MAILAM ENGINEERING COLLEGE
MAILAM (PO), Villupuram (Dt). Pin: 604 304
(Approved by AICTE New Delhi, Affiliated to Anna University Chennai & Accredited by TCS, Chennai)
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Subject Code & Name: EE2036 - FLEXIBLE AC TRANSMISSION SYSTEMS

Unit : I
Year/Sem : IV / VIII
Total No. Page : 36

INTRODUCTION

The concept of flexible AC transmission - reactive power control in electrical power transmission lines -uncompensated transmission line – series and shunt compensation. Overview of FACTS devices - Static Var Compensator (SVC) – Thyristor Switched Series capacitor (TCSC) – Unified Power Flow controller (UPFC) - Integrated Power Flow Controller (IPFC).

Updated Questions:

PART-A:

Apr/May 2015: Qn.37 on Pg.5 & Qn.38 on pg.5
Nov/Dec 2014: Qn.20 on Pg.3, & Qn.36 on Pg.5

PART-B:

Apr/May 2015: Qn.12 on pg.28, Qn.13 on Pg.28 & Qn.14 on Pg.31
Nov/Dec 2014: Qn.16 on Pg.35 & Qn.15 on Pg.35

Reference Books:

1. Mohan Mathur, R., Rajiv. K. Varma, "Thyristor – Based Facts Controllers for Electrical Transmission Systems", IEEE press and John Wiley & Sons, Inc.

Prepared by	Verified by	Verified by	Approved by
N. Jaiganesh			
Mr.N.JAIGANESH, AP/EEE	BC	HOD/EEE	PRINCIPAL
Mr.G.VEERAPATHIRAN, AP/EEE			

MAILAM ENGINEERING COLLEGE
MAILAM (PO), Villupuram (Dt). Pin: 604 304
(Approved by AICTE New Delhi, Affiliated to Anna University Chennai & Accredited by TCS, Chennai)
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE2036 FLEXIBLE AC TRANSMISSION SYSTEMS

UNIT I INTRODUCTION

The concept of flexible AC transmission - reactive power control in electrical power transmission lines -uncompensated transmission line – series and shunt compensation. Overview of FACTS devices - Static Var Compensator (SVC) – Thyristor Switched Series capacitor (TCSC) – Unified Power Flow controller (UPFC) - Integrated Power Flow Controller (IPFC).

PART-A

1. What is FACTS?

The FACTS (Flexible AC transmission Systems) is a concept based on power-electronic controllers, which enhance the value of transmission networks by increasing the use of their capacity.

2. What is meant by FACTS controller?

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

3. Define 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).

4. Define Thyristor – controlled Reactor (TCR)?

A shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve.

5. Define Thyristor-controlled series capacitor (TCSC)?

A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide smoothly variable series capacitive reactance.

6. List the limits of loading capability?

- Thermal
- Dielectric
- Stability

7. List the various types of stability limits?

- Transient stability
- Dynamic stability
- Steady state stability
- Frequency collapse
- Voltage collapse
- Sub synchronous resonance

8. What is the need for transmission interconnection?

Transmission interconnection enable taking advantage of diversity of loads at minimum cost with requires reliability.

9. Define Interline power flow controllers?

The combination of two or more static synchronous series compensator which are coupled via a common DC link to facilitate bi- directional flow of real power between the AC terminal of the sssc and are controlled to provide independent reactive compensation for the adjustment of real power flow.

10. What are the objectives of FACTS? (DEC-2012)

i) The power transfer capability of transmission system is to be increased.
ii) The power flow is to be kept over designated routes.

11. How to control the power / current in a transmission line? (DEC-2012)

(OR)

What is mean by reactive power control in electrical power transmission system? (MAY-2011)

- Power/ current flow can be controlled by regulating the magnitude of voltage phasor E1 or voltage phasor E2.

- Change in magnitude of E1 the magnitude of driving voltage phasor E1-E2 does not change by much, but its phase angle differs.

12. Write the equation for maximum power transfer in transmission line? (DEC-2010)

Reactive component of the current flow at E1 is:

Active power at the E1 end:

$$P_1 = E_1\,(E_2 \sin\,\delta)/X$$

Reactive power at the E1 end:

$$Q_1 = E_1\,(E_1 - E_2 \cos\,\delta)/X$$

Reactive component of the current flow at E_2 is:

Active power at the E2 end:

$$P_2 = E_2\,(E_1 \sin\,\delta)/X$$

Reactive power at the E2 end:

$$Q_2 = E_2\,(E_2 - E_1 \cos\,\delta)/X$$

13. List the classification of FACTS controllers?

- Series controllers
- Shunt controllers
- Series-series controllers
- Series-shunt controllers

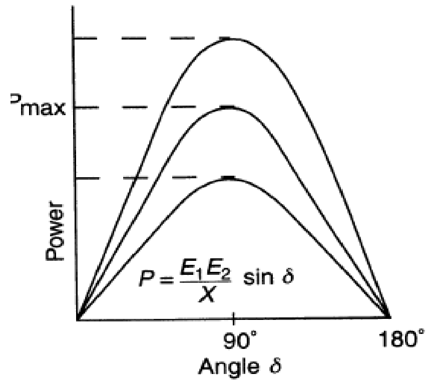
14. Which at factor of power system is improved through series compensation? (MAY-2011)

X effective=X-Xc
= (1-K) X
Where K=Xc/X; 0<X<1
25%- 75% of line reactance

15. List the advantage of FACTS technology? ***(JUNE-2011)***

- Provide secure tie line
- Provide greater flexibility in sitting new generation\
- Upgrade of line
- Reduce reactive power flow, thus allowing the line carry more active power
- Reduce loop flow
- Increase utilization of lowest cost generation

16. Draw the power angle curve (or) P- δ curve in a power flow dynamic stability consideration?



17. Define STATCOM?

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.

18. List the objective of line compensation?

- To increase the power –transmission capacity of the line
- To keep the voltage profile of the line along its length within the acceptable bound to ensure the quality of supply, to minimize the line insulation cost.

19. Define UPFC?

The **Unified Power Flow Controller** (UPFC) is the most versatile FACTS controller developed so far, with all encompassing of voltage regulation, series compensation and phase shifting. It can independently and very rapidly control both real and reactive power flows in a transmission line.

20. What are the applications of FACTS? ***(Dec 2014)***

- Control of power flow as ordered. The use of control of the power flow may be to follow a contract, meet the utilities' own needs, ensure optimum power flow, ride through emergency conditions, or a combination thereof.
- Increase the loading capability of lines to their thermal capabilities, including short term and seasonal. This can be accomplished by overcoming other limitations, and sharing of power among lines according to their capability. It is also important to note that thermal capability of a line varies by a very large margin based on the environmental conditions and loading history.
- 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.

21. Define Static synchronous series compensator (SSSC)

- A static synchronous generator operated without an external electric energy source as a series compensator whose 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 and thereby controlling the transmitted electric power.
- The SSSC may include transiently rated energy-storage or energy-absorbing devices to enhance the dynamic behavior of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real (resistive) voltage drop across the line

22. Define Battery-energy–storage system (BESS)

A chemical-based energy-storage system using shunt-connected switching converters to supply or absorb energy to or from an ac system which can be adjusted rapidly.

23. Define Inter phase power controller (IPC)

A series-connected controller of active and reactive power consisting, in each phase, of inductive and capacitive branches subjected to separately phase-shifted voltages. The active and reactive power can be set independently by adjusting the phase shifts and/ or the branch impedances using mechanical or electronic switches. In the particular case where the inductive and capacitive impedances form a conjugate pair, each terminal of the IPC is a passive current source dependent on the voltage at the other terminal.

24. Define Static condenser (STATCON)

This term is deprecated in favor of the static synchronous compensator (SSC or STATCOM).

25. Define Static synchronous generator (SSG)

A static, self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multiphase output voltages, which may be coupled to an ac power system for the purpose of exchanging independently controllable real and reactive power.

26.Define Static var generator or absorber (SVG)

A static electrical device, equipment, or system that is capable of drawing controlled capacitive and/ or inductive current from an electrical power system and thereby generating or absorbing reactive power. Generally considered to consist of shunt-connected, thyristor-controlled reactor(s) and/ or thyristor-switched capacitors.

27.Define Static var system (SVS)

A combination of different static and mechanically switched VAR compensators whose outputs are coordinated.

28. Define Superconducting magnetic energy storage (SMES)

A superconducting electromagnetic-based energy-storage system using shunt-connected switching converters to rapidly exchange energy with an ac system.

29. What is meant by Thyristor-controlled braking resistor (TCBR)

A shunt-connected, thyristor switched resistor, which is controlled to aid stabilization of a power system or to minimize power acceleration of a generating unit during a disturbance.

30. Define Thyristor-controlled phase-shifting transformer (TCPST)

A phase-shifting transformer, adjusted by thyristor switches to provide a rapidly variable phase angle.

31. Define Thyristor-switched capacitor (TSC)

A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.

32. Define Thyristor-switched reactor (TSR)

A shunt-connected, thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.

33. What is meant by Thyristor-switched series capacitor (TSSC) (April 2014)

A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor switched reactor to provide a stepwise control of series capacitive reactance.

34. Define Thyristor-switched series compensation

An impedance compensator which is applied in series on an ac transmission system to provide a stepwise control of series reactance.

35. Define Thyristor-switched series reactor (TSSR)

An inductive reactance compensator which consists of a series reactor shunted by a thyristor-switched reactor in order to provide a stepwise control of series inductive reactance.

36. What is reactive power? (Dec 2014)

The reactive power flows from load to source. The average value for reactive power is zero. It does not result in any active power consumption. Unit: Volt Ampere Reactive (VAR)

37. What are the two main reasons for incorporating FACTS devices in electric power system? (April 2014, May 2015)

i. Raising dynamic stability limits
ii. Provide better power control

38. State the features of Interline Power Flow Controller (IPFC). (May 2015)

- It has better load balancing.
- It has high X/R ratio.
- Transmission line losses are low.
- It controls both real and reactive power with high operating efficiency.

PART-B (16 MARKS)

1. Explain the concept of flexible AC transmission system?

Basics of Power Transmission Networks

- A 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 (caused by flashovers due to over voltages on the lines or reduced clearances to ground). A CB is rated for a limited number of open and close operations at a time and cannot be used.

- For power flow control. (Unlike a high power electronic switch such as Thyristor, GTO, IGBT, IGCT, etc.). Fortunately, ac lines have inherent power flow control as the power flow is determined by the power at the sending end or receiving end.

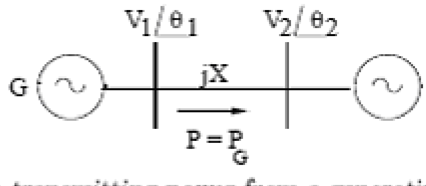
- For example, consider a transmission line connecting a generating station to a load centre in Fig.1.1 (a). Assuming the line to be lossless and ignoring the line charging, the power flow (P) is given by

$$P = \frac{V_1 V_2}{X} \sin(\theta_1 - \theta_2) \qquad 1.1$$

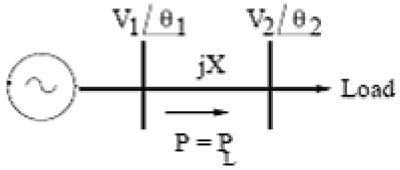
Where X is the series line reactance.

- Assuming V_1 and V_2 to be held constants (through voltage regulators at the two ends), the power injected by the power station determines the flow of power in the line. The difference in the bus angles is automatically adjusted to enable P = PG (Note that usually there could be more than one line transmitting power from a generating station to a load centre).

- If one or more lines trip, the output of the power station may have to be reduced by tripping generators, so as to avoid overloading the remaining lines in operation.



(a) A line transmitting power from a generating station



(b) A line supplying power to a load

- Fig. above shows another situation where a line supplies power to a load located at bus (2). Here also the eq. (1.1) applies but the power flow in the line is determined by the load supplied.

- The essential difference between the two situations is that in Fig. above (a), the load centre is modelled as an infinite bus which can absorb (theoretically) any amount of power supplied to it from the generating station. This model of the load centre assumes that the generation available at the load centre is much higher than the power supplied from the remote power station (obviously, the total load supplied at the load centre is equal to the net generation available at that bus).

- 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.

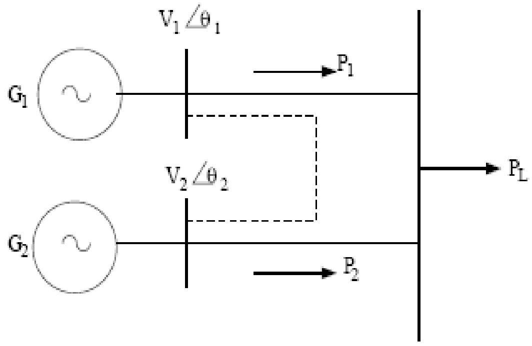


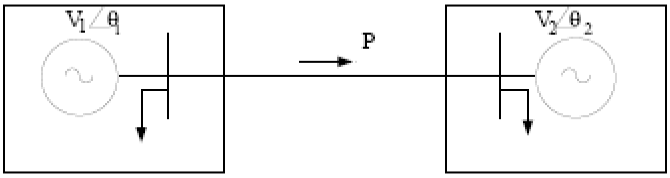
Figure 1.2: Two generating stations supplying a load

Here, P_1 is the output of G_1 while P_2 is the output of G_2 (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.

However, in steady state, P_1 can be higher or lower than PG_1 (the output of G_1). The actual power flows in the 3 lines forming a mesh are determined by Kirchoff's Voltage Law (KVL). In general, the addition of an (interconnecting) line can result in increase of power flow in a line (while decreasing the power low n some other line).

This is an interesting feature of AC transmission lines and not usually well understood (in the context of restructuring). In general, it can be stated that in an uncontrolled AC transmission network with loops (to improve system reliability), the power flows in individual lines are determined by KVL and do not follow the requirements of the contracts (between energy producers and customers).

It is ensure that the power flow between two nodes follows a predetermined path. This is only feasible in radial networks (with no loops), but the reliability is adversely affected as even a single outage can result in load curtailment. Consider two power systems, each with a single power station meeting its own local load, interconnected by a tie line as shown in Fig below.



(a)Single line diagram

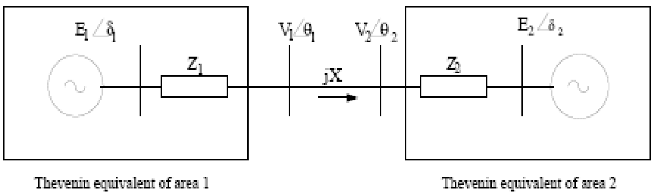
In this case, the power flow in the tie line (P) in steady state is determined by the mismatch between the generation and load in the individual areas. Under dynamic conditions, this power flow is determined from the equivalent circuit shown in Fig. If the capacity of the tie is small compared to the size (generation) of the two areas, the angles δ_1 and δ_2 are not affected much by the tie line power flow. Thus, power flow in AC tie is generally uncontrolled and it becomes essential to trip the tie during a disturbance, either to protect the tie line or preserve system security.

In comparison with a AC transmission line, the power flow in a HVDC line in controlled and regulated. However, HVDC converter stations are expensive and HVDC option is used primarily for

(a) Long distance bulk power transmission

(b) Interconnection of asynchronous systems

(c) Underwater (submarine) transmission. The application of HVDC transmission (using Thyristor converters) is also constrained by the problem of commutation failures affecting operation of multi terminal or multi-feed HVDC systems. This implies that HVDC links are primarily used for point-to-point transmission of power and asynchronous interconnection (using Back to Back (BTB) links).



(b)Equivalent circuit

Figure 1.3: Two areas connected by a tie line

2. What are the Opportunities for FACTS in a power system network?

- FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded lines. The possibility that current through a line can be controlled at a reasonable cost enables a large potential of increasing the capacity of existing lines with larger conductors, and use of one of the FACTS Controllers to enable corresponding power to flow through such lines under normal and contingency conditions.

- These opportunities arise through the ability of FACTS Controllers to control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle, and the damping of oscillations at various frequencies below the rated frequency.

- These constraints cannot be overcome, while maintaining the required system reliability, by mechanical means without lowering the useable transmission capacity. By providing added flexibility, FACTS Controllers can enable a line to carry power closer to its thermal rating. Mechanical switching needs to be supplemented by rapid-response power electronics. It must be emphasized that FACTS is an enabling technology, and not a one-on-one substitute for mechanical switches.

- 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 mentioned above.

- A well-chosen FACTS Controller can overcome the specific limitations of a designated transmission line or a corridor. Because all FACTS Controllers represent applications of the same basic technology, their production can eventually take advantage of technologies of scale. Just as the transistor is the basic element for a whole variety of microelectronic chips and circuits, the thyristor or high-power transistor is the basic element for a variety of high-power electronic Controllers. FACTS technology also lends itself to extending usable transmission limits in a step-by-step manner with incremental investment as and when required.

- It is also worth pointing out that, in the implementation of FACTS technology, we are dealing with a base technology, proven through HVDC and high-power industrial drives. Nevertheless, as power semiconductor devices continue to improve, particularly the devices with turn-off capability, and as FACTS Controller concepts advance, the cost of FACTS Controllers will continue to decrease.

3. Describe the procedure to locate the FACTS devices in an electrical network?

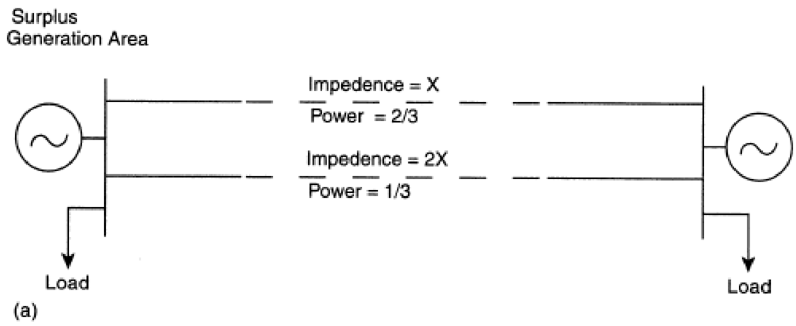
- At present, many transmission facilities confront one or more limiting network parameters plus the inability to direct power flow .In ac power systems, given the insignificant electrical storage, the electrical generation and load must balance at all times. To some extent, the electrical system is 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.

- However, there are only a few percent margins for such a self-regulation. If voltage is propped up with reactive power support, then the load will go up, and consequently frequency will keep dropping, and the system will collapse. Alternately, if there is inadequate reactive power, the system can have voltage collapse. When adequate generation is available, active power flows from the surplus generation areas to the deficit areas, and it flows through all parallel paths available which frequently involve extra high-voltage and medium-voltage lines.

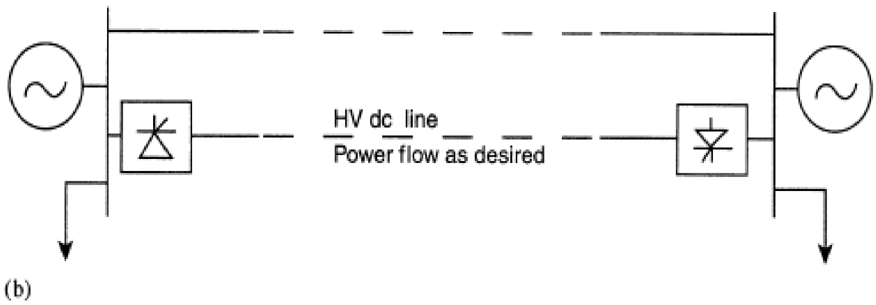
<u>Power Flow in Parallel Paths :</u>

- Consider a very simple case of power flow [Figure below (a)], through two parallel paths (possibly corridors of several lines) from a surplus generation area, 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. Apart from ownership and contractual issues over which lines carry how much power.

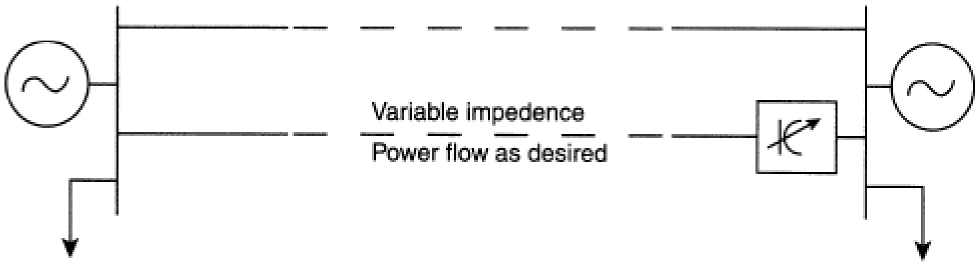
➢ It is likely that the lower impedance line may become overloaded and thereby limit the loading on both paths even though the higher impedance path is not fully loaded. There would not be an incentive to upgrade current capacity of the overloaded path, because this would further decrease the impedance and the investment would be self-defeating particularly if the higher impedance path already has enough capacity.



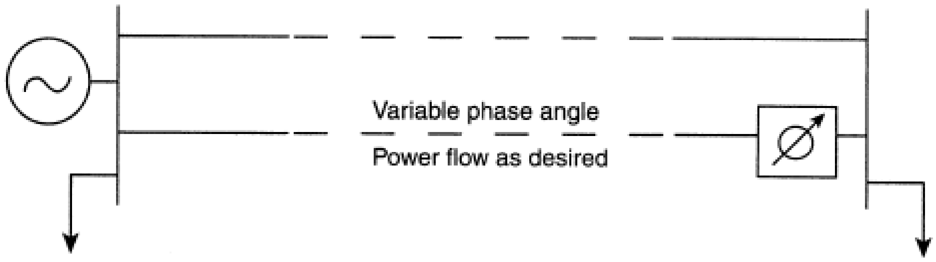
➢ Figure below below(b) shows the same two paths, but one of these has HVDC transmission. With HVDC, power flows as ordered by the operator, because with HVDC power electronics converters power is electronically controlled. Also, because power is electronically controlled, the HVDC line can be used to 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 Inter tie on which power flows as ordered by the operator. As alternative FACTS Controllers,



➢ Figures (c) and (d) show one of the transmission lines with different types of series type FACTS Controllers. By means of controlling impedance [Figure (c)] or phase angle [Figure (d)], or series injection of appropriate voltage (not shown) a FACTS 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.



(c)



(d)

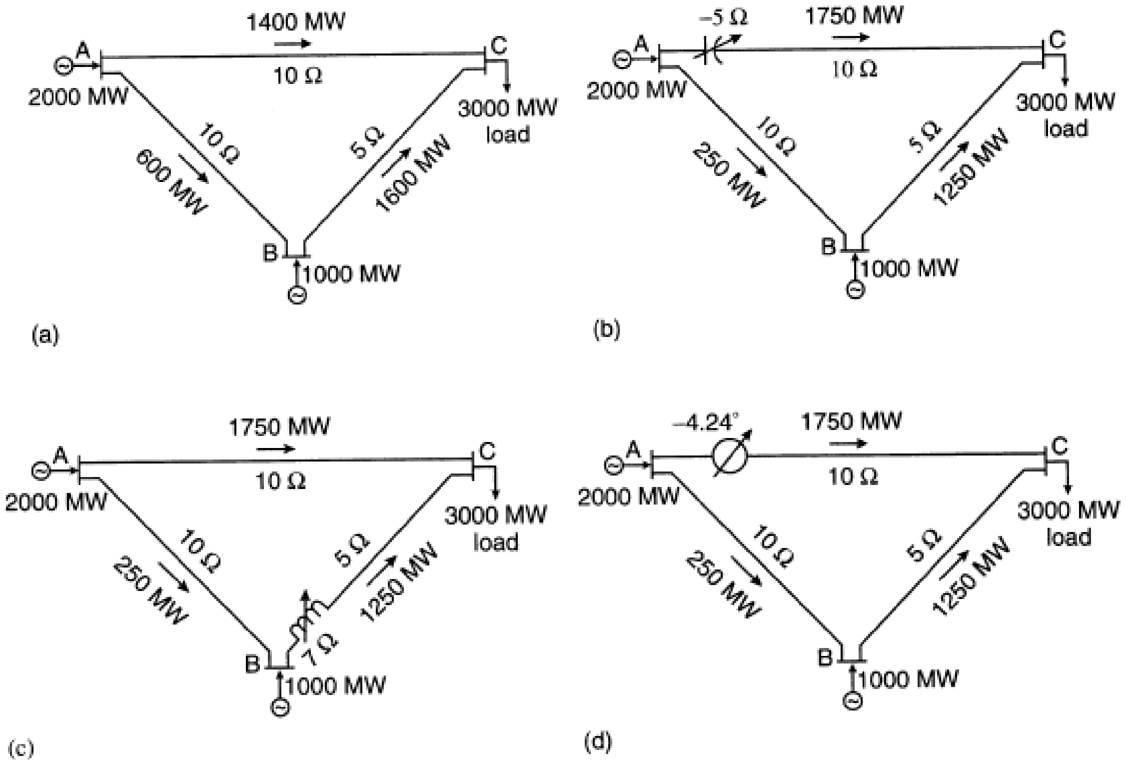
Power Flow in a Meshed System:

- To understand the free flow of power, consider a very simplified case in which generators at two different sites are sending power to a load center through a network consisting of three lines in a meshed connection (Figure below). Suppose the lines AB, BC, and AC have continuous ratings of 1000 Mw, 1250 MW, and 2000 MW, respectively, and have emergency ratings of twice those numbers for a sufficient length of time to allow rescheduling of power in case of loss of one of these lines.

- If one of the generators is generating 2000 MW and the other 1000 MW, a total of 3000 MW would be delivered the load center. For the impedances shown, the three lines would carry 600, 1600, and L400 Mw, respectively, as shown in Figure. Such a situation would overload line BC (loaded at 1600 MW for its continuous rating of 1250 MW), and therefore generation would have to be decreased at B, and increased at A. in order to meet the load without overloading line BC' power, in short, flows in accordance with transmission line series impedances (which are inductive) that bear no direct relationship to transmission ownership, contracts, thermal limits, or transmission losses.

- If, however, a capacitor whose reactance is 10^{-5} ohms at the synchronous frequency is inserted in one line, it reduces the line impedance L_0 , that power flow through the lines AB, BC, and AC will be 250,1250, and 1750 MW, respectively. It is clear that if the series capacitor is adjustable, then other power-flow levels may be realized in accordance with the ownership, contract, thermal limitations, transmission losses, and a wide range of load and generation schedules. Although this capacitor could be modular and mechanically switched, the number of operations would be severely limited by wear on the mechanical components because the line loads vary continuously with load conditions, generation schedules, and line outages.

- Other complications may arise if the series capacitor is mechanically controlled. A series capacitor in a line may lead to sub synchronous resonance (typically at 10-50 Hz for a 60Hz system). This resonance occurs when one of the mechanical resonance frequencies of the shaft of a multiple-turbine generator unit coincides with 60 Hz



- The electrical resonance frequency of the capacitor with the inductive impedance of the line. If such resonance persists, it will soon damage the shaft. Also while the outage of one line forces other lines to operate at their emergency ratings and carry higher loads, power flow oscillations at low frequency (typically 0.3-3 Hz) may cause generators to lose synchronism, perhaps prompting the system's collapse.

- The part of the series capacitor is thyristor-controlled, however, it can be varied as often as required. It can be modulated to rapidly damp any sub synchronous resonance conditions, as well as damp low frequency oscillations in the power flow. This would allow the transmission system to go from one steady-state condition to another without the risk of damage to a generator shaft and also help reduce the risk of system collapse. In other words, a thyristor-controlled series capacitor can greatly enhance the stability of the network. More often than not though, it is practical for part of the series compensation to be mechanically controlled and part thyristor controlled, so as to counter the system constraints at the least cost.

- Similar results may be obtained by increasing the impedance of one of the lines in the same meshed configuration by inserting a reactor (inductor) in series with line AB. Again, a series inductor that is partly mechanically and partly thyristor-controlled, it could serve to adjust the steady-state power flows as well as damp unwanted oscillations. As another option, a thyristor-controlled phase-angle regulator could be installed instead of a series capacitor or a series reactor in any of the three lines to serve the same purpose.

.

- The balancing of power flow in the above case did not require more than one FACTS Controller, and indeed there are options of different controllers and in different lines. If there is only one owner of the transmission grid, then a decision can be made on consideration of overall economics alone. On the other hand, if multiple owners are involved, then a decision mechanism is necessary on the investment and ownership.

4. What are the factors which limits the Loading Capability? Explain?

Assuming that ownership is not an issue, and the objective is to make the best use of the transmission asset, and to maximize the loading capability (taking into account contingency conditions),

Basically, there are three kinds of limitations:

- Thermal
- Dielectric
- Stability

Thermal :

- Thermal capability of an overhead line is a function of the ambient temperature, wind conditions, condition of the conductor, and ground clearance. It varies perhaps by a factor of 2 to 1 due to the variable environment and the loading history. The nominal rating of a line is generally decided on a conservative basis, envisioning a statistically worst ambient environment case scenario.

- This scenario occurs but rarely which means that in reality most of the time, there is a lot more real time capacity than assumed. Some utilities assign winter and summer ratings, yet this still leaves a considerable margin to play with. There are also off-line computer programs that can calculate a line's loading capability based on available ambient environment and recent loading history. Then there are the on-line monitoring devices that provide a basis for on-line real-time loading capability.

- These methods have evolved over a period of many years, and, given the age of automation (typified by GPS systems and low-cost sophisticated communication services), it surely makes sense to consider reasonable, day to day, hour to hour, or even real-time capability information. Sometimes, the ambient conditions can actually be worse than assumed, and having the means to determine actual rating of the line could be useful. During planning/design stages, normal loading of the lines is frequently decided on a loss evaluation basis under assumptions which may have changed for a variety of reasons; however losses can be taken into account on the real-time value basis of extra loading capability.

- Increasing the rating of a transmission circuit involves consideration of the real-time ratings of the transformers and other equipment as well, some of which may also have to be changed in order to increase the loading on the lines. Real-time loading capability of transformers is also a function of ambient temperature, aging of the transformer and recent loading history. Off-line and on-line loading capability monitors can also be used to obtain real time loading capability of transformers.

- Transformer also lends itself to enhanced cooling. Then there is the possibility of upgrading a line by changing the conductor to that of a higher current rating, which may in turn require structural upgrading. Finally, there is the possibility of converting a single-circuit to a double-circuit line. Once the higher current capability is available, then the question arises of how it should be used. Will the extra power actually flow and be controllable, Will the voltage conditions be acceptable with sudden load dropping, etc., The FACTS technology can help in making an effective use of this newfound capacity.

Dielectric:

- From an insulation point of view, many lines are designed very conservatively. For a given nominal voltage rating, it is often possible to increase normal operation by +10 Vo voltage (i.e., 500 kV-550 kV) or even higher.

- That dynamic and transient over voltages are within limits. Modern gapless arresters or line insulators with internal gapless arresters, or powerful thyristor-controlled overvoltage suppressors at the substations can enable significant increase in the line and substation voltage capability. The FACTS technology could be used to ensure acceptable over-voltage and power flow conditions.

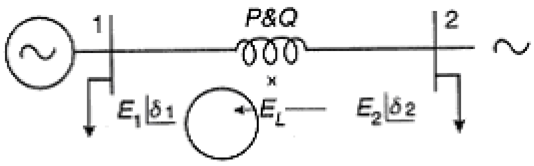
Stability :

There are a number of stability issues that limit the transmission capability.
These include:

- Transient stability
- Dynamic stability
- Steady-state stability
- Frequency collapse
- Voltage collapse
- Sub synchronous resonance

5. Derive an expression for power transfer between the two bus systems assuming that transmission line is lossless. Calculate degree of series compensation that is required to enhance the power transfer capability? (DEC-2012),(JUNE-2011)

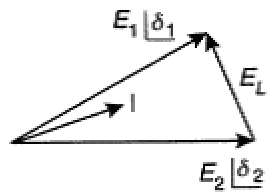
- Figure below (a) shows a simplified case of power flow on a transmission line. Locations 1 and 2 could be any transmission substations connected by a transmission line. Substations may have loads, generation, or may be interconnecting points on the system and for simplicity they are assumed to be stiff busses. E_r and E_2 are the magnitudes of the bus voltages with an angle δ between the two. The line is assumed to have inductive impedance X, and the line resistance and capacitance are ignored.



(a) Simple two-machine system;

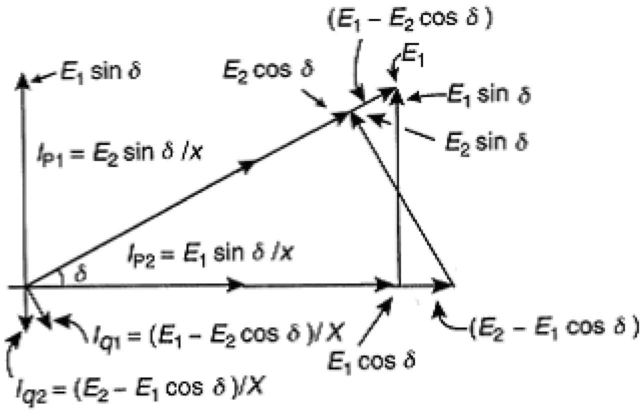
- As shown in the phasor diagram [Figure (b)] the driving voltage drop in the Line is the phasor difference E1 between the two line voltage phasor, El and E2.The line current magnitude is given by:

  I= E_L / X, and lags E_L by 90°

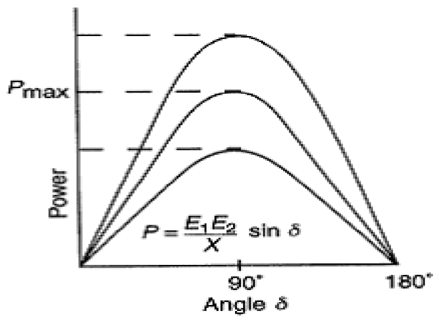


(b) Current flow perpendicular to the driving voltage;

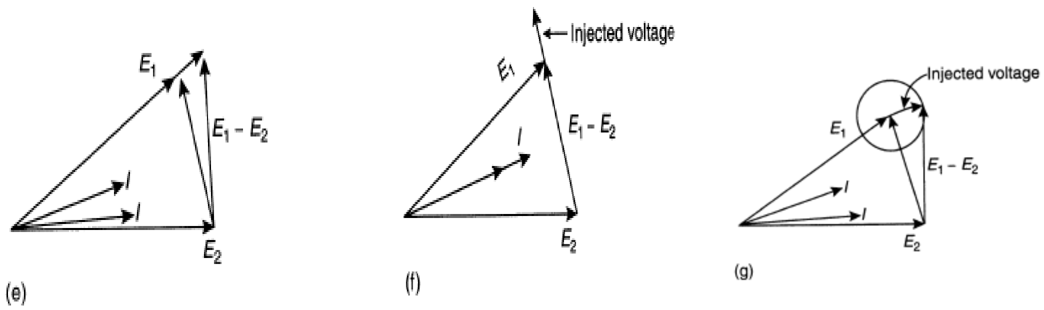
Figure 1.3(b) shows that the current flow phasor is perpendicular to the driving voltage (90° phase lag). If the angle between the two bus voltages is small, the current flow largely represents the active power. Increasing or decreasing the inductive impedance of a line will greatly affect the active power flow. Thus impedance control, which in reality provides current control, can be the most cost-effective means of controlling the power flow. With appropriate control loops, it can be used for power flow control and/or angle control for stability.



(c) Active and reactive power flow phasor diagram;



(d) power angle curves for different values of" X;



(e) Regulating voltage magnitude mostly changes reactive power.
(f) Injecting voltage perpendicular to the line current mostly changes active power;
(g) Injecting voltage phasor in series with the line Relationship between the active and reactive currents with reference to the voltage at the two ends.

Active component of the current flow at E_1 is: $I_{P1} = (E_2 \sin\delta)/X$

Reactive component of the current flow at E_1 is: $I_{q1} = (E_1 - E_2 \cos\delta)/X$

Active Power at the E_1 End: $P_1 = E_1 (E_2 \, \mathrm{Sin}\, \delta)/X$

Reactive power at the E_1 End: $Q1 = E_1 (E_1 - E_2 \mathrm{Cos}\delta)/X$

Similarly, active component of the current flow at E_2 is: $I_{P2} = (E_1 \mathrm{Sin}\delta)/X$

Reactive component of the current flow at E_2 is: $I_{q2} = (E_2 - E_1 \, \mathrm{Cos}\, \delta)/X$

Active power at the end E_2:$P_2 = E_2 (E_1 \, \mathrm{Sin}\, \delta)/X$

Reactive power at the E_2 End: $Q_2 = E_2 (E_2 - E_1 \mathrm{Cos}\delta)/X$

Naturally p_1 and p_2 are the same: $P = E_1 (E_2 \mathrm{Sin}\delta)/X$

Because it is assumed that there are no active power losses in the line. Thus, varying the value of X will vary P, Q_1, and Q_2 in accordance with and respectively.
Assuming that E_1 and E_2 are the magnitudes of the internal voltages of the two internal impedance of the two equivalent machines, figure shows that the half sine wave cure of active of power increasing to a peak with an increase in $\delta\ to\ 90\ degrees.$ power then falls with further increase in angle, and finally to zero at $\delta = 180^{\circ}$. It is easy to appreciate that without high speed control of any of the parameters E_1, E_2
$E_1 - E_2$, X and δ, the transmission line can be utilized only to a level well below that corresponding to 90 degrees. This is necessary, in order to maintain an adequate margin needed for transient and dynamic stability and to ensure that the system does not collapse following the outage of the largest generator and /or a line.

Increase and decrease of the value of X will increase and decrease the height of the curves, respectively, as shown in figure. For a given power flow, varying of X will correspond vary the angle between the two ends.

Power/current flow can also be controlled by regulating the magnitude of voltage phasor E_1 or voltage phasor E_2, However, it is seen from figure that with change in the magnitude of E_1, the magnitude of the driving voltage phasor $E_1 - E_2$ does not change by much, but its phase angle does. This also means that regulation of the magnitude of voltage phasor E_1 and/or E_2 has much more influence over the reactive power flow than the active power flow, as seen from the two current phasors corresponding to the two driving voltage phasors $E_1 - E_2$ shown in figure.

Current flow and hence power flow can also be changed by injecting voltage in series with the line. It is seen from figure that when the injected voltage is in phase quadruped with the current (which is approximately in phase with the driving voltage, figure, it directly influences the magnitude of the current flow, and with small angle influences substantially the active power flow.

Alternatively, the voltage injected in series can be a phasor with variable magnitude and phase relationship with the line voltage. It is seen that varying the amplitude and phase angle of the voltage injected in series, both the active and reactive current flow can be influenced. Voltage injection methods form the most important portfolio of the FACTS Controllers and will be discussed in detail in subsequent chapters.

6. Explain how changing the value of line Impedance, the maximum amount of reactive power flow will change?

Relative importance of controllable parameters? (DEC-2010)

- Control of the line impedance X (e.g., with a thyristor-controlled series capacitor) can provide a powerful means of current control.
- When the angle is not large, which is often the case, control of X or the angle substantially provides the control of active power.

- Control of angle (with a Phase Angle Regulator, for example), which in turn controls the driving voltage, provides a powerful means of controlling the current flow and hence active power flow when the angle is not large.

- Injecting a voltage in series with the line, and perpendicular to the current flow, can increase or decrease the magnitude of current flow. Since the current flow lags the driving voltage by 90 degrees, this means injection of reactive power in series, (e.g., with static synchronous series compensation) can provide.

- Powerful means of controlling the line current, and hence the active power when the angle is not large.

- Injecting voltage in series with the line and with any phase angle with respect to the driving voltage can control the magnitude and the phase of the line current. This means that injecting a voltage phasor with variable phase angle can provide a powerful means of precisely controlling the active and reactive power flow. This requires injection of both active and reactive power in series.

- Because the per unit line impedance is usually a small fraction of the line voltage, the MVA rating of a series Controller will often be a small fraction of the throughput line MVA.

- When the angle is not large, controlling the magnitude of one or the other line voltages (e.g., with a thyristor-controlled voltage regulator) can be a very cost-effective means for the control of reactive power flow through the interconnection.

- Combination of the line impedance control with a series Controller and voltage regulation with a shunt Controller can also provide a cost-effective means control both the active and reactive power flow between the two systems.

7. Explain the Power Flow Control in Ac Transmission Line. (JUNE-2011)

To control the power flow in a AC transmission line to

(a) Enhance power transfer capacity.

(b) To change power flow under dynamic conditions (subjected to disturbances such as sudden increase in load, line trip or generator outage) 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.

