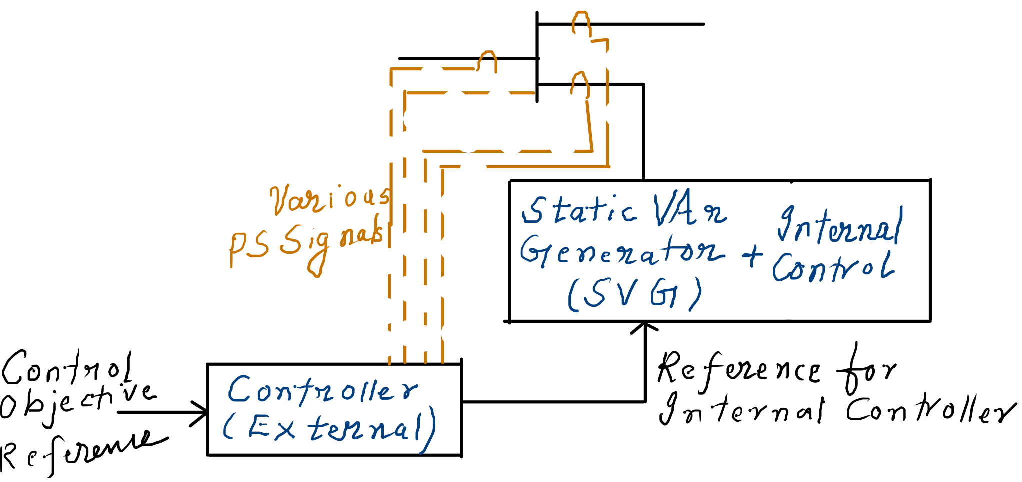
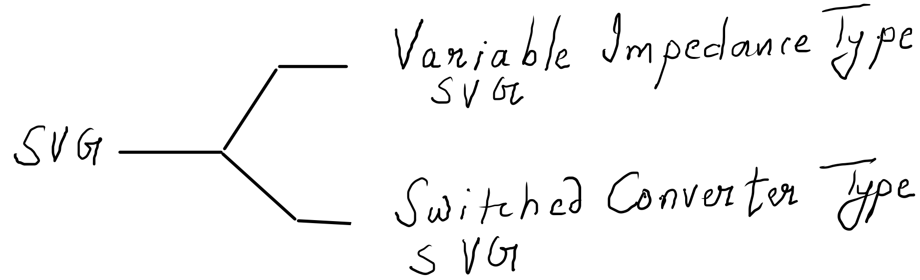
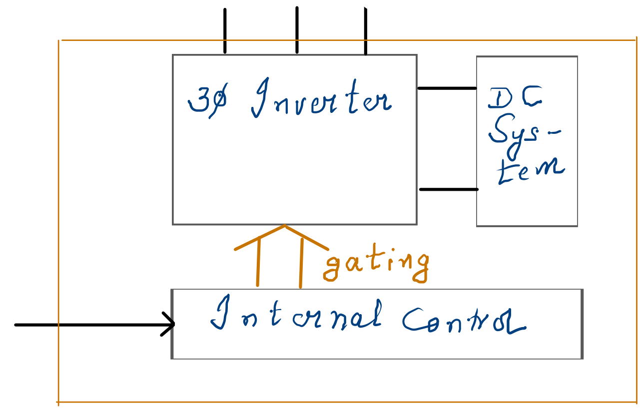
[You may use Chapter 5 from "Understanding FACTS" by Narain G. Hingorani & Laszlo Gyugyi as Reference Text for this Topic.]

Shunt Capacitive Compensation using fixed/switched Capacitors or SVC or STATCOM is routinely used at various locations in a Power System to derive various operational advantages.

SVC ? STATCOM ?







Static Synchronous Generator (SSG) if DC System has energy source.

Static Synchronous Condensor (SSC) if DC System is a Self-sustained DC Bus.

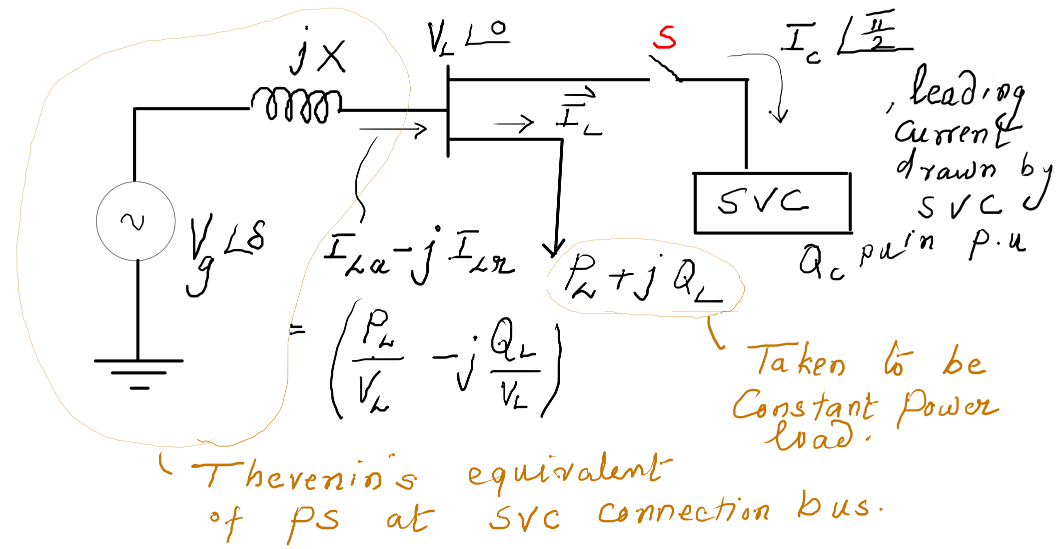
When the SVG is a Variable Impedance Type SVG, Then, SVG + External Controller is called SVC, Static VAr Compensator.

