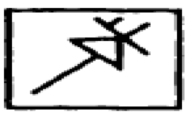
BEE016 FLEXIBLE AC TRANSMISSION SYSTEMS

Flexible AC Transmission System (FACTS):

- Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability.

FACTS Controller:

- A power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters.



General symbol of FACTS controller

BENEFITS FROM FACTS TECHNOLOGY

- Control of power flow as ordered.
- Increase the loading capability of lines to their thermal capabilities, including short term and seasonal.
- Increase the system security through raising the transient stability limit, limiting short-circuit currents and overloads, managing cascading blackouts and damping electromechanical oscillations of power systems and machines.
- Provide secure tie line connections to neighboring utilities and regions thereby decreasing overall generation reserve requirements on both sides.
- Provide greater flexibility in siting new generation.
- Reduce reactive power flows, thus allowing the lines to carry more active power.
- Increase utilization of lowest cost generation.

Basic types of FACTS Controllers

Based on the connection, generally FACTS controller can be classified as follows:

Series controllers

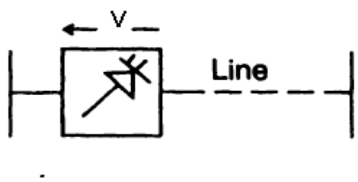
Shunt controllers

Combined series-series controllers

Combined series-shunt controllers

Series controllers

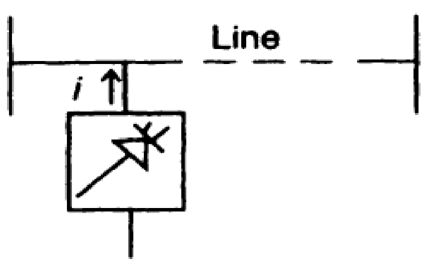
The series controller could be a variable impedance or a variable source, both are power electronics based devices to serve the desired needs. In principle, all series controllers inject voltage in series with the line.



General symbol of Series controller

Shunt controllers

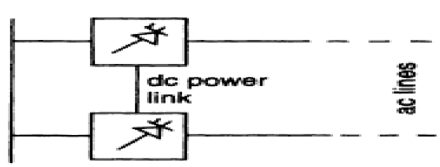
The shunt controllers may be variable impedance, variable sources or combination of these. In principle, all shunt Controllers inject current into the system at the point of connection. As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies or consumes variable reactive power



General symbol of Shunt controller

Combined series-series controllers:

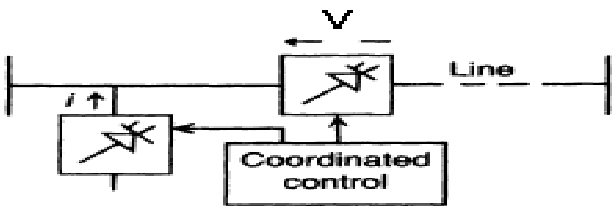
The combination could be separate series controllers or unified series-series controller. Series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link- Interline Power Flow Controller



Symbol of Series- Series controller

Combined series-shunt controllers:

- The combination could be separated series and shunt controllers or a unified power flow controller. In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller.



Symbol of Series- Shunt controller

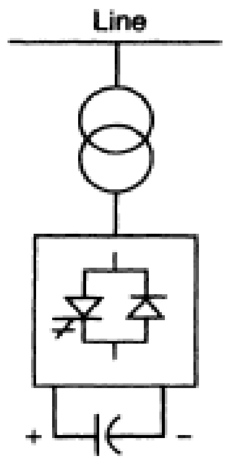
Shunt connected controllers

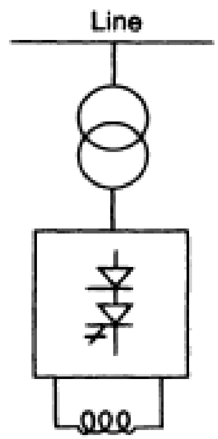
- *Static Synchronous Generator (SSG)*
- *Static Synchronous Compensator (STATCOM)*
- Battery *Energy* Storage *System (BESS)*
- *Superconducting Magnetic Energy* Storage (SMES)
- *Static Var Compensator (SVC)*
- *Thyristor Controlled Reactor (TCR)*
- *Thyrlstor Swltched Reactor (TSR)*
- *Thyristor Switched Capacitor (TSC)*
- *Static Var Generator or Absorber (SVG)*

Thyristor Controlled Braking Resistor (TCBR

Static Synchronous Compensator (STATCOM):

A Static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage

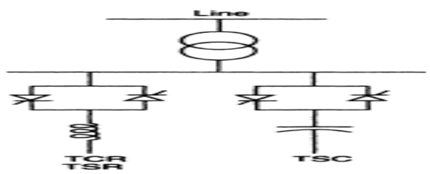




STATCOM based on voltage-sourced converters **STATCOM based on current-sourced converters**

Static Var Compensator (SVC):

❖ A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).



✓ The thyristor-controlled reactor (TCR) or thyristor-switched reactor (TSR) for absorbing reactive power and thyristor-switched capacitor (TCS) for supplying the reactive power.

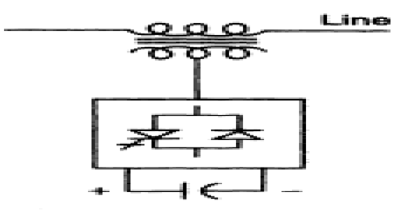
✓ SVC is considered by some as a lower cost alternative to STATCOM.

Series connected controllers

- Static Synchronous Series Compensator (SSSC)
- Interline Power Flow Controller (IPFC)
- Thyristor Controlled Series Capacitor (TCSC)
- Thyristor-Switched Series Capacitor (TSSC)
- Thyristor-Controlled Series Reactor (TCSR)
  Thyristor-Switched Series Reactor (TSSR)

Static Synchronous Series Compensator (SSSC):

- *In a Static Synchronous Series Compensator, output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line*

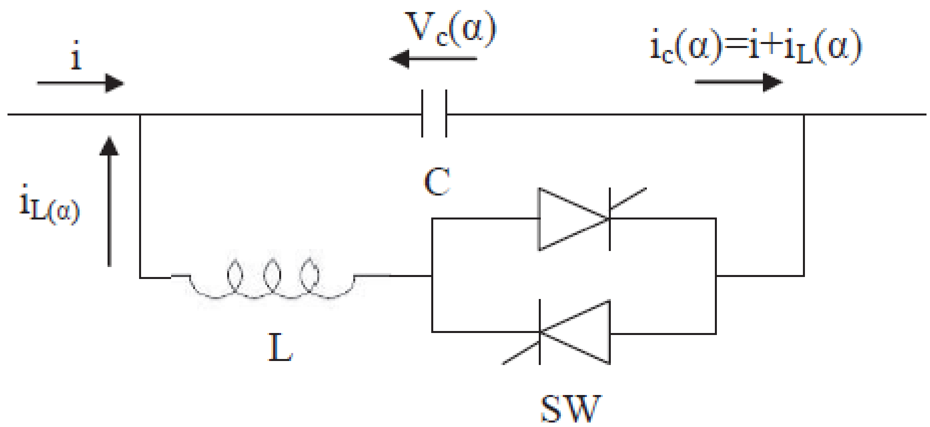


It is like a STATCOM, except that the output ac voltage is in series with the line.

TCSC

- TCSC is a series compensating FACTS device using to control power flow in transmission lines and improves transient stability in power system.
- It controls the effective line reactance by connecting a variable reactance in series with line.

- It is a capacitive/ inductive reactance compensator which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive/ inductive reactance.
- TCSC controls the power flow in transmission lines by varying the impedance of TCSC by controlling the delay angle of thyristor valves.
- The basic scheme of TCSC is shown in Fig.



- A TCSC is typically made up of the following major components:
  - A series compensating capacitor (C)
  - Bypass inductor (L)
  - Back to back thyristors (SW)
- The degree of TCSC compensation is controlled by the size of capacitor C. Thyristors are used to transform the equivalent impedance of TCSC which fulfills the need in improving the stability increasing the transmission capability, restraining hypo-synchronization resonance etc.
- The basic idea behind power flow control with the TCSC is to decrease or increase the overall lines effective series transmission impedance, by adding a capacitive or inductive reactive correspondingly. In capacitive mode TCSC reduces the transfer reactance between the buses at which the line is connected and increases the maximum power that can be transmitted.
- TCSC is that of a parallel LC circuit, consisting of a fixed capacitive impedance, Xc,and a variable inductive impedance, $X_L(\alpha)$, that is,

