EE6004 FLEXIBLE AC TRANSMISSIONSYSTEMS

UNIT I

INTRODUCTION

Reactive power control in electrical power transmission lines -Uncompensated transmission line – series compensation – Basic concepts of Static Var Compensator (SVC) – Thyristor Controlled Series capacitor (TCSC) – Unified power flow controller (UPFC).

1. Reactive power control in electrical power transmission lines

1.1 Reactive Power

- When an AC system is energized the networks and the devices connected to them create
    - Time-varying electrical fields related to the applied voltage
    - Magnetic fields related to the current flow.
- When they build up, these fields store energy that is released when they collapse.
- The energy dissipation occurs in resistive components, transformers, generators and motors.
- They operate based on their capacity to store and release energy.

In an ac circuit the instantaneous power is given by, $P = VI$ (1.1)

Under steady state condition, $V = V_{max}Cos(\omega t)$ (1.2)

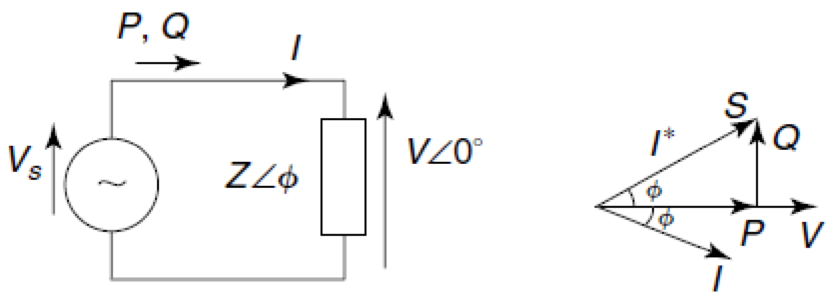
$$I = I_{max}\cos(\omega t - \varphi) \quad (1.3)$$

Now,

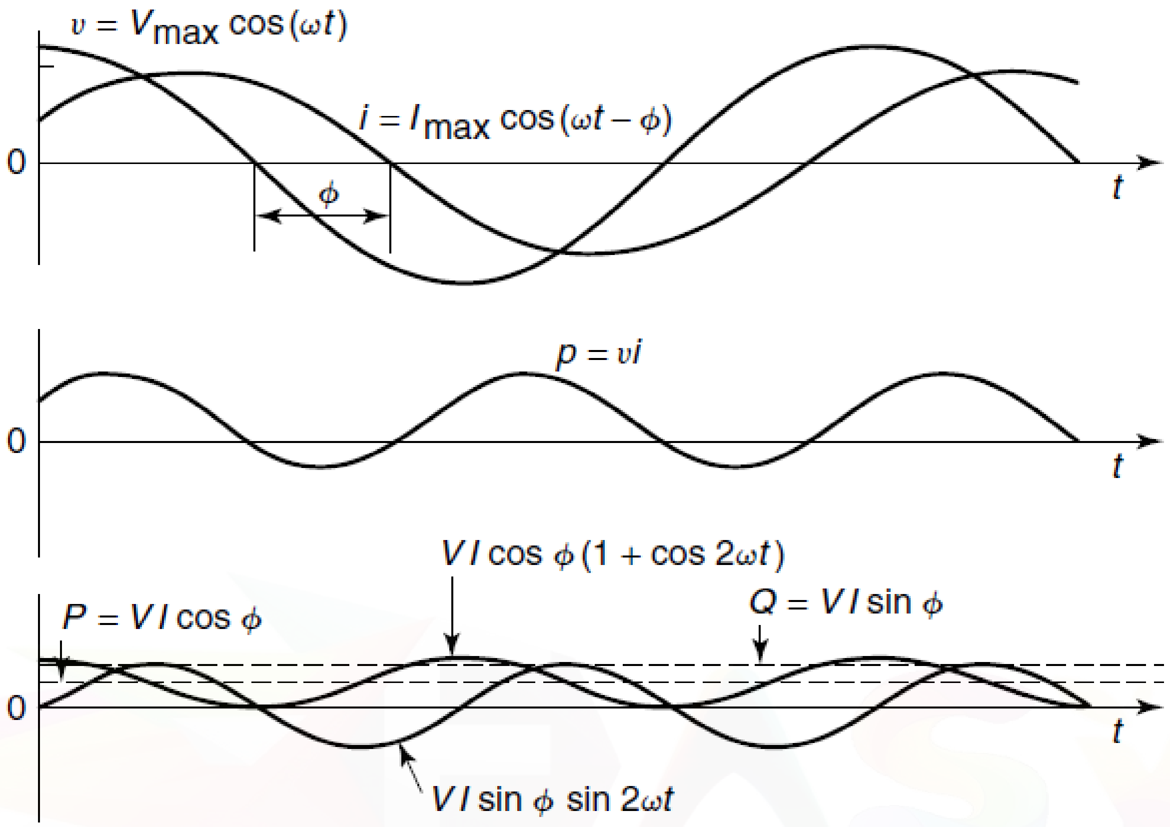
$$P = \frac{V_{max}I_{max}}{2}(\cos(\emptyset + \cos(2\omega t - \varphi))$$

$$= VrmsIrms\cos\varphi(1 + \cos2\omega t) + VrmsIrmssin\varphi sin2\omega t$$

The equation has two double frequency components. The first term has an average value as well as a peak magnitude of VrmsIrms cosφ which is the active power flowing from the source to the load. The average value of the second term is zero and its peak value is VrmsIrms sinφ , which is the reactive power.



The complex power, $S = VI^* = P + jQ = VrmsIrmsCos\varphi + jVrmsIrmsSin\varphi$ (1.4)



1.1.1 Need of reactive power

i. To create coupling fields for energy devices.

ii. It is an important component in all ac networks which constitutes the voltage and current loading of circuits.

1.1.2 Generation and Absorption of reactive power

- The electromagnetic devices absorb reactive power as they store energy in their magnetic fields. They draw lagging current as they absorb reactive power.
- The electrostatic devices generate reactive power as they store electric energy in fields. They draw leading current as they generate reactive power.

2. Uncompensated Transmission Line

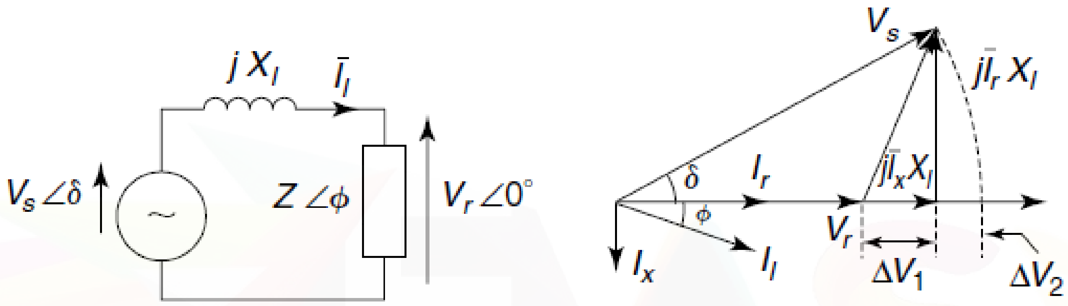
In transmission lines, a magnitude variation and phase difference is caused between the sending and receiving voltages. The deviation due to the voltage drop in the line reactance is due to the reactive power component of the load current.

The voltage in the line can be maintained by:

- Load Compensation
- System Compensation

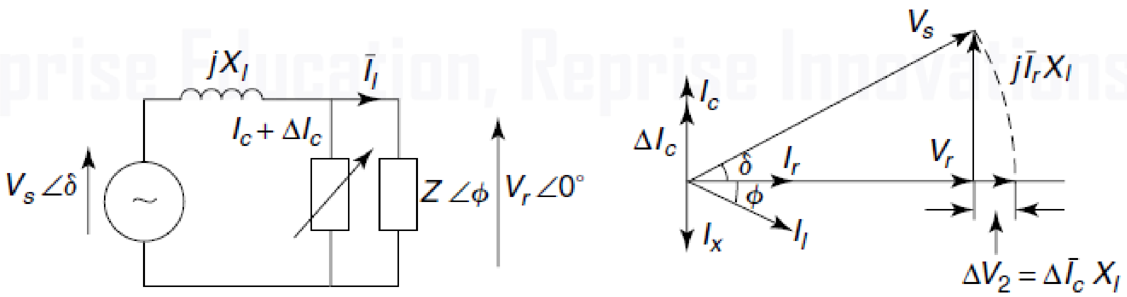
2.1 Load Compensation

- In Load compensation, the reactive power current can be compensated by adding a parallel capacitive load such that, $I_c = I_x$, where Ic is the capactive current and Ix is the reactive component of the load current.
- The addition of parallel capacitive load leads to unity power factor.
- The Ix is eliminated which makes voltage drop zero.
- Now the receiving end voltage is equal to the sending end voltage.
- Load compensation reduces the line drop but donot eliminate.



2.2 System compensation

- The power utility installs reactive power compensators and regulates the receiving end voltage; it is called as System Compensation.
- The system compensator draws reactive current to overcome the voltage drop and the consequence of load current through the line reactance.
- The System compensation is done to ensure the power quality in the system.



2.3 Lossless Distributed parameter Lines

- The transmission lines are characterized based on the series resistance, series inducatance, shunt conductance and shunt capacitance.
- The behavior of the transmission line is dominated by the series inducatance and shunt capacitance.
- The loss in the transmission line is based on the series resistance and shunt conductance.

- The voltage and Current equations of the transmission line is given by:

$$\bar{V}(x) = \bar{V}_s\cos\beta x - jZ_0\bar{I}_s\sin\beta x \qquad (1.5)$$

$$\bar{I}(x) = \bar{I}_s\cos\beta x - j\frac{\bar{V}_s}{Z_0}\sin\beta x \qquad (1.6)$$

Where, x - distance from the sending end

Z_0 - $\sqrt{\frac{l}{c}}$,surge impedance (SIL) or characteristic impedance

β - $\omega\sqrt{lc}$,wave number in rad/ km

βa - Electrical length of an a km line

From 1.5 and 1.6, The sending end current, $\bar{I}_s = \frac{\bar{V}_s\cos\beta a - \bar{V}_r}{jZ_0\sin\beta x}$ (1.7)

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

$$\bar{I}_s = \frac{\bar{V}_s\cos\beta a - V_r(\cos\delta - j\sin\delta)}{jZ_0\sin\beta x} = \frac{V_r\sin\delta + j(V_r\cos\delta - V_s\cos\beta a)}{Z_0\sin\beta a} \qquad (1.8)$$

The power at the sending end, $S_s = P_s + jQ_s = \overline{V_s I_s^*} = \frac{V_sV_r\sin\delta + j(V_s^2\cos\beta a - V_sV_r\cos\delta)}{Z_0\sin\beta a}$ (1.9)

Similarly the power at the receiving end,

$$S_r = P_r + jQ_r = -\frac{V_sV_r\sin\delta + j(V_r^2\cos\beta a - V_sV_r\cos\delta)}{Z_0\sin\beta a} \qquad (1.10)$$

From equation 1.9 and 1.10, for a loss less line,

i. $P_s = -P_r$ (1.11)

ii. $Q_s \neq Q_r$, due to the generation and absorption of reactive power. (1.12)

iii. The real power flow in the transmission line, $P = \frac{V_sV_r\sin\delta}{Z_0\sin\beta a}$ (1.13)

In short transmission lines,

$$P = \frac{V_sV_r\sin\delta}{X_l} \text{ (since } Z_0\sin\beta a = Z_0\beta a = \omega la = X_l) \qquad (1.14)$$

iv. The maximum power transfer is dependant on the line length, therefore for long transmission the value of V_s and V_r should be high.

2.4 Symmetrical Lines

- When the sending end voltage and the receiving end voltages are same, the line is said to be symmetrical (i.e) $V_s = V_r = V$
- From equation 1.11, $P_s = -P_r = \frac{V^2\sin\delta}{Z_0\sin\beta a}$ (1.15)
- From equation 1.12, $Q_s = Q_r = \frac{V^2\cos\beta a - V^2\cos\delta}{Z_0\sin\beta a}$ (1.16)
- The value of P_s and Q_s are normalized by choosing the SIL as the base

Surge Impedance Loading (SIL), $P_0 = \frac{V_{nom}^2}{Z_0}$, $V_{nom}$is the rated voltage

In symmetrical line, $V_s = V_r = V_{nom}$

$$\therefore \frac{P_s}{P_0} = -\frac{P_r}{P_0} = \frac{\sin\delta}{\sin\beta a} \quad \text{and} \quad \frac{Q_s}{Q_0} = \frac{Q_r}{Q_0} = \frac{\cos\delta}{\sin\beta a} \tag{1.17}$$

2.5 Midpoint condition of a symmetrical line

- The voltage variation at the midpoint of the transmission line is maximum in symmetrical lines. For a line splitted into two equal sections, the receiving end voltage is:

$$\overline{V_r} = \overline{V_m}\cos\frac{\beta a}{2} - jZ_0\overline{I_m}\sin\frac{\beta a}{2} \tag{1.18}$$

Where, V_m and I_m are the voltage and current at the midpoint.

- For symmetrical and lossless line,

$$P_s = -P_r = P_m = P$$

$$Q_m = 0$$

$$I_m = \frac{P}{V_m}$$

$$\therefore \overline{V_r} = \overline{V_m}\cos\frac{\beta a}{2} - jZ_0\frac{P}{V_m}\sin\frac{\beta a}{2}$$

$$\Rightarrow \quad {V_r}^2 = {V_m}^2\cos^2\frac{\beta a}{2} + {Z_0}^2\frac{P^2}{{V_m}^2}\sin^2\frac{\beta a}{2}$$

Setting, $V_r = V_{nom}$ and $\frac{{V_{nom}}^2}{Z_0} = P_0$

$$\Rightarrow \quad \frac{{V_r}^2}{{V_{nom}}^2} = \frac{{V_m}^2}{{V_{nom}}^2}\cos^2\frac{\beta a}{2} + \left(\frac{Z_0}{{V_{nom}}^2}\right)^2 P^2\frac{{V_{nom}}^2}{{V_m}^2}\sin^2\frac{\beta a}{2}$$

$$\Rightarrow \quad = \frac{{V_m}^2}{{V_{nom}}^2}\cos^2\frac{\beta a}{2} + \left(\frac{P}{P_0}^2\right)\frac{{V_{nom}}^2}{{V_m}^2}\sin^2\frac{\beta a}{2}$$

Let $\frac{V_m}{V_{nom}} = \widetilde{V_m}$ and $\frac{V_r}{V_{nom}} = 1$

$$\Rightarrow \quad 1 = \widetilde{V_m}^2\cos^2\frac{\beta a}{2} + \left(\frac{P}{P_0}^2\right)\frac{1}{\widetilde{V_m}^2}\sin^2\frac{\beta a}{2}$$

$$\Rightarrow \quad 1 = \frac{1}{\widetilde{V_m}^2}\left[\widetilde{V_m}^4\cos^2\frac{\beta a}{2} + \left(\frac{P}{P_0}^2\right)\sin^2\frac{\beta a}{2}\right]$$

$$\Rightarrow \quad \widetilde{V_m}^2 - \widetilde{V_m}^4\cos^2\frac{\beta a}{2} + \left(\frac{P}{P_0}^2\right)\sin^2\frac{\beta a}{2} = 0$$

$$\Rightarrow \quad \widetilde{V_m}^4 - \frac{\widetilde{V_m}^2}{\cos^2\frac{\beta a}{2}} + \frac{\left(\frac{P}{P_0}^2\right)\sin^2\frac{\beta a}{2}}{\cos^2\frac{\beta a}{2}} = 0$$

$$\Rightarrow \quad \widetilde{V_m}^4 - \frac{\widetilde{V_m}^2}{\cos^2\frac{\beta a}{2}} + \left(\frac{P}{P_0}^2\right)\tan^2\frac{\beta a}{2} = 0$$

$$\Rightarrow \widetilde{V_m} = \left[\frac{1}{2\cos^2\frac{\beta a}{2}} \pm \sqrt{\frac{1}{4\cos^2\frac{\beta a}{2}} - \left(\frac{P}{P_0}\right)^2 \tan^2\frac{\beta a}{2}}\right]^{1/2} \qquad (1.19)$$

2.6 Key considerations for compensation:

i. In long transmission line, under lightly loaded condition overvoltage occurs due to the line charging capacitance.

ii. The overvoltage can be limited by installing fixed or switched shunt reactors at the middle or end of the line.

iii. The power transfer capability is enhanced due to the var compensators.

iv. The var controllers have to be selected based on their continuous operating range to maintain the voltage within an acceptable range.

3. Passive Compensation

3.1 Compensation

- External devices or system that is connected to the transmission line to control the reactive power is called as a compensator.
- Reactive power control using compensators is called as compensation.
- When fixed inductors and/ or capacitors are employed to absorb or generate reactive power, it is called as passive compensation.
- Active compensation includes the active var control in which the reactive power is changed irrespective of terminal voltage.
- The compensator is used to reduce the severe effects of the system parameters.
- **Objectives of the compensation:**

  i. To increase the power transfer capability

  ii. To maintain the voltage profile in the line.

  iii. To ensure the quality of power.

  iv. To minimize the insulation cost.

  v. Improves the system stability
- The compensation is classified as:

  i. Shunt compensation

  ii. Series compensation

3.2 Shunt Compensation

- When shunt compensators are connected permanently or through a switch it is called as shunt compensation.

- Shunt compensators may be shunt reactors, shunt capacitors or combination of both.

3.2.1 Compensation using Shunt Reactor

- Shunt reactors compensate the line capacitance by which the over voltages are controlled.
- The shunt reactors may be gapped core reactors or air cored.