When the SVG is a SSC, Then, SSC + External Controller is called STATCOM, Static Synchronous Compensator.

Beneficial Effects of Shunt Capacitive Compensation

1. Improvement in Bus Voltages
2. Control of voltage profile over a long transmission line
3. Reduction in line flows
4. Release of Capacity of various equipment
5. Reduction of system losses everywhere
6. Increase of power Transfer capability of lines and consequent increase in transient stability limits
7. Improvement in voltage stability margins.
8. With fast controls, damping of power oscillations in lines and tie lines can be achieved by varying shunt compensation level suitably.

Shunt Compensation for Voltage Support at T/ST/D Levels

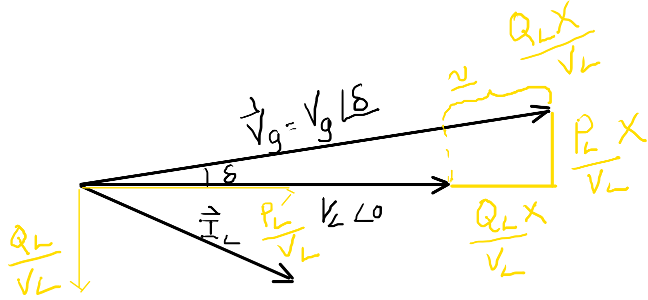


With S open, bus voltage is V_L p.u.

With S closed, bus voltage is $V_L' = V_L + \Delta V_L$ pu

What is ΔV_L ?

We find V_L and δ first with the help of a phasor diagram.



$$\therefore \; V_g \simeq V_L + \frac{Q_L X}{V_L} \quad \& \quad \delta \simeq \frac{\frac{P_L X}{V_L}}{V_L + \frac{Q_L X}{V_L}} \text{ rad}$$

Solving this,

$$\Rightarrow V_L^2 - V_g V_L + Q_L X = 0$$

$$V_L = \frac{V_g \pm V_g \sqrt{\left(1 - \frac{4 Q_L X}{V_g^2}\right)}}{2}$$

$$\simeq \frac{V_g \pm V_g \left(1 - \frac{2 Q_L X}{V_g^2}\right)}{2}$$

$$= V_g - \frac{Q_L X}{V_g}$$

$$X_c = \frac{1}{\omega C}$$

$$\frac{V_L}{X_C} = I_C$$

[Note : If V_L can be assumed to be very close to 1 pu, Then I_{Lr} is very close to Q_L itself in pu and

$$V_g \simeq V_L + I_{Lr} X$$
$$= V_L + Q_L X$$

So $V_L = V_g - X Q_L$ can be used]

Now WITH S CLOSED, the leading reactive current drawn by the SVC will depend on whether it is a fixed capacitor or variable impedance type or STATCOM. We look at all the 3 cases assuming same capacitive rating of Q_c p.u for all.

Case 1 : Fixed Capacitor of value C such that it consumes Q_c pu leading reactive power from nominal voltage of 1 pu.

$\therefore$ Current taken by C when bus voltage is 1 pu $= I_c = Q_c$ pu numerically

$\therefore X_c$ in pu $= \dfrac{1 \text{ pu voltage}}{Q_c \text{ pu current}} = \dfrac{1}{Q_c}$

$\therefore I_c$ drawn when voltage is V_L' pu $= Q_c V_L'$ pu

$\therefore$ Net reactive current flowing through X with C acting $= \left(\dfrac{Q_L}{V_L'} - Q_c V_L'\right)$ pu lag

$$\therefore V_L' \simeq V_g - \left(\frac{Q_L}{V_L'} - Q_c V_L'\right) X$$

$$\therefore V_L'^2 (1 - Q_c X) - V_g V_L' + Q_L X = 0$$

ie $$V_L'^2 - \frac{V_g}{1 - Q_c X} V_L' + \frac{Q_L X}{1 - Q_c X} = 0$$

$$V_L' = \frac{V_g}{2(1 - Q_c X)}\left(1 \pm \sqrt{1 - \frac{4 Q_L X (1 - Q_c X)}{V_g^2}}\right)$$

$$\simeq \frac{V_g}{1 - Q_c X}\left(1 - \frac{Q_L X (1 - Q_c X)}{V_g^2}\right)$$

$$= \frac{V_g}{\underbrace{1 - Q_c X}_{\text{usually} \ll 1}} - \frac{Q_L X}{V_g}$$

$$\simeq V_g (1 + Q_c X) - \frac{Q_L X}{V_g}$$

$$= \left(V_g - \frac{Q_L X}{V_g}\right) + Q_c X V_g$$

$$= V_L + Q_c X V_g$$

$$\therefore \Delta V_L = Q_c X V_g$$

[Note : ~~If~~ of V_g & V_L' are close to 1 pu, $I_c \simeq Q_c$, and reactive current in $X \simeq Q_L - Q_c$

