LECTURE NOTES

ON

FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS

VIII Semester (IARE –R16)

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UNIT - I

INTRODUCTION

1.1 Introduction:

The electric power supply systems of whole world are interconnected, involving connections inside the utilities, own territories with external to inter-utility, internationals to inter regional and then international connections. This is done for economic reasons, to reduce the cost of electricity and to improve reliability of power supply. We need the interconnections to pool power plants and load centres in order to minimize the total power generation capacity and fuel cost. Transmission lines interconnections enable to supply, electricity to the loads at minimized cost with a required reliability. The FACTS Technology is adopted in the transmissions to enhance grid reliability and to over come the practical difficulties which occur in mechanical devises used as controllers of the transmission network.

The FACTS Technology has opened a new opportunity to the transmission planner for controlling power and enhancing the useable capacity presently, also to upgrade the transmission lines. The current through the line can be controlled at a reasonable cost which enables a large potential of increasing the capacity of existing lines with large conductors and by the use of FACTS controllers the power flow through the lines is maintained stable. The FACTS controllers control the parameters governing the operation of transmission systems, such as series impedance, shunt impedance, current, voltage, phase angle and damping of oscillations at various frequencies below the rated frequency.

In an A.C power flow, the electrical generation and load must be balanced all the times. Since the electrical system is self regulating, therefore, if one of the generators supplies less power than the load, the voltage and frequency drop, thereby load goes on decreasing to equalize the generated power by subtracting the transmission losses. However there is small margin of self-regulating. If voltage is dropped due to reactive power, the load will go up and frequency goes on decreasing and the system will collapse ultimately. Also the system will collapse if there is a large reactive power available in it. In case of high power generation the active power flows from surplus generating area to the deficit area.

1.2 Need for Transmission Networks Interconnections:

- To make electric energy generation more economical, the generating stations are sited remotely from the load centers, and closer to the source of power.

- For example, the primary concern to hydroelectric power plants is the availability of water and benefits of the sites having higher heads with significant water flows, while thermoelectric power stations are situated near to coal mines and the nuclear power plants are located distantly away from the urban centers for safety.

- Consequently, the transmission lines serve the purpose to pool the generating sites and load centers covering large distances between generation and end-users in order to minimize the total generation capacity and fuel cost.

- To enhance the system reliability, the electric power supply systems are widely interconnected, i.e., interlinking the neighboring power supply utilities, which further extend to inter-regional and international connections.

- Moreover, with the probable unavailability of some generating units, the interconnection lines could force the electric power flows to be redirected through longer routes to provide emergency assistance (e.g., when encountering partial blackouts).

- As such, transmission interconnections enable taking benefit of diversity of loads, availability of sources and fuel price to provide consistent and uninterrupted service to the loads.

1.3 Opportunities for FACTS

* FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded, lines.

* By providing added flexibility, FACTS Controllers can enable a line to carry power closer to its thermal rating

* The *FACTS* technology is not a single high-power Controller, but rather a collection of Controllers, which can be applied individually or in coordination with others to control one or more of the interrelated system parameters.

* FACTS technology is that this umbrella concept revealed the large potential opportunity for power electronics technology to greatly enhance the value of power systems, and thereby unleashed an array of new and advanced ideas to make it a reality.

1.3 Power Flow In AC Transmission Line:

A large majority of power transmission lines are AC lines operating at different voltages (10 kV to 800 kV). The distribution networks generally operate below 100 kV while the bulk power is transmitted at higher voltages. The lines operating at different voltages are connected through transformers which operate at high efficiency. Traditionally, AC lines have no provision for the control of power flow. The mechanically operated circuit breakers (CB) are meant for protection against faults

Fortunately, ac lines have inherent power flow control as the power flow is determined by the power at the sending end or receiving end.

For example, consider a transmission line connecting a generating station to a load centre in Fig.1.1.

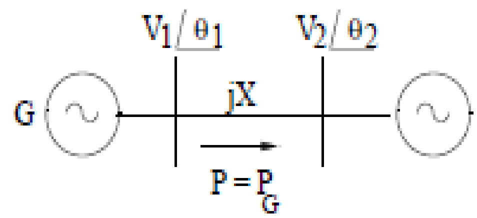


Fig1.1 A line transmitting power from a generating station

Assuming the line to be lossless and ignoring the line charging, the power flow (P) is given by

$$P = \frac{V_1 V_2}{X} \sin(\theta_1 - \theta_2)$$

In ac power systems, given the insignificant electrical storage, the electrical generation and load must balance at all times. To some extent, the electrical system is self-regulating. If generation is less than load, the voltage and frequency drop, and thereby the load, goes down to equal the generation minus the transmission losses.

The reliability of the power supply at a load bus can be improved by arranging two (or more) sources of power as shown in Fig. 1.2

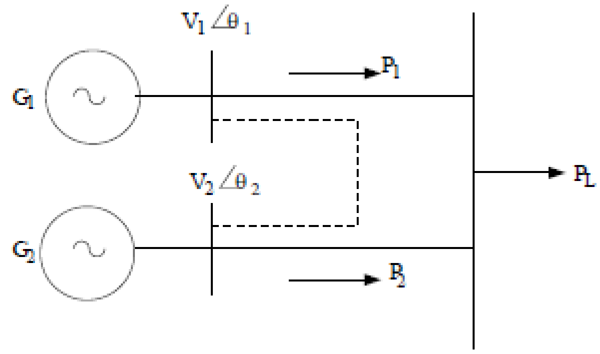
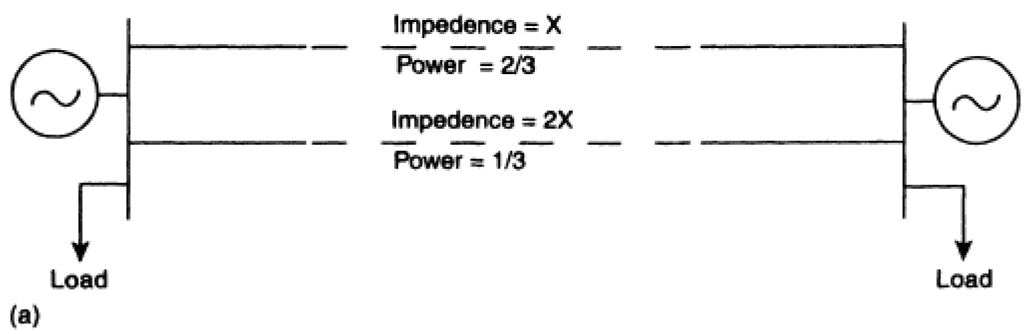


Fig1.2 Two generating stations supplying a load

Here, P1 is the output of G1 while P2 is the output of G2 (Note that we are neglecting losses as before). However, the tripping of any one line will reduce the availability of power at the load bus. This problem can be overcome by providing a line (shown dotted in Fig. 1.2) to interconnect the two power stations. Note that this results in the creation of a mesh in the transmission network. This improves the system reliability, as tripping of any one line does not result in curtailment of the load.

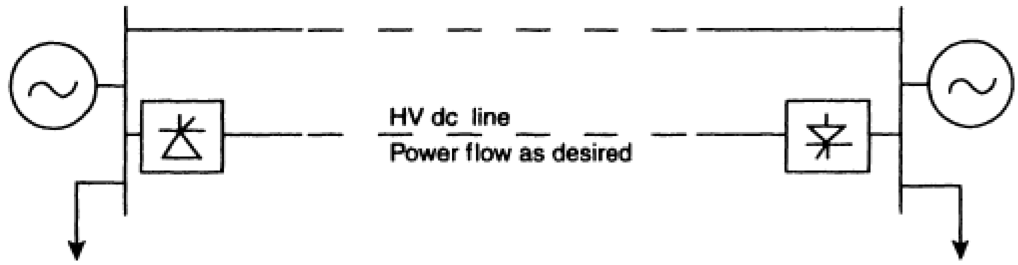
1.3.1 Power Flow In Parallel Paths

Consider a very simple case of power flow [Fig1.1(a)], through two parallel paths



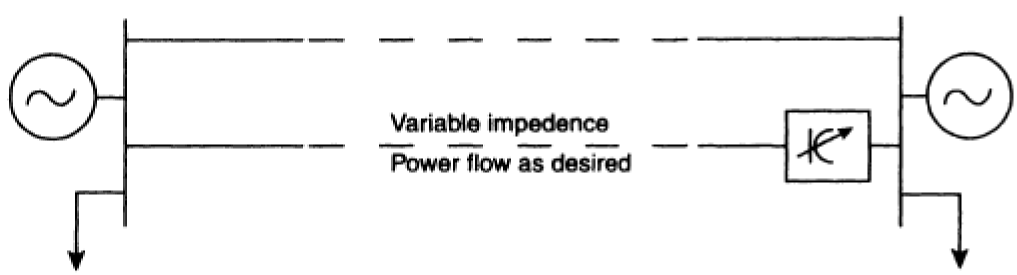
The above Fig1.3 (a) shown as an equivalent generator on the left, to a deficit generation area on the right. Without any control, power flow is based on the inverse of the various transmission line impedances. How much power, it is likely that the lower impedance line may become overloaded and thereby limit the loading on both paths even though the higher impedance path is not fully loaded.

Figure 1.3(b) shows the same two paths, but one of these has HVDC transmission.

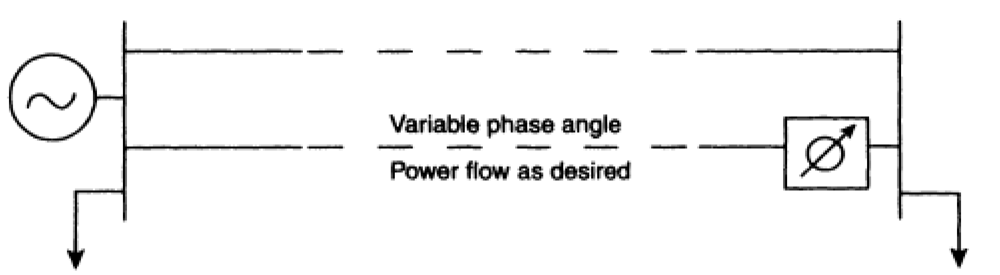


(b)

With HVDC, power electronics converters power is electronically controlled. Also, because power is electronically controlled, the HVDC line can be used to its full thermal capacity if adequate converter capacity is provided. Furthermore, an HVDC line, because of its high-speed control, can also help the parallel ac transmission line to maintain stability. However, HVDC is expensive for general use, and is usually considered when long distances are involved, such as the Pacific DC Intertie on which power flows as ordered by the operator.



(c)



(d)

Fig1.3 Power flow in parallel paths: (a) ac power flow with parallel paths; (b) power flow control with HVDe; (c) power flow control with variable impedance; (d) power flow control with variable phase angle.

As alternative FACfS Controllers, Figures 1.3(c) and 1.1(d) show one of the transmission lines with different types of series type FACfS Controllers. By means of controlling impedance [Figure 1.3(c)] or phase angle [Figure 1.3(d)], or series injection of appropriate voltage (not shown) a FACfS Controller can control the power flow as required. Maximum power flow can in fact be limited to its rated limit under contingency conditions when this line is expected to carry more power due to the loss of a parallel line.

