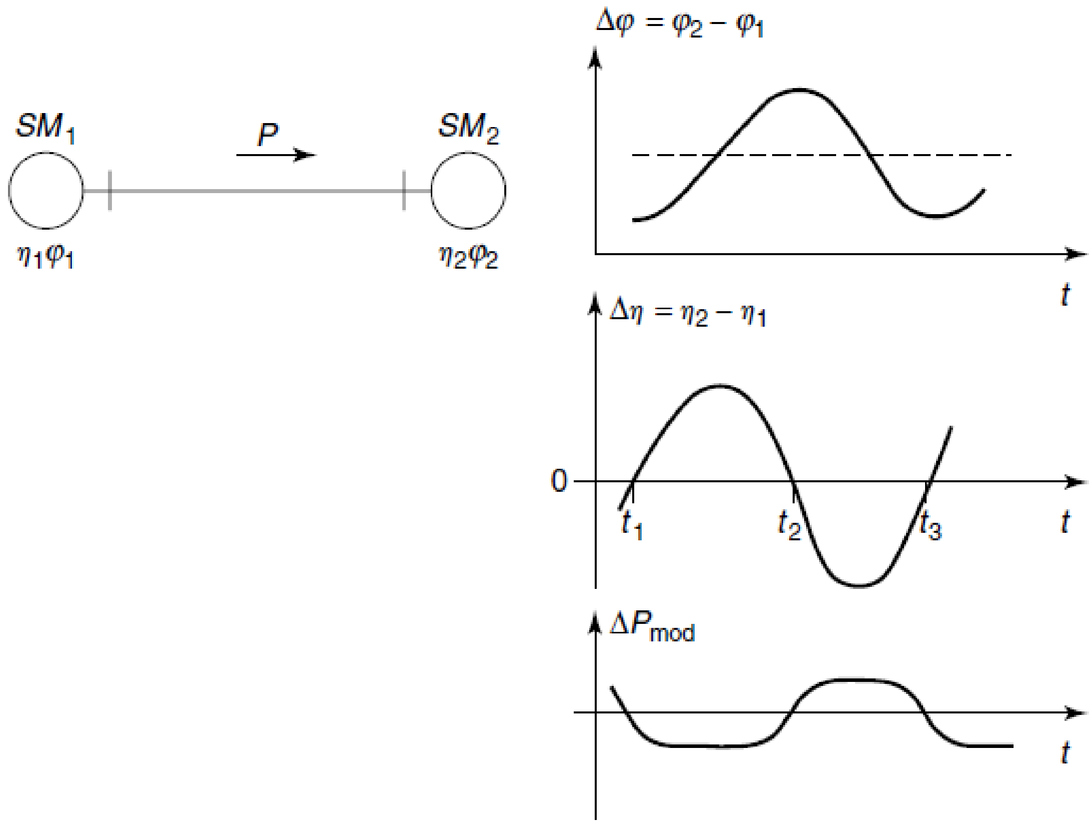
### 3.3.3.2 Principle of Damping

- The concept of damping enhancement by line-power modulation can be illustrated with the two-machine system depicted in Fig.
- The machine $SM_1$ supplies power to the other machine, $SM_2$, over a lossless transmission line. Let the speed and rotor angle of machine $SM_1$ be denoted by $\eta_1$ and $\varphi_1$, respectively; of machine $SM_2$, denoted by $\eta_2$ and $\varphi_2$, respectively.
- During a power swing, the machines oscillate at a relative angle

  $$\Delta\,\varphi = (\varphi_2 - \varphi_1).$$
- If the line power is modulated by the TCSC to create an additional machine torque that is opposite in sign to the derivative of the rotor-angle deviation, the oscillations will get damped. This control strategy translates into the following actions: When the receiving end–machine speed is lower than the sending end–machine speed, that is, $\Delta h = (\eta_2 - \eta_1)$ is negative, the TCSC should increase power flow in the line.
- In other words, while the sending-end machine accelerates, the TCSC control should attempt to draw more power from the machine, thereby reducing the kinetic energy responsible for its acceleration.
- On the other hand, when $\Delta\eta$ is positive, the TCSC must decrease the power transmission in the line.
- This damping control strategy is depicted in Fig. through plots of the relative machine angle $\Delta\varphi$, the relative machine speed $\Delta\eta$, and the incremental power variation $\Delta P_{\text{mod}}$.
- The incremental variation of the line-power flow D$P$, given in megawatts (MW), with respect to D$Q$TCSC, given in MVAR, is as follows

$$\frac{\Delta P}{\Delta Q_{\text{TCSC}}} = \frac{1}{2\tan\delta/2}\left(\frac{I}{I_N}\right)^2$$

where $\delta$ = the angular difference between the line-terminal voltages
$I$ = the operating-point steady-state current
$I_N$ = the rated current of the TCSC



The TCSC line power modulation for damping enhancement

- Thus the TCSC action is based on the variation of line-current magnitude and is irrespective of its location.
- Typically, the change in line-power transfer caused by the introduction of the full TCSC is in the range of 1–2, corresponding to an angular difference (d) of 308–408 across the line.
- The influence of any bus load on the torque/ power control of the synchronous generator is derived for the case of a resistive load and completely inductive generator impedance.
- The ratio of change in generator power to the ratio of change in the power injected from the line into the generator bus is expressed as

$$\frac{\Delta P_m}{\Delta P} = \frac{\cos(\delta/2 \pm \alpha)}{\cos(\delta/2)}$$

where the + sign corresponds to the sending end; the – sign, the receiving end.
Also,

where $\Delta P_m$ = the variation in generator power
$\Delta P$ = the variation in power injected from the transmission line into the machine bus
$\alpha = \tan^{-1}(X_{source}/R_{load})$ (it is assumed that $R_{load} \gg X_{source}$)

- The effect of all practical passive loads is generally moderate, and the sign of generator power is not changed. In the absence of any bus load,

$$\Delta P_m = \Delta P.$$

- The controlled-to-fixed ratio of capacitive reactance in most applications is in the 0.05–0.2 range, the exact value determined by the requirements of the specific application.

### 3.3.3.3 Bang – Bang Control

- Bang-bang control is a discrete control form in which the thyristors are either fully switched on ($\alpha = 90^0$) or fully switched off ($\alpha = 180^0$).
- Thus the TCSC alternates between a fixed inductor and a fixed capacitor, respectively, and it is advantageous that such control is used not only for minimizing first swings but for damping any subsequent swings as well.
- Bang-bang control is employed in face of large disturbances to improve the transient stability.

### 3.3.3.4 Auxiliary Signals for TCSC Modulation

- The supplementary signals that could be employed for modulating TCSC impedance are listed in the text that follows:

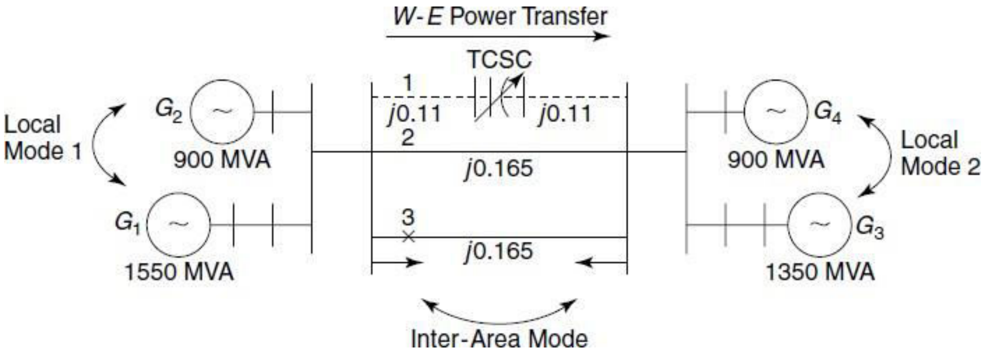
#### 3.3.3.4.1 Local Signals

- These signals constitute the following:
  1. The line current,
  2. The real-power flow,
  3. The bus voltage, and
  4. The local bus frequency.

#### 3.3.3.4.2 Remote Signals

- These signals constitute the following:
  1. The rotor-angle/ speed deviation of a remote generator,
  2. The rotor-angle/ speed (frequency) difference across the system, and
  3. The real-power flow on adjacent lines.
- The angular difference between remote voltages can be synthesized by using local voltages at the two terminals of the TCSC and through the line current. Alternatively, a recent approach may be adopted wherein the phase angles of remote areas can be measured directly by using synchronized phasor measurement units.
- Adjacent-line real-power flow can be measured remotely and transmitted to the TCSC control system through telecommunication.

- Despite telecommunication delays, this signal can be used satisfactorily and economically for line power scheduling, which itself is a slow control.



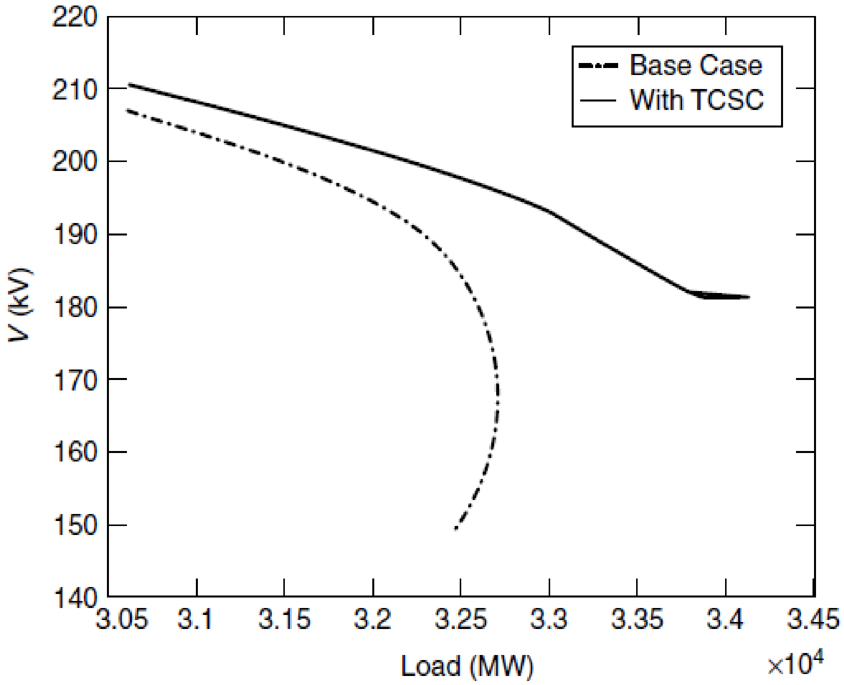
A two –area, four – machine system

## Selection of Input Signals

- It is a desirable feature that the TCSC controller input signals can extend as far as possible without sensitivity to the TCSC output. This feature ensures that the control signals represent mainly the system conditions for which the TCSC is expected to improve.
- Local bus frequency is seen to be less responsive to system power swings as compared to the synthesized-voltage frequency,although both line current and bus voltage are also shown to be fairly effective.