From eq. (1.1), we have the maximum power (P_{max}) transmitted over a line as

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

Where δ_{max} (30°-40°) is selected depending on the stability margins and the stiffness of the terminal buses to which the line is connected. For line lengths exceeding a limit, P_{max} is less than the thermal limit on the power transfer determined by the current carrying capacity of the conductors (Note this is also a function of the ambient temperature). As the line length increases, X increases in a linear fashion and P_{max} reduces as shown in Fig.

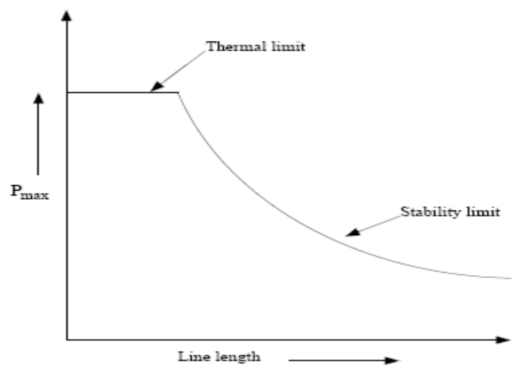


Figure 1.4: Power transfer capacity as a function of line length

The series compensation using series connected capacitors increases P_{max} as the compensated value of the series reactance (Xc) is given by

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

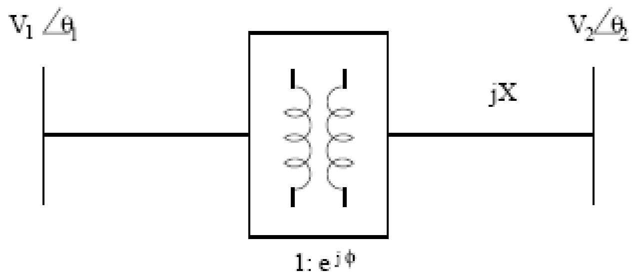
where k_{se} is the degree of series compensation. The maximum value of kse that can be used depends on several factors including the resistance of the conductors. Typically k_{se} does not exceed 0.7.

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. However, the control of series compensation using Thyristor. switches has been introduced only 10-15 years ago for fast power flow control. 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 turn’s ratio with magnitude of unity. The power flow in a lossless transmission line with an ideal PST (see Fig) is given by

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

where $\theta = \theta_1 - \theta_2$.



A lossless line with an ideal PST

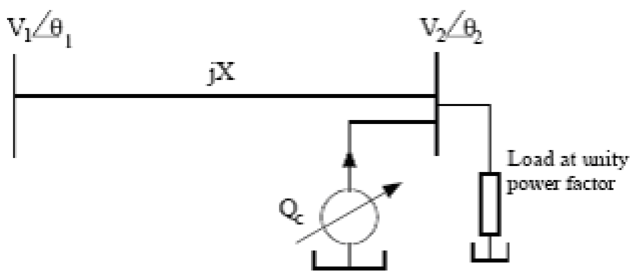
Again, manually controlled PST is not fast enough under dynamic conditions. Thyristor switches can ensure fast control over discrete (or continuous) values of Á, depending on the configuration of PST used. Pmax can also be increased by controlling (regulating) the receiving end voltage of the AC line. When a generator supplies a unity power factor load, the maximum power occurs when the load resistance is equal to the line reactance. It is to be noted that V2 varies with the load and can be expressed as

$$V_2 = V_1 \cos(\theta_1 - \theta_2)$$

Substituting (1.5) in (1.1) gives

$$P = \frac{V_1^2 \sin[2(\theta_1 - \theta_2)]}{2X}$$

By providing dynamic reactive power support at bus (2) as shown in Fig below, it is possible to regulate the bus voltage magnitude. The reactive



Transmission line compensated by controllable reactive power source at receiving end

Power (QC) that has to be injected is given by

$$Q_C = \frac{V_2^2 - V_1 V_2 \cos(\theta_1 - \theta_2)}{X}$$

Comparing the above eq. it can be seen that the maximum power transfer can be doubled just by providing dynamic reactive power support at the receiving end of the transmission line. This is in addition to the voltage support at the sending end. It is to be noted that while steady state voltage support can be provided by mechanically switched capacitors, the dynamic voltage support requires synchronous condenser or a power electronic controller such as Static Var Compensator (SVC) or Static synchronous Compensator (STATCOM).

8. List the types of FACTS controllers. Explains any one type with neat diagram? (MAY-2011),(DEC-2012)

Flexible Ac Transmission System Controllers

General Description

The large interconnected transmission networks (made up of predominantly overhead transmission lines) are susceptible to faults caused by lightning discharges and decrease in insulation clearances by undergrowth. The power flow in a transmission line is determined by Kirchoff's laws for a specified power injection (both active and reactive) at various nodes. While the loads in a power system vary by the time of the day in general, they are also subject to variations caused by the weather (ambient temperature) and other unpredictable factors. The generation pattern in a deregulated environment also tends to be variable (and hence less predictable). Thus, the power flow in a transmission line can vary even under normal, steady state conditions. The occurrence of a contingency (due to the tripping of a line, generator) can result in a sudden increase/decrease in the power flow. This can result in overloading of some lines and consequent threat to system security.

A major disturbance can also result in the swinging of generator rotors which contribute to power swings in transmission lines. It is possible that the system is subjected to transient instability and cascading outages as individual components (lines and generators) trip due to the action of protective relays. If the system is operating close to the boundary of the small signal stability region, even a small disturbance can lead to large power swings and blackouts.

The increase in the loading of the transmission lines sometimes can lead to voltage collapse due to the shortage of reactive power delivered at the load centers. This is due to the increased consumption of the reactive power in the transmission network and the characteristics of the load (such as induction motors supplying constant torque).

The factors mentioned in the previous paragraphs point to the problems faced in maintaining economic and secure operation of large interconnected systems. The problems are eased if sufficient margins (in power transfer) can be maintained. This is not feasible due to the difficulties in the expansion of the transmission network caused by economic and environmental reasons. The required safe operating margin can be substantially reduced by the introduction of fast dynamic control over reactive and active power by high power electronic controllers. This can make the AC transmission network flexible' to adapt to the changing conditions caused by contingencies and load variations. Flexible AC Transmission System (FACTS) is defined as `Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability'. The FACTS controller is defined as a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters.

The facts controllers can be classified as,

1. Shunt connected controllers
2. Series connected controllers
3. Combined series-series controllers
4. Combined shunt-series controllers

Depending on the power electronic devices used in the control, the FACTS controllers can be classified as,

(A) Variable impedance type

(B) Voltage Source Converter (VSC) - based.

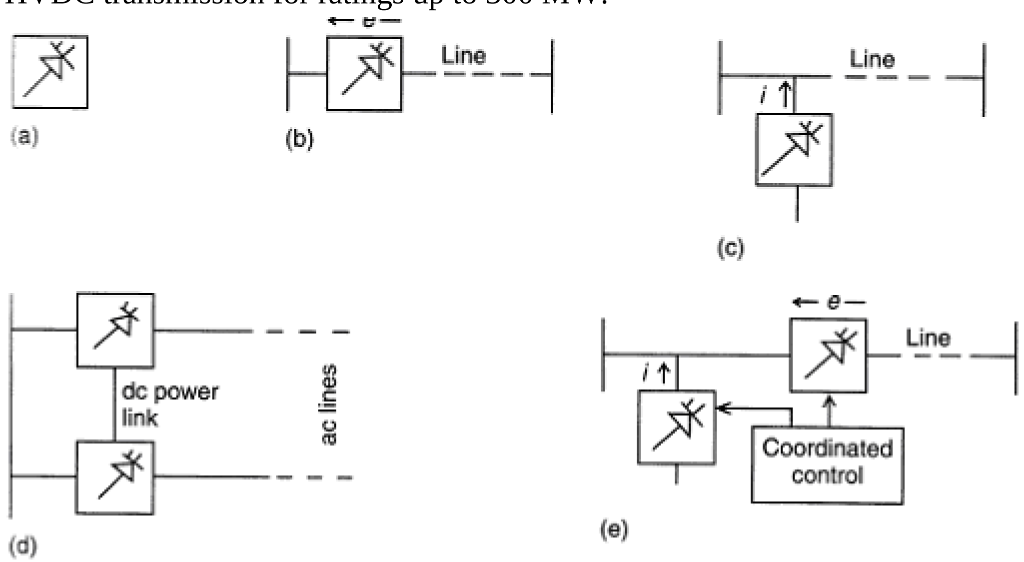
The variable impedance type controllers include:

(i) Static Var Compensator (SVC), (shunt connected)
(ii) Thyristor Controlled Series Capacitor or compensator (TCSC), (series connected)
(iii) Thyristor Controlled Phase Shifting Transformer (TCPST) of Static PST (combined shunt and series)

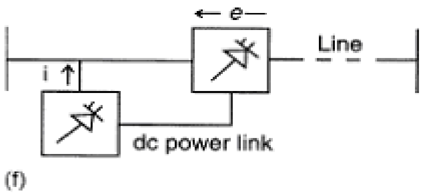
The VSC based FACTS controllers are:
(i) Static synchronous Compensator (STATCOM) (shunt connected)
(ii) Static Synchronous Series Compensator (SSSC) (series connected)
(iii) Interline Power Flow Controller (IPFC) (combined series-series)
(iv) Unified Power Flow Controller (UPFC) (combined shunt-series)

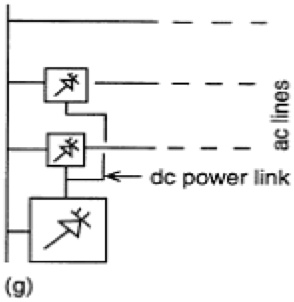
Some of the special purpose FACTS controllers are:
(a) Thyristor Controller Braking Resistor (TCBR)
(b) Thyristor Controlled Voltage Limiter (TCVL)
(c) Thyristor Controlled Voltage Regulator (TCVR)
(d) Inter phase Power Controller (IPC)
(e) NGH-SSR damping.

The FACTS controllers based on VSC have several advantages over the variable impedance type. For example, a STATCOM is much more compact than a SVC for similar rating and is technically superior. It can supply required reactive current even at low values of the bus voltage and can be designed to have in built short term overload capability. Also, a STATCOM can supply active power if it has an energy source or large energy storage at its DC terminals. The only drawback with VSC based controllers is the requirement of using self commutating power semiconductor devices such as Gate Turn-of (GTO) Thyristor, Insulated Gate Bipolar Transistors (IGBT), and Integrated Gate Commutated Thyristor (IGCT). Thyristor do not have this capability and cannot be used although they are available in higher voltage ratings and tend to be cheaper with reduced losses. However, the technical advantages with VSC based controllers coupled will emerging power semiconductor devices using silicon carbide technology are expected to lead to the wide spread use of VSC based controllers in future. It is interesting to note that while SVC was the first FACTS controllers (which utilized the Thyristor valves developed in connection with HVDC line commutated converters) several new FACTS controller based on VSC have been developed. This has led to the introduction of VSC in HVDC transmission for ratings up to 300 MW.

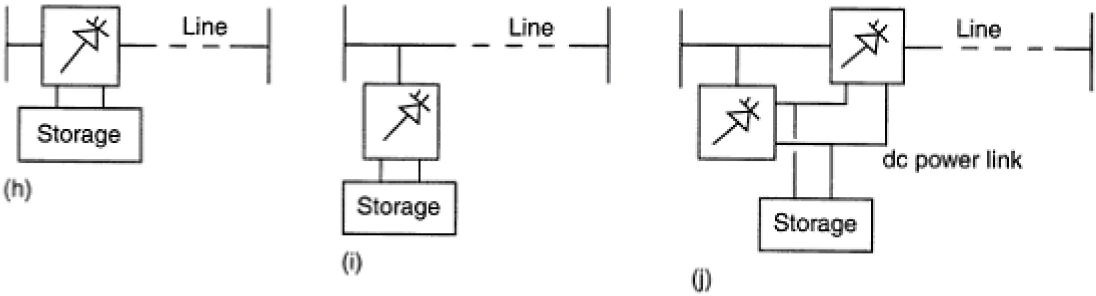


a) FACTS controller, b)series controller, C) shunt controller,d) unified series- series controller, e) coordinated series and shunt controller





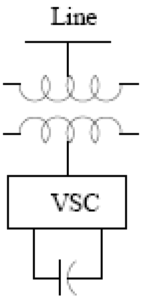
f)unified series- shunt controller, g) unified controller for multiple line.



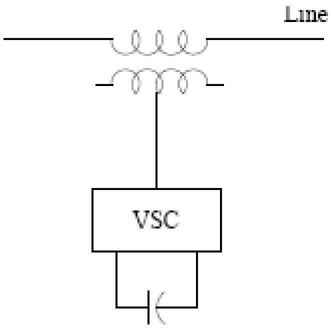
h) Series controller with storage, i) shunt controller with storage, j) unified series- shunt controller with storage.

9. Explain briefly Voltage Source Converter Based Controllers? (MAY-2011)

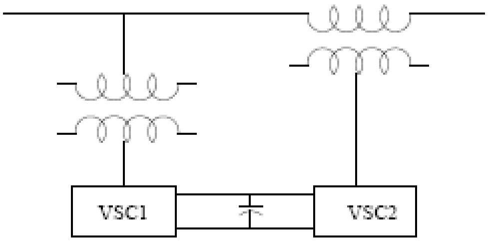
The schematic diagram of a STATCOM is shown in Fig. below 1while that of a SSSC is shown in Fig. below 2 the diagram of a UPFC is shown in Fig. below 3.



Shunt connected STATCOM

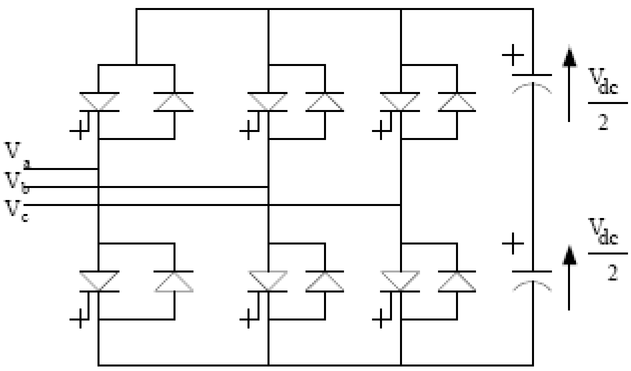


Series connected SSSC



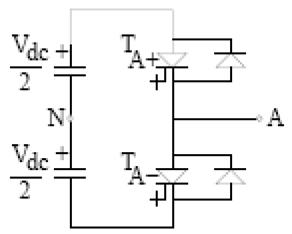
Unified power flow controller

A six pulse Voltage Source Converter (VSC) is shown in Fig. By suitable control, the phase and the magnitude of the AC voltage injected by the VSC can be controlled. The Phase Lock Loop (PLL) ensures that the sinusoidal component of the injected voltage is synchronized (matching in frequency and required phase angle) with the voltage of the AC bus to which VSC is connected through an inductor. Often, the leakage impedance of the interconnecting transformer serves as the inductive impedance that has to separate the sinusoidal bus voltage and the voltage injected by the VSC (which contains harmonics). The injection of harmonic voltages can be minimized by multi pulse (12, 24 or 48), and/or multilevel convectors. At low power levels, it is feasible to provide pulse width modulation (PWM) to control the magnitude of the fundamental component of the injected voltage. The high voltage IGBT devices can be switched up to 2 kHz and high frequency of sinusoidal modulation enables the use of simple L-C (low pass) filters to reduce harmonic components.



A three phase, six pulse VSC

The operation of a VSC can be explained with reference to a single Phase (half-wave) converter shown in Fig below, This can represent one leg of the 3 phase VSC.



A single phase half wave converter

T_{A+} and T_{A-} are controllable switches which can be switched on or off at controllable instants in a cycle. The diodes ensure that the current can flow in both directions in the DC capacitor. The switches T_{A+} and T_{A-} work in complementary fashion - only one of them is on while the other is of. If the switch is turned on only once during a cycle, this is called as the square-wave switching scheme with each switch conducting for 180° in a cycle. The peak value of the fundamental component (V_{AN1}) is given by

$$V_{AN1} = \frac{4}{\pi}\left(\frac{V_{dc}}{2}\right) = 1.273\left(\frac{V_{dc}}{2}\right)$$

The waveform contains odd harmonics with the magnitudes

$$V_{ANh} = \frac{V_{AN1}}{h}, \quad h = 3, 5, 7, \ldots$$

It is to be noted that in the square wave switching scheme, only the phase angle of the voltage injected by the VSC can be controlled (and not the magnitude). It will be shown in chapter 6 that in a three phase converter with3 legs the triplen harmonics will disappear such that the non-zero harmonic order (h) is given by

h=6n (±)1 n=1,2,3 …….

It is to be noted that in the square wave switching scheme, only the phase angle of the voltage injected by the VSC can be controlled (and not the magnitude). It will be shown in chapter 6 that in a three phase converter with 3 legs the triplen harmonics will disappear such that the non-zero harmonic order (h) is given by

h = 6n (±) 1; n = 1; 2…..

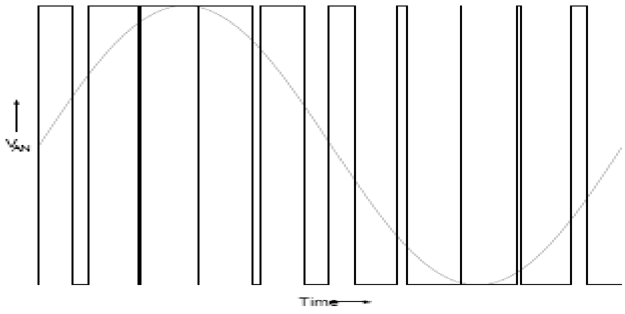
Increasing the pulse number from six to twelve has the effect of eliminating the harmonics corresponding to odd values of n. The introduction of PWM has the effect of controlling the magnitude of the fundamental component of the injected voltage by the VSC. For this case, the waveform of the voltage V_{AN} is shown in Fig. 1.12. Using sinusoidal modulation (with triangular carrier wave), the peak value of the injected sinusoidal voltage can be expressed as

$$V_{AN1} = m\left(\frac{V_{dc}}{2}\right), \quad 0 < m \leq 1$$

where m is called the modulation index. The maximum modulation index can be achieved with space vector modulation and is given by.

$$m_{\max} = \frac{2}{\sqrt{3}} = 1.1547$$

It is to be noted that the modulation index (m) and the phase angle(α) are controlled to regulate the injected current by the shunt connected VSC. Neglecting losses, a STATCOM can only inject reactive current in steady state reference can be controlled to regulate the bus voltage. In a similar fashion the reactive voltage injected by a lossless SSSC can be controlled to regulate the power flow in a line within limits. The combination of a STATCOM and a SSSC, in which the STATCOM feeds (or absorbs) power on the DC side to SSSC, can be used to regulate both active and reactive power flow in a line (subject to the constraints imposed by the ratings of the converters in addition to the limits on bus voltages).



Waveform of v_{AN} and the fundamental component

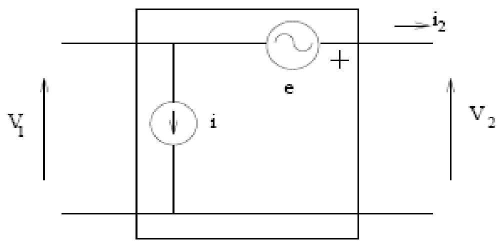
10. Draw and explain the General Equivalent Circuit for FACTS Controllers?

The UPFC (shown in Fig below) is the most versatile FACTS controller with 3 control variables (the magnitude and phase angle of the series injected voltage in addition to the reactive current drawn by the shunt connected (VSC). The equivalent circuit of a UPFC on a single phase basis is shown in Fig below. The current i is drawn by the shunt connected VSC while the voltage e is injected by the series connected VSC. Neglecting harmonics, both the quantities can be represented by phasor I and E. Neglecting power losses in the UPFC, the following constraint equation applies.

$$Re[V_1 I^*] = Re[E I_2^*]$$

Assuming that $\hat{V}_1 = V_1 e^{j\theta_1}$, $\hat{I}_2 = I_2 e^{j\phi_2}$, $\hat{I}$ and $\hat{E}$ can be expressed as

$$\hat{I} = (I_p - jI_r)e^{j\theta_1}$$



An equivalent circuit for UPFC

$$\hat{E} = (V_p + jV_r)e^{j\phi_2}$$

where I_p and I_r are `real' and `reactive' components of the current drawn by the shunt connected VSC. Similarly V_p and V_r and the `real' and `reactive' voltages injected by the series connected VSC. Positive I_p and V_p indicate positive `real' (active) power flowing into the shunt connected VSC and flowing out of the series connected VSC. The positive values of I_r and V_r indicate reactive power drawn by the shunt converter and supplied by the series converter.

Using this equations

$X_C = X(1 - K_{SC})$

$P = V_1 V_2 / X \,\mathrm{Sin}(\theta \pm \Phi)$

$V_2 = V_1 \,\mathrm{COS}\,(\theta_1 - \theta_2)$

Can be expressed as

$V_1 I_p = I_2 V_p$

The remaining shunt and series connected FACTS controllers can be viewed as special cases of a UPFC. For example in a SVC,

$V_P=0, V_R=0, I_P=0, I_R=-B_{svc}V_1$

There are 3 constraint equations and one control variable (BSV C) in a SVC. In a STATCOM, Ir is the control variable.

11. List the benefits with the Application of FACTS Controllers.

The benefits FACTS controllers under due to steady state and dynamic conditions are listed below
1. They contribute to optimal system operation by reducing power losses and improving voltage profile.

2. The power flow in critical lines can be enhanced as the operating margins can be reduced due to fast controllability. In general, the power carrying capacity of lines can be increased to values up to the thermal limits (imposed by current carrying capacity of the conductors).

3. The transient stability limit is increased thereby improving dynamic security of the system and reducing the incidence of blackouts caused by cascading outages.

4. The steady state or small signal stability region can be increased by providing auxiliary stabilizing controllers to damp low frequency oscillations.
5. FACTS controllers such as TCSC can counter the problem of Sub- synchronous Resonance (SSR) experienced with fixed series capacitors connected in lines evacuating power from thermal power stations (with turbo generators).

6. The problem of voltage fluctuations and in particular, dynamic over-voltages can be overcome by FACTS controllers.

The capital investment and the operating costs (essentially the cost of power losses and maintenance) are offset against the benefits provided by the FACTS controllers and the `payback period' is generally used as an index in the planning. The major issues in the deployment of FACTS controllers are (a) the location (b) ratings (continuous and short term) and (c) control strategies required for the optimal utilization. Here, both steady-state and dynamic operating conditions have to be considered. Several systems studies involving power flow, stability, short circuit analysis are required to prepare the specifications. The design and testing of the control and protection equipment is based on Real Time Digital Simulator (RTDS) or physical simulators.

It is to be noted that a series connected FACTS controller (such as TCSC) can control power flow not only in the line in which it is connected, but also in the parallel paths (depending on the control strategies).

Application of FACTS Controllers

Although the concept of FACTS was developed originally for transmission network; this has been extended since last 10 years for improvement of Power Quality (PQ) in distribution systems operating at low or medium voltages.

In the early days, the power quality referred primarily to the continuity of power supply at acceptable voltage and frequency. However, the pro-lific increase in the use of computers, microprocessors and power electronic systems has resulted in power quality issues involving transient disturbances in voltage magnitude, waveform and frequency. The nonlinear loads not only cause PQ problems but are also very sensitive to the voltage deviations.

In the modern context, PQ problem is defined as “Any problem manifested in voltage, current or frequency deviations that result in failure or misoperation of customer equipment".

The PQ problems are categorized as follows
1. Transients
(a) Impulsive
(b) Oscillatory
2. Short-duration and Long-duration variations
(a) Interruptions
(b) Sag (dip)
(c) Swell
3. Voltage unbalance
4. Waveform distortion
(a) DC offset
(b) Harmonics
(c) Inter harmonics
(d) Notching
(e) Noise
5. Voltage Flicker
Power frequency variations
The propose FACTS controllers for improving PQ. He termed them as Custom Power Devices (CPD). These are based on VSC and are of 3 types given below.

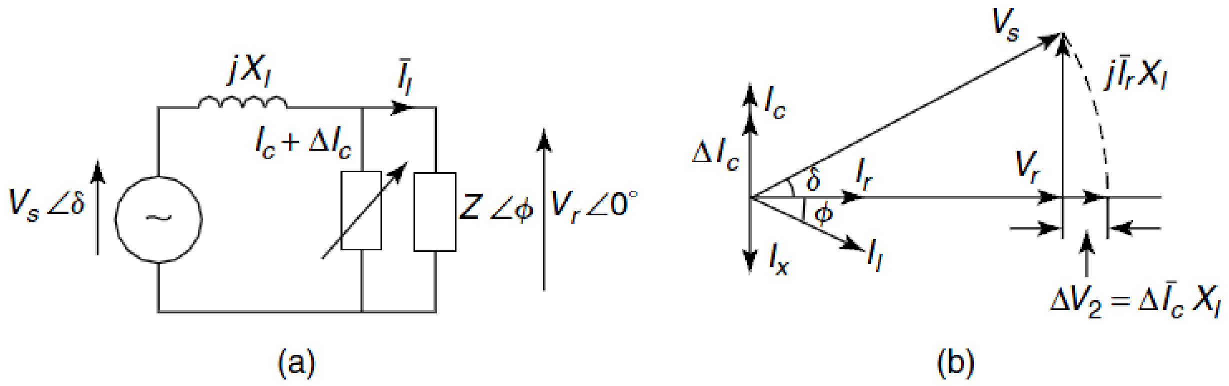
1. Shunt connected Distribution STATCOM (DSTATCOM)
2. Series connected Dynamic Voltage Restorer (DVR)
3. Combined shunt and series, Unified Power Quality Conditioner (UPQC).

The DVR is similar to SSSC while UPQC is similar to UPFC. In spite of the similarities, the control strategies are quite different for improving PQ. A major difference involves the injection of harmonic currents and voltages to isolate the source from the load. For example, a DVR can work as a harmonic isolator to prevent the harmonics in the source voltage reaching the load in addition to balancing the voltages and providing voltage regulation. A UPQC can be considered as the combination of DSTATCOM and DVR.

A DSTATCOM is utilized to eliminate the harmonics from the source currents and also balance them in addition to providing reactive power compensation (to improve power factor or regulate the load bus voltage). The terminology is yet to be standardized. The term `active filters' or `power conditioners' is also employed to describe the custom power devices. ABB terms DSTATCOM as `SVC light'. Irrespective of the name, the trend is to increasingly apply VSC based compensators for power quality improvement.

12. Explain briefly about load compensation. *(May 2015)*

It is possible to compensate for the reactive current I_x of the load by adding a parallel capacitive load so that $I_c = -I_x$. Doing so causes the effective power factor of the combination to become unity. The absence of Ix eliminates the voltage drop $\Delta V1$, bringing Vr closer in magnitude to Vs; this condition is called *load compensation*.



Actually, by charging extra for supplying the reactive power, a power utility company makes it advantageous for customers to use load compensation on their premises. Loads compensated to the unity power factor reduce the line drop but do not eliminate it; they still experience a drop of $\Delta V2$ from $jIrXl$.

13. What are the objectives of line compensation? Explain the effect of shunt and series compensation on power transmission capacity of a short symmetrical transmission line.

(May 2015)

The objectives of line compensation are invariably

1. to increase the power-transmission capacity of the line, and/or
2. to keep the voltage profile of the line along its length within acceptable bounds to ensure the quality of supply to the connected customers as well as to minimize the line-insulation costs.

Consider a short, symmetrical electrical line as shown in Fig. 2.13.
The power equation is

$$P = \frac{V_s V_r}{X_l} \sin\delta \quad \text{--- (1)}$$

For an uncompensated line, and assuming $Vs = Vr = V$. the power equation (1) becomes

$$P = \frac{V^2}{X_l} \sin\delta = \frac{V^2}{X_l} 2\sin\frac{\delta}{2}\cos\frac{\delta}{2} \quad \text{--- (2)}$$

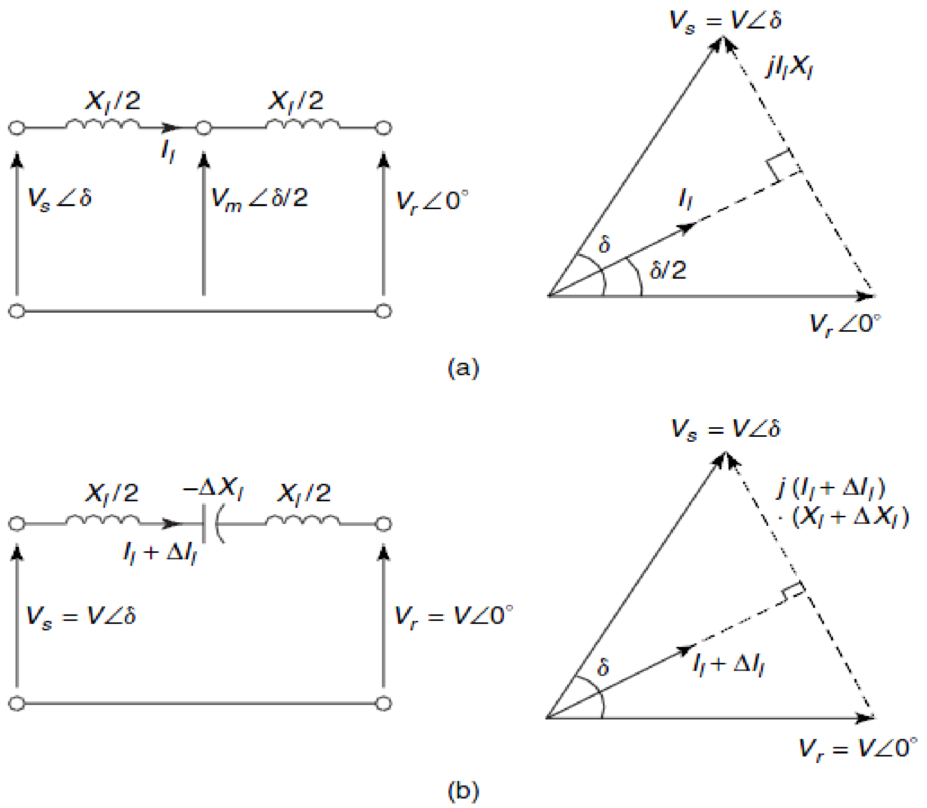


Figure 2.13 The series compensation of a short, symmetrical transmission line.

From the voltage-phasor equations and the phasor diagram in Fig. 2.13(a),

$$I_l = \frac{2V}{X_l}\sin\frac{\delta}{2} \qquad \text{--- (3)}$$

Series Compensation: If the effective reactance of a line is controlled by inserting a series capacitor, and if the line terminal voltages are held unchanged, then a ΔXl change in the line reactance will result in a ΔIl change in the current, where

$$\Delta I_l = -\frac{2V}{X_l^2}\sin\frac{\delta}{2}\,X_l = -I_l\frac{\Delta X_l}{X_l} \qquad \text{----(4)}$$

Therefore, from Eq. (2), the corresponding change in the power transfer will be

$$\Delta P = -\frac{V^2}{X_l^2}\,2\sin\frac{\delta}{2}\cos\frac{\delta}{2}\,\Delta X_l \qquad \text{---(5)}$$

Using 3 & 4 in 5, we get

$$\Delta P = \frac{1}{2\tan\frac{\delta}{2}}\left(-\Delta X_l I_l^2\right)$$

As $-\Delta Xl$ is the reactance added by series capacitors, $\Delta XlIl^2 = \Delta Q$se represents the incremental var rating of the series capacitor. Therefore

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

Shunt Compensation: Reconsider the short, symmetrical line described in Fig. 2.13(a). Apply a shunt capacitor at the midpoint of the line so that a shunt susceptance is incrementally added (ΔBc), as shown in Fig. 2.14.

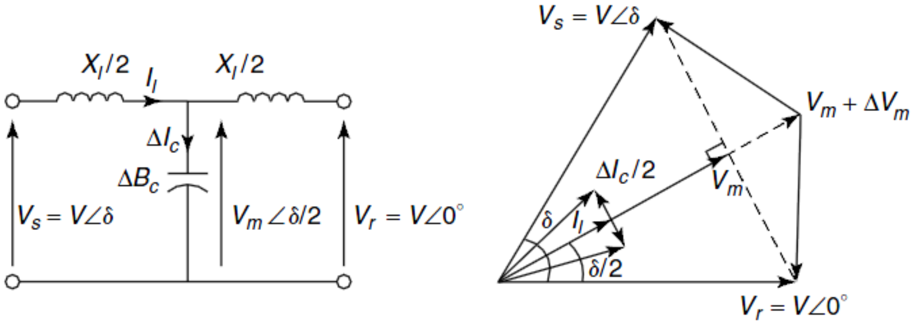


Figure 2.14 The midpoint-capacitor compensation of a short, symmetrical line.

For the system in this figure, the power transfer in terms of the midpoint voltage on the line is

$$P = \frac{VV_m}{\frac{X_l}{2}} \sin\frac{\delta}{2} \tag{2.26}$$

The differential change in power, ΔP, as a result of a differential change, ΔVm, is given as

$$\Delta P = \frac{2V}{X_l} \sin\frac{\delta}{2}\,\Delta V_m \tag{2.27}$$

Also as shown in Fig. 2.14,

$$\Delta I_c = V_m \Delta B_c$$

The current ΔI_c in the midline shunt capacitor modifies the line currents in the sending and receiving ends of the line to the following:

$$I_{ls} = I_l - \frac{\Delta I_c}{2} \quad \text{and} \quad I_{lr} = I_l + \frac{\Delta I_c}{2}$$

As $V_m = V_r + jI_{lr}X_l/2$,

$$\Delta V_m = \frac{\Delta I_c X_l}{4} = \frac{V_m X_l}{4}\,\Delta B_c \tag{2.28}$$

Substituting the results of Eq. (2.28) in Eq. (2.27), we get

$$\Delta P = \frac{VV_m}{2} \sin\frac{\delta}{2}\,\Delta B_c$$

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

$$\frac{\Delta P}{\Delta Q_{sh}} = \frac{1}{2} \tan \frac{\delta}{2} \tag{2.29}$$

By comparing Eqs. (2.25) and Eqs. (2.29), we deduce that for an equivalent power transfer on a short electrical line,

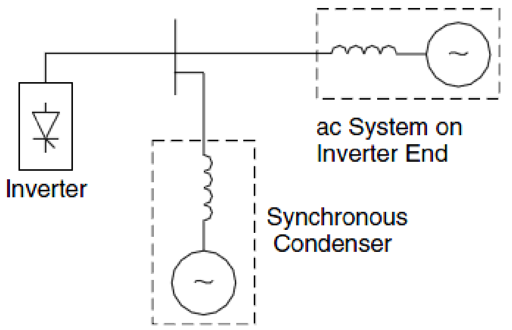
$$\frac{\Delta Q_{se}}{\Delta Q_{sh}} = \left(\tan \frac{\delta}{2}\right)^2 \tag{2.30}$$

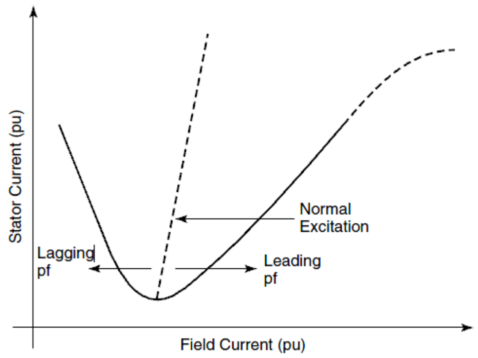
14. Describe the working principle of the two types of Static Var Compensator (SVC) with neat schematic diagrams. ***(May 2015)***

An SVC is a shunt-connected static generator and/ or absorber of reactive power in which the output is varied to maintain or control specific parameters of an electrical power system.

SYNCHRONOUS CONDENSERS:
A synchronous condenser is a synchronous machine, the reactive-power output of which can be continuously controlled by varying its excitation current, as shown by the *V*-curves and performance characteristics of the machine. When the synchronous machine is connected to the ac system and is under excited, it behaves like an inductor, absorbing reactive power from the ac system. However, when it is overexcited, it functions like a capacitor, injecting reactive power into the ac system. The machine is normally excited at the base current when its generated voltage equals the system voltage; it thus floats without exchanging reactive power with the system. The broken-line characteristic curve corresponds to loading beyond the machine's rated stator current.

A synchronous condenser is usually connected to the EHV ac system through a coupling transformer.





Synchronous condensers are connected at the inverter end of an HVDC line to provide the controllable part of the reactive-power requirement of the inverter station and also to help regulate the inverter ac voltage by increasing the short circuit capacity of the ac system.

The HVDC links are often connected to weak ac systems at the receiving end, which are susceptible to commutation failure if adequate control measures are not taken. Hence the compensation of ac system strength becomes an important consideration for utilities to adopt synchronous condensers instead of the much faster-acting SVCs, which do not contribute to the ac system fault level.

THE SATURATED REACTOR (SR)

This compensator comprises a polyphase, harmonic-compensated self-saturating reactor in shunt with a switched capacitor. The saturated reactor (SR) provides the control of reactive power, whereas the capacitor gives the bias in the leading power-factor range.

A simple saturated iron-core reactor cannot be used in this compensator, as it would result in highly distorted voltage and current waveforms. The harmonics are minimized by employing a specially designed multicoupled, core treble-tripler reactor. This reactor, shown in Fig. 3.3, constitutes nine equally displaced limbs, of which only one is unsaturated at a given instant.

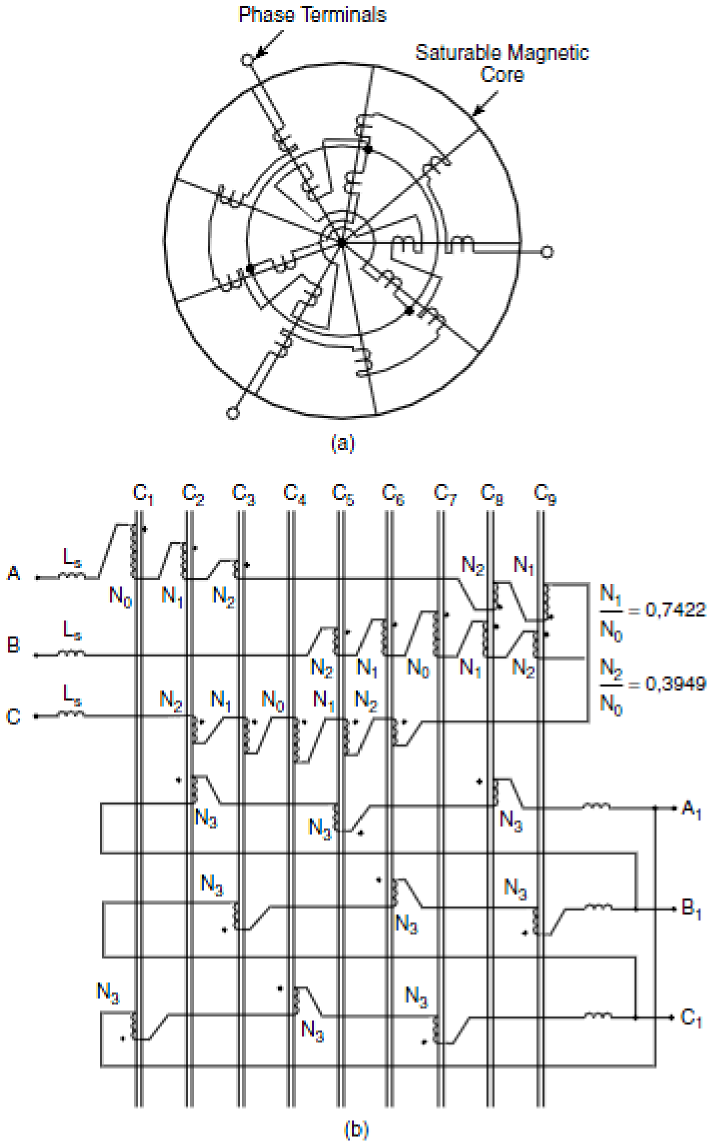


Figure 3.3 A polyphase treble-tripler SR: (a) magnetic-core layout and (b) winding

Furthermore, each limb saturates alternately in either a positive or a negative direction, resulting in a total of 18 distinct unsaturations in a cycle. This activity leads to the generation of characteristic harmonics of the order 18*k* ± 1, where *k*c 1, 2, 3, . . . , that is, 17, 19, 35, 37, and so on. Additional internal compensation attenuates the level of these harmonics to less than 2%, thereby reducing the need for external filters.

