Module 2

Static Shunt Compensators: SVC and STATCOM

Objectives of Shunt Compensation

- The steady state transmittable power can be increased and the voltage profile along the line can be controlled by appropriate reactive shunt compensation.

- The shunt connected, fixed or mechanically switched inductors are applied to minimize line overvoltage under light load conditions and shunt connected fixed or mechanically switched capacitors are applied to maintain voltage levels under heavy load conditions.

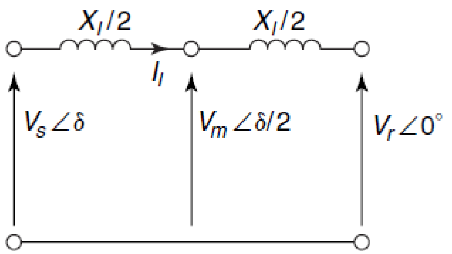
- The ultimate objective of applying reactive shunt compensation in a transmission system is to increase the transmittable power. This also helps in improving the stability of the system.

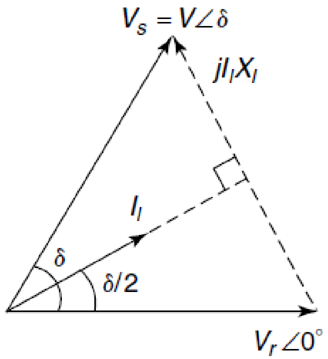
- VAR compensation is thus used for voltage regulation at the midpoint or some intermediate segment of the transmission line and at the end of the radial line to prevent voltage instability, as well as for dynamic voltage control to increase transient stability and damp power oscillations.

Midpoint Voltage Regulation for Line Segmentation

Uncompensated Case: Let us consider a simplified model of the uncompensated system.

Let $|V_S|=|V_R|=V$. The voltage at the midpoint of the line is V_M which is the minimum voltage in the voltage profile.





The real power of line $$P = \frac{V^2}{X_l} \sin\delta = \frac{V^2}{X_l} 2\sin\frac{\delta}{2}\cos\frac{\delta}{2}$$

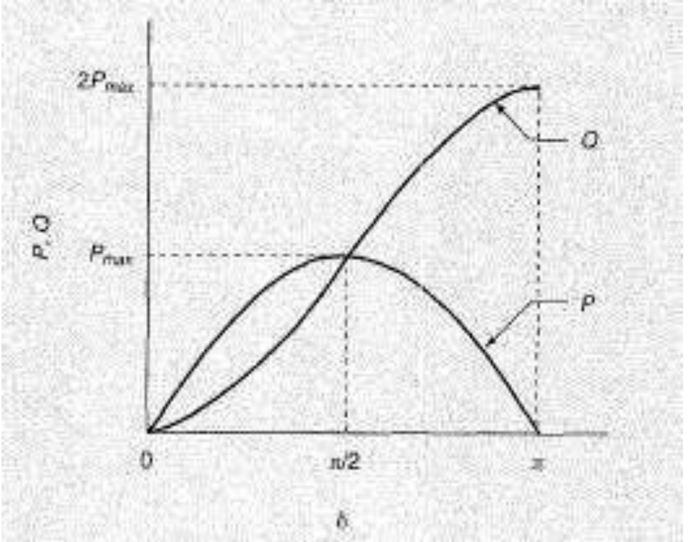
From the phasor diagram, $$I_l = \frac{2V}{X_l}\sin\frac{\delta}{2}$$

The line absorbs reactive power Q, as a function of the line current.

$Q=I^2X=4V^2/Sin^2\delta/2=2V^2/X(1-Cos\delta)$----------(3)

$P = V^2/X \, Sin\delta = P_{max} \, sin\delta$------------(1)

$Q = (2V^2/X)(1 - Cos\delta) = 2P_{max}(1 - Cos\delta)$



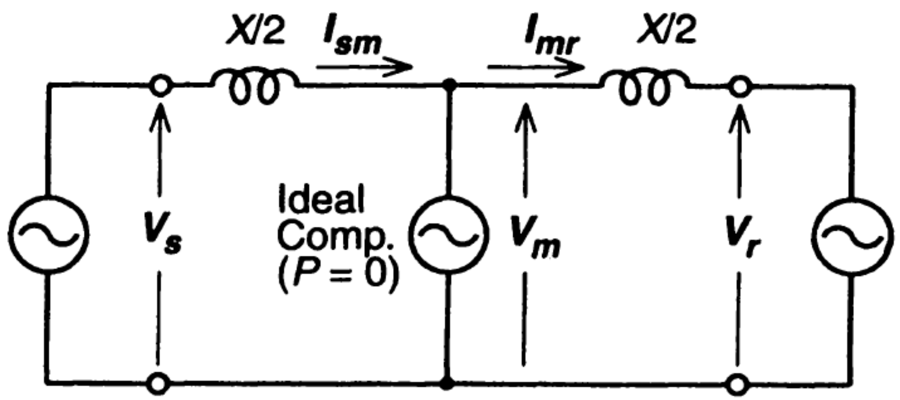
If the line is naturally loaded then the voltage profile would be flat i.e the voltage magnitude would be equal at all points along the line and no compensation is requ ired.

Thus the application of line compensation can be seen as a means of approximating a flat voltage profile. This , however, implies that compensation is distribut ed along the line which is clearly impractical.

So , the next best approach is to provide compensation at the midpoint, which will divide the line into two equal sections.

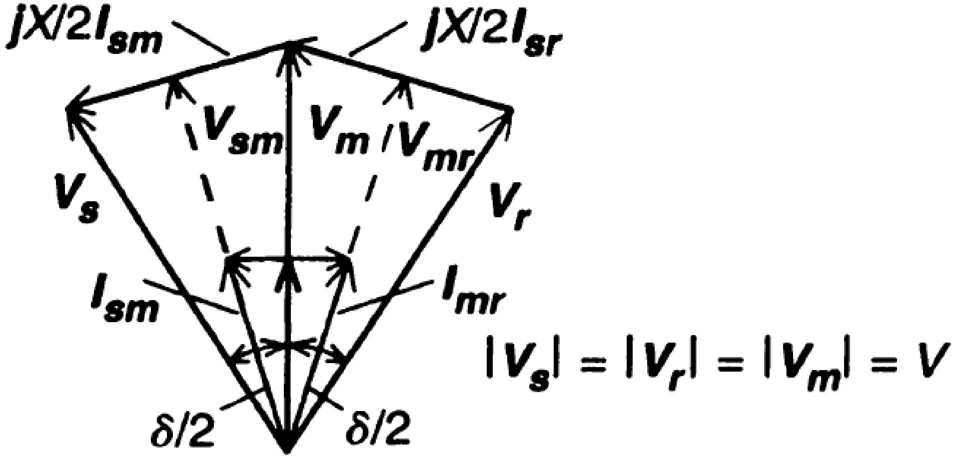
$$V_{sm} = V_{mr} = V\cos\frac{\delta}{4}; \qquad I_{sm} = I_{mr} = I = \frac{4V}{X}\sin\frac{\delta}{4}$$

