Unit: 05
Static Series Compensator

Unit Content:

Objectives of the series compensation, variable Impedance type series compensation (GCSC, TSSC, TCSC), switching converter type series compensators (SSSC), characteristics of series compensator.

5.1 Introduction:

It was always recognized that ac power transmission over long lines was primarily limited by the series reactive impedance of the line. Series capacitive compensation was introduced decades ago to cancel a portion of the reactive line impedance and thereby increase the transmittable power. Subsequently, within the FACfS initiative, it has been demonstrated that variable series compensation is highly effective in both controlling power flow in the line and in improving stability.

Controllable series line compensation is a cornerstone of FACTS technology. It can be applied to achieve full utilization of transmission assets by controlling the power flow in the lines, preventing loop flows and, with the use of fast controls, minimizing the effect of system disturbances, thereby reducing traditional stability margin requirements.

5.2 Objectives of the series compensation:

i) To decrease the overall effective series transmission impedance from the sending end to the receiving end, i.e., X in the $P = (V^2/X) \sin \delta$ relationship characterizing the power transmission over a single line.

ii) Series capacitive compensation can also be used to reduce the series reactive impedance to minimize the receiving-end voltage variation and the possibility of voltage collapse.

iii) The powerful capability of series line compensation to control the transmitted power can be utilized much more effectively to increase the transient stability limit.

iv) Controlled series compensation can be applied effectively to damp power oscillations.

v) Sustained oscillation below the fundamental system frequency can be done by series capacitive compensation.

5.3 Concept of Series Capacitive Compensation:

The basic idea behind series capacitive compensation is to decrease the overall effective series transmission impedance from the sending end to the receiving end, i.e., X in the $P = (V^2/X) \sin \delta$ relationship characterizing the power transmission over a single line. Consider the simple two machine model with a series capacitor compensated line, which, for convenience, is assumed to be composed of two identical segments, as shown in Figure 5.3(a). The corresponding voltage and current phasors are shown in Figure 5.3(b). Note that for the same end voltages the magnitude of the total voltage across the series line inductance, $V_x = 2V_{x/2}$ is increased by the magnitude of the opposite voltage, V_C developed across the series capacitor; this results from an increase in the line current.

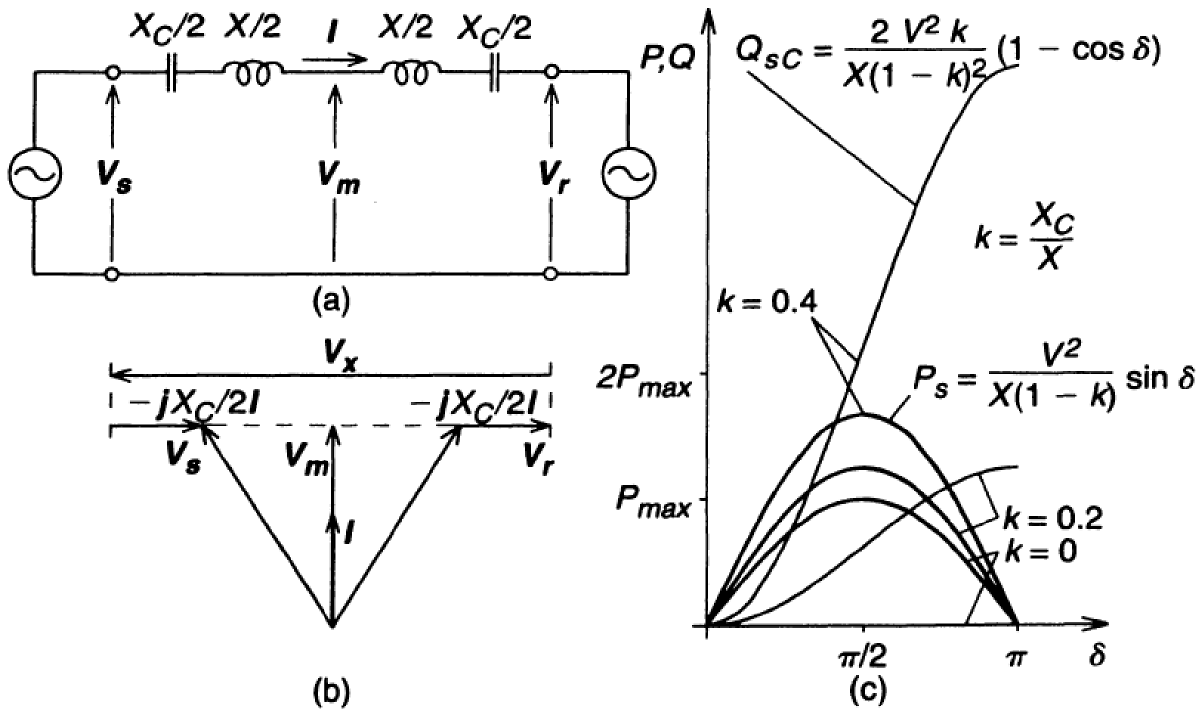

Fig.5.3 (a) Two-machine power system with series capacitive compensation
(b) Corresponding phasor diagram
(c)Real power and series capacitor reactive power vs. angle characteristics