15. Give the complete analysis of lossless distributed parameter transmission lines and derive power equations for symmetrical case. (April 2014)

Most power-transmission lines are characterized by distributed parameters:
series resistance, r; series inductance, l; shunt conductance, g; and shunt capacitance, c—all per-unit (pu) length. These parameters all depend on the conductors' size, spacing, clearance above the ground, and frequency and temperature of operation. In addition, these parameters depend on the bundling arrangement of the line conductors and the nearness to other parallel lines. The characteristic behavior of a transmission line is dominated by its l and c parameters. Parameters r and g account for the transmission losses. The fundamental equations governing the propagation of energy along a line are the following wave equations:

$$\frac{d^2\overline{V}}{dx^2} = zy\overline{V} \qquad (2.4a)$$

$$\frac{d^2\overline{I}}{dx^2} = zy\overline{I} \qquad (2.4b)$$

where $zy = (r + j\omega l)(g + j\omega c)$.

For a lossless line, the general solutions are given as

$$\overline{V}(x) = \overline{V}_s \cos \beta x - jZ_0\overline{I}_s \sin \beta x \qquad (2.5a)$$

$$\overline{I}(x) = \overline{I}_s \cos \beta x - j\frac{\overline{V}_s}{Z_0} \sin \beta x \qquad (2.5b)$$

These equations are used to calculate voltage and current anywhere on line, at a distance x from the sending end, in terms of the sending-end voltage and current and the line parameters. In Eqs. (2.4) and (2.5),

$$Z_0 = \sqrt{\frac{l}{c}}\ \Omega = \text{the surge impedance or characteristic impedance}$$

$$\beta = \omega\sqrt{lc}\ \text{rad/km} = \text{the wave number}$$

$$\beta a = \omega\sqrt{lca}\ \text{rad} = \text{the electrical length of an } a\text{-km line}$$

where l is the line inductance in henries per kilometer (H/km), c is the line-shunt capacitance in farads per kilometer (F/km), and $1/\sqrt{lc}$ is the propagation velocity of electromagnetic effects on the transmission line. (It is less than the velocity of light.)

From Eq. (2.5), we get

$$\overline{I}_s = \frac{\overline{V}_s \cos \beta a - \overline{V}_r}{jZ_0 \sin \beta a}$$

If $\overline{V}_s = V_s\angle 0^\circ$ and $\overline{V}_r = V_r\angle - \delta = V_r(\cos\delta - j\sin\delta)$, then

$$\overline{I}_s = \frac{V_r \sin\delta + j(V_r\cos\delta - V_s\cos\beta a)}{Z_0 \sin\beta a} \qquad (2.6)$$

Therefore, the power at the sending end is given as

$$
\begin{aligned}
S_s = P_s + jQ_s &= \overline{V}_s \overline{I}_s^* \\
&= \frac{V_s V_r \sin \delta}{Z_0 \sin \beta a} + j \frac{V_s^2 \cos \beta a - V_s V_r \cos \delta}{Z_0 \sin \beta a}
\end{aligned}
\tag{2.7}
$$

Likewise, power at the receiving end is given as

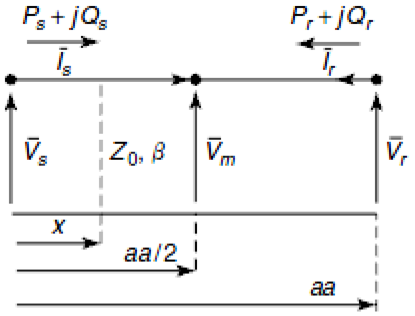


Figure 2.4 The power on a lossless distributed line.

$$
S_r = P_r + jQ_r = -\frac{V_s V_r \sin \delta}{Z_0 \sin \beta a} + j \frac{V_r^2 \cos \beta a - V_s V_r \cos \delta}{Z_0 \sin \beta a} \tag{2.8}
$$

Comparing Eqs. (2.7) and (2.8) and taking the directional notation of Fig. 2.4 into account, it is concluded that for a lossless line, $P_s = -P_r$, as expected. However, $Q_s \neq Q_r$ because of the reactive-power absorption/generation in the line.

From Eqs. (2.7) and (2.8), the power flow from the sending end to the receiving end is expressed as

$$
P = \frac{V_s V_r \sin \delta}{Z_0 \sin \beta a}
$$

In electrically short power lines, where βa is very small, it is possible to make a simplifying assumption that $\sin \beta a = \beta a$ or $Z_0 \sin \beta a = Z_0 \beta a = \omega l a$, where $\omega l a = X_l$ is the total series reactance of a line. This substitution results in the following well-recognized power equation:

$$
P = \frac{V_s V_r}{X_l} \sin \delta \tag{2.9}
$$

Accordingly, the maximum power transfer is seen to depend on the line length. When the power-transfer requirement for a given length of a line increases, higher transmission voltages of V_s and V_r must be selected.

This chapter is not intended to provide a comprehensive analysis of transmission lines. Rather, its objective is to examine those aspects that enhance the understanding of the interplay between voltages on the line and the resulting reactive-power flows.

16. Write a brief note on IPFC. *(April 2014)*

The Interline Power Flow Controller is a new member of inverter- based family of FACTS controllers. The Interline Power Flow Controller employs a number of dc to ac inverters each providing series compensation for a different line.

In other words, the IPFC comprises a number of Static Synchronous Series Compensators. However, within the general concept of the IPFC, the compensating inverters are linked together at their de terminals, as illustrated in Fig. 1.

With this scheme, in addition to providing series reactive compensation, any inverter can be controlled to supply real power to the common dc link from its own transmission line. Thus, an overall surplus power can be made available from the underutilized lines which then can be used by other lines for real power compensation.

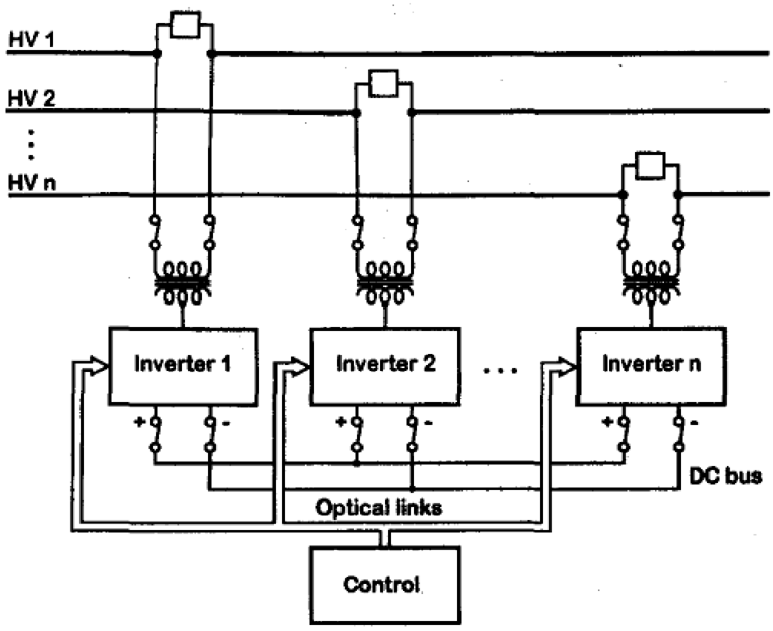


Fig. 1 'n' Inverters Configured for an Interline Power Flow Controller

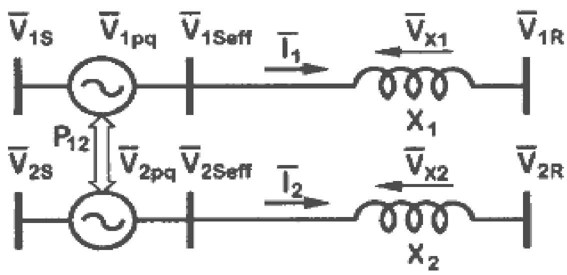


Fig. 2 Basic Two-Inverter Interline Power Flow Controller

In this way, some of the inverters, compensating overloaded lines or lines with a heavy burden of reactive power flow, can be equipped with full two-dimensional, reactive *and* real power control capability.

Consider an elementary IPFC scheme consisting of two back to-back dc to ac inverters, each compensating a transmission line by series voltage injection. This arrangement is shown functionally in Fig. 2, where two synchronous voltage sources, with phasors V_{lpq} and V_{2pq} in series with transmission Lines 1 and 2, represent the two back-to-back de to ac inverters.

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 the free controllability of System 1 imposes upon the power flow control of System 2.

MAILAM ENGINEERING COLLEGE
MAILAM (PO), Villupuram (Dt). Pin: 604 304
(Approved by AICTE New Delhi, Affiliated to Anna University Chennai & Accredited by TCS, Chennai)
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Subject Code & Name: EE2036 - FLEXIBLE AC TRANSMISSION SYSTEMS

Unit : II
Year/Sem : IV / VIII
Total No. Page : 41

STATIC VAR COMPENSATOR (SVC) AND APPLICATIONS

Voltage control by SVC – advantages of slope in dynamic characteristics – influence of SVC on system voltage. Applications - enhancement of transient stability – steady state power transfer – enhancement of power system damping – prevention of voltage instability.

Updated Questions:

PART-A:

Apr/May 2015: Qn.22 on Pg.6 & Qn.23 on Pg.6
Nov/Dec 2014: Qn.20 on Pg.6, & Qn.21 on Pg.6

PART-B:

Apr/May 2015: Qn.1 on Pg.8 & Qn.8 on Pg.31
Nov/Dec 2014: Qn.1 on Pg.8 & Qn.4 on Pg.15

Reference Books:

1. Mohan Mathur, R., Rajiv. K. Varma, "Thyristor – Based Facts Controllers for Electrical Transmission Systems", IEEE press and John Wiley & Sons, Inc.

Prepared by	Verified by	Verified by	Approved by
N. Jaiganesh	18	N. 26/11/1	
Mr.N.JAIGANESH, AP/EEE	BC	HOD/EEE	PRINCIPAL

Mr.G.VEERAPATHIRAN, AP/EEE

MAILAM ENGINEERING COLLEGE
MAILAM (PO), Villupuram (Dt). Pin: 604 304
(Approved by AICTE New Delhi, Affiliated to Anna University Chennai & Accredited by TCS, Chennai)
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE2036 FLEXIBLE AC TRANSMISSION SYSTEMS

UNIT II STATIC VAR COMPENSATOR (SVC) AND APPLICATIONS

Voltage control by SVC – advantages of slope in dynamic characteristics – influence of SVC on system voltage. Applications - enhancement of transient stability – steady state power transfer – enhancement of power system damping – prevention of voltage instability.

PART-A (TWO MARKS)

1. What is the need for compensation in a power system?(DEC-10)

- To increase the power transmission capacity of the line.
- To keep the voltage profile of the line along its length within the acceptable bounds to ensure the quality of supply to the connected customer as well as to minimize the line insulation costs

2. Compare shunt and series compensation?

Series compensator:

The improvement of the maximum power transmission capacity of the line.Effectively reduce the overall line reactance.

Shunt compensator:

It is mainly used to compensate for the reactive voltage drop in the line To increase the power transfer capacity.

3.List the objective of shunt compensation?

- Mid point voltage regulator
- End point voltage instability
- Transient stability
- Power oscillation Damping

4.List the effects of series compensation?

- Improve the maximum Power transmission
- Steady state power transmission line
- Transient stability
- Voltage stability
- Power oscillation damping.

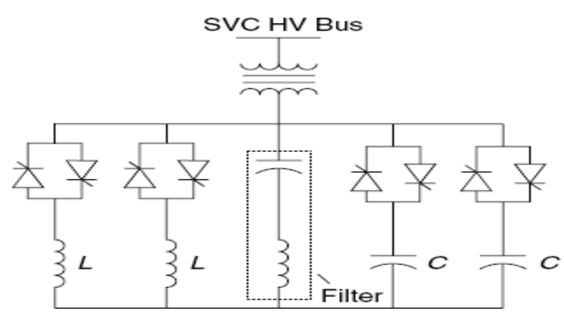
5. How shunt compensation is classified?

- TCR
- TSR (on or off control)
- FC\
- FC-TCR
- TSC

6. What is the TSC application?

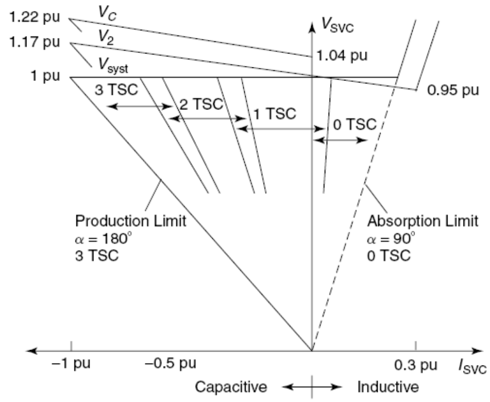
TSC can be abbreviated as thyristor switched capacitor it consists of a capacitor in series with a bidirectional thyristorswitch.It is supplied from an ideal ac voltage source with neither resistor nor reactance present in the circuit.

7.What is TSC-TSR explain?



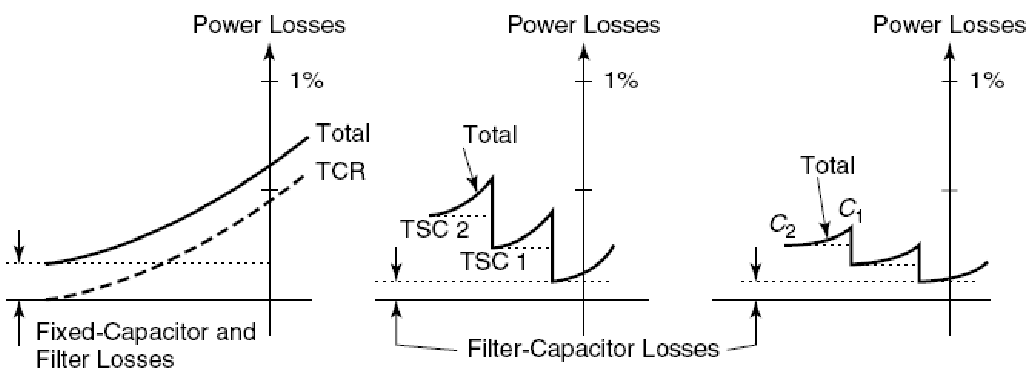
The TSC–TCR compensator shown in Fig. usually comprises n TSC banks and a single TCR that are connected in parallel. The rating of the TCR is chosen to be 1/ n of the total SVC rating. The capacitors can be switched in discrete steps, whereas continuous control within the reactive-power span of each step is provided by the TCR. Thus the maximum inductive range of the SVC corresponds to the rating of the relatively small interpolating TCR.

8.Draw the V-I characteristic of TSC-TSR?



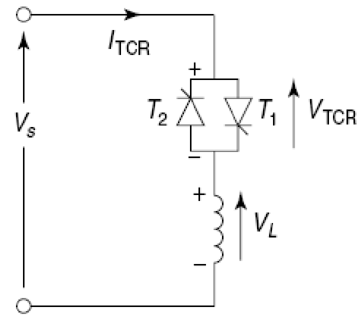
9.List the comparison lossess for different SVC (FC-TCR, TSC-TSR, MSC-TCR)? (JUNE-11)

- Small, resistive losses are in the permanently connected filter branches in the TSC–TCR and MSC–TCR.
- Losses in the main capacitors in all three SVCs.
- Valve-conduction losses and switching losses in the thyristor power circuit.
- Resistive losses in the inductor of the TCR, which increases substantially with the TCR current.

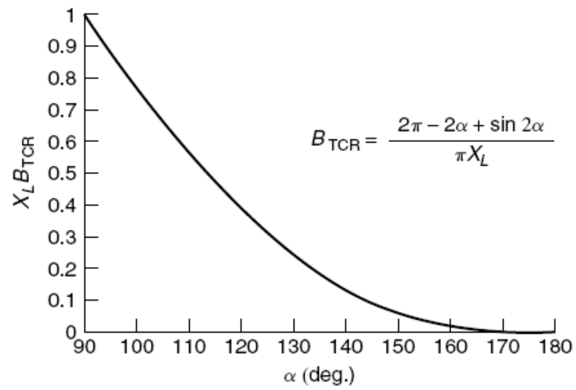


10.What is meant by TCR explain?

A basic single-phase TCR comprises an anti-parallel–connected pair of thyristor valves, T1 and T2, in series with a linear air-core reactor, as illustrated in Fig. The anti-parallel–connected thyristor pair acts like a bidirectional switch,withthyristor valve T1 conducting in positive half-cycles and thyristor valve T2 conducting in negative half-cycles of the supply voltage. The firing angle of the thyristors is measured from the zero crossing of the voltage appearing across its terminals.



11. Draw the control characteristic of TCR?



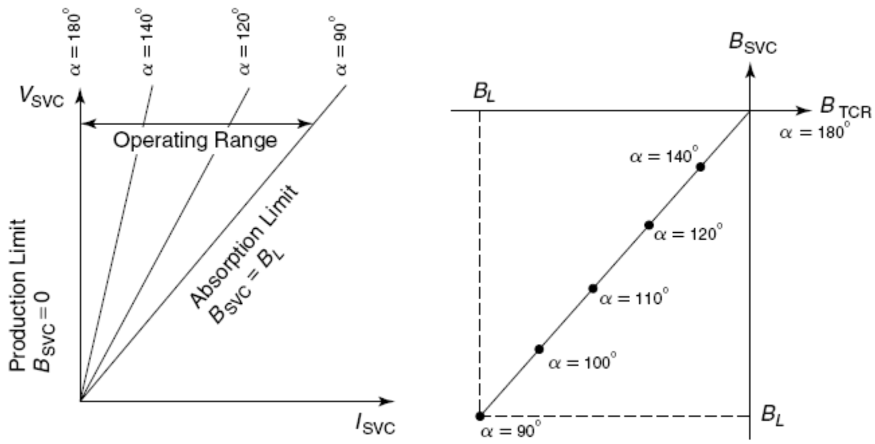
12. What is meant by TSR explain?

The TSR is a special case of a TCR in which the variable firing-angle control option is not exercised. Instead, the device is operated in two states only: either fully on or fully off.

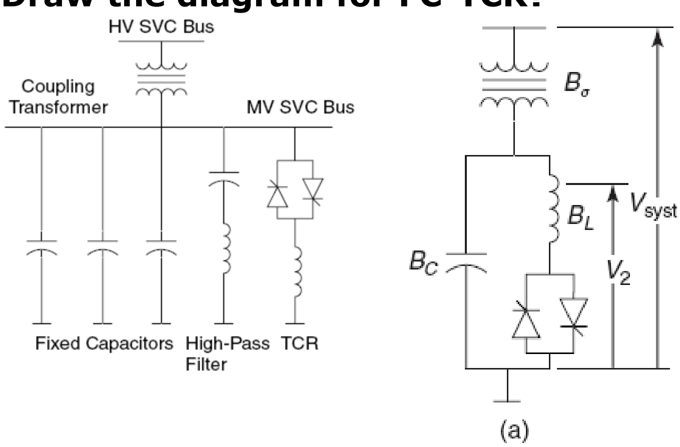
If the thyristor values are fired exactly at the voltage peaks corresponding to $\alpha = 90^\circ$ for the forward – thyristor value T_1 and $\alpha = 270^\circ(90^\circ + 180^\circ)$ for the reverse thyristor value T_2, as depicted in figure, full conduction results. The maximum inductive current flows in the TCR as if the thyristor switches were replaced by short circuits. However, if no firing pulses are issued to the thyristors, the TSR will remain in a blocked – off state, and no current can flow.

The TSR ensures a very rapid availability of rated inductive reactive power to the system. When a large magnitude of controlled reactive power, Q is usually assigned to a small TSR of rating, say, Q/2; the rest is realized by means of a TCR also of a reduced rating Q/2. This arrangement results in substantially decreased losses and harmonic content as compared to a single TCR of rating Q.

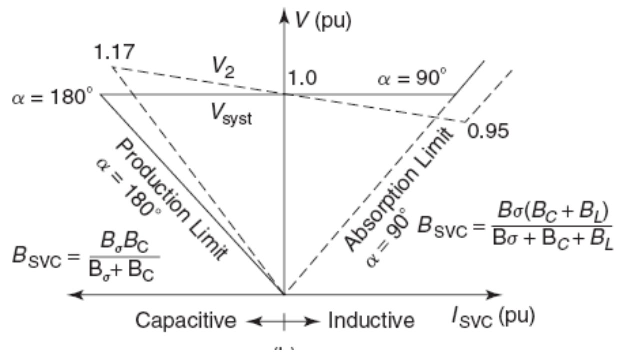
13.Draw the V-I characteristic of TCR?



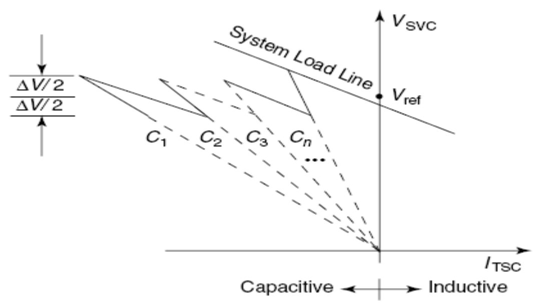
14.Draw the diagram for FC-TCR?



15.Draw the V-I Characteristic of FC-TCR?



16. Draw the operating characteristic of TSC?



17. List the application of SVC?-(MAY-11)

- Increase in steady state power transfer capacity
- Enhancement of transient stability
- Synchronizing torque
- Modulation of SVC bus voltage.

18. Name the different limit of power flow in shunt controller?-(MAY-11)

- Maximum of thermal limit
- Angle of limit is very less
- Power enhancement is very less
- Control the power at different voltages

19. List the advantages of slope in SVC dynamic characteristic? (JUNE-11)

- Substantially reduces the reactive power rating of the SVC
- Prevents the SVC from reaching its reactive power limit

- Facilitates the sharing of reactive power among multiple compensators operating in parallel.

20. What are the controller used in the influence of the SVC sites?(Dec-2014)

The controllability is seen to increase with transmitted power, indicating that the SVC become effective in damping power oscillation which is very desirable.

21. What are the objectives of static VAR? (Dec-2014)

- Increase power transfer in long lines.
- Improve stability with fast acting voltage regulation.
- Damp low frequency oscillations due to swing (rotor) modes.
- Damp sub synchronous frequency oscillations due to torsional modes.
- Control dynamic over voltages.

22. What are the three basic modes of SVC control?(April 2015)

i. Voltage control based on balanced control of the three phases of SVC:

a. 3-phase–rectified root mean square / average voltage

b. Positive-sequence voltage

c. 3-phase average / root mean square currents

ii. Squared voltage, V2 2. Individual-phase voltage / reactive-power control:

a. Individual-phase voltages

b. Positive- and negative-sequence voltages

c. Squared voltage, V2

d. Individual-phase currents

e. Individual-phase reactive power

iii. Auxiliary control for electrical damping enhancement using the following major supplementary signals:

a. Transmission-line current

b. Transmission-line active / reactive power

c. Bus angle

d. Bus frequency

e. Angular velocity or accelerating power of a synchronous generator

23. How is voltage instability identified in a power system (April/May 2015)

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.

24. Define ‘ Effective Short circuit Ratio(ESCR)’ of SVC.(April 2014)

The ESCR relates to the total fundamental-frequency impedance of the power system as viewed from TCR terminals. The power system then includes all the filters, shunt capacitors, and the SVC coupling transformer. The ESCR is usually expressed in per units on the basis of full-conduction admittance of the TCR.

25. What are the factors that limits the power transfer capacity of a transmission line?(April 2014)

- Thermal limit
- Steady-state stability limit
- Transient-stability limit
- System damping

PART- B (16 MARKS)

1. **Derive the Transfer function & explain Dynamic performance of static VAR compensator?(DEC-2010)(Nov/Dec 2014)(May 2015)(April 2014)**

Voltage Control V-I Characteristics Of The Svc

The steady-state and dynamic characteristics of SVCs describe the variation of SVC bus voltage with SVC current or reactive power. Two alternative representations of these characteristics are shown in Fig. part (a) illustrates the terminal voltage–SVC current characteristic. part (b) depicts the terminal voltage–SVC reactive-power relationship. The dynamic V-I characteristics of SVCs are described.

Reference Voltage, V_{ref} This is the voltage at the terminals of the SVC duringthe floating condition, that is when the SVC is neither absorbing nor generatingany reactive power. The reference voltage can be varied between themaximum and minimum limits—V_{ref} max and $V_{ref}$by the SVC controlsystem.

In case of thyristor-controlled compensators, or by the taps of the coupling transformer, in the case of saturated reactor compensators. Typicalvalues of $V_{ref\ max}$ and $V_{ref\ min}$ are 1.05 pu and 0.95 pu, respectively.

LinearRange of SVC Control this is the control range over which SVCterminal voltage varies linearly with SVC current or reactive power, as the latteris varied over its entire capacitive-to-inductive range.Slope or Current Droop The slope or droop of the V-I characteristic is defined as the ratio of voltage-magnitude change to current-magnitude change over thelinear-controlled range of the compensator. Thus slope KSL is given by

$$K_{SL} = \frac{\Delta V}{\Delta I}\ \Omega$$

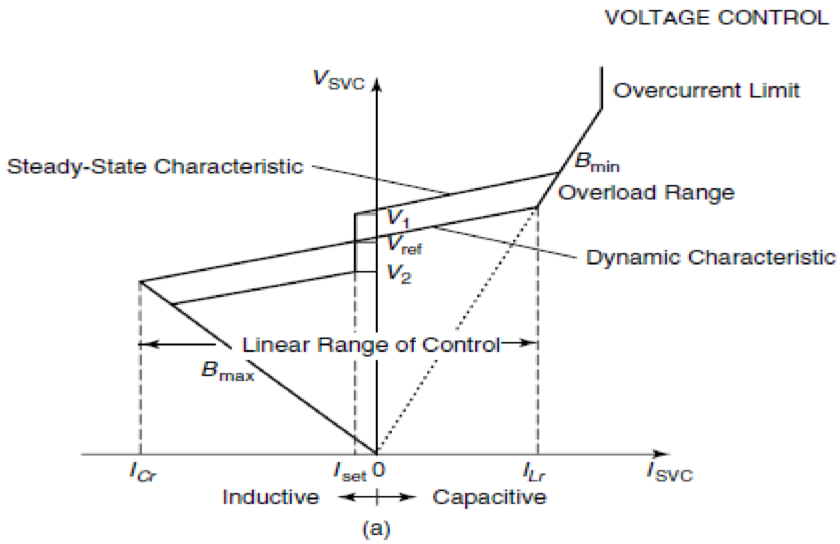
where $\Delta V =$ the change in voltage magnitude (V)
$\Delta I =$ the change in current magnitude (A)

The per-unit value of the slope is obtained as

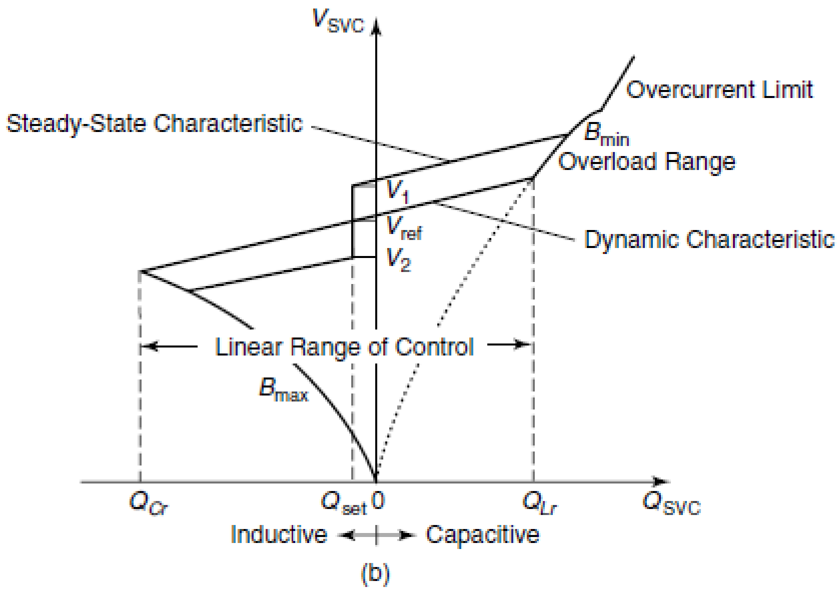
$$K_{SL} = \frac{\Delta V/V_r}{\Delta I/I_r}\ \text{pu}$$

where V_r and I_r represent the rated values of SVC voltage and current, respectively.

For $\Delta I = I_r$,



The voltage–current characteristic of the SVC



(b) The voltage–reactive-power characteristic of the SVC.

$$K_{SL} = \frac{\Delta V(\text{at } I_r \text{ or } Q_r)}{V_r} \text{ pu}$$

$$= \frac{\Delta V(\text{at } I_r \text{ or } Q_r)}{V_r} \cdot 100\%$$

where $Q_r$represents the rated reactive power of SVC.Thus the slope can be defined alternatively as the voltage change in percentof the rated voltage measured at the larger of the two—maximum inductive- ormaximum capacitive-reactive-power outputs, as the larger output usually correspondsto the base reactive power of the SVC. In some literature, the reactivepowerrating of the SVC is defined as the sum of its inductive and capacitiverating. The slope is often expressed as an equivalent reactance:

X_{SL}= K_{SL} in pu

The slope can be changed by the control system in thyristor-controlled compensators, whereas in the case of saturated reactor compensators, the slope is adjusted by the series slope-correction capacitors. The slope is usually kept within 1–10%, with a typical value of 3–5%. Although the SVC is expected to regulate bus voltage, that is, maintain a flat voltage-current profile with a zeroslope, it becomes desirable to incorporate a finite slope in the V-I characteristics for reasons described below.

Overload Range When the SVC traverses outside the linear-controllablerange on the inductive side, the SVC enters the overload zone, where it behaveslike a fixed inductor.

Over current Limit To prevent the thyristor valves from being subjected to excessive thermal stresses, the maximum inductive current in the overload range is constrained to a constant value by an additional control action.

Steady-State Characteristic The steady-state V-I characteristic ofthe SVC is very similar to the dynamic V-I characteristic except for a deadbandin voltage, In the absence of this deadband,in the steady state the SVC will tend to drift toward its reactive-power limitsto provide voltage regulation. It is not desirable to leave the SVC with verylittle reactive-power margin for future voltage control or stabilization excursionsin the event of a system disturbance.

To prevent this drift, a deadband aboutV_{ref} holds the I_{SVC} at or near zero value, depending on the location of thedeadband. Thus the reactive power is kept constant at a setpoint, typically equalto the MVA output of the filters. This output is quite small; hence the totaloperating losses are minimized. A slow susceptance regulator is employed to implement the voltage deadband, which has atime constant of several minutes. Hence the susceptance regulator is renderedvirtually ineffective during fast transient phenomena, and it does not interferewith the operation of the voltage controller.

2. What is the regulation slope? What is the reason for regulation slope? Explain with V-I characteristic of SVC & STATCOM Voltage?(DEC-2010)

The voltage-control action of the SVC can be explained through a simplifiedblock representation of the SVC and power system, Thepower system is modeled as an equivalent voltage source, Vs, behind an equivalentsystem impedance, Xs, as viewed from the SVC terminals. The systemimpedance Xsindeed corresponds to the short-circuit MVA at the SVC busand is obtained as

$$X_s = \frac{V_b^2}{S_c} \cdot \mathrm{MVA}_b \qquad \text{in pu}$$

where $S_c =$ the 3-phase short circuit MVA at the SVC bus

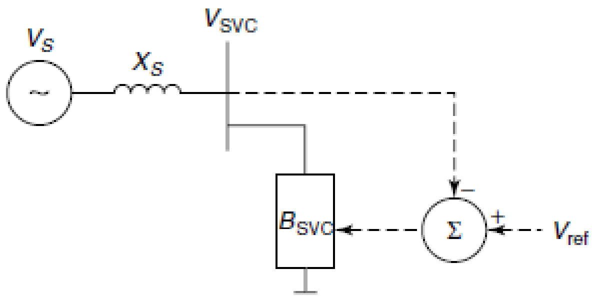
$V_b =$ the base line-to-line voltage

$\mathrm{MVA}_b =$ the base MVA of the system

If the SVC draws a reactive current I_{SVC}, then in the absence of the SVC voltage regulator, the SVC bus voltage is given by

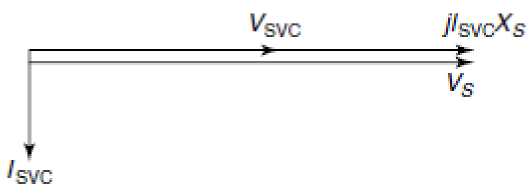
$V_s = V_{SVC} + I_{SVC} X_s$

$V_s = V_{SVC}\angle 0^\circ + I_{SVC}\angle -90^\circ X_s \angle 90^\circ)$



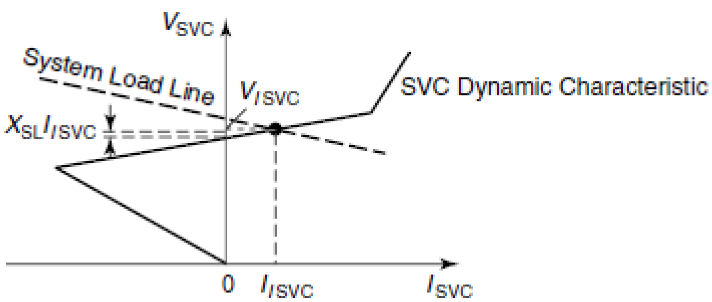
(a)

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



(b)

a phasor diagram of the ac system for the inductive SVC current.



(c)

characteristics of the simplified power system and the SVC.

$V_s = (V_{SVC} + I_{SVC} X_s)\angle 0^\circ$

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

The SVC current thus results in a voltage drop of $I_{SVC}X_s$ in phase with the system voltage V_s. The SVC bus voltage decreases with the inductive SVC current and increases with the capacitive current. Equation (5.6d) represents the power-system characteristic or the system load line. An implication of Eq. (5.6d) is that the SVC is more effective in controlling voltage in weak ac systems (high X_s) and less effective in strong ac systems (low X_s).

The dynamic characteristic of the SVC depicted in reactive-power compensation provided by the SVC in response to a variationin SVC terminal voltage. The intersection of the SVC dynamic characteristicand the system load line provides the quiescent operating point of the SVC.

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

$$V_{SVC} = V_{ref} + X_{SL} I_{SVC}$$

Where I_{SVC} is positive if inductive, negative if capacitive.It is emphasized that the V-I characteristics described here relate SVC current- reactive power to the voltage on the high-voltage side of the coupling transformer. An example characteristic describing the relationship between the voltages on the low-voltage side of the coupling transformer

3. Discuss the Advantages of the Slope in the SVC Dynamic Characteristic in detail? (JUNE-11, DEC-12)

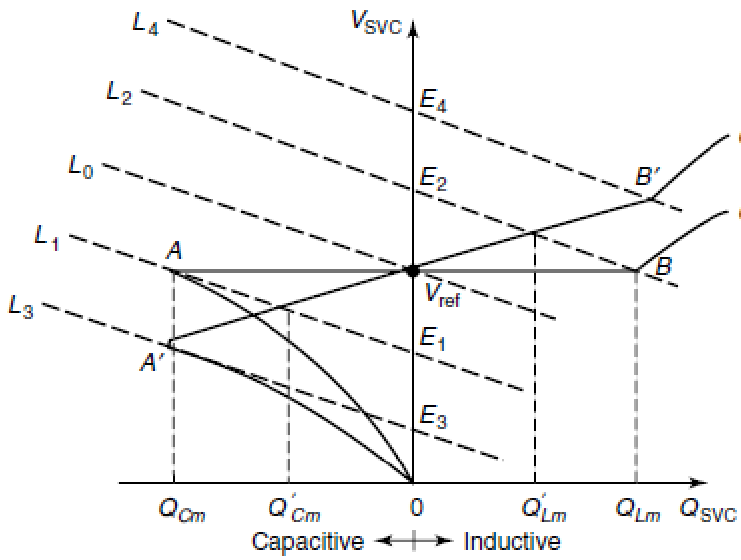
The SVC is a controller for voltage regulation, that is, for maintaining constant voltage at a bus, a finite slope is incorporated in the SVC's dynamic characteristic and provides the following advantages despite a slight deregulation of the bus voltage.

a. substantially reduces the reactive-power rating of the SVC for achieving nearly the same control objectives;
b. Prevents the SVC from reaching its reactive-power limits too frequently.
c. Facilitates the sharing of reactive power among multiple compensators operating in parallel.

Reduction of the SVC Rating The two dynamic V-I characteristics of an SVC. Characteristic OA'B'C' incorporates a finite slope, whereas characteristic OABC does not. The slope has been deliberately exaggerated to demonstrate its effect. Assuming that the system load line varies between L_1 and L_2, the reactive-power rating of the SVC needed for providing flat voltage regulation is Q C_m capacitive to QL_m

inductive, as determined from the characteristic OABC. However, if a small deregulation in the SVC bus voltage is considered acceptable (as demonstrated by the characteristic OA′B′C′),the maximum reactive-power rating of the SVC required for performing the voltage control corresponding to the same variation in the system load line isQ′Cm capacitive to Q′Lminductive. Evidently, Q′CmQCmand Q′LmQLm.

Thus a much lower SVC reactive-power rating and, hence, a much lower cost is required for nearly the same control objective.That the SVC rating can be reduced to half, with a 5% slope in the V-I characteristic. The resulting tradeoffis a 2.5% voltage excursion.



Reduction in the SVC reactive-power rating by the current slope.

Prevention of Frequent Operation at Reactive-Power Limits:

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

The reactive-power limits of the SV Care reached more frequently if the ac system tends to be strong, that is, when the slope of the system load line is quite small. The effectiveness of the SVC as a voltage-control device therefore becomes limited. With a finite slope in the V-I characteristic, the SVC continues to operate in the linear-controllable range for a much larger variation in the load line of the external ac system.

The SVC can exercise voltage control for a significantly larger variation, $E_4 - E_3$, in the equivalent ac system no-load voltage. When the external ac system is subjected to a disturbance, both the slope of the load line (indicative of the equivalent system reactance) and the system no-load voltage are influenced. However, the feature discussed here has been explained in terms of changes in the no-load voltage only.

Load Sharing Between Parallel-Connected SVCs:

Reliability via redundancy, and also for minimizing the net harmonic generation, it is not uncommon to divide the net-required SVC range into several equal-sized compensators. When more than one compensator is used at one location, the control action must be coordinated. This section discusses such co-ordination. The two SVCs have the same ratings but the reference voltages, V_{ref}, of the two control characteristics differ by a small amount.

Two cases are examined: one in which both the SVCs have a zero slope, and the other in which the two SVCs have a finite slope, as The composite V-I control characteristic of the two SVCs is derived by summing up the individual currents of both SVCs for the same bus-voltage magnitude—procedure that is repeated over the entire range of SVC bus voltage. The composite characteristic is indicated by the thicker line.

In the case of zero current slopes, the composite operating characteristic is beset with a discontinuity around point A. When the system load line intersects the V-I characteristic at A, a quiescent operating point results that corresponding full reactive-power production on SVC_1 (point B) and full inductive-reactive power absorption on SVC_2 (point C). Thus one SVC partially compensates the output of the other, which is uneconomical because the losses are high.

On the left of point A, SVC_2 controls the bus voltage, whereas SVC_1 remains at full production. However, on the right of point A, it is SVC_1 that controls the bus voltage and SVC_2 that is at full absorption. This operation clearly demonstrates that the two SVCs are not well coordinated.

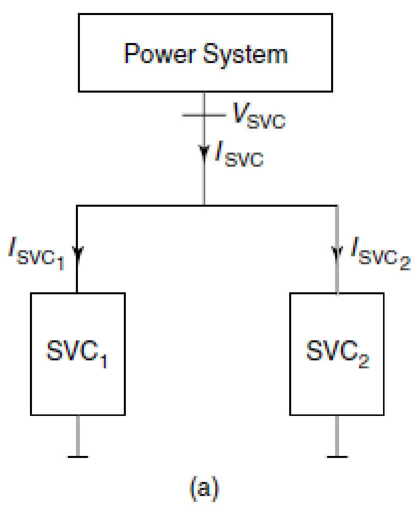
The current droop ensures that the composite V-I control characteristic of both SVCs is continuous despite the difference in the voltage-reference set points. If the two SVCs and the power system achieve a stable-operating point at A, SVC_1 operates at B and SVC_2 at C. The reactive-load sharing of the two compensators is improved, and the losses are minimized. The zones where only one compensator controls the voltage while the other is already at a limit reduce to small portions at both ends of the control range. In practice, the error is much smaller.