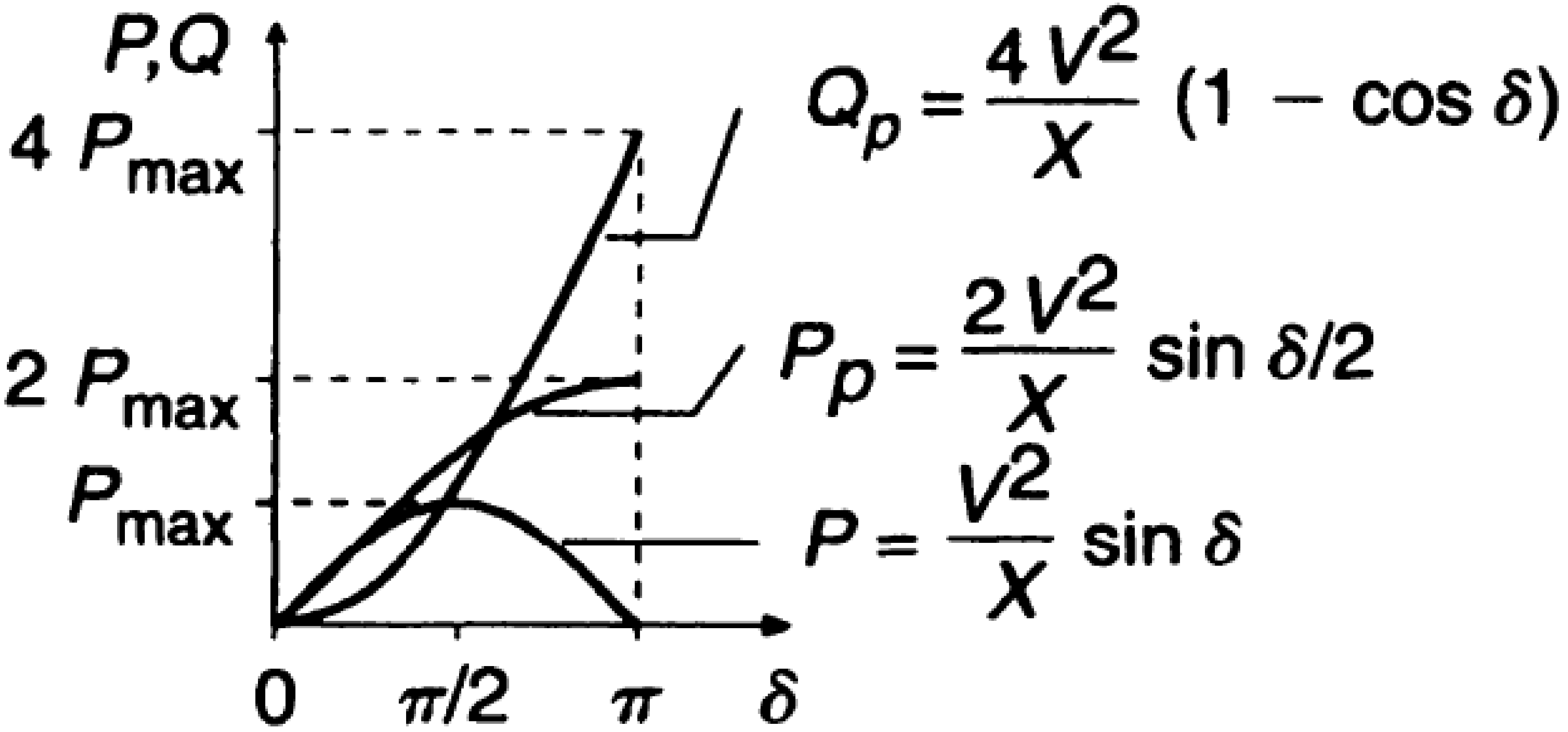
$$P = V_{sm}I_{sm} = V_{mr}I_{mr} = V_m I_{sm}\cos\frac{\delta}{4} = VI\cos\frac{\delta}{4}$$



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

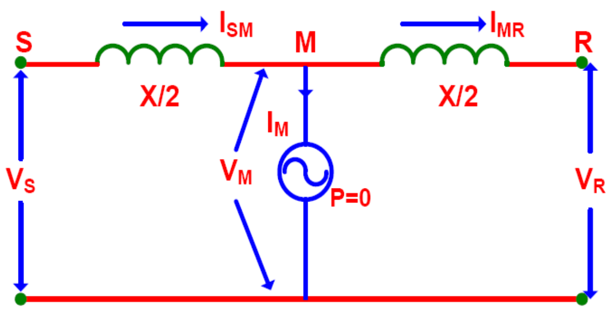
$$Q = VI\sin\frac{\delta}{4} = \frac{4V^2}{X}\left(1 - \cos\frac{\delta}{2}\right)$$



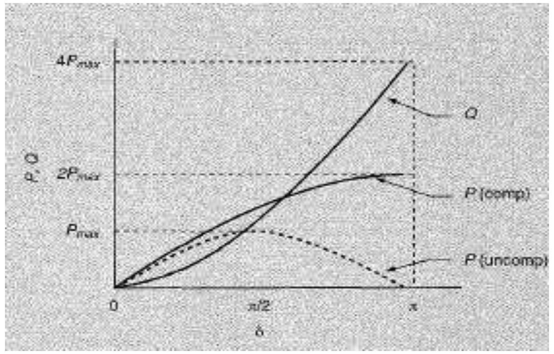


P,Q
4 P_{max}
2 P_{max}
P_{max}
0
π/2
π
δ
$Q_p = \frac{4V^2}{X}(1 - \cos\delta)$
$P_p = \frac{2V^2}{X}\sin\delta/2$
$P = \frac{V^2}{X}\sin\delta$

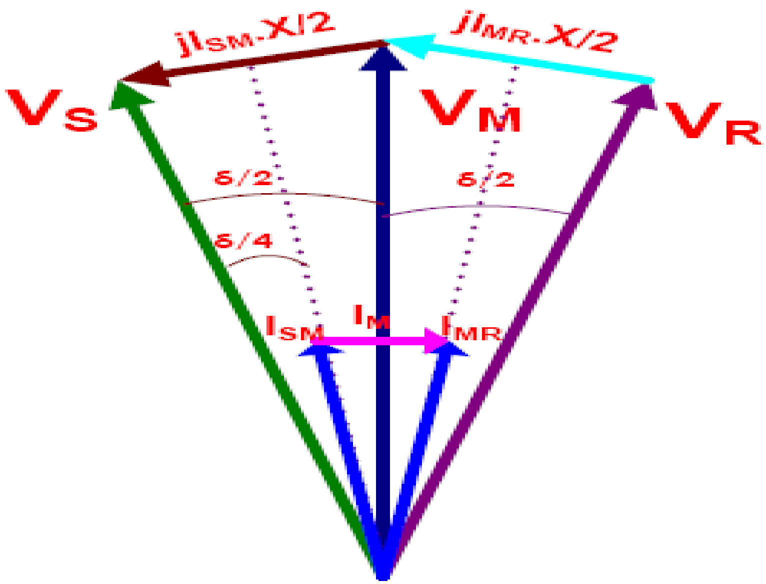
Mid point compensation



The figure shows the arrangement of the ideal midpoint shunt compensator which maintains a voltage ,V_M, equal to bus voltages such that $|V_S|=|V_R|=|V_M|=V$



