Module-3

Subject: Flexible AC Transmission System (FACTS)

Content: Static VAR Compensator (static var compensator (SVC) systems to provide reactive power, load balancing, power factor improvement, and to reduce voltage variations and associated light flicker due to arc furnace loads.)

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3.0 Shunt and Series Compensation

In this chapter, we will be discussing about shunt reactive compensation. For the sake of completeness, we should mention that it is possible to provide a series compensation. In particular, transmission capability can be significantly increased by installing series capacitors in the middle of a line. As is well known, the maximum power transfer between two buses is inversely proportional to the reactance between the two buses. By installing a series capacitor in the middle of the line, we will decrease the reactance and increase the power transfer capability between the two buses. A careful design of series capacitor installation is necessary to avoid the following problems.

(a) If there is a power station at one end of the line with series capacitors, shaft damage can occur due to subharmonic resonances in the system.
(b) Provision should be made to short circuit the series capacitor if any fault develops in the series capacitors.
(c) The series capacitor bank should be properly designed to withstand overvoltages under different transient conditions.

Considerable progress has been made in the design of series capacitor installations, and many of them are operating satisfactorily. Zinc oxide arresters are used in some of these installations to reduce the overvoltages under transient conditions after fault clearing.
In addition, SVCs are also used

i. In transmission systems
   - a. To reduce temporary overvoltages
   - b. To damp subsynchronous resonances
   - c. To damp power oscillations in interconnected power systems

ii. In traction systems
   - a. To balance loads
   - b. To improve power factor
   - c. To improve voltage regulation

iii. In HVDC systems
   - a. To provide reactive power to ac–dc converters

iv. In arc furnaces
   - a. To reduce voltage variations and associated light flicker

3.1 Static VAR Compensator Systems versus Synchronous Condensers, Capacitors, and Reactors

Prior to the development of SVC systems, synchronous condensers, capacitors, and reactors were the only devices available for reactive power control. But today, all these devices are used depending on the specific requirements of a particular application. Reactors and capacitors are used to reduce or increase voltage at a particular bus under light or peak load sinusoidal steady-state operating conditions. However, these are not suitable for the load balancing of single-phase loads or for smooth control of voltage at a particular bus. Synchronous condensers (or compensators) can either absorb or supply reactive power to the power system, providing a smooth control of the voltage at a particular bus, have overload capability, and generate negligible harmonics. In the case of
HVDC applications, synchronous condensers can provide extra short-circuit capacity in weak ac systems, which SVC systems cannot provide. The disadvantages of the synchronous condensers are high capital costs, maintenance costs, slow control response, and inability to balance single-phase loads.

3.2 Static VAR Compensators for Transmission Systems

There are several variations of SVCs discussed in the literature making use of thyristor-controlled reactors (TCR). For reasons of space, we will consider only the following types of SVCs in this chapter:

(a) SVC using a TCR and a fixed capacitor (FC)

(b) SVC using a TCR and thyristor-switched capacitors (TSC)

(c) SVC using forced commutation inverters

(d) SVC using a saturated reactor (SR)

For details of other types of SVCs such as high-impedance thyristor-controlled transformer, mechanically switched capacitors (MSC), and TCR. We will briefly consider the relative merits of the previously listed four SVCs.

3.2.1 THE THYRISTOR-CONTROLLED REACTOR (TCR)

A TCR is one of the most important building blocks of thyristor-based SVCs. Although it can be used alone, it is more often employed in conjunction with fixed or thyristor-switched capacitors to provide rapid, continuous control of reactive power over the entire selected lagging-to-leading range.

3.2.1.1 The Single-Phase TCR

A basic single-phase TCR comprises an anti-parallel–connected pair of thyristor valves, T_1 and T_2, in series with a linear air-core reactor, as illustrated in Fig. 3.1. The anti-parallel–connected thyristor pair acts like a bidirectional switch, with thyristor valve T_1 conducting in positive half-cycles and thyristor valve T_2 conducting in negative half-cycles of the supply voltage. The firing angle of the thyristors is measured from the zero crossing of the voltage appearing across its terminals.

The controllable range of the TCR firing angle, α extends from 90° to 180°. A firing angle of 90° results in full thyristor conduction with a continuous sinusoidal current flow in the TCR. As the firing angle is varied from 90° to close to 180°, the current flows in the form of discontinuous pulses symmetrically located in the positive and negative half-cycles, as displayed in Fig. 3.2. Once the thyristor valves are fired, the cessation of current occurs at its natural zero crossing, a process known as the line commutation. The current reduces to zero for a firing angle of 180°. Thyristor firing at angles below 90º introduces dc components in the current, disturbing the symmetrical operation of the two antiparallel valve branches. A characteristic of the line-commutation process with which the TCR operates is that once the valve conduction has commenced, any change in the firing angle can only be implemented in the next half-cycle, leading to the so-called thyristor dead time.

Let the source voltage be expressed as

$$v_s(t) = V \sin \omega t \tag{3.1}$$

where V is the peak value of the applied voltage and ω is the angular frequency of supply voltage. The TCR current is then given by the following differential equation

$$L \frac{di}{dt} - v_s(t) = 0 \tag{3.2}$$

where L is the inductance of the TCR. Integrating Equation. (3.2), we get

$$i(t) = \frac{1}{L} \int v_s(t)\, dt + C \tag{3.3}$$

where C is the constant.

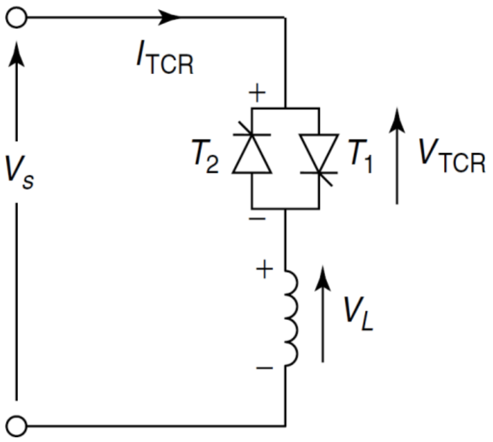


Figure 3.1 A TCR

Alternatively,

$$i(t) = -\frac{V}{\omega L} \cos \omega t + C \tag{3.4}$$

For the boundary condition, i (ωt=α) =0;

$$i(t) = -\frac{V}{\omega L} (\cos \alpha - \cos \omega t) \tag{3.5}$$

where α = the firing angle measured from positive going zero crossing of the applied voltage. Fourier analysis is used to derive the fundamental component of the TCR current $I_1(\alpha)$, which, in general, is given as

$$I_1(\alpha) = a_1 \cos \omega t + b_1 \sin \omega t \tag{3.6}$$

where b_1=0 because of the odd-wave symmetry, that is, f (x)=f (−x). Also, no even harmonics are generated because of the half-wave symmetry, that is, f (x + T /2)= −f (x).