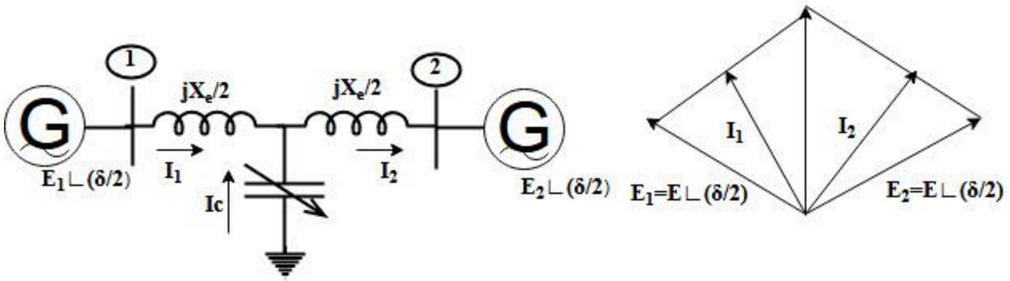
3.2.2 Compensation using Shunt capacitor

- Shunt capacitors are used to compensate the voltage drop in the line.
- The advantages are:
  i. It increases the power transfer capability.
  ii. Enhances the system stability
  iii. Improves the quality of power
- The disadvantages of shunt capacitor are:
  i. It creates higher frequency resonant circuits which lead to harmonic overvoltages.
  ii. Careful system design is required.
  iii. The location of the shunt capacitor is crucial.
  iv. May require circuit breakers

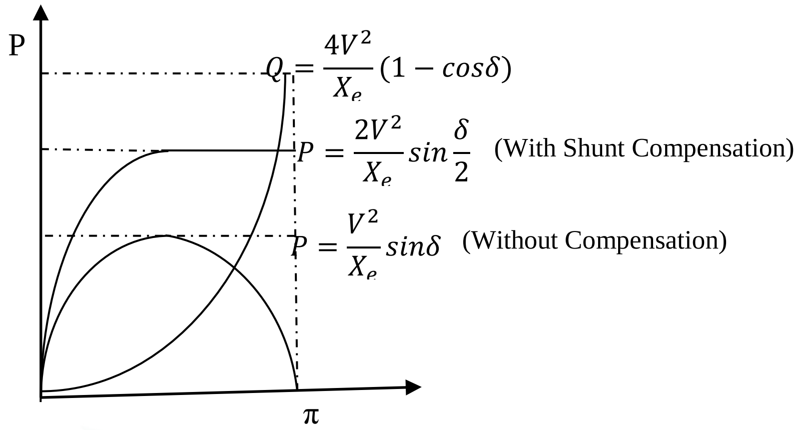
3.2.3 Shunt Compensation at the midpoint of the line

- The best location to maximize the power flow in the line is the midpoint of the transmission line.
- Assume that a shunt capacitor is connected at the midpoint of the transmission line.
- Let $V_s=V_r= V$ be the voltage magnitude, δ be the phase angle between the voltage magnitudes and Xe be the line reactance.
- With shunt compensation, the active power at bus 1 and bus 2 are equal.

$$P_1 = P_2 = \frac{2V^2}{X_e} sin\frac{\delta}{2} \qquad (1.20)$$

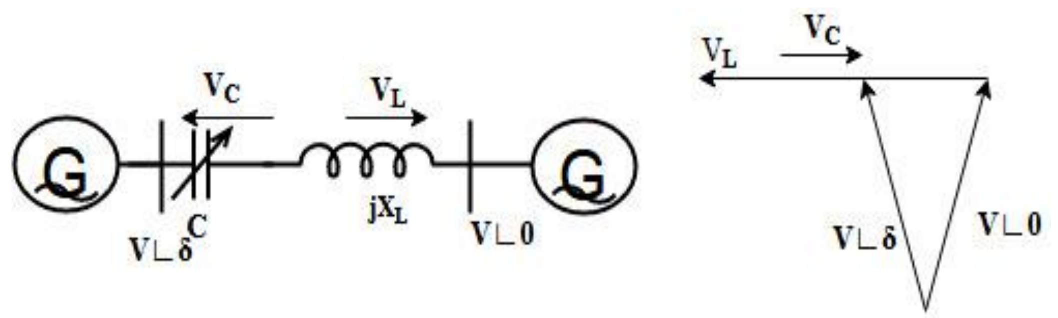


- The injected reactive power by the capacitor to regulate the voltage at the midpoint of the transmission line is: $Q = \frac{4V^2}{X_e}\left[1 - cos\frac{\delta}{2}\right]$ (1.21)



3.3 Series Compensation

- Series capacitors are used to balance the effect of series inductance in the line. It adds a voltage in opposition to the transmission line voltage drop, thereby reducing the series line impedance.
- The advantages are:
    - i. Improves the power transfer capability
    - ii. Higher stability margin
    - iii. The absorption of reactive power depends on the current flow, so automatically the reactive power compensation is adjusted.
    - iv. Net voltage drop is less
- The disadvantages are:
    - i. Makes the line resonant at sub-synchronous frequency.
    - ii. Both the ends of the capacitor should be insulated for the line voltages.
    - iii. Requires more protection and monitoring.
    - iv. Needs isolation and bypass arrangement.
- Factors to be considered in application are:
    - i. The voltage magnitude across the capacitor.
    - ii. The fault current at the terminals.
    - iii. Placement of shunt reactors in relation to the series capacitors.
    - iv. Number of capacitor banks and their location.
- Consider a simplified model of a transmission system with a series compensation,



The capacitance of C, $\mathrm{X_C} = \mathrm{kX_L}$ (1.22)

Where $k = \frac{\mathrm{X_C}}{X}$

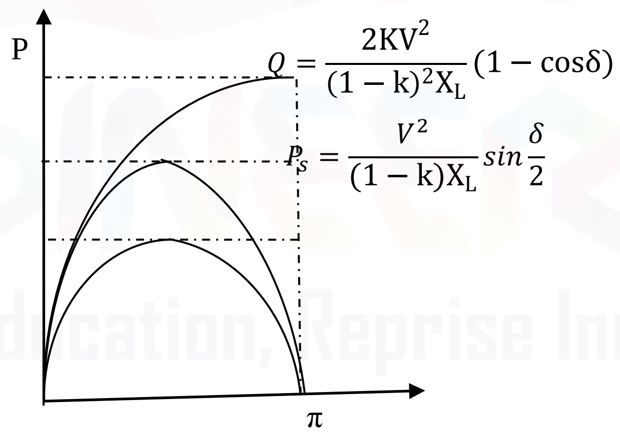
The resultant series inductance of the transmission line,

$$\mathrm{X} = \mathrm{X_L} - \mathrm{X_C} = (1-\mathrm{k})\mathrm{X_L} \tag{1.23}$$

The power transmitted is $\mathrm{P} = \frac{\mathrm{V}^2}{(1-\mathrm{k})\mathrm{X_L}}\sin\delta$ (1.24)

The reactive power supplied by the capacitor is, $Q_C = \frac{2\mathrm{V}^2}{(1-\mathrm{k})^2\mathrm{X_L}}(1-\cos\delta)$(1.25)

- The active power transmission depends on the value of k, when the value of k increases the active power transfer increases.

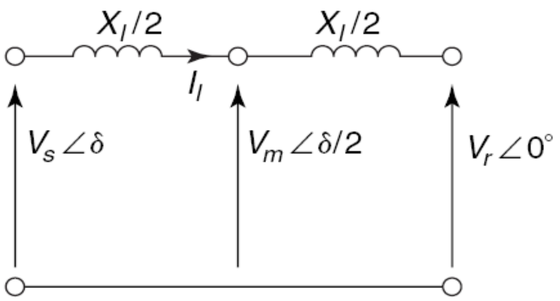


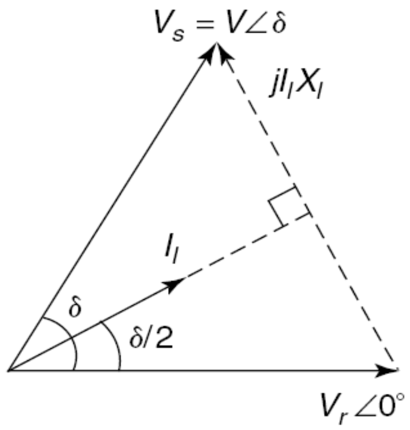
3.4 Influence of compensation on Power Transfer capability

- Consider a short, symmetrical and uncompensated line,

  Let Vs=V_r=V

$$\text{Power, } P = \frac{V^2}{X_L} sin\delta = 2\frac{V^2}{X_L} sin\frac{\delta}{2} cos\frac{\delta}{2} \tag{1.26}$$





From the phasor diagram and the voltage-phasor equation,

$$sin\frac{\delta}{2} = \frac{I_LX_L/_2}{V} = \frac{I_LX_L}{2V}$$

$$\Rightarrow \; I_L = 2\frac{V}{X_L}sin\frac{\delta}{2} \qquad (1.27)$$

$$\Rightarrow \; {I_L}^2 = 4\frac{V^2}{{X_L}^2}sin^2\frac{\delta}{2} \qquad (1.28)$$

3.4.1 Influence of series compensation on Power Transfer capability

- Consider a series capacitor is inserted,

  Let ΔX_L be the change in the line reactance due to the insertion of the series capacitor

  ΔI_L be the change in current

$$\frac{\Delta I_L}{\Delta X_L} = -2\frac{V}{{X_L}^2}sin\frac{\delta}{2} \qquad \text{since, } I_L = \frac{2V}{X_L}\sin\frac{\delta}{2}$$

$$\Rightarrow \; \Delta I_L = -2\frac{V}{{X_L}^2}sin\frac{\delta}{2}\,\Delta X_L = -I_L\frac{\Delta X_L}{X_L} \qquad (1.29)$$

From equation (1.26), $P = 2\frac{V^2}{X_L}sin\frac{\delta}{2}cos\frac{\delta}{2}$

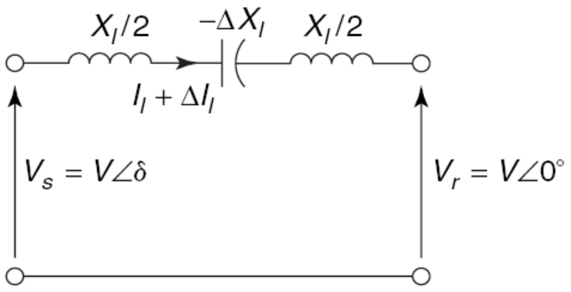
The change in power $\frac{\Delta P}{\Delta X_L} = -\frac{V^2}{{X_L}^2}2sin\frac{\delta}{2}cos\frac{\delta}{2}$

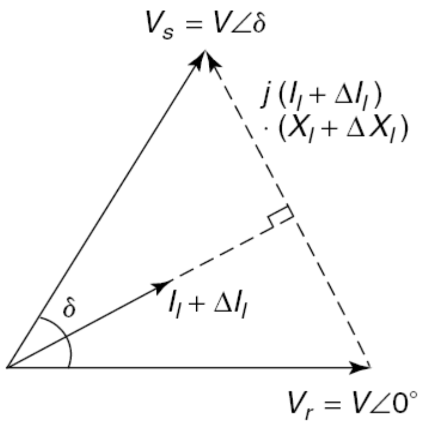
$$\Delta P = -\frac{4V^2}{2{X_L}^2}\frac{sin^2\frac{\delta}{2}}{sin\frac{\delta}{2}}cos\frac{\delta}{2}\Delta X_L$$

$$\Rightarrow \; \Delta P = -\frac{4V^2}{2{X_L}^2}\frac{sin^2\frac{\delta}{2}}{sin\frac{\delta}{2}}cos\frac{\delta}{2}\Delta X_L$$

$$\Rightarrow \; \Delta P = -\frac{\Delta X_L {I_L}^2}{2tan\frac{\delta}{2}}$$

$$\Rightarrow \; \Delta P = -\frac{\Delta Q_{se}}{2tan\frac{\delta}{2}} \qquad (1.30)$$





where, Q_{se} is the incremental var rating supplied by the series capacitor

$$\Rightarrow \frac{\Delta P}{\Delta Q_{se}} = -\frac{1}{2tan\frac{\delta}{2}} \tag{1.31}$$

3.4.1 Influence of Shunt compensation on Power Transfer capability

- Consider that a shunt capacitor is connected to the midpoint of the transmission line.
- The addition of the shunt capacitor increases the shunt susceptance by ΔB_C.
- The power transfer in terms of mid-point voltage, $P = \frac{V_s V_r}{X_L}\sin\delta = \frac{V_s V_m}{X_L/_2}\sin\frac{\delta}{2}$

$$\Rightarrow P = \frac{2VV_m}{X_L}\sin\frac{\delta}{2} \tag{1.32}$$

The differential change in power due to the change in voltageΔV_m,

$$\frac{\Delta P}{\Delta V_m} = \frac{2V}{X_L}\sin\frac{\delta}{2}$$

$$\Rightarrow \Delta P = \frac{2V\Delta V_m}{X_L}\sin\frac{\delta}{2} \tag{1.33}$$

The change in current, $\Delta I_C = V_m \Delta B_C$ (1.34)

The change in current leads to the change in line current in the sending and receiving end.

Sending end current, $\Delta I_S = I_l - \frac{\Delta I_C}{2}$ (1.35)

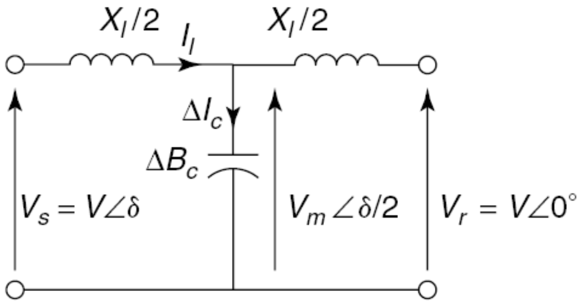
Receiving end current, $\Delta I_R = I_l + \frac{\Delta I_C}{2}$ (1.36)

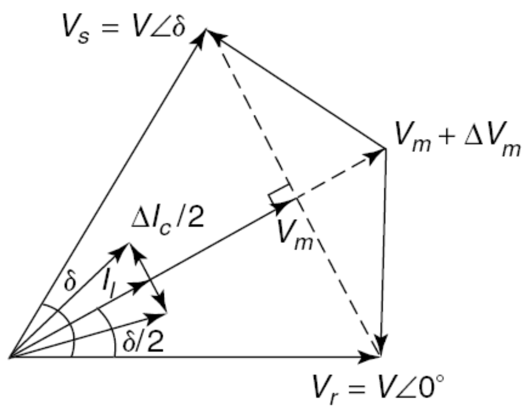
The voltage at the mid-point, $V_m = V_R + j\frac{I_R X_L}{2} = V_R + j\frac{\left(I_l + \frac{\Delta I_C}{2}\right)X_L}{2}$ (1.37)

The change in the mid-point voltage,

$$\Delta V_m = \frac{\Delta I_C X_L}{4} = \frac{V_m \Delta B_C X_L}{4} \text{(fromequation1.34)} \tag{1.38}$$

Substituting in equation (1.33), $\Delta P = \frac{2V}{X_L}\sin\frac{\delta}{2} \times \frac{V_m \Delta B_C X_L}{4} = \frac{VV_m}{2}\sin\frac{\delta}{2}\Delta B_C$ (1.39)





- From the phasor diagram, $\cos\frac{\delta}{2} = \frac{V_m}{V}$

$$\Rightarrow \; V_m = V\cos\frac{\delta}{2} \qquad (1.40)$$

$\therefore$ Equation (1.39) becomes, $\Delta P = \frac{VV\cos\frac{\delta}{2}}{2}\sin\frac{\delta}{2}\Delta B_C$ (1.41)

- The incremental var rating of the capacitor is, $Q_{sh} = {V_m}^2\Delta B_C$ (1.42)
- The incremental var rating supplied with respect to the shunt capacitor,

$$\frac{\Delta P}{\Delta Q_{sh}} = \frac{\frac{V^2\cos\frac{\delta}{2}}{2}\sin\frac{\delta}{2}\Delta B_C}{{V_m}^2\Delta B_C} = \frac{\frac{V^2\cos\frac{\delta}{2}}{2}\sin\frac{\delta}{2}\Delta B_C}{V^2\cos^2\frac{\delta}{2}\Delta B_C}$$

$$\Rightarrow \; \frac{\Delta P}{\Delta Q_{sh}} = \frac{\tan\frac{\delta}{2}}{2} \qquad (1.43)$$

3.4.2 Var net rating of the series compensator of that required of a shunt compensator

- Dividing equation (1.31) and (1.43), $\frac{\frac{\Delta P}{\Delta Q_{sh}}}{\frac{\Delta P}{\Delta Q_{se}}} = \frac{\frac{\tan\frac{\delta}{2}}{2}}{\frac{1}{2\tan\frac{\delta}{2}}}$

$$\Rightarrow \; \frac{\Delta Q_{se}}{\Delta Q_{sh}} = \tan^2\frac{\delta}{2} \qquad (1.44)$$

- When δ=30^0, $\frac{\Delta Q_{se}}{\Delta Q_{sh}} = 0.0717 = 0.072 = 7.2\%$

$$\Rightarrow \; \Delta Q_{se} = 7.2\% \text{ of } \Delta Q_{sh}$$

From this it is inferred that the var required for the series compensator is only 7.2% of that var required by a shunt compensator for the same change in power transfer.

3.5 Comparison of series and shunt compensation

S. No	Factor	Series Compensation	Shunt Compensation
1.	Power Transfer	High increase in power transfer	Less increase in power transfer
2.	Sub Synchronous Resonance	Danger of sub synchronous resonance exist	No danger of sub synchronous resonance
3.	Effectiveness	More effective	Less effective
4.	Maintain the voltage Profile	Cost effective way to improve the voltage profile.	More effective in maintaining the voltage profiles of substations.
5.	Rating	Required rating is less	Required rating is high
6.	Cost	Cost is high	Cost is less

4. Introduction to Flexible AC Transmission Systems

4.1 Need of FACTS Controllers

The various disturbances in the system such as sudden change in load, contingency causes problems in large interconnected power systems. So maintaining the economic conditions and security of the system becomes difficult. The problem can be solved by maintaining sufficient operating margins. By using sufficient fast dynamic controllers to control the active and reactive power, it is possible to be operate in substantial margins. Power electronic controllers are used as fast dynamic controllers. The inclusion of power electronics devices as controllers makes the AC system flexible to adopt the condition due to the disturbances. Therefore FACTS is an alternating current transmission system incorporating power electronic based devices and other static devices to improve the power transfer capability and controllability.

IEEE definition of FACTS: Power electronics based system and other static equipment that provides control of one or more AC transmission system parameters.

4.2 Types of FACTS Deices

- The FACTS devices are classified as:

  i. Series controller

ii. Shunt controller

iii. Combined series-series controller

iv. Combined series shunt controller

4.2.1 Series Controllers

- Series controllers inject voltage in series with the line.
- When Voltage magnitude is in phase quadrature with current, series controller generates or absorbs reactive power.
- The series controllers may be:

i. Static Synchronous series compensator (SSSC)

ii. Thyristor Controlled Series Capacitor (TCSC)

iii. Thyristor Controlled Series Reactor (TCSR)

iv. Thyristor Switched Series Capacitor (TSSC)

v. Thyristor Switched Reactor (TSR)

vi. Thyristor Controlled Series Compensation

4.2.2 Shunt Controllers

- Shunt controllers injects current at the point of connection.
- As long as current is in phase quadrature with voltage, shunt controllers absorbs or reactive power.
- Shunt Controllers may be:

i. Static Synchronous Compensator (SSC)

ii. Static Condenser

iii. Static VAR Compensator (SVC)

iv. Static VAR System (SVS)

v. Thyristor Switched Reactor (TSR)

vi. Thyristor Controlled Reactor (TCR)

vii. Thyristor switched Capacitor (TSC)

4.2.3 Combined series-series controllers

- Separate series controllers are combined and controlled in a coordinated manner. It transfers real power.
- It is independent of series reactive power compensation.

- Interline Power Flow Controller (IPFC) is a series-series controller.

4.2.4 Combined series-shunt controllers

- Separate series and shunt controllers are combined and operated in a coordinated manner.
- The various combined series shunt controllers are:

i. Unified Power Flow Controller (UPFC)
ii. InterPhase Controller (IPC)
iii. Thyristor controlled Phase Shifting Transformer (TCPST)

4.3 Classification based on Power Electronic Devices

- Depending on the power electronic devices used in the control, FACTS devices areclassified as
  i. Variable impedance type
  ii. Voltage source converter (VSC) based
- The variable impedance type are:

i. Static VAR Compensator (SVC)
ii. Thysitor Controlled Series Capacitor (TCSC)
iii. Thyristor controlled Phase Shifting Transformer (TCPST)

- The Voltage Source Converter based type are:

i. Static Synchronous Compensator (STATCOM)
ii. Static Synchronous series compensator (SSSC)
iii. Interline Power Flow Controller (IPFC)
iv. Unified Power Flow Controller (UPFC)

4.4 Special purpose FACTS Controllers

The special purpose FACTS controllers are:

i. Thyristor Controlled braking resistor (TCBR)
ii. Thyristor Controlled Voltage limiter (TCVL)
iii. Thyristor Controlled Voltage Regulator (TCVR)
iv. InterPhase Power Controller (IPC)
v. NGH-SSR damping

4.5 Benefits of FACTS Controllers

The various benefits of FACTS controllers are:

i. Provides regulation and voltage support at the critical buses.
ii. It improves voltage profile.

iii. Reduce the power loss.

iv. Control of power flow is ordered

v. Lines are upgraded.

vi. High system security

vii. Suitable for interconnection of power grids of different frequencies.

viii. Power Transfer capability is increased up to the thermal limits.

ix. The transient stability is increased. Due to the increase in the transient stability dynamic security of the system in improved and thereby the blackouts are reduced.

x. Increases the steady state or small signal stability region.

xi. Voltage fluctuations and dynamic over-voltages are avoided.