The effective transmission impedance X_{eff} with the series capacitive compensation is given by

$$X_{eff} = X - Xc$$

$$X_{eff} = (1 - k)X$$

Where, k is the degree of series compensation, i.e.,

$$K = Xc/X \qquad 0 \le k \le 1$$

Assuming $VS = Vr = V$ in Figure 3.3(b), the current in the compensated line, and the corresponding real power transmitted, can be derived in the following forms:

$$I = \frac{2V}{(1-k)X} \sin\frac{\delta}{2}$$

$$P = V_m I = \frac{V^2}{(1-k)X} \sin\delta$$

The reactive power supplied by the series capacitor can be expressed as follows:

$$Q_C = I^2 X_C = \frac{2V^2}{X}\frac{k}{(1-k)^2}(1-\cos\delta)$$

The relationship between the real power P, series capacitor reactive power Qc, and angle δ is shown plotted at various values of the degree of series compensation k in Figure 5.3 (c). It can be observed that, as expected, the transmittable power rapidly increases with the degree of series compensation k. Similarly, the reactive power supplied by the series capacitor also increases sharply with k and varies with angle δ in a similar manner as the line reactive power.

5.4 Variable Impedance type series compensation:

Just as in reactive shunt compensation, variable impedance type series compensators are composed of thyristor-switched/controlled capacitors or thyristor-controlled reactors with fixed capacitors.

5.4.1 GTO Thyristor-Controlled Series Capacitor (GCSC)

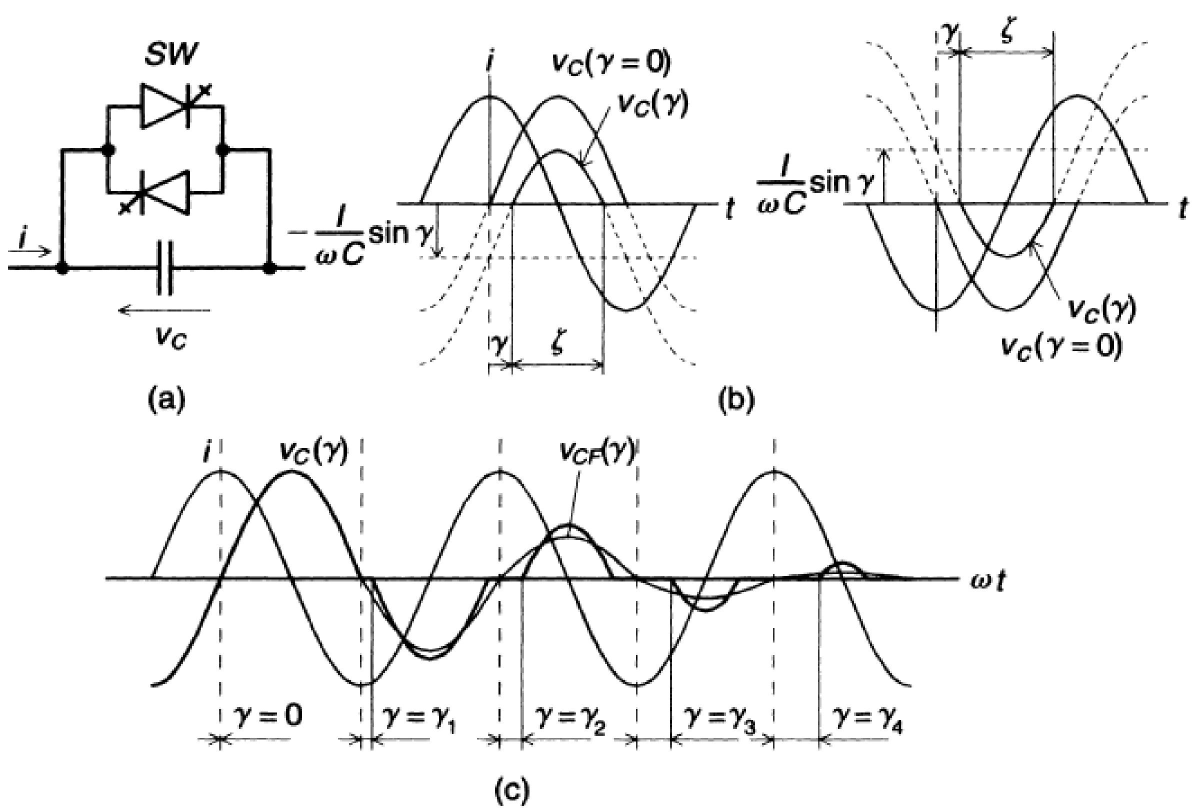

Fig. 5.4(a): Basic GTO-Controlled Series Capacitor, Fig. 5.4(b): principle of turn-off delay angle control, Fig. 5.4(c): attainable compensating voltage waveform

An elementary GTO Thyristor-Controlled Series Capacitor (GCSC) consists of a fixed capacitor in parallel with a GTO thyristor switch that has the capability to turn on and off upon command. This compensator scheme is interesting in that it has the unique capability of directly varying the capacitor voltage by delay angle control.