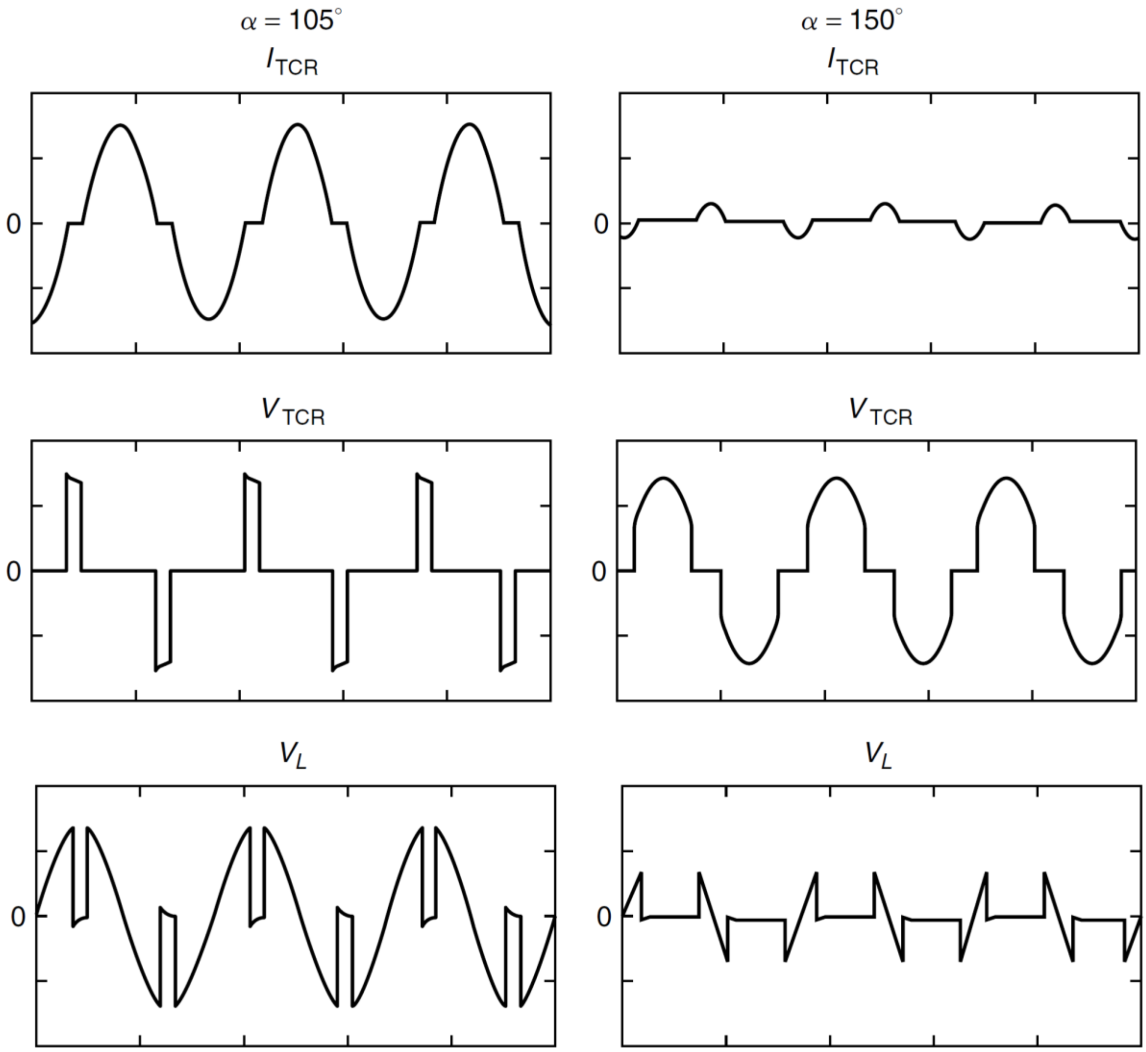


Figure 3.2 Current and voltages for different α in a TCR.

The coefficient a_1 is given by

$$a_1 = \frac{4}{T} \int_0^{T/2} f(x) \cos \frac{2\pi x}{T} \, dx \tag{3.7}$$

solving

$$I_1(\alpha) = \frac{V}{\omega L} \left(1 - \frac{2\alpha}{\pi} - \frac{1}{\pi} \sin 2\alpha \right) \tag{3.8}$$

Equation (3.8) can also be rewritten as

$$I_1(\alpha) = V B_{\text{TCR}}(\alpha) \tag{3.9}$$

where

$$B_{TCR}(\alpha) = B_{max}\left(1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha\right) \tag{3.10}$$

$$B_{max} = \frac{1}{\omega L} \tag{3.11}$$

The firing angle α is related to the conduction angle σ, as follows:

$$\alpha + \frac{\sigma}{2} = \pi \tag{3.12}$$

Substituting Eq. (3.12) in Eq. (3.8) gives the alternative expression of the fundamental component of the TCR current:

$$I_1(\sigma) = VB_{max}\left(\frac{\sigma - \sin\sigma}{\pi}\right) \tag{3.13}$$

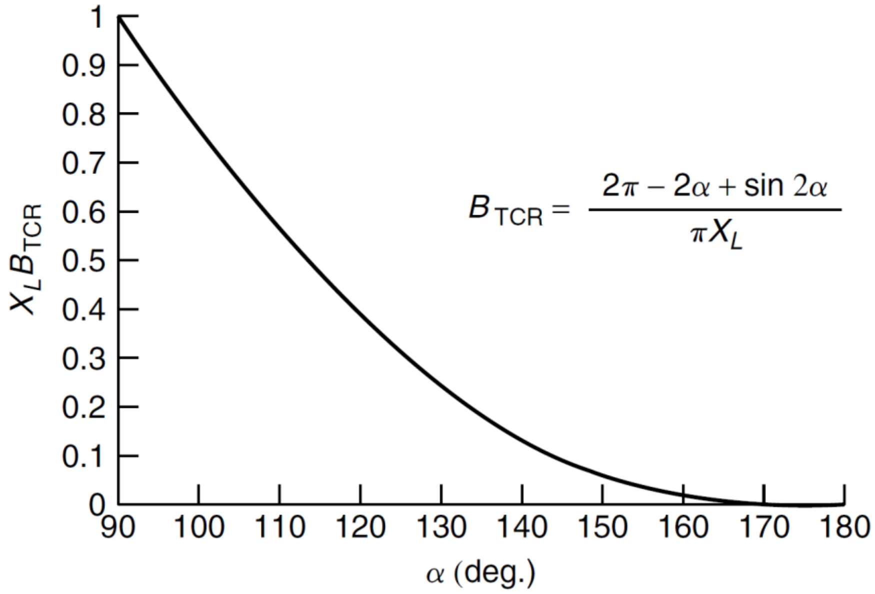


Figure 3.3 Control characteristics of the TCR susceptance, BTCR.

$$I_1(\sigma) = VB_{TCR}(\sigma) \tag{3.14}$$

where

$$B_{TCR}(\sigma) = B_{max}\left(\frac{\sigma - \sin\sigma}{\pi}\right) \tag{3.15}$$

The variation of per-unit value of B_{TCR} with firing angle α is depicted in Fig. 3.3. The per-unit value of B_{TCR} is obtained with respect to its maximum value B_{max} as the base quantity.
The TCR thus acts like a variable susceptance. Variation of the firing angle changes the susceptance and consequently, the fundamental-current component, which leads to a variation of reactive power absorbed by the reactor because the applied ac voltage is constant.

However, as the firing angle is increased beyond 90^0, the current becomes nonsinusoidal, and harmonics are generated. If the two thyristors are fired symmetrically in the positive and negative half-cycles, then only odd-order harmonics are produced. The harmonics can be deduced through a Fourier analysis of higher-frequency components.
The rms value of the nth-order harmonic is expressed as a function of α in the following equation:

$$I_n(\alpha) = \frac{V}{\omega L}\,\frac{2}{\pi}\left[-2\,\frac{\cos\alpha}{n}\,\sin n\alpha + \frac{\sin(n-1)\alpha}{n-1} + \frac{\sin(n+1)\alpha}{n+1}\right]$$

$$= \frac{V}{\omega L}\,\frac{4}{\pi}\left[\frac{\sin\alpha\cos(n\alpha) - n\cos\alpha\sin(n\alpha)}{n(n^2-1)}\right] \quad (3.16)$$

where n=2k + 1 and k=1, 2, 3, . . .

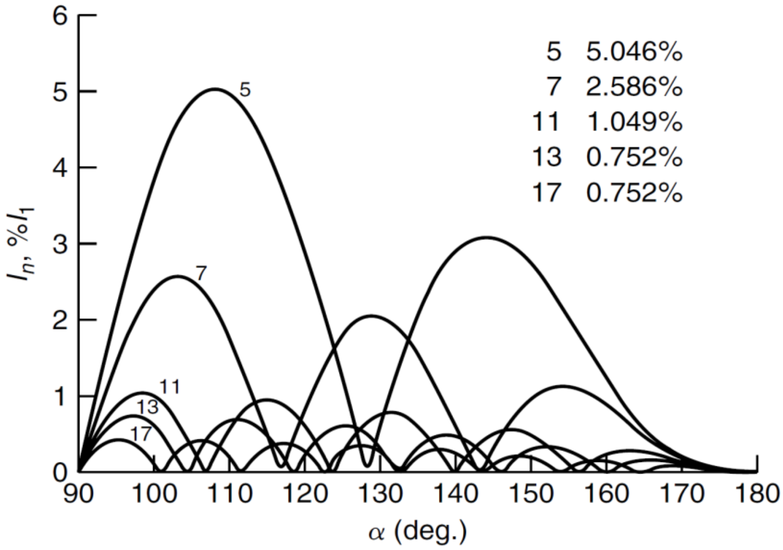


Figure 3.4 Harmonics in a TCR current.