$V_L' = V_g - (Q_L - Q_c) X = (V_g - Q_L X) + Q_c X$

and $\Delta V_L = Q_c X$]

We can express the voltage improvement ΔV_L in terms of bus voltage V_L before switching on the shunt compensation equipment as below.

$$V_g \simeq V_L + \frac{Q_L X}{V_L}$$

$$\Delta V_L = Q_c X V_g \text{ pu}$$

$$= Q_c X \left(V_L + \frac{Q_L X}{V_L} \right)$$

$$\therefore \% \text{ Improvement} = \frac{\Delta V_L}{V_L} \times 100 = Q_c X \left(1 + \frac{Q_L X}{V_L^2} \right) 100 \ \%$$

[If you want to calculate % improvement even before you know the value of V_L, you may use $V_L \simeq 1$ pu and calculate % Improvement $= Q_c X (1 + Q_L X) \times 100$ provided $V_L \simeq 1$ pu is justified.

For example, say $V_g = 1.05$ pu, $Q_L = 1$ pu, $X = 0.1$ pu

Then $V_L = V_g - \dfrac{Q_L X}{V_g} = 1.05 - \dfrac{0.1 \times 1}{1.05}$

$= 0.9548$ pu

Let $Q_c = 0.75$ pu

Then % improvement $= 0.075\left(1 + \dfrac{0.1}{.9548^2}\right) \times 100 = 8.32\%$

If V_L is not calculated and is taken as $\simeq 1$ pu

% improvement $= 0.075(1 + 0.1) \times 100 = 8.25\%$

$\Delta V_L = 0.9548 \times \dfrac{8.32}{100} = 0.0794$ pu in the first case and $= 1 \times 0.0825 = 0.0825$ pu in the second case. They are close.]

Case 2: Variable Impedance Type SVC with rating Q_c pu.

Here, the value of capacitance can be varied from 0 to C (same value as in Case 1). So ΔV_L can vary from 0 to $Q_c X V_g$ pu.

Case 3: STATCOM with rating of Q_c pu.

Rated current of STATCOM $= \frac{Q_c \text{ pu}}{1 \text{ pu}} = Q_c$ pu.

STATCOM can deliver this much current at any bus voltage.

$\therefore I_c = Q_c$ pu always.

$\therefore$ Reactive current in $X = \frac{Q_L}{V_L'} - Q_c$

$$\therefore V_g = V_L' + \frac{Q_L X}{V_L'} - Q_c X$$

$$\therefore V_L'^2 - (V_g + Q_c X) V_L' + Q_L X = 0$$

$$V_L' = \frac{(V_g + Q_c X) \pm \sqrt{(V_g + Q_c X)^2 - 4 Q_L X}}{2}$$

$$= \frac{(V_g + Q_c X)}{2} \left(1 \pm \sqrt{1 - \frac{4 Q_L X}{(V_g + Q_c X)^2}} \right)$$

$$= \frac{V_g + Q_c X}{2} \left(1 + 1 - \frac{2 Q_L X}{(V_g + Q_c X)^2} \right)$$