1.3.2 Power Flow In a Meshed System:

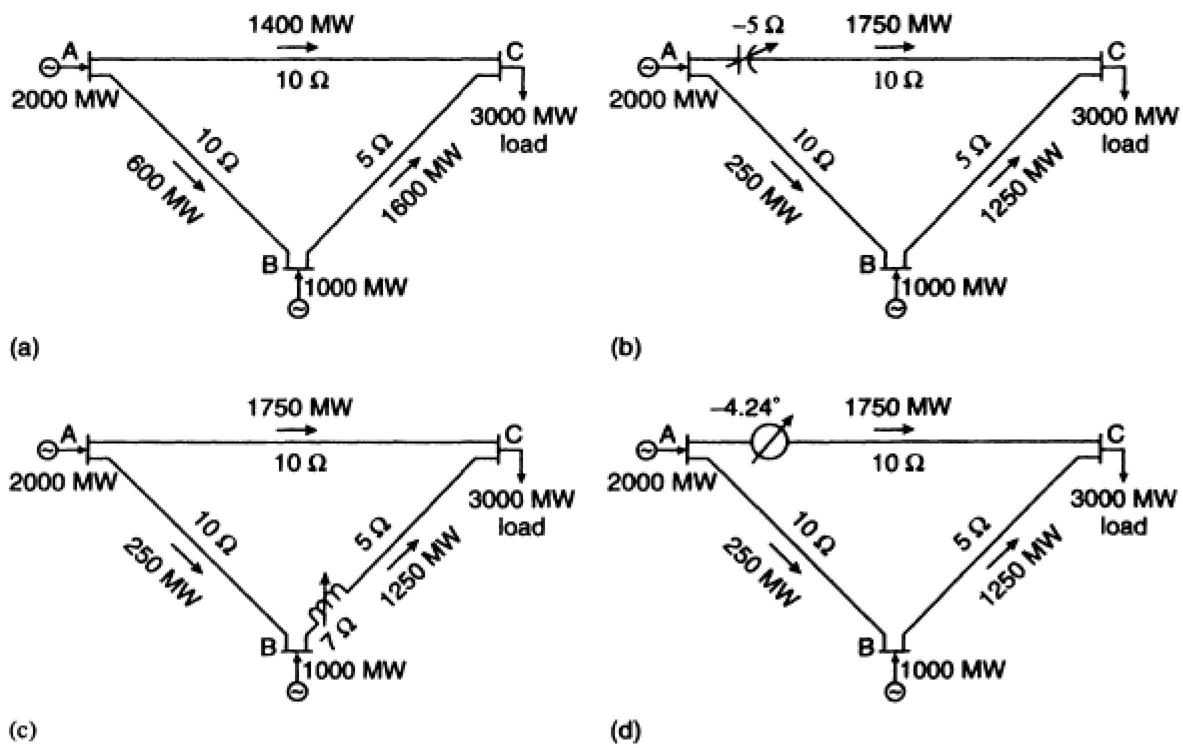


Figure 1.4 Power flow in a mesh network: (a) system diagram; (b) system diagram with Thyristor-Controlled Series Capacitor in line AC; (c) system diagram with Thyristor-Controlled Series Reactor in line BC; (d) system diagram with Thyristor-Controlled Phase Angle Regulator in line AC.

1.4 Control of Power Flow in AC Transmission Line

We may like to control the power flow in a AC transmission line to

(a) enhance power transfer capacity

(b) to change power flow under dynamic conditions to ensure system stability and security.

The stability can be affected by growing low frequency, power oscillations (due to generator rotor swings), loss of synchronism and voltage collapse caused by major disturbances.

The maximum power (P_{max}) transmitted over a line as

$$P_{\max} = \frac{V_1 V_2}{X} \sin \delta_{\max}$$

where δmax (30-40) is selected depending on the stability margins and the stifness of the terminal buses to which the line is connected. For line lengths exceeding a limit, Pmax is less than the thermal limit on the power transfer determined by the current carrying capacity of the conductors. As the line length increases, X increases in a linear fashion and Pmax reduces as shown in Fig. 1.5.

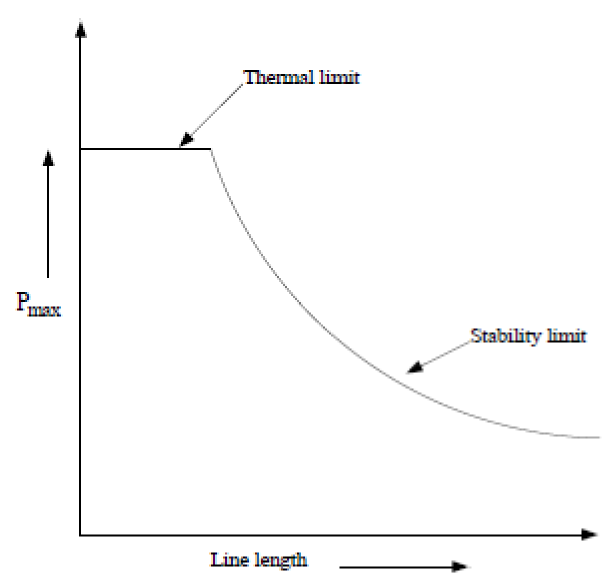


Fig.1.5 Power transfer capacity as a function of line length

The series compensation using series connected capacitors increases Pmax as the compensated value of the series reactance (Xc) is given by

$$X_c = X(1 - k_{se})$$

Fixed series capacitors have been used since a long time for increasing power transfer in long lines. They are also most economical solutions for this purpose.

The use of Thyristor Controlled Reactors (TCR) in parallel with fixed capacitors for the control of Xc, also helps in overcoming a major problem of Sub synchronous Resonance (SSR) that causes instability of torsional modes when series compensated lines are used to transmit power from turbo generators in steam power stations.

In tie lines of short lengths, the power flow can be controlled by introducing Phase Shifting Transformer (PST) which has a complex turns ratio with magnitude of unity

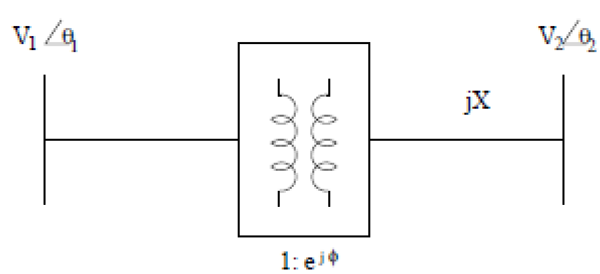


Fig1.6 A lossless line with an ideal PST

The power flow in a lossless transmission line with an ideal PST is given by

$$P = \frac{V_1 V_2}{X} \sin(\theta \pm \phi)$$

1.5 Compensation

Why Compensation Techniques are used in Power system?

Power System network consist of three kinds of powers, namely, active, reactive and apparent power. Active power is the useful or true power that performs a useful work in the system or load.

Reactive power is caused entirely by energy storage components and the losses due to reactive power may be considerable, although reactive power is not consumed by the loads.

The presence of reactive power reduces the capability of delivering the active power by the transmission lines. And the apparent power is the combination of active and reactive power.

In order to achieve maximum active power transmission, the reactive power must be compensated. This compensation is necessary for

- Improving the voltage regulation
- Increasing system stability
- Reducing the losses associated with the system
- Improving the power factor
- Better utilization of machines connected to the system

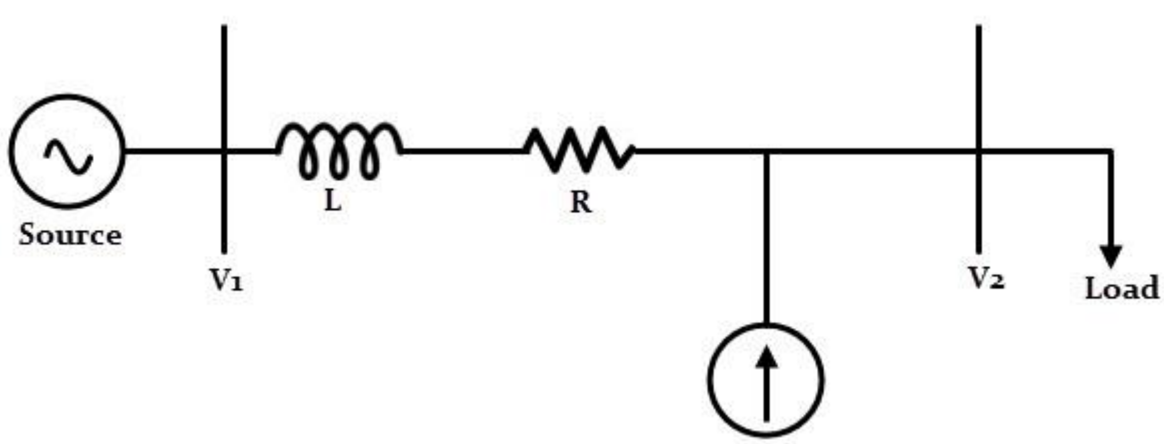
The compensation techniques of the power system supplies the inductive or capacitive reactive power (to its particular limits) in order to improve the quality and efficiency of the power transmission system. The following are the two popular compensation techniques used in power system.

Shunt Compensation

In this type of reactive power compensation, various compensation or FACTS devices (which can be either switched or controlled) are connected in parallel to the transmission lines at particular nodes.

These devices inject the current into the lines so that the reactive component of the load current is compensated thereby the losses are reduced and voltage regulation is improved.

The types of shunt compensation devices include static synchronous compensator (STATCOM) and static VAR compensator (SVC).

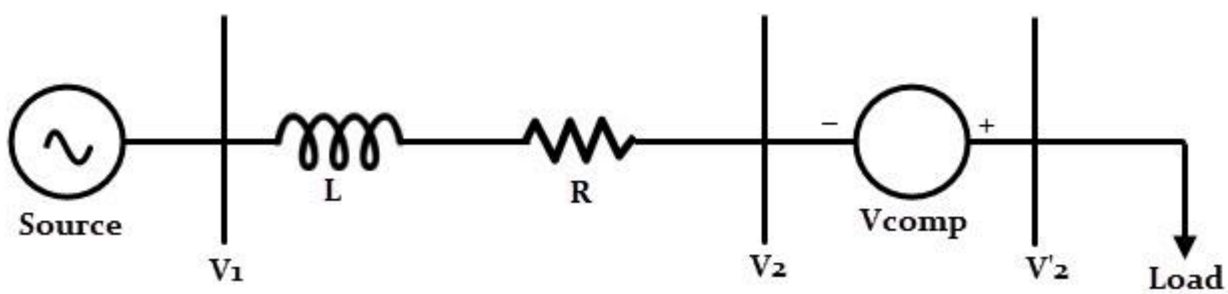


Series compensation

In this, various compensation or FACTS devices (which can be either switched or controlled) are connected in series with the transmission lines at particular nodes. This compensation will give more control of power flow through the line and also improves the dynamic stability limit of the power system.

Mostly, capacitors are installed in series with the lines. The amount of compensation is varied by installing several capacitor banks in series with the lines. This is achieved by thyristors controlled series capacitors.

Thyristor controlled switched capacitors (TCSC) and fixed series capacitor (FSC) techniques are widely used for series compensation.



Types of FACTS Controllers

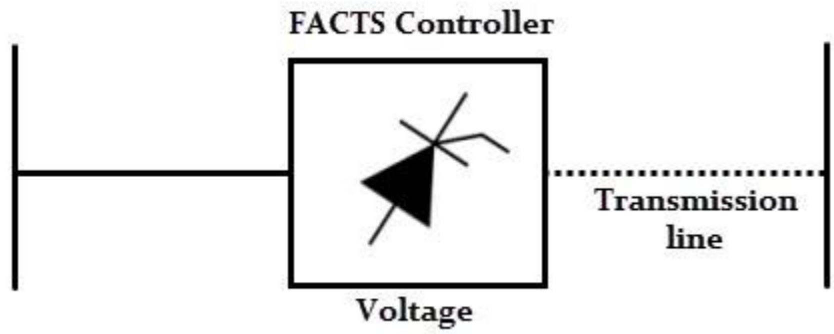
FACTS controllers are classified as

- Shunt connected controllers
- Series connected controllers
- Combined series-series controllers
- Combined shunt-series controllers

Series connected controllers

These controllers inject a voltage in series with the line. If this voltage is in phase quadrature with the current, the controller consumes or supplies variable reactive power to the network.