## 3.3.4 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 load ability of the transmission lines or the available transfer capability (ATC).
- The TCSCs can significantly enhance the load ability of transmission networks, thus obviating voltage collapse at existing power-transfer levels.
- 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.



TCSC Compensation

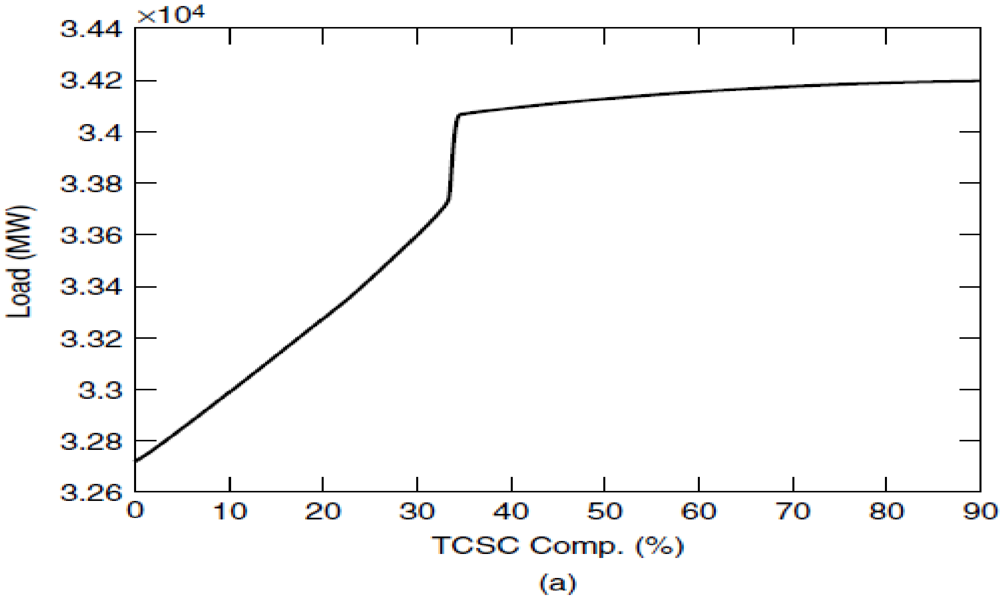
- The system faces voltage collapse or a maximum loading point corresponding to a 2120-MW increase in the net load.
- If a TCSC is installed to provide 50% compensation of the line experiencing the highest increase in power at the point of collapse, the maximum load ability will be enhanced to 3534 MW.
- The influence of the TCSC on the voltage profile of a critical bus is illustrated in Fig.
- A performance factor, $f_p$, is proposed in that indicates the maximum increase in load ability, $\lambda_0$, for a given percent of line compensation:

$$f_p = \frac{\lambda_0 \text{ [MW]}}{X_{\text{ref}} \text{ [ \% compensation of } X_{\text{line}}]}$$

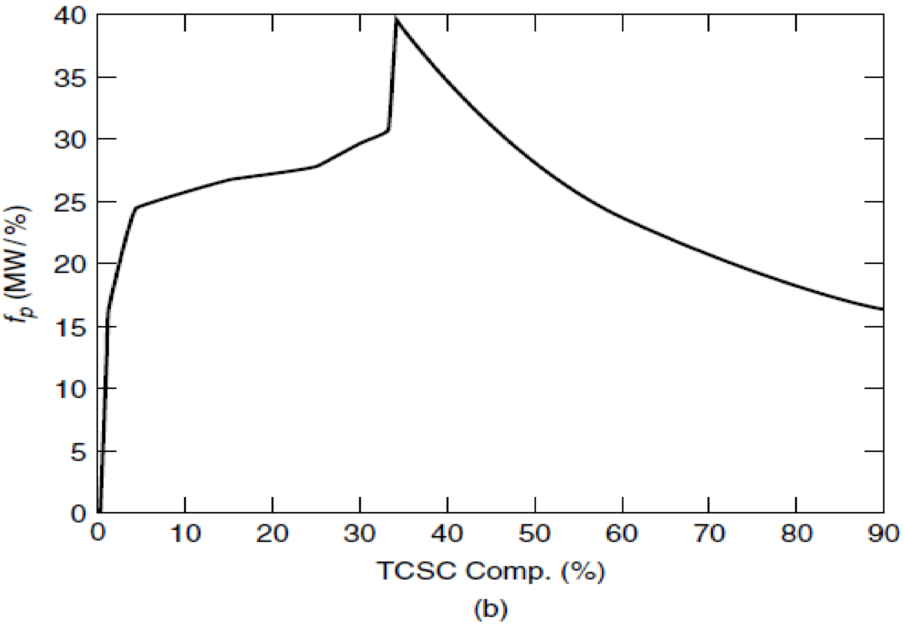
where $X_{\text{ref}}$ = the reactance-reference setting of the TCSC
$X_{\text{line}}$ = the line reactance

- This index can be gainfully employed to obtain the best location of the TCSC in a system.
- The enhancement of system loading and variation of the performance factor with TCSC compensation are depicted in Fig.

- It is suggested that TCSC reactance-modulation schemes based on line current or line power, or on the angular difference across lines, may prove unsuccessful for voltage-stability enhancement. The reason is that these controls constrain any variation in the corresponding variables that may be necessary with changing loads, thereby limiting any power-flow enhancement on the line.



The loading Margin



The performance Measure $f_p$

# UNIT IV

# EMERGING FACTS CONTROLLERS

## 4.1 STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

- The STATCOM (or SSC) is a shunt-connected reactive-power compensation device that is capable of generating and/ or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system.
- It is in general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals.
- Specifically, the STATCOM considered is a voltage-source converter that, from a given input of dc voltage, produces a set of 3-phase ac-output voltages, each in phase with and coupled to the corresponding ac system voltage through a relatively small reactance (which is provided by either an interface reactor or the leakage inductance of a coupling transformer).
- The dc voltage is provided by an energy-storage capacitor and a STATCOM can improve power-system performance in such areas as the following:
    1. The dynamic voltage control in transmission and distribution systems;
    2. The power-oscillation damping in power-transmission systems;
    3. The transient stability;
    4. The voltage flicker control; and
    5. The control of not only reactive power but also (if needed) active power in the connected line, requiring a dc energy source.

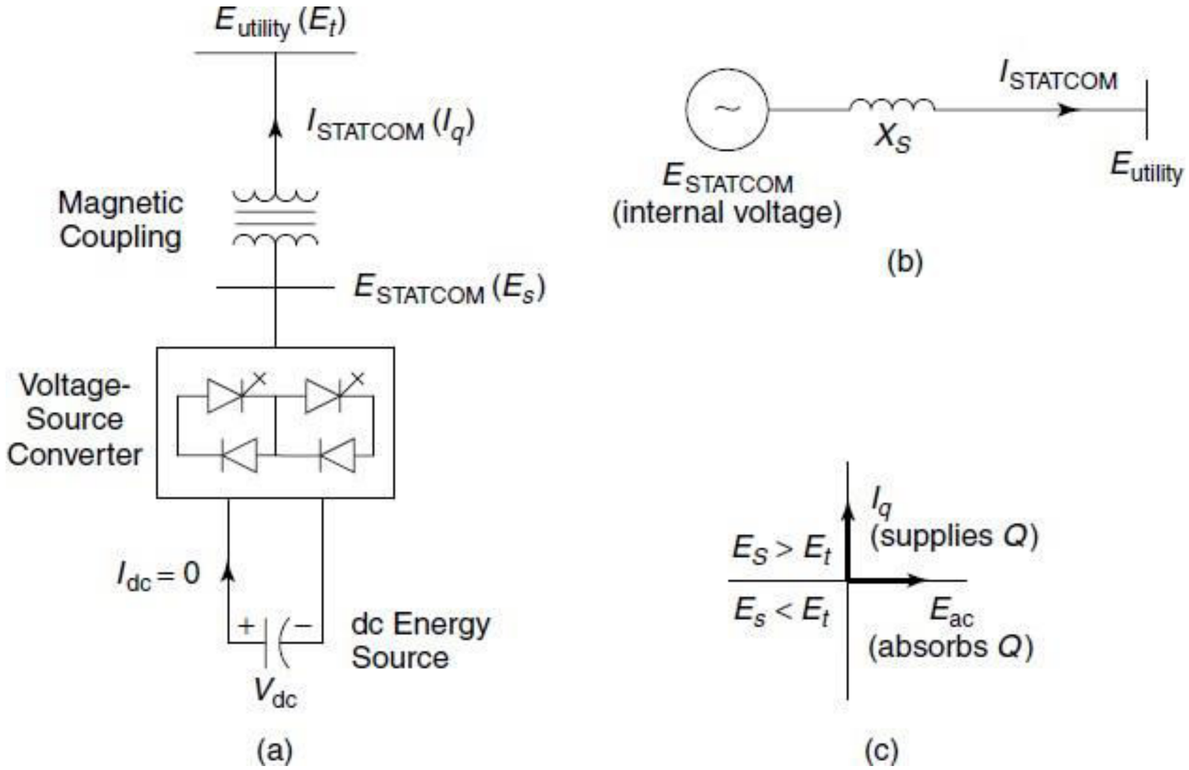
### Advantages of STATCOM

1. It occupies a small footprint, for it replaces passive banks of circuit elements by compact electronic converters;
2. It offers modular, factory-built equipment, thereby reducing site work and commissioning time; and
3. It uses encapsulated electronic converters, thereby minimizing its environmental impact.