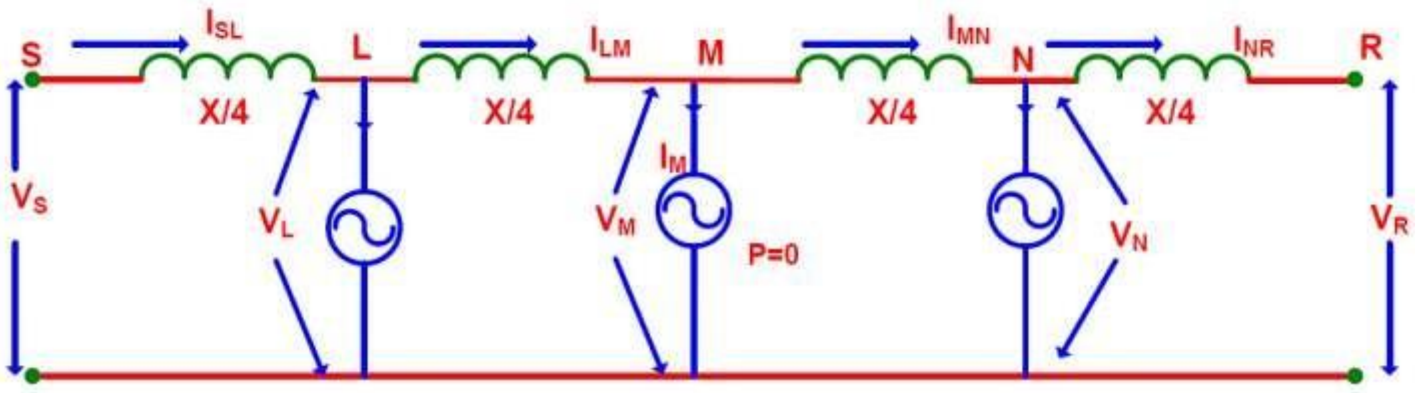
The compensator does not consume any real power (P=0) since the compensator voltage V_M, and its current I_M are in quadrature.



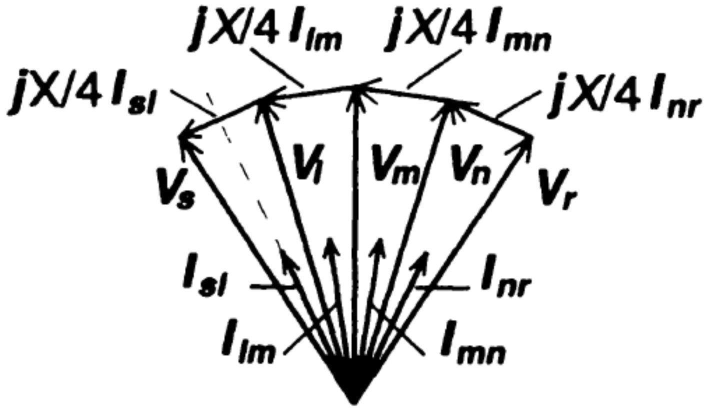
$$P=2V^2/X \, Sin\delta/2=2P_{max} \, sin\delta/2$$

$$Q_P=4V^2/X(1-Cos\delta/2)$$

- It is observed that the midpoint shunt compensation can significantly increase the transmittable power(doubling its maximum value) at the expense of a rapidly increasing reactive power demand on the midpoint compensator.
- With long transmission lines a single midpoint compesator may not be adequate to prop up the line voltage and several shunt compensator cnnected at intervals down the line may be needed.
- Theoretically, the transmittable power would double with each doubling of the segments for the same overall line length.
- With the increase of the no. of segments the voltage variation along the line would rapidly decrease approaching the ideal case of constant voltage profile.



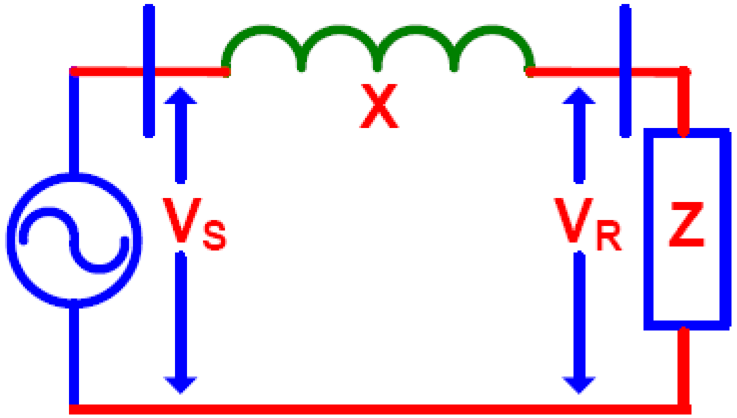
The concept of transmission line segmentation can be expanded to the use of multiple compensators, located at equal segments of the transmision line as illustrated for 4 line segments



End of Line Voltage Support to prevent Voltage Instability

The assumption of adequate reactive power control at the receiving end to maintain a constant voltage will not in general apply where the receiving end represents a load centre with little or no generation

A simple radial system with feeder line reactance X and load impedance Z is shown.

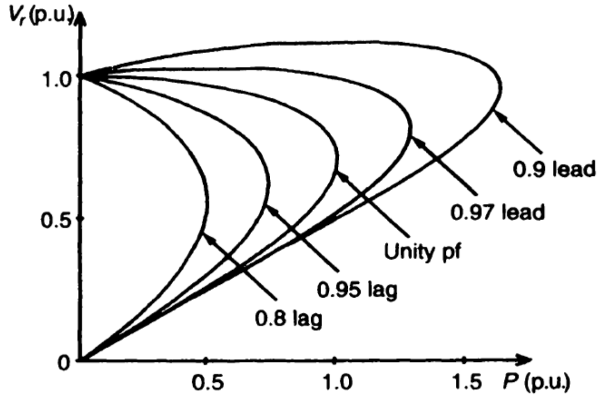


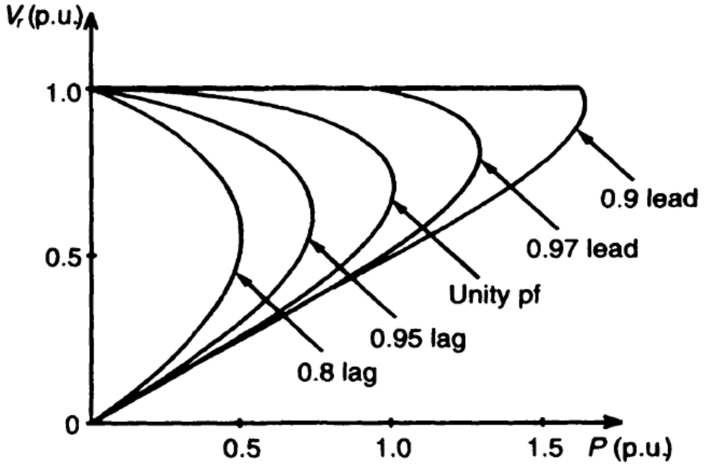
The normalised terminal voltage V_R versus power P plot at various load power factors, ranging from 0.8 lag to 0.9 lead.