4.6 Applications of FACTS Controllers

- The major application of FACTS controllers is to improve the power quality in distributed systems.
- The various applications are:

i. Power flow control

ii. Increase the power transfer capability

iii. Voltage control

iv. Power conditioning

v. Flicker mitigation

vi. Interconnection of renewable energy generation system and distributed energy generation

vii. Improve the stability

4.7 Static Var Compensator (SVC)

- A SVC is a shunt connected static generator or absorber of reactive power in which the output is varied to maintain or control specific parameters of an electrical power system.
- Static Var System (SVS) is a combination of different static and mechanically switched Var compensators (Capacitors or Reactors) in which the outputs are coordinated.
- The characteristics of SVC are:

i. Fast control response time

ii. Diminished losses

iii. High reliability

iv. Lower maintenance because of absence of rotating parts

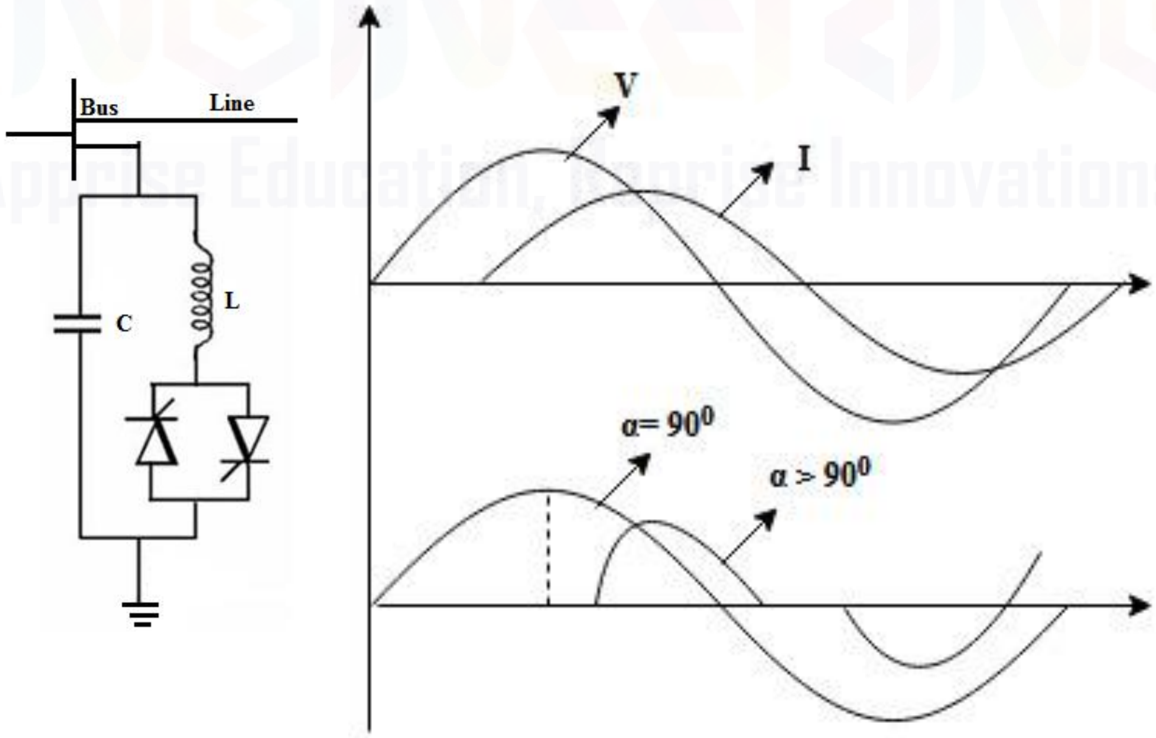
- The improved building block of SVC are:

i. Thyristor Controlled Reactor (TCR)

ii. Thyristor Switched Capacitor (TSC)

4.7.1 Thyristor Controlled Reactor (TCR)

- A linear air core reactor is connected in series with back to back connected pair of thyristors T_1 and T_2. The anti-parallel connected thyristor pair acts like a bidirectional switch. T_1 conducts in the positive half cycle and T_2 conducts in the negative half cycle.
- The firing angle of the thyristors is varied from 90^0 to 180^0. The variation of firing angle changes the suceptance and current, thereby the reactive power absorbed by the reactor can be controlled.
- A firing angle of 90^0 results in full thyristor conduction with a continuous sinusoidal current flow in the TCR.
- When the firing angle is 180^0, the current reduces to zero.
- When the thyristors are fired, the discontinuation of current occurs at the zero crossing, which is known as line commutation.
- When the firing angle is beyond 90^0, the current becomes non-sinusoidal and harmonics are generated.



- When the firing angle is below 90^0, it causes DC components in the current which leads to the disturbance in the symmetrical operation of the two anti-parallel valve branches.
- In order to have a controllable capacitive reactive power, a capacitor is connected in shunt with the TCR. The capacitor may be fixed or it may be switchable by means of mechanical or thyristor switches.

4.7.1.1 Advantages

The advantages of TCR are:

i. Flexibility to control
ii. Response time is fast.
iii. Control strategies can be easily implemented
iv. Dynamic load factor improvement
v. Voltage stability
vi. Medium loss

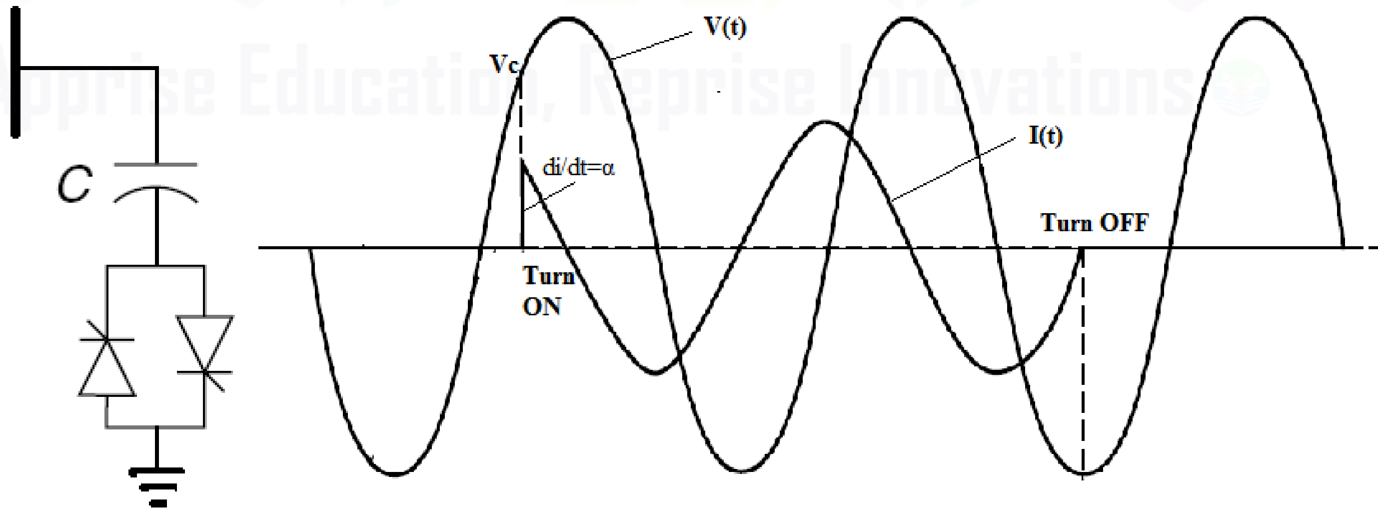
4.7.1.2 Disadvantages

The disadvantages of TCR are:

i. Do not have high overloading capacity as air core reactors are used.
ii. Causes harmonics and undesirable situation due to harmonics.

4.7.2 Thyristor Switched Capacitor (TSC)

- Thyristor Switched Capacitor (TSC) has a capacitor in series with a bidirectional thyristor switch.



- When the capacitor voltage is not equal to the supply voltage and the thyristor is made ON, a current of high magnitude flows and charge the capacitor in a very short time. Now the switch will Fail.

- Also when the capacitor voltage is equal to the supply voltage, the current will jump immediately to the steady state current value. In a very short time period the steady state condition is reached. Here the change in current with respect to time in infinite and the thyristor switch fail here.
- From the factors it is inferred that a simple TSC in not suitable.

4.7.2.1 Advantages:

i. Fast response between one half to one cycle. But the response time can be extended.

ii. Losses are small and it increases with leading current.

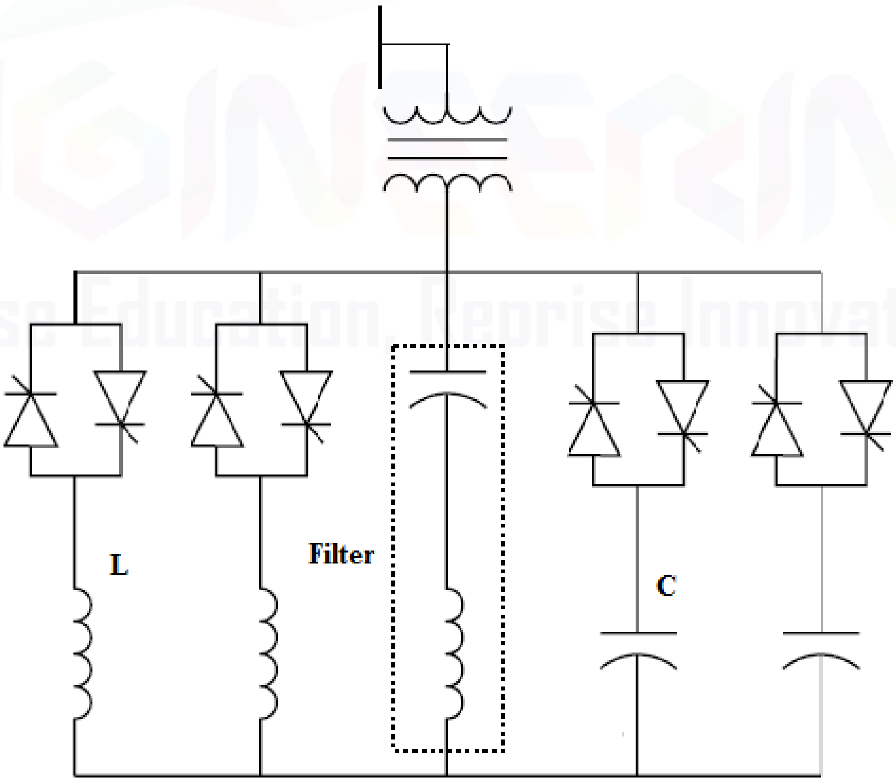
4.7.2.3 Disadvantages:

i. Voltage and Individual phase control are limited.

ii. Some transients occur during energization.

4.7.3 Thyristor Switched Capacitor- Thyristor Controlled Reactor (TSC-TCR)

- A Thyristor Switched Capacitor- Thyristor Controlled Reactor (TSC-TCR) comprises of a n number of TSC banks and a single TCR connected in parallel.
- The rating of TCR is 1/n^th of the total SVC rating.



- The capacitors are switched in discrete steps whereas a continuous control is provided by TCR.

- The TSC is tuned to different harmonic frequencies by using a series reactor.
- An additional filter bank is provided to avoid situation such that all TSC are switched off.

4.7.3.1 Advantages:

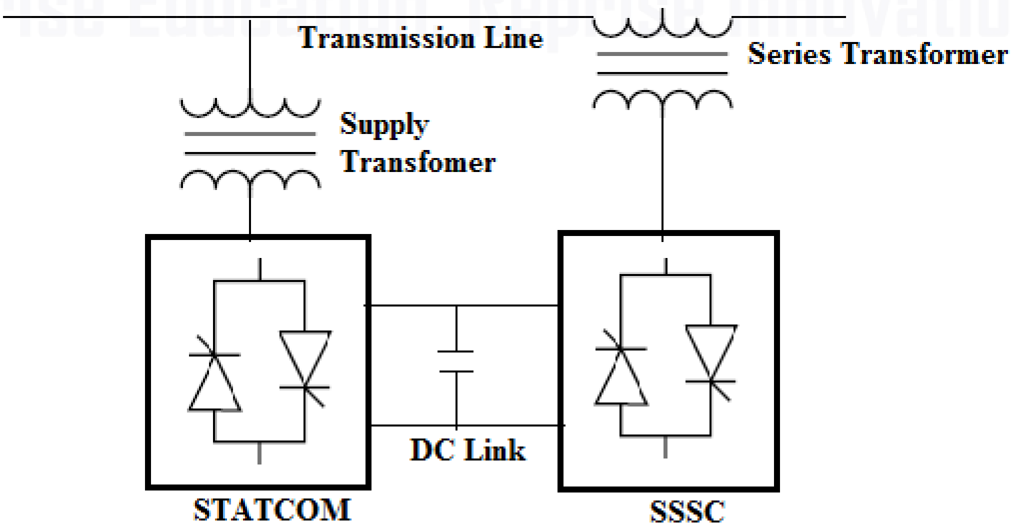
i. The size of TCR is small and thereofore less harmonic generation.
ii. Flexible operation.
iii. Steady state losses are reduced.
iv. Fast Response time
v. Controllability is good.

4.7.3.2 Disadvantages:

i. During large disturbances resonance with the AC system is setup.
ii. The feature of disconnecting capacitor during exigency is not available.

4.8 Unified Power Flow Controller (UPFC)

- It is most versatile controller which controls both the active and reactive power. It is a combination of Static Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC)
- It comprises of two Voltage Source Converters (VSC) coupled through a DC terminal.
- One VSC is connected in shunt with a line through a coupling transformer to supply the real power demand of the other VSC connected in series. It maintains the voltage of the DC bus and it also acts as a STATCOM. The power drawn from the system is equal to the losses in the VSCs and the power transformers.



- The other is connected in series with the transmission line through an interface transformer. It is controlled to inject phasor voltage in series with the line. The voltage can be varies from 0 to V_{pq}max and the phase angle can be varies from 0 to 180^0. It exchanges both real and reactive power with the transmission line.
- A capacitor bank provides DC voltage for both the VSCs. The real power generation and absorption is feasible by the capacitor bank.

4.8.1 Advantages

i. Posses encompassing capabilities like voltage regulation, series compensation and phase shifting.

ii. Independent and rapid control

iii. Power compensation, flow control and SSR mitigation are performed.

iv. Provides very significant damping to power oscillations when operated at power flows within operating limits.

v. Provides enhanced power-oscillation damping

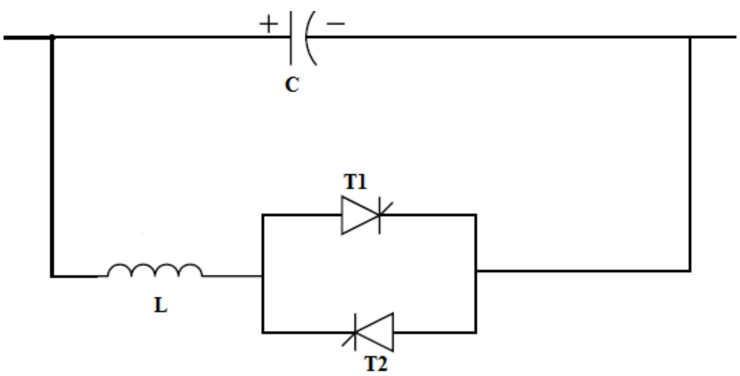
4.8.2 Applications

i. Improve damping of power system oscillations.

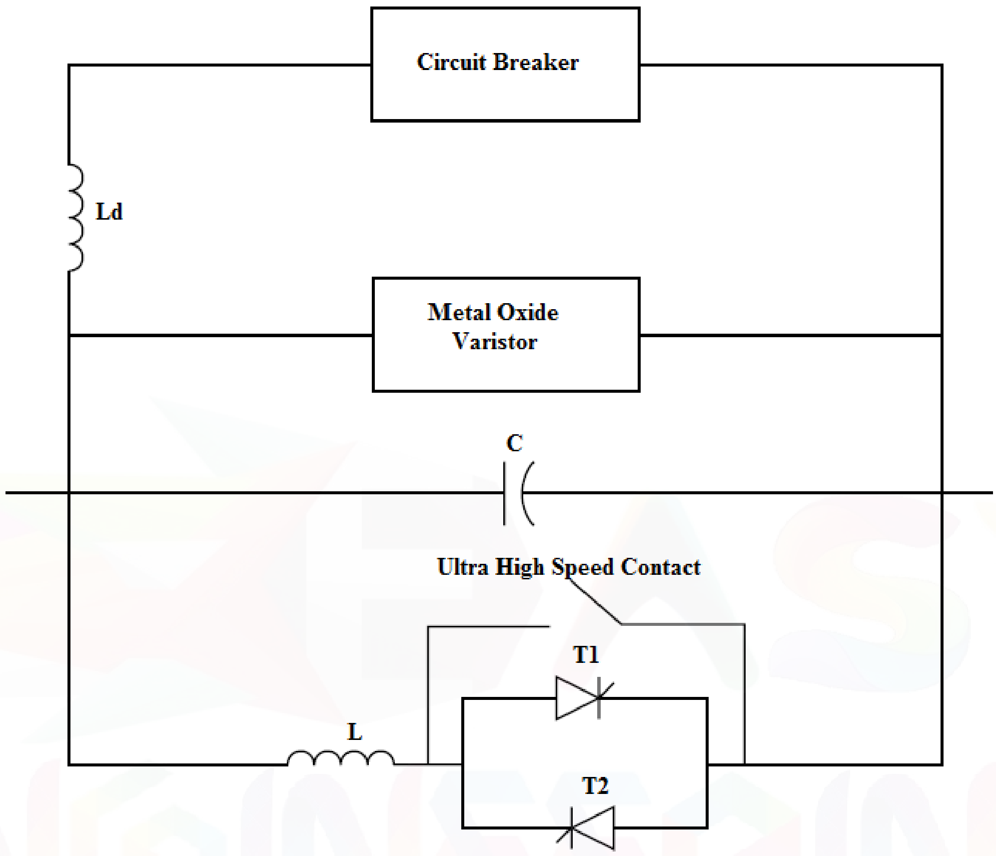
ii. Power system stability enhancement using PSS and UPFC

4.9 Thyristor Controlled Series Capacitor (TCSC)

- The Thyristor Controlled Series Capacitor (TCSC) has a series capacitor in parallel to a thyristor controlled reactor.
- Protective equipments are installed with the series capacitor in the TCSC module.
- The protective equipment includes a nonlinear resistor, a Metal Oxide Varistor (MOV) connected across the series capacitor. The resistor prevents high capacitor over voltages. It also allows the capacitor in the circuit during the fault condition and thereby improves the transient stability.



- A circuit breaker (CB) is also installed to control the insertion in the line. The circuit breaker bypasses the capacitor when severe fault or event occurs.



- An inductor is included to restrict the magnitude and frequency of capacitor current when the capacitor is bye-passed.
- The Ultra High Speed Contact (UHSC) is connected across the valve to minimize the conduction losses. The conduction loss occurs when the TCSCs are operated for long duration.