## 4.2 PRINCIPLE OF OPERATION

- A STATCOM is a controlled reactive-power source. It provides the desired reactive-power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC).
- A single-line STATCOM power circuit is shown in Fig.(a),where a VSC is connected to a utility bus through magnetic coupling.
- In Fig. (b), a STATCOM is seen as an adjustable voltage source behind a reactance meaning that capacitor banks and shunt reactors are not needed for reactive-power generation and absorption, thereby giving a STATCOM a compact design, or small footprint, as well as low noise and low magnetic impact.

- The exchange of reactive power between the converter and the ac system can be controlled by varying the amplitude of the 3-phase output voltage, *Es*, of the converter, as illustrated in Fig. (c).
- If the amplitude of the output voltage is increased above that of the utility bus voltage, *Et*, then a current flows through the reactance from the converter to the ac system and the converter generates capacitive-reactive power for the ac system.
- If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the ac system to the converter and the converter absorbs inductive-reactive power from the ac system.



The STATCOM principle diagram: (a) a power circuit;(b) an equivalent circuit;(c) a power exchange

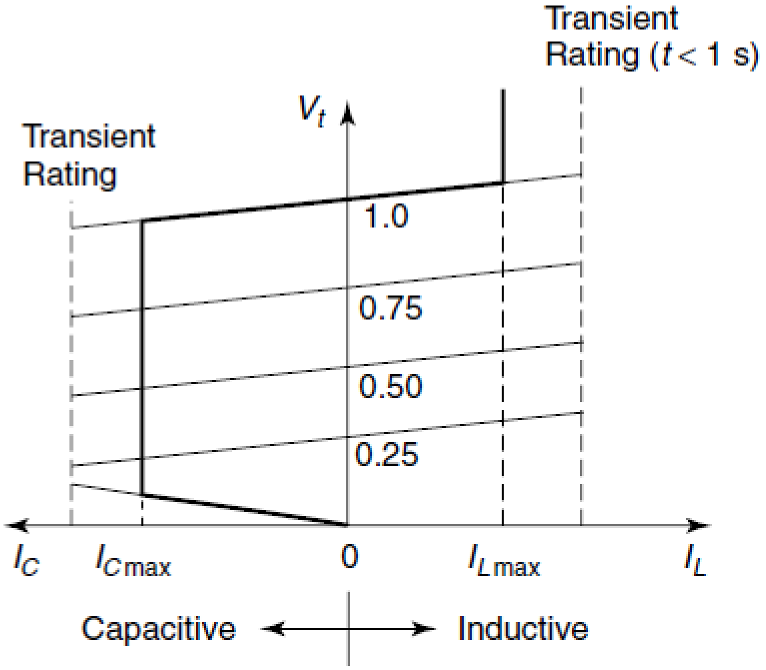
- If the output voltage equals the ac system voltage, the reactive-power exchange becomes zero, in which case the STATCOM is said to be in a floating state.
- Adjusting the phase shift between the converter-output voltage and the acsystem voltage can similarly control real-power exchange between the converter and the ac system. In other words, the converter can supply real power to the ac system from its dc energy storage if the converter-output voltage is made to lead the ac-system voltage.
- On the other hand, it can absorb real power from the ac system for the dc system if its voltage lags behind the ac-system voltage.

- A STATCOM provides the desired reactive power by exchanging the instantaneous reactive power among the phases of the ac system.
- The mechanism by which the converter internally generates and/ or absorbs the reactive power can be understood by considering the relationship between the output and input powers of the converter. The converter switches connect the dc-input circuit directly to the ac-output circuit. Thus the net instantaneous power at the acoutput terminals must always be equal to the net instantaneous power at the dc-input terminals (neglecting losses).
- Assume that the converter is operated to supply reactive-output power. In this case, the real power provided by the dc source as input to the converter must be zero.
- Furthermore, because the reactive power at zero frequency (dc) is by definition zero, the dc source supplies no reactive ower as input to the converter and thus clearly plays no part in the generation of reactive-output power by the converter.
- In other words, the converter simply interconnects the three output terminals so that the reactive-output currents can flow freely among them. If the terminals of the ac system are regarded in this context, the converter establishes a circulating reactive-power exchange among the phases. However, the real power that the converter exchanges at its ac terminals with the ac system must, of course, be supplied to or absorbed from its dc terminals by the dc capacitor.
- Although reactive power is generated internally by the action of converter switches, a dc capacitor must still be connected across the input terminals of the converter.
- The primary need for the capacitor is to provide a circulating-current path as well as a voltage source.
- The magnitude of the capacitor is chosen so that the dc voltage across its terminals remains fairly constant to prevent it from contributing to the ripples in the dc current. The VSC-output voltage is in the form of a staircase wave into which smooth sinusoidal current from the ac system is drawn, resulting in slight fluctuations in the output power of the converter.
- However, to not violate the instantaneous power-equality constraint at its input and output terminals, the converter must draw a fluctuating current from its dc source.
- Depending on the converter configuration employed, it is possible to calculate the minimum capacitance required to meet the system requirements, such as ripple limits on the dc voltage and the rated-reactivepower support needed by the ac system.
- The VSC has the same rated-current capability when it operates with the capacitive- or inductive-reactive current.
- Therefore, a VSC having a certain MVA rating gives the STATCOM twice the dynamic range in MVAR (this also contributes to a compact design). A dc capacitor bank is used to support (stabilize) the controlled dc voltage needed for the operation of the VSC.
- The reactive power of a STATCOM is produced by means of power-electronic equipment of the voltage-source-converter type.
- The VSC may be a 2- level or 3-level type, depending on the required output power and voltage . A number of VSCs are combined in a multi-pulse connection to form the STATCOM.
- In the steady state, the VSCs operate with fundamental-frequency switching to minimize converter losses. However, during transient conditions caused by line faults, a pulse width–modulated (PWM) mode is used to prevent the fault current from entering the

VSCs . In this way, the STATCOM is able to withstand transients on the ac side without blocking.

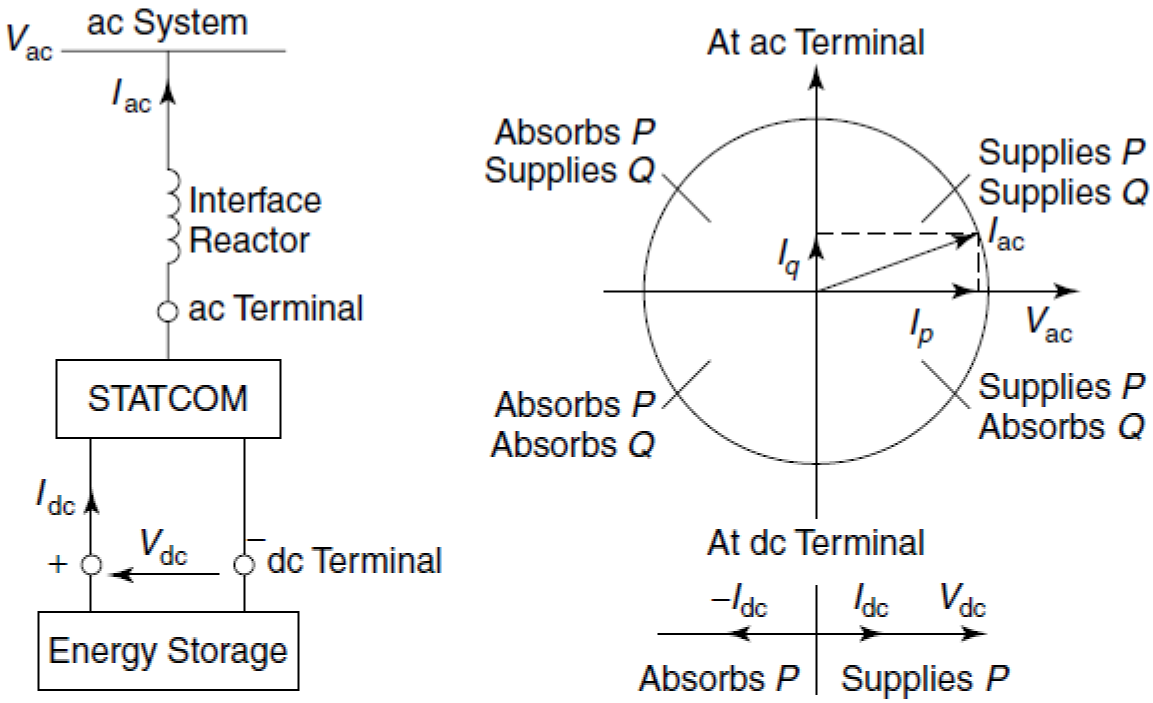
## 4.3 V-I CHARACTERISTICS OF STATCOM

- A typical *V-I* characteristic of a STATCOM is depicted in Fig.
- The STATCOM can supply both the capacitive and the inductive compensation and is able to independently control its output current over the rated maximum capacitive or inductive range irrespective of the amount of ac-system voltage.
- The STATCOM can provide full capacitive-reactive power at any system voltage—even as low as 0.15 pu.



- The characteristic of a STATCOM reveals another strength of this technology: that it is capable of yielding the full output of capacitive generation almost independently of the system voltage (constant-current output at lower voltages). This capability is particularly useful for situations in which the STATCOM is needed to support the system voltage during and after faults where voltage collapse would otherwise be a limiting factor.
- Figure illustrates that the STATCOM has an increased transient rating in both the capacitive- and the nductive-operating regions.
- The maximum attainable transient overcurrent in the capacitive region is determined by the maximum current turn-off capability of the converter switches.
- In the inductive region, the converter switches are naturally commutated; therefore, the transient-current rating of the STATCOM is limited by the maximum allowable junction temperature of the converter switches.

- In practice, the semiconductor switches of the converter are not lossless, so the energy stored in the dc capacitor is eventually used to meet the internal losses of the converter, and the dc capacitor voltage diminishes.
- However, when the STATCOM is used for reactive-power generation, the converter itself can keep the capacitor charged to the required voltage level. This task is accomplished by making the output voltages of the converter lag behind the ac-system voltages by a small angle (usually in the 0.18–0.28 range).
- In this way, the converter absorbs a small amount of real power from the ac system to meet its internal losses and keep the capacitor voltage at the desired level.
- The same mechanism can be used to increase or decrease the capacitor voltage and thus, the amplitude of the converter-output voltage to control the var generation or absorption.
- The reactive- and real-power exchange between the STATCOM and the ac system can be controlled independently of each other.
- Any combination of realpower generation or absorption with var generation or absorption is achievable if the STATCOM is equipped with an energy-storage device of suitable capacity, as depicted in Fig.With this capability, extremely effective control strategies for the modulation of reactive- and real-output power can be devised to improve the transient- and dynamic-system-stability limits.