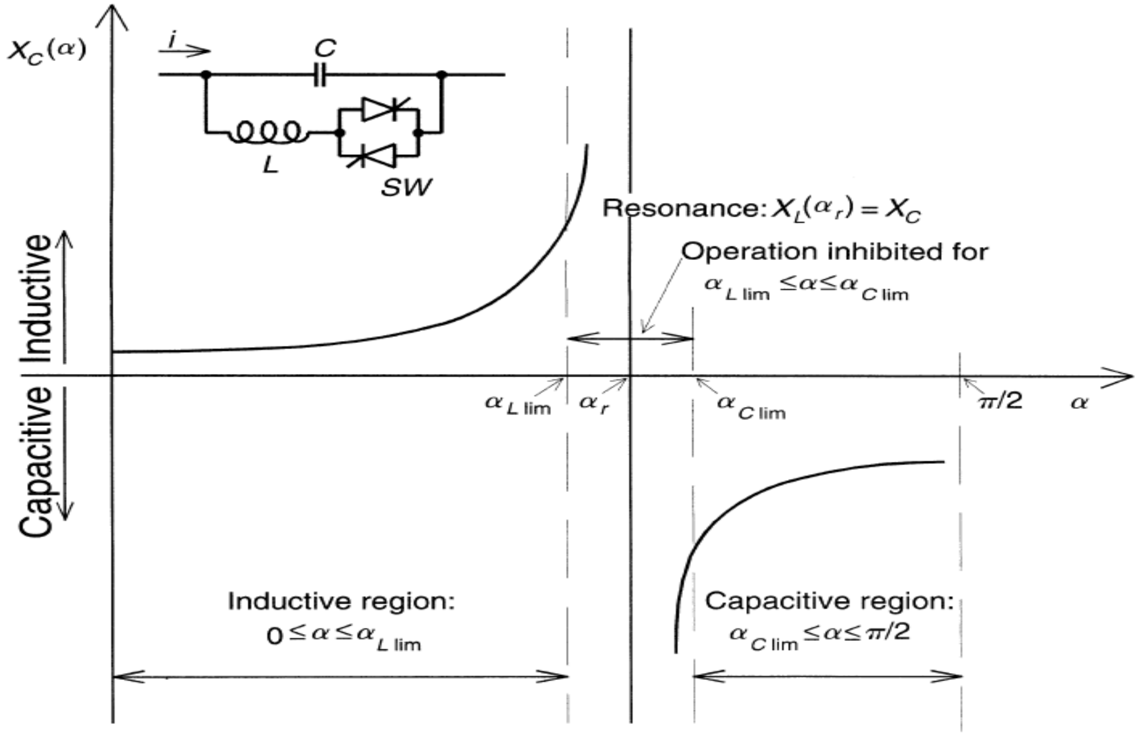
$$X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C}$$

Where

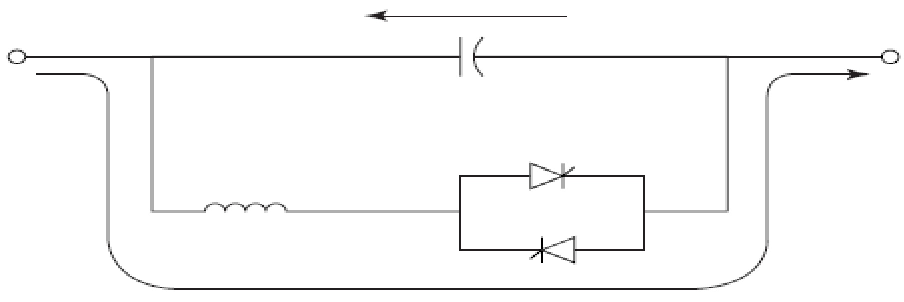
$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin 2\alpha}, X_L \le X_L(\alpha) \le \infty$$

- $X_L = \omega_L$, and α is the delay angle measured from the crest of the capacitor voltage (or, equivalently, the zero crossing of the line current).
- The TCSC thus presents a tunable parallel LC circuit to the line current that is substantially a constant alternating current source.
- As the impedance of the controlled reactor, $X_L(\alpha)$, is varied from its maximum (infinity) toward its minimum (ωL), the TCSC increases its minimum capacitive impedance, $X_{TCSC}=X_c=1/(\omega c)$ and thereby the degree of series capacitive compensation) until parallel resonance at $X_c=X_L(\alpha)$is established and $X_{TCSC\ max}$ theoretically becomes infinite.
- Decreasing $X_L(\alpha)$ further,the impedance of the TCSC, $X_{TCSC}(\alpha)$ becomes inductive, reaching its minimum value of $X_L Xc/(X_L - X_c)$ at α =0, where the capacitor is in effect bypassed by the TCR.
- Therefore, with the usual TCSC arrangement in which the impedance of the TCR reactor, X_L is smaller than that of the capacitor, Xs, the TCSC has two operating ranges around its internal circuit resonance

1. $\alpha clim \leq \propto \leq \pi/2$ range where $X_{TCSC}(\alpha)$ is capacitive
2. $0 \leq \propto \leq \propto L_{lim}$ range where $X_{TCSC}(\alpha)$ is inductive as shown in Figure



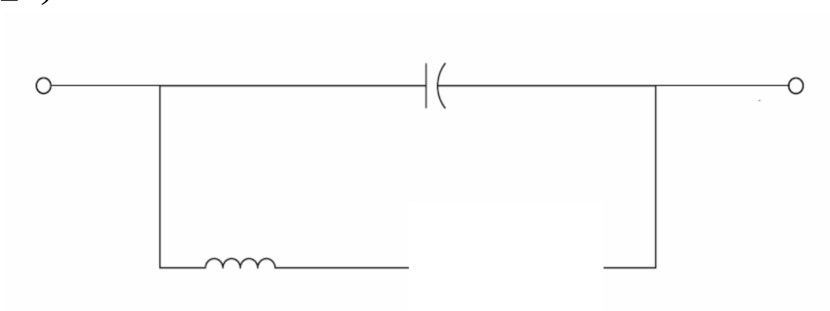
1. ***Thyristor valve bypass mode (inductive region operation: 0 L ≤α ≤α $_{Llim}$)***



(a)

In the bypass mode thyristors are gated for full conduction and the current flow in the reactor is continuous and sinusoidal. In this case the net reactance is slightly inductive because the susceptance of reactor is larger than that of the capacitor. This mode is mainly used for protecting the capacitor against the overvoltage (during transient over currents in the line).

2.Thyristor valve blocked mode (resonance region for inhibited operation: L_{lim} C_{lim} α ≤α ≤α *):*



- 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 transmissionsystem transformers.

3.**Partially Conducting Thyristor or Vernier Mode**

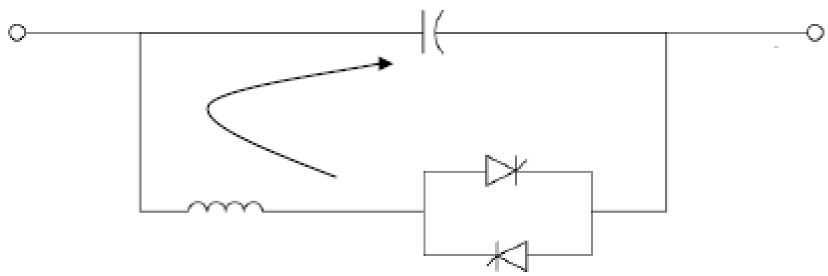
This mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. It is achieved by varying the thyristor-pair firing angle in an appropriate range. A smooth transition from the capacitive to inductive mode is not permitted because of the resonant region between the two modes.

Capacitive-vernier-control mode

inductive-vernier mode

***(i)Capacitive-vernier-control* mode**, In this, the thyristors are fired when the capacitor voltage and capacitor current have opposite polarity.

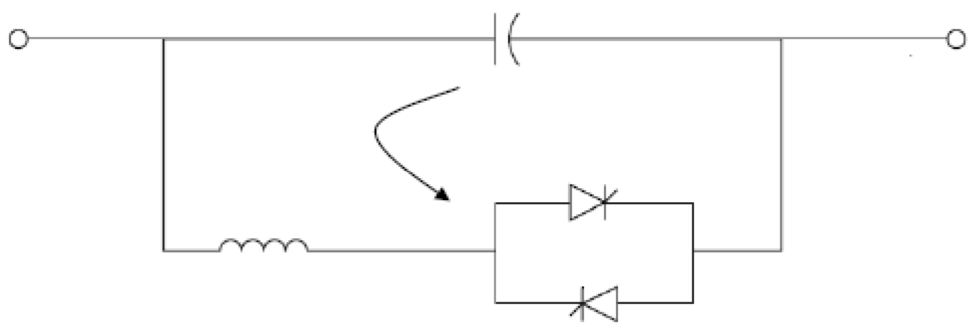
- This condition causes a TCR current that has a direction opposite that of the capacitor current, thereby resulting in a loop-current flow in the TCSC controller.
- This loop current increases the voltage across the FC, effectively enhancing the series compensation level.



- The maximum TCSC reactance permissible with α=αmin is typically two-and-a half to three times the capacitor reactance at fundamental frequency.

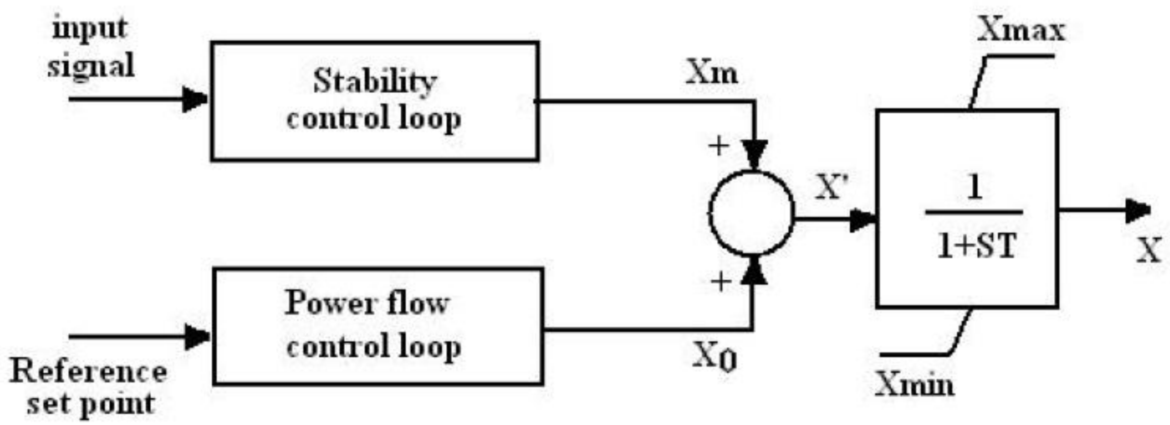
(ii)Inductive-vernier mode

- 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.