The variation of the amplitude of different harmonics is shown in Fig. 3.4, whereas the same for the total harmonic-current content is displayed in Fig. 3.5. It is seen that all the harmonics do not peak at the same firing angle. The maximum values of various harmonic currents, each expressed as a percentage of the fundamental component, are listed in Fig. 3.4. It should be noted that a thryistor valve usually comprises many parallel-connected strings, each constituting many serially connected thyristors. The series connection enhances the voltage-blocking capability of the valve to correspond to the secondary voltage of the coupling transformer. On the other hand, the parallel connection of strings extends the current capability of the valve. The exact number of thyristors in series and parallel is determined from an optimization process that depends on the rating of individual valves and the coupling transformer.

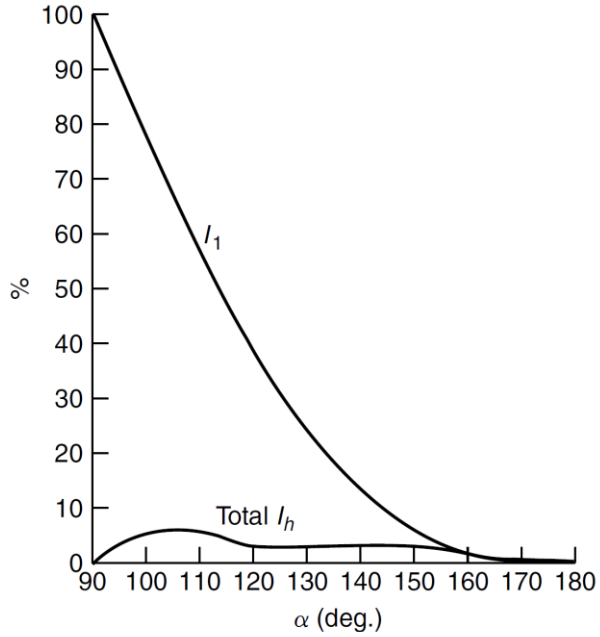
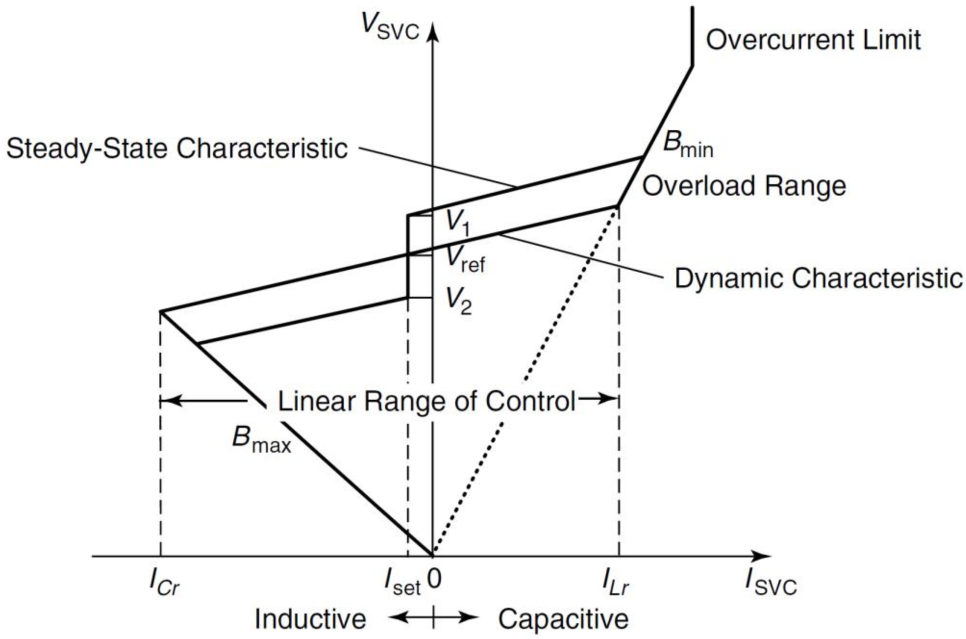


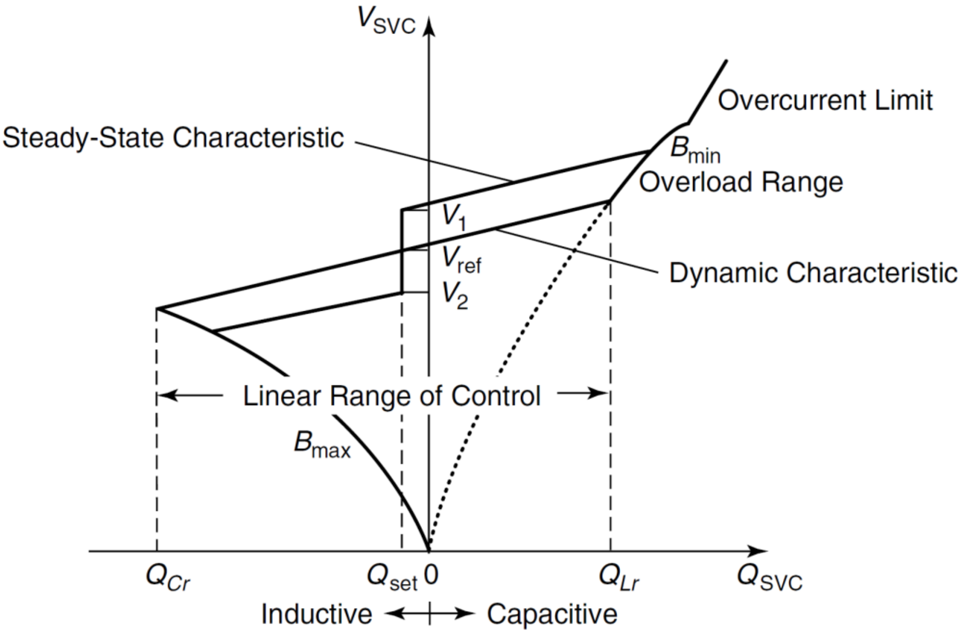
Figure 3.5 The I_1 and total I_h.

3.3 V-I Characteristics of the SVC

The steady-state and dynamic characteristics of SVCs describe the variation of SVC bus voltage with SVC current or reactive power. Two alternative representations of these characteristics are shown in Fig. 3.6: part (a) illustrates the terminal voltage–SVC current characteristic and part (b) depicts the terminal voltage–SVC reactive-power relationship. The dynamic V-I characteristics of SVCs are described in the following text.



(a)



(b)

Figure 3.6 (a) The voltage–current characteristic of the SVC and (b) the voltage–reactive-power characteristic of the SVC.

3.3.1 Dynamic Characteristics

Reference Voltage, V_{ref} is the voltage at the terminals of the SVC during the floating condition, that is, when the SVC is neither absorbing nor generating any reactive power. The reference voltage can be varied between the maximum and minimum limits—$V_{ref\ max}$ and $V_{ref\ min}$—either by the SVC control system, in case of thyristor-controlled compensators, or by the taps of the coupling transformer, in the case of saturated reactor compensators. Typical values of $V_{ref\ max}$ and $V_{ref\ min}$ are 1.05 pu and 0.95 pu, respectively.

Linear Range of SVC Control This is the control range over which SVC terminal voltage varies linearly with SVC current or reactive power, as the latter is varied over its entire capacitive-to-inductive range.

Slope or Current Droop The slope or droop of the V-I characteristic is defined as the ratio of voltage-magnitude change to current-magnitude change over the linear-controlled range of the compensator. Thus slope K_{SL} is given by:

$$K_{\mathrm{SL}} = \frac{\Delta V}{\Delta I}\ \Omega \tag{3.17}$$

where ΔV=the change in voltage magnitude (V)
ΔI=the change in current magnitude (A)

The per-unit value of the slope is obtained as

$$K_{\mathrm{SL}} = \frac{\Delta V/V_r}{\Delta I/I_r}\ \mathrm{pu} \tag{3.18}$$

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

For $\Delta I = I_r$,

$$K_{SL} = \frac{\Delta V(\text{at } I_r \text{ or } Q_r)}{V_r} \text{ pu}$$
$$= \frac{\Delta V(\text{at } I_r \text{ or } Q_r)}{V_r} \cdot 100\% \qquad (3.19)$$

where Q_r represents the rated reactive power of SVC.