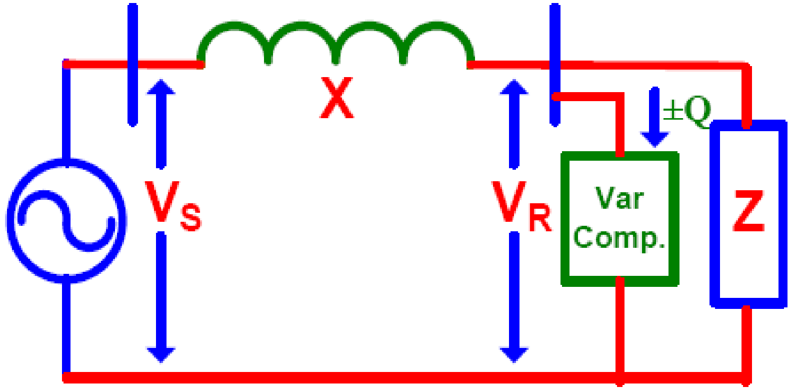
The nose-point at each plot given for a specific power factor represents the voltage instability corresponding to that system condition.

End of Line Voltage Support to prevent Voltage Instability

It is evident that for a radial line, the end of the line, the end of the line, where the largest voltage variation is experienced, is the best location for the compensator.







Reactive shunt compensation is often used in practical applications to regulate the voltage at a given bus against load variations or to provide voltage support for the load .

Improvement of Transient Stability

The transient stability studies involve the determination of whether or not synchronism is maintained after the machine has been subjected to severe disturbance. This may be sudden application of load, loss of generation, loss of large load or a fault on the system.

A method known as the equal area criterion can be used for a quick prediction of stability.

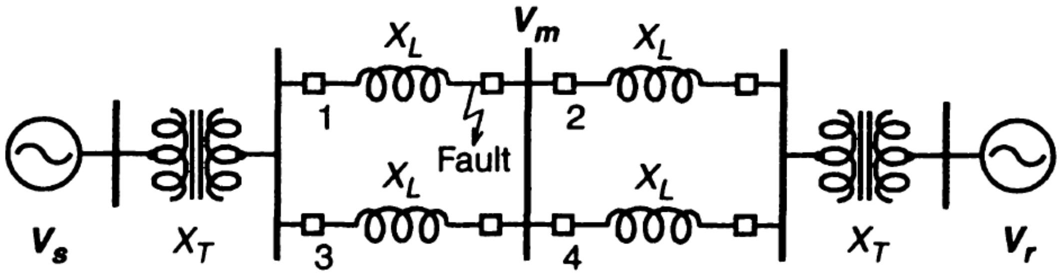
This method is based on the graphical interpretation of the energy stored in the rotating mass as an aid to determine if the machine maintains its stability after a disturbance.

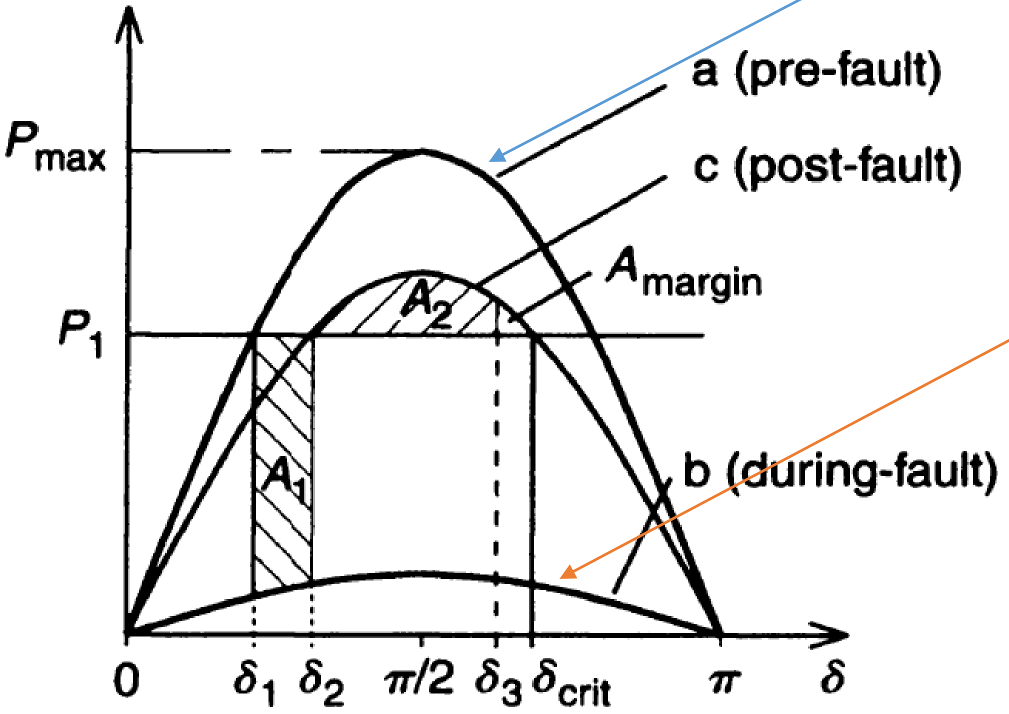
This method is only applicable to a one machine system connected to an infinite bus or a two machine system.

- With suitable and fast controls, shunt compensation will be able to change the power flow in the system during and following dynamic disturbances so as to increase the transient stability limit and provide effective power oscillation damping

- The potential effectiveness of shunt (as well as other compensation and flow control techniques) on transient stability improvement can be conveniently evaluated by the *equal area criterion*.

- The meaning of the equal area criterion is explained with the aid of the simple two machine (the receiving end is an infinite bus), two line system shown in Figure.