MODELING OF THE TCSC

The Fig.(a) shows the general block diagram of the TCSC controller for dynamic and steady state stability studies . It consists of Power flow controller and stability controller.



(a)General block diagram of TCSC controller model for stability studies

Power flow controller is used to control power flow in the transmission line under steady state condition by comparing power flow in transmission line with reference power set point.

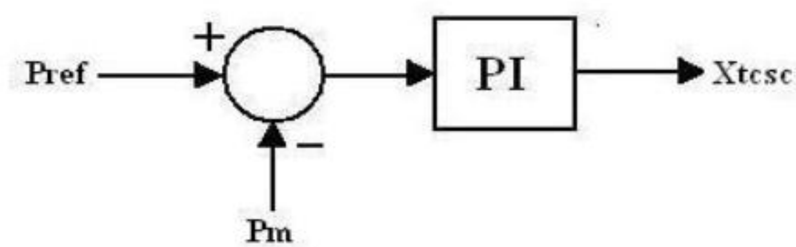


Fig b Power flow controller diagram for TCSC

If this controller is slow due to the large time constant of PI controller or if it is manually operated, the output (X0) of power flow controller is to be constant during large disturbances, because of this power oscillations increase. To reduce power oscillations the TCSC must be in a position to provide maximum compensation level immediately after the fault is cleared. This is achieved by adding the stability control loop to power flow control loop as shown in Fig.(a).

The stability controller gives modulation reactance (Xm) during transient or dynamic periods. The sum of two outputs (X0) of power flow controller and (Xm) of the stability controller yields the X‟ which is the final value of reactance required to the system during transient and dynamic periods.

Variable-reactance model of TCSC

The variable-reactance model of TCSC shown in Fig is widely used for transient- and oscillatory-stability studies.

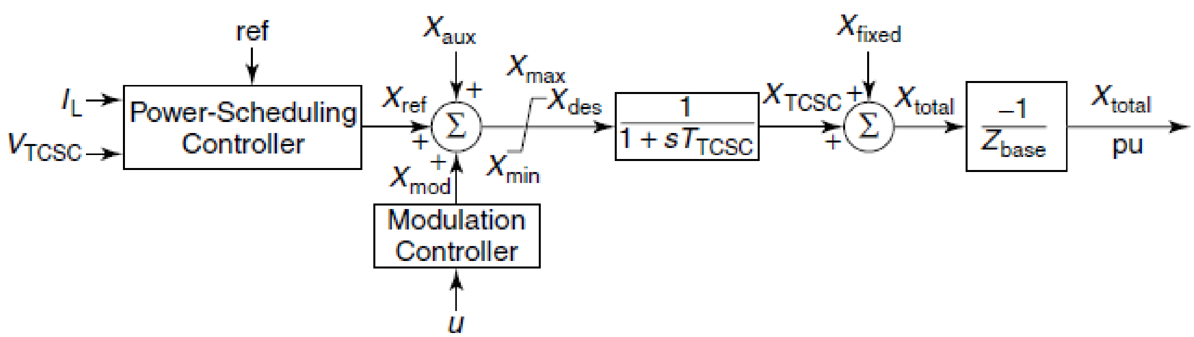


Fig.(c) A block diagram of the variable-reactance model of the TCSC

Xref - Power scheduling controller based on power flow specification

Xmod – Modulation controller for damping enhancement

Xaux – External power flow controller

Xdes – Desired magnitude of TCSC

TTcsc – Time constant

Xfixed – reactance of TCSC installation's FC component

Where

$$Zbase = \frac{(kV[TCSC])^2}{MVA_{sys}}$$

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

MVA_{sys}=the 3-phase MVA base of the power system

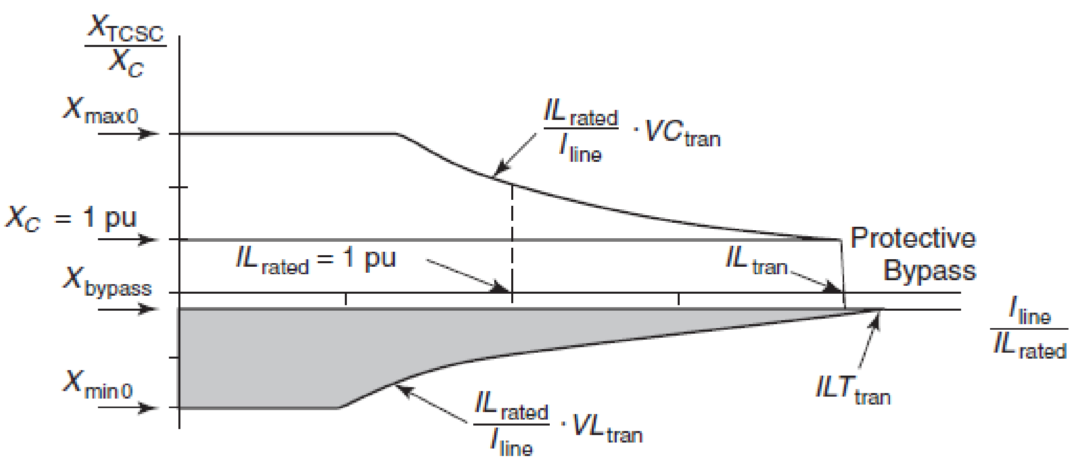
- *X*ref, is generated from a power-scheduling controller based on the power-flow specification in the transmission line. The reference *X*ref value may also be set directly by manual control in response to an order from an energy-control center, and it essentially represents the initial operating point 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.
- *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 resulting *X*TCSC is added to the *X*fixed, which is the reactance of the TCSC installation's FC component.
- To obtain per-unit values, the TCSC reactance is divided by the TCSC base reactance, *Z*base, given as
- $Zbase = \frac{(kV\,[TCSC])^2}{MVA_{sys}}$

  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 reactance capability curve of the multimodal TCSC is shown in Fig. 7.23.



A simplified reactance-capability curve of a multimodule TCSC

In the Capacitive region, there are three different TCSC reactance constraints which are given below

- The limit of TCSC firing angle,represented by constant reactance limit Xmax 0
- The limit on the TCSC voltageVCtran. The corresponding reactance constraint is given by

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

- Limit on the line current (ILtrans), beyond which the TCSC enter in to 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:

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

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

- The limit on the firing angle, represented by a constant-reactance limit, Xmin 0
- The harmonics-imposed limit, represented by a constant-TCSC-voltage limit *VL*tran.

The equivalent-reactance constraint is given by

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

- The limit on the fundamental component of current that is permitted to flow through the thyristors in the bypassed-thyristor mode during a transient. This current limit is also expressed as a minimum-reactance limit:

$$X_{\min\ ILT} = \left[1 - \frac{ILT_{\text{tran}} \cdot IL_{\text{rated}} \cdot (1 - X_{\text{bypass}})}{I_{\text{line}}}\right]$$

The final inductive-reactance limit in the inductive-vernier operation is obtained as a maximum of the foregoing constraints:

$$X_{\min\ \text{limit}} = \max(X_{\min\ 0}, X_{\min\ VL}, X_{\min\ ILT})$$

TCSC is used for the improvement of the stability of a system.

- 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 loaded.
- 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 influnece 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.
- 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.

Enhancement of System Damping

Introduction

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

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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 η1 and φ1, respectively; of machine *SM*2, denoted by η2 and φ2, 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.

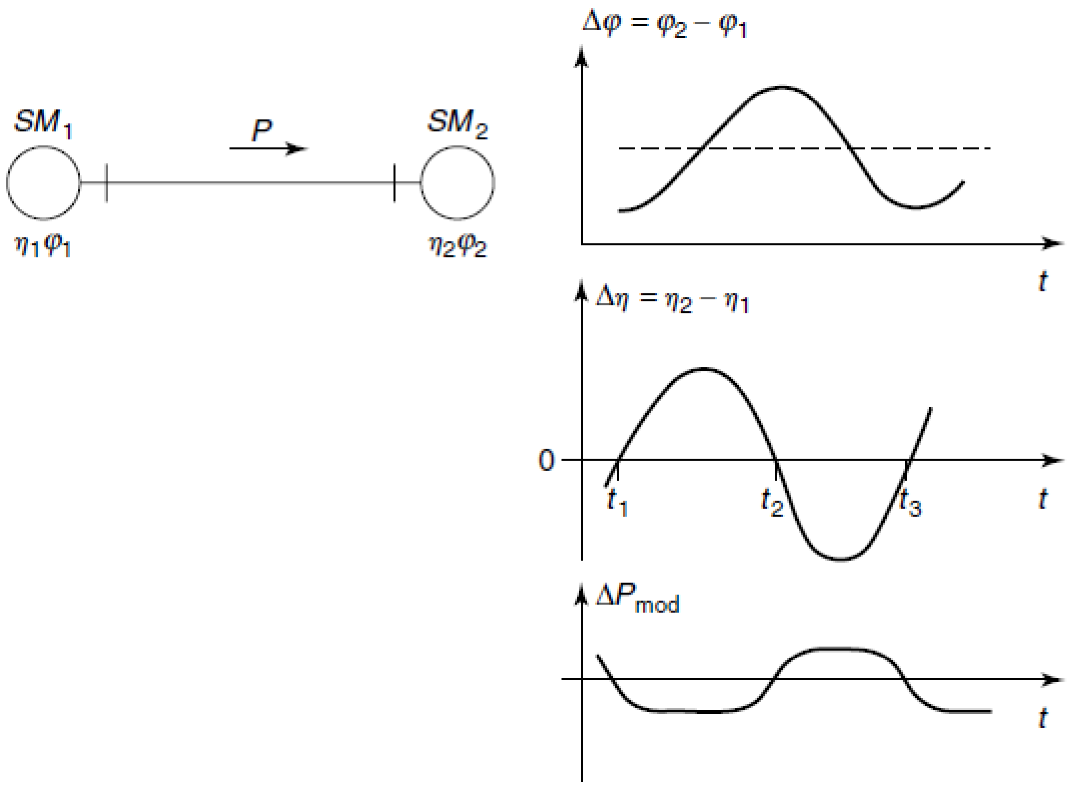
- In other words, while the sending-end machine accelerates, the TCSC control should attempt to draw more power from the machine, thereby reducing the kinetic energy responsible for its acceleration.
- On the other hand, when $\Delta\eta$ is positive, the TCSC must decrease the power transmission in 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 ΔPmod.
- The incremental variation of the line-power flow D*P*, given in megawatts (MW), with respect to D*Q*TCSC, given in MVAR, is as follows

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

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



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 ΔP_m = the variation in generator power

ΔP = the variation in power injected from the transmission line into the machine bus

$\alpha = \tan^{-1}(X_{source}/R_{load})$ (it is assumed that $R_{load} \gg X_{source}$)

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

$\Delta Pm = \Delta P$.