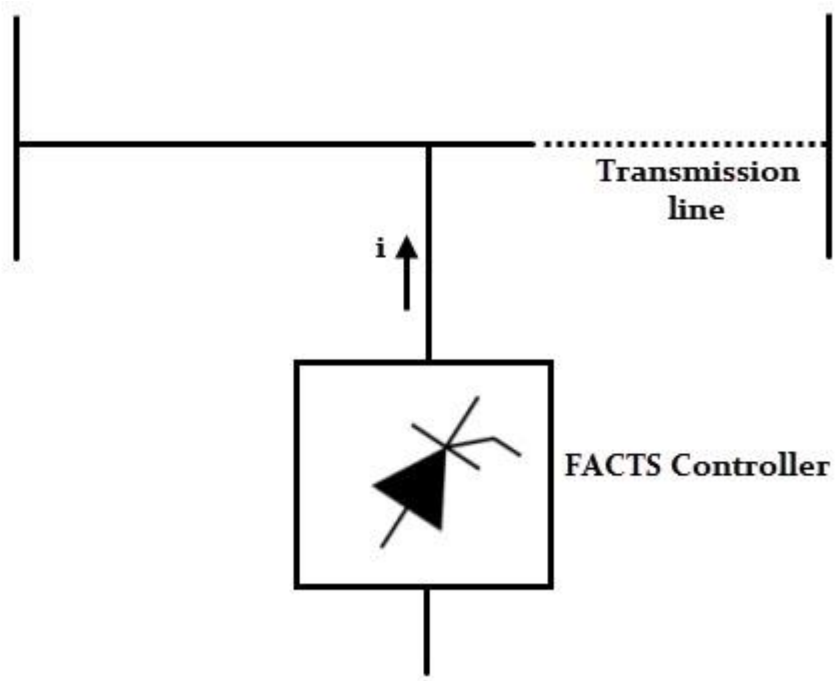
These controllers could be variable impedance such as a reactor or capacitor or a power electronic based variable source. Examples of the series controllers include SSSC, TCSR, IPFC, TSSC, TCSC, and TCSR.



Shunt connected controllers

These controllers inject a current into the system at the point of connection. If this current is in phase quadrature with the line voltage, a shunt controller consumes or supplies variable reactive power to the network.

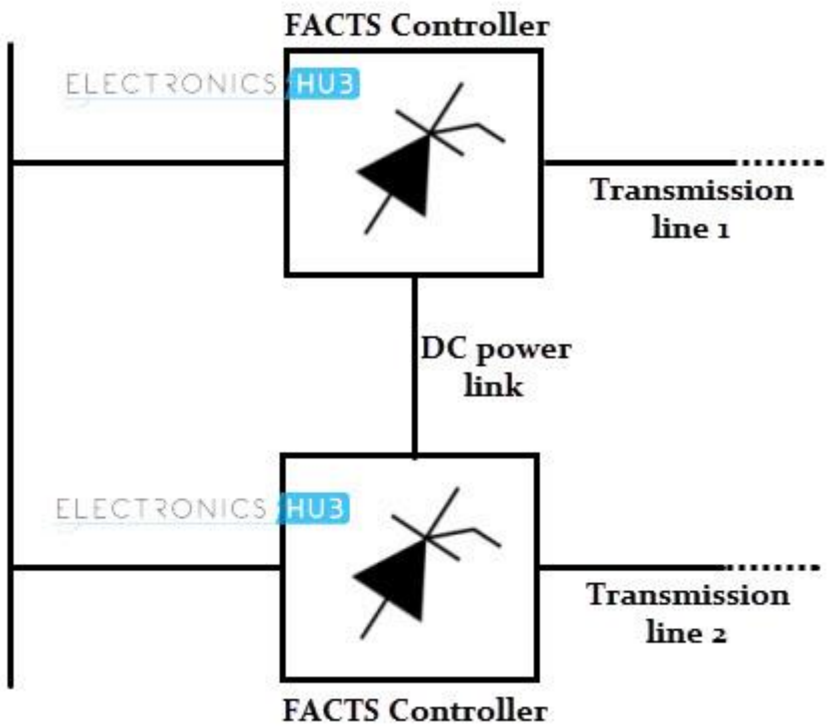
Similar to the series connected controllers, these controllers could be a variable reactor or capacitor or a power electronic based variable source. Examples of the shunt controllers include TCR, STATCOM, TSR, TCBR and TSC.



Combined series-series controllers

These controllers are the combination of individual series controllers that are controlled in a coordinated manner in multiple power transmission systems. Or these could be a unified controllers in which separate series controllers are employed in each line for series reactive power compensation and also to transfer the real power among the lines via proper link.

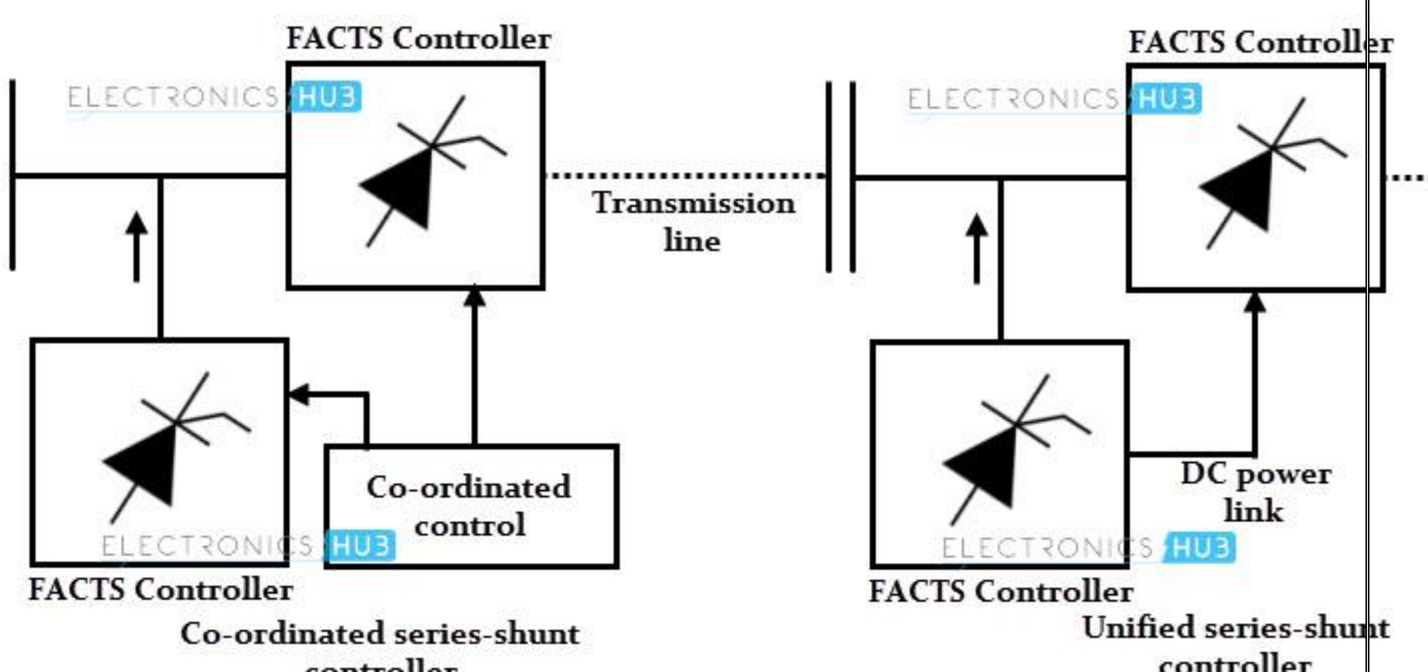
Example of this controller is IPFC that balances the real and reactive power flow in the lines in order to maximize the power transmission.



Combined series-shunt controllers

These are the combination of separate series and shunt controllers that are controlled in a coordinate manner or a unified power flow controller (UPFC) with series and shunt elements.

These combined controllers inject current into the system with series part of the controller and voltage in series in the line with shunt part of the controller. Examples of these controllers include TCPST, UPFC and TCPAR.

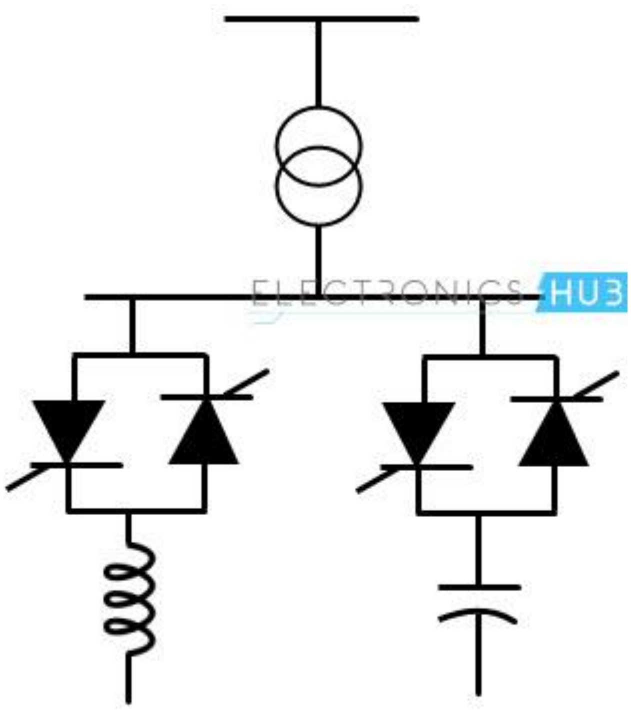


Overview of 10 FACTS Devices or Controllers

In this section we will discuss above mentioned controllers in brief.

Static Var Compensator

It is a shunt type controller which controls the power flow in transmission system and improves the transient stability of power grids. This controller regulates the voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system.

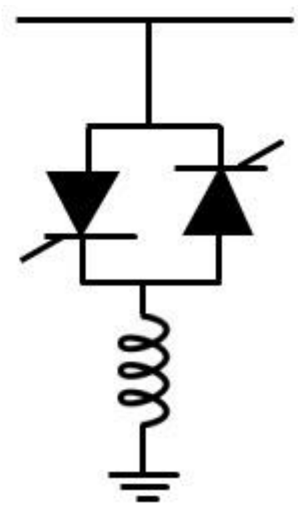


When the system voltage is low, SVC generates the reactive power and when the voltage is high it absorbs the reactive power. The reactive power is varied by switching the three phase inductor and capacitor banks. SVCs are basically thyristor controlled reactive power devices and common types of SVC are given below.

Thyristor controlled Reactor (TCR)

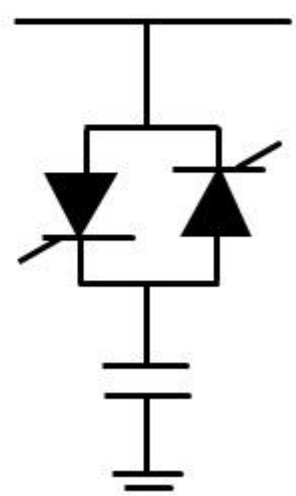
It is a shunt connected static var absorber or generator. It consists of a fixed reactor in series with bidirectional thyristor switches. The impedance of this device varied in a continuous manner by varying the conduction angles of thyristors.

The output of this device is adjusted to exchange either inductive or capacitive current. It maintains and controls the parameters (typically a bus voltage) of the power system. It is an alternative to STATCOM in terms of cost.



Thyristor Switched Capacitor (TSC)

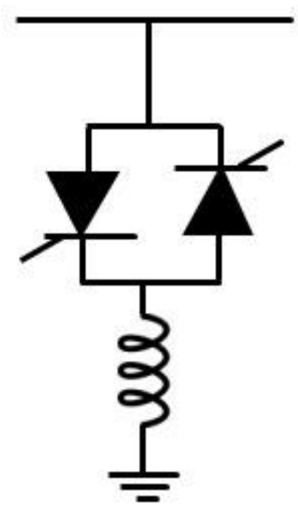
It consists of a shunt connected capacitor which is connected in series with bidirectional thyristor switches. The impedance or reactance of this device is varied in a stepwise manner by controlling the thyristors either in a zero or full conduction operation. This controller offers no harmonics, no transients, and low losses.



Thyristor Switched Reactor (TSR)

It is a special case of a TCR where phase control of the current is not exercised, instead the reactor is switched such that thyristors are either fully ON or OFF as in case of TSC. The advantage of TSR over TCR is that no harmonics current generation. Also, this controller use thyristors without firing control and hence lower cost and losses.

The reactive compensation control in electric power system use the above stated SVC types in different configuration, such as combination of TCR and TSC, combination of TCR and TSC with filter circuit and TCR with filter circuit as shown in figure.