The objective of the GCSC scheme shown in Fig.3.4(a) is to control the ac voltage (Vc) across the capacitor at a given line current i. When the GTO switch (SW) is closed, the voltage across the capacitor is zero, and when the switch is open, it is maximum. For controlling the capacitor voltage, the closing and opening of the switch is carried out in each half-cycle in synchronism with the ac system frequency. The GTO switch is stipulated to close automatically (through appropriate control action) whenever the capacitor voltage crosses zero. (Recall that the thyristor switch of the TCR opens automatically whenever the current crosses zero.)

The turn-off instant of the valve in each half-cycle is controlled by a (turn-off) delay angle γ ($0 \leq \gamma \leq \pi/2$), with respect to the peak of the line current. When the valve sw is opened at the crest of the (constant) line current ($\gamma = 0$), the resultant capacitor voltage Vc will be the same as that obtained in steady state with a permanently open switch, as shown in fig. 5.4(b). When the opening of the valve is delayed by the angle γ with respect to the crest of the line current, the capacitor voltage can be expressed with a defined line current, $i(t) = I \cos \omega t$, as follows:

$$v_C(t) = \frac{1}{C}\int_{\gamma}^{\omega t} i(t)\, dt = \frac{I}{\omega C}(\sin \omega t - \sin \gamma)$$

Since the switch opens at γ and stipulated to close at the first voltage zero, above equation is valid for the interval $\gamma \leq \omega t \leq \pi-\gamma$. For subsequent positive half-cycle intervals the same expression remains valid. For subsequent negative half-cycle intervals, the sign of the terms in above equation becomes opposite.

The GTO valve automatically turns on at the instant of voltage zero crossing, this process actually controls the non-conducting (blocking) interval (or angle) of the GTO valve. That is, the turn-off delay angle γ defines the prevailing blocking angle $\zeta = \pi - 2\gamma$. Thus, as the turn-off delay angle γ increases, the correspondingly increasing offset results in the reduction of the blocking angle of the valve, and the consequent reduction of the capacitor voltage. At the maximum delay of $\gamma = \pi/2$, the capacitor voltage become zero. It is evident that the magnitude of the capacitor voltage can be varied continuously by this method of turn-off delay angle control from maximum ($\gamma = 0$) to zero ($\gamma = \pi/2$), as illustrated in Figure 3.4(c), where the capacitor voltage $V_C(\gamma)$, together with its fundamental component $V_{CF}(\gamma)$, are shown at, various turn-off delay angles, γ.

Operating V-I Characteristics of GCSC:

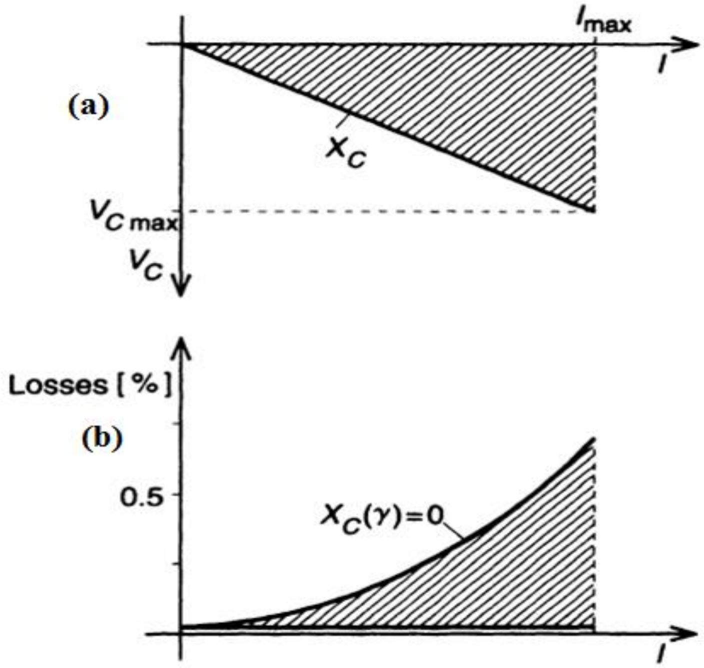

Fig. (a): V-I characteristics of the GCSC when operated in reactance control mode,

Fig. (b): Loss vs. line current characteristics

In the impedance compensation mode, the GCSC is to maintain the maximum rated compensating reactance at any line current up to the rated maximum, as illustrated in Fig. (a) The loss versus line current characteristic of the GCSC for this operating mode is shown in Fig. (b). For zero compensating impedance (capacitor is bypassed by the GTO valve) and for maximum compensating impedance (the GTO valve is open and the capacitor is fully inserted).