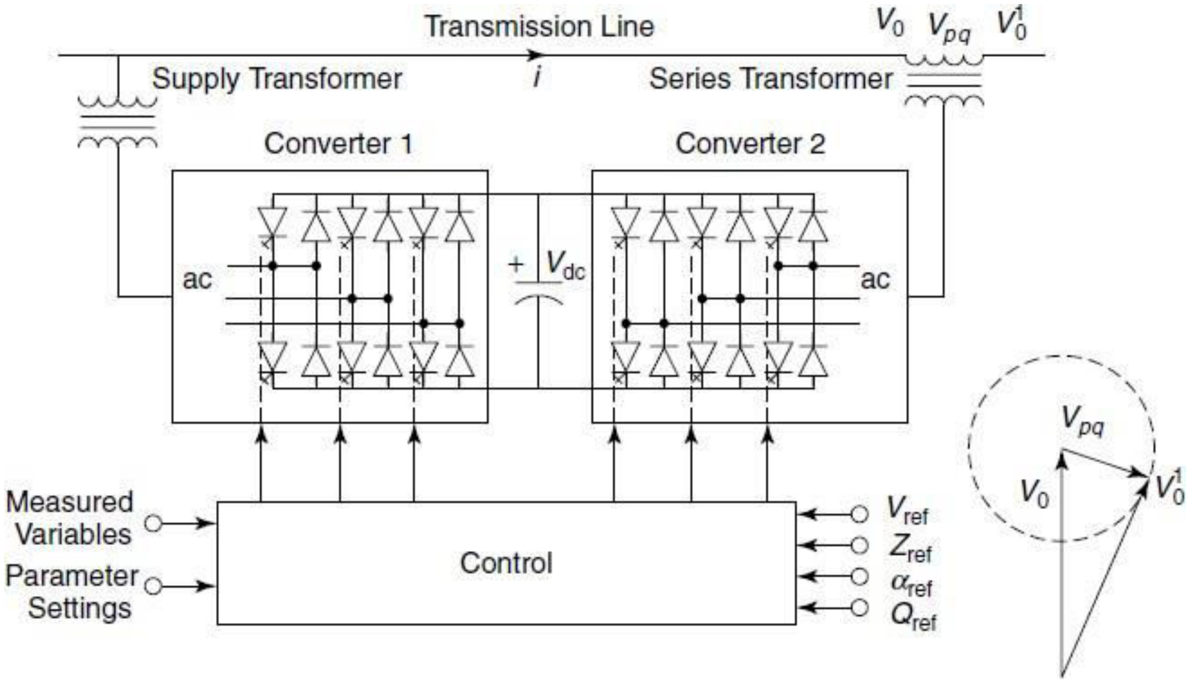
The power exchange between the STATCOM and the ac system

## 4.4 UNIFIED POWER FLOW CONTROLLER (UPFC)

UPFC is a combination of STATCOM and SSSC coupled via a common DC voltage link.

### 4.2.1 Principle of Operation

- The UPFC is the most versatile FACTS controller developed so far, with all encompassing capabilities of voltage regulation, series compensation, and phase shifting.
- It can independently and very rapidly control both real- and reactive power flows in a transmission.
- It is configured as shown in Fig. and comprises two VSCs coupled through a common dc terminal.

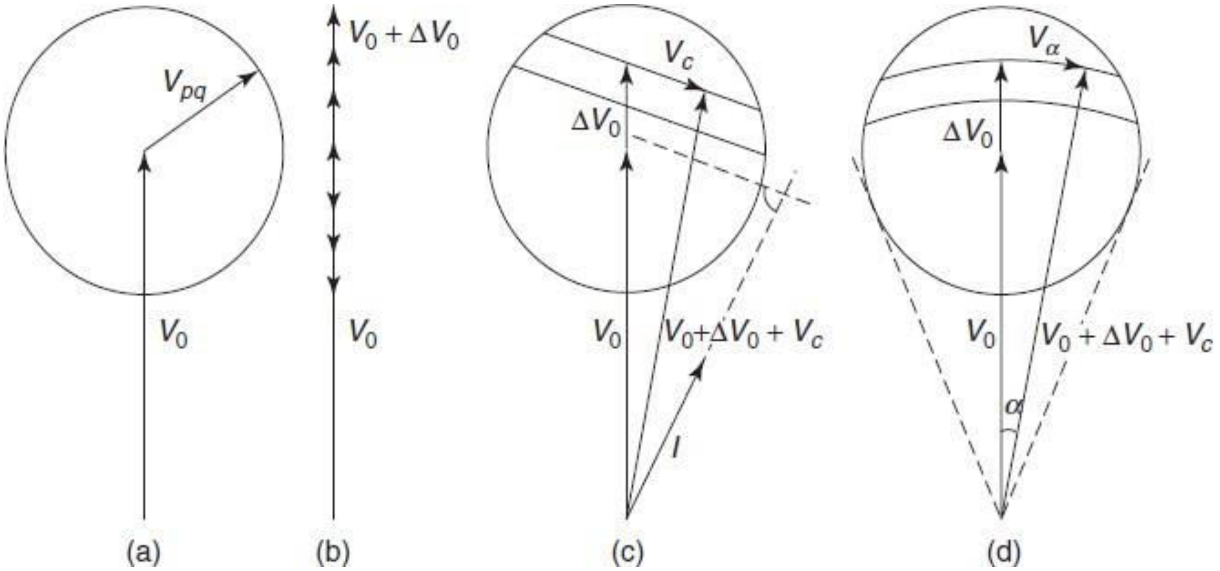


The implementation of the UPFC using two "back – to –back" VSCs with a common DC-terminal capacitor

- One VSC converter 1 is connected in shunt with the line through a coupling transformer; the other VSC converter 2 is inserted in series with the transmission line through an interface transformer.
- The dc voltage for both converters is provided by a common capacitor bank.
- The series converter is controlled to inject a voltage phasor, *Vpq*, in series with the line, which can be varied from 0 to *Vpq* max. Moreover, the phase angle of *Vpq* can be independently varied from $0^0$ to $360^0$.

- In this process, the series converter exchanges both real and reactive power with the transmission line.
- Although the reactive power is internally generated/ absorbed by the series converter, the real-power generation/ absorption is made feasible by the dc-energy–storage device that is, the capacitor.
- The shunt-connected converter 1 is used mainly to supply the real-power demand of converter 2, which it derives from the transmission line itself. The shunt converter maintains constant voltage of the dc bus.
- Thus the net real power drawn from the ac system is equal to the losses of the two converters and their coupling transformers.
- In addition, the shunt converter functions like a STATCOM and independently regulates the terminal voltage of the interconnected bus by generating/ absorbing a requisite amount of reactive power.

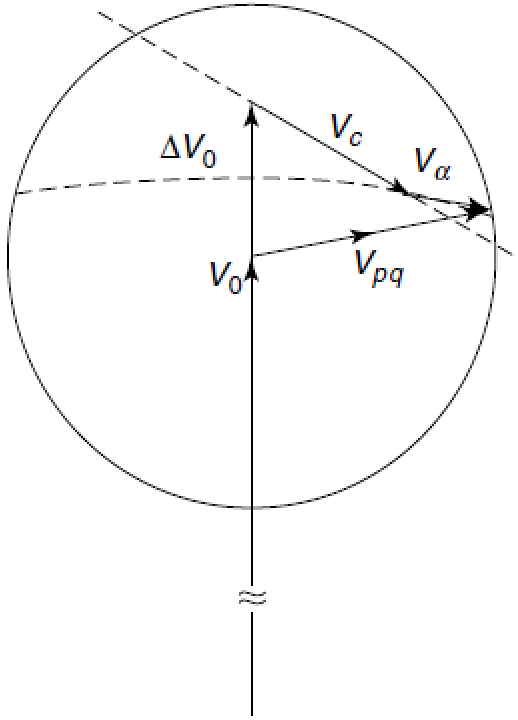
### 4.2.2 Modes of Operation



The phasor diagram illustrating the general concept of sries-voltage injection and attainable power flow control functions a) Series-voltage injection;(b)terminal-voltage regulation;(c)terminal-voltage and line-impedance regulation and (d) terminal-voltage and phse-angle regulation

The concepts of various power-flow control functions by use of the UPFC are illustrated in Figs. 10.26(a)–(d). Part (a) depicts the addition of the general voltage phasor *Vpq* to the existing bus voltage, *V*0, at an angle that varies from $0^0$ to $360\ ^0$.

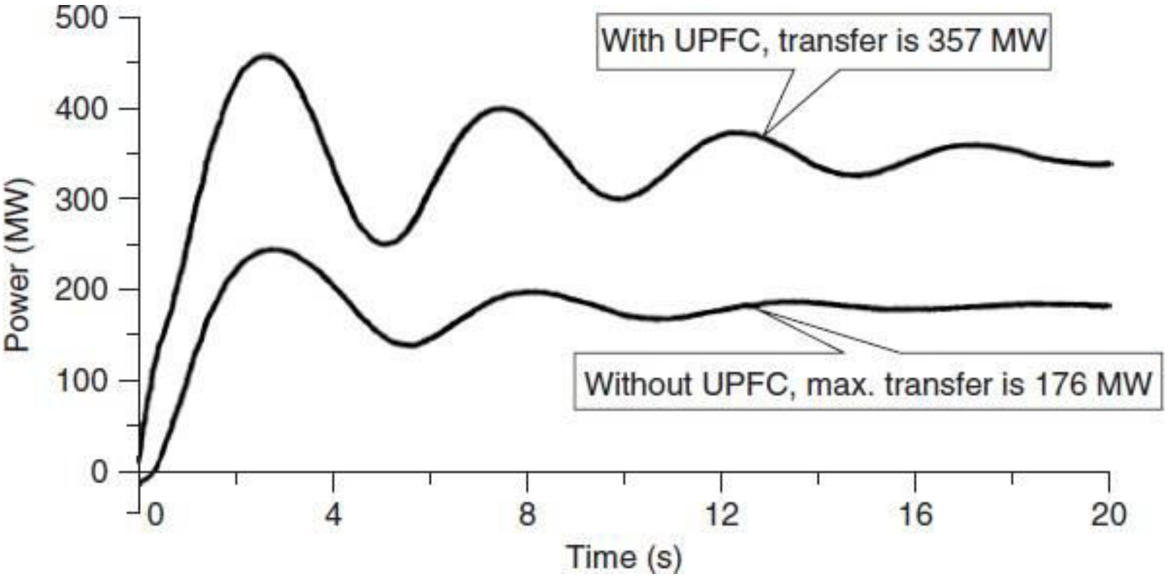
- Voltage regulation is effected if *Vpq* =Δ*V*0 is generated in phase with *V*0, as shown in part (b). A combination of voltage regulation and series compensation is implemented in part (c), where *Vpq* is the sum of a voltageregulating component Δ*V*0 and a series compensation providing voltage component *Vc* that lags behind the line current by $90^0$. In the phase-shifting process shown in part (d), the UPFC-generated voltage *Vpq* is a combination of voltage-regulating component Δ*V*0 and phase-shifting voltage component *V*a.
- The function of *V*a is to change the phase angle of the regulated voltage phasor, *V*0 + Δ*V*, by an angle α. A simultaneous attainment of all three foregoing power-flow control functions is depicted in Fig.
- The controller of the UPFC can select either one or a combination of the three functions as its control objective, depending on the system requirements.
- The UPFC operates with constraints on the following variables :
  1. The series-injected voltage magnitude;
  2. The line current through series converter;
  3. The shunt-converter current;
  4. The minimum line-side voltage of the UPFC;
  5. The maximum line-side voltage of the UPFC; and
  6. The real-power transfer between the series converter and the shunt converter