$$= (V_g + Q_c X) \left(1 - \frac{Q_L X}{(V_g + Q_c X)^2} \right)$$

$$= V_g + Q_c X - \frac{Q_L X}{V_g + Q_c X}$$

$$= V_g + Q_c X - \frac{Q_L X}{V_g\left(1 + \frac{Q_c X}{V_g}\right)}$$

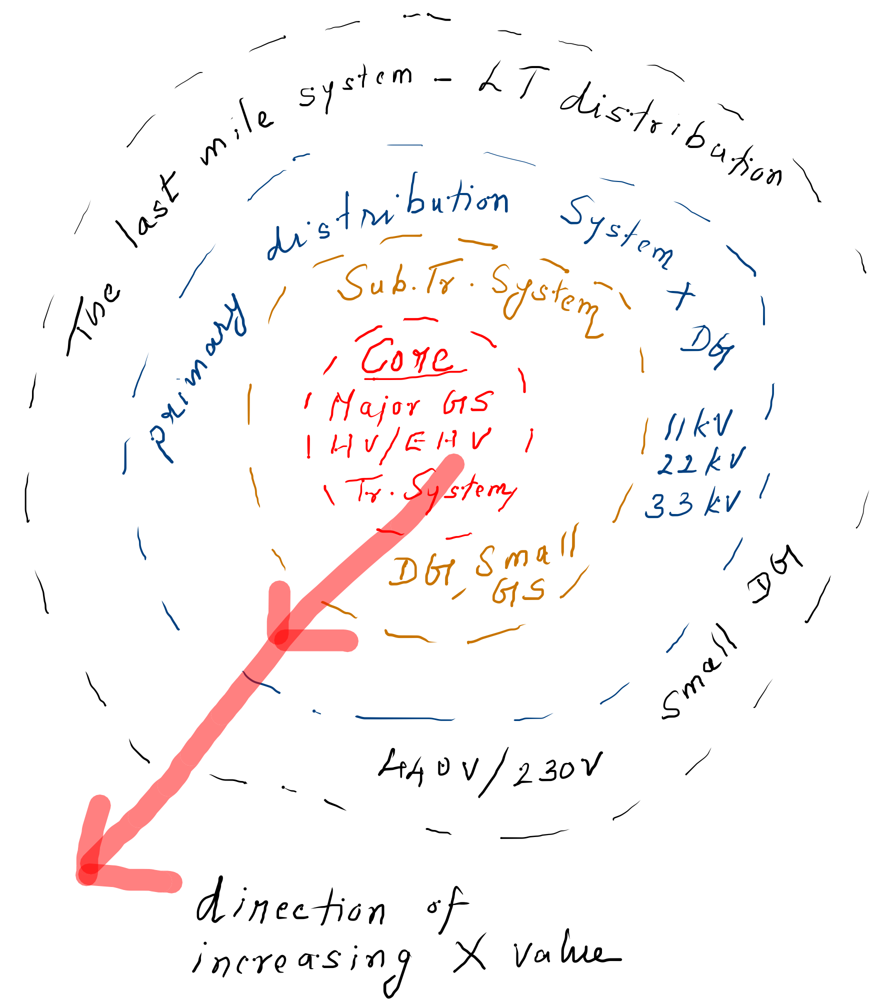
$$\simeq V_g + Q_c X - \frac{Q_L X}{V_g}\left(1 - \frac{Q_c X}{V_g}\right)$$

$$= \overbrace{\left(V_g - \frac{Q_L X}{V_g}\right)}^{V_L} + \overbrace{Q_c X\left(1 + \frac{Q_L X}{V_g^2}\right)}^{\Delta V_L}$$

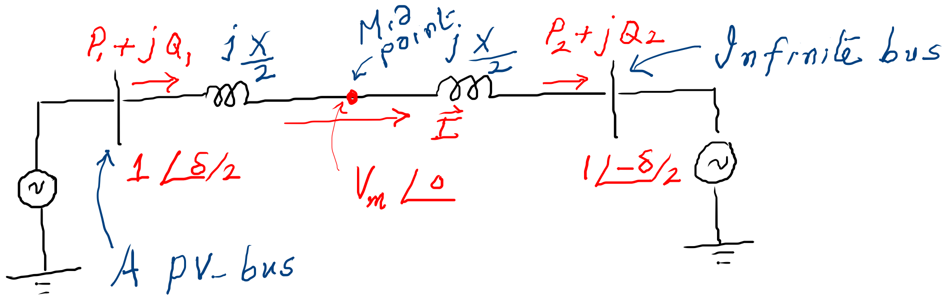
$$\therefore \Delta V_L = Q_c X\left(1 + \frac{Q_L X}{V_g^2}\right)$$

- Importance of X value for a given Q_c value in creating bus voltage improvement.

X versus location in a Power System.



Mid-Point Shunt Compensation of a Long Transmission Line for Increasing Power Transfer Capability