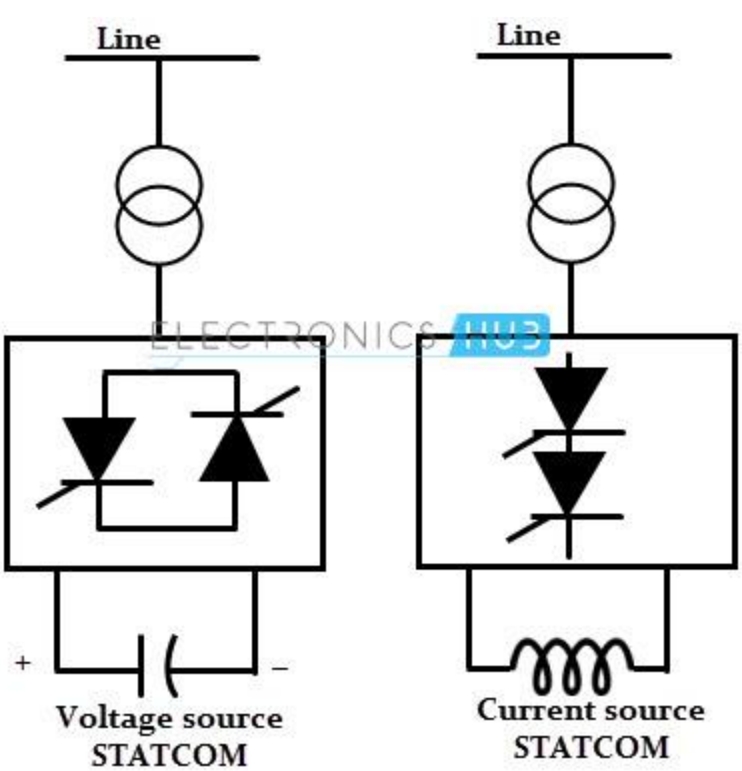


STATCOM

STATCOM means static synchronous compensator and it has the similar characteristics to that of synchronous condenser but it has no inertia as it is an electronic device.

It consists of a solid state voltage source inverter coupled with a transformer and this arrangement is tied to a transmission line. This arrangement supplies or draws reactive power at a faster rate compared with synchronous motor condenser.

This controller injects the current almost in quadrature with the line voltage, so that it matches a capacitive or an inductive reactance at the point where it is connected. STATCOM can be either voltage source or current source based controller but mostly voltage source is preferred.



Static Series Synchronous Compensator (SSSC)

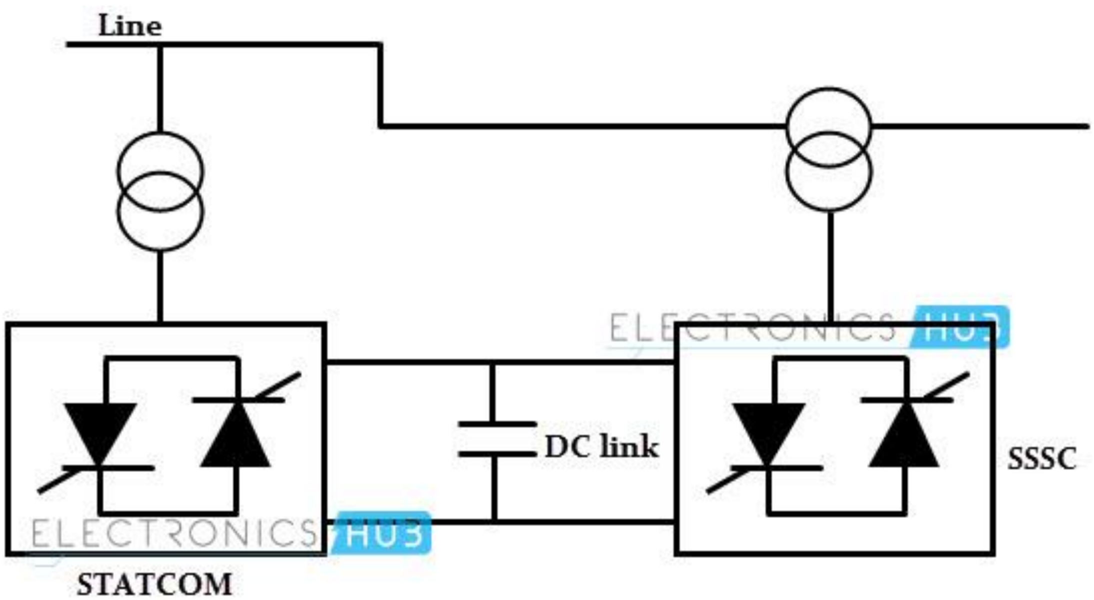
It is a series version of STATCOM and it is an advanced kind of control series compensation. It produces the output voltage in quadrature with the line current such that the overall reactive voltage drop across the line is increased or decreased.

Although it is like a STATCOM, the output voltage is in series with the line and hence it controls the voltage across the line, so its impendence. It has a capability to induce both inductive and capacitive voltage in series with the line and hence the power control.

Unified Power Flow Controller (UPFC)

UPFC is the combination of STATCOM and SSSC which are coupled by via a common DC link. It can exhibit the characteristics of both SSSC with series voltage injection and STATCOM with shunt current injection, with added features.

It has a unique ability to perform independent control of real and reactive power flow. Also, these can be controlled to provide concurrent reactive and real power series line compensation without use of an external energy source.



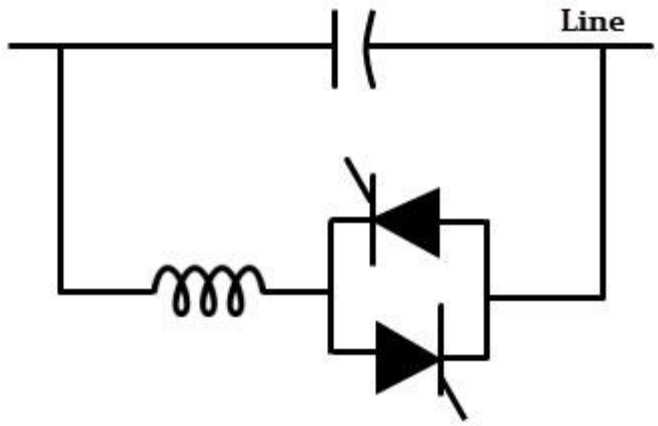
In the above UPFC, SSSC (or converter-2) injects a voltage with controllable magnitude and phase angle in series with the line though a series transformer. The function of STATCOM (or converter-1) is to absorb or supply the reactive power demanded by SSSC at the common DC link.

It can also supply or absorb the controllable reactive power to the transmission line to provide independent shunt reactive compensation.

Thyristor Controlled Series Capacitor (TCSC)

It is a capacitive reactance compensator. It consists of a series capacitor bank which connected in parallel with a thyristor controlled reactor that provides a smooth variable series capacitive reactance.

The total impedance of the system can be varied by changing the conduction angle of the thyristors and hence the circuit becomes either inductive or capacitive. If the total circuit impedance is inductive, the fault current is limited by this controller. A simple model of TCSC is shown in figure below.



Simple model of
TCSC and TSSC

Thyristor Switched Series Capacitor (TSSC)

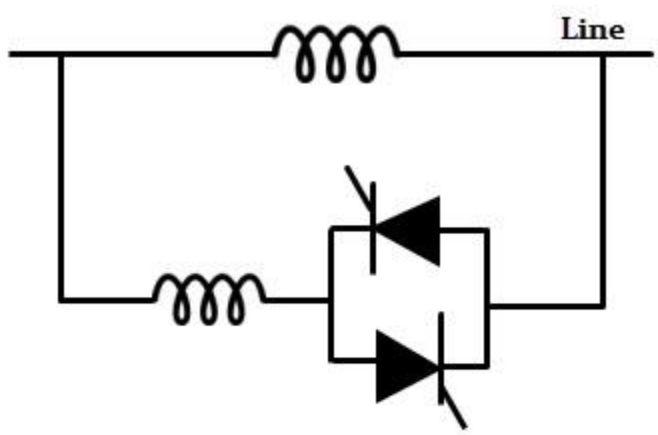
Similar to TCSC, it is also a capacitive reactance compensator consisting of thyristor switched reactor in parallel with a series capacitor. It provides the stepwise control of series capacitive reactance.

Instead of controlling in continuous manner, it switches the reactor such that the thyristors are fired at 900 and 1800. This controller can be implemented without firing angle control to reduce the cost and losses.

Thyristor Controlled Series Reactor (TCSR)

It is an inductive reactance compensator which consists of a series reactor in parallel with thyristor switched reactor. This controller provides a smooth variable inductive reactance.

When the thyristors firing angle is 180^0, the reactor stops conducting and hence the uncontrolled reactor only is in series with the line that acts as a fault current limiter. If the firing angle is below 180^0, the net (or overall) inductance decreases, thereby voltage is controlled in the network.



Simple model of
TCSR and TSSR

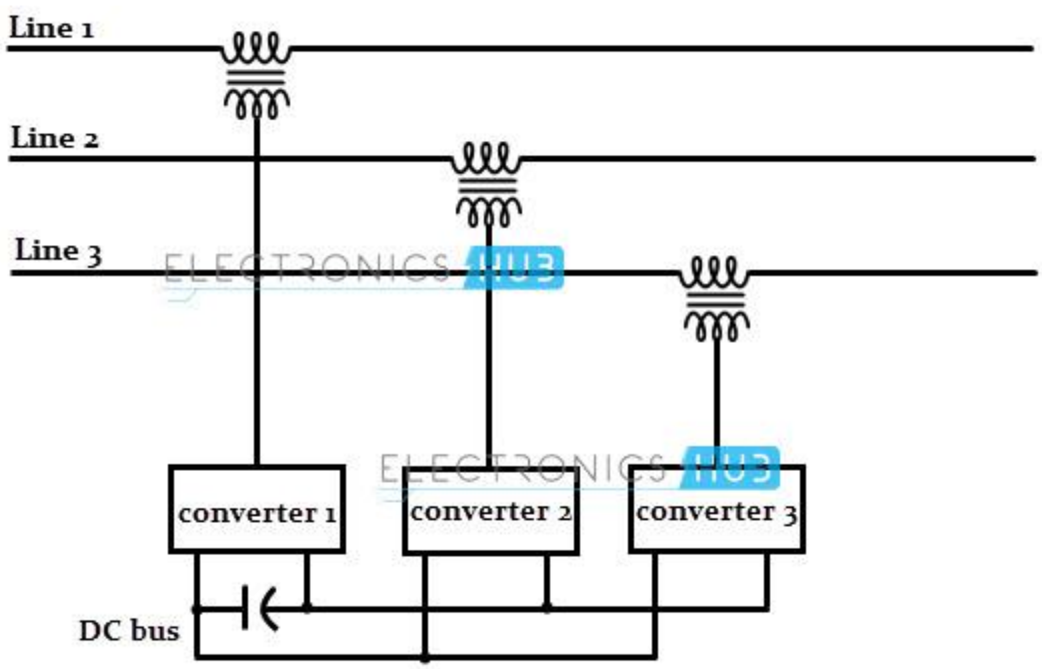
Thyristor Switched Series Reactor (TSSR)

Similar to TCSR, TSSR is also an inductive reactance compensator but it provides the stepwise control. This controller switches thyristors such that they are either fully ON or fully OFF in order to achieve stepped series inductance.

Interline Power Flow Controller (IPFC)

It is the new technique for effective power flow and compensation management of multiline transmission systems. It consists of a number of converters which are connected with a common DC link and each converter is provided for series compensation for a selected transmission line.

In addition to the reactive power compensation, this controller can able to transfer real power among the transmission lines due to a common DC link. So it is possible to equalize both real and reactive power between the lines.



Thyristor Controlled Phase Shifting Transformer (TCPST)

It is a variable phase angle controller, which consists of thyristors and phase shifting transformer. The variable phase angle control is achieved by switching the thyristor for different conduction angles.