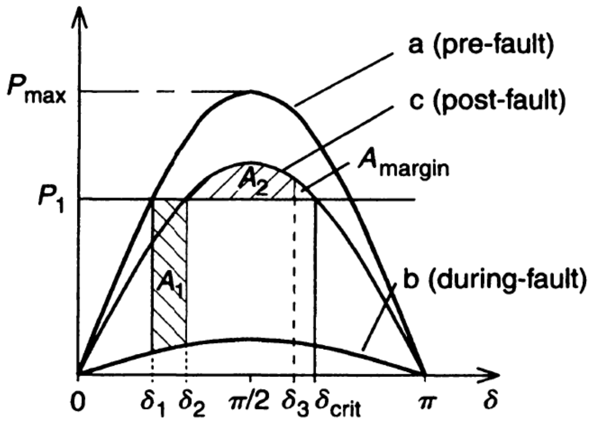
Assume that the complete system is characterized by the *P* versus delta curve "a" and is operating at angle delta1 to transmit power Pl when a fault occurs at line segment "I.“

During the fault the system is characterized by the *P* versus delta curve *"b"* and thus, over this period, the transmitted electric power decreases significantly while mechanical input power to the sending-end generator remains substantially constant corresponding to *P1;*

As a result, the generator accelerates and the transmission angle increases from delta1 to delta2 at which the protective breakers disconnect the faulted line segment "1" and the sending-end generator 'absorbs *accelerating* energy, represented by area *"A1."*

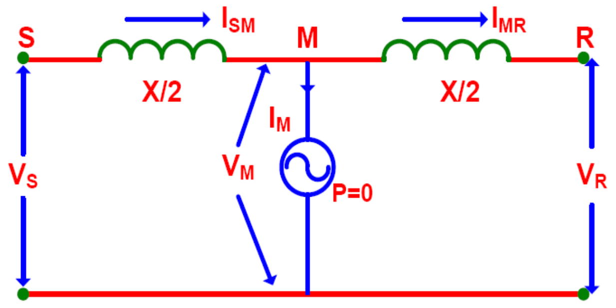
After fault clearing, without line segment "1" the degraded system is characterized by the *P* versus B curve "c." At angle delta2 on curve "c" the transmitted power exceeds the mechanical input power *PI* and the sending end generator starts to decelerate; however, angle delta further increases due to the kinetic energy stored in the machine. The maximum angle reached at *delta3,* where the decelerating energy, represented by area *"A2, "*becomes equal to the accelerating energy represented by area *"AI".*

The limit of transient stability is reached at delta 3 = *delta cri,* beyond which the decelerating energy would not balance the accelerating energy and synchronism between the sending end and receiving end could not be restored. The area *"Amargin,"* between B3 and deltacri represent the transient stability margin of the system.



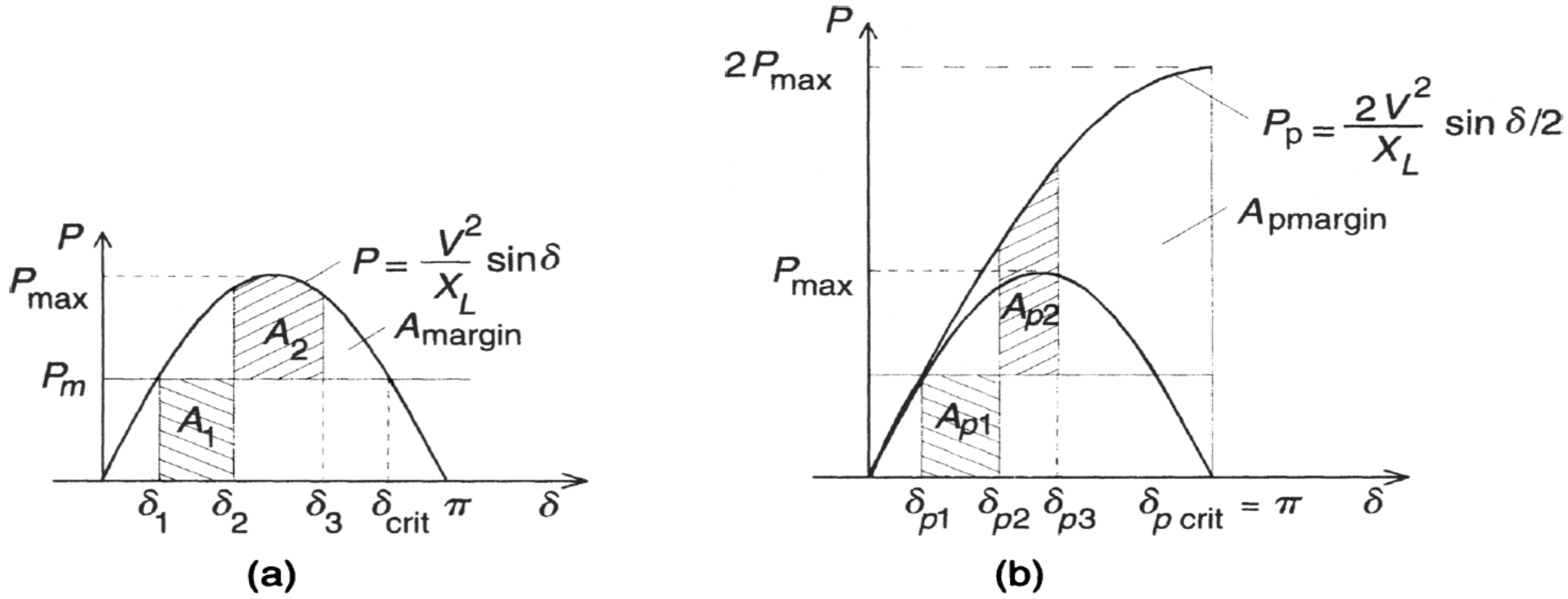
From the above general discussion it is evident that the transient stability, at a given power transmission level and fault clearing time, is determined by the *P* versus delta characteristic of the post-fault system.

Since appropriately controlled shunt compensation can provide effective voltage support, it can increase the transmission capability of the post-fault system and thereby enhance transient stability.



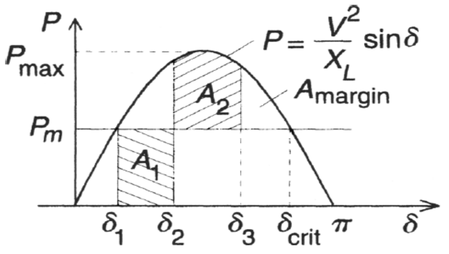
Suppose that this system of Figure with and without the midpoint shunt compensator, transmits the same steady-state power.

Assume that both the uncompensated and the compensated systems are subjected to the same fault for the same period of time.