4.9.1 Modes of operation of TCSC

The TCSC operates in three modes. The various modes are:

i. Bypassed-Thyristor mode

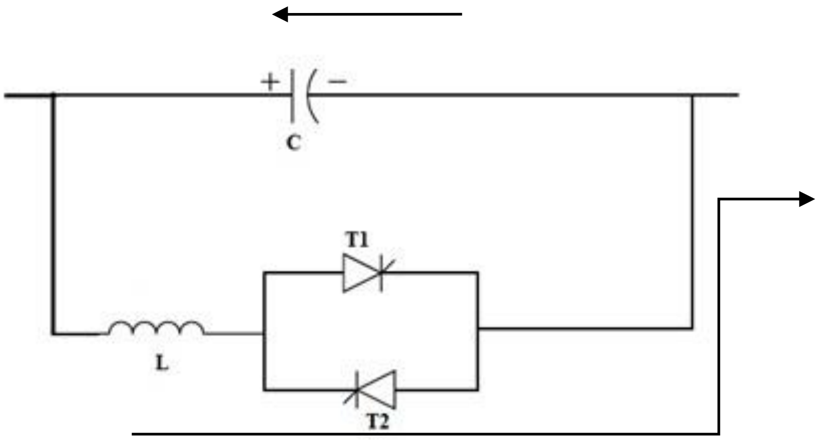
ii. Blocked Thyristor mode (waiting mode)

iii. Vernier mode (Partially conducting mode)

4.9.1.1 Bypassed-Thyristor mode

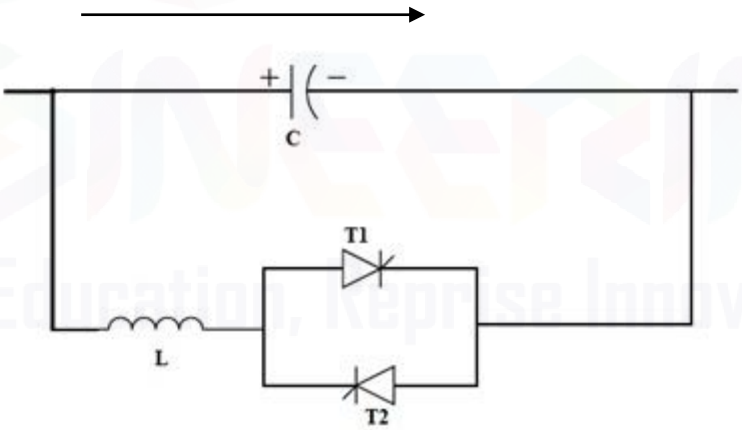
- Thyristors are made to fully conduct with a conduction mode of 180^0.
- It is also called as Thyristor Switched Reactor (TSR) mode.

- IT is used for control purpose and for initiating certain protective functions.



4.9.1.2 Blocked Thyristor mode

- Blocked Thyristor mode is also called as waiting mode.
- The firing pulses of the thyristor are blocked. Once it is blocked, the thyristors turn off as soon as the current through them reaches zero crossing. The circuit behaves as a fixed capacitance.

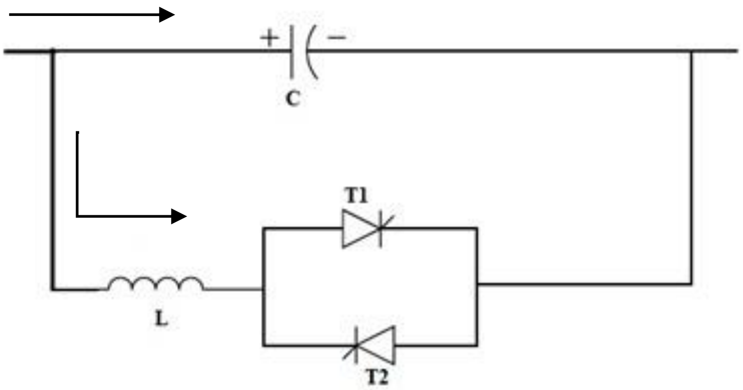


4.9.1.3 Vernier mode

In this mode, TCSC will behave as a controllable inductive reactance or as a controllable capacitive reactance. The behavior is changed by varying the firing angle of the thyristor in an appropriate range.

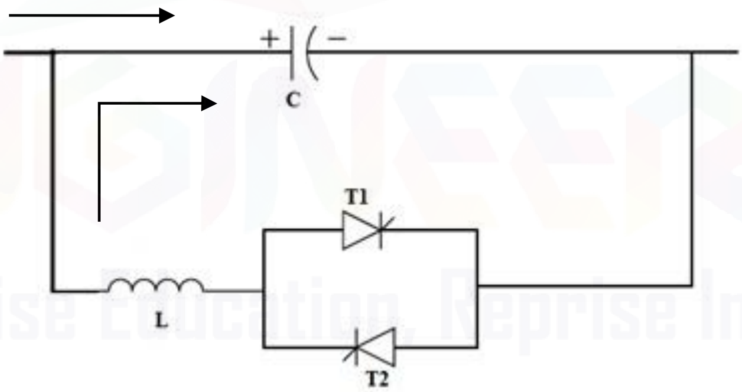
Inductive Vernier mode

- The direction of line current and the capacitor voltage are of opposite direction.
- The controller provides a inductive impedance as the line current and the current through the inductor or of same direction.



Capacitive Vernier mode

- If the thyristors are fired when the capacitor voltage and capacitor currents have opposite polarity, then the mode is capacitive Vernier mode.
- This mode causes a TCR current that has a direction opposite that of capacitor current, thereby resulting in loop current flow in the TCSC controller.
- Capacitive reactance is enhanced as the loop current increases the voltage across the fixed capacitor.



4.9.2 Advantages

i. Rapid and Continuous control of the series compensation level

ii. Dynamic control of power flow

iii. Damping of the power swings

iv. Voltage support

v. Enhanced level of protection

vi. Prevents loop flow

UNIT II
STATIC VAR COMPENSATOR (SVC) AND APPLICATIONS

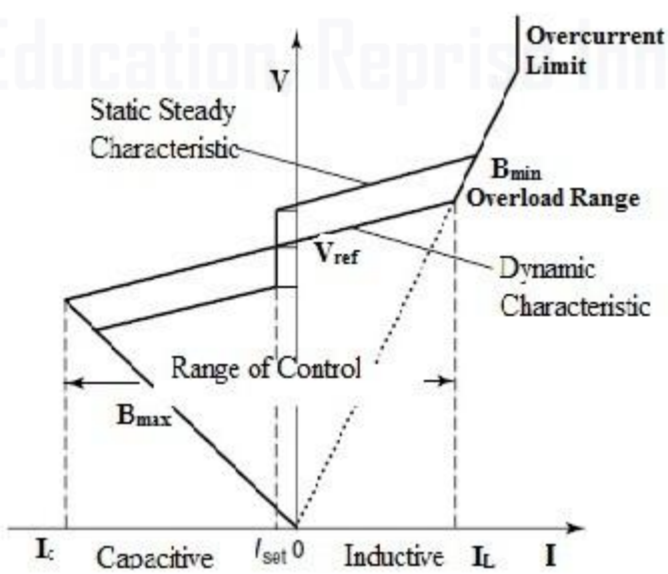
Voltage control by SVC – Advantages of slope in dynamic characteristics – Influence of SVC on system voltage – Design of SVC voltage regulator – Modeling of SVC for power flow and fast transient stability – Applications: Enhancement of transient stability– Steady state power transfer – Enhancement of power system damping.

2.1 Concept of voltage control by SVC

- The main objective of using SVC in power system is to control the voltage and to stabilize the system under disturbances.
- The voltage control by SVC depends on:
  - i. Network resonance
  - ii. Transformer saturation
  - iii. Geomagnetic effects
  - iv. Voltage distortion

2.1.1 V-I Characteristics of SVC

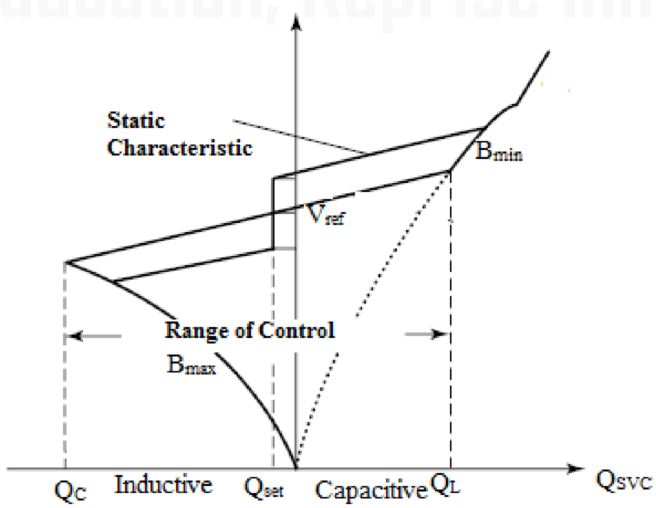
- The Voltage Current Characteristic of SVC is :



- Reference voltage (V_{ref}) – The voltage at the terminal of the SVC when it is at floating state. The reference voltage can be varied between the minimum (V_{min}) and maximum (V_{max}).
- Range of control – It is the control range in which the terminal voltage of the SVC varies linearly with current or reactive power.
  - Slope or Droop – It is the ratio of the change in voltage magnitude (ΔV) to the change in current(ΔI). The slope of the SVC is $K_s == \frac{\Delta V}{\Delta I}\Omega$.
  - The per unit value of the slope is $K_{s\ (p.u)} == \frac{\Delta V/V_r}{\Delta I/I_r}\Omega$

    Where, V_r – rated voltage of SVC

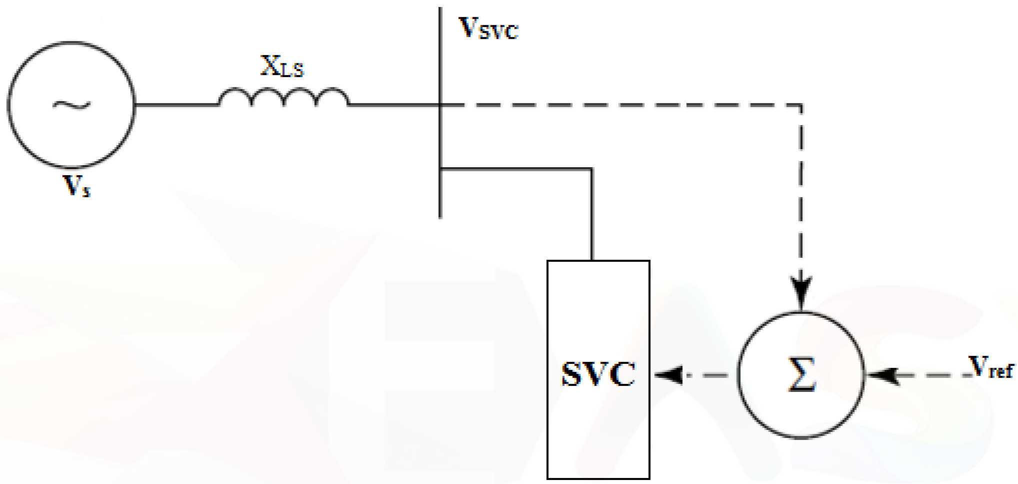
    I_r – rated current of SVC
  - When, $\Delta I = I_r$, $K_s = \Delta V/V_r$ p.u$=\Delta V/V_r \times 100\%$
  - Therefore slope is defined as voltage change in percentage of the rated voltage. The rated voltage is measured at the larger of the maximum inductive or maximum capacitive power outputs.
  - The slope is expresses as an equivalent reactance i.e. $K_s = X_{SVC}$
  - The SVC is expected to maintain a flat voltage profile with a zero slope.
- Overload range – When SVC moves away from the range of control on the inductive side, it enters the overload range. In the overload range the SVC acts as a fixed capacitor.
- Over current limit –The inductive current is limited to a constant value inorder to avoid the valves of the thyristor subjected to thermal stresses.
- The Voltage –reactive power Characteristic of SVC is



- The steady state characteristic of the SVC is same as the dynamic characteristics except the dead band in voltage. When the dead band is not present, under the steady state the SVC will drift towards its reactive power limit to provide voltage regulation.

2.1.2 Voltage control by SVC

- Consider a power system model with V_s as the source voltage; with equivalent system impedance X_{LS}. The system impedance, X_{LS} is the short circuit MVA at the SVC bus.



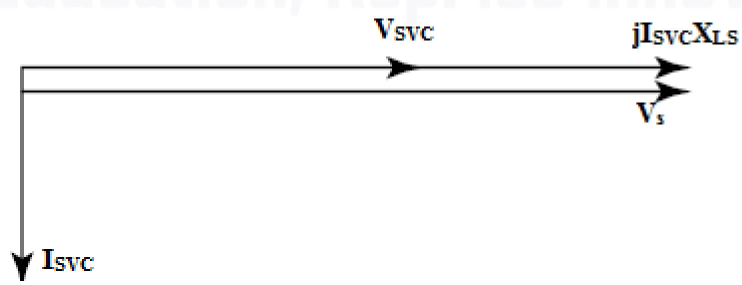
$$X_{LS}{}^2 = \frac{V_b{}^2}{S_{SVC}}.MVA_b \tag{2.1}$$

Where , MVA_b - Base MVA

V_b - Base voltage

S_{SVC} – Three phase short circuit MVA at the SVC

- The voltage at the SVC bus, $V_S = V_{SVC} + I_{SVC}X_{LS}$ (2.2)



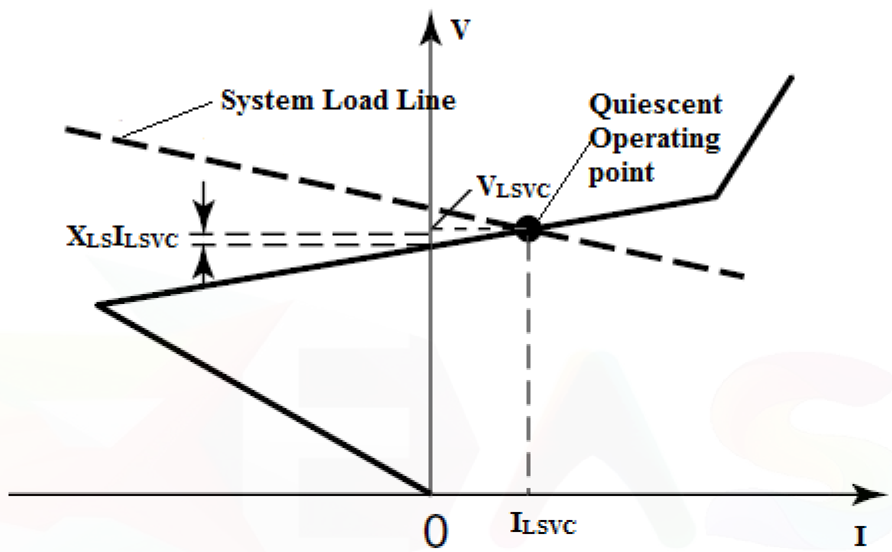
⇨ $V_S = V_{SVC}\angle 0^0 + (I_{SVC}\angle -90^0 \times X_{LS}\angle 90^0)$ (2.3)

⇨ $V_S = (V_{SVC} + I_{SVC}X_{LS})\angle 90^0$

⇨ $V_S = V_{SVC} + I_{SVC}X_{LS}$ (2.4)

- Thus the SVC current results in a voltage drop of $I_{SVC}X_{LS}$ in phase withV_S.

- The SVC bus voltage increases with inductive current and decreases with capacitive current of the SVC.
- The SVC is more effective in controlling the voltages when the X_{LS} is high.
- The voltage current characteristics of the power system and SVC is



- The point of inactivity or dormancy operating point is the intersection of the SVC dynamic characteristic and the system load line.
- From equation 2.4, $V_{SVC} = V_S + I_{SVC}X_{LS}$

  The value of I_{SVC} is positive and negative when inductive and capacitive respectively.

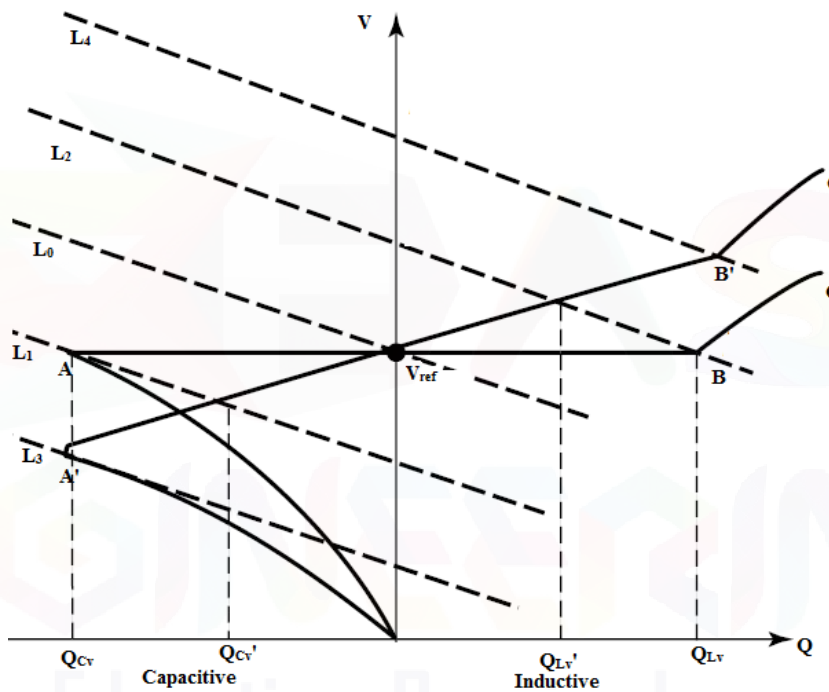
2.2 Advantages of slope in dynamic characteristics

- SVC regulates the voltage and maintains a nominal voltage.
- The advantages due to the addition of a finite slope in the SVC dynamic characteristics are:
  i. Reduces the SVC rating
  ii. Prevents frequent operation at reactive power limits
  iii. Load sharing between parallel connected SVCs.

2.2.1 Reduces the SVC rating

- Two dynamic characteristics ABC and A'B'C' are depicted.
- The characteristic A'B'C' incorporates a finite slope and whereas the characteristic ABC does not.

- When the load varies between L_1 to L_2, the reactive power to be supplied varies between Q_{Cv} and Q_{Lv}.
- When a small deregulation in the SVC bus voltage is considered, the reactive power to be supplied reduces between Q_{Cv}' and Q_{Lv}' for the same variation in the system load line.
- Thus it is inferred that much lower reactive power rating is required is required for meeting the same objective.
- The cost of the SVC is reduced.

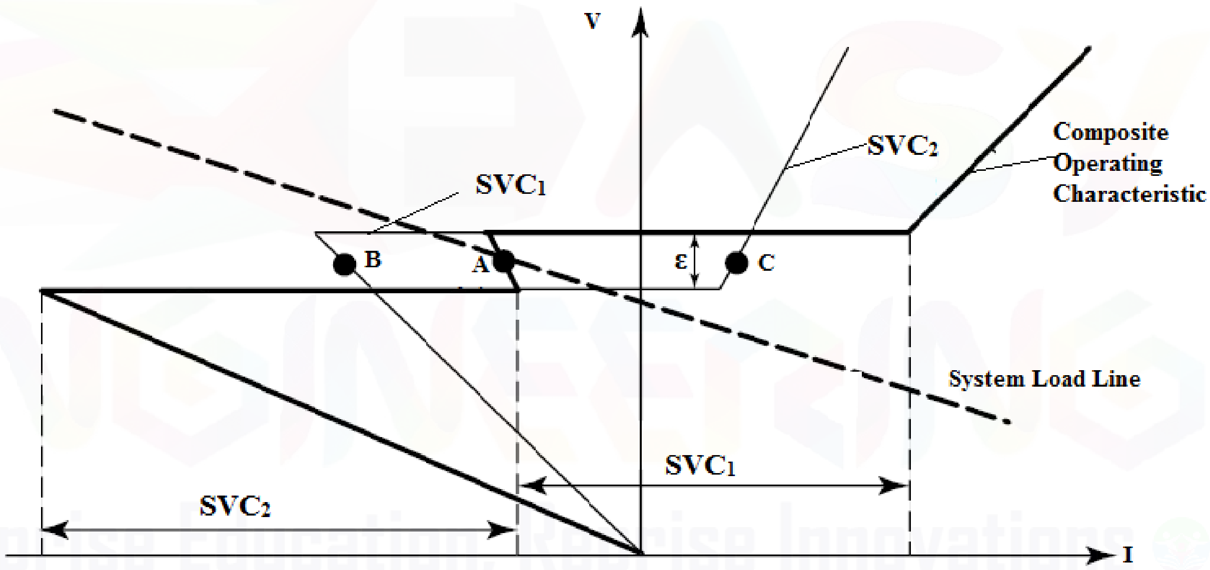


2.2.2 Prevents frequent operation at reactive power limits

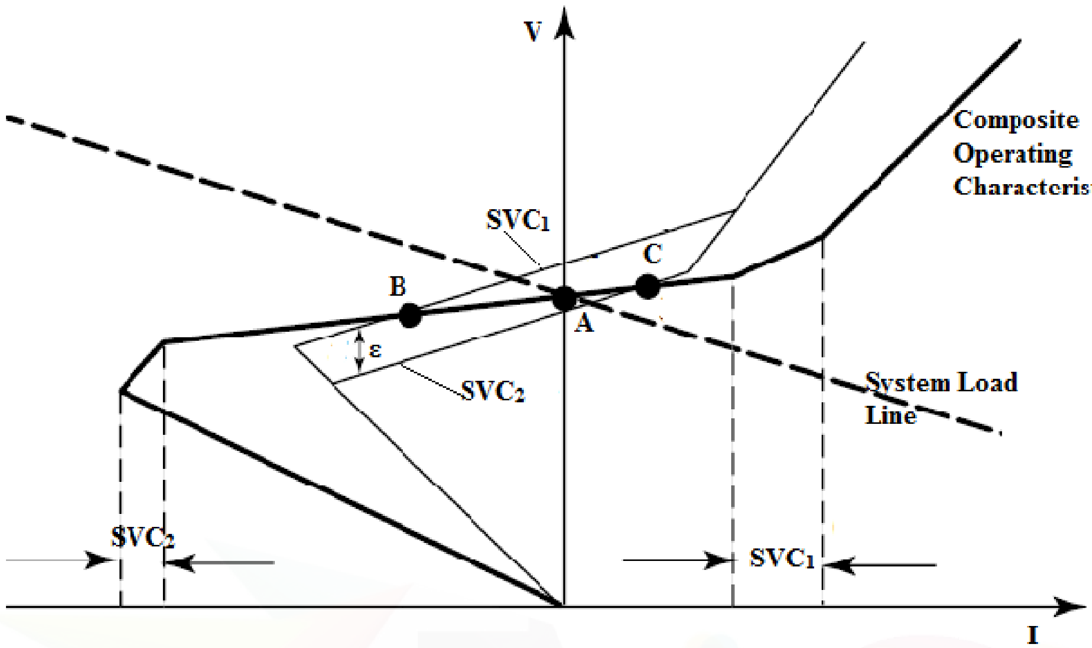
- The effectiveness of SVC is desolate:
  i. When there is no slope in the dynamic characteristics, even a small change in the system load line may cause the SVC to move from one end of the reactive power range to the other end to maintain constant voltage.
  ii. When the slope of the system load line is very small, the reactive power limits are reached more frequently if the system is strong.
- When the slope in the dynamic characteristics is finite, the SVC can operate in the linear controllable range for higher variations in the system load line.