UNIT -II

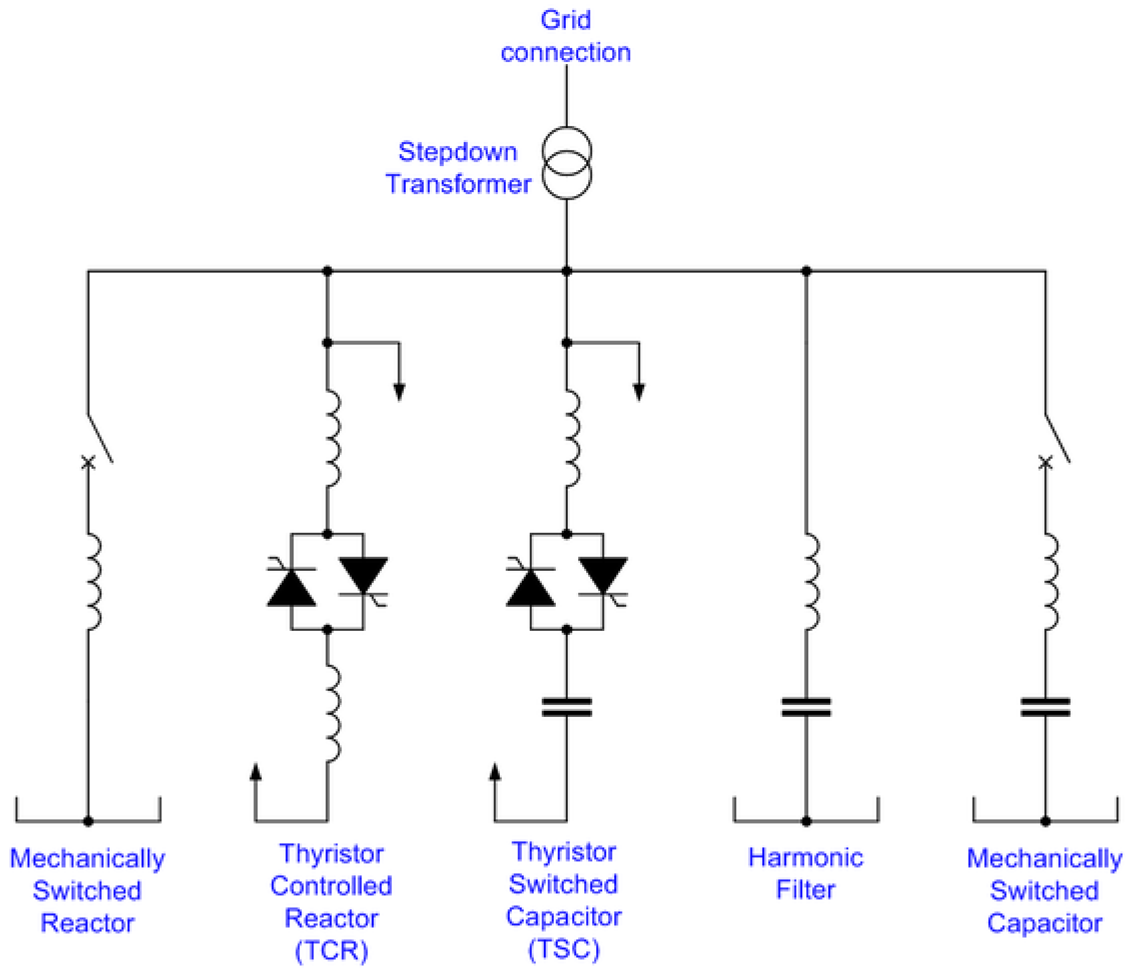
STATIC VAR COMPENSATOR (SVC)

Introduction:

The Static Var Compensator (SVC) is a device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow on power grids. The SVC regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive). The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer. Each capacitor bank is switched on and off by three thyristor switches (Thyristor Switched Capacitor or TSC). Reactors are either switched on-off (Thyristor Switched Reactor or TSR) or phase-controlled (Thyristor Controlled Reactor or TCR).

Typically, an SVC comprises one or more banks of fixed or switched shunt capacitors or reactors, of which at least one bank is switched by thyristors. 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 (switched by a circuit breaker)



One-line diagram of a typical SVC configuration; here employing a thyristor controlled reactor, a thyristor switched capacitor, a harmonic filter, a mechanically switched capacitor and a mechanically switched reactor

By means of phase angle modulation switched by the thyristors, the reactor may be variably switched into the circuit and so provide a continuously variable VAR injection (or absorption) to the electrical network.[2] In this configuration, coarse voltage control is provided by the capacitors; the thyristor-controlled reactor is to provide smooth control. Smoother control and more flexibility can be provided with thyristor-controlled capacitor switching.[7]

The thyristors are electronically controlled. Thyristors, like all semiconductors, generate heat and deionized water is commonly used to cool them.[5] Chopping reactive load into the circuit in this manner injects undesirable odd-order harmonics and so banks of high-power filters are usually provided to smooth the waveform. Since the filters themselves are capacitive, they also export MVARs to the power system.

More complex arrangements are practical where precise voltage regulation is required. Voltage regulation is provided by means of a closed-loop controller.[7] Remote supervisory control and manual adjustment of the voltage set-point are also common.

Advantages:

The main advantage of SVCs over simple mechanically switched compensation schemes is their near-instantaneous response to changes in the system voltage.[7] 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.

They are, in general, cheaper, higher-capacity, faster and more reliable than dynamic compensation schemes such as synchronous condensers.[7] However, static VAR compensators are more expensive than mechanically switched capacitors, so many system operators use a combination of the two technologies (sometimes in the same installation), using the static VAR compensator to provide support for fast changes and the mechanically switched capacitors to provide steady-state VARs.

2.2 ADVANTAGES OF THE SLOPE IN THE SVC DYNAMIC CHARACTERISTICS

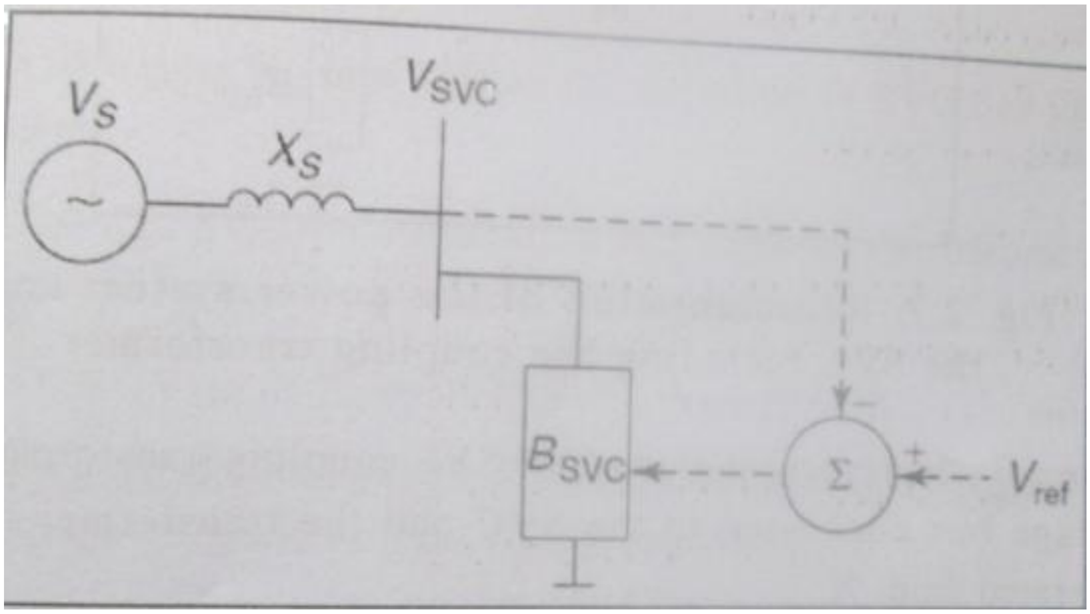
1. Substantially reduces the reactive-power rating of the SVC for achieving nearly the same control objectives.
2. Prevents the SVC from reaching its reactive-power limits too frequently.
3. Facilitates the sharing of reactive power among multiple compensators operating in parallel.

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

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

On substitution

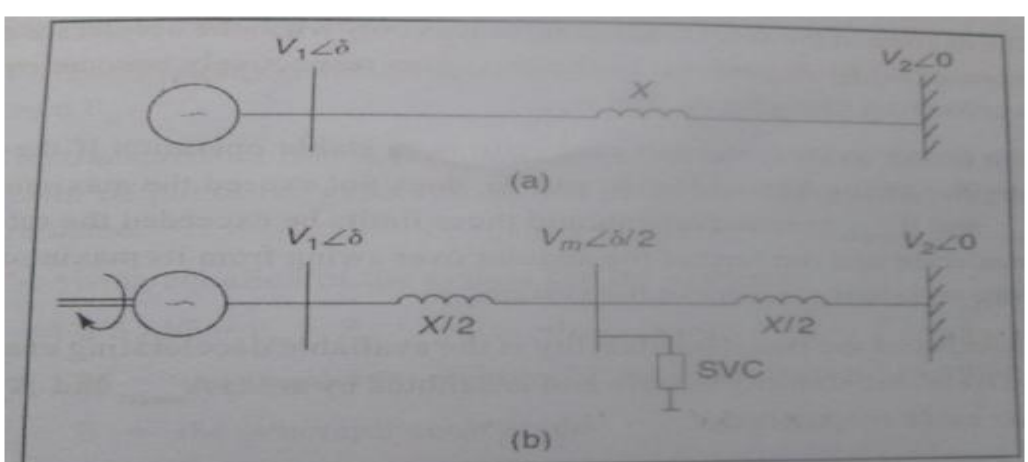
$\Delta V_{SVC} / \Delta B_{SVC} = -\, V_{SVC0} / (ESCR + B_{SVC0})$

Where ESCR = Effective short circuit Ratio

Representation of power system and the SVC including the coupling transformer

Enhancement of Transient Stability

Power-angle curves



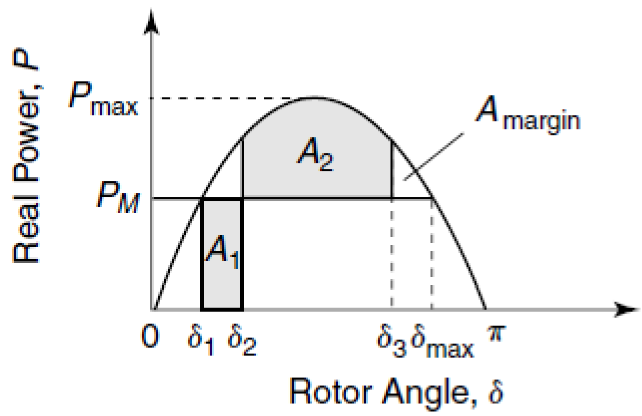
The SMIB system: (a) an uncompensated system (b) an SVC-compensated system

An enhancement in transient stability is achieved primarily through voltage control exercised by the SVC at the interconnected bus.

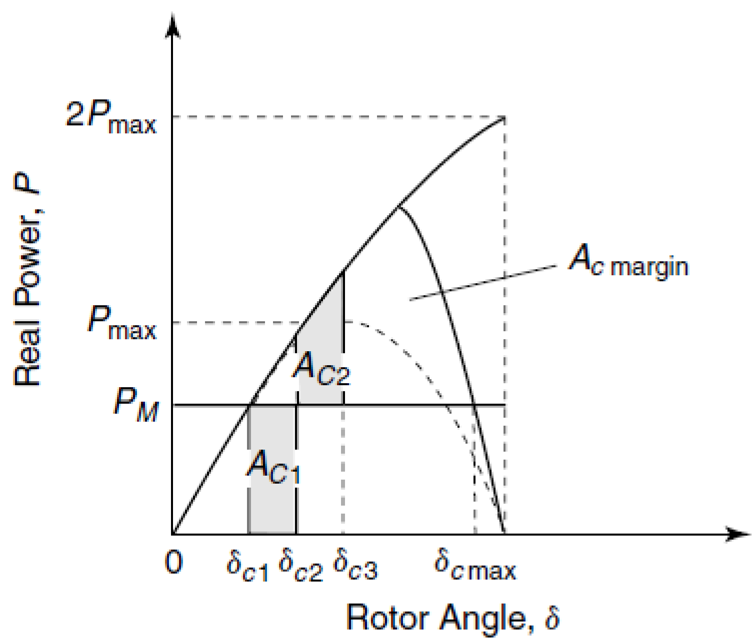
- A simple understanding of this aspect can be obtained from the power-angle curves, of the uncompensated and midpoint SVC–compensated SMIB system.
- Consider both the uncompensated and SVC-compensated power system depicted in Fig.
- Assume that both systems are transmitting the same level of power and 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 δ_3 and $\delta c3$ from the stored kinetic energy in the rotor.
- The decline in the rotor angle commences only when the decelerating energies represented by A_2 and A_{C2} in the two cases, respectively, become equal to the accelerating energies A_1 and A_{C1}.
- The power system in each case returns to stable operation if the post-fault angular swing, denoted by d_3 and d_{C3}, does not exceed the maximum limit of d_{max} and dc max, respectively. Should these limits be exceeded, the rotor will not decelerate.
- The farther the angular overswing from its maximum limit, the more transient stability in the system.
- An index of the transient stability is the available decelerating energy, termed the *transient-stability margin*, and is denoted by areas A_{margin} and A_c margin in the two cases, respectively. Clearly, as Ac margin significantly exceeds A_{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

ΔPM =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 Ks 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 *KS* 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.