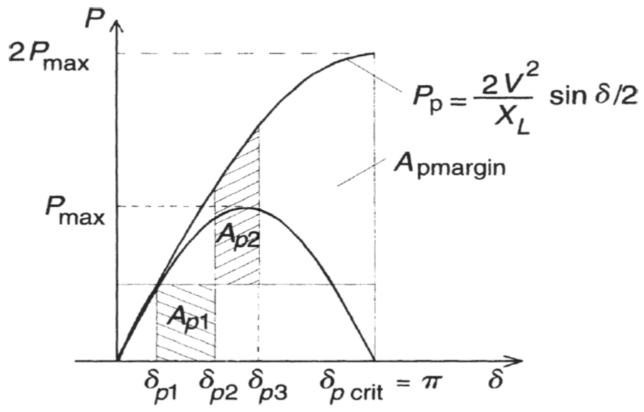


Prior to the fault both of them transmit power *Pm* (subscript m stands for "mechanical") at angles delta 1 and *deltap1,* respectively. During the fault, the transmitted electric power (of the single line system considered) becomes zero while the mechanical input power to the generators remains constant *(Pm).*Therefore, the sending-end generator accelerates from the steady-state angles 61 and 6p l to angles 62 and *6p2,* respectively, when the fault clears

During the fault, the transmitted electric power (of the single line system considered) becomes zero while the mechanical input power to the generators remains constant *(Pm)*. Therefore, the sending-end generator accelerates from the steady-state angles delta1 and deltaPl to angles delta2 and *delta*P2, respectively, when the fault clears



(a)

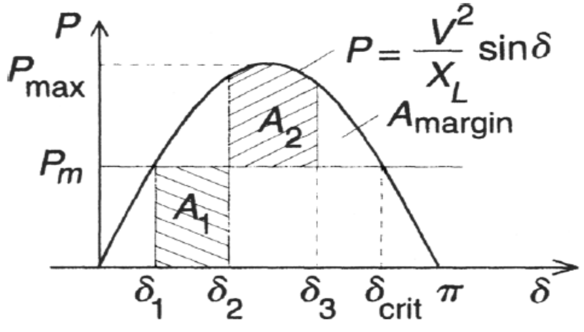


(b)

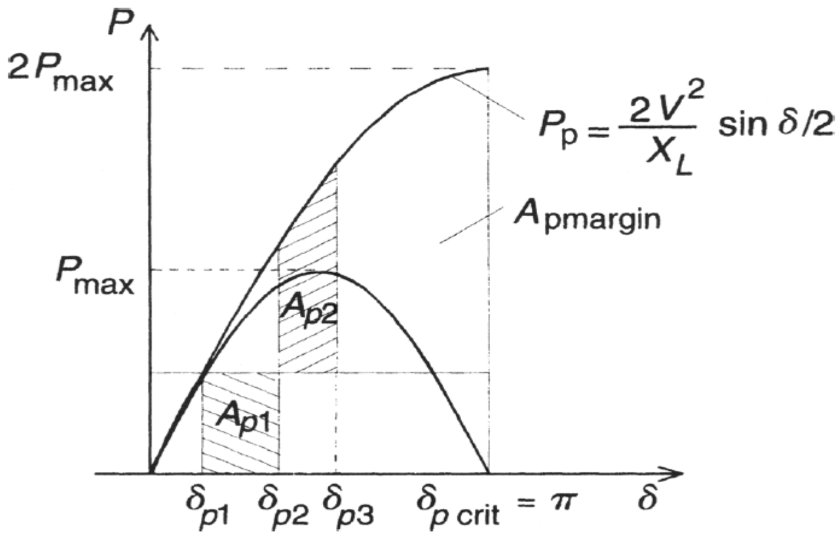
The accelerating energies are represented by areas *Al* and *Ap1.*

After fault clearing, the transmitted electric power exceeds the mechanical input power and the sending-end machine decelerates, but the accumulated kinetic energy further increases until a balance between the accelerating and decelerating energies, corresponding to areas *A1, Apt* and *A2, Ap2,* respectively, is reached at delta3 and *deltap3,* representing the maximum angular swings for the two cases.

Comparison of Figures (a) and (b) clearly shows a substantial increase in the transient stability margin the ideal midpoint compensation with unconstrained var output can provide by the effective segmentation of the transmission line. Alternatively, if the uncompensated system has a sufficient transient stability margin, shunt compensation can considerably increase the transmittable power without decreasing this margin.



(a)



(b)

Power oscillations damping

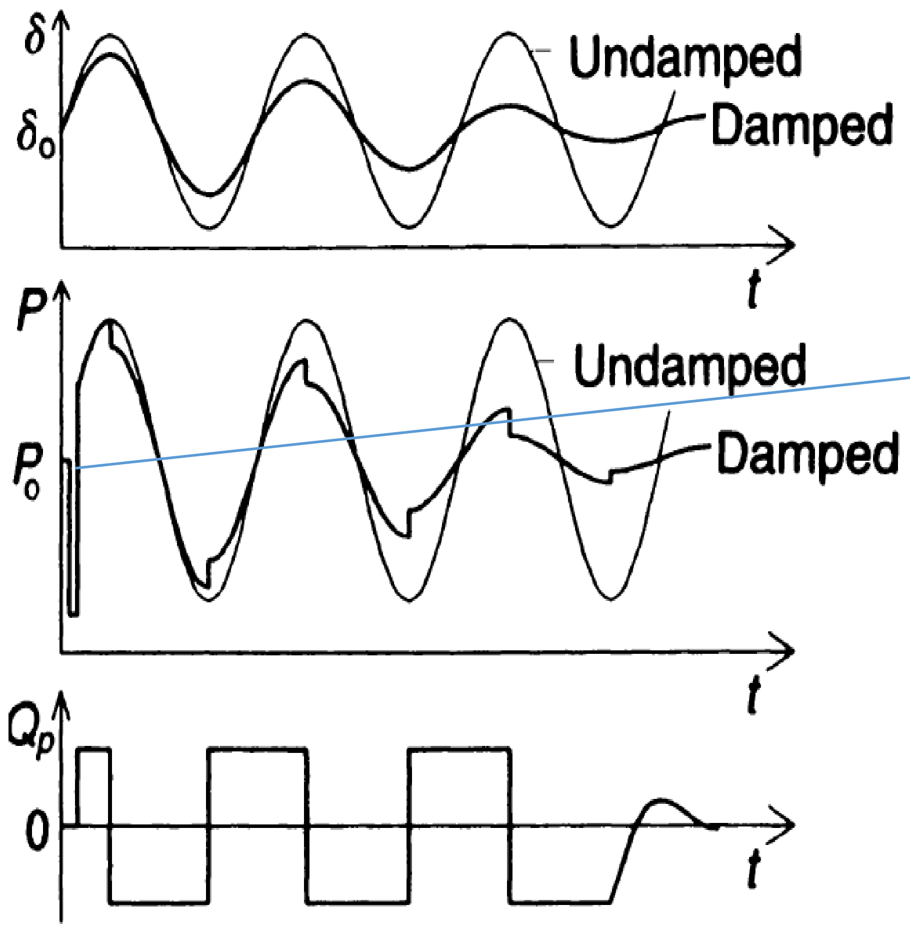
In the case of an under-damped power system, any minor disturbance can cause the machine angle to oscillate around its steady-state value at the natural frequency of the total electromechanical system.
The angle oscillation, of course, results in a corresponding power oscillation around the steady-state power transmitted. The lack of sufficient damping can be a major problem in some power systems and, in some cases, it may be the limiting factor for the transmittable power.

$(d\delta/dt > 0)$,

when the rotationally oscillating generator accelerates and angle delta increases, the electric power transmitted must be increased to compensate for the excess mechanical input power

$(d\delta/dt < 0)$

when the generator decelerates and angle delta decreases the electric power must be decreased to balance the insufficient mechanical input power.