2.2.3 Load sharing between SVCs connected in parallel

- Assume that two SVCs, SVC_1 and SVC_2 are connected to a power system. The two SVCs are of same rating but the reference voltage of the two varies by a small value ε.
- When the SVCs have zero slope,
  - The composite operating characteristic is with a discontinuity around point A.
  - When the system load line and the characteristic of SVC intersects at point A, a quiescent point results that corresponds to generation of reactive power at point B on SVC_1 and absorption of reactive power at point C on SVC_2.
  - One SVC partially compensates the output of the other, so the losses are high and it is uneconomical.
  - The two SVCs are not coordinated.



- When the SVCs have finite slope,
  - The composite operating characteristic is continuous.
  - When a stable operating point is achieved by the SVCs and the power system, SVC_1 operates at B and SVC_2 at C.
  - The load sharing of the compensators is improved.
  - Losses are minimized.



2.3 Influence of SVC on system voltage

The influence of SVC on system voltage depends on the relative strength of the connected ac system. The system strength determines the magnitude of voltage variation caused by the change in the reactive current of the SVC.

2.3.1 Influence of SVC on voltage when coupling transformer is ignored

- The influence of SVC is analyzed by
  - i. Ignoring the effect of coupling transformer
  - ii. SVC acts as a variable susceptance at the HV bus
  - iii. SVC absorbs reactive power when it is at inductive mode.
- The SVC bus voltage is $V_{SVC} = V_S + I_{SVC} X_{LS}$ (2.5)

  Where, V_s is the source voltage

  X_{LS} is the short circuit MVA at the SVC bus

  I_{SVC} is the SVC current
- For a constant equivalent source voltage $V_{s,}$ $\Delta V_{SVC} = -\Delta I_{SVC} X_S$ (2.6)

  Where, X_S is the system impedance

  ΔI_{SVC} is the change in the SVC current
- The SVC current is given by, $I_{SVC} = B_{SVC} V_{SVC}$ (2.7)
- Linearizing the incremental changes, $\Delta I_{SVC} = B_{SVC_0} \Delta V_{SVC} + \Delta B_{SVC} V_{SVC_0}$ (2.8)

- substituting 2.8 in 2.6,

$$\Delta V_{SVC} = -(B_{SVC_0}\Delta V_{SVC} + \Delta B_{SVC} V_{SVC_0})X_S$$

⇨ $\Delta V_{SVC} + B_{SVC_0}\Delta V_{SVC} X_S = -\Delta B_{SVC} \Delta V_{SVC_0} X_S$

⇨ $\Delta V_{SVC} (1 + B_{SVC_0} X_S) == -\Delta B_{SVC} V_{SVC_0} X_S$

⇨ $\frac{\Delta V_{SVC}}{\Delta B_{SVC}} = \frac{-V_{SVC_0} X_S}{1+B_{SVC_0} X_S} = \frac{-V_{SVC_0}}{\frac{1}{X_S}+B_{SVC_0}} = \frac{-V_{SVC_0}}{ESCR + B_{SVC_0}}$ (2.9)

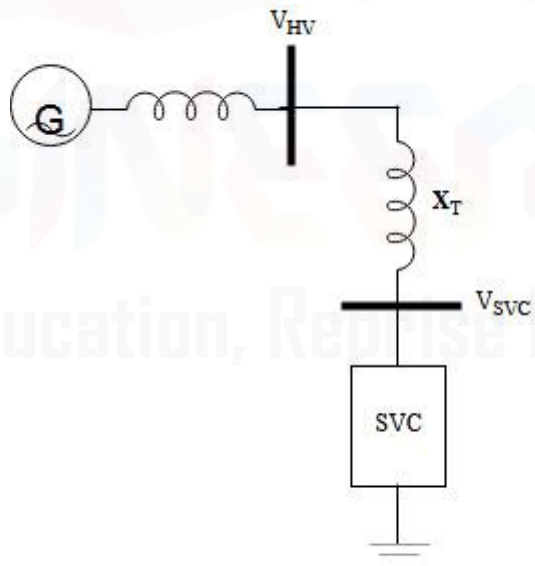
Where, ESCR is the effective short circuit current ratio, $ESCR = \frac{1}{X_S} = B_S$

B_S is the equivalent system susceptance

$X_S = -\frac{\Delta V_{SVC}}{\Delta I_{SVC}}$

2.3.2 Influence of SVC on voltage when coupling transformer is considered

- The inclusion of the coupling transformer leads to:
  - i. Low voltage bus connected to SVC
  - ii. Separation of transformer reactance, X_T from the systems reactance X_s.
- The representation of the power system and the SVC is given by,



- Voltage at the High voltage bus, $V_{HV} = V_{SVC} + I_{SVC} X_T$ (2.10)

⇨ $V_{HV} = V_{SVC} + V_{SVC} B_{SVC} X_T$

⇨ $V_{HV} = V_{SVC} (1 + B_{SVC} X_T)$

⇨ $\frac{V_{SVC}}{V_{HV}} = \frac{1}{1+B_{SVC} X_T}$ (2.11)

- Linearizing 2.11, Change in the voltage at the high voltage bus,

$$\Delta V_{HV} = \left(1 + B_{SVC_0} X_T\right)\Delta V_{SVC} + V_{SVC_0} X_T \Delta B_{SVC} \tag{2.12}$$

From (2.9), $\frac{\Delta V_{SVC}}{\Delta B_{SVC}} = \frac{-V_{SVC_0}}{ESCR + B_{SVC_0}}$

$$\Rightarrow \Delta V_{SVC} = \frac{-V_{SVC_0}}{ESCR + B_{SVC_0}} \Delta B_{SVC} \tag{2.13}$$

Substituting (2.13) in (2.12), $\Delta V_{HV} = \left(1 + B_{SVC_0} X_T\right) \frac{-V_{SVC_0}}{ESCR + B_{SVC_0}} \Delta B_{SVC} + V_{SVC_0} X_T \Delta B_{SVC}$

$$\Rightarrow \Delta V_{HV} = \frac{-V_{SVC_0}}{ESCR + B_{SVC_0}} \Delta B_{SVC} + \frac{-V_{SVC_0}}{ESCR + B_{SVC_0}} \Delta B_{SVC} B_{SVC_0} X_T + V_{SVC_0} X_T \Delta B_{SVC}$$

$$\Rightarrow \Delta V_{HV} = -\Delta B_{SVC} \left[\frac{V_{SVC_0}}{ESCR + B_{SVC_0}} + \frac{V_{SVC_0}}{ESCR + B_{SVC_0}} B_{SVC_0} X_T - V_{SVC_0} X_T\right]$$

$$\Rightarrow \Delta V_{HV} = -\Delta B_{SVC} \left[\left(\frac{1 + B_{SVC_0} X_T}{ESCR + B_{SVC_0}}\right) V_{SVC_0} - V_{SVC_0} X_T\right]$$

$$\Rightarrow \frac{\Delta V_{HV}}{\Delta B_{SVC}} = \frac{-V_{SVC_0} - B_{SVC_0} X_T V_{SVC_0} - V_{SVC_0} X_T\, ESCR + V_{SVC_0} X_T B_{SVC_0}}{ESCR + B_{SVC_0}}$$

$$\Rightarrow \frac{\Delta V_{HV}}{\Delta B_{SVC}} = \frac{-V_{SVC_0} - V_{SVC_0} X_T\, ESCR}{ESCR + B_{SVC_0}}$$

$$\Rightarrow \frac{\Delta V_{HV}}{\Delta B_{SVC}} = \frac{-V_{SVC_0}(1 - X_T\, ESCR)}{ESCR + B_{SVC_0}} \tag{2.14}$$

From (2.11), $\frac{V_{SVC}}{V_{HV}} = \frac{1}{1 + B_{SVC} X_T}$

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

$$\Rightarrow V_{SVC_0} = \frac{V_{HV_0}}{1 + B_{SVC_0} X_T} \tag{2.15}$$

Substituting (2.15) in (2.14), $\frac{\Delta V_{HV}}{\Delta B_{SVC}} = \frac{-V_{HV_0}(1 - X_T\, ESCR)}{(1 + B_{SVC_0} X_T)(ESCR + B_{SVC_0})}$ (2.16)

2.3.3 Influence of SVC on voltage based on system gain

- Voltage control action in the linear range is, $V_S = V_{SVC} + X_S I_{SVC}$ (2.17)
- The SVC current is given by, $I_{SVC} = B_{SVC} V_{SVC}$ (2.18)

$$\Rightarrow V_S = V_{SVC} + X_S B_{SVC} V_{SVC}$$

$$\Rightarrow V_S = V_{SVC}(1 + X_S B_{SVC})$$

$$\Rightarrow V_{SVC} = \frac{V_S}{1 + X_S B_{SVC}}$$

$$\Rightarrow V_{SVC} = \frac{V_S}{1 + \frac{B_{SVC}}{ESCR}} \tag{2.19}$$

- In a ac system, $X_S \ll {}^{1}/_{B_{SVC}}$, therefore $ESCR >> B_{SVC}$.

Equation (2.19) can be written as, $V_{SVC} \approx V_S\left(1-\frac{B_{SVC}}{ESCR}\right)$

- The change in system voltage, $\Delta V = V_S - V_{SVC} = V_S - \left[V_S\left(1-\frac{B_{SVC}}{ESCR}\right)\right] = V_S\frac{B_{SVC}}{ESCR}$ (2.20)

  ⇨ Change in voltage $\Delta V = K_n B_{SVC}$

  Where K_n is the system gain, $K_n = \frac{V_S}{ESCR} = \frac{V_S}{B_S}$

- The system gain depends on the equivalent system voltage and equivalent impedance. As both the parameters tend to change the system gain is not a constant. If the system is weak, then the system gain is high. Whereas when the system is strong it corresponds to low system gain.

- **System gain in per unit:**

  Let the base voltage be V_b and the base susceptance be B_b

  Now, System gain, $K_n(p.u) = \frac{V_S/\boldsymbol{V_b}}{B_S/\boldsymbol{B_b}}$

  ⇨ $K_n(p.u) = \frac{V_S}{V_b} \times \frac{B_b}{B_S}$

  Multiplying by $\frac{V_b^{\,2}}{V_b^{\,2}}$, $K_n(p.u) = \frac{V_S}{V_b} \times \frac{B_b}{B_S} \times \frac{V_b^{\,2}}{V_b^{\,2}}$

  ⇨ $K_n(p.u) = \frac{V_S I_{SVC} V_b}{V_b B_S V_b^{\,2}}$ (as $B_b V_b = I_{SVC}$)

  ⇨ $K_n(p.u) = \frac{V_S Q_{SVC}}{V_b B_S V_b^{\,2}}$ (as $I_{SVC} V_b = Q_{SVC}$)

  ⇨ $K_n(p.u) = \frac{V_S}{V_b}\frac{Q_{SVC}}{\frac{B_S V_b^{\,2} V_S}{V_S}} = \frac{V_S}{V_b}\frac{Q_{SVC}}{\frac{S_C V_b}{V_S}}$ (2.21)

  (as $B_S V_b V_S = S_C$, short circuit power = Base Voltage x Short circuit current)

  ⇨ $K_n(p.u) = \frac{Q_{SVC}}{S_C}$ (assuming $\frac{V_S}{V_b}$ is close to unity)

- Then system gain will change with variation in network configuration and line switching.

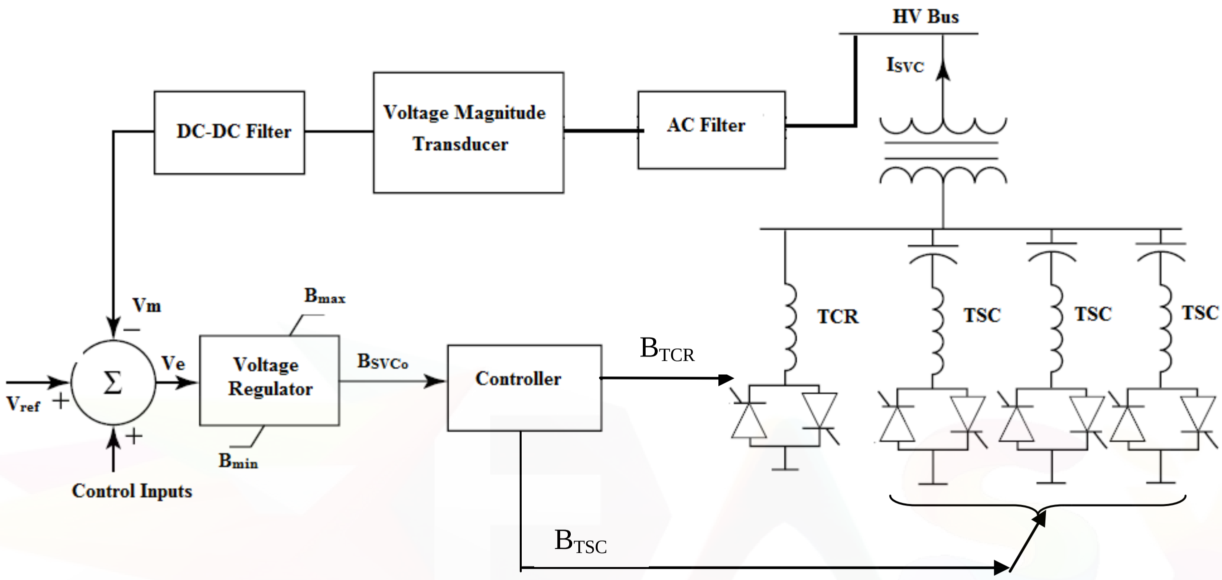
2.4 Design of SVC voltage regulator

- The basic block diagram of a voltage control system for a TSC- TCR SVC is shown in fig.
- The voltage regulator can be modeled in two ways:
  - i. Gain-time constant form
  - ii. Integrator-droop form
- The gain-time constant form of the voltage regulator is, $G_{VR} = \frac{K_{VR}}{1+ST_{VR}}$ (2.22)

Where, K_{VR} is the gain of the voltage regulator

T_{VR} is the time constant of the voltage regulator in secs

$K_{VR} = \frac{1}{K_{SL}}$, where K_{SL} is the current droop in p.u

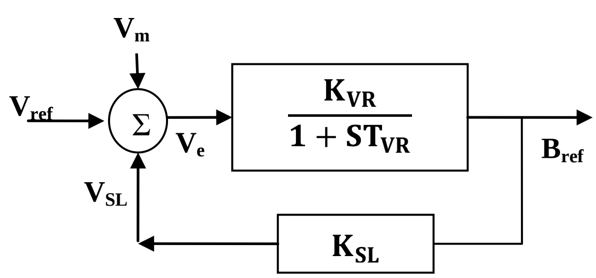


Additional transient gain, $K_T = \frac{K_{VR}}{T_{VR}}$

- In the integrator-current droop model, the voltage regulator is represented as an integrator.

$$G'_{VR} = \frac{1}{SR_{VR}} \tag{2.23}$$

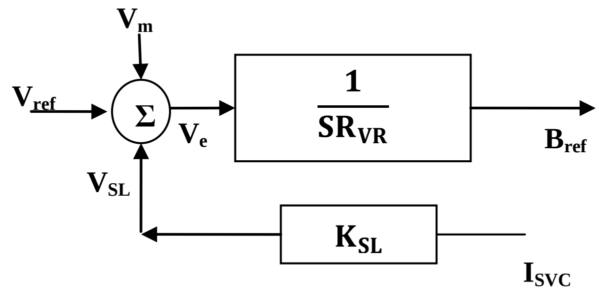
where, R_{VR} is the response rate of the voltage regulator in ms/p.u



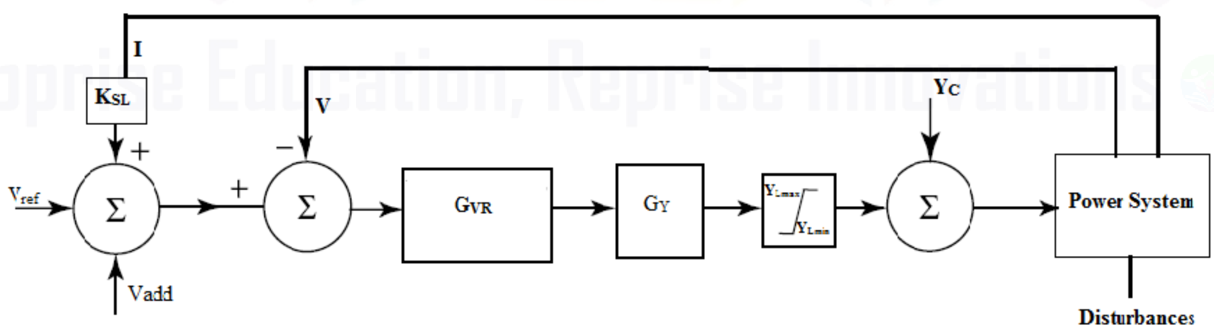
- The time constant and the response rate of the voltage regulator is related as, $T_{VR} = \frac{R_{VR}}{K_{SL}}$.