Thus the slope can be defined alternatively as the voltage change in percent of the rated voltage measured at the larger of the two—maximum inductive- or maximum capacitive-reactive-power outputs, as the larger output usually corresponds to the base reactive power of the SVC. In some literature, the reactive power rating of the SVC is defined as the sum of its inductive and capacitive rating. The slope is often expressed as an equivalent reactance:

$$X_{SL} = K_{SL} \text{ in pu} \qquad (3.20)$$

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

Overload Range When the SVC traverses outside the linear-controllable range on the inductive side, the SVC enters the overload zone, where it behaves like a fixed inductor.
Overcurrent Limit: To prevent the thyristor valves from being subjected to excessive thermal stresses, the maximum inductive current in the overload range is constrained to a constant value by an additional control action.

3.4 Advantages of the Slope in the SVC Dynamic Characteristic

Although the SVC is a controller for voltage regulation, that is, for maintaining constant voltage at a bus, a finite slope is incorporated in the SVC's dynamic characteristic and provides the following advantages despite a slight deregulation of the bus voltage. The SVC slope substantially reduces the reactive-power rating of the SVC for achieving nearly the same control objectives;

- prevents the SVC from reaching its reactive-power limits too frequently; and
- facilitates the sharing of reactive power among multiple compensators operating in parallel.
- Reduction of the SVC Rating

Figure 3.7 illustrates two dynamic V-I characteristics of an SVC. Characteristic OA′B′C′ incorporates a finite slope, whereas characteristic OABC does not. The slope has been deliberately exaggerated to demonstrate its effect. Assuming that the system load line varies between L_1 and L_2, the reactive-power rating of the SVC needed for providing flat voltage regulation is Q_{Cm} capacitive to Q_{Lm} inductive, as determined from the characteristic OABC. However, if a small deregulation in the SVC bus voltage is considered acceptable (as demonstrated by the characteristic OA′B′C′), the maximum reactive-power rating of the SVC required for performing the voltage control corresponding to the same variation in the system load line is Q'_{Cm} capacitive to Q'_{Lm} inductive. Evidently, $Q'_{Cm'} < Q_{Cm}$ and $Q'_{Lm'} < Q_{Lm}$. Thus a much lower SVC reactive-power rating and, hence, a much lower cost is required for nearly the same control objective. It has been shown for an example system that the SVC rating can be reduced to half, with a 5% slope in the V-I characteristic. The resulting tradeoff is a 2.5% voltage excursion.

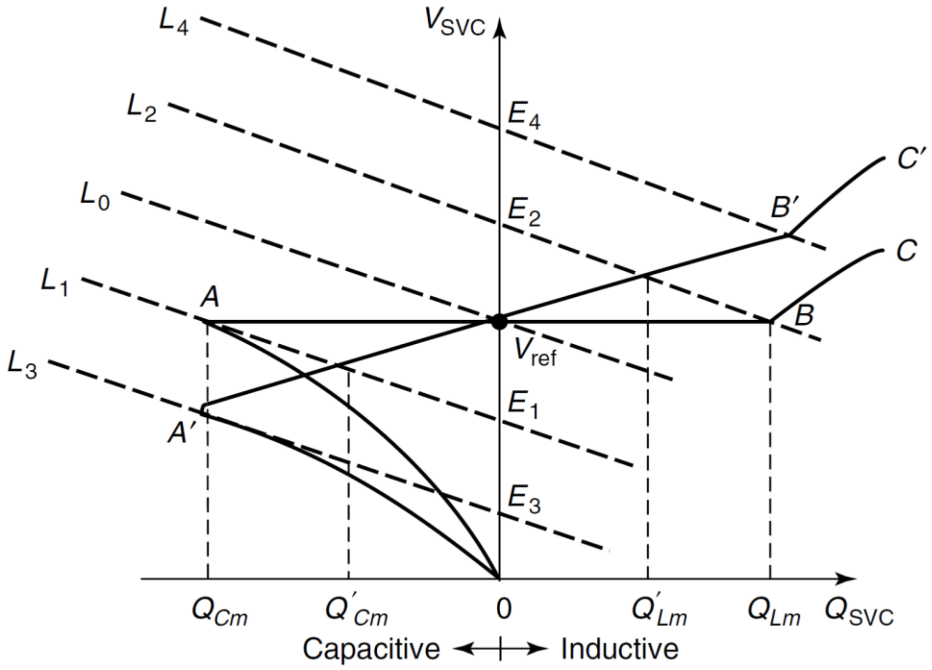


Figure 3.7 Reduction in the SVC reactive-power rating by the current slope.

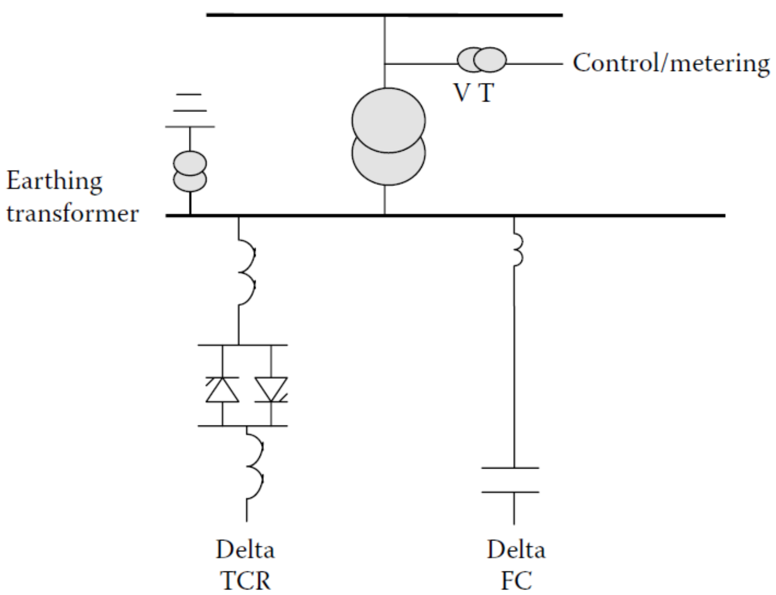


Figure 3.8 SVC of the FC/TCR type.

3.4 SVC using a TCR and an FC

In this arrangement, two or more FC (fixed capacitor) banks are connected to a TCR (thyristor controlled reactor) through a step-down transformer (see Figure 3.8). The rating of the reactor is chosen larger than the rating of the capacitor by an amount to provide the maximum lagging vars that have to be absorbed from the system. By changing the firing angle of the thyristor controlling the reactor from 90^0 to 180^0, the reactive power can be varied over the entire range from maximum lagging vars to leading vars that can be absorbed from the system by this compensator.

The main disadvantage of this configuration is the significant harmonics that will be generated because of the partial conduction of the large reactor under normal sinusoidal steady-state operating condition when the SVC is absorbing zero MVAr. These harmonics are filtered in the following manner. Triplex harmonics are canceled by arranging the TCR and the secondary windings of the step-down transformer in delta connection. The capacitor banks with the help of series reactors are tuned to filter the fifth, seventh, and other higher-order harmonics as a high-pass filter. Further losses are high due to the circulating current between the reactor and capacitor banks. The losses in these types of SVCs are shown in Figure 3.9.

These SVCs do not have a short-time overload capability because the reactors are usually of the air-core type. In applications requiring overload capability, TCR must be designed for short-time overloading, or separate thyristor-switched overload reactors must be employed. By segmenting the fixed reactor and also by using 12-pulse operation by employing two coupling transformers or one transformer with two secondary windings (one wye connected, the other delta), other configurations of the SVC can be obtained.

Both these modifications reduce harmonics but increase costs due to the requirement of more thyristor switches. In the latter case, further a complex transformer and additional complexity in the thyristor firing angle control, as a result of the 30° angle difference in the wye and delta secondary windings, are required.