5.4.2 Thyristor Switched Series Capacitor (TSSC):

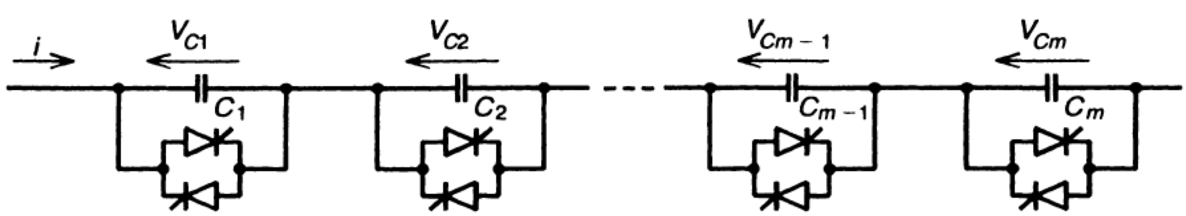

Fig. (a): Thyristor Switched Series Capacitor (TSSC)

The basic circuit arrangement of the thyristor-switched series capacitor is shown in Fig. (a). It consists of a number of capacitors, each shunted by an appropriately rated bypass switch composed of a string of reverse parallel connected thyristors, in series. It is similar to the circuit structure of the sequentially operated GCSC, but its operation is different due to the imposed switching restrictions of the conventional thyristor valve.

The degree of series compensation is controlled in a step-like manner by increasing or decreasing the number of series capacitors inserted. A capacitor is inserted by turning off, and it is bypassed by turning on the corresponding thyristor valve. A thyristor valve commutates "naturally," that is, it turns off when the current crosses zero. Thus a capacitor can be inserted into the line by the thyristor valve only at the zero crossings of the line current. Since the insertion takes place at line current zero, a full half-cycle of the line current will charge the capacitor from zero to maximum and the successive, opposite polarity half-cycle of the line current will discharge it from this maximum to zero, as shown in fig. (b).

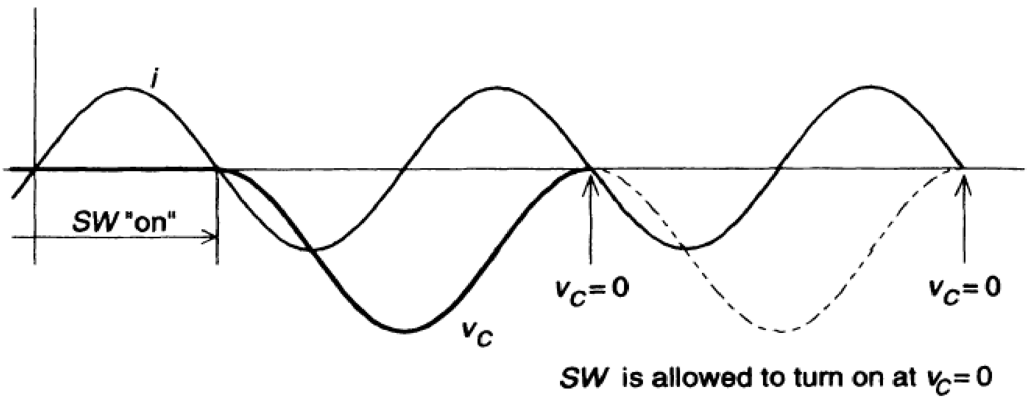

Fig. (b): Capacitor offset voltage resulting from the restriction of inserting at zero line current.

Operating V-I Characteristics of TSSC:

In the impedance compensation mode, the TSSC is applied to maintain the maximum rated compensating reactance at any line current up to the rated maximum, as illustrated in Figure (c). In this compensation mode the capacitive impedance is chosen so as to provide the maximum series compensation at rated current, *4Xc = Vcmax/Imax*, that the TSSC can vary in a step-like manner by bypassing one or more capacitor banks.

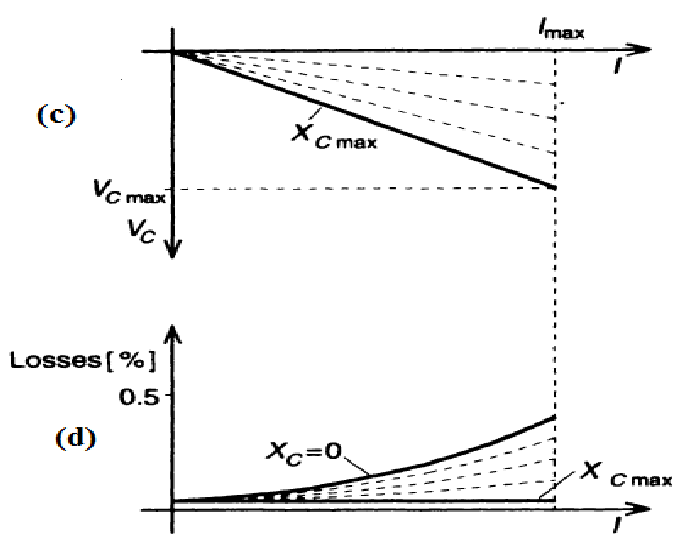

Fig. (c): V-I characteristics of the TSSC when operated in reactance control mode
Fig. (d): Loss vs. line current characteristics

The loss versus line current characteristic for this compensation mode is shown in Figure (d) for zero compensating impedance (all capacitor banks are bypassed by the thyristor valves) and for maximum compensating impedance (all thyristor valves are off and all capacitors are inserted).