2.4.1 Simplistic Design of SVC voltage regulator

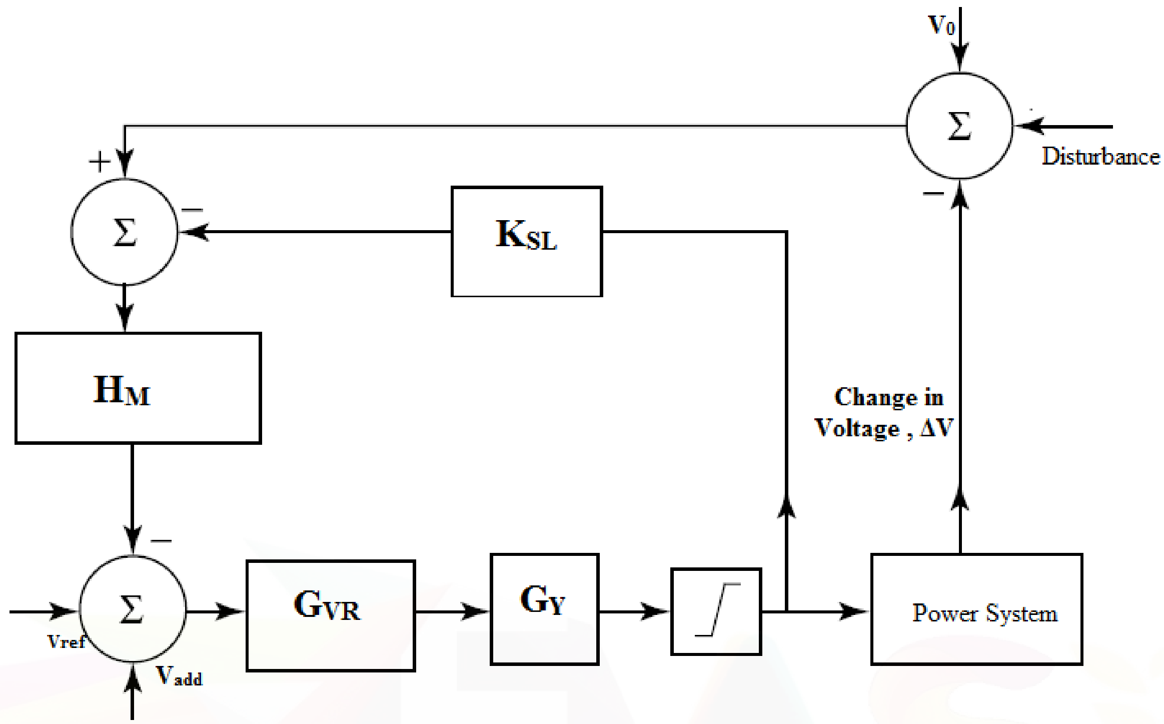
- In the design a proportional Integral controller with an explicit current feedback is considered.



- Advantages:
  i. The power system is modeled with a pure reactance or gain. So the method is simple.
  ii. The influence of system strength and current droop on the controller response is clearly explained.
- Disadvantage:
  i. The effect of generator dynamics on controller performances is not considered.
- Assumptions:
  i. The change in system voltage due to SVC is small.
  ii. The SVC voltage is 1 p.u
  iii. The variation of the SVC reference voltage is small.



- The current due to the inductance in the TCR, $I_L = Y_L V_{SVC} \approx Y_L$
- The current due to the capacitance on the TSC, $I_C = Y_C V_{SVC} \approx Y_C$
- The design is simplified by, ignoring the TSC witching, merging the droop effect of the capacitive current with the reference voltage and by ignoring the power system disturbances.



- In the block, G_Y is the thyristor phase control.

$$G_Y(S) = \frac{e^{-ST_d}}{1+ST_Y} \tag{2.24}$$

where, T_d is the thyristor dead time (1/12th cycle time)

T_Y is the thyristor firing delay time caused during sequential switching (one-quarter cycle time.

- The proportional integral controller with fastest response for the weakest system with gain K_N^{max} is given by, $G_R(S) = K_p\left(1+\frac{1}{ST_Y}\right) = -\frac{1}{2(K_{SL}+K_N^{max})}\left(1+\frac{1}{ST_Y}\right)$ (2.25)

where, K_p is the proportional gain of the voltage regulator.

- The overall closed loop transfer function of the control system,

$$G_{CS}(S) = \frac{\Delta V(s)}{\Delta V_{ref}(S)} = \frac{K_N G_R G_Y}{1+(K_{SL}+K_N)G_R G_Y H_M} \tag{2.26}$$

- The response time is obtained by increasing the time constants as

$$T_{CS} = 2\left(\frac{K_{SL}+K_N^{max}}{K_{SL}+K_N}\right)T_Y \tag{2.27}$$

Now the overall transfer function becomes,

$$G_{CS}(S) = \left(\frac{K_N}{K_{SL}+K_N}\right)\left(\frac{ST_{CS}}{1+ST_{CS}}\right) \tag{2.28}$$

- The change in SVC bus voltage for a change in reference voltage is

$$\Delta V = \frac{K_N}{K_{SL}+K_N}\Delta V_{ref}\left(1-e^{-\left(t/T_{CS}\right)}\right) = k\Delta V_{ref}\left(1-e^{-\left(t/T_{CS}\right)}\right) \tag{2.29}$$

- From the above, it is inferred that
  - i. ΔV_{ref} causes the V_{SVC} to vary by k.
  - ii. The response is fast when $K_N = K_N^{max}$.
- The voltage controller has to maintain the stability under all stages and should have a good response time. So the controller is optimized for the lowest short circuit level.
- Equation 2.27 can be written as, $\frac{T_{CS}}{2T_Y} = \frac{T_{CS}}{2T_{CS_{opt}}} = \frac{K_{SL}+K_N^{max}}{K_{SL}+K_N}$

$$\Rightarrow \frac{T_{CS}}{2T_{CS_{opt}}} = \frac{\frac{K_{SL}}{K_N^{max}}+1}{\frac{K_{SL}}{K_N^{max}}+\frac{K_N}{K_N^{max}}} = \frac{\frac{K_{SL}}{K_N^{max}}+1}{\frac{K_{SL}}{K_N^{max}}+\frac{S_{C_{min}}}{S_C}} \tag{2.30}$$

2.5 Modeling of SVC in power system studies

- SVC application studies require appropriate power system models and study methods covering the particular problems to be solved by the SVC application. SVC can be included in various power system studies like:
  - i. Power flow studies
  - ii. Fault analysis
  - iii. Small and large disturbance studies
  - iv. Harmonic studies
  - v. Electromagnetic transient studies
- The SVC model should be such that:
  - i. It represents the steady state, fundamental frequency and balanced behavior of SVC.
  - ii. Should be sufficient to evaluate the steady state fundamental frequency behavior of any SVC both with active and inherent control.
  - iii. Three phase modeling is required when unbalanced networks and loading conditions are to be analyzed.

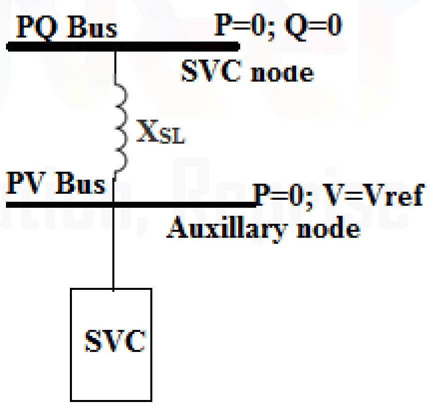
2.5.1 Model of SVC in power flow studies

- The SVC has features as that of the loads or generators connected to the power system.
- The steady state characteristics of SVC describes the relationship between the terminal voltage (V) and total reactive current (I), both within and outside the range of control.

- The SVC behaves as an inductor if the value of Reactive power flowing into the SVC (Q) >0 or the equivalent susceptance of the SVC (B) >0.
- The SVC behaves as capacitor if the value of Q < 0 or B < 0.
- The SVC models are used to determine the required SVC rating irrespective of the type of SVC. It is also used to determine the effect of the SVC without considering transformer saturation.
- The inappropriate representation of the SVC under overloaded condition is PV node with Q-limits. In such representation the behavior will be incorrect outside the range of control.

2.5.1.1 SVC operating within the control range

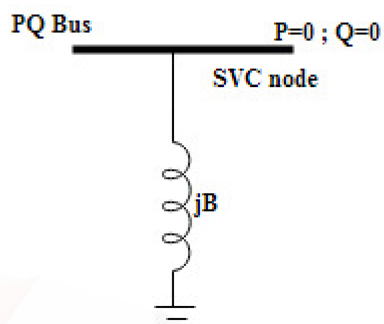
- SVC operates within the control range means $I_{min} < I < I_{max}$ and $V<V_{min.}$
- If the slope of the steady state characteristics is zero, then the SVC is represented as a PV bus at the point of coupling with P=0 and $V=V_{ref}$.
- If the slope is not zero then the SVC is represented as a PV bus at an auxiliary bus with P=0 and $V=V_{ref}$. A reactance equivalent to the slope is connected between the auxiliary node and the point of coupling of the system to represent the slope of the characteristics. The node at the point of coupling is a PQ node with P=0 and Q=0.
- The SVC model with slope for operation within control range is:



2.5.1.2 SVC operating outside the control range

- SVC operates outside the control range means $I_{SVC} > I_{max}$ and $V<V_{min}$.
- SVC is represented as a shunt element with susceptance (B), depending on the operating point.
- When $I_{SVC} > I_{max}$, then $B = B_{min} = -\frac{Q_{max}}{V_{max}^2}$ (2.31)

- When $V < V_{min}$ then $B = B_{max} = -\frac{Q_{min}}{V_{min}^2}$ (2.32)
- The result of the load flow calculation will be the reactive power Q at the point of coupling required to maintain the voltage according to the SVC characteristics for a given network and loading situation.
- The SVC model with slope for operation outside the range of control is:



2.5.1.3 Extension of the basic model

- The SVC basic model can be extended as
    i. Modelling as voltage controlled Susceptance
    ii. Modelling by function Q
    iii. Modelling as controlled PV and PQ node
- **Modeling as voltage controlled susceptance**, the value of the B is increases or decreased stepwise to the error ($V-V_{ref}$) within the range of control.
- **Modelling by function Q**, in load flow problem based on newton raphson method, it is accomplished by including the derivative of the SVC reactive power with respect to the voltage in the jacobian matrix. The calue of the derivative will be updated at every step of the iterative process.

The SVC reactive power, $Q = (V - V_{ref})\frac{V}{X_{LS}}$ within the range of control (2.33)

$Q = -BV^2$ outside the control range (2.34)

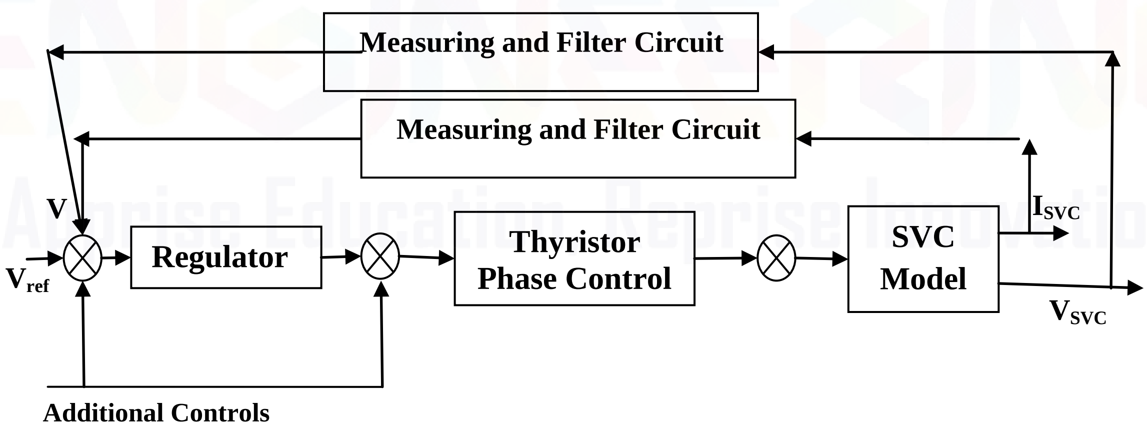
- **Modelling as controlled PV and PQ node**, compliments the basic model with a controller with the SVC at the auxillary node. The controller decides the node is either a PV node or aconstant admittance load based on the current between the SVC bus and the auxiliary bus.

2.5.2 Model of SVC for fast transient stability

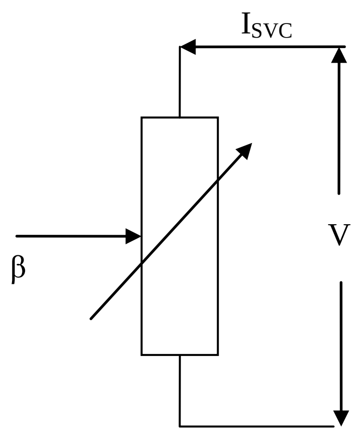
- SVC model for small and large disturbance and transient stability should represent the positive sequence system behaviour.
- Electromagnetic transients in the network and SVC can be ignored.
- The effect of thyristor firing valve pulse synchronizing control on the overall control response can be neglected.
- The model should accurately represent the SVC characteristics under steady state, dynamic and transient conditions.

2.5.2.1 Basic model of SVC

- The basic model of the SVC is the classical representation of the generator control.
- The basic model of the SVC comprises of:
    - i. Voltage and Current measuring filter system
    - ii. Regulator
    - iii. Additional controllers for improving the damping
    - iv. Model of the thyristor control
    - v. Synchronizing control unit
    - vi. An SVC model with controlled susceptance or controlled current source.



- The SVC model converts the output signal of the control (β) into a controlled network element connected to the SVC node.
- The two models of SVC are:
    - i. As a variable susceptance (B)

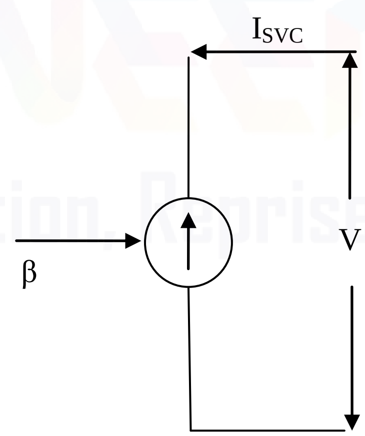


- ✓ The admittance matrix has to be updated if the value of susceptance changes.
- ✓ Susceptance (B) =β. B_{max} (2.35)
- ✓ SVC current, I_{SVC} = jβBmaxV (2.36)

  Where, β is the control output

ii. As a controlled current source

- ✓ Constant admittance matrix can be used.



- ✓ SVC current, I_{SVC} = jβBmaxV

- The parameters of the SVC model have to be selected according to the SVC rating and performance criteria considering the behaviour of the power system under various operating conditions.

- The basic SVC model is suitable for modeling the electromechanical transient performance of any type of SVC in conjunction with the response of the network model.
- In small and large signal disturbance studies,
  i. In electromechanical problems with Eigen frequencies the thyristor control block and synchronizing control can be neglected.
  ii. The time constants of the regulator can be ignored in the initial part of the study.
  iii. Interaction between the control system and the network at harmonics and sub-harmonic frequencies is not considered in the model.
  iv. Resonant frequencies close to the fundamental frequency may be filtered.

2.6 Applications of Static Var Compensator

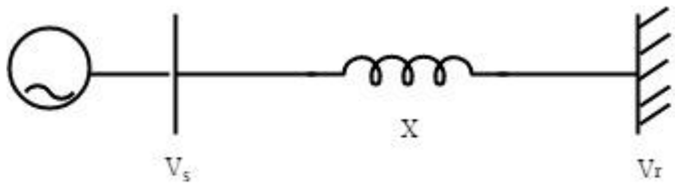
- Static Var Compensator has been used in various applications in the modern power system.
- SVCs are used for
  i. Load compensation
  ii. Transmission line applications
  iii. Voltage control
  iv. Damping control
  v. Stability enhancement
  vi. Improvement of HVDC link performance
- The various applications are:
  i. Increase in steady state power transfer capability
  ii. Enhancement of transient stability
  iii. Augmentation of power system damping

2.6.1 Application of SVC: Increase in steady state power transfer

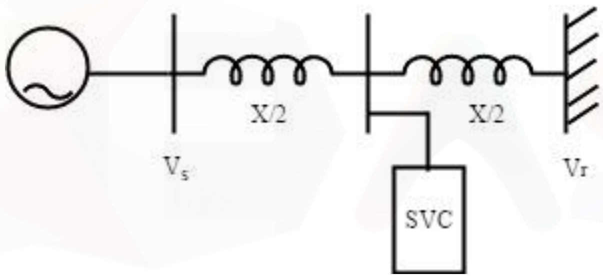
- SVC can be used to improve the power transfer capability.
- Consider a Single Machine Infinite Bus (SMIB),

  Let the voltage of the sending end (generator) is $V_s\angle\delta$ and the voltage at the receiving end (infinite bus) is $V_r\angle\delta$.

  The reactance of the lossless line is assumes as X



- Power transfer, $P = \frac{V_s V_r}{X} \sin\delta$ (2.37)
- Let $V_s = V_r = V$, $P = \frac{V^2}{X} \sin\delta$ (2.38)
- When $\delta = 90^0$, the maximum power transfer is maximum. i.e. $P = \frac{V^2}{X}$ (2.39)
- Assume that the transmission line is compensated at the mid-point by SVC. The SVC is connected such that it could supply unlimited reactive power at the mid-point of the line and can maintain the voltage to be constant for all loads.

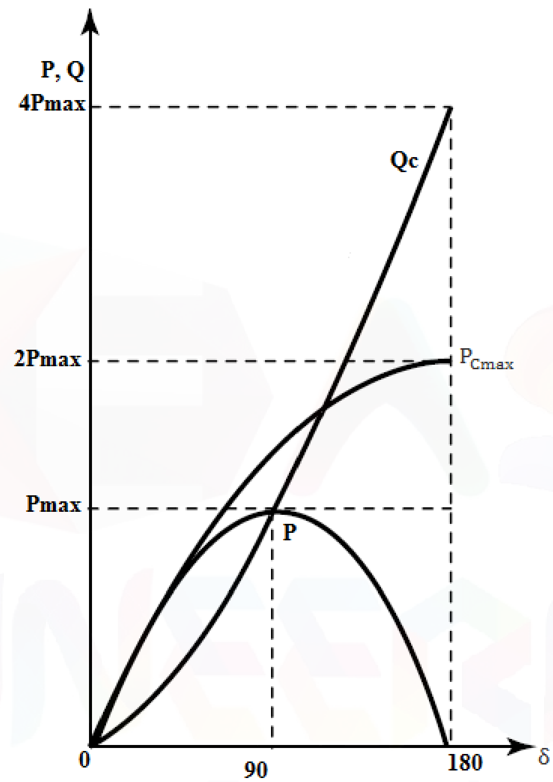


- The voltage at the SVC is $V_m \angle \frac{\delta}{2}$
- Power transfer across the generator and the SVC is, $P_C = \frac{V_s V_m}{X/2} \sin\frac{\delta}{2}$ (2.40)
- The power transfer across the SVC and the infinite bus is $\frac{V_r V_m}{X/2} \sin\frac{\delta}{2}$ (2.41)
- Assuming $V_s = V_m = V_r = V$, Now $P_C = \frac{2V^2}{X} \sin\frac{\delta}{2}$ (2.42)
- The maximum power transfer across the line is $P_{Cmax} = \frac{2V^2}{X}$, which is twice the maximum power transfer that occurs without SVC.
- From the equation it is inferred that due to the placement of SVC at the mid-point of the line
  i. the steady state power transfer has doubled
  ii. The stable angular difference between the generator and the infinite has increased from 90 to 180 degree.
- When the transmission line is sectionalized into n sections with a SVC at each junction of the section and if a voltage V is maintained at each part, the power transfer of the line is:

$$P_C{}' = \frac{V^2}{X/_n}\sin\frac{\delta}{n} \tag{2.43}$$

The maximum power transfer is $P_C{}'_{max} = \frac{V^2}{X/_n} = \frac{nV^2}{X}$ (2.44)

From the above equation, it is inferred that sectionalization by n sections leads to increase in power transfer by n times. But it is not practically possible as the system is constrained to thermal limits of the transmission line.