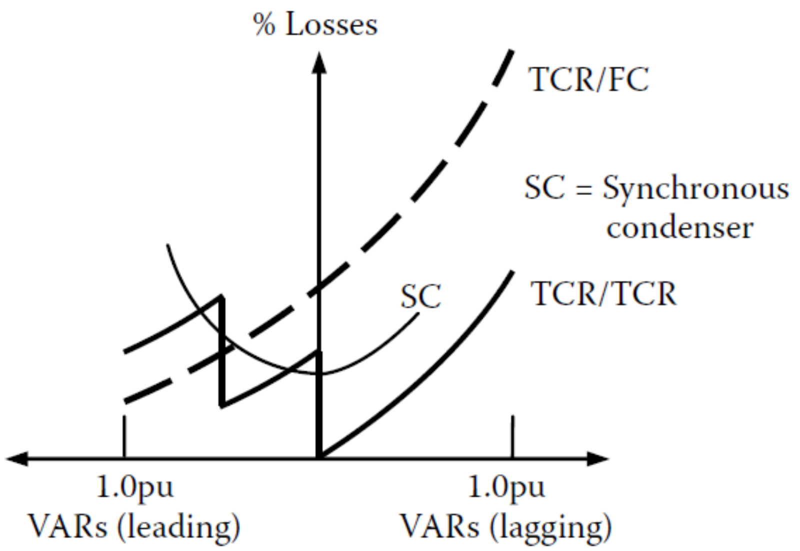


Figure 3.9 Comparison of the loss characteristics of TSC–TCR, TCR–FC compensators and synchronous condenser.

3.5 Steady-State Characteristics of an SVC Using a TCR and an FC

The sinusoidal steady-state characteristics such as voltage–current (or voltage and MVArs supplied by the SVC) relationship of an SVC is shown in Figure 3.10. It consists of three parts. In the regulated region, the voltage and current are linearly related. Outside the regulated interval, output current (var) versus voltage characteristic of the compensator is the same as that of the capacitor (low voltage) or an inductor (high voltage).

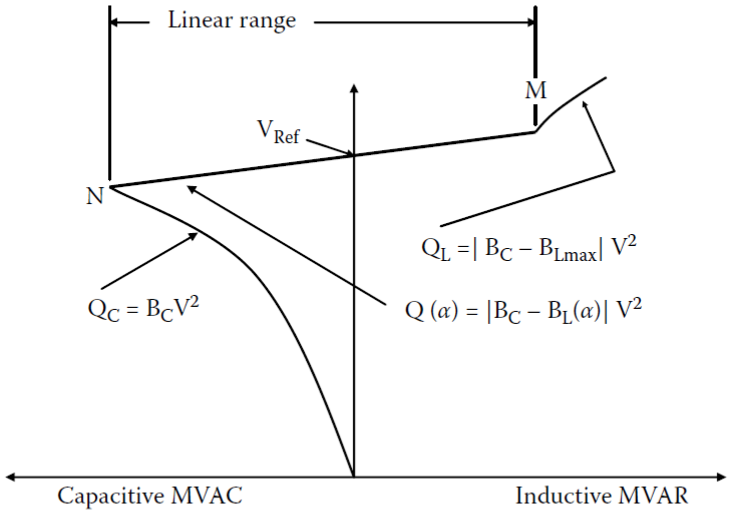


Figure 3.10 Steady-state control characteristics of SVC responding to bus voltage changes.

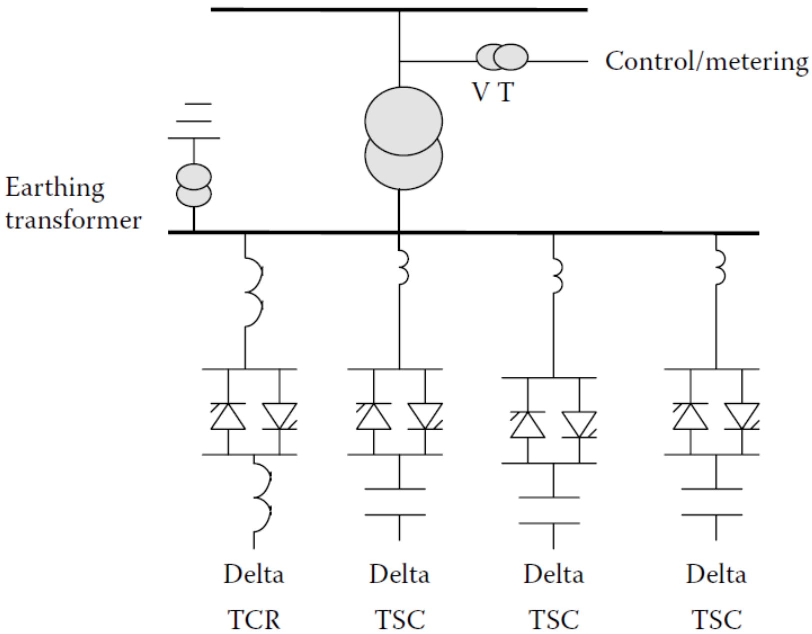


Figure 3.11 SVC of combined TSC and TCR type.

3.6 SVC Using a TCR and TSC

This compensator overcomes two major shortcomings of the earlier compensators by reducing losses under operating conditions and better performance under large system disturbances. Figure 3.11 shows the arrangement of this SVC with a TCR in parallel with several TSC banks say, *n*. In view of the smaller rating of each capacitor bank, the rating of the reactor bank will be 1/n times the maximum output of the SVC, thus reducing the

harmonics generated by the reactor. In those situations where harmonics have to be reduced further, a small amount of FCs tuned as filters may be connected in parallel with the TCR.
When large disturbances occur in a power system due to load rejection, there is a possibility for large voltage transients because of oscillatory interaction between system and the SVC capacitor bank or the parallel. The LC circuit of the SVC is the FC compensator. In the TSC–TCR scheme, due to the flexibility of rapid switching of capacitor banks without appreciable disturbance to the power system, oscillations can be avoided, and hence the transients in the system can also be avoided. The capital cost of this SVC is higher than that of the earlier one due to the increased number of capacitor switches and increased control complexity.

3.7 STATCOM (SVC Using Self-Commutated Inverters)

This SVC consists of an inverter (dc-voltage-sourced converter, i.e., VSC) using gate turn-off (GTO) thyristors. For these inverters, the dc source can be a battery or a capacitor whose terminal voltage can be raised or lowered by controlling the connected inverter. This inverter is connected to the supply system through a commutating reactance and an output transformer. When the inverter voltage *V* is equal to the system voltage, the SVC is floating. When *V* is greater than the system voltage, the SVC acts similar to a capacitor, and if *V* is less than the system voltage, the SVC acts similar to an inductor. By using several inverters with phase-angle difference between them, a higher-order pulse operation can be achieved.

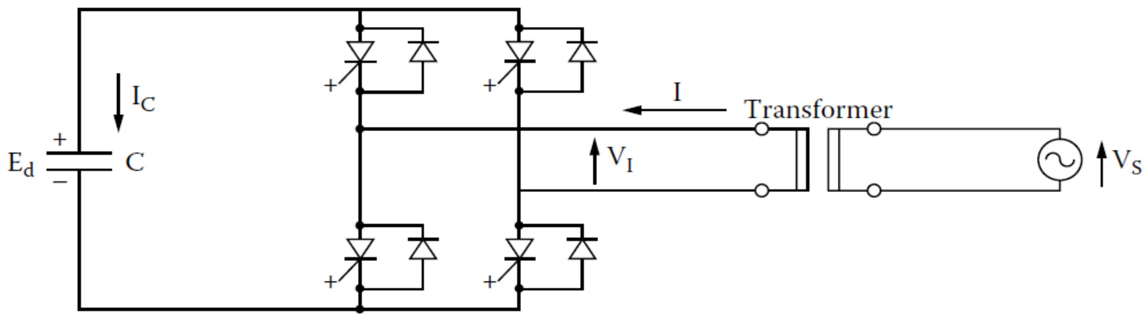


Figure 3.12 Basic circuit of SVC.