A phasor diagram illustrating the simultaneous regulaiton of the terminal voltage, line impedance, and phase angle by appropriate series-voltage injection

### 4.2.3 Applications (UPFC)

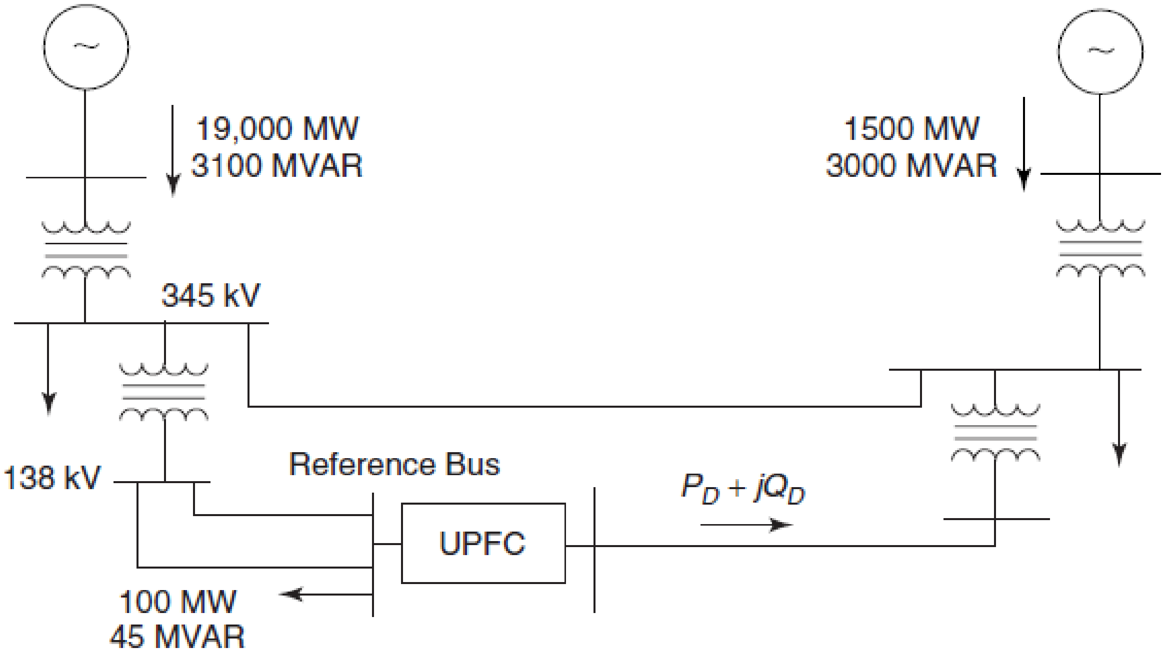
- The power-transmission capability is determined by the transient-stability considerations of the 345-kV line.
- The UPFC is installed in the 138-kV network. A 3-phase-to-ground fault is applied on the 345-kV line for four cycles, and the line is disconnected after the fault.
- The maximum stable power flow possible in the 138-kV line without the UPFC is shown in Fig. to be 176 MW.
- However, the power transfer with the UPFC can be increased 181 MW (103%) to 357 MW. Although this power can be raised further by enhancing the UPFC rating, the power increase is correspondingly and significantly lower than the increase in the UPFC rating, thereby indicating that the practical limit on the UPFC size has been attained.
- The UPFC also provides very significant damping to power oscillations when it operates at power flows within the operating limits.
- The UPFC response to a 3-phase-line-to-ground fault cleared after four cycles, leaving the 345-kV line in service, is illustrated in Fig. Because the 345-kV line remains intact, the oscillation frequency changes from that shown in Fig.



Power-transfer capability curve with the UPFC

### 4.2.4 Modeling of UPFC for power flow studies

The steady state investigation of UPFC involves power flow studies which include the calculation of busbar voltage, branch loadings, real and reactive transmission losses and the impact of UPFC.



- In this model two voltage sources are used to represent the fundamental components of the PWM controlled output voltage waveform of the two branches in the UPFC.
- The impedance of the two coupling transformers are included in the proposed model and the losses of UPFC deppicts the voltage source equivalent circuit of UPFC.
- The series injection branch a series injection voltage source and performs the main functions of controlling power flow whilst the shunt branch is used to provide real power demanded by the series branch and the losses in the UPFC.
- However in the proposed model the function of reactive compensation of shunt branch is completely neglected.

# UNIT V
# CO-ORDINATION OF FACTS CONTROLLERS

## 5.1 Introduction

- Flexible ac transmission system (FACTS) controllers either extend the powertransfer capability of existing transmission corridors or enhance the stability and security margins for given power-transmission limits. Fast controls associated with FACTS controllers do provide these system improvements, but they also can interact adversely with one another. In an interconnected power system, when the controller parameters of a dynamic device are tuned to obtain the best performance, the remaining power system is generally assumed to be passive or represented by slowly varying elements. This assumption is strictly not true; hence the adjusted parameters may not prove optimal when the dynamics of the various other controllers are, in effect, found in real systems

## 5.2 FACTS Controller Interactions

- Controller interactions can occur in the following combinations:
    1. Multiple FACTS controllers of a similar kind.
    2. Multiple FACTS controllers of a dissimilar kind.
    3. Multiple FACTS controllers and HVDC converter controllers.
- Because of the many combinations that are possible, an urgent need arises for power systems to have the ontrols of their various dynamic devices coordinated.The term *coordinated* implies that the controllers have been tuned simultaneously to effect an overall positive improvement of the control scheme.
- The frequency ranges of the different control interactions have been classified as follows:
    - 0 Hz for steady-state interactions
    - 0–3/ 5 Hz for electromechanical oscillations
    - 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

### 5.2.1 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 generally employed to investigate the foregoing control interactions.

- Steady-state indices, such as voltage-stability factors (VSF),are commonly used. Centralized controls and a combination of local and centralized controls of participating controllers are recommended for ensuring the desired coordinated performance.

### 5.2.2 Electromechanical – Oscillation Interactions

- Electromechanical-oscillation interactions between FACTS controllers also involve synchronous generators, compensator machines, and associated powersystem stabilizer controls .
- The oscillations include *local mode* oscillations, typically in the range of 0.8–2 Hz, and *inter-area mode* oscillations, typically in the range of 0.2–0.8 Hz.
- The local mode is contributed by synchronous generators in a plant or several generators located in close vicinity; the inter-area mode results from the power exchange between tightly coupled generators in two areas linked by weak transmission lines.
- Although FACTS controllers are used primarily for other objectives, such as voltage regulation, they can be used gainfully for the damping of electromechanical oscillations.
- In a coordinated operation of different FACTS controllers, the task of damping different electromechanical modes may be assumed by separate controllers.
- Alternatively, the FACTS controllers can act concertedly to damp the critical modes without any adverse interaction.
- Eigenvalue analysis programs are employed for determining the frequency and damping of sensitive modes.

### 5.2.3 Control or Small – Signal oscillations

- Control interactions between individual FACTS controllers and the network or between FACTS controllers and HVDC links may lead to the onset of oscillations in the range of 2–15 Hz (the range may even extend to 30 Hz).
- These oscillations are largely dependent on the network strength and the choice of FACTS controller parameters, and they are known to result from the interaction between voltage controllers of multiple SVCs, the resonance between series capacitors and shunt reactors in the frequency range of 4–15 Hz ,and so forth. The emergence of these oscillations significantly influences the tuning of controller gains.
- Analysis of these relatively higher frequency oscillations is made possible by frequency-scanning programs, electromagnetic-transient programs (EMTPs), and physical simulators (analog or digital).
- Eigenvalue analysis programs with modeling capabilities extended to analyze higher-frequency modes as well may be used .

### 5.2.4 Sub Synchronous resonance (SSr) Interactions

- Subsynchronous oscillations may be caused by the interaction between the generator torsional system and the series-compensated-transmission lines, the HVDC converter controls, the generator excitation controls, or even the SVCs.These oscillations, usually in the frequency range of 10–50/ 60 Hz, can potentially damage generator shafts.

- Subsynchronous damping controls have been designed for individual SVCs and HVDC links.
- In power systems with multiple FACTS controllers together with HVDC converters, a coordinated control can be more effective in curbing these torsional oscillations.