The achievable accuracy of load sharing is often acceptable without any further controls. With additional balancing controls, exact load sharing can be attained.

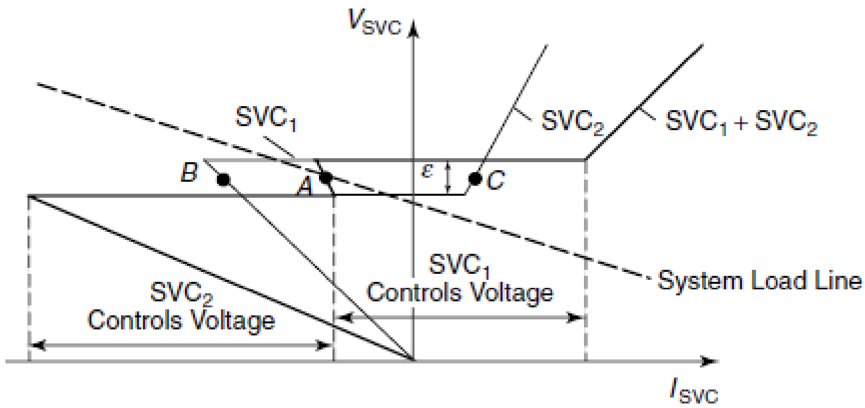
4. Explain the control (Influence) parameter of the SVC in the System Voltage? (May 2015)

Coupling Transformer Ignored: The SVC behaves like a controlled susceptance, and its effectiveness in regulating the system voltage isdependent on the relative strength of the connected ac system. The system strength or equivalent system impedance, as seen from the SVC bus, primarily determines the magnitude of voltage variation caused by the change in the SVC reactive current.

This can be understood from the simplistic representation of the power system and SVC. In this representation, the effect of the coupling transformer is ignored and the SVC is modeled as a variable susceptance at the high-voltage bus. The SVC is considered absorbing reactive power from the ac system while it operates in the inductive mode.

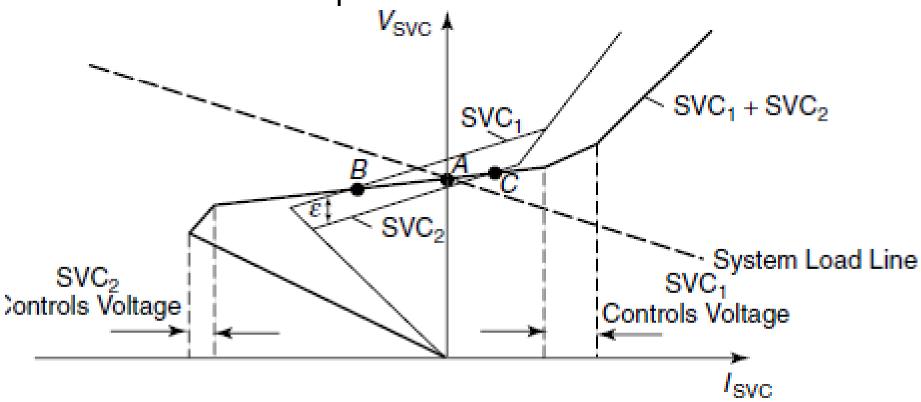


(a) Two parallel-connected SVCs at a system bus;



(b)

(b) Two SVCs in parallel with difference in the reference-voltage set points without current droop



(c)

Two SVCs in parallel with current droop and with difference in the reference-voltage set points.

The V_{svc} bus voltage

gives the variation in the V_{SVC} as a function of change in the SVC current, I_{SVC}. Thus for the constant-equivalent-source voltage V_s,

$$\Delta V_{SVC} = -X_s \Delta I_{SVC}$$

The V_{SVC} is also related to I_{SVC} through the SVC reactance, B_{SVC}, as follows:

$$I_{SVC} = B_{SVC} V_{SVC}$$

For incremental changes, Eq. (5.9) is linearized to give

$$\Delta I_{SVC} = B_{SVC_0} \Delta V_{SVC} + \Delta B_{SVC} V_{SVC_0}$$

Substituting ΔI_{SVC} from Eq. (5.10) in Eq. (5.8),

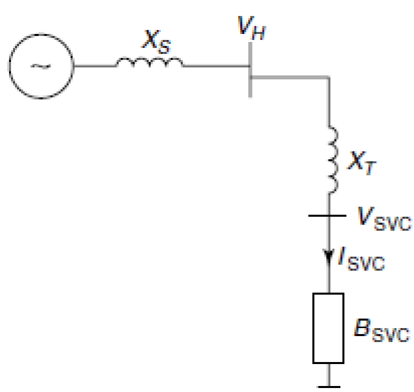
$$\frac{\Delta V_{SVC}}{\Delta B_{SVC}} = \frac{-V_{SVC_0}}{\text{ESCR} + B_{SVC_0}}$$

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

$$\text{ESCR} = \frac{1}{(-\Delta V_{SVC}/\Delta I_{SVC})} = \frac{1}{X_s} = B_s$$

where B_s = the equivalent system susceptance

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



Representation of the power system and the SVC, including the coupling transformer

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

$$\Delta V_{SVC}(1 + X_T B_{SVC_0}) + V_{SVC_0} X_T \Delta B_{SVC} = \Delta V_H$$

$$\frac{\Delta V_H}{\Delta B_{SVC}} = \frac{-V_{H_0}}{(\mathrm{ESCR} + B_{SVC_0})}\left(\frac{1 - X_T \mathrm{ESCR}}{1 + X_T B_{SVC_0}}\right)$$

The System Gain

$$V_{SVC} = \frac{V_s(1/B_{SVC})}{(X_s + 1/B_{SVC})}$$

$$= \frac{V_s}{(1 + B_{SVC}/\mathrm{ESCR})}$$

where X_s is the equivalent short-circuit impedance of the system in shunt with the capacitive reactance of SVC.

For ac systems, generally ESCR $\gg B_{SVC}$ (or effectively, $X_s \ll 1/B_{SVC}$). Thus Eq. can be expanded as

The change in SVC bus voltage, ΔV, is then given by

$$\Delta V = V_S - V_{SVC}$$

$$V_{SVC} \cong V_S\left(1 - \frac{B_{SVC}}{\mathrm{ESCR}}\right)$$

$$\Delta V = \frac{V_S B_{SVC}}{\mathrm{ESCR}}$$

$$\Delta V = K_N B_{SVC}$$

where K_N is defined as the "system gain" and is expressed as

$$K_N = \frac{V_S}{\text{ESCR}} = \frac{V_S}{B_S}$$

The system gain, K_N, thus relates the deviation in SVC bus voltage to SVC susceptance. An increase in inductive susceptance, B_{SVC}, causes ΔV to become more positive, thereby leading to a drop in the SVC bus voltage. In fact, Eq. (5.20) can be obtained from Eq. (5.11) if it is assumed that

$$V_{SVC_0} \cong V_S \quad \text{and} \quad \text{ESCR} \gg B_{SVC_0}$$

and understanding that

$$\Delta V = -\Delta V_{SVC}$$

The foregoing derived expression for system gain can be used to arrive at a preliminary design of an SVC voltage regulator. However, it may, be noted that the system gain K_N depends on the equivalent system voltage V_S and equivalent impedance X_S—both of which are subject to change with the dynamically varying power-system configuration. The gain K_N is thus not a constant and, in fact, varies in a certain range. A weak ac system would correspond to a high system gain; a strong ac system would result in a relatively lower system gain.

Equation (5.21) was derived based on the absolute values of the various parameters involved. For control studies, it is desirable to derive a corresponding equation based on per-unit values of different variables. Let the base voltage, V_b, and base susceptance, B_b, be chosen as

$$V_b = V_{\text{nominal}}$$

where V_{nominal} = the rated bus voltage

$$B_b = B_{\max} - B_{\min}$$

where $B_{\max}$ = the maximum susceptance of the SVC (fully capacitive)

$B_{\min}$ = the minimum susceptance of the SVC (fully inductive)

The per-unit system gain is therefore given from Eq. (5.21) as

$$K_N = \frac{V_S}{V_b}\,\frac{B_b}{B_S}$$

Multiplying and dividing Eq. by V_b^2,

$$K_N = \frac{V_S}{V_b}\,\frac{B_b}{B_S}\,\frac{V_b^2}{V_b^2}$$

$$= \frac{V_S}{V_b}\,\frac{Q_{SVC}}{B_S V_S V_b \dfrac{V_b}{V_S}}$$

or

$$K_N = \frac{V_S Q_{SVC}}{V_b S_c \dfrac{V_b}{V_S}}$$

where $S_c =$ the short-circuit power
$=$ the base voltage · the short-circuit current
$= V_b \cdot (B_S V_S)$

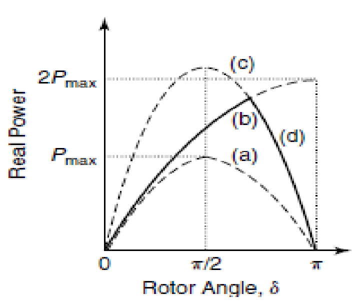
Assuming V_S/V_b is close to unity, which is usually the case in power systems, the per-unit system gain is expressed as

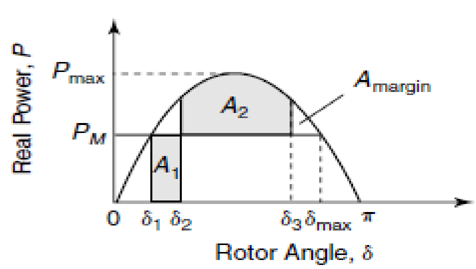
$$K_N = \frac{\Delta V_{SVC}}{B_{SVC}} = \frac{Q_{SVC}}{S_c} \text{ pu}$$

It should be noted that the system gain will change with variations in network configuration, line switchings, and any event that may change the system short-circuit level at the SVC bus.

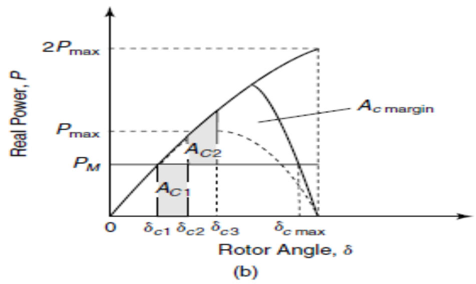
5. Explain how transient stability is enhanced due to static VAR compensator? (JUNE-11,MAY-11,DEC-12)(April 2014)

An SVC significantly enhances the ability to maintain synchronism of a power system, even when the system is subjected to large, sudden disturbances.





(a)



Power-angle curves depicting transient-stability margins in the SMIB system: (a) the uncompensated system and (b) the SVC-compensated system.

6. Show that with Power-Angle Curves the SVC can enhance the transient stability margin. (JUNE-11,MAY-11,DEC-12) (April 2014)

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. 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.

The initial operating points in the uncompensated and compensated systems are indicated by rotor angles d1 and dc1. These points correspond to the intersection between the respective power-angle curves with the mechanical input line PM, 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 remain sunchanged, the generator accelerates until fault clearing, by which time the rotor angle has reached values d2 and dC_2 and the accelerating energy, A_1 and $AC_{1,}$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 d3 and dc3 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 AC_2 in the two cases, respectively, become equal to the accelerating energies A_1 and AC_1.

The power system in each case returns to stable operation if the post-faultangular swing, denoted by d_3 and dC_3, does not exceed the maximum limit ofd_{max} and dc $_{max,}$ respectively. Should these limits be exceeded, the rotor will notdecelerate. The farther the angular overswing from its maximum limit, the moretransient stability in the system. An index of the transient stability is the availabledecelerating energy, termed the transient-stability margin, and is denotedby areas A_{margin} and Ac $_{margin}$ in the two cases, respectively. Clearly, as Ac $_{margin}$significantly exceeds A_{margin}, the system-transient stability is greatly enhancedby the installation of an SVC.

The increase in transient stability is thus obtained by the enhancement of thesteady-state power-transfer limit provided by the voltage-control operation ofthe midline SVC.

Synchronizing Torque

A mathematical insight into the increase in transient stability can be obtained through the synchronous generator is assumed to be driven with a mechanical-powerinput, PM. The transmission line is further assumed to be lossless; hence theelectrical power output of the generator, PE, and the power received by theinfinite 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 $M =$ the angular momentum of the synchronous generator

$\delta =$ the generator-rotor angle

For small-signal analysis, the Eq. (6.9) 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 analysisihence DPM The liberalized-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
= $\partial P_E/\partial\delta$

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

The characteristics equation of the differential abow equation produces two roots:

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

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

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

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

On the other hand, if the synchronizing torque $K_S$is negative, the roots are real.

A positive real root characterizes instability.

The synchronizing-torque coefficients is now determined for both the uncompensated and SVC-compensated systems.

Uncompensated System

The electrical power, P, transfer red from the generator across the lossless uncompensated tie-line is given by Eq.

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

The corresponding synchronizing torque is expressed by

$$K_{SU} = \frac{\partial P}{\partial\delta} = \frac{V_1 V_2}{X}\cos\delta$$

SVC-Compensated System

The power transfer, PC, from the generator across the lossless uncompensated tie-line is given by Eq.

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

Itcan be alternatively expressed in terms of an equivalent transfer reactance, X_T. Between the generator bus and the infinite bus.

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

or

$$X_T = X - \frac{X^2}{4} B_S$$

The net SVC susceptance, B_S, is given by

$$B_S = \frac{\alpha_c}{X_c} - \frac{\alpha_i}{X_i}$$

where $X_i = V_{\text{nom}}^2 / Q_{ir}$ = the total inductive reactance of the SVC

$X_c = V_{\text{nom}}^2 / Q_{cr}$ = the total capacitive reactance of the SVC

V_{nom} = the nominal voltage

Q_{ir}, Q_{cr} = the inductive- and capacitive-reactive-power rating of the SVC

α_i = the conducting fraction of the TCR

α_c = the conducting fraction of the TSC (= 1 for the fixed capacitor)

The SVC adjusts a $\alpha_i$and $\alpha_c$to maintain a constant voltage.V_m at the connecting bus.The synchronizing-torque coefficient of the uncompensated system is expressed as

$$K_S = \frac{\partial P_E}{\partial \delta} = \frac{V_1 V_2 \cos \delta}{X_T} + \left(\frac{V_1 V_2 \sin \delta}{V_m X_T} \right)^2 \frac{X^2}{4 X_T}$$

Thus the pure-voltage control operation of the SVC increases the synchronizing-torque coefficient by the following amount:

$$\Delta K_S = K_S - K_{SU} \tag{6.22}$$

$$\Delta K_S = \frac{V_1 V_2 \cos \delta}{X X_T} (X - X_T) + \left(\frac{P}{V_m} \right)^2 \frac{X^2}{4 X_T}$$

The frequency of oscillation also increases by a factor

$$\sqrt{1+\frac{\Delta K_S}{K_S}}$$

An enhanced synchronizing torque implies an increase in the transient-stabilitymargin of the power system. An SVC thus augments the transient stabilityof the power system.

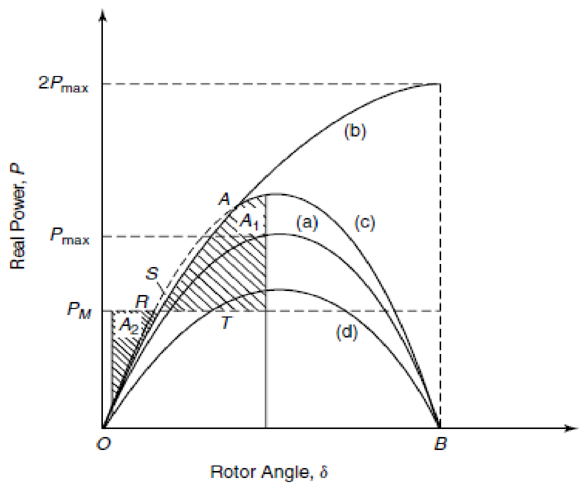
Modulation of the SVC Bus Voltage

SVC can improve the transientstability of a power system by maintaining the midpoint voltage constant.

an appropriate modulation of the SVC bus voltageis permitted, the transient stability can be substantially augmented as comparedto the constant-voltage control strategy of SVC .

This concept is illustrated through the set of power-angle curves depictedin Fig below.

Curve (a) illustrates the power-angle curve of the system withoutSVC, curve(b) Illustrates the same for the system compensated by anideal SVC of an unlimited reactive-power rating. When the real-power output.



Power-angle curves of a SMIB system

Curve (a) for an uncompensated
Case; curve (b) with an ideal midpoint-connected SVC;
Curve (c) with a midpoint-connectedfixed capacitor;
Curve (d) with a midpoint-connected fixed inductor.

The synchronous generator gradually exceeds the surge-impedance loading(SIL), the SVC tends to become increasingly capacitive.

As long as the SVC remains within its capacitive-controllable range, the power-angle curve remainsthe same as curve (b) until point A is reached,

When the capacitance limit of SVC is attained. Beyond point A, the power-angle curve switches to curve (c), or curve ORAB, which corresponds to the power-angle curve of a fixed capacitorhaving the full rating of the SVC capacitor.

This curve relates to an effectivetransfer reactance X_T, with positive B_S, that is less than the transmission-linereactance X.However,

When the power transfer is less than the SIL, the SVC is inductive, with continuously varying levels of inductive-reactive power. If the SVC reactanceis fixed at some inductive value, the power-angle curve changes to curve(d), which is below curve (a).

In this case, the transfer reactance $X_T$becomesmore than X because of the negative B_S.

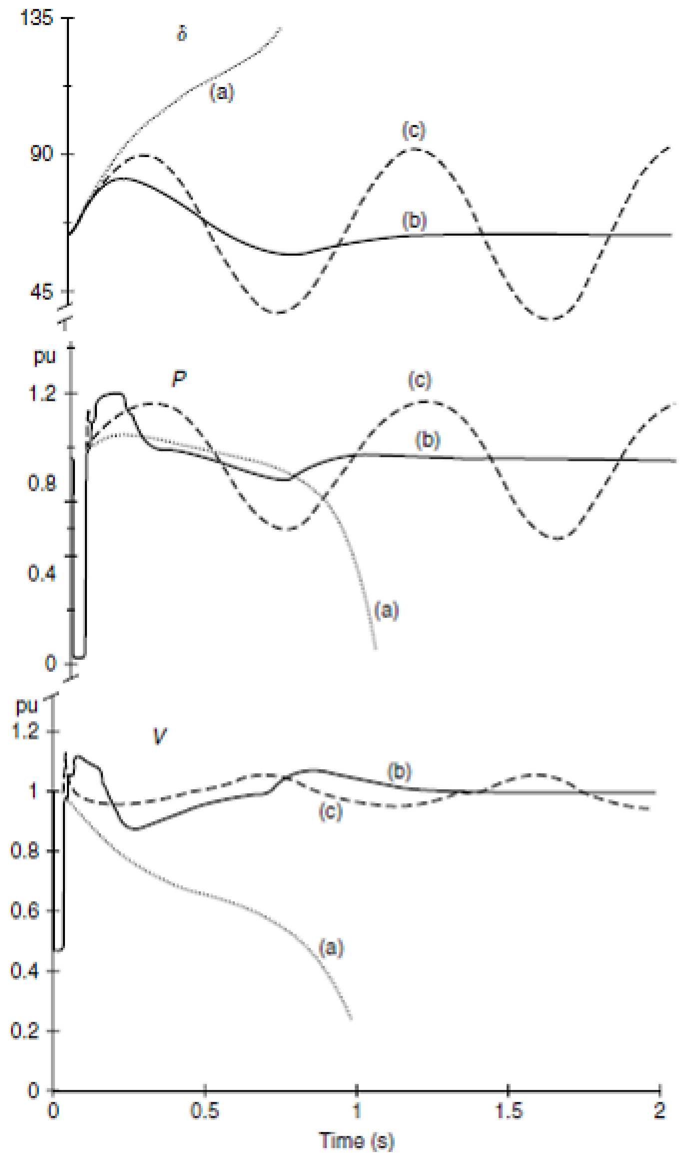
First-swing stability, in which the rotor angle increases following fault and goes through an overswing. The deceleratingenergy, which also represents the synchronizing coefficient, is indicated bythe hatched area A_1. This behavior relates to a constant-voltage control strategyof the SVC. If a higher voltage is established momentarily by making the SVCmore capacitive, additional decelerating energy, shown by area ARS, would bemade available.

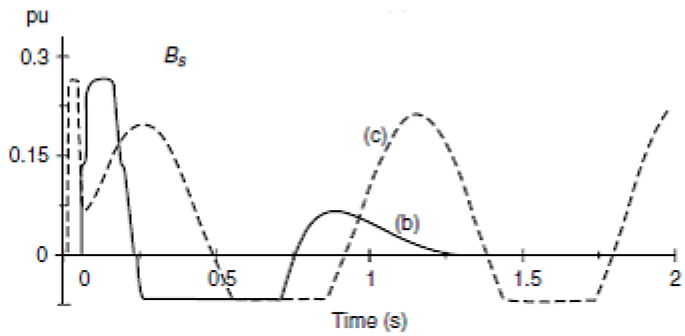
The full capacitor-swing curve is chosen only to illustrate thisconcept. Increasing the voltage temporarily thus restricts overswing and allowshigher critical fault-clearing time.Once the rotor angle reaches its maximum value, it tends to reverse, or backswing.It is important to minimize this backswing to ensure transient stability.For a constant-voltage control of the SVC, the developed accelerating poweris indicated by A_2. However, if the SVC reactive power is rapidly changedto establish a slightly lower terminal voltagemomentarilyat the instant of maximum overswing, an additional accelerating torque, indicated by area OST,becomes available. \

This reduces the magnitude of backswing.A control strategy of modulating the SVC bus voltage instead of keeping itstrictly constant thus aids in substantially improving the overall transient stability of the study system.

An example of the advantage achieved by adoptingthe voltage-modulation control strategy, in comparison to constant-voltage regulation, Figure below gives the performance of the SVCfollowing a severe fault in a power system. The time variations in the generatorrotorangle, real-power transfer, bus voltage, and SVC susceptance are depictedfor the two SVC control strategies, and the behavior of the uncompensated systemis also presented.

In the absence of an SVC, the fault clearing results in severe voltage depression followed by system instability. A voltage-modulation control strategy rapidly stabilizes the oscillations in the rotor angle, power transfer, and terminal voltage, as compared to the constant-voltage control ofSVC. Thus, higher power transfer becomes feasible with enhanced transient stability.Voltage-modulation control strategies are implemented through auxiliary





Curve (a) withoutSVC;
Curve (b) with SVC with the optimumcontrol strategy;
Curve (c) with SVC (0.27-pu capacitance0.07-pu induction) withthe constant-voltage control strategy

7. Explain how the increase in power transfers capability of SVC in steady state operation? (June-2011)

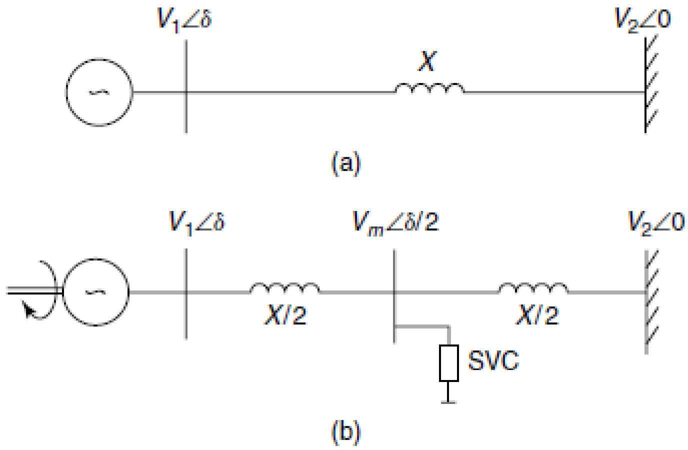
Steady-state power-transfer capacity**:**

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 $V_1\angle\delta$and $V_2\angle 0$, respectively. The power transfer red 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

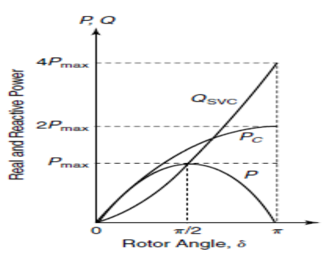
$$P = \frac{V^2}{X} \sin \delta$$



The single-machine infinite-bus (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, the maximum steady-state power that can be transferred across the uncompensated line without SVC corresponds to δ=90· it is given by

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



The variation of line real-power flow and SVC reactive-power flow in a SMIB system is given by,

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

The power transfer in the other half-line section interconnecting the SVC, and the infinite bus is also described by a similar equation.

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

Which is depicted graphically in Fig.? 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 d_2

In other words, the midpoint-located ideal SVC doubles the steady-state power limit and increases the stable angular difference between the synchronous machine and the infinite bus from 908 to 1808.If the transmission line is divided into nequal sections, with an ideal SVC ateach junction of these sections maintaining a constant-voltage magnitude (V),then the power transfer (P’c) of this line can be expressed theoretically byThe maximum power, P’cmax, that can be transmitted along this line. In other words, with n sections the power transfer can be increasedn 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, QSVC, of the midpoint SVC for the voltage stabilization is given by equations also depicts the variation of QSVC with d. It is seen that to double the power transfer to 2Pmax, the required reactive-power rating of the SVCis four times the maximum power transfer in an uncompensated case, that is, 4Pmax. Such high-rated SVCs may not be economically feasible.The power-transfer increase achievable with realistic SVCs of limited ratings.Curve (a) shows the power-angle relationship for theuncompensated case. Curve (b) shows the same relationship for an ideal SVC of a large reactive-power rating QSVC in excess of 4Pmax. Curve (c) represents the power-angle curve for a midline-located fixed capacitor. 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 inthe preceding text (QSVC _ 2Pmax) is connected at the line midpoint, it ensuresvoltage 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) of Fig. represents the power-anglecurve that shows this fixed-capacitor behavior and demonstrates that the realisticmaximum power transfer will be much lower than the theoretical limit of2Pmax if the SVC has a limited reactive-power rating.

8. Write the short notes on increasing the power system damping?(or) Explain in detail about the role of SVC in enhancing the steady state power limit and power system damping (April 2015)

The power-transfer capacity along a transmission corridor is limited by severalfactors; 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.

Oscillations in power systems are caused by various disturbances. If thesystem is not series-compensated, the typical range of oscillation frequencies extends from several tenths of 1 Hz to nearly 2 Hz. Several modes of oscillationmay 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 other words, the synchronizing torque binds the different generators into synchronism, assuring transient stability.) In addition, theMagnitude 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.Examined in this chapter is the concept of the SVC’s ability to not only impart but also enhance the damping torque in a power system through SVC

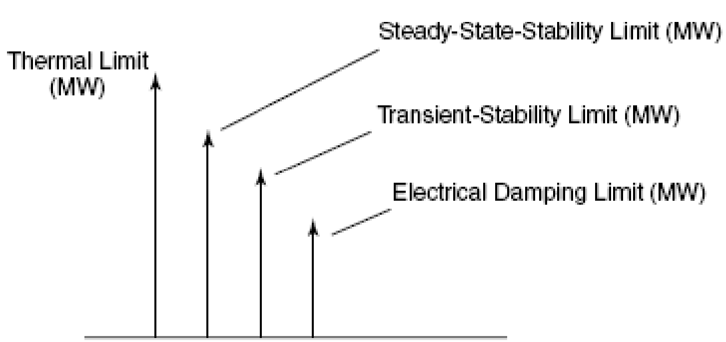


Figure 6.7 Comparison of different limits on the power flow.

9. Explain briefly how to prevent the voltage instability in a power system?(April 2014)

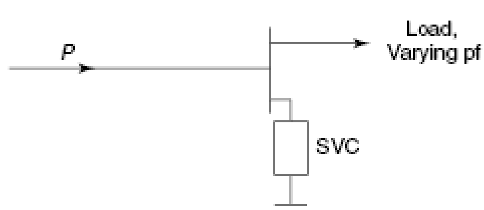
The inadequacy of the power system to supply the reactive-power demand of certain loads, such as induction motors. A drop in the load voltage leads to an increased demand for reactive power that, if not met by the power system, leads to a further decline in the bus voltage. This decline eventually leads 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.

Principles of SVC Control

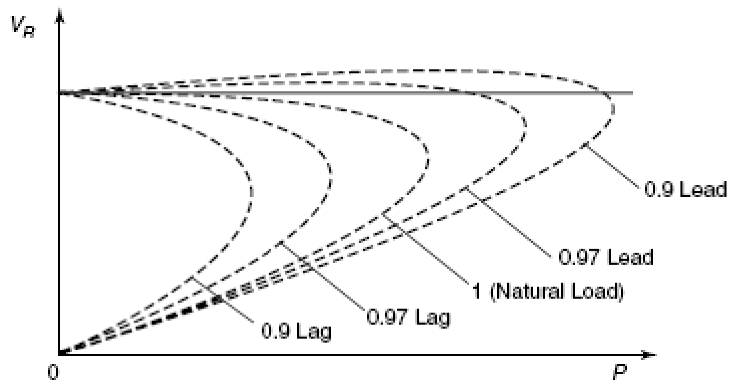
The voltage at a load bus supplied by a transmission line is dependent on the magnitude of the load, the load-power factor, and the impedance of the transmission line. Consider an SVC connected to a load bus, as shown in Fig.

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 beavoided.

A Case Study An SVC can be used successfully to prevent voltage instability. The case study presented here demonstrates the application of SVC to mitigate voltage instability in a radial system loaded by a large composite load of induction motors and static loads, all under steady-state and transient conditions



(a)

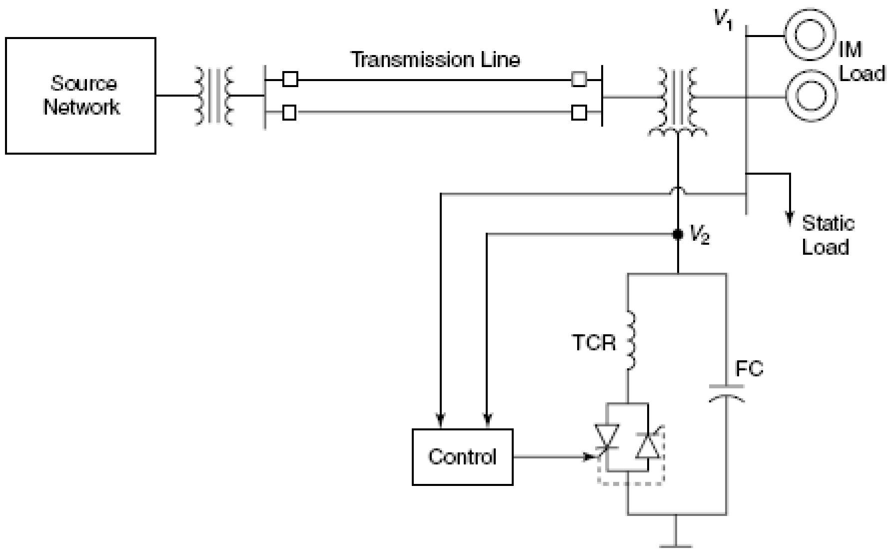


(b)

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

The 400-kV radial case-study system [40] shown in Fig.involves power supply over a double-circuit transmission line to a load center that comprises a 50% large induction motors (IM) and 50% static loads. An FC–TCR SVC is connected to the tertiary of a 3-winding load transformer, and the SVC voltagecontroller is of the PI type.

The instability is caused by tripping one of the transmission lines and is detected from eigenvalue analysis. The postdisturbance response for 1 s period is shown in Fig. 6.26. In the absence of the SVC, the load voltage falls to a level of 0.8 pu in 80 ms after the initial transients and falls further to a magnitude of 0.57 pu in less than 1 s. The onset of induction-motor instability occurs at a voltage of 0.8 pu. With falling terminal voltage, the induction-motor loadreactive power starts increasing rapidly, leading to eventual voltage collapse.If the induction motor loads are completely replaced by static loads of same value, voltage instability does not occur.When an appropriately designed SVC is connected at the load bus, the postdisturbancesystem performance alters to that depicted in Fig. After the damping of fast initial transients, the load voltage stabilizes in about 50 ms.



SVC

The final value of the stabilized load voltage is a function of the capacitivereactive- power rating of the SVC, which can be improved further by additional steady-state voltage-regulating devices. It is evident that this voltage stabilization is achieved only from the rapid response offered by the SVC. A breakerswitched shunt capacitor of equivalent rating as the SVC is unable to preventvoltage collapse.Voltage instability is also illustrated through voltage-susceptance diagrams,where it is shown that if the slope of the voltage-susceptance characteristic is negative, voltage collapse may result.

Configuration and Design of the SVC Controller

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

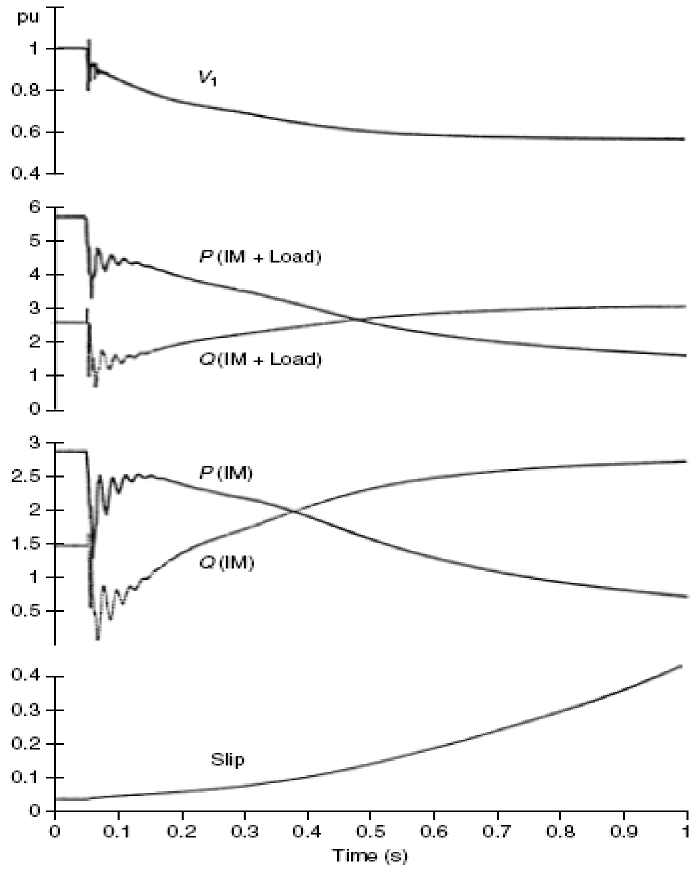


Figure The system transient response for opening one circuit in Fig. 6.25 (50%IM load without a SVC).

Rating of an SVC:

Steady-state considerations determine the capacitive rating of an SVC. During acritical outage, the capacitive-reactive power needed to regulate the load voltage to a marginally stable level is selected as the capacitive range of SVC. Alternatively, once the critical bus that needs reactive-power support is identified, the SVC rating is chosen based on the capacitive-reactive power required to maintain the bus voltage at the minimum estimated SVC voltage-control range for the specified maximum loading condition or the voltage-collapse point

The collapse is indicated by the system Jacobian's increasing singularity at that loading point and is obtained through load-flow studies. The inductance rating is chosen to be that which can restrict the dynamic over voltages at the SVC bus to 10%. This is determined from transient studies for critical-load rejections.

It is shown in that the system loading cannot be increased beyond a maximum value, irrespective of the size of the SVC connected at the critical bus. One means of obtaining the optimal SVC rating is maximization of a performance index, f p, where

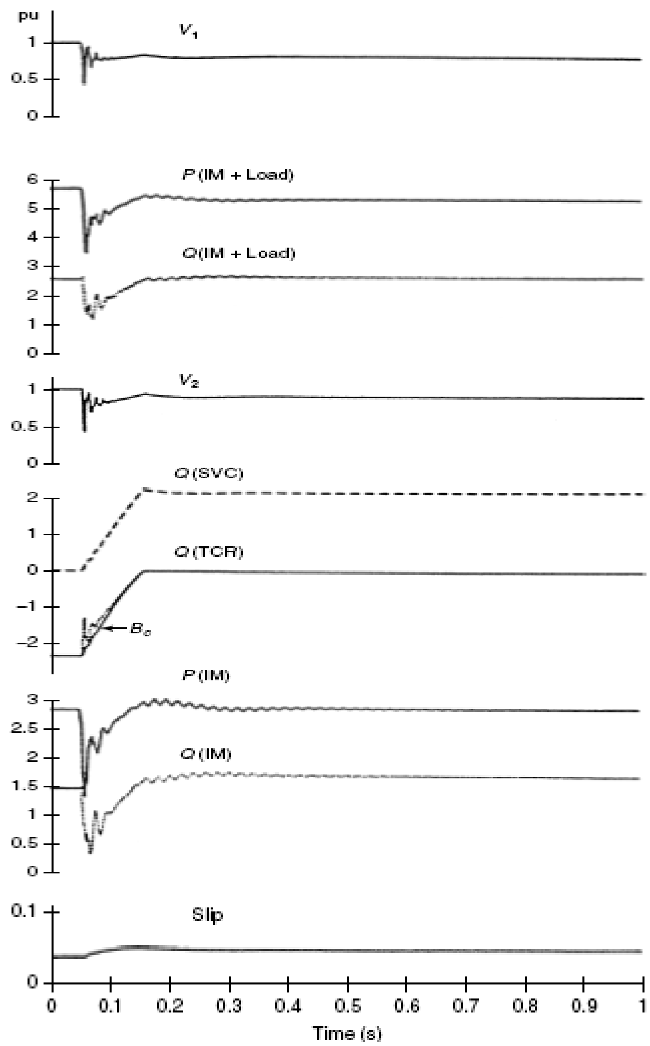


Figure The system transient response for opening one circuit in Fig. 6.25 [50%IM load with a SVC (TCR–FC)].

$$f_p = \frac{\lambda_0(\text{MW})}{Q_{SVC}(\text{MVAR})} \qquad \text{where} \quad \lambda_0 = \text{the maximum system loading}, \quad Q_{SVC} = \text{the SVC MVAR rating}$$

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

2 Marks

1. **What is the need for compensation in a power system?(DEC-10)**
2. **List the comparison losses for different SVC (FC-TCR, TSC-TSR, MSC-TCR)? (JUNE-11)**
3. **List the application of SVC?-(MAY-11)**
4. **Name the different limit of power flow in shunt controller?-(MAY-11)**
5. **List the advantages of slope in SVC dynamic characteristic?**
6. **(JUNE-11)**
7.
8. **What are the controller used in the influence of the SVC sites?(Dec-2014)**
9. **What are the objectives of static VAR? (Dec-2014)**
10. **What are the three basic modes of SVC control?(April 2015)**
11. **How is voltage instability identified in a power system (April/May 2015)**
12. **. Define ' Effective Short circuit Ratio(ESCR)' of SVC.(April 2014)**
13. **What are the factors that limits the power transfer capacity of a transmission line?(April 2014)**

16 Marks:

1. **Derive the Transfer function & explain Dynamic performance of static VAR compensator?(DEC-2010)(Nov/Dec 2014)(May 2015)(April 2014)**
2. **What is the regulation slope? What is the reason for regulation slope? Explain with V-I characteristic of SVC & STATCOM Voltage?(DEC-2010)**
3. **Discuss the Advantages of the Slope in the SVC Dynamic Characteristic in detail? (JUNE-11, DEC-12)**
4. **. Explain the control (Influence) parameter of the SVC in the System Voltage? (May 2015)**
5. **Explain how transient stability is enhanced due to static VAR compensator? (JUNE-11,MAY-11,DEC-12)(April 2014)**
6. **Show that with Power-Angle Curves the SVC can enhance the transient stability margin. (JUNE-11,MAY-11,DEC-12) (April 2014)**
7. **Explain how the increase in power transfers capability of SVC in steady state operation? (June-2011)**
8. **Write the short notes on increasing the power system damping?(or) Explain in detail about the role of SVC in**

enhancing the steady state power limit and power system damping (April 2015)

9. **Explain briefly how to prevent the voltage instability in a power system?(April 2014)**

MAILAM ENGINEERING COLLEGE
MAILAM (PO), Villupuram (Dt). Pin: 604 304
(Approved by AICTE New Delhi, Affiliated to Anna University Chennai & Accredited by TCS, Chennai)
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Subject Code & Name: EE2036 - FLEXIBLE AC TRANSMISSION SYSTEMS

Unit : III
Year/Sem : IV / VIII
Total No. Page : 39

THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC) AND APPLICATIONS

Operation of the TCSC - different modes of operation – modeling of TCSC – variable reactance model – modeling for stability studies. Applications - improvement of the system stability limit – enhancement of system damping – voltage collapse prevention.