 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.

The operation of STATCOM with its V-I characteristics.

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).

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).

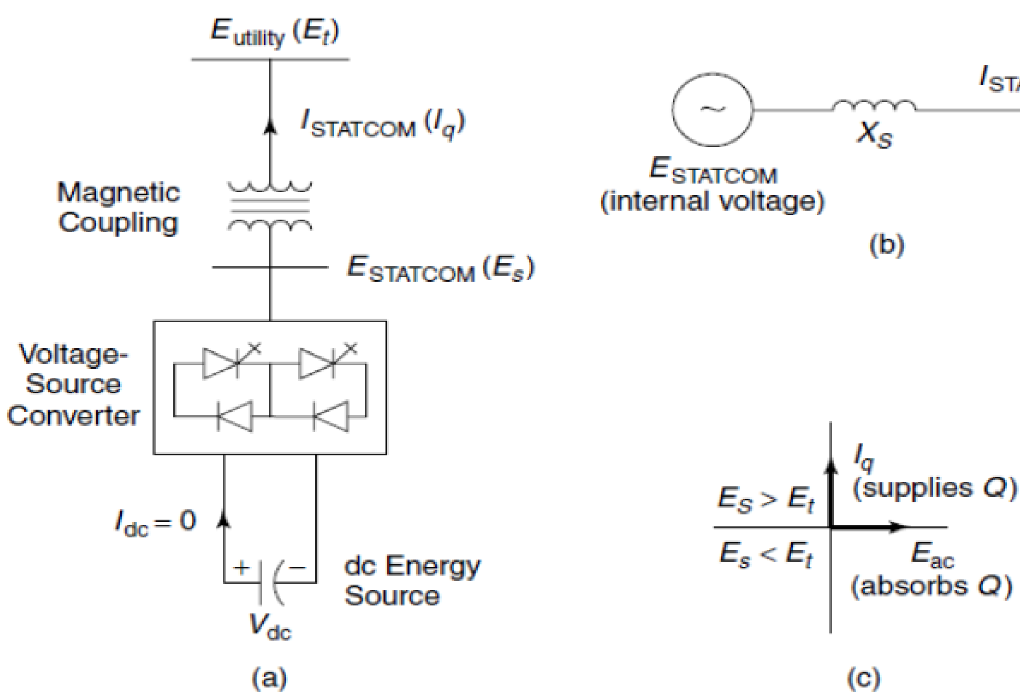
 A single-line STATCOM power circuit is shown in Fig.(a),where a VSC is connected to a utility bus through magnetic coupling.

 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.

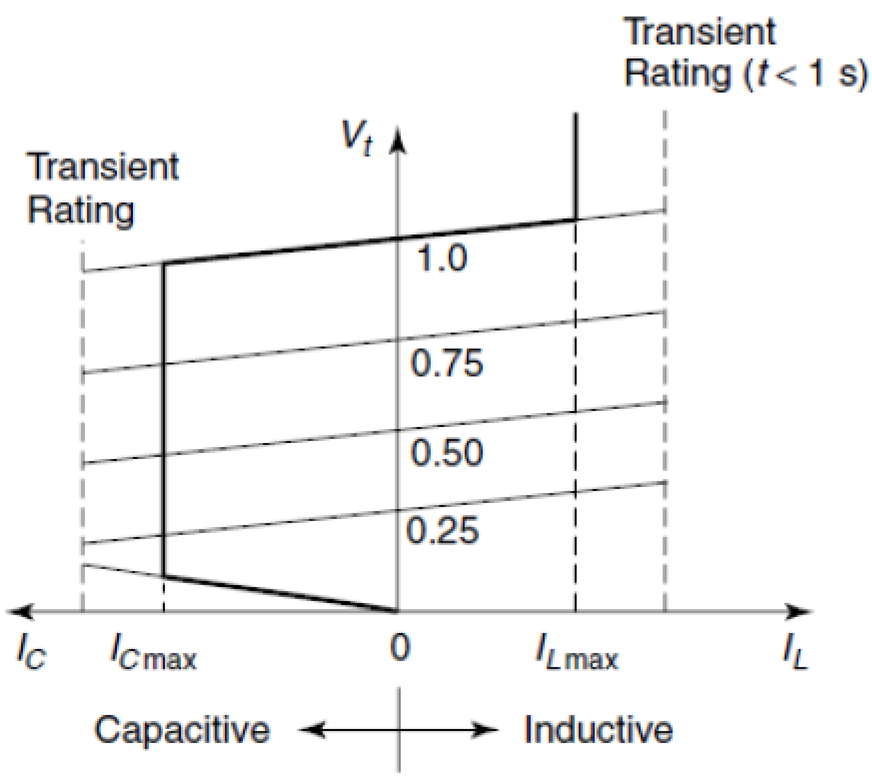
□ □ On the other hand, it can absorb real power from the ac system for the dc system if its voltage lags behind the ac-system voltage.

- 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 outputterminals 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.

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 strengthof 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.

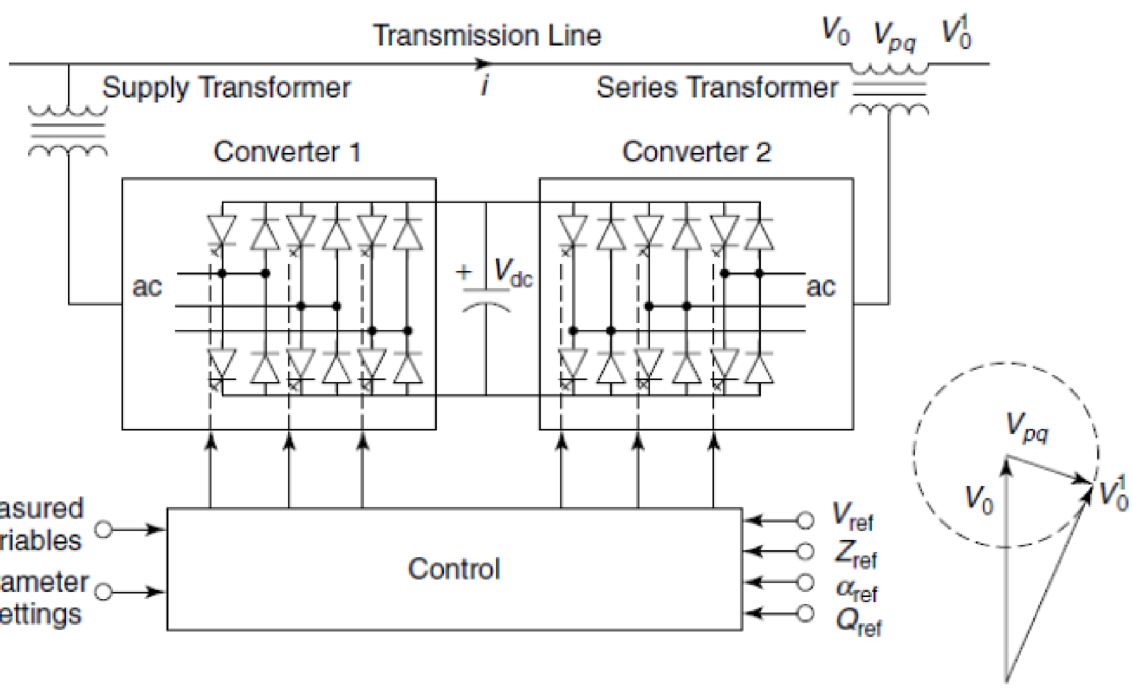
 The maximum attainable transient overcurrent in the capacitive region is determined by the maximum current turn-off capability of the converter switches.
 In the inductive region, the converter switches are naturally commutated; therefore, the transient-current rating of the STATCOM is limited by the maximum allowable junction temperature of the converter switches.