5.4.3 Thyristor Controlled Series Capacitor (TCSC):

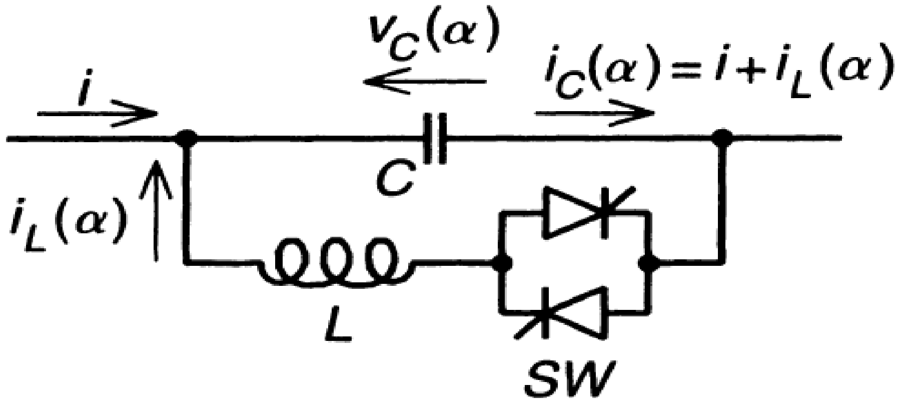

Fig. (a): Thyristor Controlled Series Capacitor (TCSC)

It consists of the series compensating capacitor shunted by a Thyristor-Controlled Reactor. In a practical TCSC implementation, several such basic compensators may be connected in series to obtain the desired voltage rating and operating characteristics. The basic idea behind the TCSC scheme is to provide a continuously variable capacitor by means of partially canceling the effective compensating capacitance by the TCR.

The TCR is continuously variable reactive impedance, controllable by delay angle α. The steady-state impedance of the TCSC is that of a parallel LC circuit, consisting of a fixed capacitive impedance, Xc, and a variable inductive impedance, $X_L(\alpha)$, that is,

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

Where,

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

$X_L = \omega L$, and α is the delay angle measured from the crest of the capacitor voltage.

As the impedance of the controlled reactor, X_L (α), is varied from its maximum (infinity) toward its minimum (ωL), the TCSC increases its minimum capacitive impedance, $X_{TCSC,min}$ = Xc = 1/ωC, (and thereby the degree of series capacitive compensation) until parallel resonance at Xc = X_L (α) is established. Decreasing $X_L(\alpha)$ further, the impedance of the TCSC, $X_{TCSC(\alpha)}$ becomes inductive, reaching its minimum value at α = 0, where the capacitor is in effect bypassed by the

TCR. Therefore, with the usual TCSC arrangement in which the impedance of the TCR reactor, X_L, is smaller than that of the capacitor, X_C, the TCSC has two operating ranges around its internal circuit resonance: one is the $\alpha_{Clim} \le \alpha \le \pi/2$ range, where $X_{TCSC}(\alpha)$ is capacitive, and the other is the $0 \le \alpha \le \alpha_{Clim}$ range, where $X_{TCSC}(\alpha)$ is inductive, as shown in fig. (b)