Steady State Power Transfer Capacity

- An SVC can be used to enhance the power-transfer capacity of a transmission line, which is also characterized as the steady-state power limit.

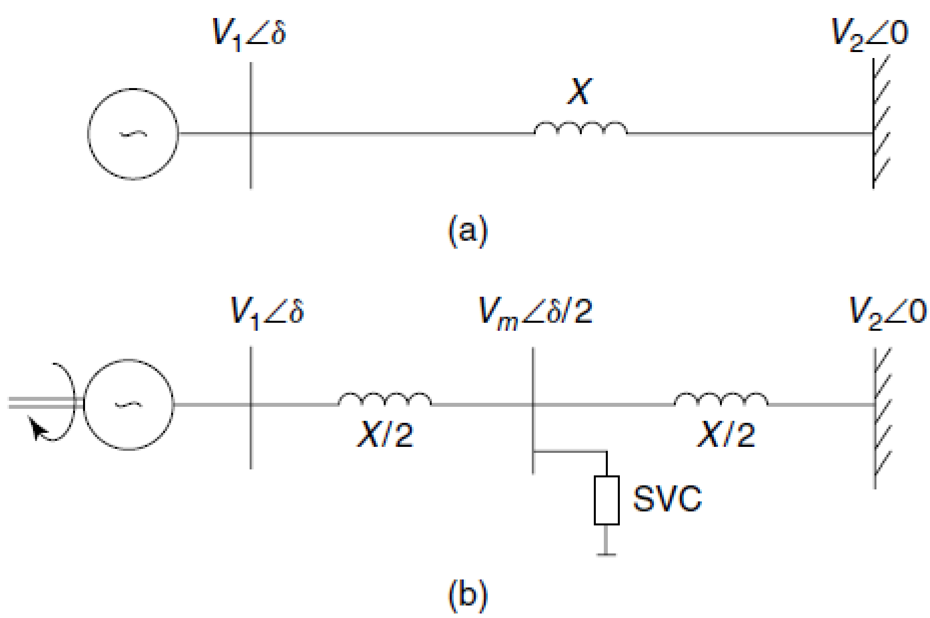
➢ Consider a single-machine infinite-bus (SMIB) system with an interconnecting lossless tie line having reactance *X* shown in Fig.

➢ Let the voltages of the synchronous generator and infinite bus be V_1/–δ and V_2/–δ, respectively. The power transferred from the synchronous machine to the infinite bus is expressed as

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

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

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

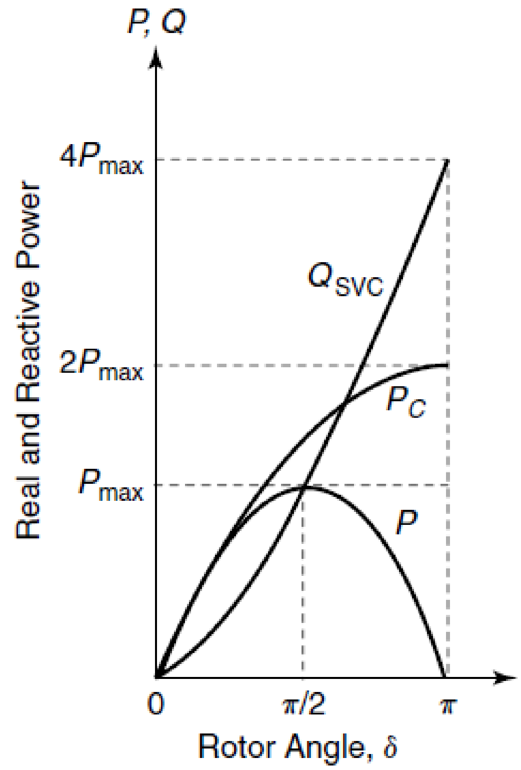


The SMIB system: (a) an uncompensated system (b) an SVC-compensated system

➢ The power thus varies as a sinusoidal function of the angular difference of the voltages at the synchronous machine and infinite bus, as depicted in Fig.

➢ The maximum steady-state power that can be transferred across the uncompensated line without SVC corresponds to $\delta = 90_0$; it is given by

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



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

Let the transmission line be compensated at its midpoint by an ideal SVC.

- The term *ideal* corresponds to an SVC with an unlimited reactive-power rating that can maintain the magnitude of the midpoint voltage constant for all real power flows across the transmission line.
- The SVC bus voltage is then given by $V_m\angle\delta/2$.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

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

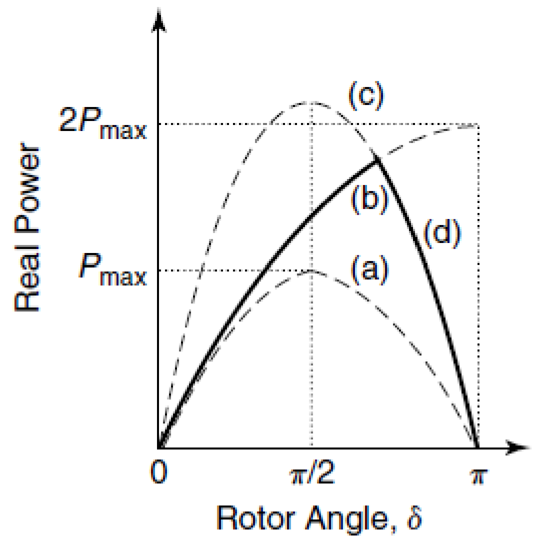
which is twice the maximum power transmitted in the uncompensated case and occurs at $\delta/2 = 90^0$.

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

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



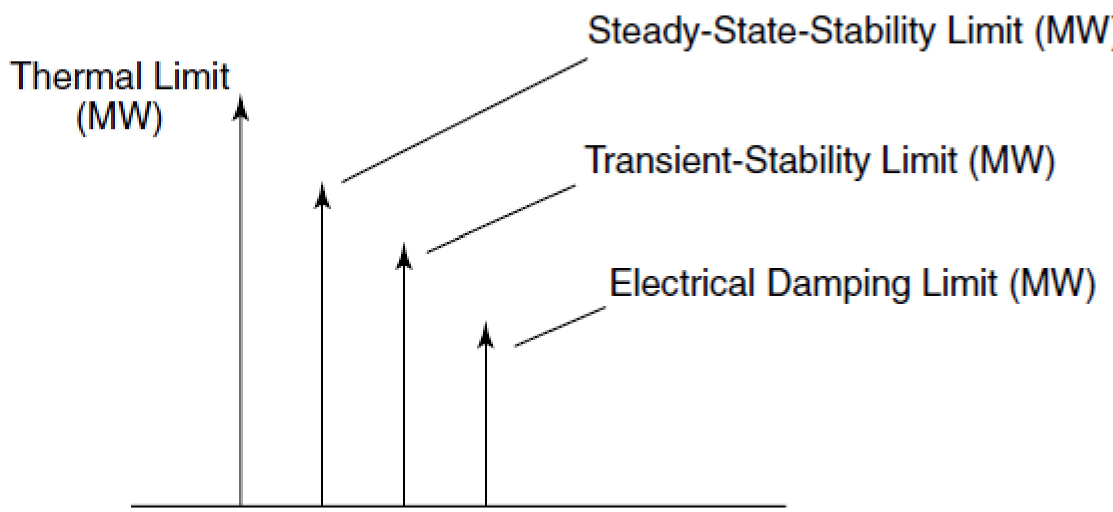
Power angle curve of a SMIB system☹a) uncompensated (b) ideal midpoint SVC unlimited rating curve (c) fixed capacitor connected at its midpoint (d) midpoint SVC limited rating curve
➢ This curve is based on the corresponding equivalent reactance between the synchronous generator and the infinite bus.

If an SVC incorporating a limited-rating capacitor as in the preceding text (QSVC _ 2Pmax) 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 2Pmax 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

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

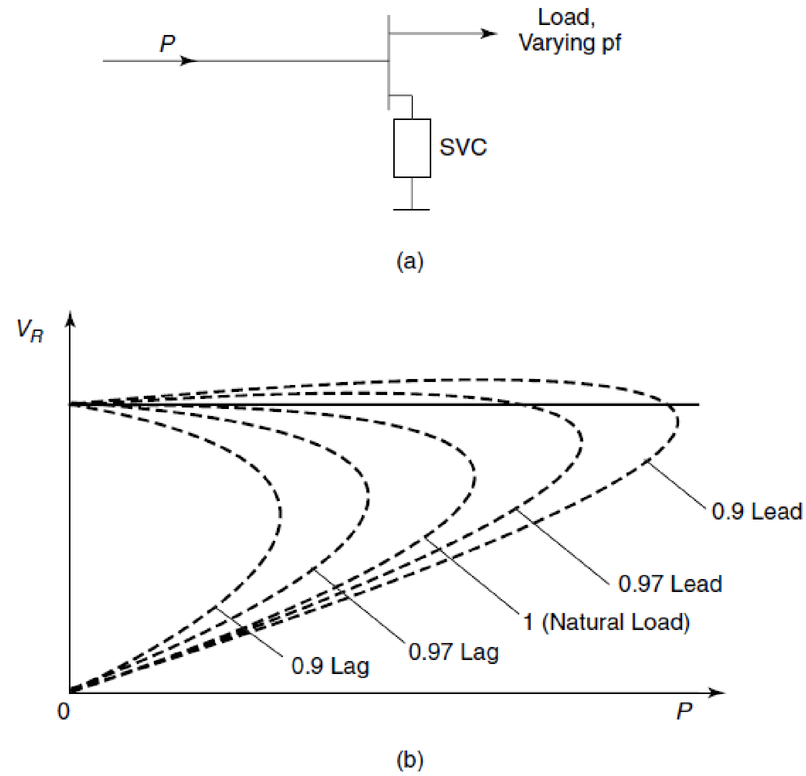


Fig: (a) An SVC connected at the load bus by a radial transmission line supplying a load and (b)the voltage profile at the receiving end of a loaded line with a varying power factor load.

Modeling of static VAR Compensator for stability studies:

The static VAR compensator (SVC) has been accurately incorporated into the structure preserving energy function (SPEF) with a detailed generator model including flux decay and transient saliency, automatic voltage regulator (AVR) and damper winding. The SVC can be modelled for transient stability studies using the steady-state control characteristic and is treated as a voltage-dependent reactive power load. This simplifies simulation and results in the derivation of an exact path-independent energy function to account for the effect of the SVC inclusive of its limits.

There is also a growing interest in the application of static var compensators (SVCs) to increase the transient stability power limit, prevent voltage instability and to control severe overvoltages 11. The use of SVC at strategic locations in the bulk power transmission system distant from generators can improve stability beyond that achievable with rapid voltage control at generator terminals only. This is mainly due to its high speed of response and continuous control.

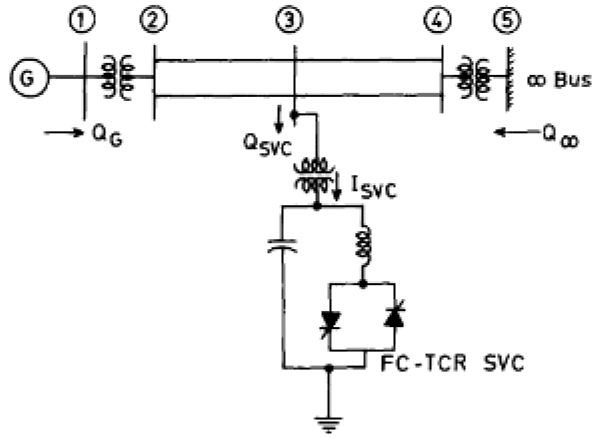
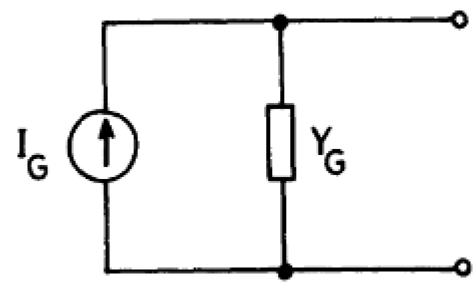


Fig: **Sample study system**



UNIT-III

THYRISTOR AND GTO THYRISTOR CONTROLLED SERIES CAPACITORS (TCSC and GCSC)

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.