UNIFIED POWER FLOW CONTROLLER (UPFC)

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

Principle of Operation

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

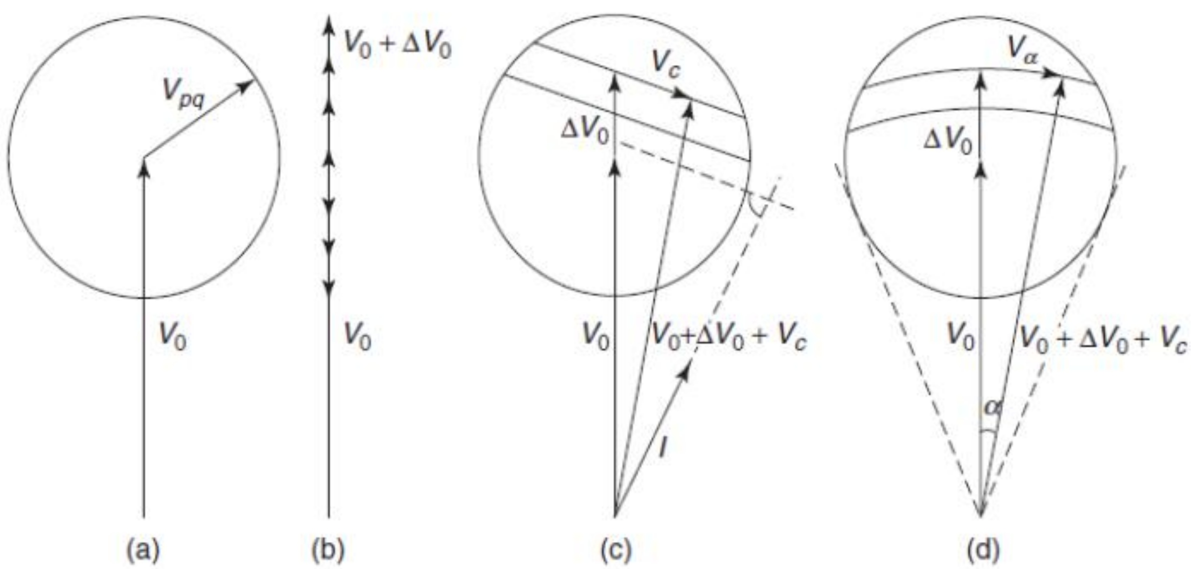


The implementation of the UPFC using two "back – to –back" VSCs with a common DC-terminal capacitor

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

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

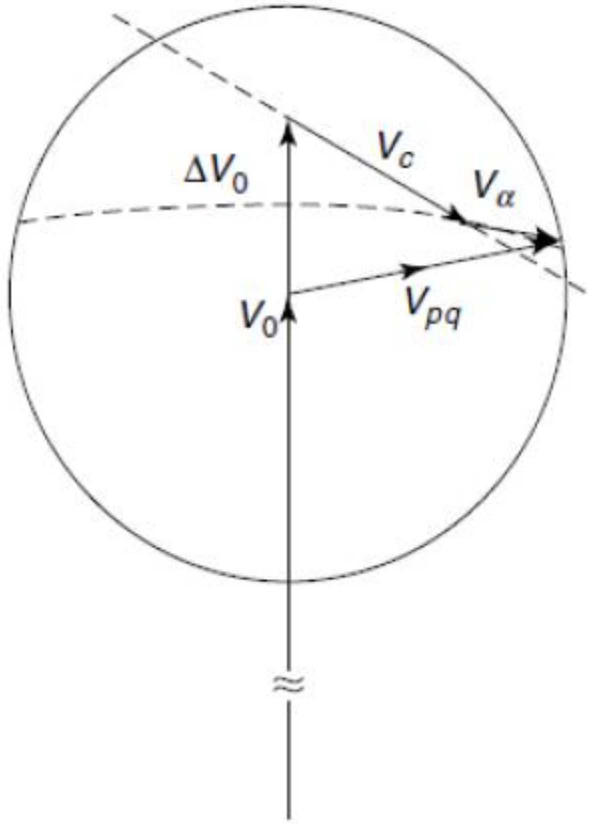
Modes of Operation



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

The concepts of various power-flow control functions by use of the UPFC are illustrated in Figs. (a)–(d). Part (a) depicts the addition of the general voltage phasor Vpq to the existing bus voltage, $V0$, at an angle that varies from 0^0 to 360^0.

□ □ Voltage regulation is effected if$Vpq = \Delta V0$ is generated in phase with $V0$, 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 $\Delta V0$ and a series compensation providing voltage component Vc that lags behind the line current by 900. In the phase-shifting process shown in part (d), the UPFC-generated voltage Vpq is a combination of voltage-regulating component $\Delta V0$ and phase-shifting voltage component Va.
□ □ The function ofVa is to change the phase angle of the regulated voltage phasor, $V0 + \Delta V$, by an angle α. A simultaneous attainment of all three foregoing power-flow control functions is depicted in Fig.
□ □ The controller of the UPFC can select either one or a combination of the three functions as its control objective, depending on the system requirements.
□ □ The UPFC operates with constraints on the following variables :
1. The series-injected voltage magnitude;
2. The line current through series converter;
3. The shunt-converter current;
4. The minimum line-side voltage of the UPFC;
5. The maximum line-side voltage of the UPFC; and
6. The real-power transfer between the series converter and the shunt converter



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

Static Synchronous Series Compensator (SSSC)

Configuration and operation

The basic scheme of SSSC is shown in Fig.4.9. The SSSC is a series compensation device of the FACTS family using power electronics based on the voltage source converter (VSC) to control power flow in transmission lines and improve transient stability in power system [33]. The SSSC controls the power flow in transmission lines by controlling the magnitude and phase angle of injected voltage (Vse) in series with the transmission line where SSSC is connected. The exchange of real and reactive power between SSSC and power system depends on the magnitude and phase displacement with respect to transmission line current.

The Fig. 4.10 shows the four-quadrant operation of SSSC. The line current I, is taken as reference phasor while the series injected voltage phasor Vse of SSSC is allowed to rotate around the center of the circle defined by the maximum inserted voltage Vse-max. In Capacitive mode of operation, the series injected voltage Vse of SSSC is made lag by 900 with transmission line current. In this case the SSSC operates like series capacitor with variable capacitance kXC, i.e., Vse = - kXC*I, where k is variable. By this action the total reactance of transmission line is reduced while the voltage across the line is increased. This leads to increase in the line current and hence the transmitted power. In the case of inductive mode of operation, the series injected voltage Vse of SSSC is made to lead by 900 with transmission line current, i.e., Vse = kXC*I. This leads to increase in the transmission line reactance, which results in a decrease in line current and hence the transmitted power. The above equation shows that the magnitude of Vse is directly proportional to the line current (I) magnitude, this is true for series capacitance, but not for SSSC. Actually the series inserted voltage Vse is set by the SSSC control is independent of the line reactance. The SSSC can control the power flow through the transmission line by controlling the magnitude of Vse and injecting in qudarture with transmission line current I as mentioned in the following equation

$Vse=V2-V1=Vd+jVq$

$Vd \sim 0$

$Vq>0$: SSSC is Capacitive

$Vq<0$: SSSC is Inductive

The magnitude of Vse is controlled through the changes in the amplitude modulation ratio mse, as the output voltage magnitude is directly proportional to mse according to the following equation mse = √ (8*Vse/Vdc) ------------------(4.7) **Fig.**

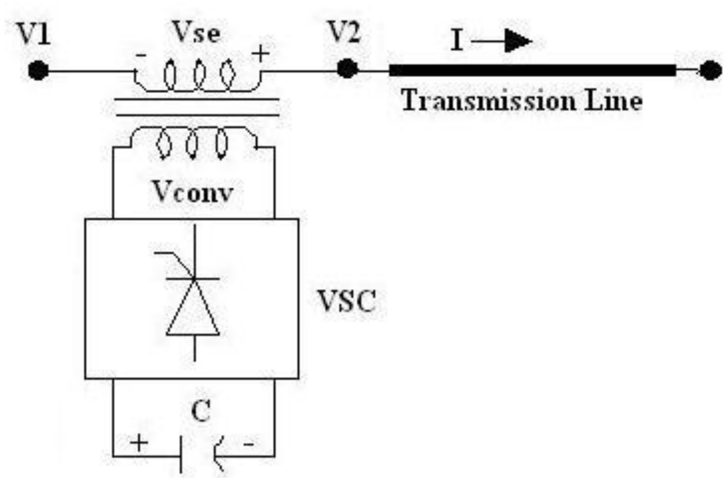


Fig.4.9. The basic scheme of SSSC

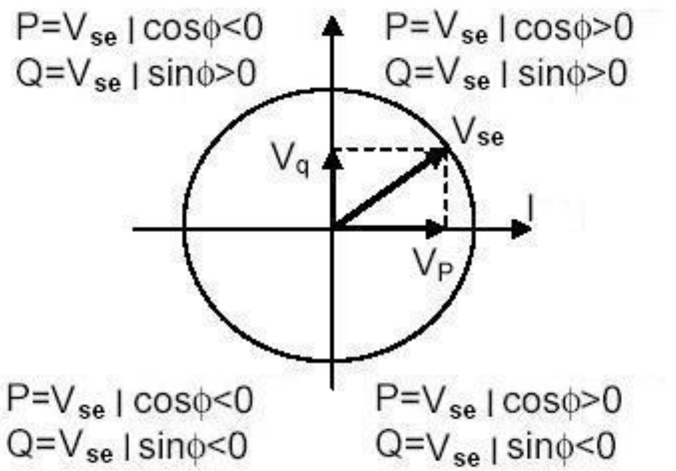


Fig. 4.10 four-quadrant operation of SSSC

V-I Characteristics of SSSC

The fig.4.11 shows the V-I Characteristic of SSSC. The SSSC can provide capacitive voltage and inductive voltage up to its specified maximum current rating. The SSSC can generate a controllable compensating capacitive or inductive voltage, which implies that the amount of transmittable power can be increased as well as decreased from natural power.