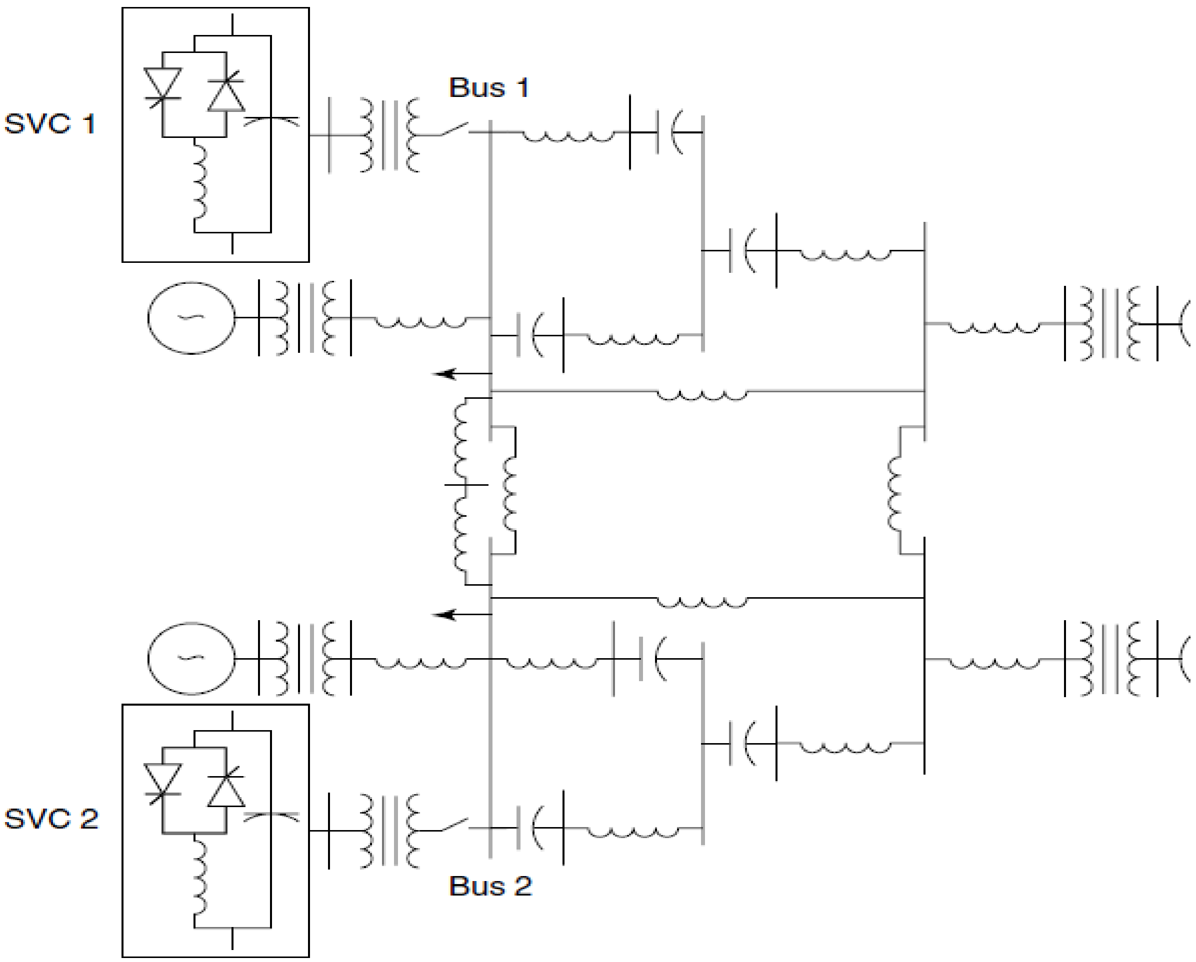
### 5.2.5 High – Frequency Interactions

- High-frequency oscillations in excess of 15 Hz are caused by large nonlinear disturbances, such as the switching of capacitors, reactors, or transformers, for which reason they are classified as electromagnetic transients.
- Control coordination for obviating such interactions may be necessary if the FACTS and HVDC controllers are located within a distance of about three major buses. Instabilities of harmonics (those ranging from the 2nd to the 5th) are likely to occur in power systems because of the amplification of harmonics in FACTS controller loops.
- Harmonic instabilities may also occur from synchronization or voltage-measurement systems, transformer energization, or transformer saturation caused by geomagnetically induced currents (GICs).

## 5.3 SVC – SVC Interactions

### 5.3.1 The Effect of Electrical Coupling and Short-Circuit Levels

- The interaction phenomena are investigated as functions of electrical distance (electrical coupling) between the SVCs and the short-circuit level at the SVC buses.



SVC interaction – analysis network

### 5.3.1.1 Uncoupled SVC Buses

- A simplified test system shown in Fig. is considered for the interaction analysis performed through eigenvalue analyses and root-loci plots.
- All the generating units are represented by infinite buses. If the transfer reactance between buses 1 and 2 is high, making the buses electrically uncoupled, then the SVCs connected to those buses do not interact adversely.
- Increasing the proportional gain of SVC 1 connected to bus 1, even to the extent of making the SVC unstable, does not affect the eigenvalues of SVC 2—implying that the controller designs of SVCs can be done independently for multiple SVCs in a power system if the transfer reactance between their connecting buses is high.

#### 5.3.1.2 Coupled SVC Buses

- If the reactance between the two SVC buses is low, it constitutes a case of high electrical coupling between the SVCs.
- Here again, two ossibilities exist with respect to short-circuit capacity of the region where the SVCs are installed: the SVC region with a high shortcircuit capacity and the SVC region with a low short-circuit capacity.
- For high short-circuit capacity conditions in the same system as Fig. reveal that by increasing the proportional gain of one SVC, the eigenvalues of the other SVC are impacted very slightly. Almost no control interaction exists between the two SVCs irrespective of their electrical coupling, as long as they are in a high short-circuit-level region, that is, when the ac system is stiff.
- The reason for this condition is that the interlinking variable between the two SVCs is the bus voltage.
- Thus the controls of both SVCs can be independently designed and optimized, but if the short-circuit capacity of the SVC region is low, varying the proportional gain of SVC 1 will strongly influence the eigenvalues associated with SVC 2.
- Therefore imperative that a coordinated control design be undertaken for both SVCs.
- Despite simplifications in the study system and in the analysis approach, the aforementioned interaction results are general, for the phenomena investigated are independent of the number of buses, transmission lines, or generators.

## 5.4 Co-Ordination of Multiple Controllers using Linear – Control Techniques

### 5.4.1 Introduction

- The term *coordination* does not imply centralized control; rather, it implies the simultaneous tuning of the controllers to attain an effective, positive improvement of the overall control scheme.
- It is understood that each controller relies primarily on measurements of locally available quantities and acts independently on the local FACTS equipment.

### 5.4.2 The Basic Procedure for Controller Design

The controller-design procedure involves the following steps:

1. Derivation of the system model;
2. Enumeration of the system-performance specifications;
3. Selection of the measurement and control signals;
4. Coordination of the controller design; and
5. Validation of the design and performance evaluation.

#### Step 1: Derivation of System Model

- First, a reduced-order nonlinearsystem model must be derived for the original power system and this model should retain the essential steady-state and dynamic characteristics of the power system .

- Then, the model is linearized around an operating point to make it amenable to the application of linear-control design techniques. If a controllermust be designed for damping electromechanical oscillations, a further reducedlinear model is selected that exhibits the same modal characteristics over the relevant narrow range of frequencies as the original system.
- In situations where linearized-system models may not be easily obtainable, identification techniques are employed to derive simple linear models from time-response information.

**Step 2: Enumeration of the System – performance Specifications**

- The damping controller is expected to satisfy the following criteria.

1. It should help the system survive the first few oscillations after a severe system disturbance with an adequate safety margin. This safety factor is usually specified in terms of bus-voltage levels that should not be violated after a disturbance.
2. A minimum level of damping must be ensured in the steady state after a disturbance.
3. Potentially deleterious interactions with other installed controls should be avoided or minimized.
4. Desired objectives over a wide range of system-operating conditions should be met (i.e., it should be robust).

**Step 3: Selection of the Measurement and Control Signals**

- The choice of appropriate measurement and control signals is crucial to controller design.
- The signals must have high observability and controllability of the relevant modes to be damped, and furthermore, the signals should only minimally affect the other system modes.
- The selection of these signals is usually based on system-modal magnitudes, shapes, and sensitivties—all of which can be obtained from small-signal-stability analysis.

**Step 4: Controller Design and Coordination**

- The FACTS controller structures are usually chosen from industry practice. Typically, the controller transfer function, *Hj*(*s*), of controller *j* is assumed to be

$$H_j(s) = k_j G_j(s) = k_j \frac{sT_W}{1 + sT_W} \left( \frac{1 + s\tau_1}{1 + s\tau_2} \right)^p \frac{1}{(1 + sT_1)(1 + sT_2) \cdots (1 + sT_n)}$$

- This transfer function consists of a gain, a washout stage, and a *p*th-order leadlag block, as well as low-pass filters. Alternatively, it can be expressed as

$$H_j(s) = k_j G_j(s) = k_j \left[ k_0 \frac{(s + \cdots + b_m s^m}{1 + a_1 s + \cdots + a_n s^n} \right], \qquad m \le n$$

- Although the basic structure of different controllers is assumed as from the preceding text, the coordination of controllers involves the simultaneous selection of gains and time constants through different techniques.
- Doing so permits the system-operating constraints and damping criteria to be satisfied over a wide range of operating conditions.
- The coordination techniques may use linearized models of the power system and other embedded equipments, capitalizing on the existing sparsity in system representation.
- This model may be further reduced by eliminating certain algebraic variables yet still retaining the essential system behavior in the frequency range of interest.
- Eigenvalue analysis–based controller-optimization and -coordination techniques are applicable to power systems typically with a thousand states occurring when full modal analysis must be performed. However, sometimes a limited number of electromechanical modes must be damped; hence the eigenvalue analysis of a selected region can be performed even for relatively larger power systems.

### Step 5: Validation of the Design and performance Evaluation

- Even though the controller design is performed on the simplified system model, the performance of the controller must still be established by using the most detailed system model.
- The controller should meet the specifications over a wide range of operating conditions and consider all credible contingencies.This validation is generally performed with nonlinear time-domain
- simulations of the system.