Updated Questions:

PART-A:

Apr/May 2015: Qn.11 on Pg.5 & Qn.22 on pg.9
Nov/Dec 2014: Qn.21 on Pg.9, & Qn.23 on Pg.10

PART-B:

Apr/May 2015: Qn.4 on Pg.14 & Qn.5 on Pg.18
Nov/Dec 2014: Qn.4 on Pg.14 & Qn.5 on Pg.16

Reference Books:

1. Mohan Mathur, R., Rajiv. K. Varma, "Thyristor – Based Facts Controllers for Electrical Transmission Systems", IEEE press and John Wiley & Sons, Inc.

Prepared by	Verified by	Verified by	Approved by
N. Jaiganesh			
Mr.N.JAIGANESH, AP/EEE	BC	HOD/EEE	PRINCIPAL

Mr.G.VEERAPATHIRAN, AP/EEE

MAILAM ENGINEERING COLLEGE
MAILAM (PO), Villupuram (Dt). Pin: 604 304
(Approved by AICTE New Delhi, Affiliated to Anna University Chennai & Accredited by TCS, Chennai)
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE2036 FLEXIBLE AC TRANSMISSION SYSTEMS

UNIT III THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC) AND APPLICATIONS

Operation of the TCSC - different modes of operation – modeling of TCSC – variable reactance model – modeling for stability studies. Applications - improvement of the system stability limit –enhancement of system damping – voltage collapse prevention.

PART-A

1. How series compensation can be used for power oscillation damping?

For dynamic control action of the power oscillation damping to not exceed the controllable range of the TCSC, the lead lag filters are provided with non-wind up limiters. Thus the effectiveness of the TCSC in damping the power oscillation is greatly eliminated.

2.What is the GCSC type of series controllers?

GCSC Type of series controller is :Variable impedances type.:

3.What do you mean by variable impedances type switching converter type FACTS devices?

- Variable impedance Type are Reactor and capacitor.

  →Series- Series capacitor,Series inductor, TCSC,TSSC.

  →Shunt –FC,TSC,TSR,SVC.

4. How voltage stability at load bus can be achieved using series compensator? (or) what are the loading capability limitations?(Nov/Dec-2010)

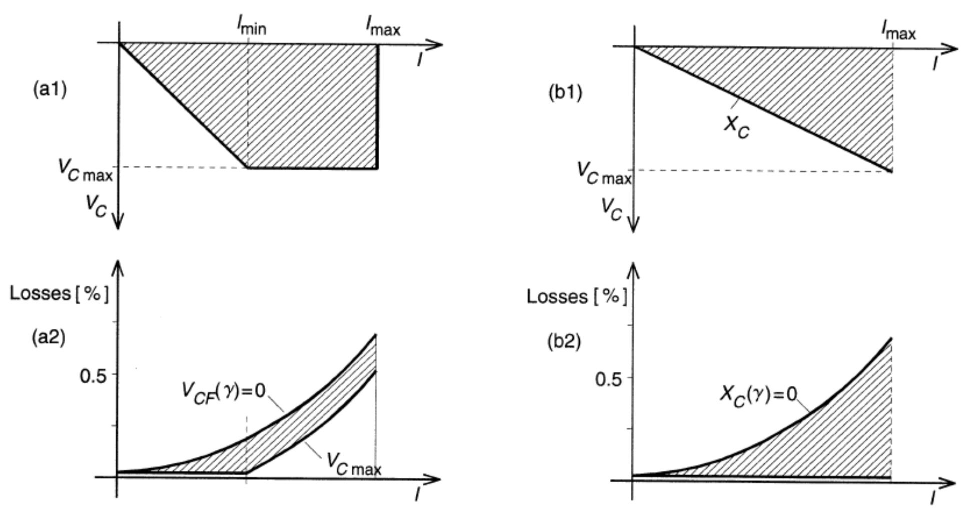
Voltage stability at load bus can be achieved by using degree of compensation of line reactance.

- ➔ K=Xc/X; 0<K>1.

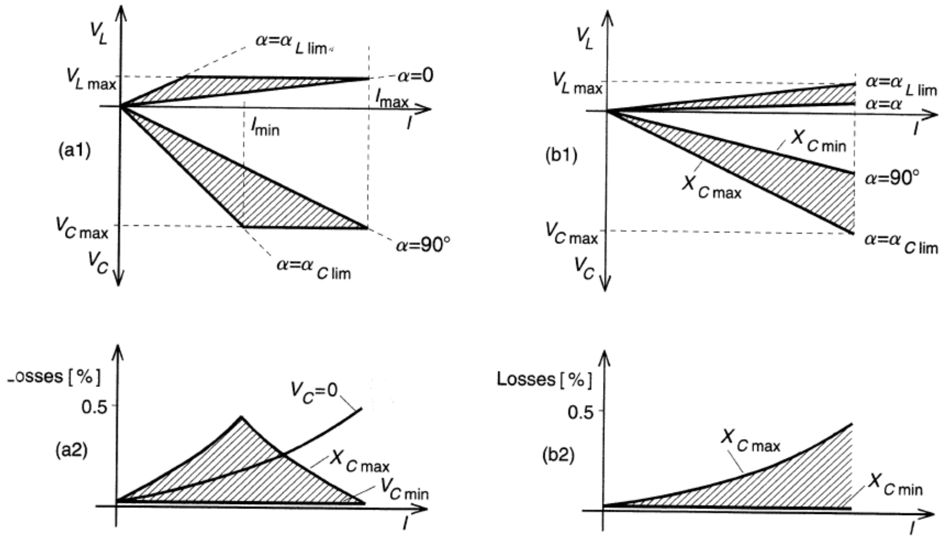
5. How series FACTS devices responds to the problem of sub synchronous resonances?

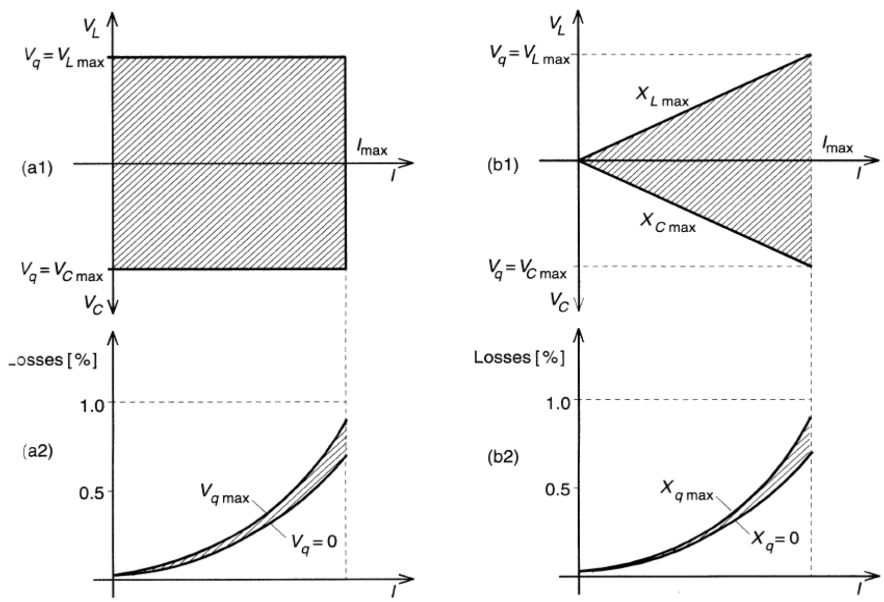
Sub synchronous resonances operate at series FACTS device if K>30%

6.Draw the V-I characteristic and loss characteristic for GCSC?



7. Draw the V-I characteristic and loss characteristic for TCSC? (June-2011)(Nov/Dec 2014)





8. Give the limitation of series capacitor?

- Fault current is high
- Load balancing with parallel path
- Power flow control is different
- Sub synchronous resonance if K>30%

9. Give the condition for transient free switching for the TSC for different residual voltage? (or) Name the different limits of power flow? (April/May 2011)

Transient free switching of capacitor If

Vc is less than V

Vc is greater than V

10. What is the need for variable series compensation?

(or)

What are the two basic approaches for controllable series compensation? (Nov/Dec -2012)

The Need for Variable-Series Compensation of transmission lines by series capacitors is likely to result in the following

1. enhanced base-power flow and loadability of the series-compensated line;

2. additional losses in the compensated line from the enhanced power flow;

3. increased responsiveness of power flow in the series-compensated line from the outage of other lines in the system

11. List the advantage of TCSC? (OR) State any two advantages of TCSC (May 2015)

1. Rapid, continuous control of the transmission-line series-compensation level.

2. Dynamic control of power flow in selected transmission lines within the network to enable optimal power-flow conditions and prevent the loop flow of power.

3. Damping of the power swings from local and inter-area oscillations.

4. Suppression of subsynchronous oscillations. At subsynchronous frequencies, the TCSC presents an inherently resistive–inductive reactance. The subsynchronous oscillations cannot be sustained in this situation and consequently get damped.

5. Decreasing dc-offset voltages. The dc-offset voltages, invariably resulting from the insertion of series capacitors, can be made to decay very quickly (within a few cycles) from the firing control of the TCSC thyristors.

6. Enhanced level of protection for series capacitors. Fast bypasses of the series capacitors can be achieved through thyristor control when large overvoltages develop across capacitors following faults. Likewise, the capacitors can be quickly reinserted by thyristor action after fault clearing

to aid in system stabilization.

7. Voltage support. The TCSC, in conjunction with series capacitors, can generate reactive power that increases with line loading, thereby aiding

the regulation of local network voltages and, in addition, the alleviation of any voltage instability.

8. Reduction of the short-circuit current. During events of high short-circuit current, the TCSC can switch from the controllable-capacitance to the controllable-inductance mode, thereby restricting the short-circuit currents.

12.What are the various modes of operation of TCSC? (Nov/Dec - 2012)

- By passed thyristor mode
- Blocked thyristor mode
- Partially conducting thyristor mode –(or) vernier mode

13.List the TCSC losses?

- Series capacitor loss
- Reactor- conduction loss
- Thyristor –conduction loss
- Switching lossess from heating the snubber resistor when voltage drop.

14.List the various Auxiliary signals for TCSC modulation?

Local signal:

- Line current
- Real power flow
- Bus voltage
- Local bus frequency

Remote signal:

- the rotor-angle/ speed deviation of a remote generator,
- the rotor-angle/ speed (frequency) difference across the system, and
- The real-power flow on adjacent lines.

15. How the placement of TCSC will locate?

- The TCSCs should be located in lines that experience limiting power oscillations.

- The swing of voltages on each side of the TCSC must be within acceptable limits; otherwise, multiple sites may be necessary.

- The control action of the TCSC in one transmission path should not cause undue power swings in a parallel path. If it does, then variable series compensation may become necessary in the parallel path.

- Sometimes, it may be advisable to distribute the control action among multiple TCSCs rather than confining the control action to one large-rating TCSC. Doing so ensures some system reliability if one of the TCSCs should fail.

16. Define SSR? (or) what is sub synchronous resonances (SSR) ? (April/May 2011) (or) Explain what do you understand by SSR (Nov/Dec-2010)

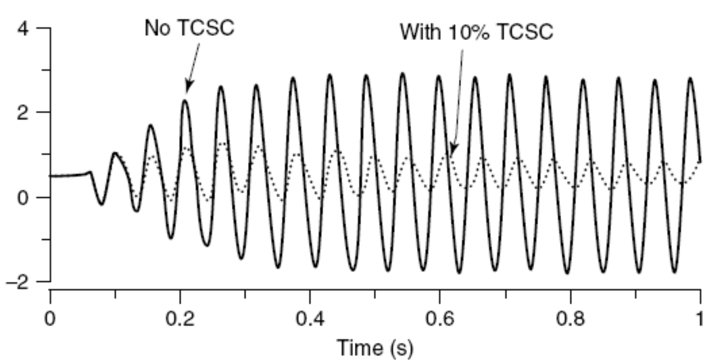
Sustained oscillation below the fundamental frequency is known as Sub synchronous Resonance “SSR”

17. List the SSR mitigation method? (or) What is the effect of TCSC in SSR Problem? (June-2011)

- *Subsynchronous oscillations*, caused by interaction between the electrical network and the generator torsional system.

- *Low-frequency (≈10 Hz) oscillations*, caused by interaction between the series capacitors and the shunt inductors, especially during line switchings and faults. These oscillations have large magnitudes and last for long periods because of high shunt-reactor *Q*-factors.
- *Switching oscillations*, caused by the switching of lines.

18.How to minimize the transient torque in TCSC? (or) What are the loading capability limitations ? (Nov/Dec 2010)



- The TCSC should be able to damp the SSR effects simultaneously on all turbine generators.

- If the TCSC is unable to damp the SSR, the TCSC control must act to remove the capacitor from the transmission line.

- If some remaining SSR effects are observed on turbine generators because of other series capacitors in the network, they must be identified and mitigated independently.

-

19.What are the synchronous voltage reversal (SVR) control scheme

- A higher boost level implies higher TCSC current that requires an increase in the capacitor bank rating.

- A higher boost factor also raises the magnitude of thyristor current

- A higher boost level also increases the harmonic voltage inserted in series with the line.

- A minimum boost level is needed to ensure that the thyristors do not need to turn on near the voltage zero crossing.

20.Give the range of firing angle in inductive and capacitive mode of operation (April/May -2011)

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

1. The limit on the firing angle, represented by a constant-reactance limit $X_{\min 0}$.
2. The harmonics-imposed limit, represented by a constant-TCSC-voltage limit VL_{tran}. The equivalent-reactance constraint is given by

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

3. 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:

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

21. What are the methods of protection against over voltage (Dec-2014)

- Earthing Screen
- Overhead ground wires
- Lightning arrestors or surge diverters

22. Mention the disadvantages of fixed series compensation of transmission lines(April 2014)

(i) Additional losses in the compensated line from the enhanced power flow

(ii)Increased responsiveness of power flow in the series compensated line from the outage of other lines in the system.

23. What are the functions of damping control of a TCSC (April 2014), (May 2015)

(i) To stabilize both post disturbance oscillations and spontaneous growing oscillations during normal operation.

(ii) To obviate the adverse interaction with high-frequency phenomena in power systems.

(iii) To preclude local instabilities with in the controller band width.

16 MARKS

1. What is the necessity of series compensation in TCSC applications?

Fixed-Series Compensation

Series capacitors offer certain major advantages over their shunt counterparts.With series capacitors, the reactive power increases as the square of line current,whereas with shunt capacitors, the reactive power is generated proportional tothe square of bus voltage. For achieving the same system benefits as those of series capacitors, shunt capacitors that are three to six times more reactivepower–rated than series capacitors need to be employed. Furthermore, shunt capacitors typically must be connected at the line midpoint, whereas no such requirement exists for series capacitors.Let *Q*se and *Q*sh be the ratings of a series and shunt capacitor, respectively, to achieve the same level of power transfer through a line that has a maximum angular difference of dmax across its two ends. Then

$$\frac{Q_{se}}{Q_{sh}} = \tan^2\left(\frac{\delta_{max}}{2}\right)$$

Specifically, for Δ_{max} **of 35°,***Q*se will be approximately 10% of *Q*sh. Even thoughseries capacitors are almost twice as costly as shunt capacitors (per-unit var) because of their higher operating voltages, the overall cost of series compensationis lower than shunt compensation

The Need for Variable-Series Compensation

Compensation of transmission lines by series capacitors is likely to result inthe following [4]:

1. enhanced base-power flow and loadability of the series-compensated line;
2. additional losses in the compensated line from the enhanced power flow;
3. increased responsiveness of power flow in the series-compensated linefrom the outage of other lines in the system.

Studies [4] have revealed that with increasing level of fixed-series compensation, even though the losses in remaining transmission lines decrease, the overall system losses are exacerbated from the enhanced losses in the seriescompensatedline. Also, the increased sensitivity or responsiveness of the compensated line to other network outages may cause a line loading that exceeds the enhanced loadability level of the line itself. These undesirable effects canbe avoided by employing variable levels of series compensation instead of fixed compensation. Series compensation can be varied, depending on the enhancement of power transfer desired at that time, without affecting other system-performance criteria.

2. List the Advantages of the TCSC?

Use of thyristor control in series capacitors potentially offers the following little-mentioned advantages:

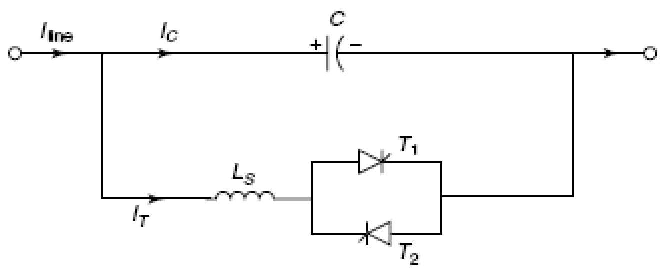
1. Rapid, continuous control of the transmission-line series-compensation level.
2. Dynamic control of power flow in selected transmission lines within the network to enable optimal power-flow conditions and prevent the loopflow of power.
3. Damping of the power swings from local and inter-area oscillations.
4. Suppression of subsynchronous oscillations. At subsynchronous frequencies,the TCSC presents an inherently resistive–inductive reactance. The subsynchronous oscillations cannot be sustained in this situation and consequently get damped.
5. Decreasing dc-offset voltages. The dc-offset voltages, invariably resultingfrom the insertion of series capacitors, can be made to decay very quickly(within a few cycles) from the firing control of the TCSC thyristors.
6. Enhanced level of protection for series capacitors. A fast bypass of theseries capacitors can be achieved through thyristor control when large overvoltages develop across capacitors following faults. Likewise, the capacitors can be quickly reinserted by thyristor action after fault clearing to aid in system stabilization.
7. Voltage support. The TCSC, in conjunction with series capacitors, can generate reactive power that increases with line loading, thereby aidingthe

regulation of local network voltages and, in addition, the alleviationof any voltage instability.

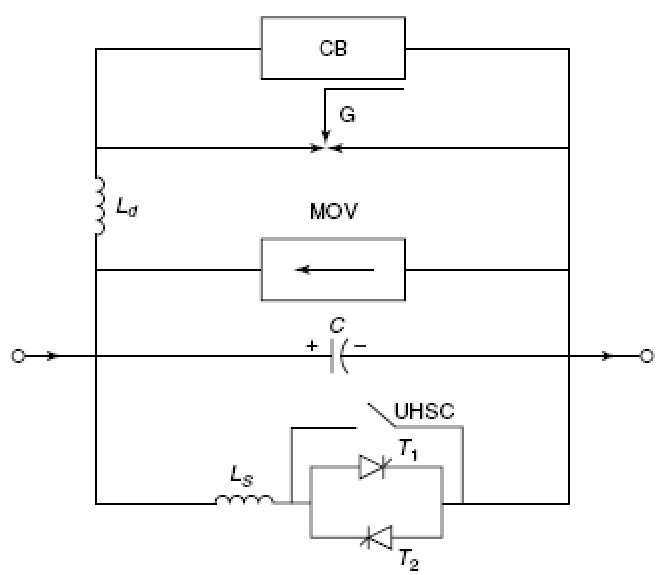
8. Reduction of the short-circuit current. During events of high short-circuitcurrent, the TCSC can switch from the controllable-capacitance to the controllable-inductance mode, thereby restricting the short-circuit currents.

3.Explain the Basic of TCSC CONTROLLER?

The basic conceptual TCSC module comprises a series capacitor, *C*, in parallel with a thyristor-controlled reactor, *LS*, as shown in Fig(a). However, a practical TCSC module also includes protective equipment normally installedwith series capacitors, as shown in Fig.(b).A metal-oxide varistor (MOV), essentially a nonlinear resistor, is connectedacross the series capacitor to prevent the occurrence of high-capacitor over-

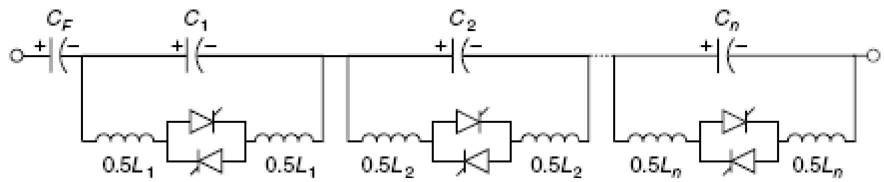


(a)



(b)

Figure .1 A TCSC module: (a) a basic module and (b) a practical module.



voltages. Not only does the MOV limit the voltage across the capacitor, but itallows the capacitor to remain in circuit even during fault conditions and helpsimprove the transient stability.Also installed across the capacitor is a circuit breaker, CB, for controlling its insertion in the line. In addition, the CB bypasses the capacitor if severe fault or equipment-malfunction events occur. A current-limiting inductor, *Ld*,is incorporated in the circuit to restrict both the magnitude and the frequency of the capacitor current during the capacitor-bypass operation.If the TCSC valves are required to operate in the fully "on" mode for prolonged durations, the conduction losses are minimized by installing an ultra–high-speed contact (UHSC) across the valve. This metallic contact offers a virtually lossless feature similar to that of circuit breakers and is capable of handling many switching operations. The metallic contact is closed shortly after the thyristor valve is turned on, and it is opened shortly before the valve is turnedoff.

During a sudden overload of the valve, and also during fault conditions, the metallic contact is closed to alleviate the stress on the valve.An actual TCSC system usually comprises a cascaded combination of many such TCSC modules, together with a fixed-series capacitor, *CF*. This fixedseriescapacitor is provided primarily to minimize costs. A conceptual TCSC system with basic TCSC modules is shown in Fig. The capacitors—*C*1, *C*2. *Cn*—in the different TCSC modules may have different values to provide a wider range of reactance control. The inductor in series with the antiparallelthyristor is split into two halves to protect the thyristor valves in case ofinductor short circuits.

4. Explain the operation of GTO thyristor controlled series capacitor?(Nov/Dec-2010) (or) (NOV/DEC 2014) (May 2015) April 2014) (or)

Explain the different modes of operation of TCSC (June-2011)

OPERATION OF THE TCSC

A TCSC is a series-controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. From the system viewpoint, the principle of variable-series compensation is simply to increase the fundamental-frequency voltage across an fixed capacitor (FC) in a seriescompensatedline through appropriate variation of the firing angle.This enhanced voltage changes the effective value of the series-capacitive reactance.

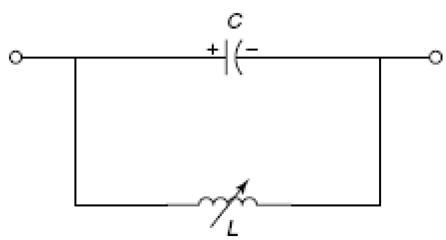


Figure A variable inductor connected in shunt with an FC.

A simple understanding of TCSC functioning can be obtained by analyzing thebehavior 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.

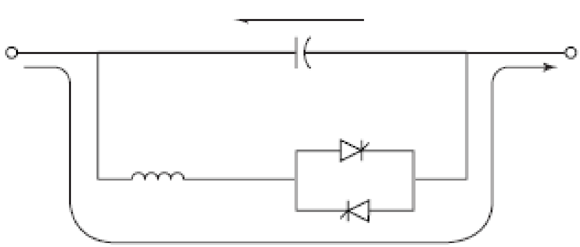
If $\omega C-(1/\omega L)=0$, a resonance develops that results in an infinite-capacitive impedance—an obviously unacceptable condition. If, however, $\omega C-(1/\omega L)<0$, the LC combination provides inductance above the value of the fixed inductor. This situation corresponds to the inductive-vernier 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 reactance 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.

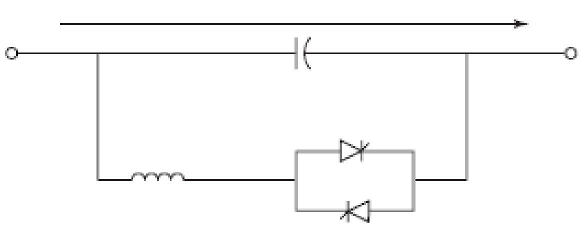
The behavior of the TCSC is similar to that of the parallel LC combination. The difference is that the LC-combination analysis is based on the presence of pure sinusoidal voltage and current in the circuit, whereas in the TCSC, because of the voltage and current in the FC and thyristor-controlled reactor (TCR) are not sinusoidal because of thyristor switchings. The exact analysis of

Modes of TCSC Operation:

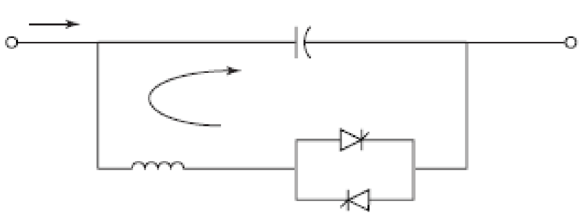
There are essentially three modes of TCSC operation are described in the following text.



(a)



(b)



(c)

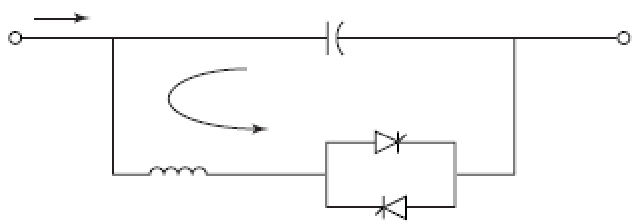


Figure Different operating modes of a TCSC: (a) the bypassed-thyristor mode;(b) the blocked-thyristor mode; (c) the partially conducting thyristor (capacitive-vernier)mode; and (d) the partially conducting thyristor (inductive-vernier) mode.

Bypassed-Thyristor ModeIn this bypassed mode, the thyristorsare made to fully conduct with a conduction angle of 180°. Gate pulses areapplied as soon as the voltage across the thyristors reaches zero and becomespositive, 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 susceptanceof the reactor is chosen to be greater than that of the capacitor.

Also known as the *thyristor-switched-reactor* (TSR) mode, the bypassedthyristormode is distinct from the *bypassed-breaker* mode, in which the circuitbreaker provided across the series capacitor is closed to remove the capacitor orthe TCSC module in the event of TCSC faults or transient overvoltages acrossthe TCSC.
This mode is employed for control purposes and also for initiating certainprotective functions. Whenever a TCSC module is bypassed from the violationof the current limit, a finite-time delay, *T*delay, must elapse before the modulecan be reinserted after the line current falls below the specified limit.

Blocked-Thyristor ModeIn 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 thyristor 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.

Partially Conducting Thyristor, or Vernier, ModeThis 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 whichthe thyristor are fired when the capacitor voltage and capacitor current haveopposite 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 a of the forward-facing thyristor, as measured from the positive reaching a zero crossing of the capacitor voltage, isconstrained in the range amin $\leq\alpha\leq\alpha 180^{\circ}$. This constraint provides a continuous vernier control of the TCSC module reactance. The loop current increases asa is decreased from $180^{\circ}$to amin. The maximum TCSC reactance permissible witha c amin 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 net inductiveimpedance.

Based on the three modes of thyristor-valve operation, two variants of theTCSC emerge:

1. *Thyristor-switched series capacitor* (TSSC), which permits a discrete controlof the capacitive reactance.
2. *Thyristor-controlled series capacitor* (TCSC), which offers a continuouscontrol of capacitive or inductive reactance. (The TSSC, however, is morecommonly employed.)

5. Discuss the modelling of the TCSC for various power system studies in detail? (Nov/Dec-2012)(May 2015)(April 2014)

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

Variable-Reactance Model

A TCSC model for transient- and oscillatory-stability studies, used widely forits 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. Theother dynamics of the TCSC model—the variation of the TCSC response withdifferent firing angles, for example—are neglected It is assumed that the transmission system operates in a sinusoidal steadystate, 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 angularstability studies.

As described previously, the reactance-capability curve of a single-moduleTCSC, 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 multimodule TCSC configurations. This model is generally used for inter-area mode analysis, andit provides high accuracy when the reactance-boost factor (=XTCSC/XC) is lessthan 1.5.

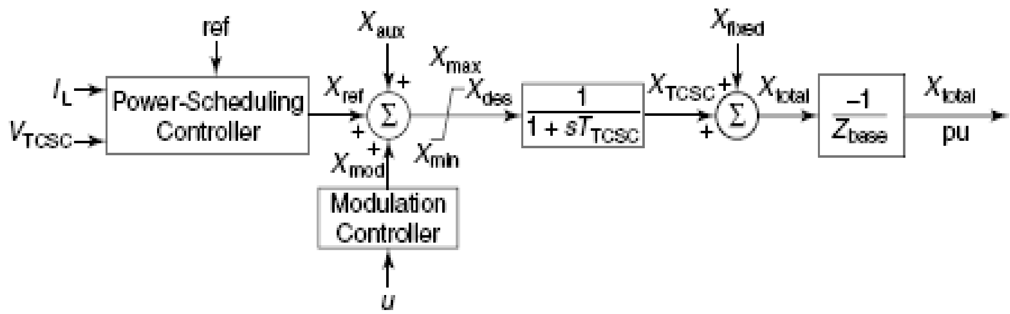


Figure A block diagram of the variable-reactance model of the TCSC.

Transient-Stability Model In the variable-reactance model for stability studies, a reference value of TCSC reactance, X_{ref}, is generated from a power-scheduling controller based on the power-flow specification in the transmission line. The reference X_{ref} value may also be set directly by manual control in response to an order from an energy-control center, and it essentially represents the initial operating point of the TCSC; it does not include the reactance of FCs (if any). The reference value is modified by an additional input, X_{mod}, from a modulation controller for such purposes as damping enhancement. Another input signal, this applied at the summing junction, is the open-loop auxiliary signal, X_{aux}, which can be obtained from an external power-flow controller.

A desired magnitude of TCSC reactance, X_{des}, is obtained that is implemented after a finite delay caused by the firing controls and the natural response of the TCSC. This delay is modeled by a lag circuit having a time constant, T_{TCSC}, of typically 15–20 ms The output of the lag block is subject to variable limits based on the TCSC reactance-capability curve shown in Fig. The resulting X_{TCSC} is added to the X_{fixed}, which is the reactance of the TCSC installation's FC component.

To obtain per-unit values, the TCSC reactance is divided by the TCSC base reactance, Z_{base}, given as

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

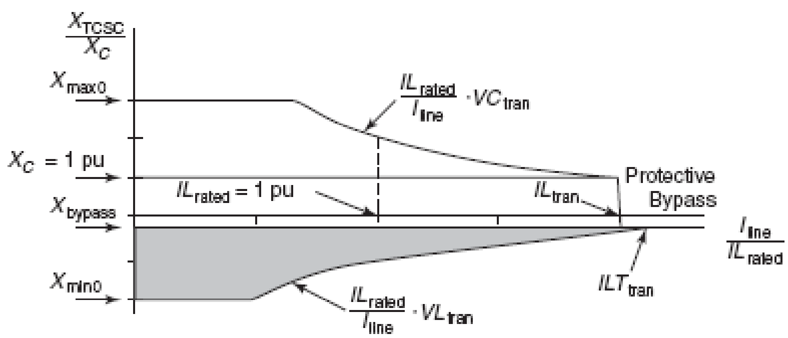
where kV_{TCSC} = the rms line–line voltage of the TCSC in kilovolts (kV)
MVA_{sys} = the 3-phase MVA base of the power system

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

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

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 overcurrent, 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. The typical TCSC data that can be used for stability studies are listed in Tables 1 and All reactances are expressed in per units on X_C; all voltages, in per units on $IL_{rated} \cdot X_C$; and all currents, in amps.

In the capacitive region, the different TCSC reactance constraints are caused by the following:

1. The limit on the TCSC firing angle, represented by constant reactance limit $X_{max\,0}$.
2. The limit on the TCSC voltage VC_{tran}. The corresponding reactance constraint is give by

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

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

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

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

1. The limit on the firing angle, represented by a constant-reactance limit $X_{min\ 0}$.
2. The harmonics-imposed limit, represented by a constant-TCSC-voltage limit VL_{tran}. The equivalent-reactance constraint is given by

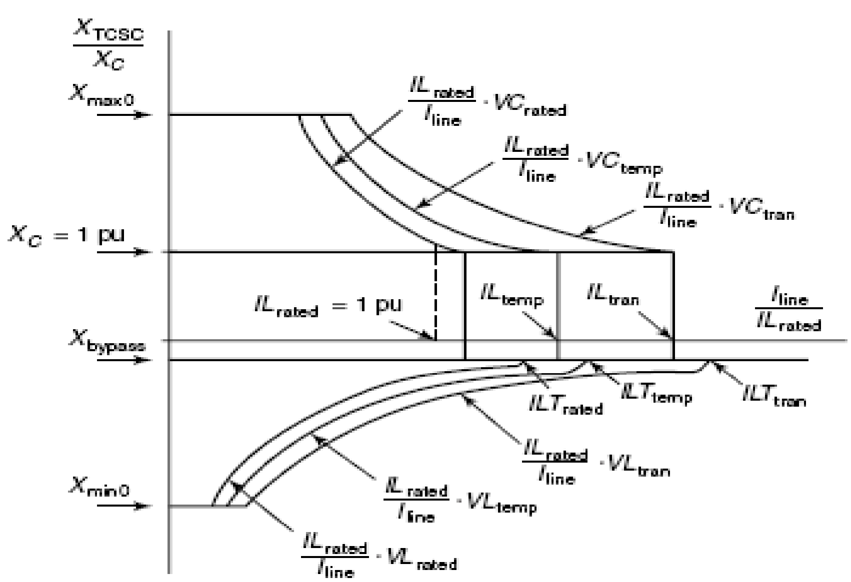
$$X_{min\ VL} = (VL_{tran}) \frac{IL_{rated}}{I_{line}}$$

3. 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:

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

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

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



If a TCSC is not expected to operate in the inductive-vernier mode, the minimum-reactance limit is *X*bypass irrespective of the line-current magnitude.

Long-Term-Stability Model The capability curves of the TCSCdepend on the duration for which the voltage- and current-operating conditions persist on the TCSC. In general, two time-limited regions of TCSC operationexist: the *transient-overload region*, lasting 3–10 s, and the *temporary-overloadregion*, lasting 30 min; both are followed by the *continuous region*. The overallreactance-versus-line-current (X-I) capability curve of the TCSC is depicted in Fig with the relevant data presented in Table 3.

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 Xmax limit and Xmin limit. It thenapplies the same modifications to the controller.The variable-reactance model does not account for the inherent dependenceof TCSC response time on the operating conduction angle. Therefore, entirely incorrect results may be obtained for the high-conduction-angle operation ofthe TCSC or for whenever the power-swing frequency is high (>2 Hz).However, the model is used widely in commercial stability programs becauseof its simplicity, and it is also used for system-planning studies as well as forinitial investigations of the effects of the TCSC in damping-power oscillations.

A reason for the model's widespread use lies in the assumption that controlsdesigned 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 situationswhere this assumption is not satisfied, a more detailed stability model is requiredthat accurately represents the inherent slow response of the TCSC.

An Advanced Transient-Stability Studies Model

An alternate TCSC model for transient-stability studies has been developed that effectively solves the differential equations pertaining to the TCSCcapacitor and the TCR. The TCSC model is invoked at every half-cycle of theline current. A variable is used to store the instantaneous capacitor voltage at theline zero crossing—at the end of each half-cycle—to be used as the initial conditionfor the next sample process. The TCR is represented by a current sourceupdated by the fundamental component of TCR current that the model calculatesat each half-cycle. Also, the model incorporates the effects of both thyristor firingand synchronization. The triggering instant is a function of the signal that is usedfor synchronization, such as the TCSC voltage or line current.The model is compatible with conventional transient-stability programs inthat it updates the capacitor voltage at every half-cycle while the stability programupdates the line current with the same frequency. It is also flexible enoughto integrate not only controls for minimizing the TCSC-response delay buthigher-order controls as well. Although slightly complex, the model correlatedclosely with EMTP results of TCSC performance.

TCSC Applications

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

OPEN-LOOP CONTROL

The open-loop impedance control is the most basic type of TCSC control, used primarily for power-flow control. The control system is depicted in Fig. Thedesired steady-state level of series compensation or line power flow is expressed in the form of a reactance reference applied to the controller. The controller is modeled by a delay block that represents TCSC action; its magnitude is typically chosen as 15 ms. The controller outputs a reactance-order signal that is linearized to obtain the necessary firing angle; then, the firing-angle signal is transmitted to the firing-pulse generator, which issues the gating pulses for the TCSCthyristor to implement the desired reactance.

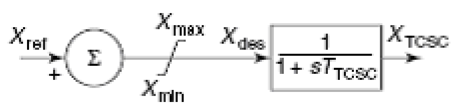


Figure A TCSC constant-impedance controller.

6. Explain the constant current control strategy in TCSC application? (June 2011)

CLOSED-LOOP CONTROL

Constant-Current (CC) Control:

As a reference signal to the TCSC controller, this strives to maintain the actual line current at this value. A typical TCSC CC-controller model is depicted in Fig. The 3-phase current is measured and rectified in the measurement unit. The rectified signal is passed through a filter block that comprises a 60-Hz and a 120-Hz notch filter as well as a high-pass filter. The emanating signal is then normalized to ensure per-unit consistency with the reference-current signal.

The controller is typically of the proportional–integral (PI) type that outputs the desired susceptance signal within the preset limits.A linearizer block converts the susceptance signal into a firing-angle signal. An operation-mode selector unit is generally used for TCSC protection.During short-circuit conditions, at which time the current through the metal oxidevaristor (MOV) exceeds a threshold, the TCSC is made to switch to the bypassed-thyristor mode or the thyristor-switched reactor (TSR) mode. In this mode, the thyristor conduct fully (σ=180°), reducing both the TCSC voltage and the current substantially and thereby reducing the stress on the MOV. During the clearance of faults, the "waiting mode" is implemented; when the capacitors are brought back into the circuit, a dc-voltage offset builds up that is discharged into this waiting mode.

The steady-state control characteristic of the CC control on the *V*TCSC – *IL*(the TCSC voltage–line current) plane is depicted in Fig.(a). The convention used in the figure is to treat the capacitor voltage as positive (which is opposite of the convention used in load flow). The characteristic is divided into three segments: *OA*, *AB*, and *BC*. Segments *OA* and *BC* represent the maximum andminimum TCSC reactance limits, respectively. Segment*AB*represents the control range in which the TCSC reactance is varied through the firing control to maintain a specified line current, *I*ref.

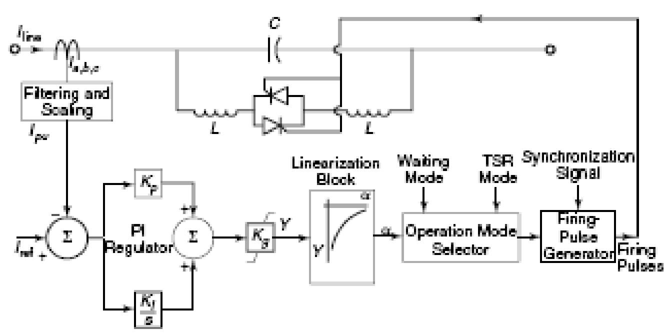


Figure : A TCSC constant-current (CC) controller model.

7. Explain the constant angle control in TCSC application?

Constant-Angle (CA) Control

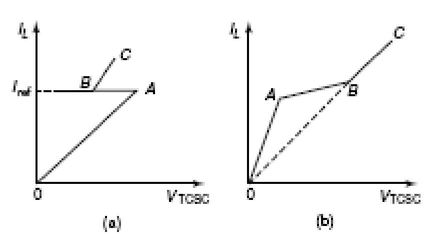


Figure : TCSC control characteristics: (a) CC control and (b) CA control.

This control is useful and relevant for situations in which transmission paths exist in parallel with the TCSC-compensated line. The control objective during transient or contingency situations is to keep the power flow unchanged in the parallel paths while allowing variations in the power transmitted across the TCSC-compensated line. To keep the power flow constant in shunt paths necessitates maintaining the angular difference constant across the lines, thus imparting the name *constant-angle control*, or CA control, to this strategy. If the voltage magnitudes at the two line ends are assumed to be regulated, then maintaining a constant angular difference implies maintaining a constant-voltage drop, *VL*, across the line.