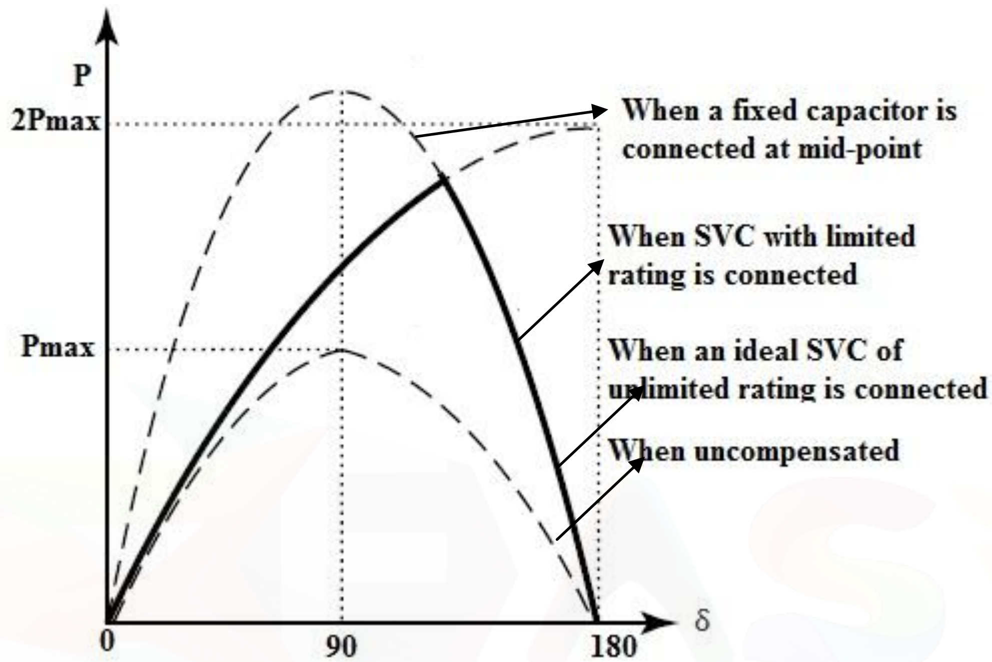
- The reactive power supplied by SVC for the maintaining the voltage is

$$Q_C = \frac{4V^2}{X}(1 - \cos\frac{\delta}{2}) \tag{2.45}$$

So in order to increase the power transfer by two times of the maximum power transfer, the required reactive power rating of the SVC is four times, which is not feasible.

- When a SVC of limited rating is connected at the mid-point of the line, it ensures voltage regulation until its capacitive out reaches its limit. If the system voltage decreases more, the SVC cannot regulate the voltage and it will act as a fixed capacitor.
- When the SVC of limited rating is connected the maximum power transfer will be less than $2P_{max}$.

- The power angle curve considering the equivalent reactance between the generator and infinite bus is:



PANIMALAR ENGINEERING COLLEGE
Department of Electrical and Electronics Engineering

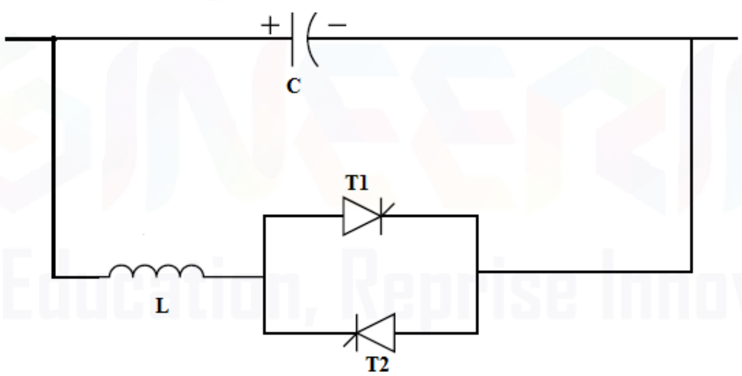
EE6004 - FLEXIBLE AC TRANSMISSION SYSTEMS

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 power flow and stability studies – Application: Improvement of the system stability limit – Enhancement of system damping.

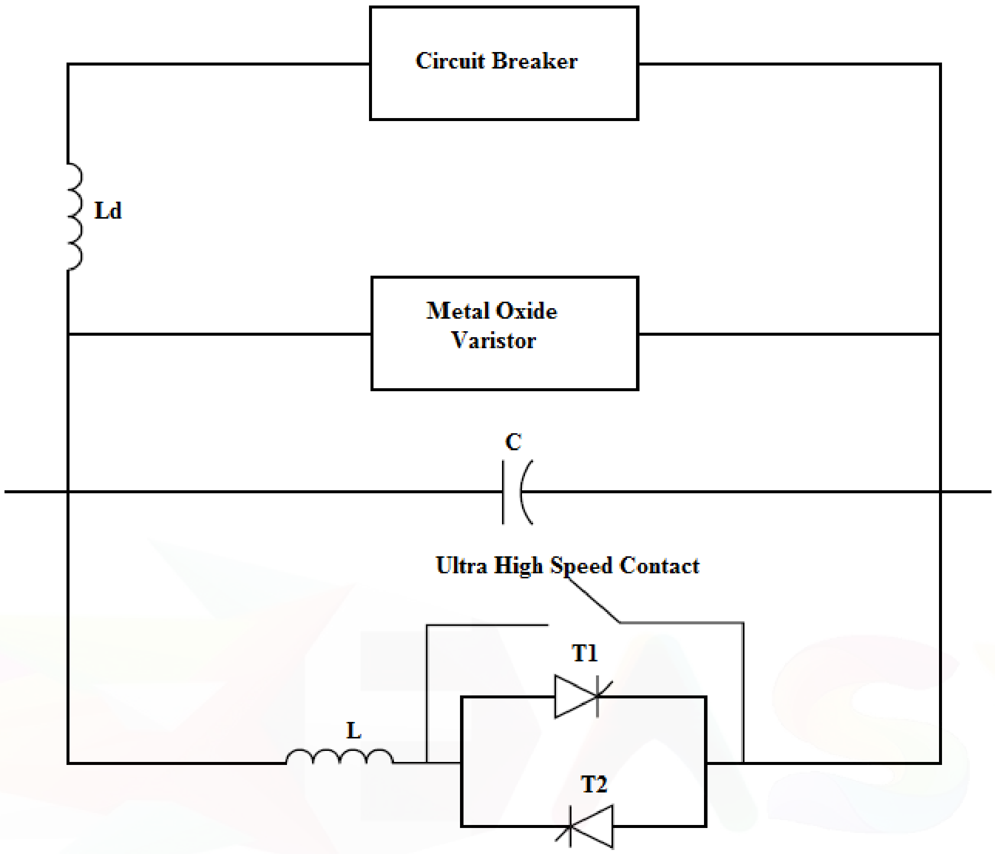
3.1 Thyristor Controlled Series Capacitor

- The Thyristor Controlled Series Capacitor (TCSC) has a series capacitor in parallel to a thyristor controlled reactor.
- Protective equipments are installed with the series capacitor in the TCSC module.
- The protective equipment includes a nonlinear resistor, a Metal Oxide Varistor (MOV) connected across the series capacitor. The resistor prevents high capacitor over voltages. It also allows the capacitor in the circuit during the fault condition and thereby improves the transient stability.



- A circuit breaker (CB) is also installed to control the insertion in the line. The circuit breaker bypasses the capacitor when severe fault or event occurs.
- An inductor is included to restrict the magnitude and frequency of capacitor current when the capacitor is bye-passed.
- The Ultra High Speed Contact (UHSC) is connected across the valve to minimize the conduction losses. The conduction loss occurs when the TCSCs are operated for long duration.

Prof. S. Selvi & Dr. D. Silas Stephen



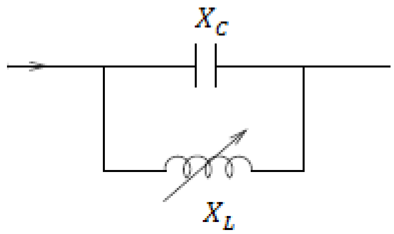
Advantages of TCSC:

i. To mitigate the SSR
ii. Protection against over voltages.
iii. Less cost
iv. Boost the capacitor voltage due to the discontinuous conduction of the TCR.
v. Rapid continous control of series line compensation.
vi. Dynamic control of power flow in selected transmission lines.
vii. Supress subsynchronous oscillation.
viii. Decrease dc-offset voltage.
ix. Reduces short circuit current
x. Supports voltages

3.2 Operation of the TCSC

- TCSC is a controlled series capacitor which controls the power on the ac line over a range.
- The variable series compensation increases the fundamental frequency voltage across a fixed capacitor.
- The compensation is done by varying the firing angle α.
- The voltage which is varied changes the effective series capacitive reactance.

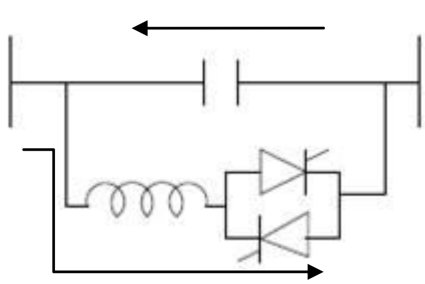
- Consider a variable inductor connected across the fixed capacitor,



- The equivalent impedance, $Z_{eq} = \frac{-jX_C.X_L}{j(X_L - X_C)} = -\frac{jX_C}{\left(1-\frac{X_C}{X_L}\right)} = -j\frac{\omega C}{1-\frac{1}{\omega C.\omega L}} = -j\frac{1}{\omega C - \frac{1}{\omega L}}$
- The impedance of the fixed capacitor is $^{-j}/_{\omega C}$.
- If $\omega C - \frac{1}{\omega L} > 0$, i.e $\omega L > \frac{1}{\omega C}$, the reactance of the fixed capacitor is less than the parallel connected variable reactor. The configuration provides a variable capacitive reactance.The inductor increases the equivalent capacitive reactance of the LC combination above the fixed capacitor.
- If $\omega C - \frac{1}{\omega L} = 0$, then it leads to infinite capacitive impedance due to the resonance. The condition is unacceptable.
- If $\omega C - \frac{1}{\omega L} < 0$, the combination provides inductance above the value of the fixed inductor. The mode is inductive vernier mode of the TCSC.
- In the variable capacitance mode of the TCSC, the inductive reactance is of the inductor is increased, whereas the 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.

3.3 Different modes of operation

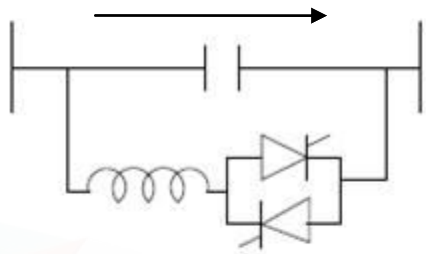
3.3.1 Mode 1: Bypassed thyristor mode (Thyistor Switched Reactor (TSR) mode)



- In this mode, thyristors conduct with a conduction angle of 180^0.
- Gate pulses are applied when the vcoltage across the thyristors reaches zero and becomes positive.

- The TCSC acts as a parallel capacitor-inductor combination.
- When the susceptanceof the reactor is greater than the capacitor, the net current through the module is inductive.
- This mode is used for control and to initiate certain protective functions.
- A finite time delay is reinserted when the line current fall below the specified limit, whnever a TCSC module is bypassed from the violation of the current limit

3.3.2 Mode 2: Blocked thyristor mode (Waiting mode)

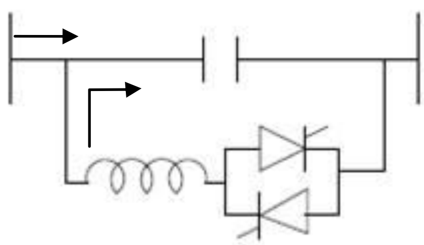


- In this mode, the firing pulses to the thyristor valves are blocked.
- When the thyristors are conducting and a blocking command is given, the thyristor will turn off as soon as the current through them reaches a zero crossing.
- Now the TCSC module is a fixed capacitor and the net reactance will be capacitive.
- The dc-offset voltage of the capacitors is monitored and quickly discharges without harming the transformer.

3.3.3 Mode 3: Partially conducting thyristor or vernier mode:

- In this mode the TCSC will behave as continously controllable capacitive reactance or inductive reactance, which is achieved by varying the thyristor pair within an appropriate range.
- A smooth variation cannot be obtained due to the resonant region between the modes.
- This mode be capacitive vernier mode or Inductive vernier mode.

3.3.3.1 Capacitive vernier mode



- In this mode the firing of the thyristor is done when the capacitive voltage and capacitive current are of opposite polarity.
- This condition leads to the opposite flow of TCR current

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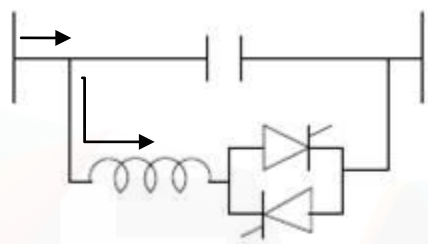
- It also leads to a loop current flow which increases the voltage across the FC, effectively enhancing the equivalent-capacitive reactance and the series-compensation level for the same value of line current.
- To preclude resonance, the firing angle of the forward-facing thyristor , as measured from the positive reaching a zero crossing of the capacitor voltage, is constrained in the range α_{min} and 180^0.
- The maximum TCSC reactance is two and a half to three times of the capacitor reactance at fundamental frequency.

3.3.3.2 Mode 4: Inductive vernier mode



- In this mode the TCSC is operated by having a high level of thyristor conduction.
- In this mode the direction of the circulating current is reversed and the controller provides a net inductive impedance.

3.3.4 Variants of the TCSC

The TCSC has tw variants based on the three modes of operation. They are:

i. Thyristor-switched series capacitor (TSSC), which permits a discrete control of the capacitive reactance.

ii. Thyristor-controlled series capacitor (TCSC), which offers a continuous control of capacitive or inductive reactance.

3.4 Capability Characteristics of TCSC

The operation limits of the TCSC are determined based on the characteristics of different components of it. The limits are:

i. Voltage limit

The voltage limit is based on the insulation level of the equipment. But the voltage constriant will vary based on the duration of voltage application.

ii. Current limit

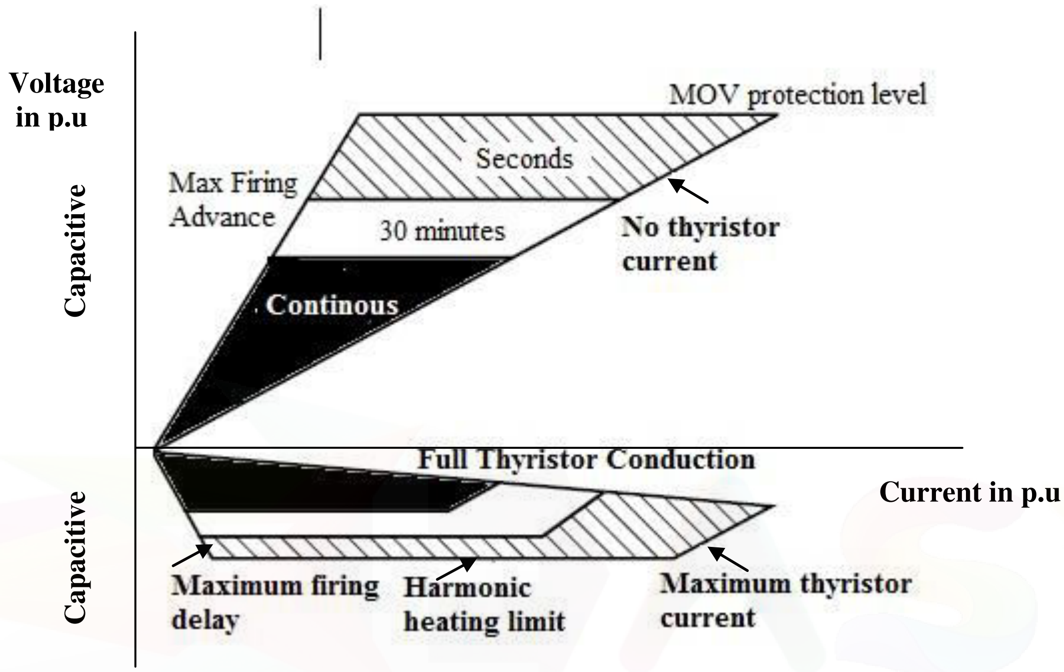
The current in the thyristor valve,fised capacitor and surge inductor have the limit based on the overheating of the component. Harmonics also causes overheating which has an influence in the operation of the TCSC.

iii. Firing angle limit of the thyristor

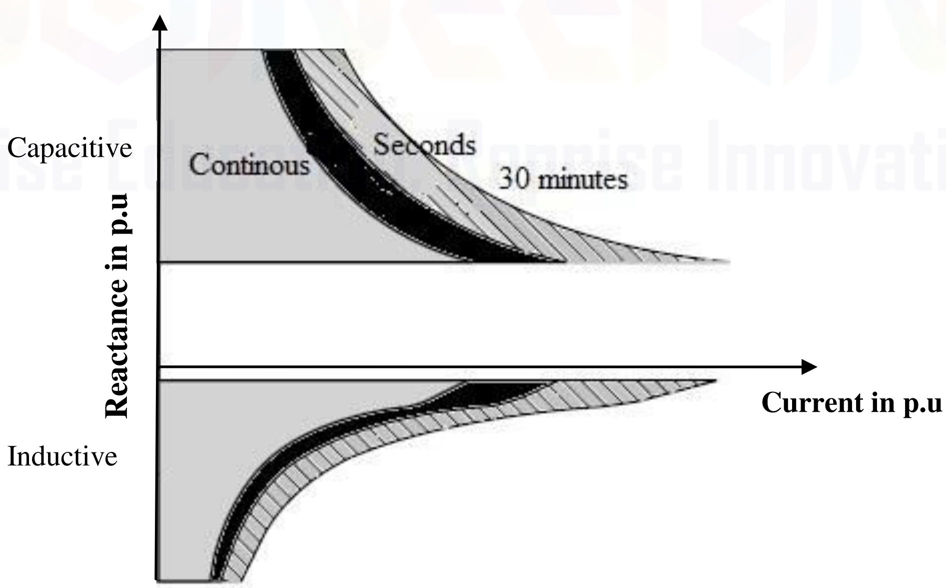
The firing angle of the TCSC should be resticted inorder to avoid entering into the resonant region.

3.4.1 Single module TCSC

- The capability curve of a single module TCSC is shown in fig.



- In both the capacitive and inductive zones, the operation is generally constrained between maximum and minimum reactance limit. The maximum reactance of TCSC is 2-3 p.u and the minimum limit is 1 p.u.



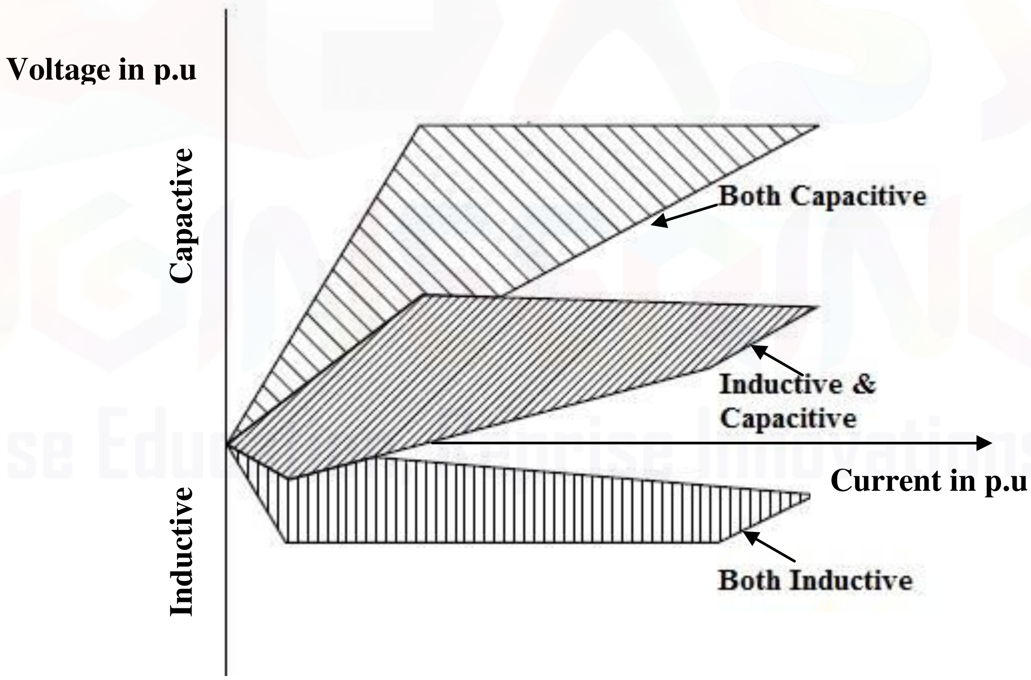
- In the inductive reactance zone, the maximum reactance limit is selected to prevent the TCSC from operating in the resonant region. Maximum inductive reactance is 2 p.u. The minimum inductive reactance is reached when the thyristors are fully conducting when α =

90^0. The increase in line currents makes the reactors and thyristors heated and the peak voltage closure to the limit of the capacitor and MOV.