$$P_1 = \frac{V_1V_2}{X}\sin\delta$$

$$P_2 = \frac{V_1V_2}{X}\sin\delta$$

$$P_X = 0$$

$$Q_1 = \frac{V_1\left[V_1 - V_2\cos\delta\right]}{X}$$

$$Q_2 = \frac{V_2\left[V_1\cos\delta - V_2\right]}{X}$$

$$Q_X = Q_1 - Q_2 = \frac{V_1^2 - 2V_1V_2\cos\delta + V_2^2}{X}$$

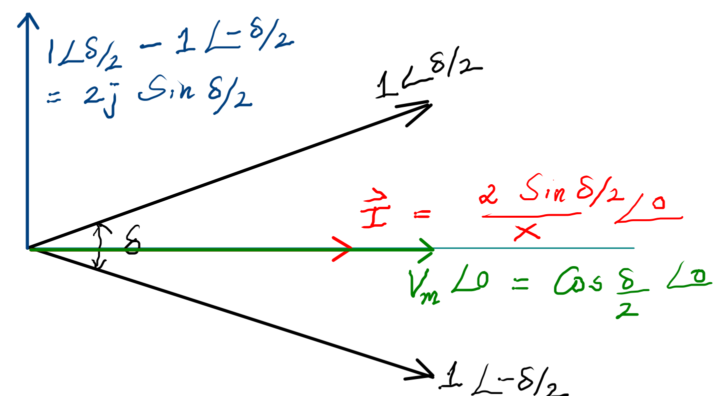
Since $V_1 = V_2 = 1$ pu,

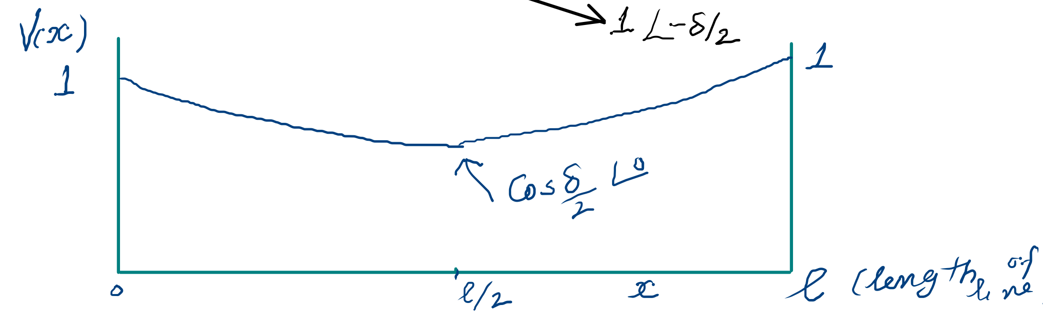
$$P_1 = P_2 = \frac{1}{X}\sin\delta \quad \text{p.u}$$

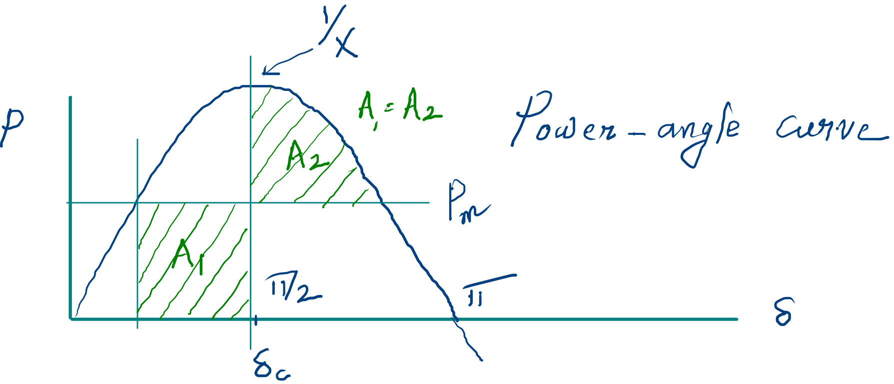
$$Q_1 = \frac{1-\cos\delta}{X} = \frac{2\sin^2\delta/2}{X} \quad \text{p.u}$$

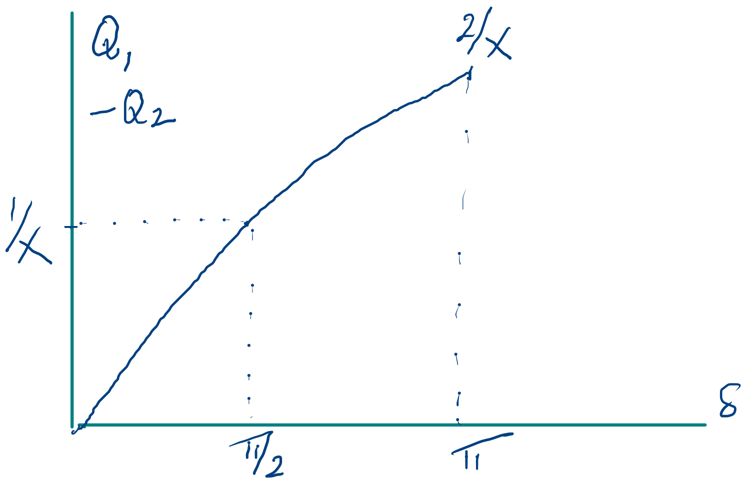
$$Q_2 = \frac{\cos\delta - 1}{X} = \frac{-2\sin^2\delta/2}{X} \quad \text{p.u}$$