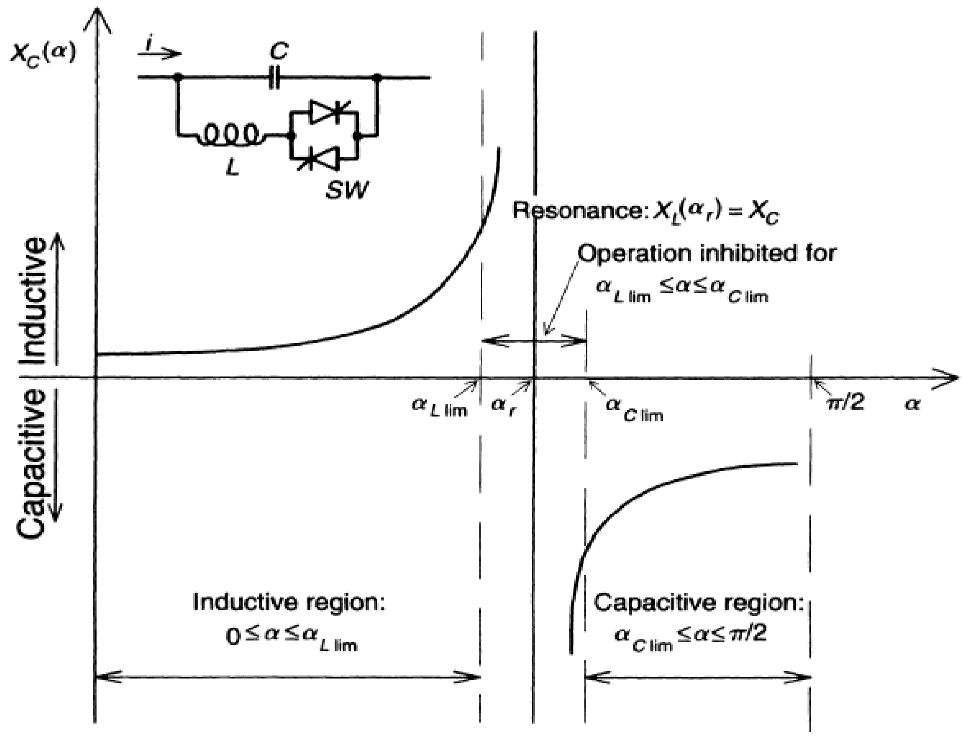

Fig. (b): The impedance vs. delay angle α characteristic of the TCSC.

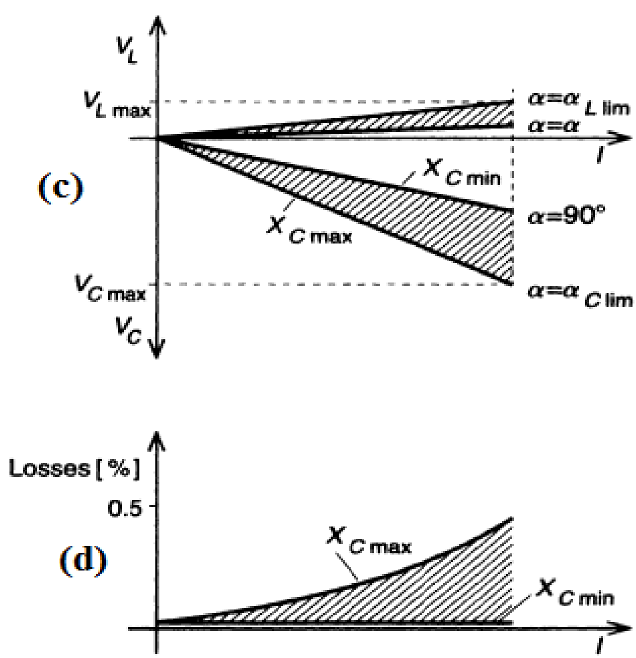

Fig. (c): V-I characteristics of the TCSC when operated in reactance control mode

Fig. (d): Loss vs. line current characteristics

In the impedance compensation mode, the TCSC is applied to maintain the maximum rated compensating reactance at any line current up to the rated maximum. For this operating mode the TCSC capacitor and thyristor-controlled reactor are chosen so that at α_{clim} the maximum capacitive reactance can be maintained at and below the maximum rated line current, as illustrated in Figure (c). The minimum capacitive compensating impedance the TCSC can provide is, of course, the impedance of the capacitor itself, theoretically obtained at $\alpha = 90°$ (with nonconducting thyristor valve). The loss versus line current characteristic for this operating mode is shown in Figure (d) for maximum and minimum capacitive compensating reactances.

5.5 Switching converter type series compensators:

The voltage-sourced converter-based series compensator, called Static Synchronous Series Compensator (SSSC), was proposed by Gyugyi in 1989 within the concept of using converter-based technology uniformly for shunt and series compensation, as well as for transmission angle control.

5.5.1 Static Synchronous Series Capacitor (SSSC):

The voltage-sourced converter with its internal control can be considered a synchronous voltage source (SVS). It can produce a set of (three) alternating, substantially sinusoidal voltages at the desired fundamental frequency with controllable amplitude and phase angle to generate, or absorb, reactive power. It can also exchange real (active) power with the ac system when its dc terminals are connected to a suitable electric dc energy source or storage.