The control objective while neglecting the line resistance is expressed

$$V_L = I_L X_{LR} - V_{\mathrm{TCSC}} = K = V_{L\mathrm{ref}}$$

Or

$$I_L = \frac{1}{X_{LR}}(K + V_{\mathrm{TCSC}})$$

Or

$$I_{\mathrm{ref}} - \left(I_L - \frac{V_{\mathrm{TCSC}}}{X_{LR}}\right) = 0$$

where K = the constant = $V_{L\mathrm{ref}}$

I_L = the magnitude of current in the TCSC-compensated line

X_{LR} = the net line reactance, including the effect of the fixed capacitor = $X_L - X_{FC}$

V_{TCSC} = the voltage across the TCSC (positive for capacitive voltage; negative for inductive voltage)

I_{ref} = the reference current = $K/X_{LR} = V_{L\mathrm{ref}}/X_{LR}$

X_L = the total-line inductive reactance

X_{FC} = the reactance of the fixed capacitor in the line (if any)

As mentioned previously, TCSCs are usually employed is conjunction with fixed capacitors for minimizing cost and improving control efficacy. The control characteristic for CA control in the $V_{\mathrm{TCSC}} - IL$ plane is depicted in Fig. Line segment *AB* represents the control range, having a slope XLR. Segments

OA and *BC* represent the minimum and maximum TCSC reactance limits, respectively. The CA control is highly effective in reducing power swings.
The TCSC control-system block diagram, incorporating features of both CC and CA control, is shown in Fig. In this figure, *Tm* indicates the time constant associated with the measurement circuit, which is generally a first-order low-pass filter. Similar measurement circuits are assumed for both TCSC-voltage and line-current measurements. In CC control, the multiplier block *S* is set to zero, whereas in CA control, *S* is assigned the value $1/X_{LR}$. The regulator is primarily a PI controller that is occasionally in cascade with a phase-lead circuit, as shown in Fig. If pure-integral action is required, *KP* is set to zero. For CC control, the integral gain *KI* is considered positive. In this control scheme, a positive current-error signal implies that the TCSC capacitive reactance must be increased to enhance the line current and thereby reduce the error signal, and in the CA control, the gain *KI* is treated negative. If the currenterror signal is positive, it is noted from Equation that the net voltage drop*VL* in the line is less than the reference $V_L$ref, necessitating a decrease in

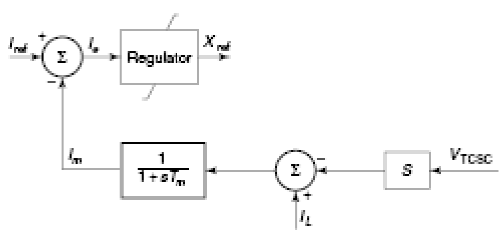


Figure A block diagram of a CC or CA controller.

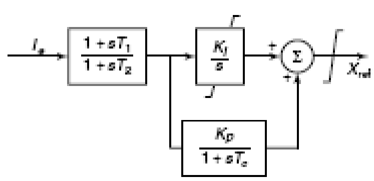


Figure A block diagram of the regulator.

the TCSC voltage *V*TCSC and consequently in the TCSC reactance *X*TCSC (or X_{ref}). For this reason, *KI* is assigned a negative sign in CA control. Although the TCSC firing delays are modeled by a single time constant of 15 ms, they may be ignored in electromechanical-stability studies as their effect is insignificant.

An elaborate case study for a single-machine infinite-bus (SMIB) system that depicts the influence of constant line-power control and CA control of the TCSC is presented. It is demonstrated that the CC and CA strategies are suitable only in SMIB systems having two or more parallel transmission paths. In case a critical contingency causes an outage of the parallel transmission paths, the line-power scheduling, controller must be disabled. If, however, the TCSC is equipped with additional damping controllers, the paths should be retained to ensure satisfactory damping levels during an outage.

8. Write short notes on Enhanced Current Control& Constant Power Control of TCSC application?

To improve the damping of certain oscillatory modes, such as subsynchronous oscillations, an optimized, derivative line-current feedback is embedded in the TCSC controller, as depicted in Fig. In this control system, the voltage regulator is a simple PI controller slightly different from the one depicted in Fig. The optimized current controller is shown to successfully damp subsynchronous oscillations for all levels of line-series compensation, unlike a conventional controller, which provides very low damping to an SSR mode.

Constant Power Control

The block diagram of a typical TCSC power controller is depicted in Fig. The line power flow is computed from the measured local voltage and current signals after the *abc*–$\alpha\beta 0$ transformation. The calculated power signal is converted into a per-unit quantity and filtered, then fed to the summing junctionof the power controller. The reference signal, P_{ref}, denotes the desired level of real-power flow in the TCSC-compensated line, and the power controller has a PI structure. The remaining control-system components were described previously.

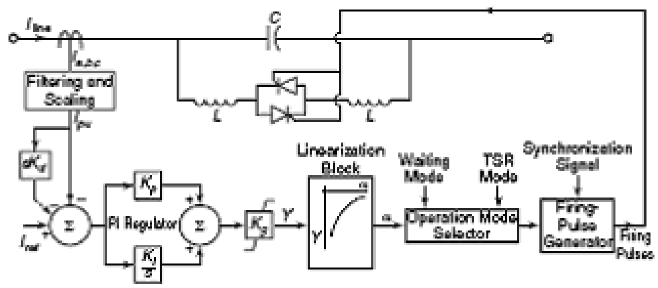


Figure An optimized TCSC CC structure.

The TCSC power controllers are usually effective if used as slow controllers for damping power oscillations or subsynchronous oscillations. An attempt to increase the controllers' speed by reducing the power-controller time constant, *Tp*, renders the response oscillatory. Usually, *Tp*is set to 100 ms.

Enhanced Power Control

The need to keep TCSC power controllers slow is potentially detrimental to the power system, as it extends the post–fault system recovery period.

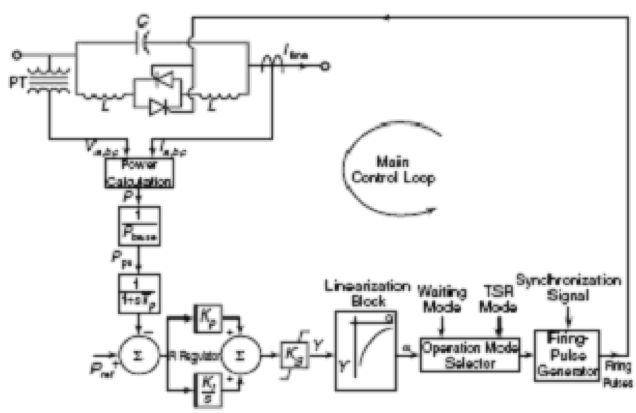


Figure A conventional TCSC power-control structure.

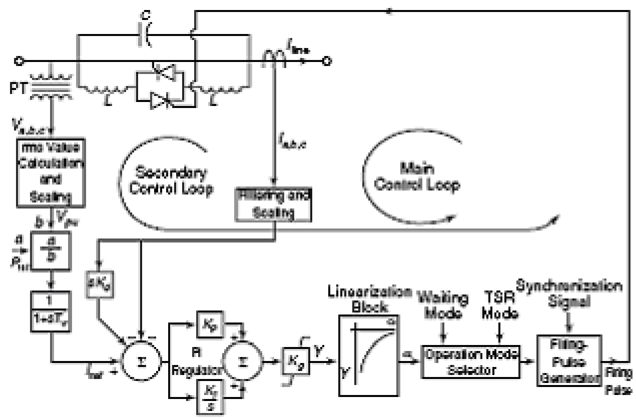


Figure An enhanced TCSC power-control structure.

A much-improved TCSC power controller that combines the beneficial influences of both power control and current control is depicted in Fig. It consists of two control loops—a fast, inner-current control loop and a slow, outerpower control loop. The power controller provides the current-reference signal for the current controller. Such a controller allows a fast TCSC response to system faults, yet it also allows a desired slow response to the electromechanical oscillations.

9. Describe the capabilities of TCSC Firing Schemes and Synchronization?

An equidistant firing scheme is most commonly employed in TCSC control. However, in some special situations in which the damping of the electrical selfexcitation modes is needed, individual firing control is shown to be advantageous. The TCSC firing controls are most effective when they are synchronizedwith line-current zero crossings primarily because the line current constitutes an almost sinusoidal signal. Synchronization with TCSC-voltage zero crossings may lead to erroneous results, as this voltage is beset with substantial harmonics and spurious noise signals.

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 over loaded. Providing fixed-series compensation on the parallel path to augment the power-transfer capability appears to be a feasible solution, but it may increasethe 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 powerflow 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

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 postdisturbance 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.

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

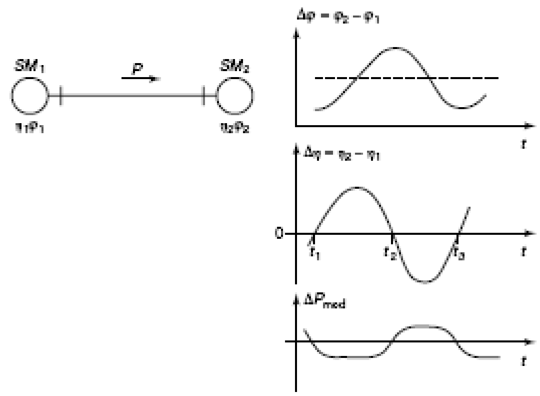


Figure The TCSC line-power modulation for damping enhancement.

following actions: When the receiving end–machine speed is lower than the sending end–machine speed, that is, $\Delta\eta$ **$(=\eta_2-\eta_1)$** 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 ΔP, given in megawatts (MW), with respect to ΔQTCSC, given in MVAR, is as follows

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

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

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 of **30**°**–40**°across the line. The influence of any bus load on the torquepower 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, **$\Delta P_m = \Delta P$.** It is not necessary to make the entire series compensation in a line controllable; in fact, the effectiveness of a TCSC is shown to increase in presence of fixed series compensation. The required series compensation in a line is therefore usually split into a fixed-capacitor component and a controllable TCSC component. 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.

Bang-Bang Control

Bang-bang control is a discrete control form in which the thyristor are either fully switched on **(α=90°)** or fully switched off **(α=180°).** 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 butfor damping any subsequent swings as well. Bang-bang control is employed in face of large disturbances to improve the transient stability

10. List some of the Auxiliary Signals for TCSC Modulation?

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.

Remote Signals These signals constitute the following:

1. the rotor-anglevsspeed deviation of a remote generator,
2. the rotor-anglevsspeed (frequency) difference across the system, and
3. The real-power flow on adjacent lines.

The angular difference between remote voltages can be synthesized by using local voltages at the two terminals of the TCSC and through the line current alternatively, a recent approach may be adopted wherein the phase angles of remote areas can be measured directly by using synchronized phasor measurement units. Adjacent-line real-power flow can be measured remotely and transmitted to the TCSC control system through telecommunication. Despite telecommunication delays, this signal can be used satisfactorily and economically for line power scheduling, which itself is a slow control.

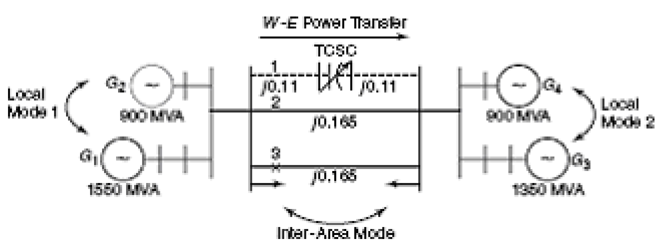


Figure A two-area, four-machine system.

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

Placement of the TCSC

The placement of FACTS controllers at appropriate locations is a critical issue. An optimally placed FACTS device requires a lower rating to achieve the same control objective than if it were located elsewhere. At times, however, the FACTS controllers may need to be placed at nonoptimal locations to minimize costs, especially when land prices and environmental concerns become important.

The following conditions generally apply when considering the placement of TCSCs:

1. The TCSCs should be located in lines that experience limiting power oscillations.
2. The swing of voltages on each side of the TCSC must be within acceptable limits; otherwise, multiple sites may be necessary.
3. The control action of the TCSC in one transmission path should not cause undue power swings in a parallel path. If it does, then variable series compensation may become necessary in the parallel path.
4. Sometimes, it may be advisable to distribute the control action among multiple TCSCs rather than confining the control action to one large-rating TCSC. Doing so ensures some system reliability if one of the TCSCs should fail.

11. Writeshort noteson SSR?

SUBSYNCHRONOUS RESONANCE (SSR) MITIGATION

Series compensation of long transmission lines may cause the following kinds of oscillations:

1. ***Sub synchronous oscillations***, caused by interaction between the electrical network and the generator torsional system.

2. ***Low-frequency (≈10 Hz) oscillation***s caused by interaction between the series capacitors and the shunt inductors, especially during line switchings and faults. These oscillations have large magnitudes and last for long periods because of high shunt-reactor *Q*-factors.

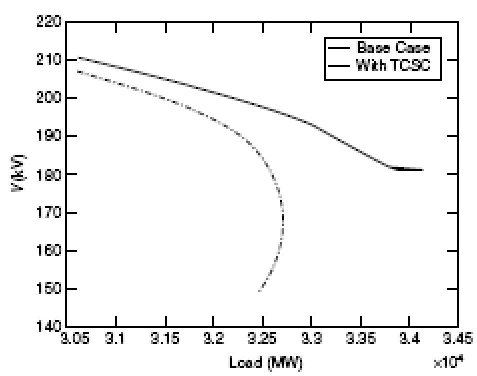
3. *Switching oscillations*, caused by the switching of lines. The TCSCs can be employed successfully to mitigate the listed oscillations

The principle of SSR mitigation by TCSCs has been obtained from the pioneering work done by Dr.N.G.Hingorani, for whom the NGH scheme of damping SSR was named. This scheme involves a thyristor-controlled discharge resistor connected in shunt with the series capacitor and is installed in practical systems. The NGH scheme is described in great length for which reason this book focuses on the impact the TCSC controller has in suppressing the SSR.

12. Briefly explain voltage collapse prevention in TCSC ?

VOLTAGE-COLLAPSE PREVENTION

Voltage-collapse problems are a serious concern for power-system engineers and planners. Voltage collapse is mathematically indicated when the system Jacobian becomes singular. The collapse points are indicative of the maximum loadability of the transmission lines or the available transfer capability (ATC) The TCSCs can significantly enhance the loadability of transmission networks, thus obviating voltage collapse at existing power-transfer levels. While theTCSC reduces the effective line reactance, thereby increasing the powerflow, it generates reactive power with increasing through-current, thus exercising a beneficial influence on the neighboring bus voltage.

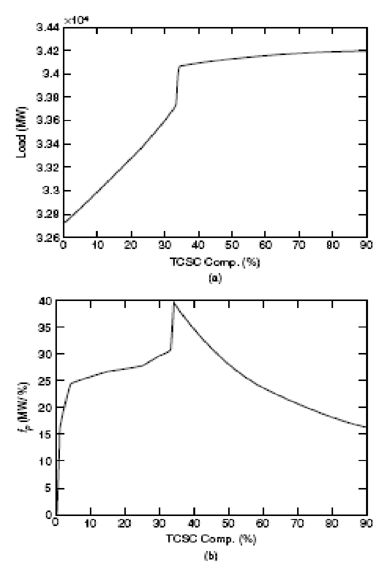


FigureThe voltage profile of the critical bus employing 50% TCSC compensation. An application of the TCSC for the preceding purpose is presented for a European system. The system faces voltage collapse or a maximum loading point corresponding to a 2120-MW increase in the net load. If a TCSCis installed to provide 50% compensation of the line experiencing the highest increase in power at the point of collapse, the maximum loadability will be enhanced to 3534 MW. The influence of the TCSC on the voltage profile of a criticalbus is illustrated in Fig. performance factor, *f p*, is proposed in ref. that indicates the maximum increase in loadability, l0, for a given percent of line compensation:

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

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

This index can be gainfully employed to obtain the best location of the TCSC in a system. The enhancement of system loading and variation of the performance factor with TCSC compensation are depicted in Fig. It is suggested that TCSC reactance-modulation schemes based on line current or line power, or on the angular difference across lines, may prove unsuccessful for voltage-stability enhancement. The reason is that these controls constrain any variation in the corresponding variables that may be necessary with changing loads, thereby limiting any power-flow enhancement on the line.



13. Describe the capabilities of TCSC in improving transient stability, power oscillation damping, and voltage stability applications? (Nov/Dec-2012)

Transient-Stability Model In the variable-reactance model for stability studies, a reference value of TCSC reactance, X_{ref}, is generated from a power-scheduling controller based on the power-flow specification in the transmission line. The reference X_{ref} value may also be set directly by manual control in response to an order from an energy-control center, and it essentially represents the initial operating point of the TCSC; it does not include the reactance of FCs (if any). The reference value is modified by an additional input, X_{mod}, from a modulation controller for such purposes as damping enhancement. Another input signal, this applied at the summing junction, is the open-loop auxiliary signal, X_{aux}, which can be obtained from an external power-flow controller.

A desired magnitude of TCSC reactance, X_{des}, is obtained that is implemented after a finite delay caused by the firing controls and the natural response of the TCSC. This delay is modeled by a lag circuit having a time constant, T_{TCSC}, of typically 15–20 ms. The output of the lag block is subject to variable limits based on the TCSC reactance-capability curve shown in Fig. The resulting X_{TCSC} is added to the X_{fixed}, which is the reactance of the TCSC installation's FC component.

To obtain per-unit values, the TCSC reactance is divided by the TCSC base reactance, Z_{base}, given as

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

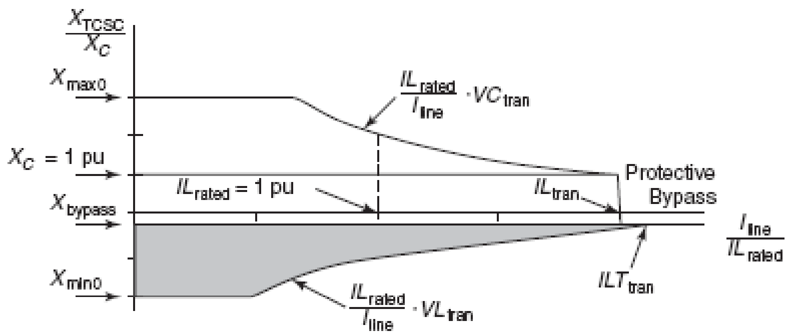
where $kV_{TCSC} =$ the rms line–line voltage of the TCSC in kilovolts (kV)
$MVA_{sys} =$ the 3-phase MVA base of the power system

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

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

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 overcurrent, 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. The typical TCSC data that can be used for stability studies and

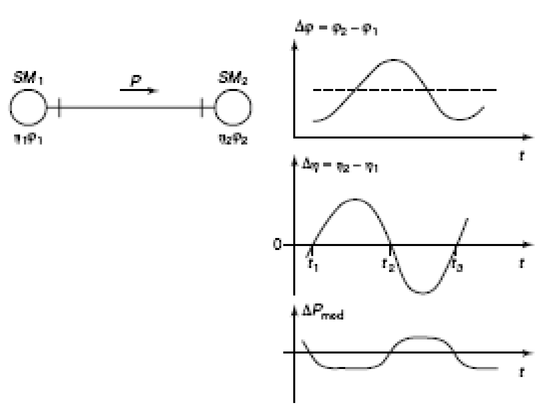
All reactances are expressed in per units on X_C; all voltages, in per units on $IL_{rated} \cdot X_C$; and all currents, in amps.

In the capacitive region, the different TCSC reactance constraints are caused by the following:

1. The limit on the TCSC firing angle, represented by constant reactance limit $X_{max\ 0}$.
2. The limit on the TCSC voltage VC_{tran}. The corresponding reactance constraint is give by

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, $\Delta\eta(=\eta 2-\eta 1)$ 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 ΔP, given in megawatts (MW), with respect to ΔQTCSC, 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

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 of **30°–40°** across the line. The influence of any bus load on the torquepower 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
$\alpha = \tan^{-1}(X_{\mathrm{source}}/R_{\mathrm{load}})$ (it is assumed that $R_{\mathrm{load}} \gg X_{\mathrm{source}}$)

The effect of all practical passive loads is generally moderate, and the sign of generator power is not changed. In the absence of any bus load, $\Delta P_m = \Delta P$. It is not necessary to make the entire series compensation in a line controllable; in fact, the effectiveness of a TCSC is shown to increase in presence of fixed series compensation. The required series compensation in a line is therefore usually split into a fixed-capacitor component and a controllable TCSC component. 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.

Bang-Bang Control

Bang-bang control is a discrete control form in which the thyristor are either fully switched on **(α=90°)** or fully switched off **(α=180°).** 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 butfor damping any subsequent swings as well. Bang-bang control is employed in face of large disturbances to improve the transient stability

14. Derive the expression of TCSC for the time interval (-β≤wt≤β)(April 2014)

Transmission-line cur- rent is assumed to be the independent-input variable and is modeled as an external current source, I S(t). It is further assumed that the line current is sinusoidal, as derived from actual measurements demonstrating that very few harmonics exist in the line current. However, the analysis presented in the following text may be erroneous to the extent that the line current deviates from a purely sinusoidal nature. Operating conditions resulting in this phenomenon are rare, and the expressions derived in the following text are used widely. The current through the fixed-series capacitor, C, is expressed as

$$C \frac{dv_C}{dt} = i_S(t) - i_T(t) \cdot u \tag{7.4}$$

The switching variable $u = 1$ when the thyristor valves are conducting, that is, when the switch S is closed. On the other hand, $u = 0$ when the thyristors are blocked, that is, when switch S is open. The thyristor-valve current, $i_T(t)$, is then described by

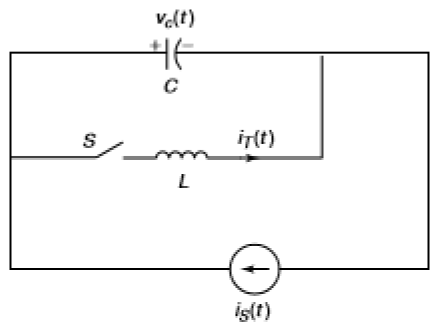


Figure 7.5 A simplified TCSC circuit.

$$\frac{Ldi_T}{dt} = v_C \cdot u \tag{7.5}$$

Let the line current, $i_S(t)$, be represented by

$$i_S(t) = I_m \cos \omega t \tag{7.6}$$

Equations (7.4) and (7.5) can be solved with the knowledge of the instants of switching. In equidistant firing-pulse control, for balanced TCSC operation, the thyristors are switched on twice in each cycle of line current at instants t_1 and t_3, given by

$$t_1 = -\frac{\beta}{\omega} \tag{7.7}$$

$$t_3 = \frac{\pi - \beta}{\omega} \tag{7.8}$$

where β is the angle of advance (before the forward voltage becomes zero). Or,

$$\beta = \pi - \alpha; \qquad 0 < \beta < \beta_{max} \tag{7.9}$$

The firing angle α is generated using a reference signal that can be in phase with the capacitor voltage. The thyristor switch S turns off at the instants t_2 and t_4, defined as

$$t_2 = t_1 + \frac{\sigma}{\omega} \tag{7.10}$$

$$t_4 = t_3 + \frac{\sigma}{\omega} \tag{7.11}$$

where α is the conduction angle, which is assumed to be the same in both the positive and the negative cycle of conduction. Also,

$$\sigma = 2\beta \tag{7.12}$$

Solving the TCSC equations (7.4)–(7.6) results in the steady-state thyristor current, i_T, as

$$i_T(t) = \frac{k^2}{k^2 - 2}\ \text{Im}\left[\cos\ \omega t - \frac{\cos\ \beta}{\cos\ k\beta}\cos\ \omega_r t\right]; \qquad -\beta \le \omega t \le \beta \tag{7.13}$$

where

$$\omega_r = \frac{1}{\sqrt{LC}} \tag{7.14}$$

$$k = \frac{\omega_r}{\omega} = \sqrt{\frac{1}{\omega L} \cdot \frac{1}{\omega C}} = \sqrt{\frac{X_C}{X_L}} \tag{7.15}$$

and X_C is the nominal reactance of the FC only. The steady-state capacitor voltage at the instant $\omega t = -\beta$ is expressed by

$$v_{C1} = \frac{\text{Im}\ X_C}{k^2 - 1}\ (\sin\ \beta - k \cos\ \beta \tan\ k\beta) \tag{7.16}$$

At $\omega t = \beta$, $i_T = 0$, and the capacitor voltage is given by

$$v_C(\omega t = \beta) = v_{C2} = -v_{C1} \tag{7.17}$$

The capacitor voltage is finally obtained as

$$v_C(t) = \frac{\text{Im}\ X_C}{k^2 - 1}\left(-\sin\ \omega t + k\ \frac{\cos\ \beta}{\cos\ k\beta}\sin\ \omega_r t\right); \qquad -\beta \le \omega t \le \beta \tag{7.18}$$

$$v_C(t) = v_{C2} + \text{Im}\ X_C(\sin\ \omega t - \sin\ \beta); \qquad \beta < \omega t < \pi - \beta \tag{7.19}$$

Because the nonsinusoidal capacitor voltage, v_C, has odd symmetry about the axis $\omega t = 0$, the fundamental component, V_{CF}, is obtained as

$$V_{CF} = \frac{4}{\pi}\int_0^{\pi/2} v_C(t) \sin\ \omega t\ d(\omega t) \tag{7.20}$$

The equivalent TCSC reactance is computed as the ratio of V_{CF} to I_m:

$$X_{\text{TCSC}} = \frac{V_{CF}}{I_m} = X_C - \frac{X_C^2}{(X_C - X_L)}\ \frac{2\beta + \sin 2\beta}{\pi} + \frac{4X_C^2}{(X_C - X_L)}\ \frac{\cos^2 \beta}{(k^2 - 1)}\ \frac{(k \tan k\beta - \tan \beta)}{\pi} \qquad (7.21)$$

Alternatively, the net reactance of the TCSC in per units of X_C, denoted by $X_{\text{net}}(= X_{\text{TCSC}}/X_C)$, can be expressed as

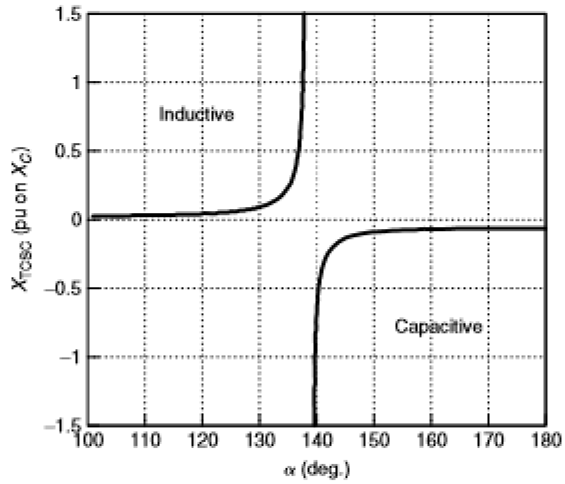


Figure 7.6 Variation of the TCSC reactance with firing angle α.

$$X_{\text{net}} = 1 - \frac{X_C}{(X_C - X_L)}\ \frac{\sigma + \sin \sigma}{\pi} + \frac{4X_C}{(X_C - X_L)}\ \frac{\cos^2(\sigma/2)}{(k^2 - 1)} \cdot \frac{[k \tan(k\sigma/2) - \tan(\sigma/2)]}{\pi} \qquad (7.22)$$

The variation of per-unit TCSC reactance, (X_{TCSC}/X_C), as a function of firing angle α is depicted in Fig. 7.6. It is noted from Eq. (7.21) that a parallel resonance is created between X_L and X_C at the fundamental frequency, corresponding to the values of firing angle α_{res}, given by

$$\alpha_{\text{res}} = \pi - (2m - 1)\ \frac{\pi\omega}{2\omega_r}; \qquad m = 1, 2 \qquad (7.23)$$

or alternatively,

$$\beta_{\text{res}} = (2m - 1)\ \frac{\pi\omega}{2\omega_r}; \qquad m = 1, 2 \qquad (7.24)$$

The different resonances can be reduced to one by a proper choice of $k = (\omega_r/\omega)$ in the range $90° < \alpha < 180°$ or $0 < \beta < 90°$. For instance, in the Kayenta TCSC [10], [11], the choice of inductance as 0.0068 H (henries) across the 15-Ω (ohms) series capacitor ($C = 177\ \mu$F) results in only one resonance at $\alpha = 143°$. If, however, the inductance is 0.0034 H, two resonances at $\alpha = 160°$ and at $\alpha = 101°$ will occur.

MAILAM ENGINEERING COLLEGE

MAILAM (PO), Villupuram (Dt). Pin: 604 304

(Approved by AICTE New Delhi, Affiliated to Anna University Chennai & Accredited by TCS, Chennai)

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Subject Code & Name: EE2036 - FLEXIBLE AC TRANSMISSION SYSTEMS

Unit	: IV
Year/Sem	: IV / VIII
Total No. Page	: 45

EMERGING FACTS CONTROLLERS

Static Synchronous Compensator (STATCOM) – operating principle – V-I characteristics Unified Power Flow Controller (UPFC) – Principle of operation - modes of operation – applications – modeling of UPFC for power flow studies.

Updated Questions:

PART-A:

Apr/May 2015: Qn.8 on Pg.4 & Qn.18 on Pg.8

Nov/Dec 2014: Qn.16 on Pg.7 & Qn.17 on Pg.7

PART-B:

Apr/May 2015: Qn.1 on Pg.8 & Qn.5 on Pg.18

Nov/Dec 2014: Qn.5 on Pg.18 & Qn.6 on Pg.23

Reference Books:

1. Mohan Mathur, R., Rajiv. K. Varma, "Thyristor – Based Facts Controllers for Electrical Transmission Systems", IEEE press and John Wiley & Sons, Inc.

Prepared by	Verified by	Verified by	Approved by
N. Jaiganesh			
Mr.N.JAIGANESH, AP/EEE	BC	HOD/EEE	PRINCIPAL
Mr.G.VEERAPATHIRAN, AP/EEE			

MAILAM ENGINEERING COLLEGE

MAILAM (PO), Villupuram (Dt). Pin: 604 304

(Approved by AICTE New Delhi, Affiliated to Anna University Chennai & Accredited by TCS, Chennai)

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE2036 FLEXIBLE AC TRANSMISSION SYSTEMS

UNIT IV EMERGING FACTS CONTROLLERS

Static Synchronous Compensator (STATCOM) – operating principle – V-I characteristics Unified Power Flow Controller (UPFC) – Principle of operation - modes of operation – applications – modeling of UPFC for power flow studies.

PART-A (Two Marks)

1. Define STATCOM?

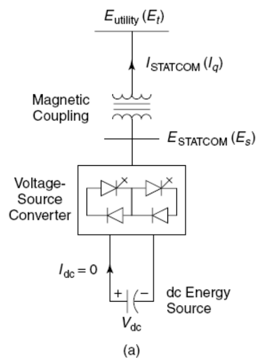
The STATCOM (or SSC) is a shunt-connected reactive-power compensation device that is capable of generating and□ □ orabsorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. It is in general a solid-state switching converter capable 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.

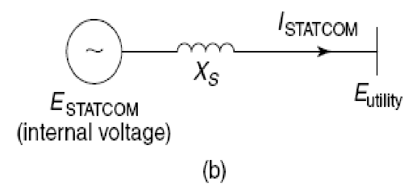
2. State the performance criteria for STATCOM?

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.

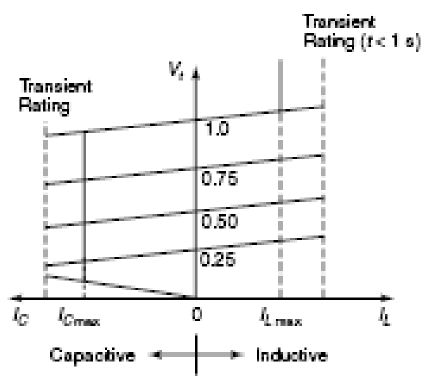
3. Draw the power circuit & equivalent circuit of STATCOM?

Power circuit: **Equivalent Circuit:**





4. Draw the V-I Characteristic of STATCOM? (Nov/dec-2010)



5. What are the dynamic characteristic of STATCOM?

- Multilevel VSC based STATCOM
- Selective harmonic –elimination modulation
- Capacitive voltage control

6. What is the role of dc link in UPFC?(Nov/Dec-2012)

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 line It comprises two VSCs coupled through a common dc terminal.

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 to 360 degree.

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 dcenergy–storage device.

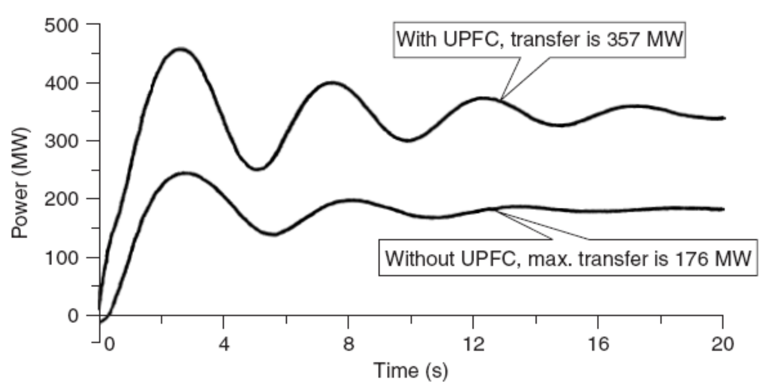
7. State the constraint in UPFC? (or)State the salient features of UPFC? (April/may-2011)

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.

8. List the application of UPFC? (May 2015)

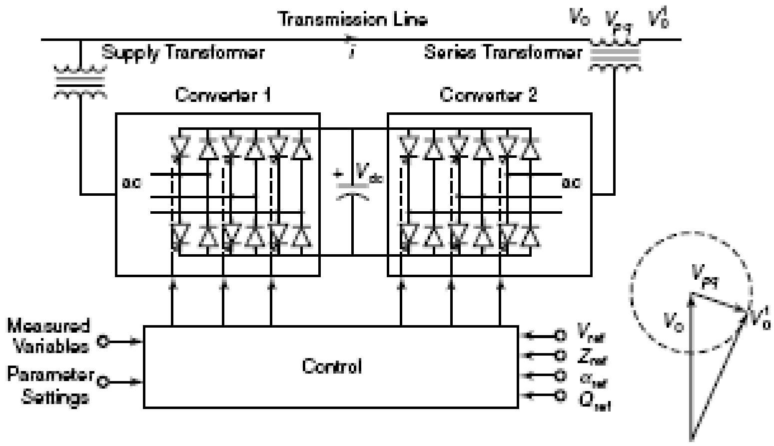
- The UPFC also provides very significant damping to power oscillations when it operates at power flows within the operating limits.
- The UPFC response to a 3-phase-line-to-ground fault cleared after four cycles, leaving the 345-kV line in service
- The application of UPFC for transient-stability improvement

9. Draw the power transfer capability with UPFC?



,

10. Draw the diagram of UPFC Back to back VSC with a common DC terminal capacitor?



11.What are the various control design issues in a FACTS controller?

- Balancing the power flow over a wide range of operating conditions (including contingencies), thereby using the power-system network most efficiently.
- Balancing the power flow in parallel networks operating at different voltage levels.
- Alleviating unwanted loop flow in large, integrated power systems.
- Mitigating inter-area power oscillations.
- Obviating or delaying the construction of new transmission facilities by significantly enhancing the power-transfer capacity of existing transmission corridors.

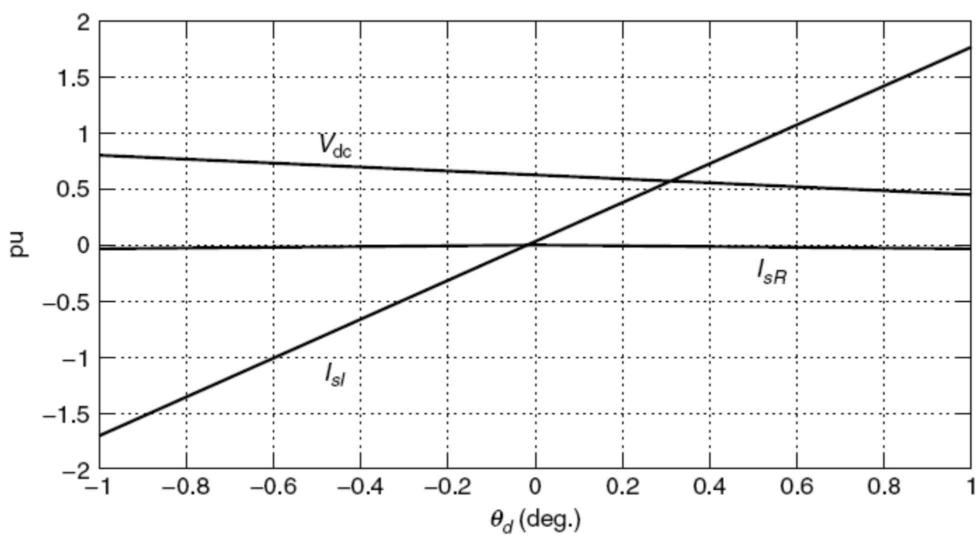
12. List the various control schemes of line compensated SSSC?

- The introduction of desired series-reactive compensation (capacitive or inductive).
- The damping of power-swing oscillations and enhancement of transient stability.
- The control of current in the SSSC-compensated line.

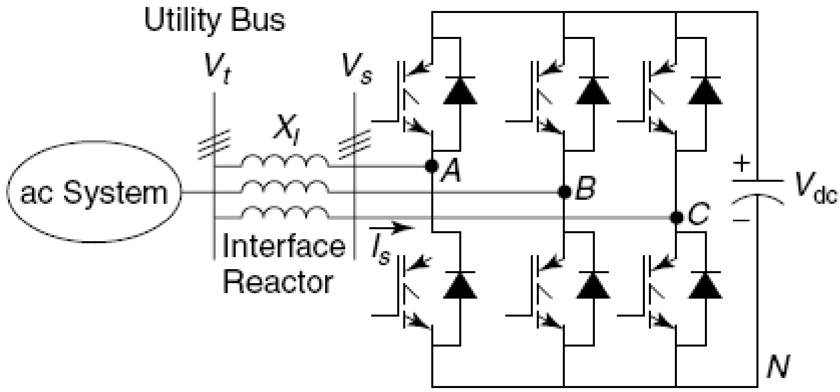
13. State the various control parameters for STATOM voltage controller for dynamic compensation?

1. The ac-voltage rating (line-to-line, rms): 13.8 kV, 60 Hz
2. The MVAR rating: ±15 MVAR
3. The normalized per-unit modulation index: 0.631 pu
4. The undermodulation (lagging var): 0.51–0.63 pu
5. The overmodulation (leading var): 0.632–0.886 pu
6. The dc-voltage regulation factor (ϵ): ±5%
7. The dc-voltage rating (V_{C1}, V_{C2}, V_{C3}): 2, 4, 8 kV
8. The dc capacitors (C_1, C_2, C_3): 6.5, 2.57, 1.6 mF
9. The K_{p1}, K_{p2}, K_{p3}, K_p (leading var): 12, 10, 12, 10
10. The K_{p1}, K_{p2}, K_{p3}, K_p (lagging var): −12, −10, −12, 10
11. The T_{p1}, T_{p2}, T_{p3}, T_p: 1, 1, 1.5, 0.8 s
12. The voltage controller (K_{vp}, T_{vi}, K_{SL}, V_{ref}): 10 s, 1 s, 1%, 1 pu

14. Draw the typical wave form for a steady state characteristic of a STATCOM?



15. Draw the diagram of an elementary 6 pulse VSC STATOM ?



16. Define UPFC.(NOV/DEC 2014)

The Unified power flow controller (UPFC) is the most versatile FACTS controller for the regulation of voltage and power flow in a transmission line. It consists of two voltage source converter (VSC), one shunt connected and other series connected. The DC capacitors of the two converters are connected in parallel.

17. Define Linear loads (NOV/DEC 2014)

In a linear circuit the output response is directly proportional to input, that means the application of sinusoidal voltage results in a sinusoidal current. As the instantaneous voltage changes over the period of the sine wave, the instantaneous current rises on falls in proportion to the voltage.

18. List any two performances of power system that can be improved by STATCOM. (April 2014, May 2015)

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.

19. State the basic UPFC power flow control functions. (April 2014)

- Terminal voltage regulation
- Combined series line compensation and terminal voltage control
- Combined phase angle regulation and terminal voltage control

- Combined terminal voltage regulation and series line compensation and phase angle regulation.