$$Q_x = \frac{4\sin^2\delta/2}{X} \quad \text{p.u.}$$

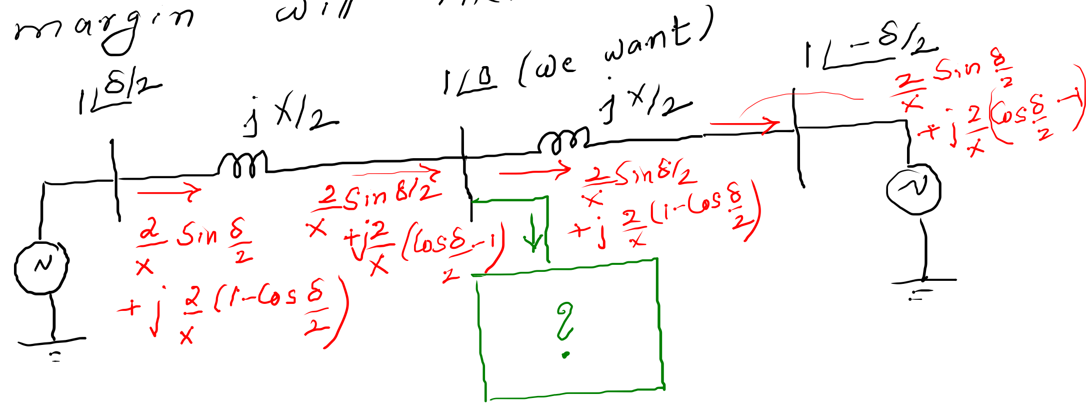






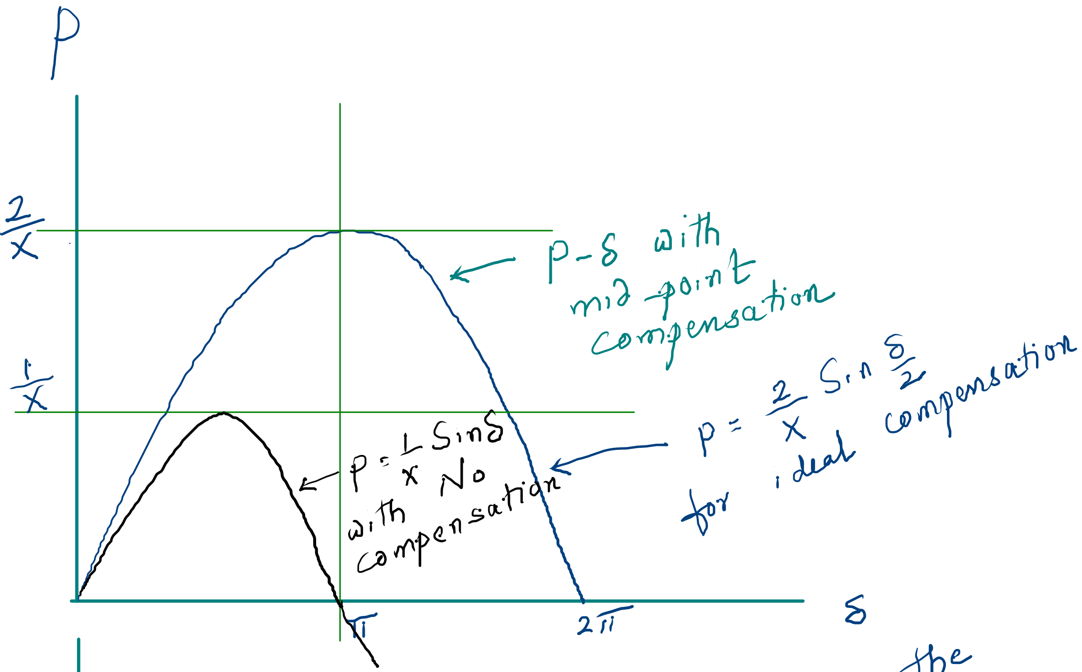


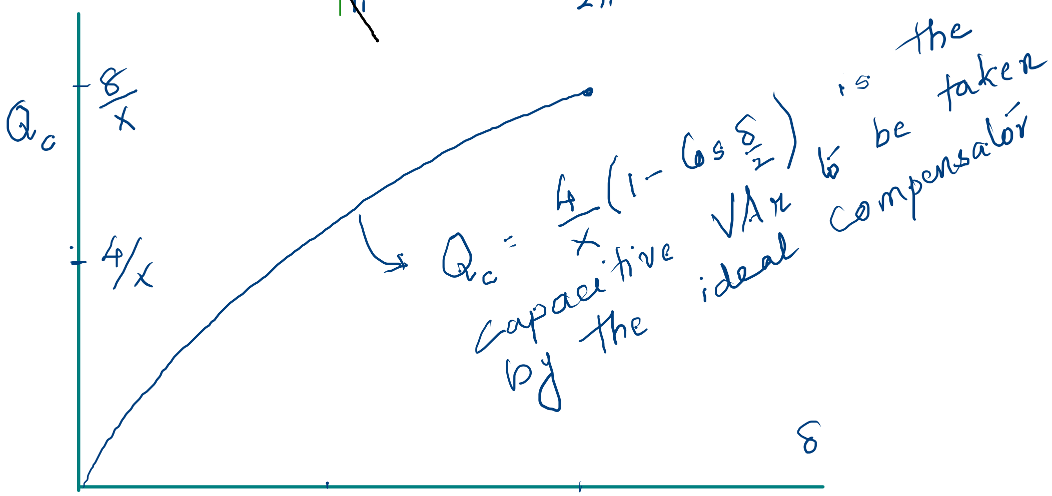
We want to maintain midpoint voltage at $1\angle 0$ so that the line will get sectionalised in to two shorter lines each with $X/2$, and both driven by PV buses at sending and receiving ends. Then $P-\delta$ curve of both lines will become $\frac{2}{X}\sin\delta/2$ and transient stability margin will increase.