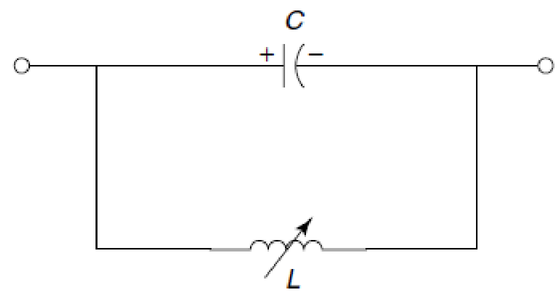


Fig: A Variable inductor connected in shunt with an FC

3.1.2 DIFFERENT MODES OF OPERATION

1. **Bypassed Thyristor mode:**

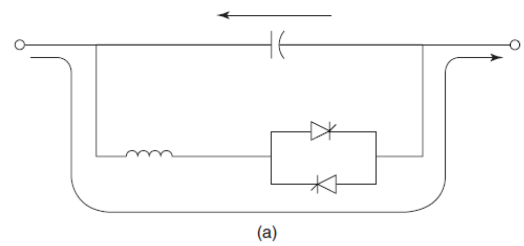


Fig: The bypassed thyristor mode

In this bypassed mode, the thyristors are made to fully conduct with a conduction angle of 180. Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous 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:

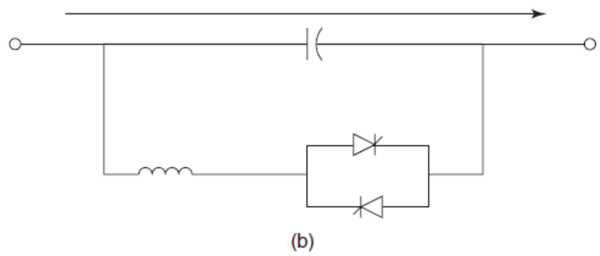
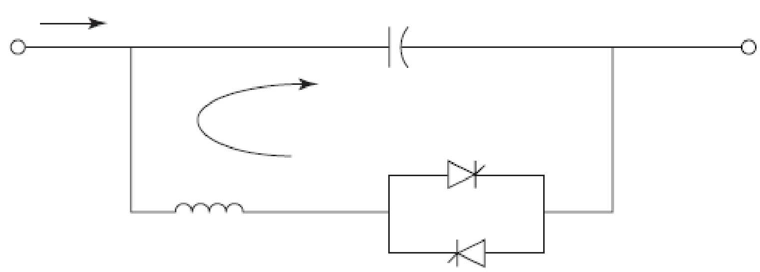


Fig: The blocked thyristor mode

- 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 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 α min ≤ α ≤ 1800.

 This constraint provides a continuous vernier control of the TCSC module reactance. The loop current increases as α is decreased from 1800 to α 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 (=XTCSC/ XC) is less than 1.5.

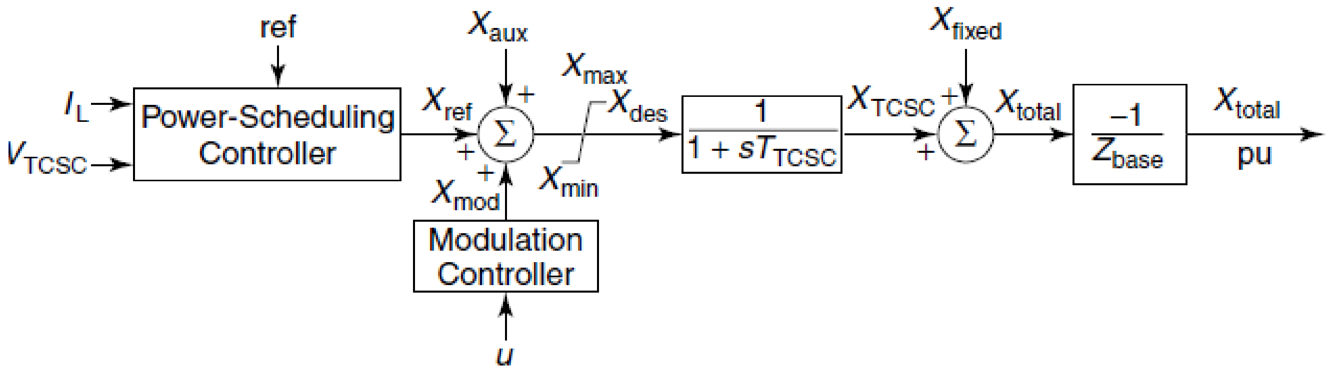


Fig: Block diagram of the variable reactance model of the TCSC

3.2.1.2 Transient – Stability Model:

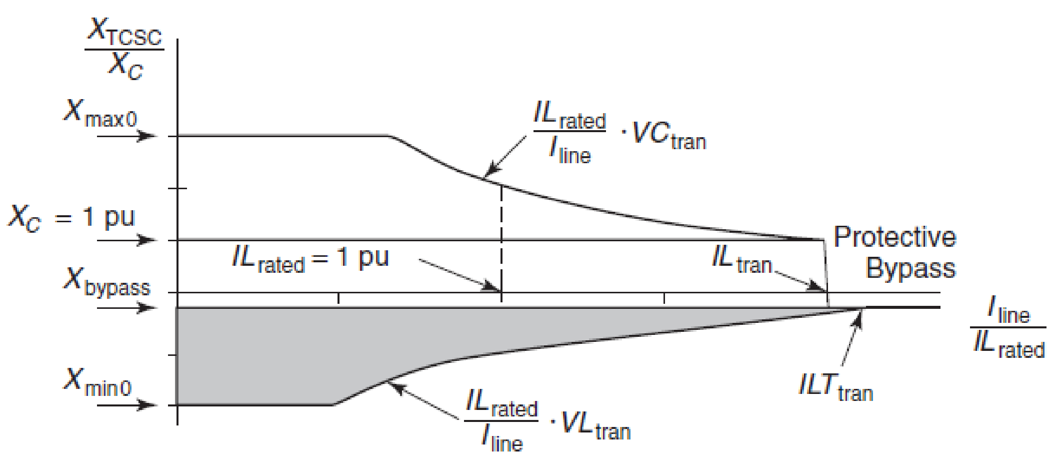


Fig: The X – I capability characteristic for a multi module TCSC

➢ 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 XTCSC 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

$$Z_{\text{base}} = \frac{(\text{kV}_{\text{TCSC}})^2}{\text{MVA}_{\text{sys}}}$$

where ,
kV_{TCSC} = the rms line–line voltage of the TCSC in kilovolts (kV)
MVA_{sys} = the 3-phase MVA base of the power system.

The TCSC model assigns a positive value to the capacitive reactance, so *X*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*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*rated. *XC* 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*max 0.
2. The limit on the TCSC voltage *VC*tran. The corresponding reactance constraint is given by

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

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

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

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

In the inductive region, the TCSC operation is restricted by the following limits:

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

o The limit on the firing angle, represented by a constant-reactance limit Xmin 0.

o The harmonics-imposed limit, represented by a constant-TCSC-voltage limit VLtran. 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

δ = 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.
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 η_1 and φ_1, respectively; of machine SM_2, denoted by η_2 and φ_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 ΔP_{mod}.
- The incremental variation of the line-power flow DP, given in megawatts (MW), with respect to DQTCSC, given in MVAR, is as follows

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

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

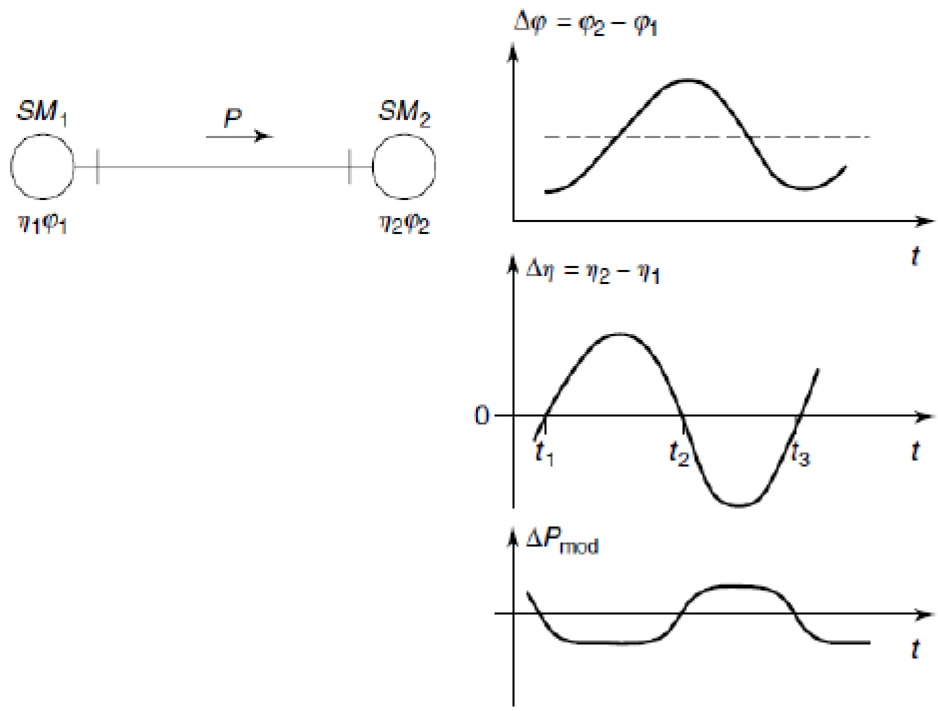


Fig:The TCSC line power modulation for damping enhancement

➢ 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,

$\boldsymbol{\Delta P_m = \Delta P}$.

- 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.

UNIT-IV
VOLTAGE SOURCE CONVERTER BASED 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

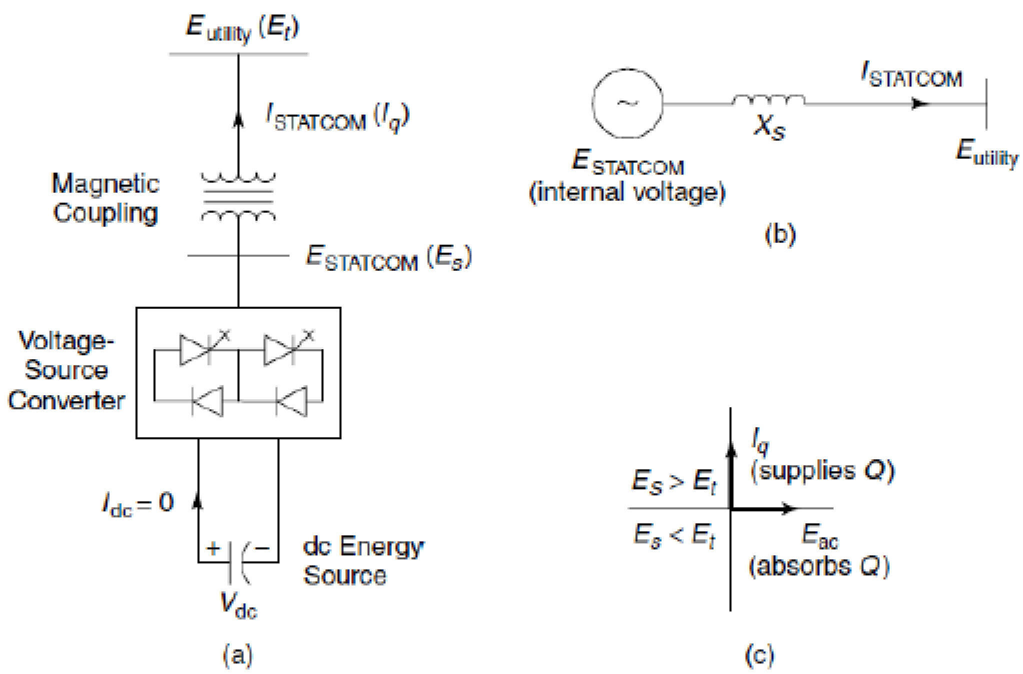
- A STATCOM is a controlled reactive-power source. It provides the desired reactive-power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC).
- A single-line STATCOM power circuit is shown in Fig.(a),where a VSC 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.