Momentarily disturbance cause the Power system angle oscillate

As the illustration shows, the var output is controlled in a "bang-bang" manner (output is varied between the minimum and maximum values). This type of control is generally considered the most effective, particularly if large oscillations are encountered.
However, for damping relatively small power oscillations, a strategy that varies the controlled output of the compensator continuously, in sympathy with the generator angle or power, may be preferred.

Summary of Compensator Requirements

The functional requirements of reactive shunt compensators used for increased power transmission, improved voltage and transient stability, and power oscillation damping can be summarized as follows:

- The compensator must stay in synchronous operation with the ac system at the compensated bus under all operating conditions including major disturbances. Should the bus voltage be lost temporarily due to nearby faults, the compensator must be able to recapture synchronism immediately at fault clearing.

- The compensator must be able to regulate the bus voltage for voltage support and improved transient stability, or control it for power oscillation damping and transient stability enhancement, on a priority basis as system conditions
- may require.

- For a transmission line connecting two systems, the best location for var compensation is in the middle, whereas for a radial feed to a load the best location is at the load end.

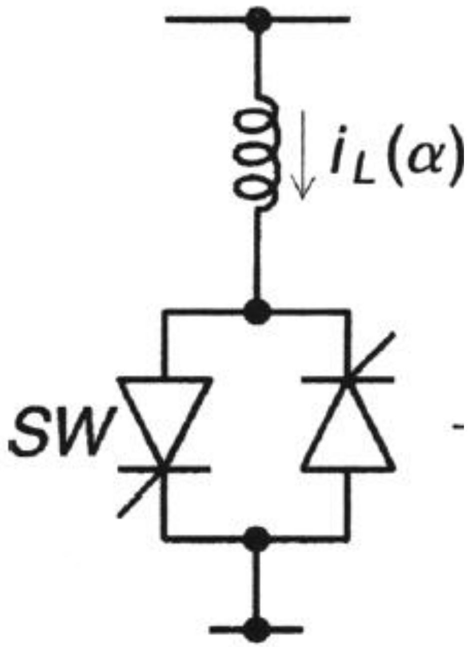
Methods of Controllable VAR generation

- **Variable Impedance type Static Var generators**
  1. **Thyristor Controlled Reactor(TCR)**
  2. **Thyristor Switched Reactor(TSR)**
  3. **Thyristor Switched Capacitor(TSC)**

- **Switching Converter type VAR generator**

1. **STATCOM**

The Thyristor-Controlled and Thyristor-Switched Reactor (TCR and TSR).



It consists of a fixed (usually air-core) reactor of inductance L, and a bidirectional thyristor valve (or switch) *sw.* Currently available large thyristors can block voltage up to 4000 to 9000 volts and conduct current up to 3000 to 6000 amperes.

Thus, in a practical valve many thyristors (typically 10 to 20) are connected in series to meet the required blocking voltage levels at a given power rating.

A thyristor valve can be brought into conduction by simultaneous application of a gate pulse to all thyristors of the same polarity. The valve will automatically block immediately after the ac current crosses zero, unless the gate signal is reapplied.

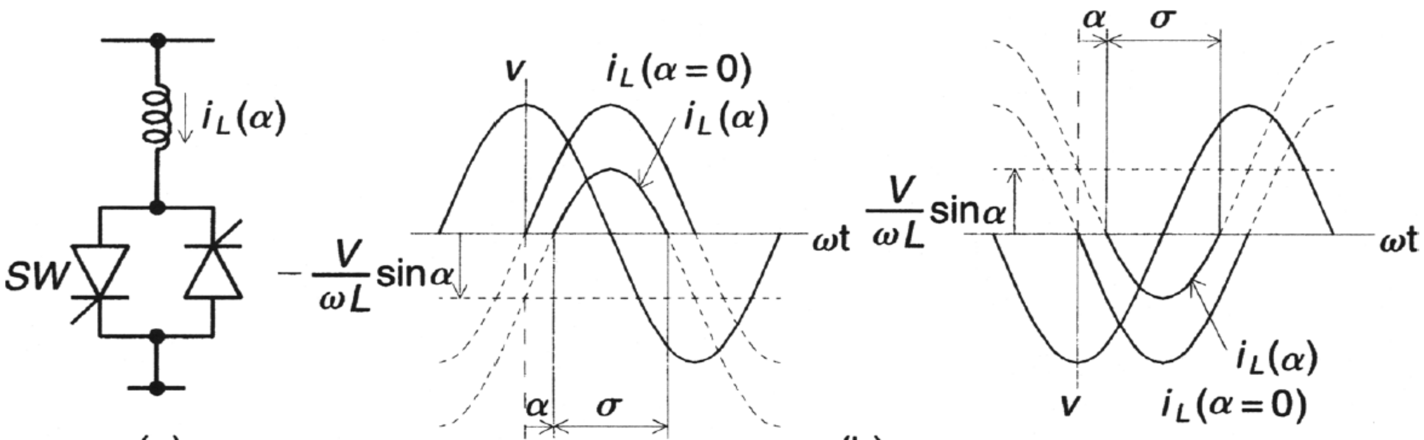
The current in the reactor can be controlled from maximum (thyristor valve closed) to zero (thyristor valve open) by the method of firing delay angle control.

That is, the closure of the thyristor valve is delayed with respect to the peak of the applied voltage in each half-cycle, and thus the duration of the current conduction intervals is controlled.

This method of current control is illustrated separately for the positive and negative current half-cycles

- in Figure (b), where the applied voltage *v* and the reactor current *iL(alpha)*, at zero delay angle (switch fully closed) and at an arbitrary *a* delay angle, are shown.

- When *a* = 0, the valve *sw* closes at the crest of the applied voltage and evidently the resulting current in the reactor will be the same as that obtained in steady state with a permanently closed switch.



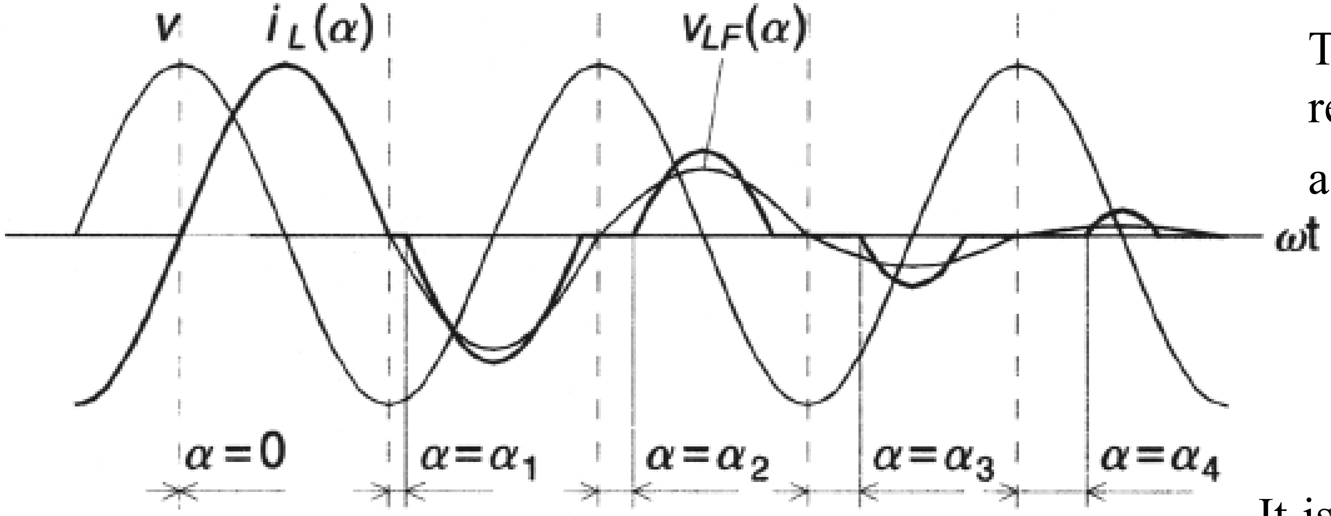
(a) (b)