## 5.5 Co-Ordination of multiple Controllers using Non Linear – Control Techniques

- Several nonlinear-control techniques have been applied for the design of FACTS controllers. These techniques are likely to yield greatly improved controllers, as they include the effects of system nonlinearities.
- Some of these methods are described briefly in the following text. One nonlinear-control technique in which the system nonlinearities are expressed as system changes constituting a function of time is the *adaptive control*.
- If the number of controller parameters to be optimized is not too large, a *cost-penalty function* technique can be used, which is based on nonlinear simulation.
- An effective technique commonly used for enhancing transient stability during large disturbances is the *discontinuous control* or *bang-bang control.*
- Another nonlinear-control technique is the *normal forms*, which includes the effects of higher-order terms in Taylor's series to represent power systems especially during high-power transfers. For damping low-frequency oscillations, FACTS controllers can be designed using the *dissipation* technique, which is based on the concept that passive systems always absorb energy. For designing the controls of FACTS controllers in large power systems, the *energy*, or *Lyapunov*, technique can be used. For stability enhancement, *nonlinear fuzzy* and *neural net* techniques are presently being researched.

- In the future, these techniques may be extended for coordination of FACTS controllers. One possible approach could be to first do a “coarse” coordination using linear-control techniques, followed by a “fine” coordination employing the nonlinear-control methods.

**“The Quantitative treatment of control coordination”**

1. Coordination of multiple controllers using linear control techniques.
2. Coordination of multiple controllers using non linear control techniques.

# QUESTION BANK

## UNIT-1 INTRODUCTION

## PART A

**1. What is meant by FACTS?**

FACTS devices are made by advanced power electronic ***control equipments***. The flexible ac transmission systems (FACTS) give solutions to the problems and limitations which were introduced in the power system with the introduction of power electronics based control for reactive power.

**2. What is the need for reactive power?**

The reactive power is essential for the ***operation of electromagnetic energy devices***; it provides required coupling fields for energy devices.

**3. What is reactive power?**

The reactive power flows from ***load to source***. The average value for reactive power is zero. It does not result in any active power consumption.

Unit: Volt Ampere Reactive (VAR)

**4. What are the sources of reactive power?**

- ***Capacitor***
- Synchronous generator (it can generate both real and reactive power)

**5. Main objectives of FACTS?**

- The power ***transfer capability of transmission system*** is to be increased.
- The power flow is to be kept over designated routes.

**6. Who implemented the FACTS concept? For what?**

The concept of FACTS was first defined in 1988 by N.G.Hingorani. It controls the interrelated parameters which are involved in power system operation such as series and shunt impedance, current, voltage and phase angle. Also it ***damps the oscillations*** at various frequencies below the rated frequency.

**7. What are the types of FACTS devices?**

SVC - ***Static Var Compensator***
TCSC - Thyristor Controlled Series Capacitor
UPFC - Unified Power Flow Controller
IPFC - Interline Power Flow Controller
SSSC - Static Synchronous Series Compensator
SSC - Static Synchronous Compensator (STATCOM)

**8. What are the types of FACTS controllers?**

- ***Series controller***
- Shunt controller
- Combined series-series controllers
- Combined series-shunt controllers

**9. Where the first STATCOM was implemented?**

Tennesee Valley Authority (TVA) installed the first static synchronous compensator (STATCOM) in 1955 to strengthen transmission line ties between its ***Sullivan substation*** and the rest of its network. It reduces the need of additional transformer bank and avoiding more labors.

**10. Where the first UPFC was implemented?**

In 1998 installation of the first unified power flow controller (UPFC) was completed at the ***Inez Substations*** owned by American Electrical Power (AEP). It represents the first controller capable of providing complete control of all the three basic transmission system parameters that is voltage, line impedance, phase angle.

## PART B

11. (a) Briefly explain about shunt and series compensation.
    (***Keywords: Improve maximum power transfer capability***)
    (b) Explain in detail about the classification of different FACTS controllers.
    (***Keywords: SVG, SVC, Static compensators, SVS***)
12. (a) Explain the basic construction, working and characteristics of any one type of SVC.
    (***Keywords: TCR-continuous control of reactive power***)
    (b)Explain the working and Characteristics of Thyristor switched serious capacitor with a neat sketch. (***Keywords: TSC-two cases-capacitor voltage equal & unequal***)
13. (a) Explain the working and Characteristics of unified power flow controller with a neat sketch. (***Keywords: Real time- dynamic compensator of AC system***)
    (b) Explain the working and Characteristics of Integrated power flow controller with a Neat sketch. (***Keywords: Control Equipment, very fast response***)
14. (a) Explain the reactive power compensation at the sending, midpoint and receiving ends Of the transmission lines. (***Keywords: Reactive power voltage control, load compensation***)
    (b) i. Explain the objectives of FACTS controllers in the power system network.
    (***Keywords: Very fast control response with time***)
    ii. Describe the procedure to locate the FACTS devices in an electrical network.
    (***Keywords: Remote generating stations, receiving ends***)

## UNIT-II STATIC VAR COMPENSATOR (SVC) AND APPLICATIONS

## PART A

**1. Short notes on voltage control by SVC?**

The transmission line voltage is maintained by connecting ***static var compensator*** (SVC) in the receiving end side. The comparator will measure the actual and reference values of transmission line voltage; depends on the comparator output the reactive power is injected Into the transmission line, and the transmission line voltage will be controlled.

**2. Write down the equation for SVC bus voltage.**

$VS = VSVC + ISVC\ XS$

**3. Give the advantages of the slope in the SVC dynamic characteristics.**

- The ***reactive power rating is reduced***
- SVC is prevented from reaching its reactive power limit too frequently
- It provides effective parallel operation of two parallel connected SVC's

**4. What is SVC slope in the dynamic characteristics?**

To ***improve the power system operating performance*** 2.5% voltage de-regulation will be provided in SVC operation. So this voltage de-regulation results in 5% slope in the SVC dynamic characteristics.

**5. How the SVC prevents the reactive power rating, reaching its limit too frequently?**

Due to slope in the SVC dynamic characteristics the no load to change in ***load Variation limit will be increased***, so the SVC is prevented from reaching its reactive power limit too frequently. Thus the total reactive power needed is reduced to certain limit.

**6. Explain the load sharing of two parallel connected SVC's.**

Without slope in the SVC dynamic characteristics there is a ***discontinuous gap*** between capacitive and inductive region. This gap will be reduced by operating two parallel connected SVC's with slope (2.5% voltage de-regulation) in the SVC dynamic characteristics.

**7. What are the conditions involved for influence of the SVC on system voltage?**

Coupling transformer ignored, with coupling transformer, ***System gain***

**8. What is ESCR?**

Effective short circuit ratio ***(ESCR) =1 / XS***

$= 1 / (-\Delta svc / \Delta Isvc)$

= BS(equivalent system susceptance)

**9. What is system gain? What is per unit system gain?**

System gain ***KN = Vs / ESCR***

= Vs / BS

Per unit System gain KN = $\Delta Vsvc / Bsvc$

= Qsvc / Sc p.u

**10. What is short circuit power?**

Short circuit power Sc = ( base voltage)×(short circuit current)

= (Vb ) × ( BS. Vs)

## PART- B

**11.** (a) Explain the design of SVC voltage regulator in detail.

(***Keywords: Q Compensation, acceptable voltage limits***)

(b) Explain in detail about using power angle curves, how SVC enhances transient stability of a power system.

(***Keywords: Maintain synchronism of power system***)

**12.** (a) i. Explain about the performance of SVC in controlling voltage in a power system.

(***Keywords: Coupling transformer incorporate with power system***)

ii. What are the advantages of slope in the dynamic characteristics of SVC?

(***Keywords: Reduction of SVC rating, reduce voltage fluctuations***)

(b) Draw and explain the IEEE basic model 1 and Model 2 for SVC control system.

(***Keywords: Prevention of frequency operation at Q limits***)

**13.** (a) Explain the different applications of SVC.

(***Keywords: Enhancement of transient stability, active power transfer***)

(b) Discuss in detail about the static and dynamic VI characteristics of SVC.

(***Keywords: Variation of voltage & current with reactive power***)

**14.** (a) Explain the method of voltage control by SVC.

(***Keywords: Manual gain switching, Bang-Bang control***)

(b) Discuss the method of improving transient stability studies.

(***Keywords: power angle curve, synchronizing torque***)

## UNIT-III THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC) AND APPLICATIONS

## PART A

**1. What is meant by TCSC?**

TCSC is a ***thyristor controlled series capacitor***. It has one parallel connected thyristor controlled inductor and a series capacitor connected with the transmission line. It provides continuous variable capacitive reactance and variable inductive reactance to control the transmission line parameters.

**2. Write down the expression for equivalent impedance, capacitive and inductive reactance of a TCSC**.

Equivalent impedance of a TCSC, $Z_{eq} = -j\left(\frac{1}{\omega c - 1/\omega L}\right)$

If $(\omega c - (1/\omega L)) < 0$ - the TCSC provides variable capacitive reactance mode.

If $(\omega c - (1/\omega L)) > 0$ - the TCSC provides variable inductive reactance mode.

**3. What are the different modes of operation of TCSC?**

- ***Bypassed- thyristor mode***
- Blocked - thyristor mode
- Partially conducting thyristor or Vernier mode.

**4. Give short notes on Bypassed- thyristor mode.**

In this mode the TCSC module behaves like a parallel capacitor - inductor combination. The susceptance (increase in power flow) value of inductor is higher than the capacitor. This mode is employed for control purposes and ***initiating certain protective functions***.

**5. Give short notes on Blocked - thyristor mode.**

In this mode, also known as the waiting mode, here the ***firing pulses of thyristor switches are blocked***. The TCSC behaves like a fixed series capacitor and the net TCSC reactance is capacitive. In this mode the dc-offset voltages of the capacitors are monitored and quickly discharged using a dc-offset control without causing any harm to the transmission system transformers.

**6. Give short notes on capacitive Vernier mode.**

In this mode the TCSC provides continuously ***controllable capacitive reactance***. It is achieved by varying the thyristor pair firing angle in an appropriate range. A variant of this mode is the capacitive vernier mode, in which the thyristors are fired when the capacitor voltage and current have opposite polarity. This condition causes a thyristor controlled reactor (TCR) current that has a direction opposite that of the capacitor current thereby resulting in a loop-current flow in the TCSC controller. This loop current increases the voltage across the fixed capacitor (FC), effectively enhancing the equivalent capacitive reactance and the series compensation level.

**7. Give short notes on inductive vernier mode.**

In this mode the TCSC provides continuously ***controllable inductive reactance***. Here the TCSC can be operated by having a high level of thyristor conduction. In this mode the direction of the circulating current is reversed and the controller presents a net inductive impedance.