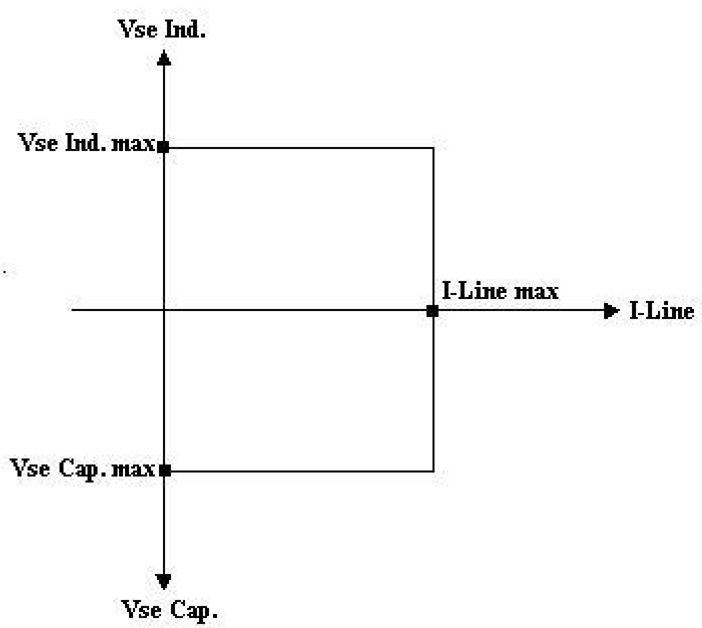


Fig.4.11 V-I Characteristics of SSSC

Basic Two-Converter Scheme For IPFC

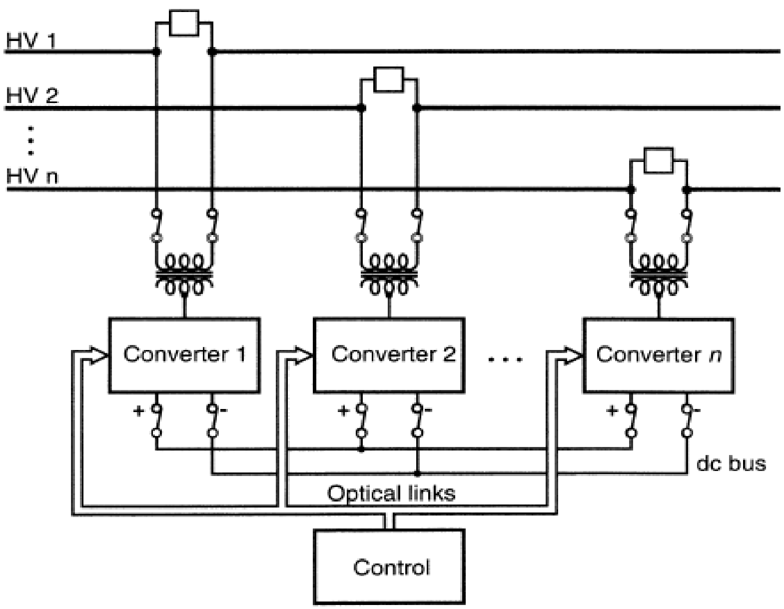


Figure : Interline Power Flow Controller comprising /n converters

The schematic representation of an IPFC shown in Figure 1.There are two back-to-back voltage-source converters (VSCs), based on the use of gate-turnoff (GTO) thyristor valves. The VSCs produce voltages of variable magnitude and phase angle. These voltages are injected in series with the managed transmission lines via series transformers. The injected voltages are represented by the voltage phasors .The converters labeled VSC1 and VSC2 are coupled together through a common dc link. Illustrates the IPFC phasor diagram. With respect to the transmission-line current, in phase and quadrature phase components of injected voltage, respectively, determine the negotiated real and reactive powers of the respective transmission lines. The real power exchanged at the ac terminal is converted by the corresponding VSC into dc power which appears at the dc link as a negative or a positive demand. Consequently, the real power negotiated by each VSC must be equal to the real power negotiated by the other VSC through the dc lines.VSC1 is

operated at point A. Therefore, VSC2 must be operated along the complementary voltage compensation line, such as point B, to satisfy the real power demand of VSC1. This is given by

Psc1+Psc2=V1pI1+V2pI2=0 (5.1)

In the IPFC structure, each converter has the capability to operate as a stand-alone SSSC under contingency conditions, such as the outage of another ac line, other converter, or opening the dc link between the two converters. The protective actions can be divided into two levels in each converter station. In case a failure occurs and affects all components, the protection system The IPFC has the in-built capacity to bypass the rest of the componentsin that, when a failure occurs at a series transformer, the associated SSSC is bypasses using the bypass breaker. For instance, when a failure takes place in a valve of the VSC, built within the GTO thyristor module, the GTO module is bypassed. This means that, where a number of failures occur affecting a single component, the protective actions is specifically employed on that particular component, bypassing the failure and setting it right.

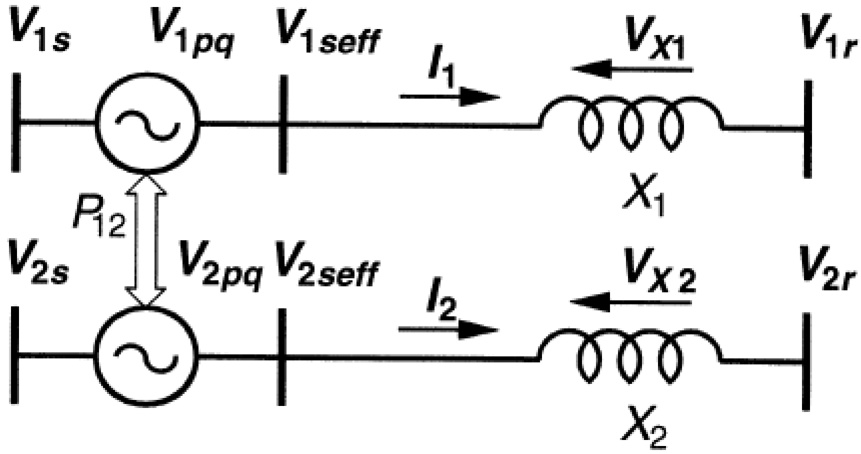


Figure Basic two-converter Interline Power Flow Controller scheme.

- Consider an elementary IPFC scheme consisting of two back-to-back dc-to-ac converters, each compensating a transmission line by series voltage injection. This arrangement is shown functionally in Figure, where two synchronous voltage sources, with phasors V_{1pq} and V_{2pq} in series with transmission Lines 1 and 2, represent the two back-to-back dc-to-ac converters.
- The common dc link is represented by a bidirectional link for real power exchange between the two voltage sources.

- Transmission Line 1, represented by reactance X_1 has a sending-end bus with voltage phasor V_{1s} and a receiving-end bus with voltage phasor V_{1r}. The sending-end voltage phasor of Line 2, represented by reactance X2, is V_{2s}" and the receiving-end voltage phasor is V_{2r}.

- all the sending-end and receiving-end voltages are assumed to be constant with fixed amplitudes,
- V1s= V1r= V2s= V2r=1.0 p.u and with fixed angles resulting in identical transmission angles, δ1= δ2=30o for the two systems.

- In order to establish the transmission relationships between the two systems,

System 1 is arbitrarily selected to be the prime system for which free controllability of both real and reactive line power flow is stipulated.
The reason for this stipulation is to derive the constraints which the free controllability of System 1 imposes upon the power flow control of System

generalize IPFC which can be operated as a STATCOM , SSSC, UPFC OR IPFC.

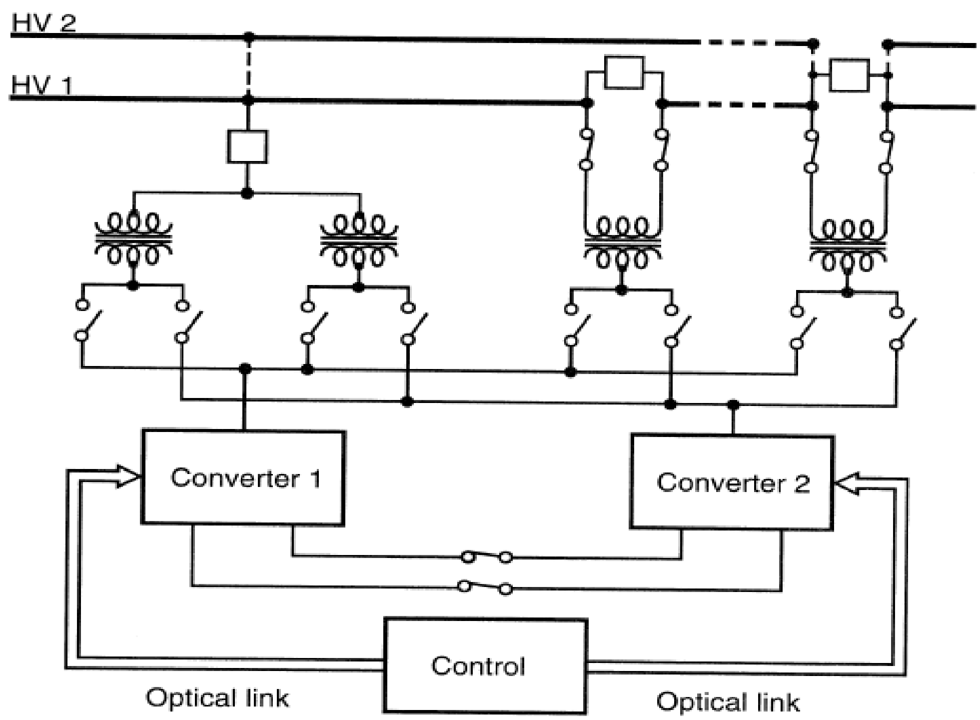


Figure -1 Illustration of the functional convertibility of a compensator scheme comprising two voltage-sourced converters.