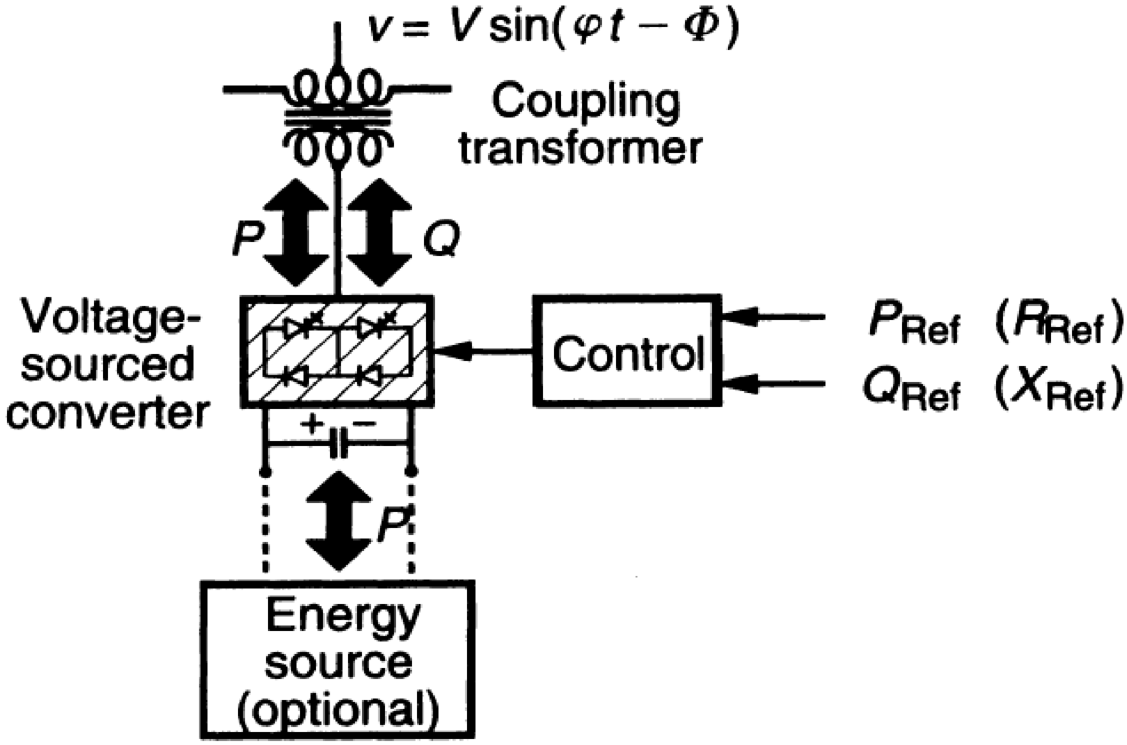

Fig. 3.5(a): Functional representation of the synchronous voltage source

A functional representation of the SVS is shown in Figure 3.5(a). References Q_{Ref} and P_{Ref} (or other related parameters, such as the desired compensating reactive impedance X_{Ref} and resistance R_{Ref}) define the amplitude V and phase angle ψ of the generated output voltage necessary to exchange the desired reactive and active power at the ac output. If the SVS is operated strictly for reactive power exchange, P_{Ref} (or R_{Ref}) is set to zero.

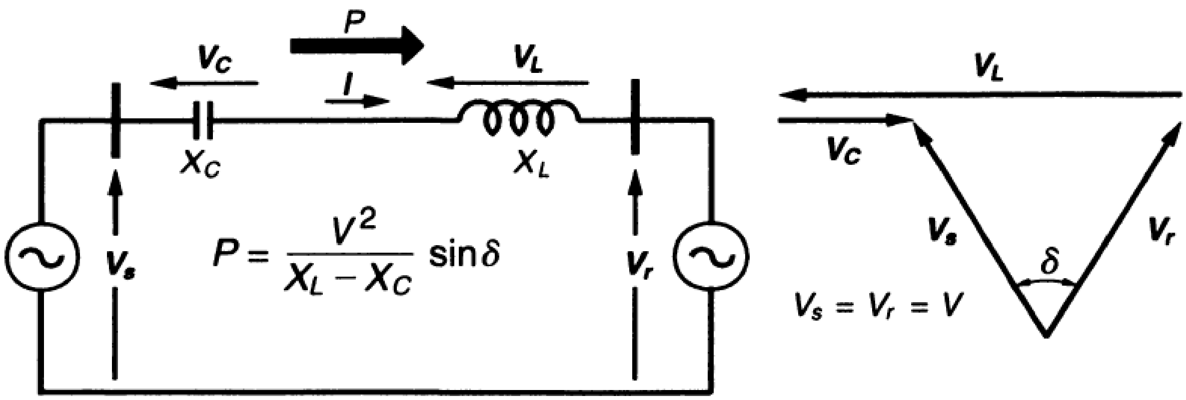

Fig. 3.5(b) Basic two-machine system with a series capacitor compensated line and phasor diagram.

The basic operating principles of the SSSC can be explained with reference to the conventional series capacitive compensation, shown simplified in Figure 3.5(b) together with the related voltage phasor diagram. The phasor diagram clearly shows that at a given line current the voltage across the series capacitor forces the opposite polarity voltage across the series line reactance to increase by the magnitude of the capacitor voltage. Thus, the series capacitive compensation works by increasing the voltage across the impedance of the given physical line, which in turn increases the corresponding line current and the transmitted power.