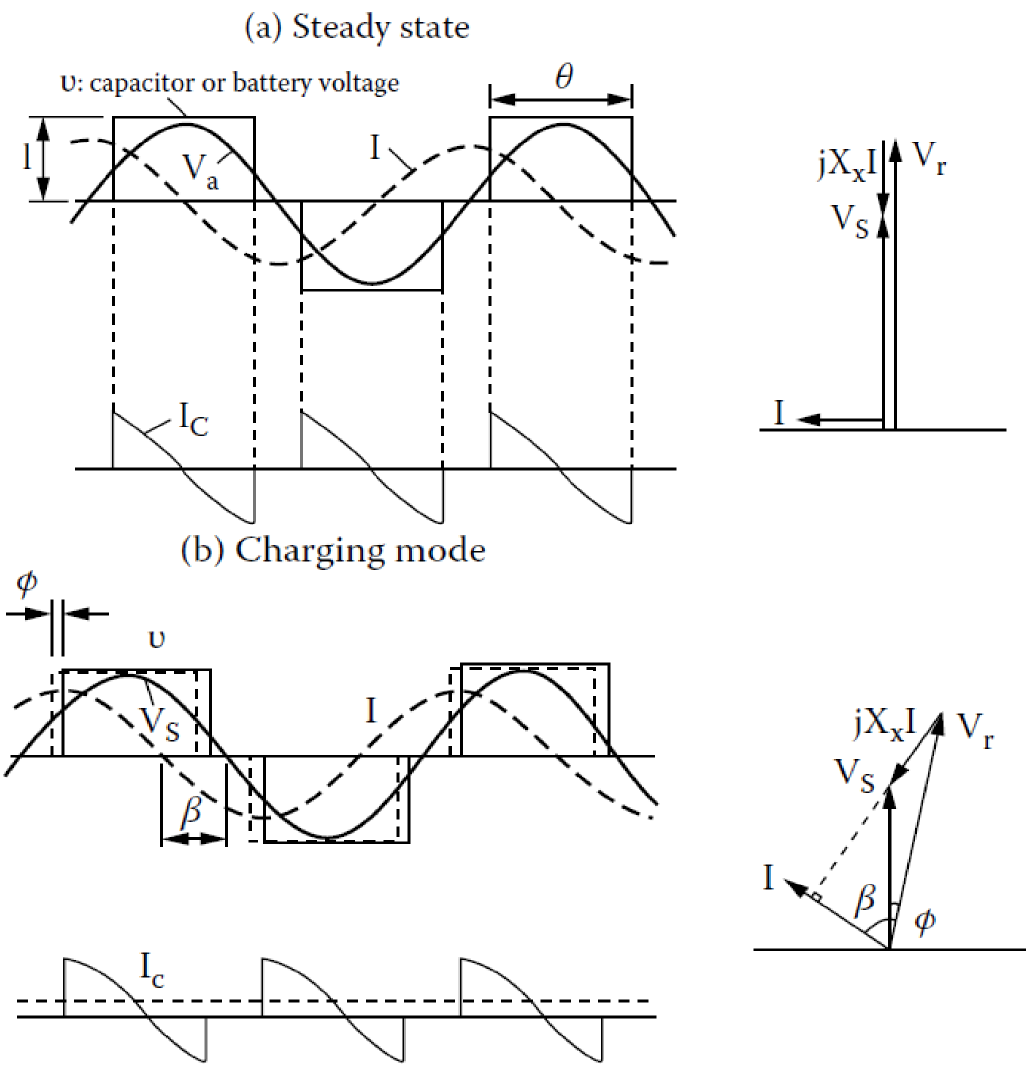
Figure 3.12 shows the basic circuit diagram of this SVC, and Figure 2.15 the voltage and current waveforms of the SVC. Figure 3.12 shows the system configuration of an 80-MVA SVC installed in the Inuyama switching station of the Kansai Electric Co. in Japan in 1991.

Originally, for start-up purposes, a separate start-up converter was used to provide the required dc supply, but this method was found to be slow. In this new system, a gapped-core design is used for the eight phase-displacement transformers to reduce the effect of dc magnetization, decrease magnetic impedance, and improve the uniformity of voltage sharing between windings.
Relocatable GTO-based SVCs have been commissioned in National Grid Company (NGC) Substations.13 The range of these SVCs are □225/−52 MVAr, including 75 MVAr STATCOM.
These types of SVCs are compact, and losses are low, typically about 2% of the output under maximum or minimum operating conditions. Under unbalanced or undervoltage conditions, commutation failure is likely in these types of SVCs, and such operating conditions are not recommended.

3.8 SVC using a Saturated Reactor (SR)

Historically, saturated reactor compensators were developed first before the advent of TCR SVCs. A saturated reactor consists of a six- or nine-limb core saturated reactor of conventional transformer-type construction. In the "Treble–Tripler" saturated reactor with nine-limb core underbalanced system voltage conditions, the harmonics are of the order (18n -□1), giving the lowest order of harmonic as 17th or 19th for *n* =□1,2,3, etc. By connecting the delta windings loaded with inductances, further reduction of the harmonics can be achieved as in Figure 3.15.

Further, slope-correcting capacitors are connected in series with the saturated reactor to reduce the internal reactance, which sometimes leads to harmonic instability. Damped by-pass filters are always applied across these filters to damp oscillations at subsynchronous frequencies. These compensators, similar to transformers, have a considerable temporary overload capability. They are useful primarily for transmission applications but not for load balancing such as traction loads.



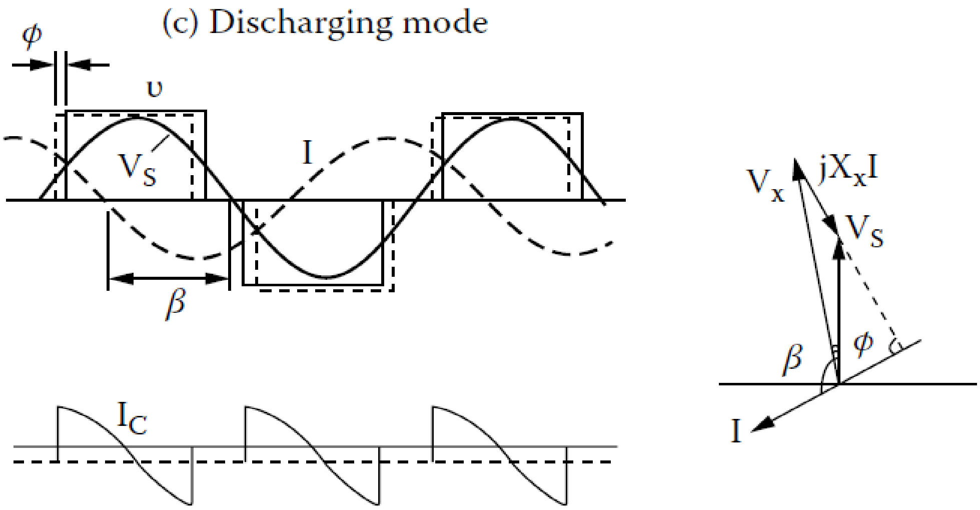


Figure 3.13 Voltage and current waveform of SVC.