- When the gating of the valve is delayed by an angle *alpha* (0 to pi/2) with respect to the crest of the voltage, the current in the reactor can be expressed with $v(t) = V\cos wt$ as follows:

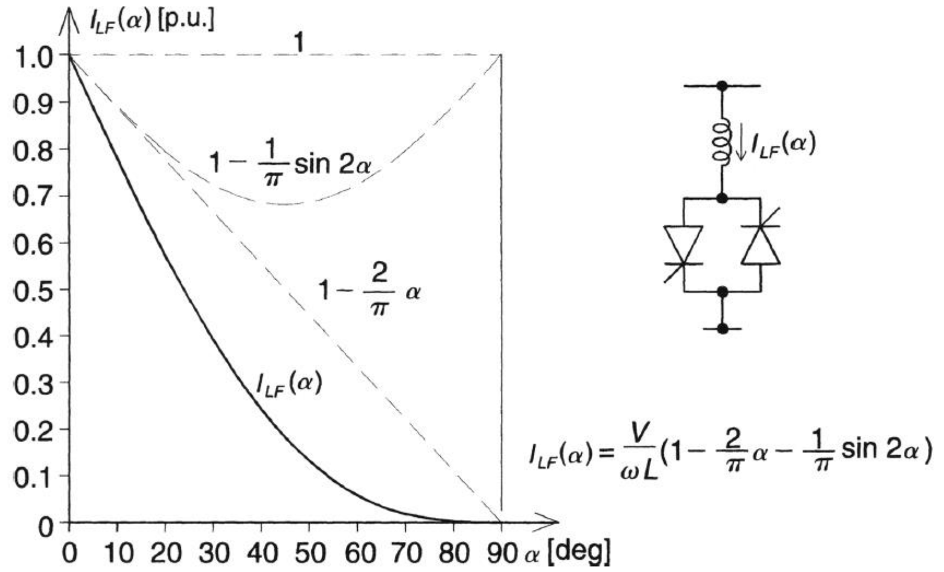
$$i_L(t) = \frac{1}{L}\int_{\alpha}^{\omega t} v(t)\,dt = \frac{V}{\omega L}(\sin\omega t - \sin\alpha)$$

Since the thyristor valve, by definition, opens as the current reaches zero, is valid for the interval *wt between alpha to pi-alpha*

For subsequent negative half-cycle intervals, the sign of the terms in (5.4) becomes opposite.



(c)



The amplitude *ILF(a)* of the fundamental reactor current *iLF(a)* can be expressed as a function of angle *a:*

$$I_{LF}(\alpha) = \frac{V}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)$$

It is clear that the TCR can control the fundamental current continuously from zero (valve open) to a maximum (valve closed) as if it was a variable reactive admittance.

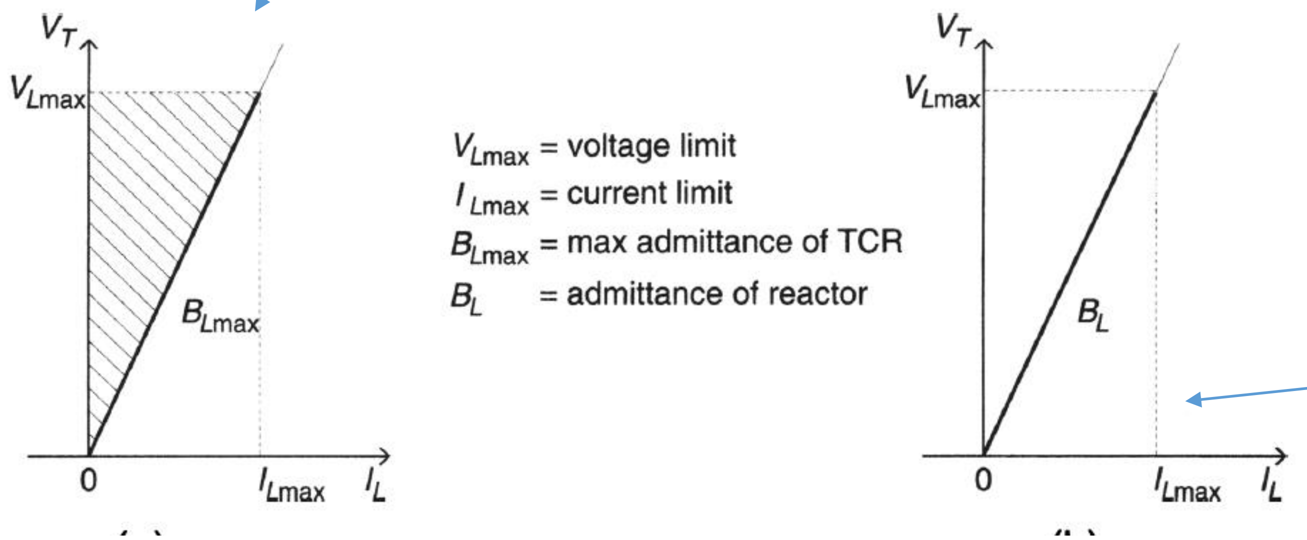
Thus, an effective reactive admittance, *BL(a),* for the TCR canbe defined. This admittance, as a function of angle *a,* can be written directly

$$B_L(\alpha) = \frac{1}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)$$

The meaning is that at each delay angle *alpha* an effective admittance *BL(alpha)* can be defined which determines the magnitude of the fundamental current, *ILF(alpha),* in the TCR at a given applied voltage *V.*

In practice, the maximal magnitude of the applied voltage and that of the corresponding current will be limited by the ratings of the power components (reactor and thyristor valve) used.

Thus, a practical TCR can be operated anywhere in a defined *V-I* area, the boundaries of which are determined by its maximum attainable admittance, voltage, and current ratings



If the TCR switching is restricted to a fixed delay angle, usually $a = 0$, then it becomes a thyristor-switched reactor (TSR). The TSR provides a fixed inductive admittance and thus, when connected to the ac system, the reactive current in it will be proportional to the applied voltage as the *V-I* plot in Figure

Complete other few topics of module 2 by completing the assignment no 3