Figure 1 shows the two converter, two-line arrangement, which could be expanded to any number of converters and lines. The inspection of this figure shows that with the appropriate closing and opening of the circuit switches connecting the converter outputs to the coupling transformers, the two converters, each with 1..0 p.u. VA rating, could be configured to function as:

- STATCOM (1.0 p.u. and 2.0 p.u. rating)
- SSSC (1.0 p.u. and 2.0 p.u. rating)
- STATCOM and SSSC (each L.0 p.u. rating)

- UPFC (1.0 p.u. series and L.0 p.u. shunt converter rating)
- IPFC (1.0 p.u. for each line)

Note that the per unit ratings shown are not the throughput ratings of the lines.
Generally, the FACTS Controller ratings are smaller than the throughput ratings.
They are more related to the per unit series inductance of the lines. The power electronic-based Controller ratings are defined by the product of the maximum voltage and maximum current the equipment handles, even if the maximum voltage and current do not occur simultaneously.
This approach may be economically savvy for the short term, it may not have the capability for broader optimization of the transmission assets, or the flexibility to handle changing transmission conditions, and ultimately it may result in a 'stranded asset.,,

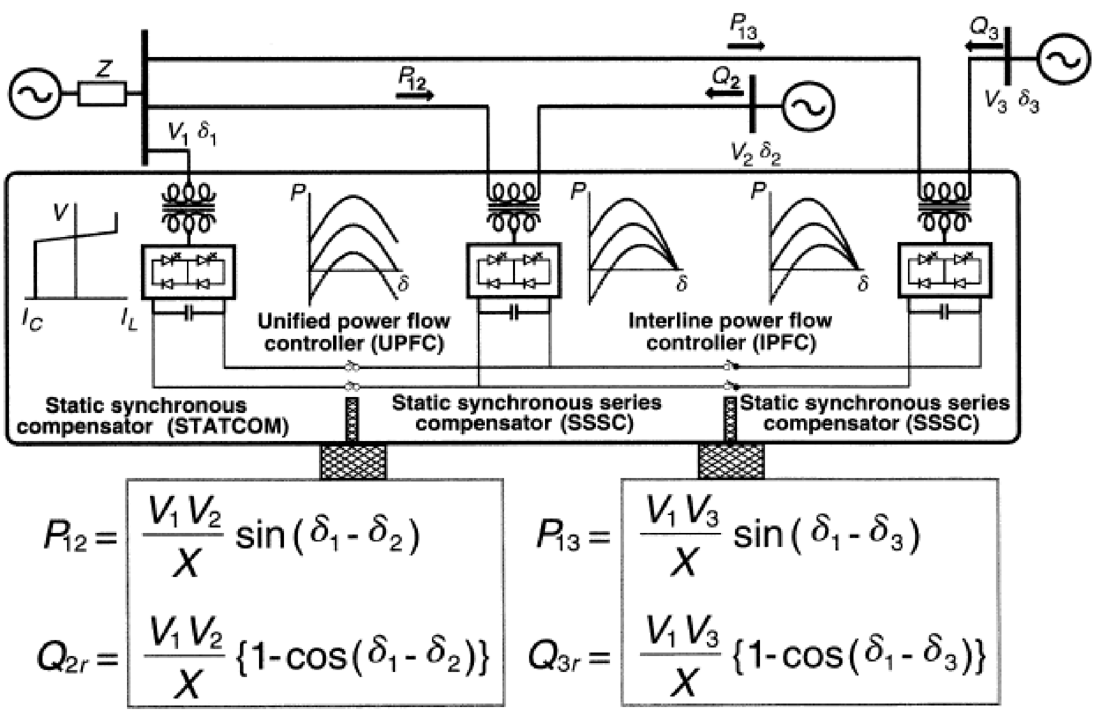


Figure 2 Illustration of a generalized IPFC concept for comprehensive real and reactive power flow control of a multiline transmission system.

Figure 2 illustrates which can function individually as conventional (voltage, impedance or angle) Controllers, but can also be converted from one functional use to another, and, more importantly, can be connected to a common dc link to provide comprehensive transmission control capabilities. As can be observed two voltage-sourced converter modules, used to control the power flow between bus 1 and bus 2, can be used

individually as a STATCOM and an SSSC, or can be combined to function as a UPFC for the comprehensive control of both real and reactive power flow between bus 1 and bus 2. With the addition of the third converter module, the second line receives an independent series reactive compensator (SSSC). However,by connecting this converter to the common dc bus, a genlralized IPFC is established which can control and optimize under the prevailing system condition the real and reactive power in both lines, from bus L to bus 2, and also from bus 1 to bus 3. This simple example shows the capability of the voltage-sourced converter-based approach to maintain full convertibility and individual functionality while also providing a powerful potential for an integrated transmission management system with capacity of real and reactive power flow control and handling of dynamic disturbances In the multifunctional FACTS Controller arrangements discussed above, each Controller in a line can independently carry out limited compensation and control functions and thus the common dc connection does not represent a significant single
point failure.

Various kinds of control interactions occurring between different FACTs controllers using their frequency response characteristics

- **FACTS Controller Interactions**
- Controller interactions can occur in the following combinations:
    - Multiple FACTS controllers of a similar kind.
    - Multiple FACTS controllers of a dissimilar kind.
    - 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

- **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.
- **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.
- **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).

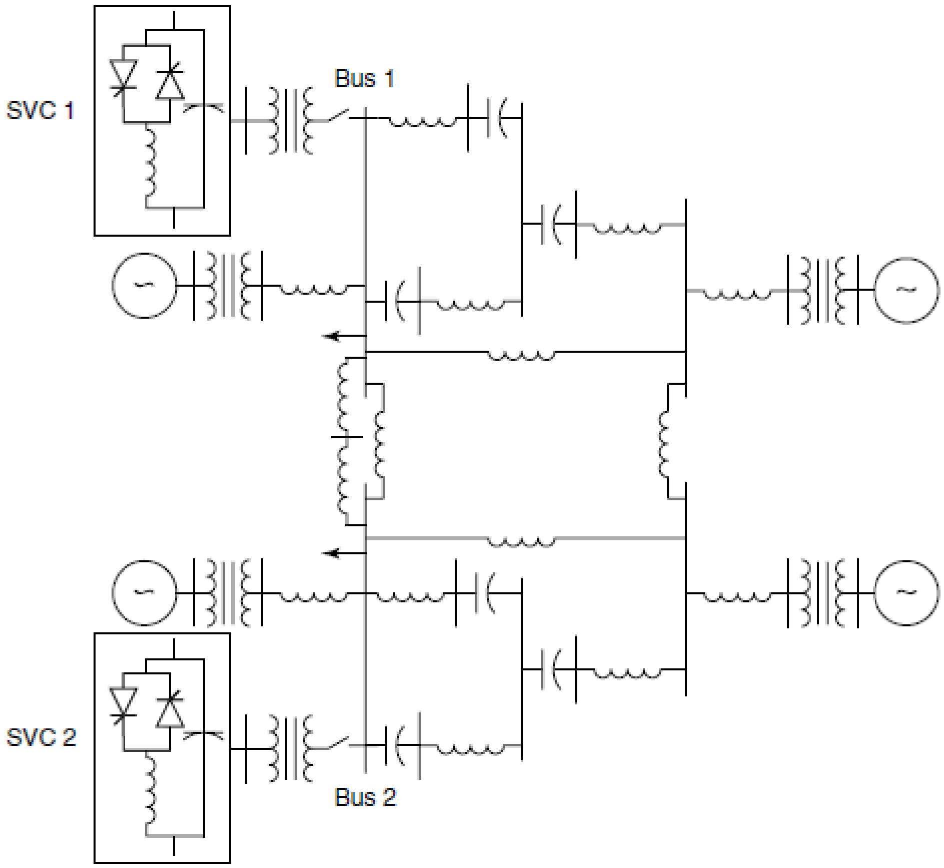
- These oscillations are largely dependent on the network strength and the choice of FACTS controller parameters, and they are known to result from the interaction between voltage controllers of multiple SVCs, the resonance between series capacitors and shunt reactors in the frequency range of 4–15 Hz ,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 .

- **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 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).

✓ **The controller interactions between multiple SVCs (SVC-SVC) in a large power system.**

- **SVC – SVC Interactions**
- **1 The Effect of Electrical Coupling and Short-Circuit Levels**

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



- SVC interaction – analysis network

    - **Uncoupled SVC Buses**

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

    - **Coupled SVC Buses**

- If the reactance between the two SVC buses is low, it constitutes a case of high electrical coupling between the SVCs.

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

the co-ordination of multiple controllers Using linear control techniques,

Co-Ordination of Multiple Controllers using Linear – Control Techniques

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

- **The Basic Procedure for Controller Design**
  - The controller-design procedure involves the following steps:
  - Derivation of the system model;
  - Enumeration of the system-performance specifications;
  - Selection of the measurement and control signals;
  - Coordination of the controller design; and
  - Validation of the design and performance evaluation.
- **Step 1: Derivation of System Model**
- First, a reduced-order nonlinearsystem model must be derived for the original power system and this model should retain the essential steady-state and dynamic characteristics of the power system .