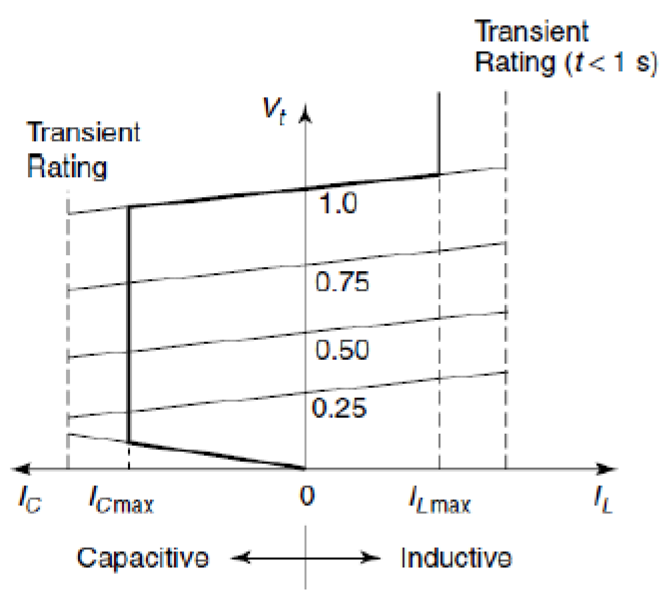
➢ On the other hand, it can absorb real power from the ac system for the dc system if its voltage lags behind the ac-system voltage.

- 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 real power 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.

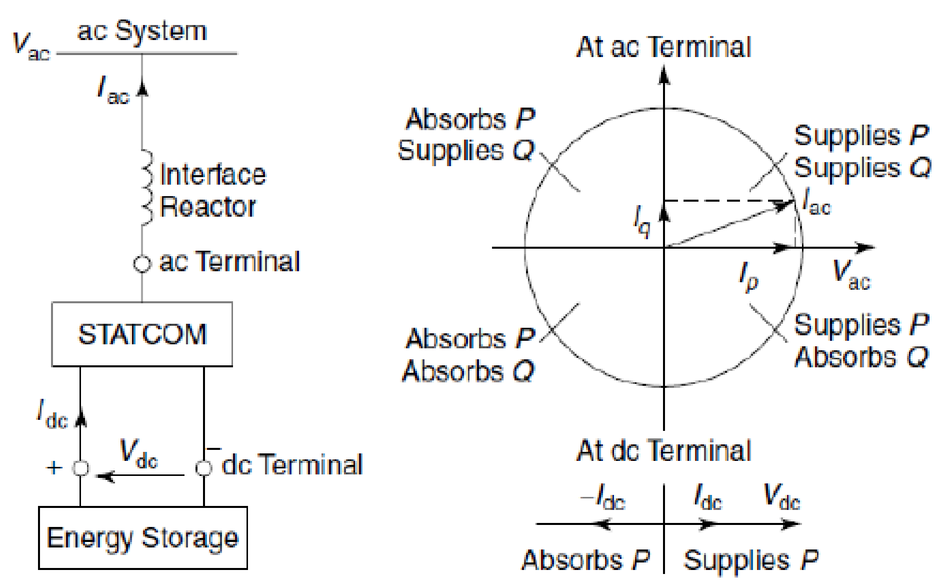


Fig: The power exchange between the STATCOM and the ac system

4.4 Unified Power Flow Controller (UPFC):

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

4.2.1Principle 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.

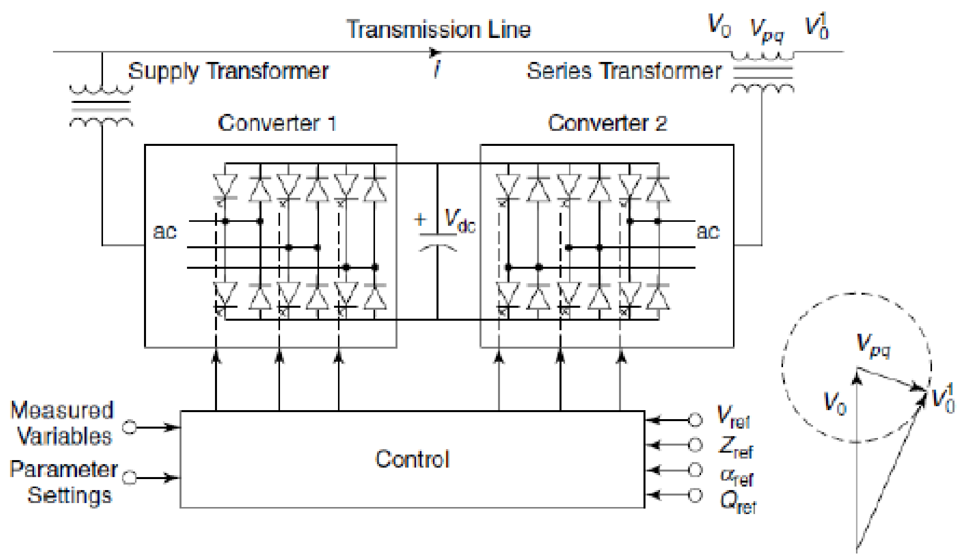


Fig: The implementation of the UPFC using two "back – to –back" VSCs with a common DC-terminal capacitor

- 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

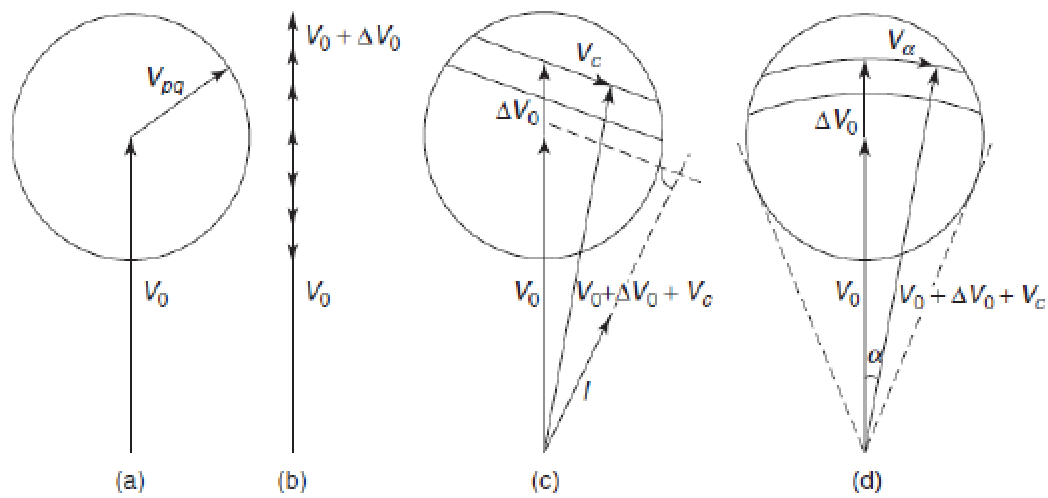


Fig:The phasor diagram illustrating the general concept of sries-voltage injection and attainable power flow control functions a) Series-voltage injection;(b)terminal-voltage regulation;(c)terminal-voltage and line-impedance regulation and (d) terminal-voltage and phse-angle regulation

The concepts of various power-flow control functions by use of the UPFC are illustrated in Fig(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

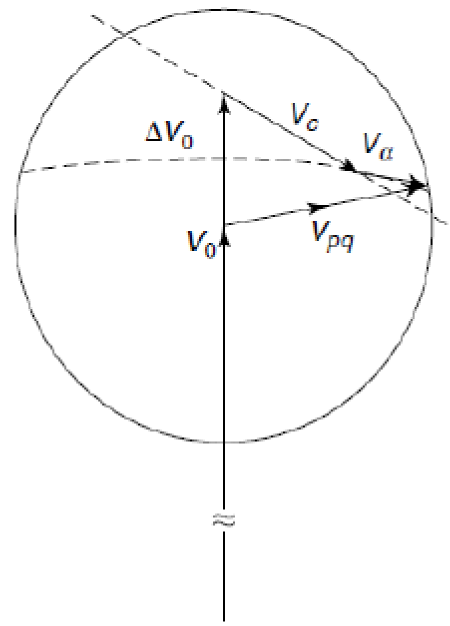


Fig:A phasor diagram illustrating the simultaneous regulaiton of the terminal voltage, line impedance, and phase angle by appropriate series-voltage injection

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.

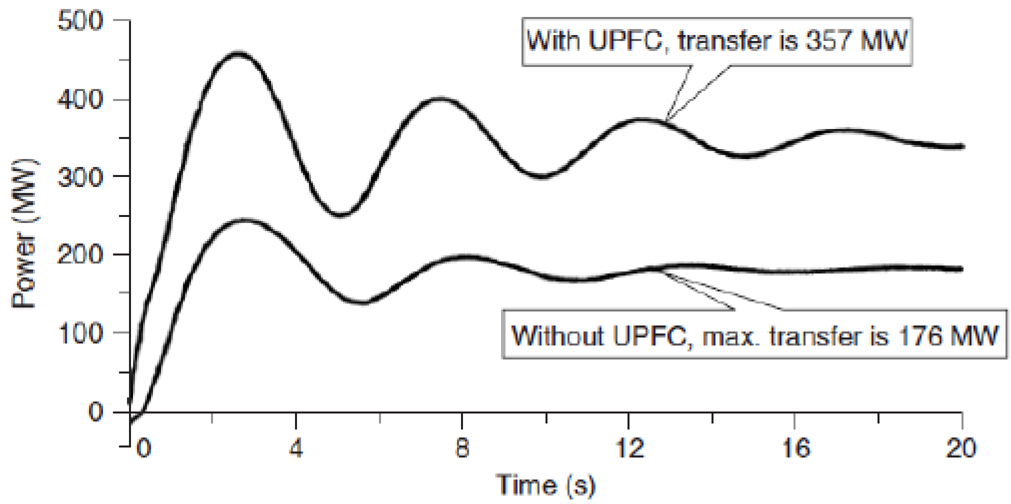
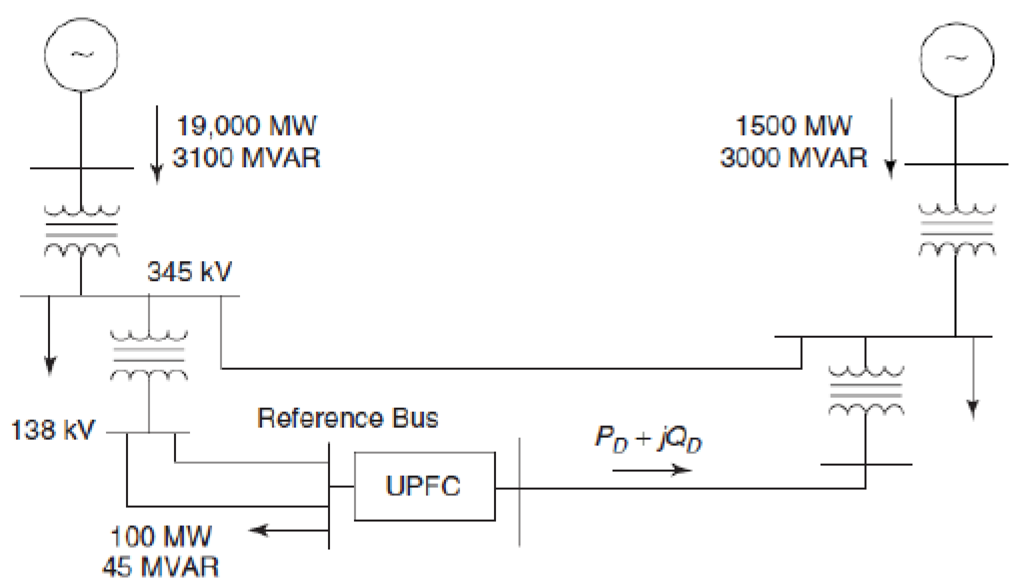


Fig: Power-transfer capability curve with the UPFC

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 depicts 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

CONTROLLERS AND THEIR COORDINATION

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.