PART-B (16 Marks)

1. Obtain the steady state concept of STATCOM? June-2011(May 2014)(May 2015)

STATCOM:

The STATCOM (or SSC) is a shunt-connected reactive-power compensationdevice that is capable of generating and or absorbing reactive power andin 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 itsoutput terminals when it is fed from an energy source or energy-storage deviceat its input terminals. Specifically, the STATCOM considered in this chapter isa voltage-source converter that, from a given input of dc voltage, produces aset of 3-phase ac-output voltages, each in phase with and coupled to the correspondingac system voltage through a relatively small reactance (which isprovided by either an interface reactor or the leakage inductance of a coupling transformer). The dc voltage is provided by an energy-storage capacitor.

A STATCOM can improve power-system performance in such areas as thefollowing:

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 powerin the connected line, requiring a dc energy source.

Furthermore, a STATCOM does the following:

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

A STATCOM is analogous to an ideal synchronous machine, which generates a balanced set of three sinusoidal voltages—at the fundamentalfrequency—with controllable amplitude and phase angle. This ideal machinehas no inertia, is practically instantaneous, does not significantly alter the existingsystem impedance, and can internally generate reactive (both capacitive and inductive).To summarize, a STATCOM controller provides voltage support by generating or absorbing reactive power at the point of common coupling without theneed of large external reactors or capacitor banks.

2. Explain the basic control scheme of STATCOM? (Nov/dec-2010)

A STATCOM is a controlled reactive-power source. It provides the desiredreactive-power generation and absorption entirely by means of electronic processingof 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. InFig. (b), a STATCOM is seen as an adjustable voltage source behind areactance—meaning that capacitor banks and shunt reactors are not needed forreactive-power generation and absorption, thereby giving a STATCOM a compactdesign, or small footprint, as well as low noise and low magnetic impact.

The exchange of reactive power between the converter and the ac system canbe controlled by varying the amplitude of the 3-phase output voltage, *Es*, of the converter, as illustrated in Fig. (c). That is, if the amplitude of the outputvoltage 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 convertergenerates capacitive-reactive power for the ac system. If the amplitude of theoutput voltage is decreased below the utility bus voltage, then the current flowsfrom the ac system to the converter and the converter absorbs inductive-reactive

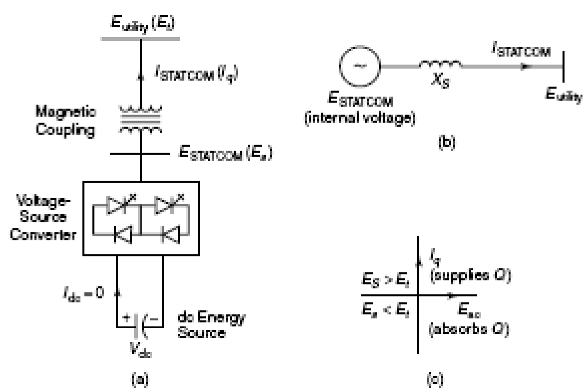


Figure The STATCOM principle diagram: (a) a power circuit; (b) an equivalentcircuit; and (c) a power exchange.

the reactive-power exchange becomes zero, in which case the STATCOM issaid to be in a floating state.

Adjusting the phase shift between the converter-output voltage and the acsystemvoltage can similarly control real-power exchange between the converterand the ac system. In other words, the converter can supply real power to theac system from its dc energy storage if the converter-output voltage is made tolead the ac-system voltage. On the other hand, it can absorb real power fromthe 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 instantaneousreactive power among the phases of the ac system. The mechanism bywhich the converter internally generates and or absorbs the reactive power canbe understood by considering the relationship between the output and inputpowers of the converter. The converter switches connect the dc-input circuit
directly to the ac-output circuit. Thus the net instantaneous power at the acoutputdc-input terminals (neglecting losses)

Assume that the converter is operated to supply reactive-output power. Inthis case, the real power provided by the dc source as input to the convertermust be zero. Furthermore, because the reactive power at zero frequency (dc)is by definition zero, the dc source supplies no reactive power as input to theconverter and thus clearly plays no part in the generation of reactive-outputpower by the converter.

In other words, the converter simply interconnects thethree output terminals so that the reactive-output currents can flow freely amongthem. If the terminals of the ac system are regarded in this context, the converterestablishes a circulating reactive-power exchange among the phases. However,the real power that the converter exchanges at its ac terminals with the ac systemmust, of course, be supplied to or absorbed from its dc terminals by the dccapacitor.

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 isin the form of a staircase wave into which smooth sinusoidal current from theac system is drawn, resulting in slight fluctuations in the output power of theconverter. However, to not violate the instantaneous power-equality constraintat its input and output terminals, the converter must draw a fluctuating currentfrom its dc source.

Depending on the converter configuration employed, itis possible to calculate the minimum capacitance required to meet the systemrequirements, such as ripple limits on the dc voltage and the rated-reactive powersupport needed by the ac system.

The VSC has the same rated-current capability when it operates with thecapacitive- or inductive-reactive current. Therefore, a VSC having a certainMVA rating gives the STATCOM twice the dynamic range in MVAR (thisalso 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-electronicequipment 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 theSTATCOM. In the steady state, the VSCs operate with fundamental-frequencyswitching to minimize converter losses. However, during transient conditionscaused by line faults, a pulse width–modulated (PWM) mode is used to preventthe fault current from entering the VSCs.In this way, the STATCOMis able to withstand transients on the ac side without blocking.

3. Explian with a neat sketch, the operating principle-I characteristic & application of static synchronous compensator? *(Nov/Dec-2012)*

V-I **Characteristic:**

A typical *V-I* characteristic of a STATCOM is depicted in Fig. 4.2. As canbe seen, the STATCOM can supply both the capacitive and the inductive compensationand is able to independently control its output current over the ratedmaximum capacitive or inductive range irrespective of the amount of ac-systemvoltage. That is, the STATCOM can provide full capacitive-reactive power atany 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 almostindependently of the system voltage (constant-current output at lower voltages).This capability is particularly useful for situations in which the STATCOM isneeded to support the system voltage during and after faults where voltage collapse would otherwise be a limiting factor.

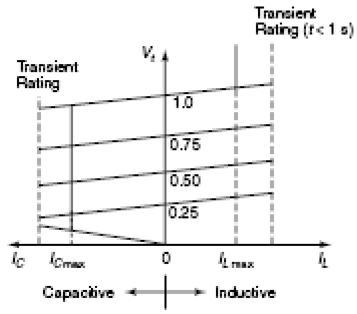


Figure (A) The *V-I* characteristic of the STATCOM.

Figure A also illustrates that the STATCOM has an increased transient ratingin both the capacitive- and the inductive-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 internallosses of the converter, and the dc capacitor voltage diminishes. However, whenthe STATCOM is used for reactive-power generation, the converter itself cankeep 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 converterabsorbs 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 samemechanism can be used to increase or decrease the capacitor voltage and thus,the amplitude of the converter-output voltage to control the var generation orabsorption.

The reactive- and real-power exchange between the STATCOM and the acsystem can be controlled independently of each other. Any combination of realpowergeneration or absorption with var generation or absorption is achievableif the STATCOM is equipped with an energy-storage device of suitable capacity, as depicted in Fig. With this capability, extremely effective controlstrategies for the modulation of reactive- and real-output power can be devised to improve the transient- and dynamic-system-stability limits.

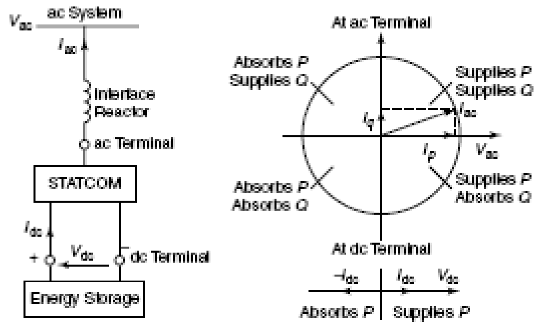


Figure a The power exchange between the STATCOM and the ac system.

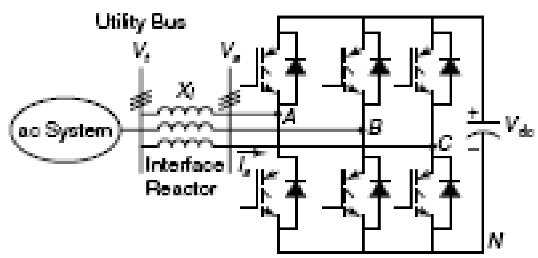


Figure b An elementary 6-pulse VSC STATCOM.

4. Discuss modeling of SSSC for transient stability studies? (Nov-Dec-2010)

An elementary 6-pulse VSC STATCOM is shown in Fig., consisting of sixself-commutated semiconductor switches (IGBT, IGCT, or GTO) with anti parallel diodes. In this converter configuration, IGBTs constitute the switching devices. With a dc-voltage source (which may be a charged capacitor), the convertercan produce a balanced set of three quasi-square voltage waveforms ofa given frequency by connecting the dc source sequentially to the three outputterminals via the appropriate converter switches.

The power quality embraces issues such as voltage flicker, voltage dip, andvoltage rise, as well as harmonic performance and high-frequency noise. Powerelectronicdevices distort voltage and current waveforms in a power network,influencing power facilities and customer equipment in a diverse manner. Harmoniccurrents induce abnormal noise and parasitic losses,

and harmonic voltagescause a loss of accuracy in measurement instruments and the faulty operationof relays and control systems. Electromagnetic noise, caused by the noiseof the high-frequency electromagnetic waves emitted from power-electronic circuits,affects electronic devices used in business and industry and often inducesinterfering voltage in communication lines. The corrective measure generally recommended for mitigating harmonics and high-frequency noise is to limit
their generation at the source.

In principle, the STATCOM-output voltage wave is a staircase-type wavesynthesized from the dc-input voltage with appropriate combinations of converterswitches. For example, the 6-pulse converter shown in Fig.b is operatedtypically with either a 120° or 180° conduction sequence for converter switches.

For a 180°conduction sequence, three switches conduct at a time;for a 120°conduction sequence, two switches conduct at a time. Figurec shows the 3-step staircase-line voltage, *vab*, along with the fundamental component,*V*fund, for a conduction sequence of 180°.The line voltage *vab*, in terms of its various frequency components, can bedescribed by the following Fourier-series equation:

$$v_{ab} = a_0 + \sum_{h=1}^{\infty} a_h \cos(h\omega t) + \sum_{h=1}^{\infty} b_h \sin(h\omega t)$$

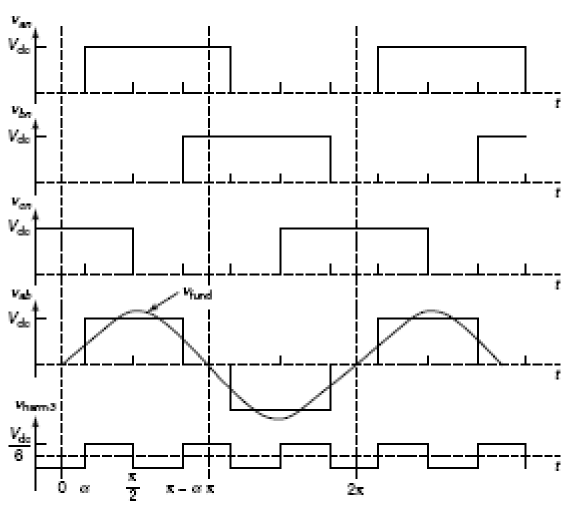


Figure c Anac line-voltage output of a 6-pulse voltage-source inverter for a 1808conduction sequence.

where coefficients a_0, a_h, and b_h can be determined by considering one fundamental period of v_{ab}. The v_{ab} waveform is symmetrical, so the average voltage $a_0 = 0$. It also has odd-wave symmetry; therefore, $a_h = 0$. The coefficient b_h is determined as

$$b_h = \frac{2}{\pi} \int_0^{\pi} V_{dc} \sin(h\omega t)\, d(\omega t)$$

$$b_h = \frac{2}{\pi} \int_{\alpha}^{\pi-\alpha} V_{dc} \sin(h\omega t)\, d(\omega t) = \frac{4V_{dc}}{\pi h} \cos(h\alpha)$$

Therefore

$$v_{ab} = \sum_{h=1,3,5}^{\infty} \frac{4V_{dc}}{\pi h} \cos(h\alpha) \sin(h\omega t)$$

For 180° conduction sequence, $\alpha = 30^\circ$; hence the triplen harmonics are zero

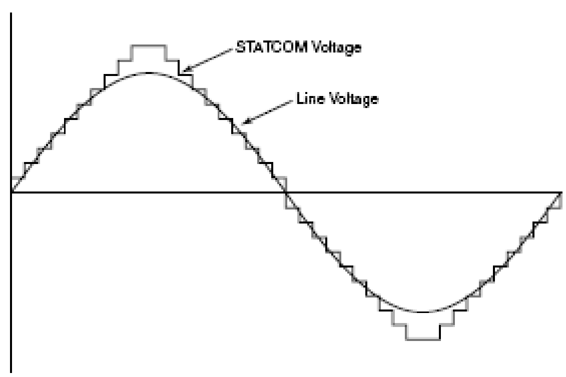


Figure The output voltage of a 48-pulse STATCOM that generates reactivepower.

To reduce harmonic generation, various converter configurations and converter-switching techniques are suggested in the literature. For example,the first installed commercial STATCOM has a 48-pulse converter configurationso that the staircase ac-line output-voltage waveform has 21 steps, asshown in Fig, and approaches an ideal sinusoidal waveform with a greatlyreduced harmonic content. Switching strategies, such as selective harmoniceliminationtechniques, also aid in limiting harmonic generation at its source.

5. What is UPFC? Draw its circuit diagram and explain the working principle as well as control principle in detail?June-2011(April 2014)

(or)

Explain the modeling procedure of UPFC in power flow studies? (Nov/Dec-2012) (NOV/DEC 2014) (May 2015)

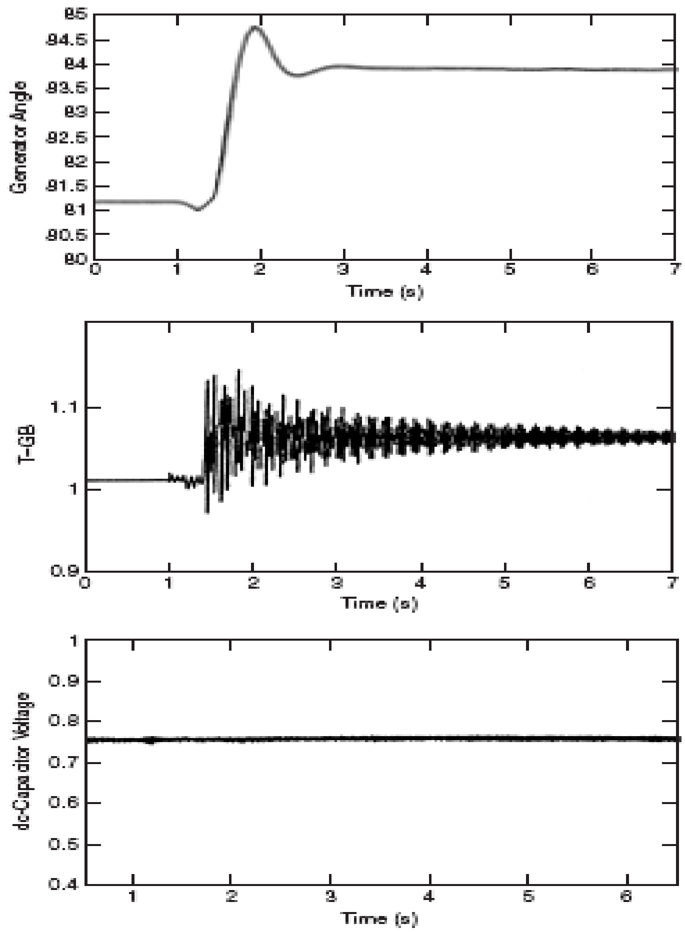
UPFC Principle of Operation:

The UPFC is the most versatile FACTS controller developed so far, with allencompassing capabilities of voltage regulation, series compensation, and phaseshifting. It can independently and very rapidly control both real- and reactivepower flows in a transmission line.

It is configured as shownin Fig. and comprises two VSCs coupled through a common dc terminal.One VSC—converter 1—is connected in shunt with the line through a couplingtransformer; the other VSC—converter 2—is inserted in series with the transmission line through an interface transformer.

The dc voltage for both converters isprovided by a common capacitor bank. The series converter is controlled to injecta 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 08 to 3608. Inthis process, the series converter exchanges both real and reactive power with thetransmission line. Although the reactive power is internally generated□ □ absorbedby the series converter, the real power generation□ □ absorption is made feasible bythe dc energy–storage device—that is, the capacitor. The shunt-connected converter 1 is used mainly to supply the real-powerdemand of converter 2, which it derives from the transmission line itself. The shunt converter maintains constant voltage of the dc bus.



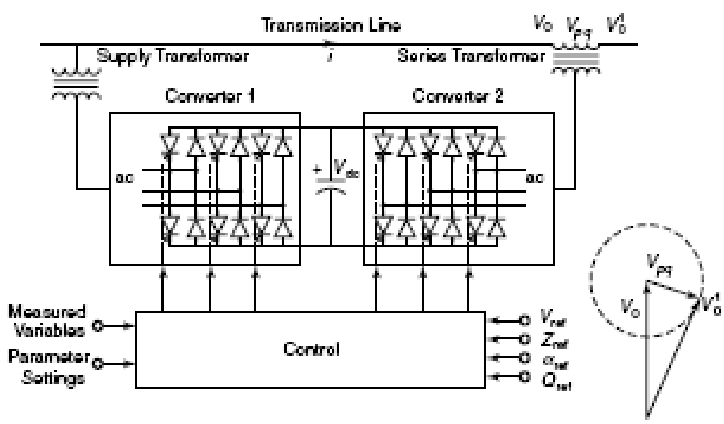


Figure b The implementation of the UPFC using two “back-to-back” VSCs witha common dc-terminal capacitor.

Thus the net realpower drawn from the ac system is equal to the losses of the two convertersand their coupling transformers. In addition, the shunt converter functions likea STATCOM and independently regulates the terminal voltage of the interconnectedbus by generating absorbing a requisite amount of reactive power.The concepts of various power flow control functions by use of the UPFCare illustrated in Figs. (a)–(d). Part (a) depicts the addition of the general

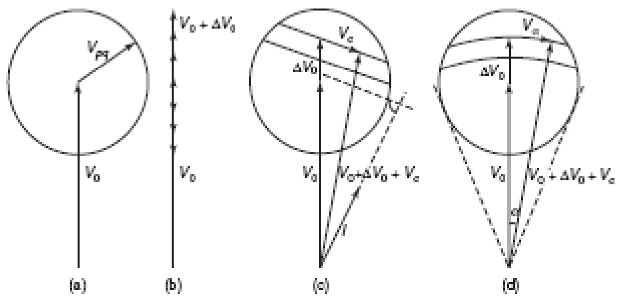


Figure c Aphasor diagram illustrating the general concept of series-voltageinjection and attainable power-flow control functions:

(a) series-voltage injection;

(b)terminal-voltage regulation;

(c) terminal-voltage and line-impedance regulation; and

(d)terminal-voltage and phase-angle regulation.

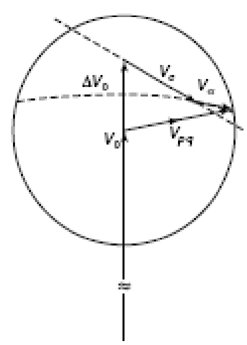
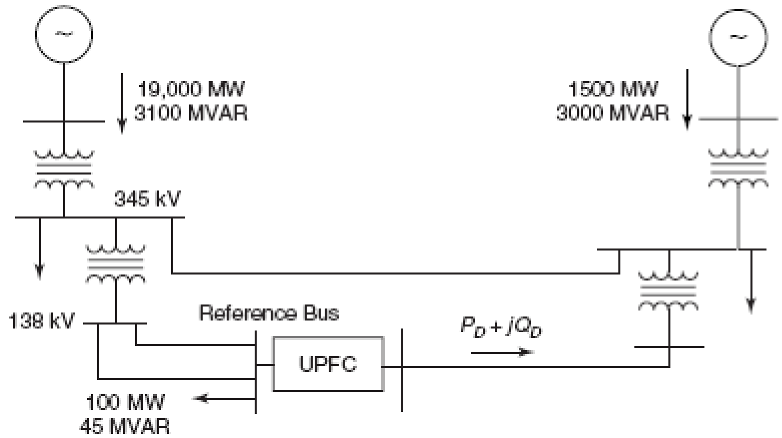


Figure d Aphasor diagram illustrating the simultaneous regulation of the terminalvoltage, line impedance, and phase angle by appropriate series-voltage injection.

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.



However, some control-application case studies are described here to illustratethe capabilities of the UPFC.

Applications :

- A case study for power-flow control and oscillation damping in the two-areasystem discussed in is presented in Fig.4.28. The two areas exchangepower via two transmission lines of unequal power-transfer capacity—one operatingat 345 kV, the other at 138 kV. Although the 345-kV line is 100 mi long,the 138-kV system is composed of two parallel 60-mi-long lines feeding a loadand a single 40-mi-long line leading to the other area.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, andthe line is disconnected after the fault. The maximum stable power flow possiblein 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 UPFCrating, the power increase is correspondingly and significantly lower than theincrease in the UPFC rating, thereby indicating that the practical limit on theUPFC size has been attained.
- The UPFC also provides very significant damping to power oscillations whenit operates at power flows within the operating limits. The UPFC response to a3-phase-line-to-ground fault cleared after four cycles, leaving the 345-kV linein service, is illustrated in Fig.
- Because the 345-kV line remains intact,the oscillation frequency changes from that shown in Fig..Dramatic enhancements in power-oscillation damping with the use of theUPFC are also reported in the planning study of the Mead–Phoenix project

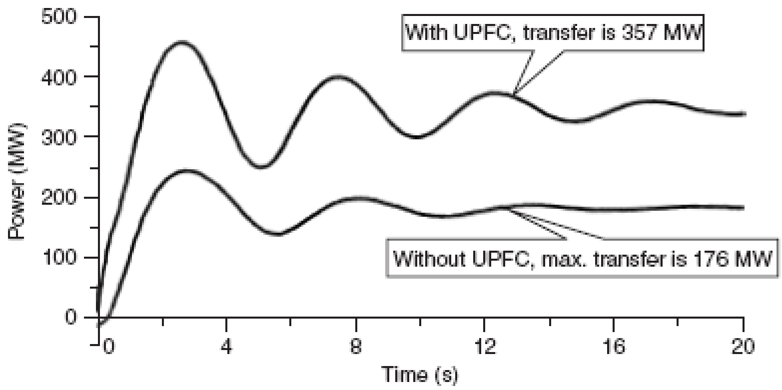


Figure Power-transfer capability with the UPFC.and also with a modulation controller–equipped UPFC in a simple system.

16Marks Question:

1. Obtain the steady state concept of STATCOM? **June-2011 (Pg:7)**
2. Explain the basic control scheme of STATCOM? **(Nov/dec-2010) (Pg:8)**
3. Explain with a neat sketch, the operating principle-I characteristic & application of static synchronous compensator? ***(Nov/Dec-2012)*****(Pg:11)**
4. Discuss modeling of SSSC for transient stability studies?(**Nov-Dec-2010) (Pg:14)**
5. What is UPFC ?Draw its circuit diagram and explain the working principle as well as control principle in detail?**June-2011 (Pg:16)**

(or)

Explain the modeling procedure of UPFC in power flow studies**? (Nov/Dec-2012)**

MAILAM ENGINEERING COLLEGE
MAILAM (PO), Villupuram (Dt). Pin: 604 304
(Approved by AICTE New Delhi, Affiliated to Anna University Chennai & Accredited by TCS, Chennai)
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Subject Code & Name: EE2036 - FLEXIBLE AC TRANSMISSION SYSTEMS

Unit : V
Year/Sem : IV / VIII
Total No. Page : 43

CO-ORDINATION OF FACTS CONTROLLERS

FACTs Controller interactions – SVC–SVC interaction - co-ordination of multiple controllers using linear control techniques – Quantitative treatment of control coordination.

Updated Questions:

PART-A:

Apr/May 2015: Qn.12 on Pg.5 & Qn.16 on pg.6
Nov/Dec 2014: Qn.14 on Pg.6, & Qn.15 on Pg.6

PART-B:

Apr/May 2015: Qn.7 on pg.26 & Qn.5 on Pg.12
Nov/Dec 2014: Qn.1on Pg.6 & Qn.2 on Pg.7

Reference Books:

1. Mohan Mathur, R., Rajiv. K. Varma, "Thyristor – Based Facts Controllers for Electrical Transmission Systems", IEEE pres and John Wiley & Sons, Inc.

Prepared by	Verified by	Verified by	Approved by
N. Jaiganesh		N. 26/11/15	
Mr.N.JAIGANESH, AP/EEE	BC	HOD/EEE	PRINCIPAL
Mr.G.VEERAPATHIRAN, AP/EEE			

MAILAM ENGINEERING COLLEGE
MAILAM (PO), Villupuram (Dt). Pin: 604 304
(Approved by AICTE New Delhi, Affiliated to Anna University Chennai & Accredited by TCS, Chennai)
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE2036 FLEXIBLE AC TRANSMISSION SYSTEMS

UNIT V CO-ORDINATION OF FACTS CONTROLLERS

FACTs Controller interactions – SVC–SVC interaction - co-ordination of multiple controllers using linear control techniques – Quantitative treatment of control coordination.

PART-A (Two Marks)

1. List the various types of FACTS controllers?

1. Multiple FACTS controllers of a similar kind.
2. Multiple FACTS controllers of a dissimilar kind.
3. Multiple FACTS controllers and HVDC converter controllers

2. What are the frequencies ranges of different control interaction?

- 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 sub synchronous resonance (SSR) interactions
- ☐☐15 Hz for electromagnetic transients, high-frequency resonance or harmonic resonance interactions, and network-resonance interactions

3.What is meant by Steady state Interaction?

- Steady-state interactions between different controllers (FACTS–FACTS or FACTS–HVDC) occur between their system-related controls. They are steady state in nature and do not involve any controller dynamics.
- These interactions are related to issues such as the stability limits of steady-state 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

4. Define Electromechnical oscillation Interaction?

- Electromechanical-oscillation interactions between FACTS controllers also involve synchronous generators, compensator machines, and associated power system stabilizer controls The oscillations include local mode oscillations, typically in the range of 0.8–2 Hz.
- 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.

5. What is meant by control or small signal oscillation?

- 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.

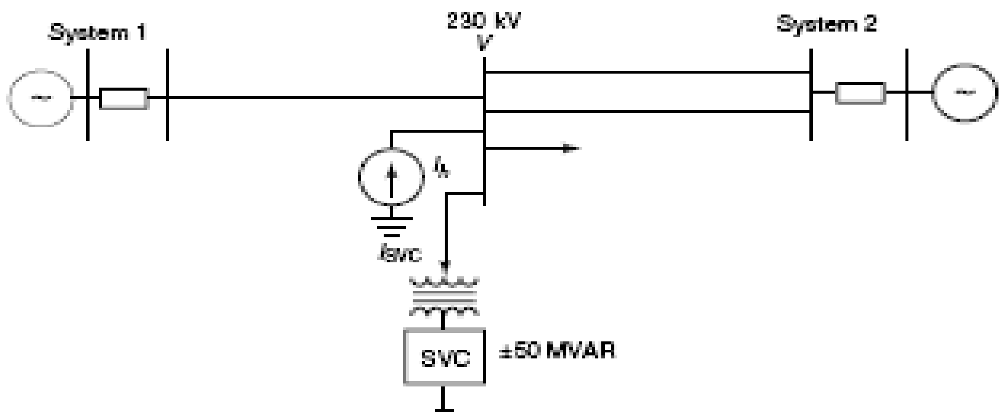
6. Define SSR interaction?

- Sub synchronous 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. Sub synchronous 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

7. What is meant by High frequency interaction?

- 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 geo magnetically induced currents (GICs).
- FACTS controllers need to be coordinated to minimize or negate such interactions.

8.Draw the Frequency response of SVC?



9. List the various SVC-SVC interaction?

The Effect of Electrical Coupling and Short-Circuit Levels

Uncoupled SVC Buses

Coupled SVC Buses

10.What is meant by Shunt-Reactor Resonance?

- If shunt reactors are present in the system (which they usually are), the series compensation of the transmission line introduces additional resonant modes from the interaction of series capacitance with the inductance of shunt inductors.
- The adverse interaction between SVCs and the shunt-reactor modes can beminimized by installing a high-pass filter with a cutoff frequency of typically 15–20 Hz on the ac-side measurement circuit

11.How co-ordination of FACTS controller is carried out?

- The essential design features of multiple FACTS controllers that can ensure secure operation with sufficient damping over a wide range of power-system operating conditions are discussed elaborately .
- The term coordination does not imply centralized control; rather, it implies the simultaneous tuningof 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.

12. List the basic procedure for controller design co-ordination of FACTS controller? (May 2015)

The controller-design procedure involves the following steps:
1. derivation of the system model;
2. enumeration of the system-performance specifications;
3. selection of the measurement and control signals;
4. coordination of the controller design; and
5. validation of the design and performance evaluation.

13. List the system performance specification for co-ordination of FACTS controller? (OR) What is the need for coordination of different FACTS controller.(April 2014)

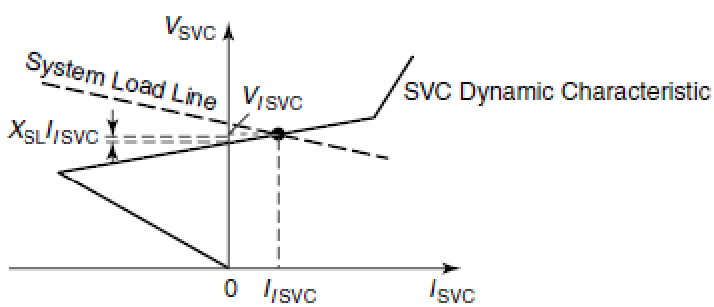
1. It should help the system survive the first few oscillations after a severe system disturbance with an adequate safety margin. This safety factor is usually specified in terms of bus-voltage levels that should not be violated after a disturbance.

2. A minimum level of damping must be ensured in the steady state after a disturbance.

3. Potentially deleterious interactions with other installed controls should be avoided or minimized.

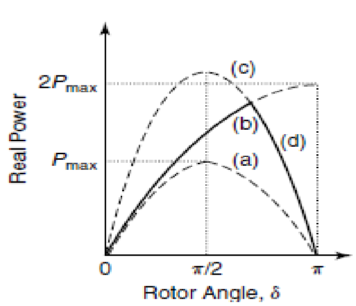
4. Desired objectives over a wide range of system-operating conditions should be met (i.e., it should be robust).

14. Draw the control characteristics of SVC.(NOV/DEC 2014)



(c)

15. Draw the power angle curve of SVC. (NOV/DEC 2014)



16. What is the main problems with multiple SVC in a power system network (May 2015)

Wen multiple SVCs are connected on the same line, the controller mode of the SVC with the lower effective short-circuit ratio (ESCR) becomes susceptible to instability.

16 Marks:

1. List the Types of Various controller interactions?(NOV/DEC 2014)

An excellent discussion on controller interactions is presented

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 forpower systems to have the controls 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 classifiedas 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 harmonicresonance interactions, and network-resonance interactions

2. Write short notes on Steady-State Interactions in co-ordination of FACTS controller?(NOV/DEC 2014)

- 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,
- 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 centralizedcontrols of participating controllers are recommended for ensuring the desired coordinated performance.

3. List the various types of Oscillation interaction in FACTS controller?

Electromechanical-Oscillation Interactions:

Electromechanical-oscillation interactions between FACTS controllers alsoinvolve 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 synchronousgenerators in a plant or several generators located in close vicinity;the inter-area mode results from the power exchange between tightly coupledgenerators 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 separatecontrollers.

Alternatively, the FACTS controllers can act concertedly to damp the critical modes without any adverse interaction.Eigenvalue analysis programs are employed for determining the frequencyand damping of sensitive modes.

Control or Small-Signal Oscillations:

Control interactions between individual FACTS controllers and the network orbetween 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 possibleby 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 maybe used.

Subsynchronous Resonance (SSR) Interactions:

Subsynchronous oscillations may be caused by the interaction between thegenerator torsional system and the series-compensated-transmission lines, theHVDC 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

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 andHVDC 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 over voltage-measurement systems, transformer energization, or transformer saturation caused by geomagnetically induced currents (GICs).FACTS controllers need to be coordinated to minimize or negate such interactions.

4. Briefly explain the frequency response of facts controllers?

The composite-frequency response of a FACTS controller, together with itsassociated ac system, provides a good indication of the control-system stability,especially while an attempt is made to coordinate several FACTS or HVDCcontrollers.

A time domain–based frequency-scanning method (FSM) is usedfor obtaining the frequency responses of individual and coordinated FACTS controllers. A current source is used to inject a spectrum of frequencies at the FACTS controller bus.

The local voltage developed at the bus is measured, and its harmonic content is evaluated through the use of Fourier analysis. The simulations are performed with an EMTP that has detailed models of FACTS controllers.

To avoid the operation of any system component in its nonlinear region, themagnitudes of injected harmonic currents are chosen to be quite small, thereby ensuring linearized system behavior around the operating point.

In HVDCconverters, an injected-current magnitude is considered sufficiently small if itdoes not cause a firing-angle oscillation in excess of

0.58 Two frequencyresponseexamples of FACTS controllers one for the SVC, the other forthe TCSC

The Frequency Response of the SVC :

The study system considered is shown in Fig 1. A 50 MVAR SVC is connected at the midpoint of the network that connects systems 1 and 2. The frequency response is obtained for two operating points.

At the first operating point, the SVC maintains a bus voltage of 1.02 pu,with a firing angle a c 1028 corresponding to a reactive-power absorption of 22.5 MVAR (inductive). Small-magnitude harmonic currentsare injected at discrete frequencies ranging from 5 to 45 Hz. The corresponding impedances are computed as the ratio of the developed voltage and the injected-harmonic disturbance- current components.

The impedance magnitude and angle-frequency responses are plotted in Figs. 2 and 3, respectively. The SVC presents a parallel resonance at 33 Hz and behaves inductively from 5 to 33 Hz, becoming capacitive at resonance and tending to resume inductive behavior as the frequency is increased beyond 33 Hz.

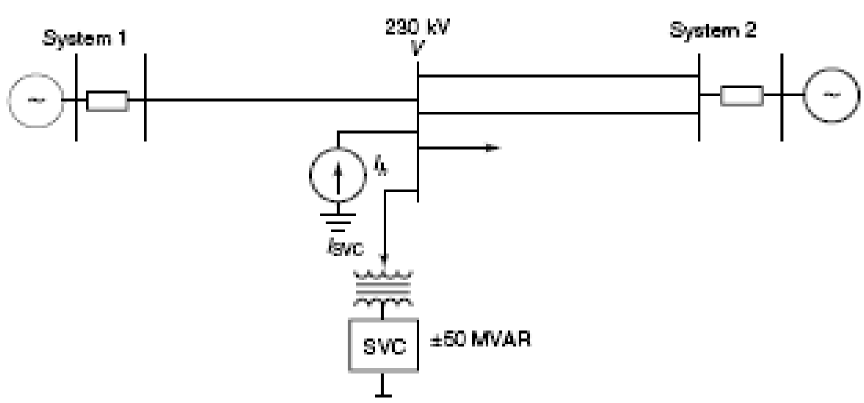


Figure 1 A study system for frequency scanning of the SVC.

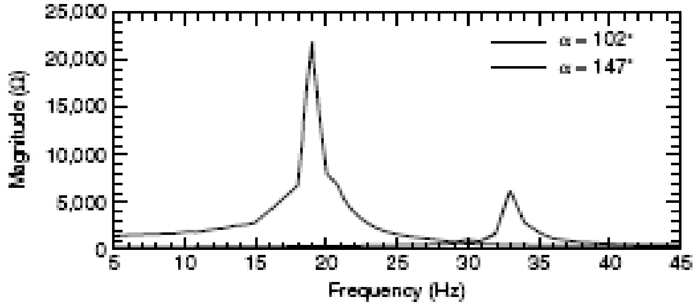


Figure 2 The impedance magnitude of the SVC frequency response.

The frequency response is obtained for the second steady state–operating point. The bus voltage is now regulated at 1.10 pu, with a thyristor firing anglea c 1478 corresponding to a reactive-power injection of 50 MVAR (capacitive).

The corresponding magnitude and angle-frequency responses are, again, plotted in Figs.2 and3, respectively. It is seen that the resonant frequency modifiesto 19 Hz and the impedance peak becomes three times that of the inductive SVC operation. The phase plot indicates that the higher the firing angle, the smaller the frequency range of inductive operation.

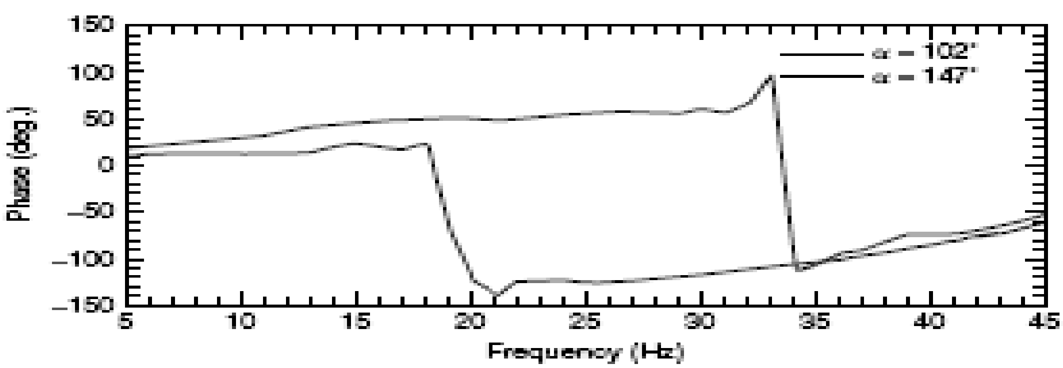


Figure 3 The impedance angle of the SVC frequency response.

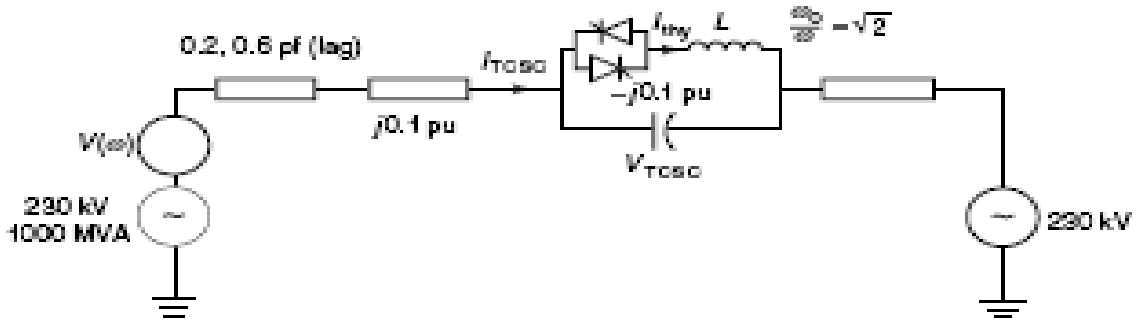


Figure 4 A study system for the TCSC frequency response.

The Frequency Response of the TCSC :

The 60-Hz test system used for evaluating the TCSC frequency response is depicted in Fig.4 thefrequency response is obtained for two conduction angles: 80° and 86°. Theimpedance magnitude and angle plots are illustrated in Fig.5 and Fig.6, respectively.

It is evident that the TCSC-compensated system presents an inductive behavior until it reaches 45–50 Hz; thereafter, its behavior tends to become capacitive, resembling that of a pure capacitor.

5. Investigate the SVC-SVC controller interaction in alarge power system? (Nov/Dec-2012), June-2011),(April/May-2011)(May 2015)

The Effect of Electrical Coupling and Short-Circuit Levels:

A detailed case study of control interaction between multiple SVCs in a largepower system,The interaction phenomena areinvestigated as functions of electrical distance (electrical coupling) between theSVCs and the short-circuit level at the SVC buses.