- Then, the model is linearized around an operating point to make it amenable to the application of linear-control design techniques. If a controllermust be designed for damping electromechanical oscillations, a further reducedlinear model is selected that exhibits the same modal characteristics over the relevant narrow range of frequencies as the original system.
- In situations where linearized-system models may not be easily obtainable, identification techniques are employed to derive simple linear models from time-response information.
- **Step 2: Enumeration of the System – performance Specifications**
- The damping controller is expected to satisfy the following criteria.
- It should help the system survive the first few oscillations after a severe system disturbance with an adequate safety margin. This safety factor is usually specified in terms of bus-voltage levels that should not be violated after a disturbance.
- A minimum level of damping must be ensured in the steady state after a disturbance.
- Potentially deleterious interactions with other installed controls should be avoided or
- minimized.
- Desired objectives over a wide range of system-operating conditions should be met (i.e., it should be robust).
- **Step 3: Selection of the Measurement and Control Signals**
- The choice of appropriate measurement and control signals is crucial to controller design.
- The signals must have high observability and controllability of the relevant modes to be damped, and furthermore, the signals should only minimally affect the other system modes.
- The selection of these signals is usually based on system-modal magnitudes, shapes, and sensitivties—all of which can be obtained from small-signal-stability analysis.
- **Step 4: Controller Design and Coordination**
- The FACTS controller structures are usually chosen from industry practice. Typically, the controller transfer function, *Hj*(*s*), of controller *j* is assumed to be
- $$H_j(s) = k_j G_j(s) = k_j \frac{sT_W}{1 + sT_W} \left(\frac{1 + s\tau_1}{1 + s\tau_2} \right)^p \frac{1}{(1 + sT_1)(1 + sT_2)\cdots(1 + sT_n)}$$
- This transfer function consists of a gain, a washout stage, and a *p*th-order leadlag block, as well as low-pass filters. Alternatively, it can be expressed as
- $$H_j(s) = k_j G_j(s) = k_j \left[k_0 \frac{(s + \cdots + b_m s^m}{1 + a_1 s + \cdots + a_n s^n} \right], \qquad m \le n$$

- Although the basic structure of different controllers is assumed as from the preceding text, the coordination of controllers involves the simultaneous selection of gains and time constants through different techniques.
- Doing so permits the system-operating constraints and damping criteria to be satisfied over a wide range of operating conditions.
- The coordination techniques may use linearized models of the power system and other embedded equipments, capitalizing on the existing sparsity in system representation.
- This model may be further reduced by eliminating certain algebraic variables yet still retaining the essential system behavior in the frequency range of interest.
- Eigenvalue analysis–based controller-optimization and -coordination techniques are applicable to power systems typically with a thousand states occurring when full modal analysis must be performed. However, sometimes a limited number of electromechanical modes must be damped; hence the eigenvalue analysis of a selected region can be performed even for relatively larger power systems.
- **Step 5: Validation of the Design and performance Evaluation**
- Even though the controller design is performed on the simplified system model, the performance of the controller must still be established by using the most detailed system model.
- The controller should meet the specifications over a wide range of operating conditions and consider all credible contingencies.This validation is generally performed with nonlinear time-domain
- simulations of the system.

Linear control techniques used for coordination of control of different FACTS controllers

- ***(i)Global coordination using nonlinear-constrained optimization***
- In the global-coordination technique, the parameters (both gain and time constants) of the damping controllers of multiple FACTS controllers are coordinated globally by using nonlinear-constrained optimization.
- It is usually observed in power systems that if the FACTS controllers have large ratings, their damping action on the real-power oscillations causes substantial reactive power oscillations.
- To restrict oscillations—in both the real and the reactive power—the optimization problem is stated as follows:
- Minimize

$$F = \int_0^{\infty} [\Delta P^{\mathrm{T}} I \Delta P + K_Q \Delta Q^{\mathrm{T}} I \Delta Q]\, dt$$

subject to

$$V_{\min} \le V_{\mathrm{bus}\,k} \le V_{\max}, \qquad k = 1, 2, m$$

where for n FACTS controllers,

$\Delta P = [\Delta P_1, \Delta P_2, ..., \Delta P_n]^{\mathrm{T}}$
= the n locally measured real-power-flow oscillations

$\Delta Q = [\Delta Q_1, \Delta Q_2, ..., \Delta Q_n]^{\mathrm{T}}$
= the n locally measured reactive-power oscillations

$V_{\mathrm{bus}\,k}$ = the voltage magnitude of the kth bus

$V_{\max}, V_{\min}$ = the upper and lower limits of the bus-voltage magnitude respectively

K_Q = the weighting factor

- If the primary control objective is to damp active-power oscillations, the
  - weighting factor *KQ* is assigned a small value, typically 0.2. However, if reactive-power swings must also be restricted, *KQ* is assigned a higher magnitude.
- The foregoing optimization scheme results in robust controllers having a significant damping influence on both large and small disturbances.
- An example of the global coordination of damping controllers of an SVC and a TCSC is presented in ref. [2]. The transfer function, *FD*(*s*), of both damping controllers is assumed to be of the form

$$F_D(s) = K \cdot \frac{sT_1}{1 + sT_2} \cdot \frac{1 + sT_3}{1 + sT_4}$$

- Although *T*2 and *T*4 are chosen a priori, parameters *K*, *T*1, and *T*3 are determined for both controllers through the optimization procedure.
- ***(ii) Control coordination using Genetics algorithm***
- Genetic algorithms are optimization techniques based on the laws of natural
  - selection and natural genetics that recently have been applied to the control
  - design of power systems .

- These techniques provide robust, decentralized control design and are not restricted by problems of nondifferentiability, nonlinearity, and nonconvexity, all of which are often limiting in optimization exercises.
- Genetic-algorithm techniques use the linearized state-space model of the power system.
- The objective function is defined as the sum of the damping ratios of all the modes of interest.
- This sum is evaluated over several likely operating conditions to introduce robustness.
- A minimum damping level is specified for all the modes; the other constraints include limits on the gain and time constants of the damping controllers assumed to be from a fixed structure, as given in Eq. (9.3).
- The optimization problem is therefore stated as follows:
  - Maximize

$$F = \sum_{i=1}^{m} \left[\sum_{j=1}^{n} (\xi_i) \right]$$

subject to the following constraints:

$$k_{j\,\min} \leq k_j \leq k_{j\,\max}$$
$$\tau_{1\,\min} \leq \tau_1 \leq \tau_{1\,\max}$$
$$\tau_{2\,\min} \leq \tau_2 \leq \tau_{2\,\max}$$
$$\xi_{\min} \leq (\xi_j)_i$$

where n = the number of modes to be damped
m = the number of different possible operating conditions
k_j = the gain of the controller
τ_1, τ_2 = the time constants of the lead-lag blocks
ξ = the damping ratio of the closed-loop eigenvalue

- This maximization yields the gain *kj* and the time constants $\tau 1$, τ 2 for all the controllers for a prespecified order *p* of the lead-lag blocks. The time constant T_W of the washout filter is assumed to be adequately large and known a priori.
- Likewise, the time constants *T*1, *T*2, . . . , *Tn* of the low-pass filters are selected beforehand.
- The foregoing optimization problem involves a computation of eigen values
- of a large system matrix, which is usually difficult to solve with conventional techniques.
- An advantage of genetic-algorithm techniques is that the parameter limits can be varied during the optimization, making the techniques computationally efficient. An application of these techniques to two large power systems

Control techniques used for coordination of multiple FACTS controllers

(1)Linear Quadratic Regular (LQR) –based technique

- The LQR technique is one of optimal control that can be used to coordinate the controllers with the overall objective of damping low-frequency inter-area modes during highly stressed power-system operations.
- The system model is first linearized and later reduced to retain the modal features of the main system over the frequency range of interest.
- The control-system specifications are laid out as described previously. Appropriate measurement and control signals are selected, based on observability and controllability considerations, to have only a minimal interaction with other system modes.
- Using a projective-controls approach , the control-coordination method involves formulating an LQR problem to determine a full-state-feedback controller in which a quadratic performance index is minimized.
- An output-feedback controller is then obtained, based on the reduced eigen space of the full-state solution.
- The dominant modes of the full-state-feedback system are retained in the closed-loop system with output feedback.
- The order of the controller and the number of independent measurements influence the number of modes to be retained.
- The output-feedback solution results in the desired coordinated control.
- The performance of coordinated controls is later tested and evaluated through time-domain simulation of the most detailed model of the nonlinear system.

- ***(ii)Non Linear – Control Techniques***
- Several nonlinear-control techniques have been applied for the design of FACTS controllers.
- These techniques are likely to yield greatly improved controllers, as they include the effects of system nonlinearities.
- Some of these methods are described briefly in the following text.
- One nonlinear-control technique in which the system nonlinearities are expressed as system changes constituting a function of time is the *adaptive*
  - *control* .
- If the number of controller parameters to be optimized is not too large, a *cost-penalty function* technique can be used, which is based on nonlinear simulation .
- An effective technique commonly used for enhancing transient stability during large disturbances is the *discontinuous control* or *bang-bang control*.

- Another nonlinear-control technique is the *normal forms*, which includes the effects of higher-order terms in Taylor's series to represent power systems—especially during high-power transfers .
- For damping low-frequency oscillations, FACTS controllers can be designed using the *dissipation* technique, which is based on the concept that passive systems always absorb energy .
- For designing the controls of FACTS controllers in large power systems, the *energy*, or *Lyapunov*, technique can be used.
- For stability enhancement, *nonlinear fuzzy* and *neural net* techniques are
    - presently being researched .
- In the future, these techniques may be extended for coordination of FACTS
- controllers.
- One possible approach could be to first do a "coarse" coordination using linear-control techniques, followed by a "fine" coordination employing
    - the nonlinear-control methods.