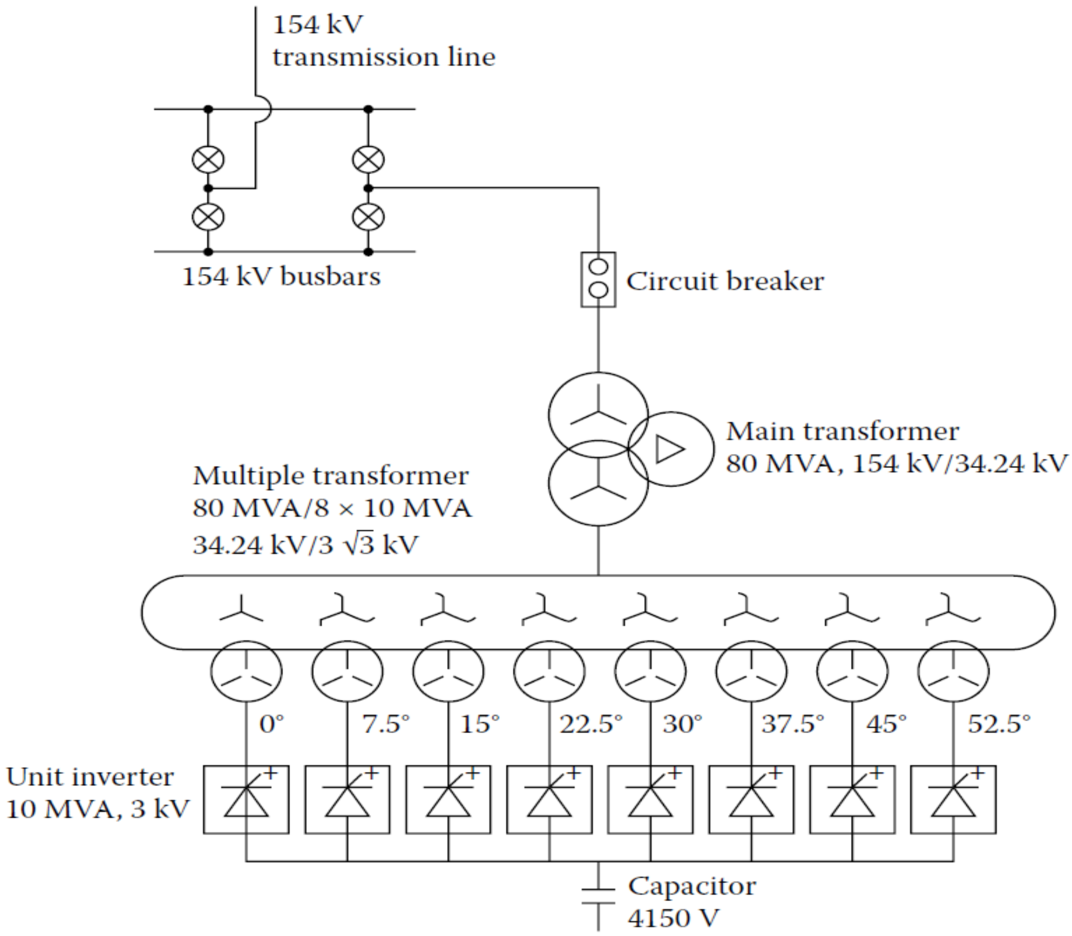


Figure 3.14 System configuration of 80-MVA SVC.

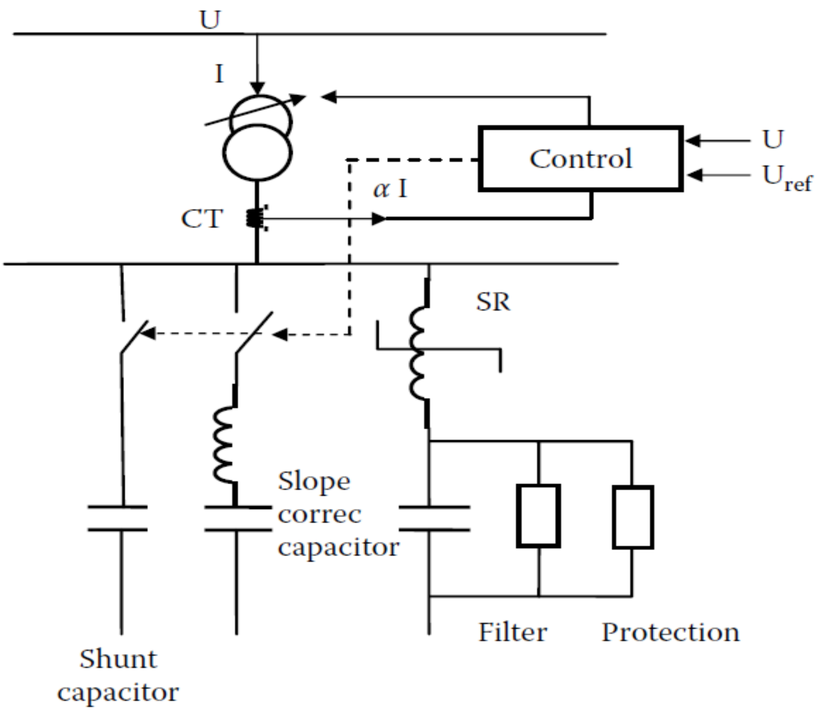


Figure 3.15 Basic scheme of saturated reactor compensator.

3.9 Increase in Transient Stability Margin

Let us try to understand how SVCs contribute to achieve these foregoing objectives. In a simple two-machine power system separated by a reactance of *X* ohms, it is assumed that the terminal voltages of both the machines are *V* volts. If δ is the angle difference between the two sources, then the transmitted power *P* in watts is given by

$$P = (V^2/X)\sin\delta \quad (3.21)$$

Let us assume that an SVC is connected at the midpoint of this two-machine system. Then, the reactance between each source and SVC will be *X*/2 ohms. Now, the power transmitted between the two sources is

$$[V^2/(X/2)]\sin\delta/2 = 2(V^2/X)\sin\delta/2 \quad (3.22)$$

Thus, the amount of maximum power transmitted between the two machines is doubled to $2(V^2/X)$ from V^2/X because the maximum value of a sine function is unity. As can be seen from Figure 2.1a, b, the transient stability limit is also increased. This can be seen by applying the equal-area criterion to the two power angle curves with and without SVC at midpoint.

Damping of Power Oscillations

The dynamic behavior of the previous simple two-machine power system will be described by the swing equation

$$M\,(d^2\delta/dt^2) = P_m - P_e \quad (3.23)$$

where M = angular momentum (also sometimes known as inertia constant),
$Pm - Pe$ = accelerating power

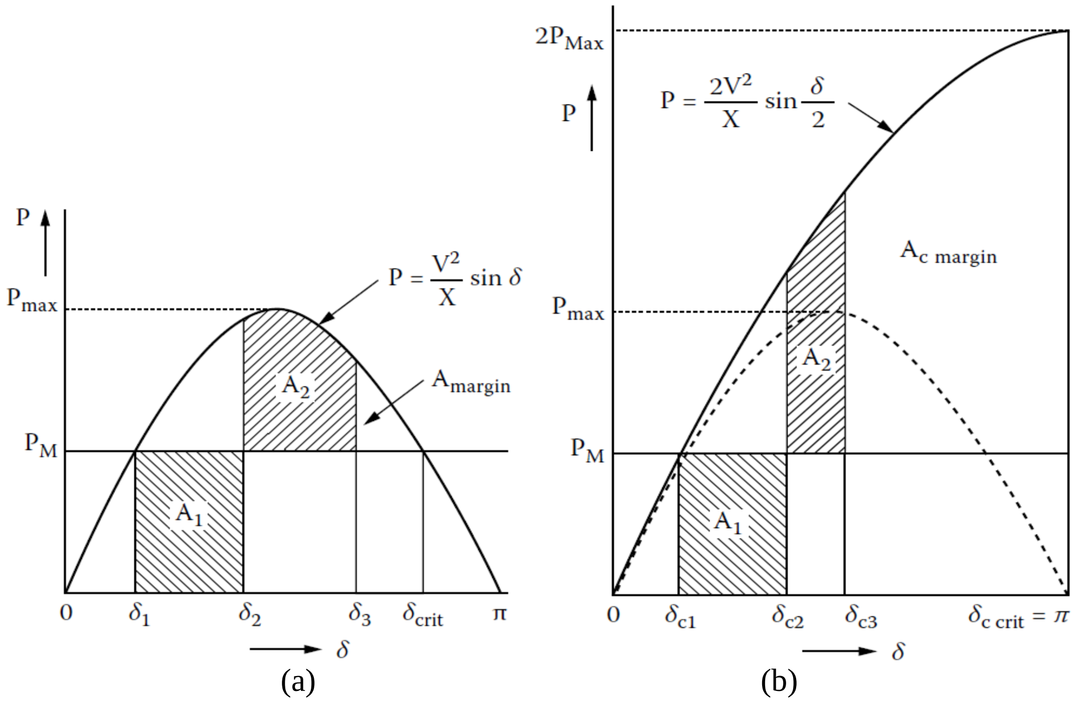


Figure 3.16 Equal area illustrating transient stability margin for a two-machine power system: (a) without compensation, and (b) with an ideal midpoint compensator.