Uncoupled SVC Buses A simplified test system shown in Fig. is considered for the interaction analysis performed through eigenvalue anal-

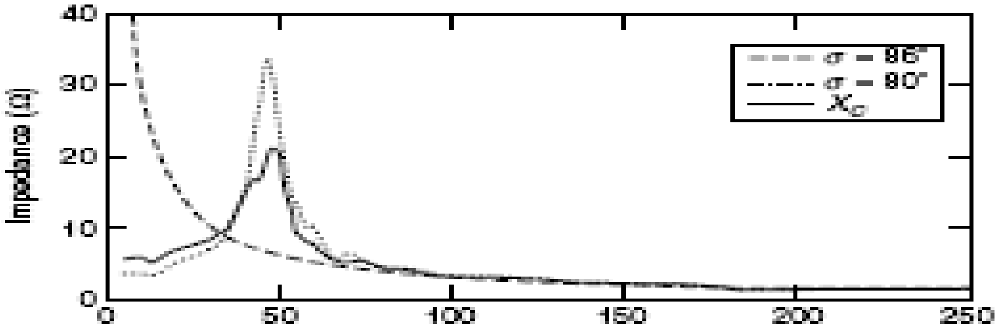


Figure 5 The impedance-magnitude plot of the TCSC frequency response.

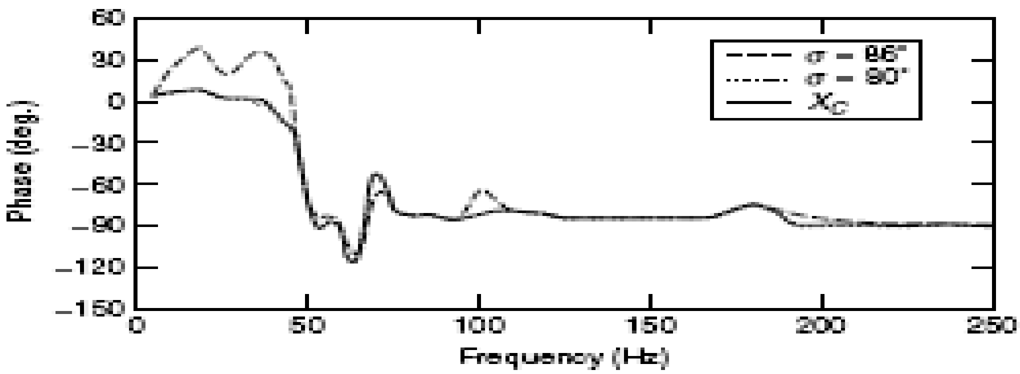


Figure 6 The impedance-angle plot of the TCSC frequency response.

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 tothe 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, however, the reactance between the twoSVC buses is low, it constitutes a case of high electrical coupling between theSVCs. Here again, two possibilities exist with respect to short-circuit capacityof 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 reveal that by increasing the proportional gain of one SVC, theEigenvalues 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 canbe independently designed and optimized, but if the short-circuit capacity ofthe SVC region is low, varying the proportional gain of SVC 1 will stronglyinfluence the Eigenvalues associated with SVC 2.

It is therefore imperative that a coordinated control design be undertaken for both SVCs.Despite simplifications in the study system and in the analysis approach, theaforementioned interaction results are general, for the phenomena investigatedare independent of the number of buses, transmission lines, or generators.

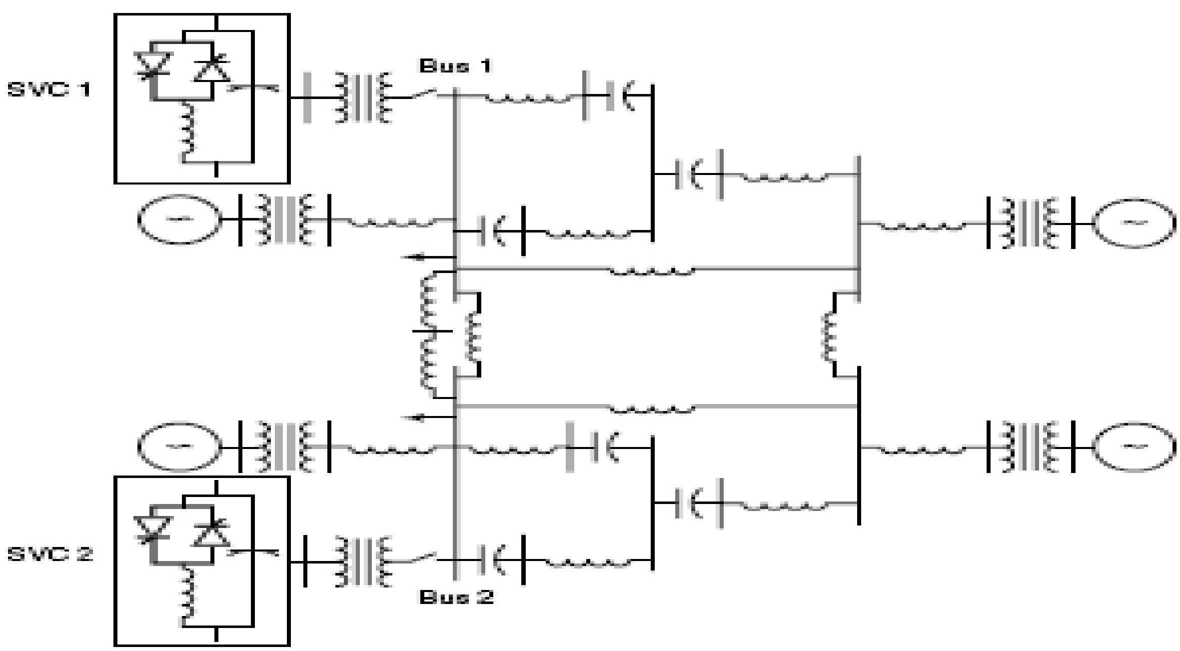


Figure 7 An SVC interaction-analysis network.

The System Without Series Compensation:

In power systems with several SVCs, the maximum response rate of the SVCsis limited by the stability of individual voltage-control loops during major contingencies.

Study System:

The Hydro-Quebec summertime power system,and studied considers a possible option of 30SVCs distributed along major transmission networks.

In the study presented a control interaction between the SVCs was investigated for the summertransmission system and was revealed to be more crucial than that of the winter transmission system not only because of the reduced short-circuit levels but the lesser loads as well.

It was noted that loads contribute to the damping of power-system oscillations.A critical contingency that influences the SVC interactions is the loss of twolines south of La Verendrye—the La Verendrye contingency.

The performance of SVCs is examined over a range of operating conditions spanning the zerooutput to the maximum capacitive output. The SVC voltage regulator is modeledby the gain–time-constant representation: the gain is the inverse of theSVC slope, whereas the time constant is the response rate. On the ac side of the SVC measurement systems are notch filters (80 Hz and 96 Hz) to counteract network resonances;

On the dc side are low-pass and harmonic-notch filters to obtain the pure dc equivalent of the SVC bus voltage. The interaction between SVC controllers is examined through both Eigenvalue analysis and the simulationof transients by using EMTP.

The response to small-reactor switching for the La Verendrye contingency, The initial conditions were selected as those likelyto occur 30 cycles after this contingency. Increasing oscillations of 16-Hz frequency are noticed in the transient response because of the adverse interaction

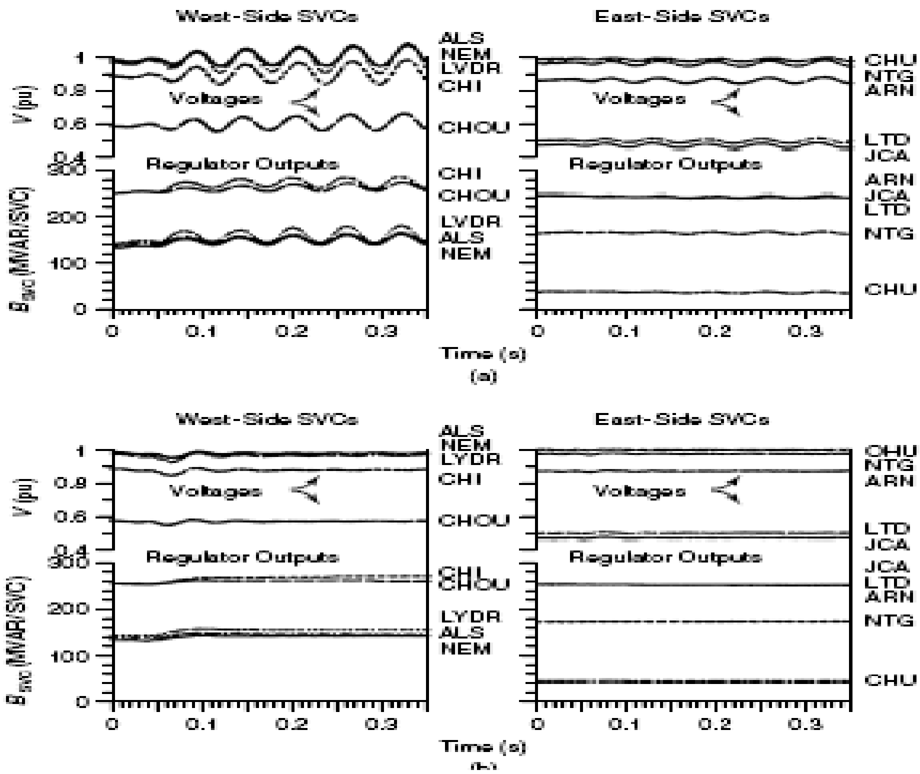


Figure 9 The SVC transient behavior in La Verendrye system due to "snapshot"reactor switching at Abitibi.

(a) The existing SVC response rate (Tr c 0.133 s) and

(b) The reduced SVC response rate (Tr c 0.5 s). Between the fast SVC controllers.

An increase in the regulator time constant (the slowing down of the SVC) from 0.133 s to 0.5 s stabilizes the response as depicted in Fig.9(b)—an activity that is also clearly revealed from the rootloci of critical modes with varying controller-response rates, Tr, as shown inbelow In the figure, the 16-Hz mode is unstable for Tr c 0.133 s (symbol2) but stable for Tr c 0.5 s (symbol 4).

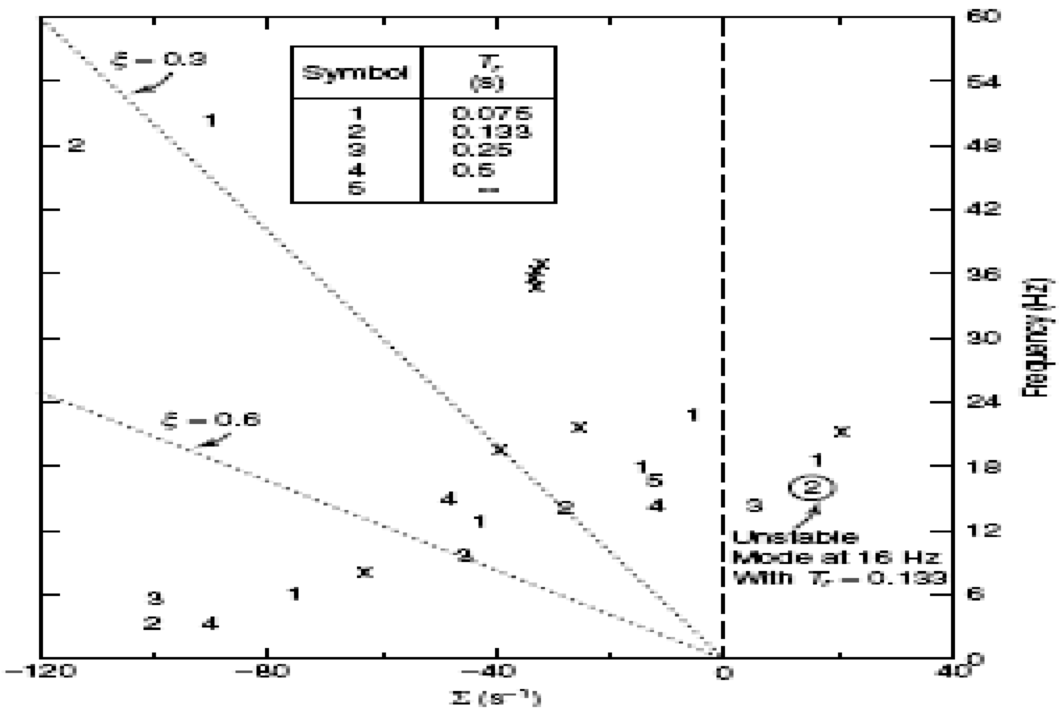


Figure 10 The effect of the SVC response rate on system eigenvalues in LaVerendrye system stimulated by reactor switching at Abitibi.

Although Fig. 10 illustrates the root loci for a general operating point, Fig.11 illustrates the loci for an operating point with highly capacitive SVCs (280MVAR□□SVC). The system in Fig. 11 is unstable, even with greatly slowed SVCs (Tr c 0.5 s), and clearly represents the worst-case scenario. To alleviate this condition, gain supervisors need to be installed on the SVCs .These, however, are not without problems; even though they slow the response rate of the relevant SVCs to stabilize the oscillations, the damping of the oscillations is very low, causing an altogether poor system response after the peak of the first major system swing.

This low-damping oscillation can be resolved onlyby the selective tripping of certain SVCs, for which, again, an elaborate evaluationof all likely contingencies must be performed and the tripping sequencesdeveloped. Obviously, therefore, a completely shunt-compensated system is not desirable from the viewpoint of voltage-regulator

The System With Series Compensation:

The main problem with multiple SVCs is the presence of large shunt capacitance to the network. This capacitance interacts with the network reactance, creating a shunt-capacitance-resonant mode that, after demodulation through the measurement system, interacts adversely with the voltage-regulator mode. It is therefore desirable to series-compensate the network and use a smaller number of SVCs. for a proposed alternative Hydro-Quebec system that is mostly series-compensated. All major 735-kV lines are assumed to be 30–40% series-compensated, and a total of 13 SVCs are placed in the system.

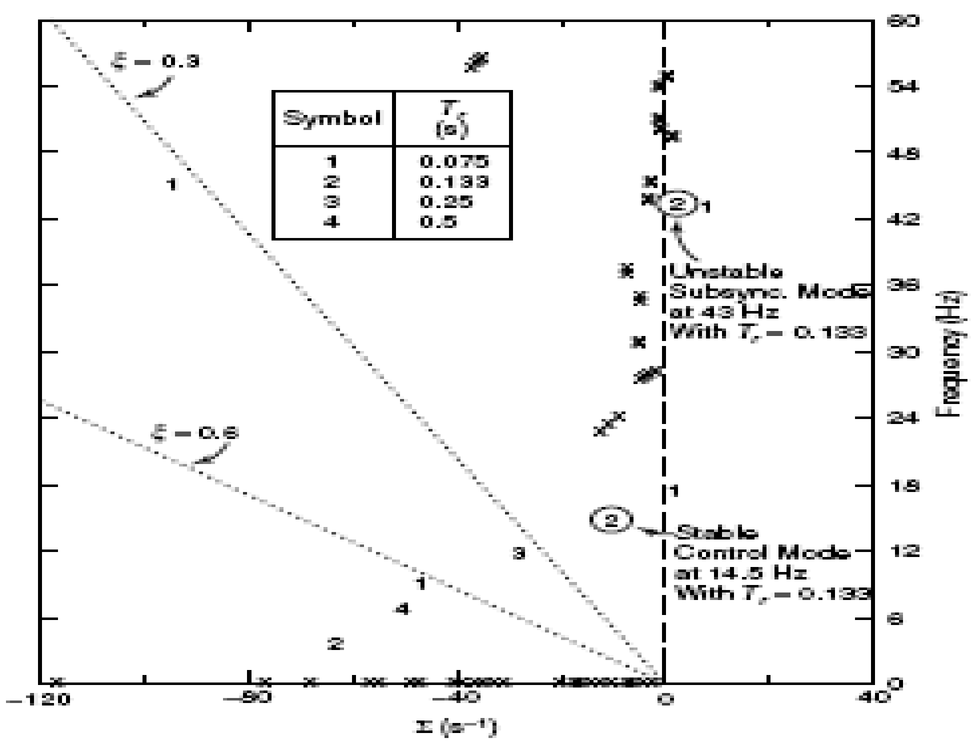


Figure 11 The effect of the SVC response rate on system Eigen values for a mostlyseries-compensated system due to a 2-line loss south of La Verendrye.

The root loci for this system, corresponding to the La Verendrye contingency,are illustrated in Fig. 13. Because of the reduced shunt capacitance, with asmaller number of SVCs and a lowered line reactance from series compensation, the shunt-capacitance-resonant mode shifts to a higher mode frequency of 83 Hz that, following the demodulation effect of the measurement system, appears as a 83 − 60 c 23 Hz component that has much less interaction withthe basic SVC voltage–regulator mode.

In the totally shunt-compensated system, the shunt-capacitance mode is of 77 Hz, which in Fig. 10 appeared as 77 − 60 Hz c 17 Hz in the root loci and was indicated as 0.5 (Tr c ∞, i.e., no regulator response).As with the case in Fig. 10, that of Fig. 13 must also have its SVC response rate lowered to ensure voltage-regulator stability. This reduction, however, need not be of the same extent; for instance, reducing the SVC response rate from 0.133 s to 0.25 s stabilizes the overall system.

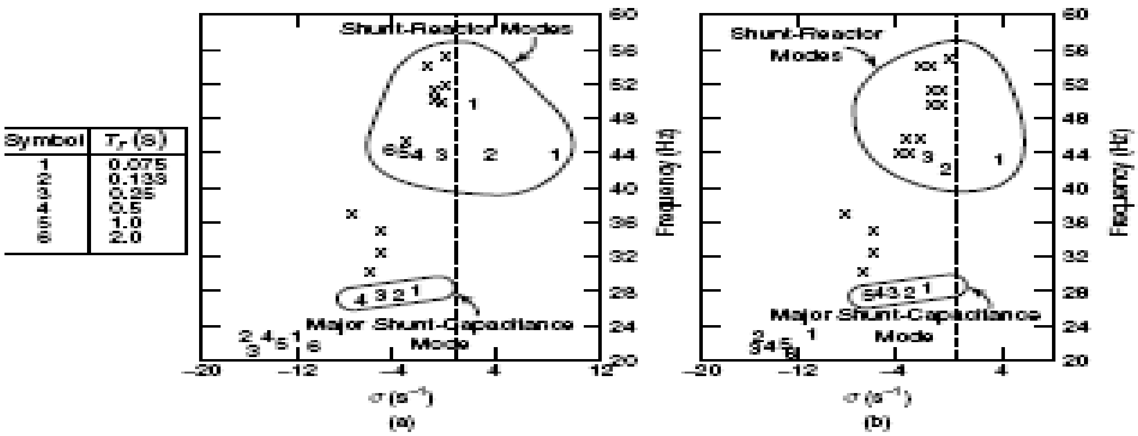
Shunt-Reactor Resonance:

If shunt reactors are present in thesystem (which they usually are), the series compensation of the transmission line introduces additional resonant modes from the interaction of series capacitancewith the inductance of shunt inductors.

These modes are visible in the driving-point-impedance plots, as seen from the different SVC locations depicted and usually lie in the range of 0–20 Hz. For the study system, three major modes are indicated at 6 Hz, 9 Hz, and 17 Hz, the magnitudes of which vary with location. Also, these modes are associated with substantially low damping because of the very small line resistance and the high Q-factor of shunt reactors.

In the root loci ofthe 17-Hz shunt-reactor-resonant mode is reflected as its 60-Hz complement, that is, 43 Hz (60 Hz − 17 Hz), again fromthe demodulation process in the measurement system. As the SVC response rate is increased (by reducing Tr), these modes become unstable.

The adverse interaction between SVCs and the shunt-reactor modes can beminimized by installing a high-pass filter with a cutoff frequency of typically 15–20 Hz on the ac-side measurement circuit. The root loci with and without a 15-Hz high-pass filter for the study system is illustrated inIt is



(a) With no high-pass filter and

(b) With a 15-Hz high-pass filter.

Evident that without the filter, the system would be barely stable for a responserate Tr c 0.25 s; however, it achieves a reasonably high damping with the filter.

The transient time responses of the system with and without the 15-Hz filter are illustrated in Fig.5.16, which confirm the observations from root loci. Theshunt-reactor mode is evidenced in the high-frequency (40–50 Hz) oscillations in the time responses.

The cutoff frequency of the high-pass filters is obtained as a trade-off between the stability of low-frequency modes and that of the shunt-reactor modes. The reason is that when the cutoff frequency is increased to stabilize the shunt-reactor modes, some lower-frequency modes become undamped.

High-Frequency Interactions:

An example of high-frequency control interaction between two SVCs in thesame electrical area Figure17 depicts the study system comprising two SVCs each rated +30 to −70 MVAR and operating on the voltage-control mode. Because high-frequency interactions are being analyzed, it may be noted that the transmission lines are represented as p sections.

The total system is modeled by 78 state variables.To analyze the control interaction, one SVC is modeled in detail using the generalized-switching-functions approach while the second SVC is represented by a passive equivalent network with same reactivepower. consumption at the operating point under consideration. In Fig. 18,the equivalent system used for the control design of SVC 1 is shown.

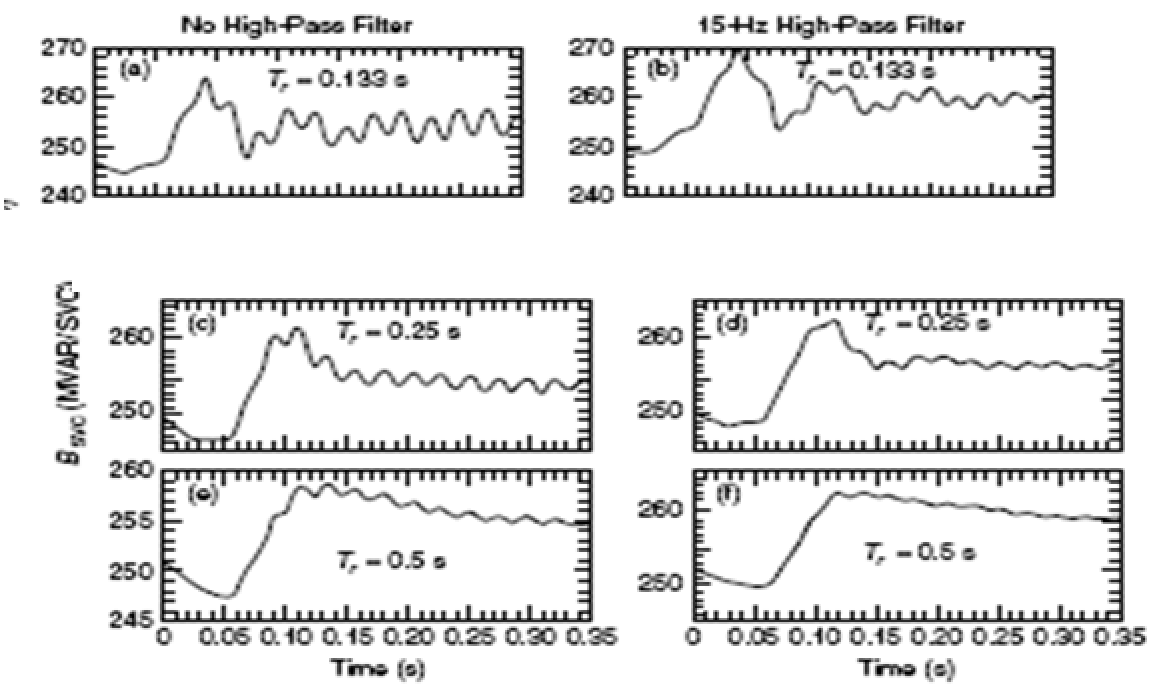


Figure 12 The SVC transient in a series-compensated system due to the SVCresponse rate and the high-pass filter (the regulator output is at Chibougamau).

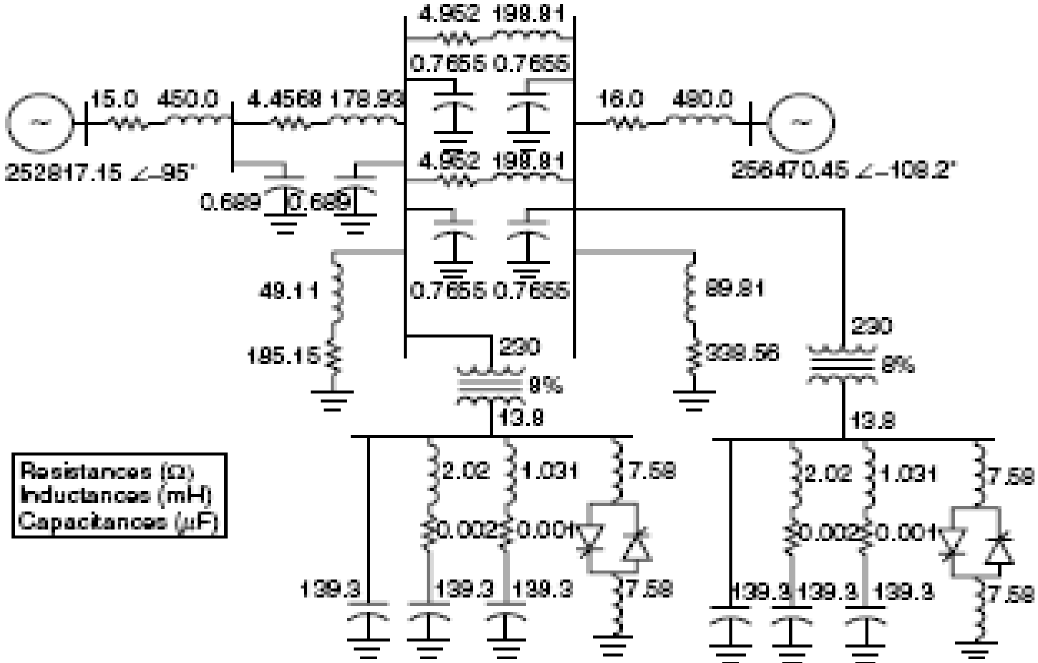
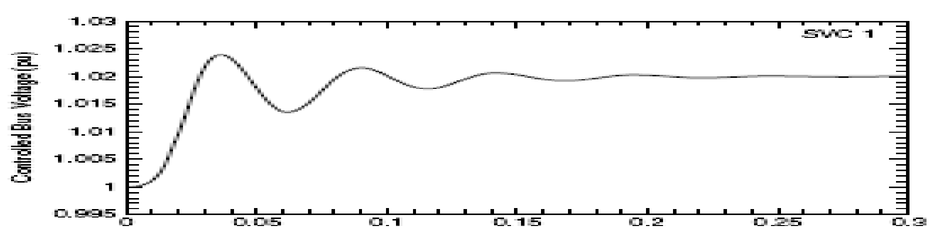


Figure 13A study systems for the analysis of high-frequency interaction between SVCs.

The SVC controller is designed to give an acceptable rise, overshoot, and settlingtimes. Eigenvalue analysis reveals that the dominant oscillation mode has anEigen value of SVC

$$\lambda_{SVC\,1}\ (= \sigma + j2\pi f) = -19 \pm j119.7.$$

This mode constitutes an oscillation of frequency 19.1 Hz in SVC 1's response to a 2% step in the reference-voltage input, as shown in Fig. 19. The system simulation is performed using a nonlinear switching function–based EMTP-type simulation.



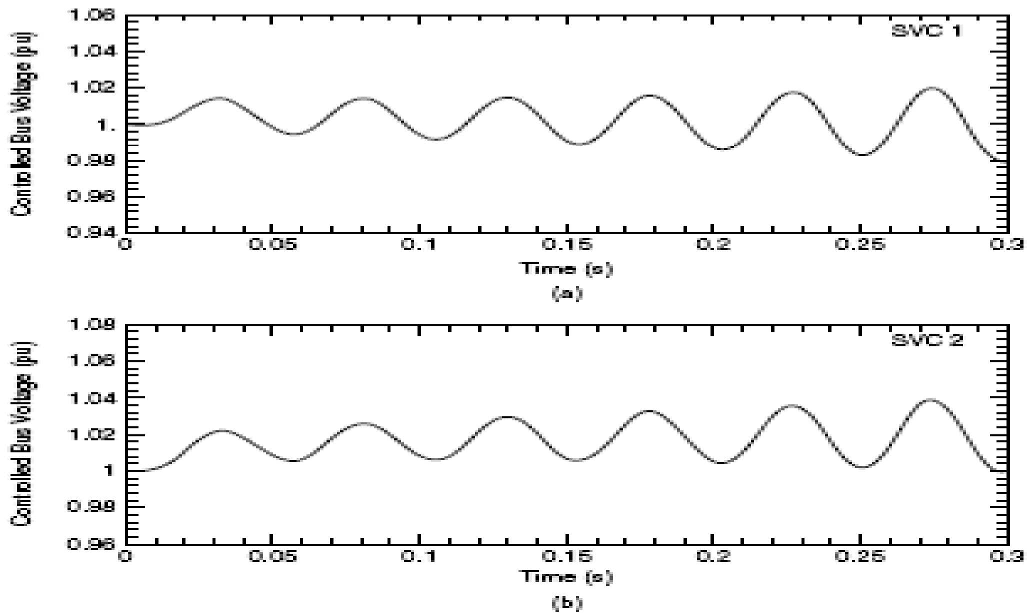


Figure 14 The response of independently designed SVCs to a step input in the referencevoltage of SVC 2.responses when a 2% step input is applied to the reference voltage of SVC 2,as depicted .

This phenomenon clearly illustrates the adverse high-frequency interactionbetween the two independently designed SVC controllers, and brings out theneed for a coordinated control design of the two SVCs.

A high-frequency Eigenvalueanalysis program is employed, and the gains of both SVC controllers areadjusted simultaneously to stabilize the unstable mode. The response of both SVCs to a 2% reference step in SVC 2 is presented in Fig. This response is rapid as well as stable.

6. Discuss the coordination of multiple controllers usinglinear-control techniques for power flow control application?(Nov/Dec-2012),(April/May-2011) ,(June-2011),(Nov/Dec-2015)

The essential design features of multiple FACTS controllers that can ensuresecure operation with sufficient damping over a wide range of power-systemoperating conditions are discussed elaborately .The term coordinationdoes not imply centralized control; rather, it implies the simultaneous tuning

of the controllers to attain an effective, positive improvement of the overallcontrol 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:

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

Derivation of the System Model:

First, a reduced-order nonlinearsystemmodel must be derived for the original power system. 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 itenable to the application of linear-control design techniques. If a controllermust be designed for damping electromechanical oscillations, a further reducedlinearmodel is selectedthat 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.

Enumeration of the System-Performance Specifications:

Thedamping controller is expected to satisfy the following criteria

1. It should help the system survive the first few oscillations after a severe system disturbance with an adequate safety margin. This safety factor isusually specified in terms of bus-voltage levels that should not be violatedafter a disturbance.

2. A minimum level of damping must be ensured in the steady state after adisturbance.

3. Potentially deleterious interactions with other installed controls should beavoided or minimized.

4. Desired objectives over a wide range of system-operating conditionsshould be met (i.e., it should be robust).

Selection of the Measurement and Control Signals:

The choiceof 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 minimallyaffect the other system modes. The selection of these signals is usually basedon system-modal magnitudes, shapes, and sensitivities—all of which can beobtained from small-signal-stability analysis.

Controller Design and Coordination :

The FACTS controllerstructures 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 leadlagblock, 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 precedingtext, 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 widerange of operating conditions.The coordination techniques may use linearized models of the power systemand other embedded equipments, capitalizing on the existing sparsity in systemrepresentation. This model may be further reduced by eliminating certain algebraic variables yet still retaining the essential system behavior in the frequencyrange 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 Eigenvalueanalysis of a selected region can be performed even for relatively largerpower systems.In the case of large systems, procedures are employed that automate the tuning and coordination of controllers.

Validation of the Design and Performance Evaluation :

Eventhough 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.

7. Describe the following Linear Control Techniques used for coordination of multiple FACTS controllers.(May 2015)

(i) Linear Quadratic Regulator(LQR).

(ii) Genetic Algorithm.

(i) Linear Quadratic Regulator(LQR).

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-feed- back 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 con- troller and the number of independent measurements influence the number of modes to be retained. The output-feedback solution results in the desired coor- dinated 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) Genetic 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, decentral- ized 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 oper- ating conditions to introduce robustness. A minimum damping level is specified for all the modes; the other constraints include limits on the gain and time con- stants 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

$$F = \sum_{i=1}^{m} \left[\sum_{j=1}^{n} (\xi_i) \right] \tag{9.10}$$

subject to the following constraints:

$$\begin{aligned} k_{j\,\min} &\le k_j \le k_{j\,\max} \\ \tau_{1\,\min} &\le \tau_1 \le \tau_{1\,\max} \\ \tau_{2\,\min} &\le \tau_2 \le \tau_{2\,\max} \\ \xi_{\min} &\le (\xi_j)_i \end{aligned} \tag{9.11}$$

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

16 Marks:

1. List the Types of Various controller interactions? **(pg:5)**

2. Write short notes on Steady-State Interactions in co-ordination of FACTS controller?**(pg:5)**

3. List the various types of Oscillation interaction in FACTS controller?(**pg:6)**

4. Briefly explain the frequency response of facts controllers? **(pg:7)**

5. Investigate the SVC-SVC controller interaction in a large power system?(**Nov/Dec-2012), June-2011),(April/May-2011)(pg:9)**

6. Discuss the coordination of multiple controllers using linear-control techniques for power flow control application?(**Nov/Dec-2012),(April/May-2011) ,(June-2011),(Nov/Dec-2010) (pg:20)**

Reg. No. : [ ][ ][ ][ ][ ][ ][ ][ ][ ][ ][ ][ ]

Question Paper Code : 91432

B.E./B.Tech. DEGREE EXAMINATION, NOVEMBER/DECEMBER 2014.

Eighth Semester

Electrical and Electronics Engineering

EE 2036/EE 809/10133 EEE 45 — FLEXIBLE AC TRANSMISSION SYSTEMS

(Regulation 2008/2010)

(Common to PTEE 2036 – Flexible AC Transmission Systems for B.E. (Part-Time) Seventh Semester – EEE – Regulation 2009)

Time : Three hours

Maximum : 100 marks

Answer ALL questions.

PART A — (10 × 2 = 20 marks)

1. What are the applications of FACTS devices?

2. Define Reactive Power.

3. Compute $\frac{X_{TCSC}}{X_C}$ and $\frac{I_{TCR}}{I_L}$ if

   (a) $X_{TCR} = 1.5 X_C$ and

   (b) $X_{TCR} = 0.75 X_C$.

4. What are the objectives of Static VAR?

5. What are the methods for protection against over voltage?

6. Define Transient stability control.

7. Define Linear Loads.

8. Define UPFC.

9. Draw the control characteristics of SVC.

10. Draw the Power Angle Curve of SVC.

PART B — (5 × 16 = 80 marks)

11. (a) Explain Uncompensated Transmission Line.

Or

(b) Explain Shunt and Series Compensation Line.

12. (a) Derive the Voltage and Power expression in SVC.

Or

(b) Explain prevention of voltage instability.

13. (a) Explain the operation of TCSC.

Or

(b) Derive the expression of TCSC for the time interval $(-\beta \leq wt \leq \beta)$.

14. (a) Explain the protection of UPFC.

Or

(b) Derive the expression of UPFC connected at the midpoint.

15. (a) Explain Linear Co-ordination technique.

Or

(b) Explain Quantitative Treatment in FACTS controller.

Reg. No. | | | | | | | | | | | | |

Question Paper Code : 71495

B.E./B.Tech. DEGREE EXAMINATION, APRIL/MAY 2015.

Eighth Semester

Electrical and Electronics Engineering

EE 2036/EE 809/10133 EEE 45 – FLEXIBLE AC TRANSMISSION SYSTEMS

(Regulation 2008/2010)

(Common to PTEE 2036 – Flexible AC Transmission Systems for B.E. (Part-Time) Seventh Semester – EEE – Regulation 2009)

Time : Three hours Maximum : 100 marks

Answer ALL questions.

PART A — (10 × 2 = 20 marks)

1. What are the two main reasons for incorporating FACTS devices in electric power systems?

2. State the features of Interline Power Flow Controller (IPFC).

3. What are the three basic modes of SVC control?

4. How is voltage instability identified in a power system?

5. State any two advantages of TCSC.

6. What are the functions of damping control of a TCSC?

7. List any two power system performances that can be improved by STATCOM.

8. Write the applications of UPFC.

9. What is the main problem with multiple SVCs in a power system network?

10. What is the significance of 'modal-performance index'?

PART B — (5 × 16 = 80 marks)

11. (a) (i) Explain briefly about load compensation. (4)

(ii) What are the objectives of line compensation? Explain the effect of shunt and series compensation on power transmission capacity of a short symmetrical transmission line. (12)

Or

(b) Describe the working principle of the two types of Static Var Compensator (SVC) with neat schematic diagrams. (8+8)

12. (a) (i) State and explain the advantages of slope in the dynamic characteristics of SVC. (8)

(ii) Explain the influence of SVC on regulating the AC system voltage for the following two cases: (4+4)

(1) Coupling transformer ignored

(2) Coupling transformer considered.

Or

(b) Explain in detail about the role of SVC in enhancing the steady state power limit and power system damping. (6+10)

13. (a) Draw the basic and practical TCSC modules. Explain the basic principle and different modes of operation of TCSC. (2+4+10)

Or

(b) Draw and explain the block diagram of the variable reactance model of TCSC and hence derive transient stability and long term stability models. (8+8)

14. (a) With neat sketches, explain the operating principle and the V-I characteristic of Static Synchronous Compensator (STATCOM). (8+8)

Or

(b) (i) Draw the phasor diagrams illustrating the concepts of various power-flow control functions by use of UPFC. (4)

(ii) Explain the modeling procedure of UPFC for power-flow studies. (12)

15. (a) What is the need for coordination of different FACTS controllers? Explain the different control interactions that are occurring in multiple FACTS controllers. (2+14)

Or

(b) Describe the following linear control techniques used for coordination of multiple FACTS controllers: (4+6+6)

(i) Linear Quadratic Regulator (LQR) based technique

(ii) Global coordination using non-linear-constrained optimization

(iii) Control coordination using Genetic Algorithms.

Reg. No. : | | | | | | | | | | | | |

Question Paper Code : 51429

B.E./B.Tech. DEGREE EXAMINATION, APRIL 2014.

Eighth Semester

Electrical and Electronics Engineering

EE 2036/EE 809/10133 EEE 45 — FLEXIBLE AC TRANSMISSION SYSTEMS

(Regulation 2008)

Time : Three hours Maximum : 100 marks

Answer ALL questions.

PART A — ($10 \times 2 = 20$ marks)

1. What are the two main reasons for incorporating FACTS devices in electric power systems?
2. What is meant by Thyristor Switched Series Capacitor (TCSC)?
3. Define 'Effective Short Circuit Ratio (ESCR)' of SVC.
4. What are the factors that limit the power-transfer capacity of a transmission line?
5. Mention the disadvantages of fixed series compensation of transmission lines.
6. What are the functions of damping control of a TCSC?
7. List any two performances of power system that can be improved by STATCOM.
8. State the basic UPFC power flow control functions.
9. What is the need for coordination of different FACTS controllers?
10. Why is it necessary to series-compensate a power system network with multiple SVCs?

PART B — ($5 \times 16 = 80$ marks)

11. (a) (i) Give the complete analysis of lossless distributed parameter transmission lines and derive power equations for symmetrical case. (12)

(ii) Write a brief note on IPFC. (4)

Or

(b) (i) What are the objectives of line compensation? Explain the effect of shunt and series compensation on power transmission capacity of a short symmetrical transmission line. (12)

(ii) List the advantages of SVCs. (4)

12. (a) (i) Write the advantages of the slope in the dynamic characteristics of SVC and comment on the reason for slope. (8)

(ii) With a case study, explain how an SVC can be used to prevent voltage instability in a power system. (8)

Or

(b) (i) Explain how an SVC can be used to enhance the steady-state power transfer capacity of a transmission line. (8)

(ii) Using power angle curves, explain how SVC enhances transient stability of a power system. (8)

13. (a) What are the advantages of TCSC? Explain the different modes of operation of TCSC. (6 + 10)

Or

(b) With a neat block diagram, explain the variable reactance model of the TCSC and derive transient stability and long-term stability models.

14. (a) Explain the principle of operation and V-I characteristics of STATCOM. (16)

Or

(b) (i) Draw the configuration of UPFC implementation using two 'back-to-back' connected voltage sourced converters with a common DC link. (4)

(ii) Explain the steady-state UPFC model for power flow studies. (12)

15. (a) Explain the various kinds of control interactions occuring between different FACTS controllers using their frequency response characteristics. (16)

Or

(b) Describe the following linear control techniques used for coordination of control of different FACTS controllers. (4 + 6 +6)

(i) Linear Quadratic Regulator (LQR)-based technique

(ii) Global coordination using nonlinear-constrained optimization.

(iii) Control coordination using Genetic Algorithms.