∴ Reactive Power Taken by this equipment must be $= j\,\frac{4}{X}\left(\cos\frac{\delta}{2}-1\right) = -j\,\frac{4}{X}\left(1-\cos\frac{\delta}{2}\right)$

$= -j\,Q_c$

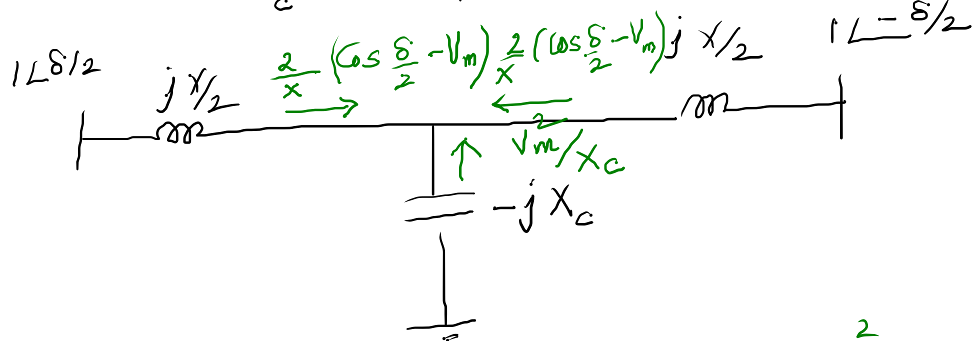




Case 1: Compensator is a fixed Capacitor of Q_c pu rating

Q_c is the reactive power at 1 pu voltage. So $X_c = \frac{1}{Q_c}$ in pu

So reactive power at voltage V_m is $= Q_c V_m^2$ pu



$$\frac{2}{X}\left(\cos\frac{\delta}{2}-V_m\right)+\frac{2}{X}\left(\cos\frac{\delta}{2}-V_m\right)+\frac{V_m^2}{X_c}=0$$

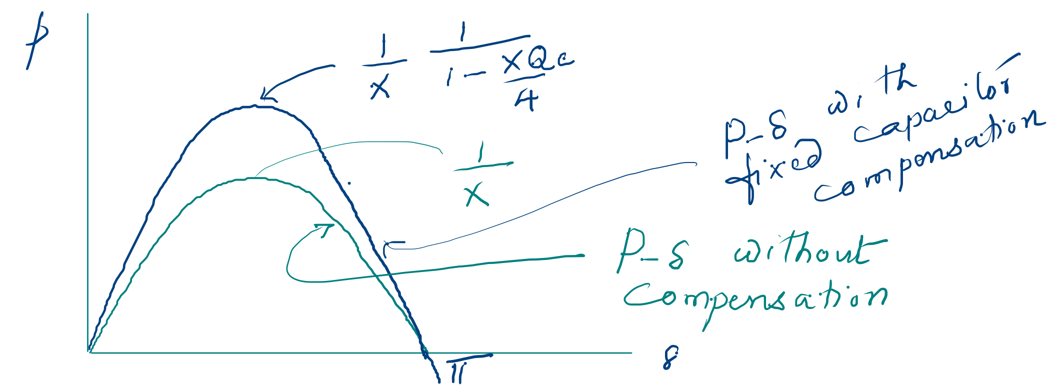
Since $X_c = \frac{1}{Q_c}$ & solving for V_m,

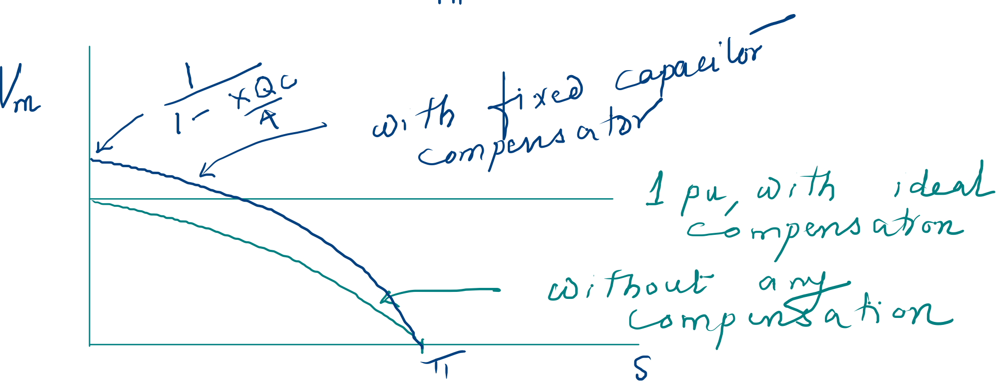
$$V_m = \frac{\cos\delta/2}{1-\frac{X Q_c}{4}}$$