**8. What are the conclusions made from the TCSC modes of operation?**

- Thyristor switched series capacitor (TSSC), which permits a ***discrete control of the capacitive reactance.***
- Thyristor controlled series capacitor (TCSC), which offers a continuous control of capacitive or inductive reactance. Practically TSSC is more commonly used.

**9. What are the modeling techniques involved in TCSC?**

- ***Variable reactance model*** (1. Transient stability model 2. Long term stability model)
- An advanced transient stability studies model

**10. What is the need for modeling of a TCSC?**

A TCSC involves continuous - time dynamics, relating to voltages and currents in The capacitor and reactor, and nonlinear discrete switching behavior of thyristors. So it is Very important to derive a model for a TCSC controller to ***maintain the stability of a power system***.

## PART -B

**11.** (a) Explain the variable reluctance model of TCSC and hence derive transient stability of a power system. (***Keywords: inter area model analysis, secure safety margin***)

(b) Explain the following controls of TCSC in its closed loop operation with their block diagram.

i. Constant current control (***Keywords: Reactance varied by firing angle***)

ii. Constant angle control (***Keywords: Additional damping control***)

iii. Enhanced current control (***Keywords: Damp sub synchronous oscillations***)

iv. Constant power control. (***Keywords: Damp out power oscillations***)

**12.** (a) With a neat block diagram, explain the different modes of operation of TCSC.

(***Keywords: Bypass thyristor mode, blocked thyristor mode, switching operations***)

(b) Explain the variable reactance model of TCSC with a neat sketch.

(***Keywords: Provides high accuracy, high fault clearing time***)

**13.** (a) Explain the different applications of TCSC.

(***Keywords: Voltage collapse prevention, fast power controllability***)

(b) Explain the different modes of operation of TCSC, with a neat block diagram.

(***Keywords: Partially conducting thyristor, active power damping***)

**14.** (a) Explain the working and characteristics of TCSC.

(***Keywords: Single module & multi module TCSC, rapid control of power***)

(b) Discuss the role of TCSC in the enhancement of system damping.

(***Keywords: Bang-Bang control, Multi model decomposition-based PSDC design***)

## UNIT-IV EMERGING FACTS CONTROLLERS

## PART A

**1. What is meant by emerging facts controllers?**

The emerging facts controllers ***exchange the reactive power*** to the transmission lines with the help of phase shifting techniques. If needed the real power is also supplied in addition to the reactive power in to the transmission line with the help of emerging FACTS devices such as STATCOM and UPFC. Here the need of large size capacitor bank and inductor bank are reduced, so the operating performance will be improved.

**2. What is meant by STATCOM?**

The static synchronous compensator (STATCOM or SSC) is a ***shunt connected reactive power compensation device*** that is capable of generating and/or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. It is capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an dc energy source or energy storage device at its input terminals.

**3 . What are the functions of STATCOM in the improvement of power system performance area?**

- It provides ***dynamic voltage control in transmission and distribution system***
- It provides damping against the oscillation in power system.
- It provides better transient stability
- It has voltage flicker control (it withstands sudden changes)
- It controls both real and reactive power

**4. What are the common advantages of STATCOM?**

- It required small space because it replaces the ***passive inductor and capacitor bank by compact electronic converters.***
- It has modular factory build electronic equipments, so site work and commissioning time will be reduced.

- It uses encapsulated electronic converters, thereby minimizing its environmental impact.

**5. Give details about first installed STATCOM device at Sullivan Sub-station.**

***Tennessee Valley Authority*** (TVA) installed the first ± 100 MVA STATCOM in 1995 at its Sullivan substation.

**6. What are the applications of first installed STATCOM device at Sullivan Sub-station?**

The application of this STATCOM is expected to reduce the TVA's need for load tap changing transformers, there by achieving savings by ***minimizing the potential*** for transformer failure. This STATCOM solves the problems against off-peak dilemma of over voltages in the Sullivan substation area while avoiding the more labor and apace intensive installation of an additional transformer bank.

**7. What are the advantages of first installed STATCOM device at Sullivan Sub-station?**

- It ***increases the capacity*** of transmission line voltage by providing instantaneous control.
- It provides greater flexibility in bulk power transactions.
- It also increases the system reliability by damping grids of major oscillations in this grid.

**8. Write short notes on principle of operation of STATCOM.**

A STATCOM is a controlled reactive power source. It provides the ***desired reactive power generation*** and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage source converter.

**9. Give the explanation about reactive power exchange between converter and the ac system.**

If the ac system ***voltage is lesser than the sending end voltage*** then the converter inject the reactive power to the transmission line. If the ac system voltage is ***higher than the sending end voltage*** then the converter absorb the reactive power from the transmission line.

**10. What is the importance of V-I characteristics of STATCOM?**

The V-I characteristics of STATCOM shows that it can supply both the capacitive and inductive compensation and is able to independently control its output current over the rated maximum capacitive or inductive range irrespective of the amount of ac system voltage. That is, the STATCOM can ***provide full capacitive reactive power*** at any ac system voltage even as low as 0.15 p.u.

## PART - B

**11.** (a) With aid of block diagram, explain the characteristics of UPFC.

(***Keywords: Voltage angle regulation, Exchange of P & Q, active power transfer***)

(b) Discuss the future direction of FACTS technology.

(***Keywords: silicon power switching devices, enhanced with auxiliary devices***)

**12.** (a) Explain the power exchange between the STATCOM and AC system using vector diagram. (***Keywords: Desire voltage at load bus maintained, safety margin***)

(b) Explain the principle of operation and applications of UPFC.
(***Keywords: phase shifting t/f with real power exchange, natural commutation***)

**13.** (a) Explain the operation of STATCOM with an aid of block diagram.
(***Keywords: Improve the transient & dynamic system stability limits***)

(b) Explain the modelling procedure of UPFC for power flow studies.
(***Keywords: Series injected voltage magnitude, active power damping***)

**14.** (a) Explain the working and characteristics of TCSC.
(***Keywords: Series controlled capacitive reactance, active power control***)

(b) Discuss the role of TCSC in the enhancement of system damping. (***Keywords: Stabilize post disturbance oscillations, preclude local instabilities***)

## UNIT-V CO-ORDINATION FACTS CONTROLLERS
## QUESTION BANK-I
## PART A

**1. What is meant by controller interactions?**

If two or more FACTS ***devices are connected in same transmission line*** then the operating variables between them must have better co-ordinated, that is called controller interaction. If FACTS devices are not co-ordinated, it creates unwanted oscillation in the transmission lines.

**2. What are the types of controller interactions?**

- ***Multiple FACTS controller of a similar kind***
- Multiple FACTS controller of a dissimilar kind
- Multiple FACTS controllers and HVDV converter controllers

**3. What are the frequencies ranges of controller interactions?**

- ***0 Hz for steady state interactions***
- 0 - 3/5 Hz for electromechanical oscillations
- 2 - 15 Hz for small signal or control oscillation
- 10 - 50/60 Hz for sub synchronous resonance (SSR) interaction
- > 15 Hz for electromagnetic transients, high - frequency resonance or harmonic resonance interactions, and network resonance interactions

**4. What is meant by steady state interaction?**

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- state voltage and steady-state power, included are evaluations of the adequacy of reactive-power support at buses, system strength and so on. ( Eg) Steady state voltage control between FACTS-HVDC for ac voltage regulation.

**5. What is the analysis method used to determine the steady state interaction?**

To determine this interaction ***Load-Flow*** and Stability programs are used.

**6. What is meant by electromechanical oscillation interaction?**

Electromechanical oscillation interaction between FACTS controllers involve synchronous generators, compensator machines and associated power system stabilizer control. The oscillations include local mode oscillations typically in the range of 0.8 - 2 Hz, and inter area mode oscillations, typically in the range of 0.2 - 0.8 Hz. The local mode is contributed by synchronous generators in a plant or several generators located in close vicinity, the inter-area mode results from the power exchange between tightly coupled generators in ***two areas linked by weak transmission lines.***

**7. What is the analysis methods used to determine the electromechanical oscillation interaction?**

To determine this interaction ***Eigen value analysis programs*** are used.

**8. What is meant by control or small signal oscillation interactions?**

Controller interactions between individual FACTS controllers and the network or between FACTS controllers and HVDC links may lead to the onset of oscillations in the range of 2 - 15 Hz. These oscillations are largely dependent on the network strength and the choice of FACTS controller parameters, and they are known to result from the interaction between voltage controllers of multiple SVC's, the series resonance between series capacitors and shunt reactors in the frequency range of 4 - 15 Hz and so forth. The emergence of these oscillations significantly influences the ***tuning of controller gain.***

**9. What are the analysis methods used to determine the control or small signal oscillation interaction?**

These high frequency oscillation interactions are determined by frequency scanning programs, ***electromagnetic transient programs (EMTP's),*** Physical simulators and eigen value analysis programs.

**10. What is meant by sub synchronous resonance interactions?**

Sub synchronous oscillations may be caused by the ***interaction between the Generator torsional system and the series compensated transmission lines***, the HVDC converters, the generator excitation control or even the SVC's. Theses oscillations usually in the frequency range of 10 - 50/60 Hz, can potentially damage generator shafts.

**PART-B**

**11.** (a) Discuss in detail about SVC-SVC interaction.

(***Keywords: Electrical coupling, phase shifting, power switching devices***)

(b) Discuss the coordination procedure of multiple controllers using linear control techniques in detail.

(***Keywords: Optimal control to co-ordinate the controllers, regulate v and Φ***)

**12.** (a) Discuss linear quadratic regulator based techniques, global coordination using non linear constrained optimization, control co ordination using genetic algorithms in detail.

(***Keywords: Optimal control, structure control, phase shifting at MVA capacity***)

(b) Explain the coordination of multiple controllers using linear control technique.

(***Keywords: Model performance index, Natural selection, power flow controllers***)

**13.** (a) Explain in detail about different control interactions.

(***Keywords: Steady state interactions, power transmission applications***)

(b) Explain about the co-ordination of FACTS controllers.

(***Keywords: Control of oscillations, tap-changing, excitation control***)

**14.** (a) Explain the co-ordination of multiple controllers using genetic algorithm.

(***Keyword: Natural selection, inject voltages to compensate line reactance***)

(b) Discuss the role of TCSC in the enhancement of system damping.

(***Keywords: Control design based on natural selection, phase shifting transformers***)