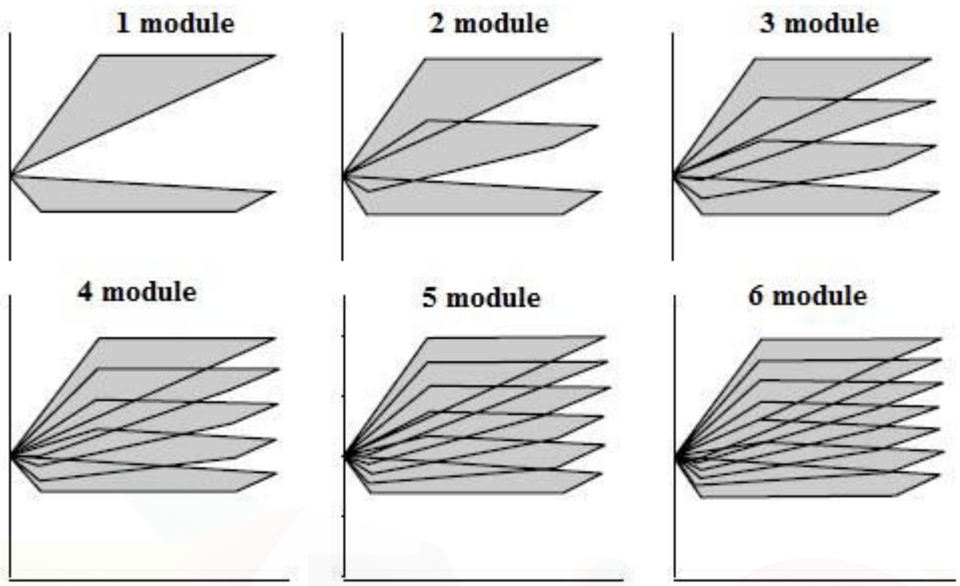
- The TCSC capability is provided in a reactance–line-current plane in Fig . The dynamic range of the TCSC reactance is reduced with increasing line current.
- A smooth transition from the inductive to capacitive region is not possible.
- The TCSC operates in the first quadrant of both the *V-I* and *X-I* characteristics.

3.4.2 Multi-module TCSC

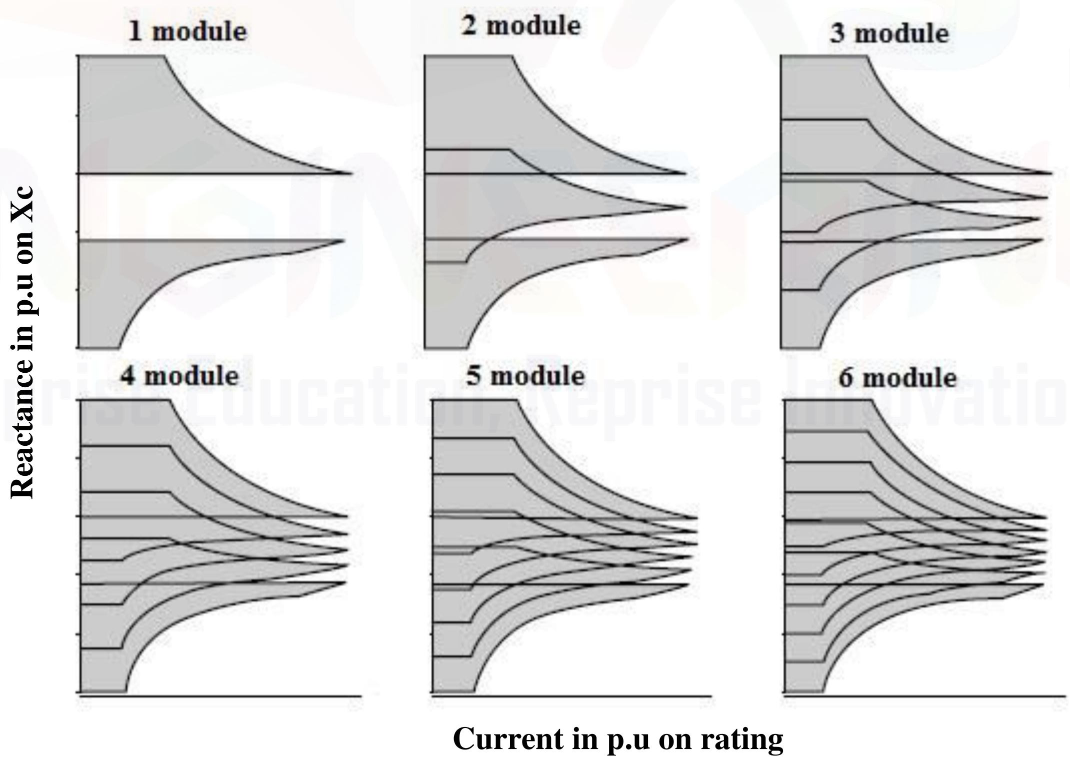
- In various power system applications a smooth variation in line reactance is desirable. So inorder to acheieve it a single TCSC is splitted into multiple modules.
- The spliited modules are operated seperately in inductive mode and capacitive mode.
- When the TCSC is spllitted into two modules, each with half MVA rating.
  - ✓ Similar operation of both modules in inductive mode or capacitive mode leads to capacbility curve same as single module TCSC.
  - ✓ Dissimilar operation leads to the intermediate characterisitcs.
  - ✓ It makes continous transition from capacitive to the inductive domain feasible.



- When the number of TCSC module increases, the control range of the TCSC for the same MVA rating increases.
- The modules are switched on and off if the desired reactance is less than the capacitive reactance of the bank.

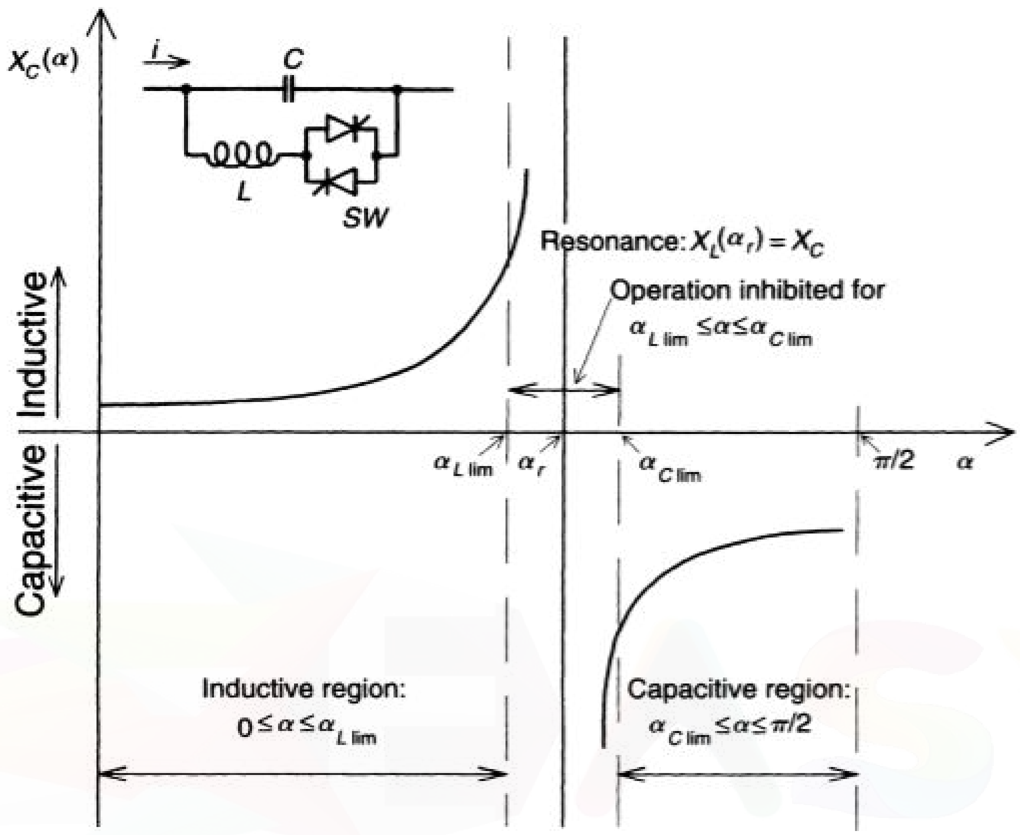


V-I capability characteristics of multimodule TCSC



X-I capability characteristics for a multimodule TCSC

3.4.3 Impedance- Delay angle characteristics



- The impedance of the TCSC is given $X_{TCSC} = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C}$

  Where $X_L(\alpha)$, variable inductive impedance $= X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha}, X_L < X_L(\alpha) < \infty$

  α is the ddelay angle measured from the crest of the capacitor voltage.
- The TCSC is a tunable parallel LC circuit to the line current that is substantially a constant alternating current source.
- As the impedance of the controlled reactor, $X_L(\alpha)$, is varied from its maximum (∞) toward its minimum (ωL), the TCSC increases its minimum capacitive impedance, $X_{TCSCmin}$ until parallel resonance at $X_C = X_L(\alpha)$ is established and $X_{TCSCmax}$, theoretically becomes infinite.
- Decreasing $X_L(\alpha)$ further, the impedance of the TCSC, $X_{TCSC}(\alpha)$ becomes inductive, reaching its minimum value of $\frac{X_C X_L}{X_L - X_C}$ at $\alpha = 0$, where the capacitor is in effect bypassed by the TCR. Therefore, with the usual TCSC arrangement in which the impedance of the TCR reactor, X_L, is smaller than that of the capacitor, X_C.
- There are two operating ranges of TCSC around its internal circuit resonance: one is the $\alpha_{Clim} \leq \alpha \leq \pi/2$ range, where $X_{TCSC}(\alpha)$ is capacitive, and the other is the $0 \leq \alpha \leq \alpha_{Llim}$ range, where $X_{TCSC}(\alpha)$is inductive. In the inductive mode, TCSC can control the power flow and can increase the impedance where as in the capacitive mode, the power flow rises and the impedance falls.
- In the bypassed mode the value of the firing angle α is taken as 0 degree, so the series capacitor bypassed and the whole TCSC works as a pure inductor.

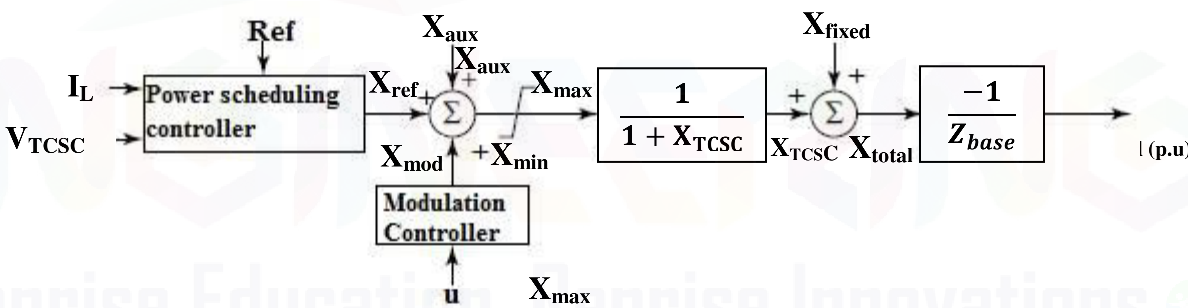
- In the blocking mode of operation, the value of the firing angle α is chosen π/2 degree, so that the anti parallel combination of the thyristor are in blocking mode and the whole circuit works as a fixed capacitor.

3.5 Modeling of TCSC – Variable Reactance model

- Variable reluctance model is a quasi-static approximation model which is widely used for transient and oscillatory stability studies because of its simplicity.
- This model is used for inter area mode analysis.
- In the model the TCSC dynamics during power swing frequencies are modeled by a variable reactance at fundamental frequency.
- The model provides high accuracy when the reactance boost factor is less than 1.5. Reactance boost factor $=\frac{X_{TCSC}}{X_C}$.
- **Assumptions:**

i. The variation of the TCSC response with various firing angles is neglected.
ii. The transmission line system operates in a sinusoidal steady state with the only dynamic associated with generator and PSS.
iii. Continuous reactance range is available

- In single module TCSC there is a discontinuity between the inductive and capacitive region of the reactance capability curve. But the gap is avoided by using multi-module TCSC.

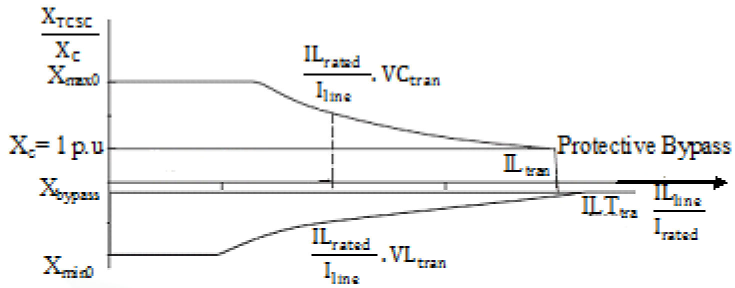


- The reference signal X_{ref} is generated from a power scheduling controller based on the power flow specification of the transmission line.
- The reference point is set by manual control and its represents the initial operating point of the TCSC.
- The reference value is modified by signal X_{mod} from a modulation controller for enhancing the damping.
- X_{aux} is an input signal from an external power flow controller.
- The desired value of x is obtained from a finite time delay caused by the firing controller and the natural response of TCSC. The valus of delay is 12-20 seconds.
- The output of the log is subjected to variable limits based on the TCSC reactance capability curve.
- X_{total} is the reactance of the installation of the DC component. $X_{total}=X_{TCSC}+X_{fixed}$.

- The TCSC model assigns a positive value to X_c. So X_{total} is multiplied by a negative sign to ensure consistency with the convention used in load flow and stability studies.
- The initial operating point of the TCSC is $Xref = X_{total} - X_{fixed}$.

3.5.1 Transient stability model

- The reactance capability curve for the multimodal TCSC is



- The curve is obtained by approximating the multimodal TCSC. The curve is acceptable for the TCSC variable reactance model and it includes the effect of TCSC transient overload levels.
- When over current occurs, some TCSC module moves into the bypass mode. It causes the line currents to decrease and makes the remaining module into the bypass mode.
- **In the capacitive region,** the different reactance in the module is due to:
  - i. Limit of firing angle, which is given by X_{max0}
  - ii. Limit of the TCSC voltage VC_{tran}. The reactance constraint of it is $XmaxVC = \frac{IL_{rated}}{I_{line}} VC_{tran}$
  - iii. The limit of the line current beyond which the TCSC moves into a protective bypass mode.

$X_{max\,I_{ine}} = \infty$ for $I_{line} < IL_{tran}\,IL_{rated}$

$X_{max\,I_{ine}} = X_{bypass}$ for $I_{line} > IL_{tran}\,IL_{rated}$

The effective capacitive reactance limit is obtained as a minimum of following limits: $X_{maxlimit} = \min\{ X_{max0}, X_{max\ Vc}, X_{maxIline}\}$

- **In the inductive region,** the TCSC operation is restricted by:
  - i. Limit of firing angle, which is given by X_{max0}
  - ii. The harmonic impoed limit represesnted by a constant TCSC voltage limit VL_{tran}.

$$XmaxVL = \frac{IL_{rated}}{I_{line}} VL_{tran}$$

  - iii. The limit of the fundamental component of the current that is permitted to flow through the thyristor in the bypass thyristor mode during transient.

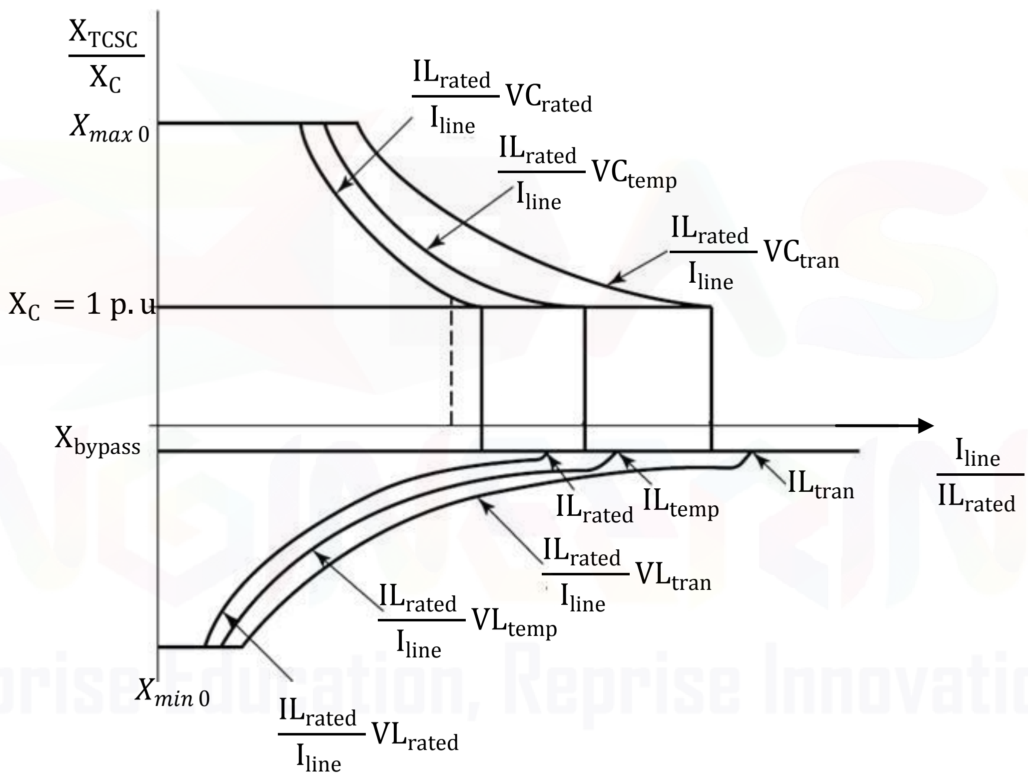
The total effective reactance is obtained as a maximum of the foregoing constraints

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

- If the TCSC is not operating at the inductive vernier mode, then the maximum reactance limit is X_{bypass}

3.5.2 Long term stability model of TCSC

- The capability curve depends on the duration of voltage and current operating condition.
- There are two time limited region in TCSC operation: They are transient overload region and temporary overload region. The transient overload region persists for 3-10 secs and the temporary overload region for 30 mins. They are followed by the continuous region.
- The X-I capability characteristics of a multimodule TCSC indicating time dependant overload limits is:



- In long-term dynamic simulations, an overload-management function is added to the control system. The function tracks the TCSC variables and their duration of application. It determines the appropriate TCSC overload range, and modifies $X_{max\ limit}$ and $X_{min\ limit}$. Then it applies the same modifications to the controller.
- The variable-reactance model does not account for the inherent dependence of TCSC response time on the operating conduction angle. Due to which incorrect results may be obtained for the high-conduction-angle operation of the TCSC or for whenever the power-swing frequency is high
- **Uses of the model:**
  - i. Commercial stability programs
  - ii. System planning studies
  - iii. Initial investigations of the effect of the TCSC in damping power oscillations