STATIC VAR COMPENSATORS AND THEIR CONTROL

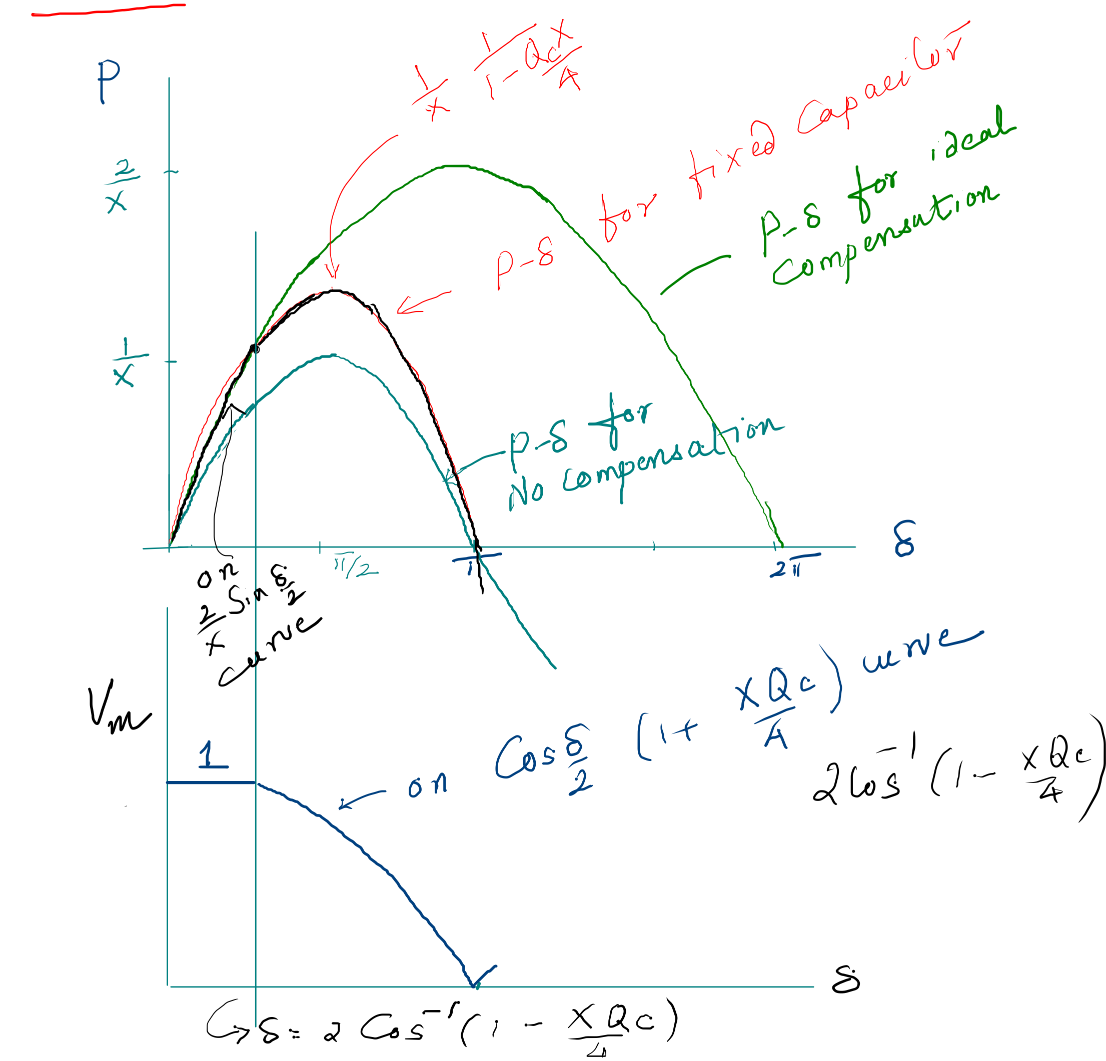
So, $P = \dfrac{1}{X/2} \cdot \dfrac{\cos\delta/2}{1 - \frac{XQ_c}{4}} \times 1 \times \sin\delta/2$

$= \dfrac{\sin\delta}{X} \cdot \dfrac{1}{1 - \frac{XQ_c}{4}}$



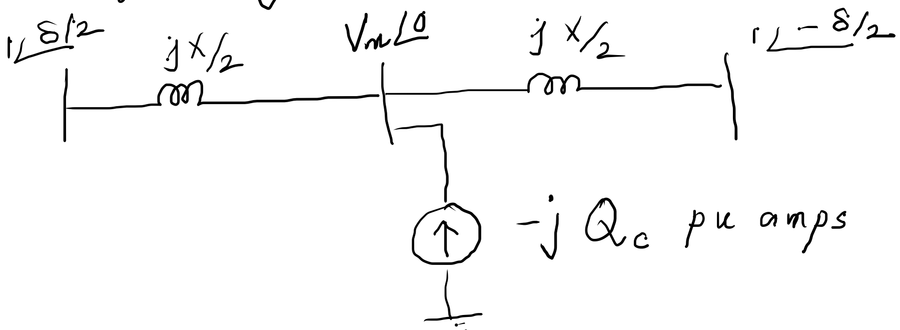


Case 2: SVC with rating Q_c pu



Case 3 : STATCOM of rating Q_c pu

After the STATCOM reaches limit, the following circuit comes into effect



By Super position Principle,

$$V_m = \cos\delta/2 + \frac{Q_c X}{4}$$

So,

$$P = \frac{1 \times \left(\frac{Q_c X}{4} + \cos\delta/2\right)}{X/2} \sin\delta/2$$

$$= \frac{\sin\delta}{X} + \frac{Q_c}{2}\sin\frac{\delta}{2}$$

STATCOM reaches limit at

$$\delta = 2\cos^{-1}\left(1 - \frac{XQ_c}{4}\right)$$