Linearizing the previous equation around an operating point, we obtain the following equation:

$$M\frac{d^2(\Delta\delta)}{dt^2}+\frac{\partial P_E}{\partial V_m}\Delta V_m+\frac{\partial P_E}{\partial \delta}\Delta\delta=0. \tag{3.24}$$

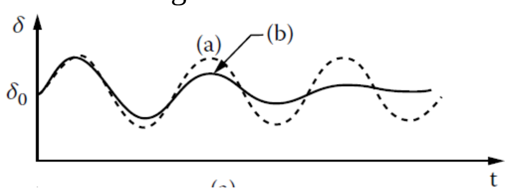
In the preceding equation, ΔVm will be zero if the midpoint voltage was kept constant by connecting an SVC at that point. Under those conditions, the angle Δd would oscillate undamped with a frequency of

$$\omega_0=\sqrt{\frac{1}{M}\frac{\partial P_E}{\partial \delta}\bigg|_0}. \tag{3.25}$$

Hence, to provide damping, ΔV_m must be varied as a function of $d(\Delta d)/dt$, that is,

$$\Delta V_m = K\frac{d(\Delta\delta)}{dt} \tag{3.26}$$

This means that the midpoint voltage is to be increased (by providing capacitive vars) when $d(\Delta\partial)/dt$ is positive (to increase the transmitted electric power and thereby to oppose the acceleration of the generator). When $d(\Delta d)/dt$ is negative, the midpoint voltage is to be decreased (by absorbing inductive vars). This in turn reduces the transmitted electric power, thereby opposing the deceleration of the generator.



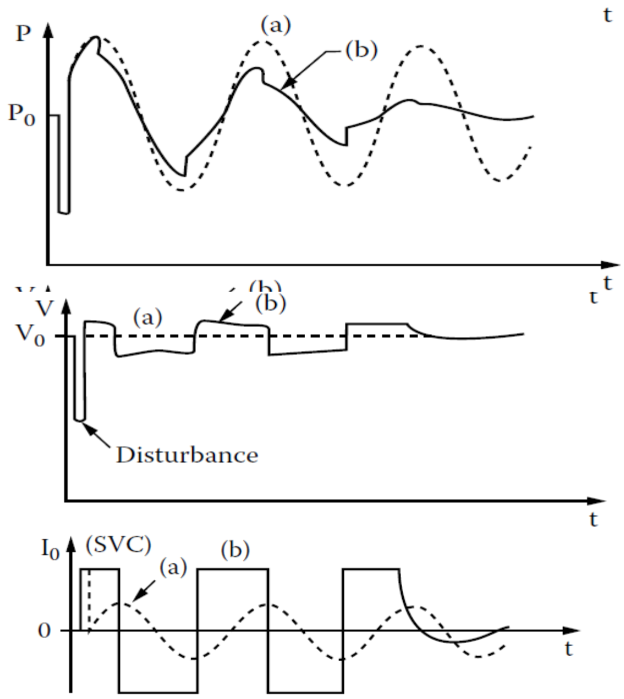


Figure 3.17 Power oscillation damping by static var compensator: (a) voltage regulation only, and (b) voltage control as a function of $\frac{d\delta}{dt}$

3.10 Voltage Support

Figure 3.18 shows the receiving end voltage characteristics of a typical lossless (radial) 275 kV line for different power factors. For different radial feeders of other voltage ratings, the receiving end voltage characteristics also will be similar. It may be seen from this figure that in weak systems, the voltage collapse occurs if the transmitted electrical power exceeds beyond a certain value. This phenomenon is usually referred to as "voltage collapse or voltage instability." Suppose a large load area is supplied from two different sources through different transmission lines and if one of these lines trip, all the load will be transferred to the other line, thus exceeding the limit sometimes for the transmitted electrical power on that line. In those situations, an SVC, which is a rapidly variable source of appropriate rating connected to the receiving end, can prevent the voltage collapse by keeping the terminal voltage constant at the receiving end.

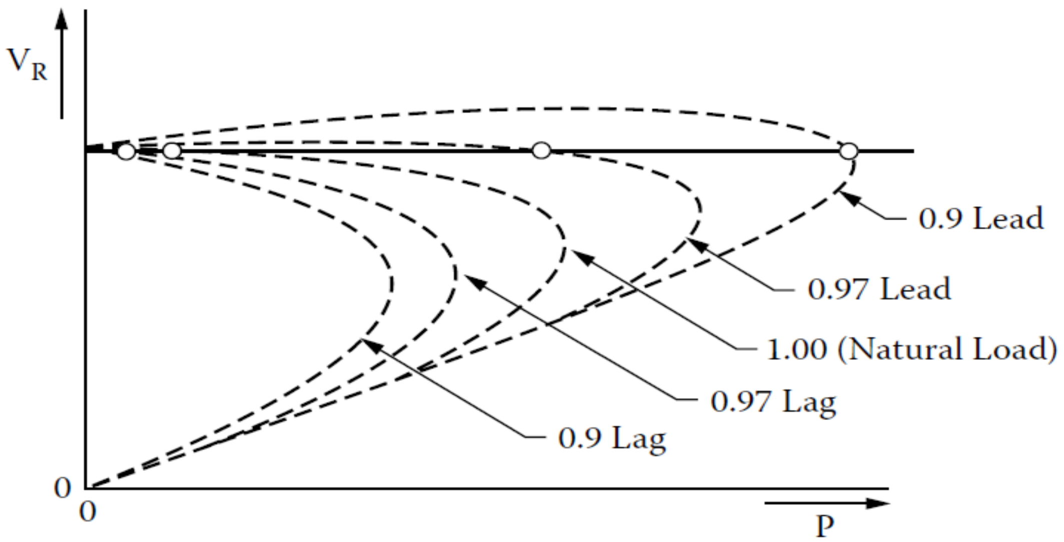


Figure 3.18 Amplitude variation of the receiving-end voltage *VR* as a function of load *P* and load power factor (dashed lines). Possible voltage regulation with a variable var source (continuous line).

Comparison of Different Types of Static Var Compensators

	TCR-Type SVC	TCR–TSC–FC-Type SVC	Self-Commutated Inverter SVC	Saturated-Reactor–Type SVC
Voltage control adjustability (set point)	Yes	Yes	Yes	Limited
Individual phase balancing	Yes	Yes	Yes, if unbalance is small	No
Speed of response	Fast, but system dependent	Fast, but system dependent	Very fast	Fast, but system dependent and slowed by slope-correction capacitors
Generation of harmonics	Filters may be necessary depending on system conditions	Very low, filters may be necessary depending on system conditions	Low	Very low
Limitation of overvoltages	Moderate	Very limited	Poor	Good, within limitation of slope-correction capacitors
Losses	Medium, increases with lagging current	Small–medium, depending on layout	Moderate	Moderate

Table 3.1 Comparison of different Compensators

3.11 Comparison of Static VAR Systems

Table 3.1 compares different compensators showing their relative merits regarding some of their important properties. The expensive components of an SVC system are thyristors, nonconventional transformer, and reactor designs, as well as HV and EHV filters. However, the total cost of losses of an SVC system during its lifetime is much more than its initial capital cost. Hence, the losses of an SVC system at its normal operating point, in most cases at zero MVAr, play a pivotal role in the economic comparison of alternative SVC systems.

3.12 Specification of SVCS

Before specifying the compensators, compensator and system details, and operation and maintenance requirements must be specified. Some of the important items are listed in the following text even though this list is not comprehensive.

a. System details

- System frequency variation under normal operating conditions, fault conditions, and generator outage conditions
- Voltage regulation that is required and its precision
- Maximum harmonic distortion with the compensator in service
- Coordination of system protection with compensator protection and reactive power limits
- Compensator energization details, including any necessary precautions

b. Compensator details

- Maximum continuous reactive power requirements: capacitive and inductive
- Overload rating and duration
- Normal-rated voltage and limits of voltage between which the reactive power ratings must not be exceeded
- Response times of the compensator for different system disturbances
- Control requirements
- Reliability and redundancy of components

c. Operation, maintenance, and installation requirements

- Spare parts, provision for future expansion
- Performance with unbalanced voltages or with unbalanced load
- Cabling details, access, enclosure, and grounding

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