While it may be convenient to consider series capacitive compensation as a means of reducing the line impedance, in reality, as explained previously, it is really a means of increasing the voltage across the given impedance of the physical line. It follows therefore that the same steady-state power transmission can be established if the series compensation is provided by a synchronous ac voltage source, as shown in Figure, whose output precisely matches the voltage of the series capacitor, i.e.,

$$V_q = V_c = -jX_cI = -jKXI$$

where, as before, Vc is the injected compensating voltage phasor, I is the line current, Xc is the reactance of the series capacitor, X is the line reactance, k = Xc/X is the degree of series compensation. Thus, by making the output voltage of the synchronous voltage source a function of the line current, the same compensation as provided by the series capacitor is accomplished. However, in contrast to the real series capacitor, the SVS is able to maintain a constant compensating voltage in the presence of variable line current, or control the amplitude of the injected compensating voltage independent of the amplitude of the line current. For normal capacitive compensation, the output voltage lags the line current by 90 degrees.

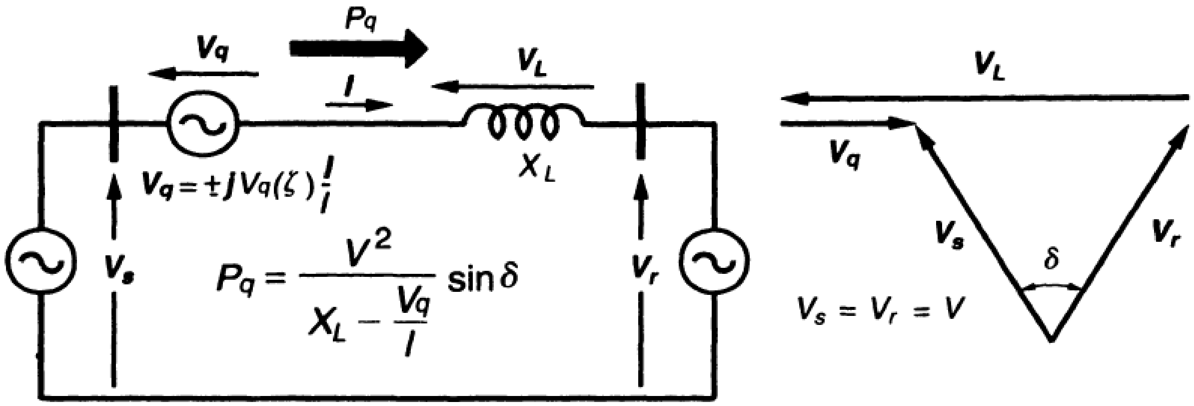

Fig. (c): Basic two-machine system with synchronous voltage source replacing the series capacitor.

For SVS, the output voltage can be reversed by simple control action to make it lead or lag the line current by 90 degrees. In this case, the injected voltage decreases the voltage across the inductive line impedance and thus the series compensation has the same effect as if the reactive line impedance was increased. With the above observations, a generalized expression for the injected voltage, Vq can simply be written:

$$V_q = \pm j V_q(\zeta) \frac{I}{I}$$

where Vq((ζ) is the magnitude of the injected compensating voltage (0 ≤ Vq(ζ) ≤Vqmax) and ζ is a chosen control parameter.

5.6 Characteristics of Series Compensators:

are variable impedance type series compensators. Although both types of compensator can provide highly effective power flow control, their operating characteristics and compensation features are different. The essential differences in characteristics and features of the two types of compensator can be summarized as follows:

1. The SSSC is capable of internally generating a controllable compensating voltage over an identical capacitive and inductive range independently of the magnitude of the line current. The compensating voltage of the GCSC and TSSC over a given control range is proportional to the line current. The TCSC can maintain maximum compensating voltage with decreasing line current over a control range determined by the current boosting capability of the thyristor-controlled reactor.
2. The SSSC has the inherent ability to interface with an external dc power supply to provide compensation for the line resistance by the injection of real power, as well as for the line

reactance by the injection of reactive power. The variable impedance type series compensators cannot exchange real power with the transmission line and can only provide reactive compensation.

3. The SSSC with an energy storage (or sink) increases the effectiveness of power oscillation damping by modulating the series reactive compensation to increase and decrease the transmitted power. The variable impedance type compensator can damp power oscillation only by modulated reactive compensation affecting the transmitted power.
4. The TSSC and TCSC employ conventional thyristors (with no internal turnoff capability). These thyristors are the most rugged power semiconductors, available with the highest current and voltage ratingsand they also have the highest surge current capability. The GCSC and the SSSC use GTO thyristors. These devices presently have lower voltage and current ratings, and considerably lower short-term surge current rating.
5. The variable impedance type compensators, TSSC, TCSC, and GCSC, are coupled directly to the transmission line and therefore installed on a high voltage platform. The SSSC requires a coupling transformer, rated for 0.5 p.u. of the total series var compensating range, and a dc storage capacitor.
6. The voltage source and the different type of variable impedance type compensators also exhibit different loss characteristics. At rated line current these losses would be about 0.5% of the rated var output for the TSSC and TCSC, about 0.7 to 0.9% for the GCSC and SSSC. The SSSC losses would be proportional to the line current and would reach a maximum of about 0.9% at rated line current.