11.2 REACTIVE POWER AND VOLTAGE CONTROL

For efficient and reliable operation of power systems, the control of voltage and reactive power should satisfy the following objectives:

(a) Voltages at the terminals of all equipment in the system are within acceptable limits. Both utility equipment and customer equipment are designed to operate at a certain voltage rating. Prolonged operation of the equipment at voltages outside the allowable range could adversely affect their performance and possibly cause them damage.

(b) System stability is enhanced to maximize utilization of the transmission system. As we will see later in this section, and in Chapters 12 to 14, voltage and reactive power control have a significant impact on system stability.

(c) The reactive power flow is minimized so as to reduce RI^2 and XI^2 losses to a practical minimum (see Chapter 6, Section 6.3). This ensures that the transmission system operates efficiently, i.e., mainly for active power transfer.

The problem of maintaining voltages within the required limits is complicated by the fact that the power system supplies power to a vast number of loads and is fed from many generating units. As loads vary, the reactive power requirements of the transmission system vary. This is abundantly clear from the performance characteristics of transmission lines discussed in Chapter 6. Since reactive power cannot be transmitted over long distances, voltage control has to be effected by using special devices dispersed throughout the system. This is in contrast to the control of frequency which depends on the overall system active power balance. The proper selection and coordination of equipment for controlling reactive power and voltage are among the major challenges of power system engineering.

We will first briefly review the characteristics of power system components from the viewpoint of reactive power and then we will discuss methods of voltage control.

11.2.1 Production and Absorption of Reactive Power

Synchronous generators can generate or absorb reactive power depending on the excitation. When overexcited they supply reactive power, and when underexcited they absorb reactive power. The capability to continuously supply or absorb reactive power is, however, limited by the field current, armature current, and end-region heating limits, as discussed in Chapter 5 (Section 5.6). Synchronous generators are normally equipped with automatic voltage regulators which continually adjust the excitation so as to control the armature voltage.

Overhead lines, depending on the load current, either absorb or supply reactive power. At loads below the natural (surge impedance) load, the lines produce net reactive power; at loads above the natural load, the lines absorb reactive power. The reactive power characteristics of transmission lines are discussed in detail in Chapter 6.

Underground cables, owing to their high capacitance, have high natural loads. They are always loaded below their natural loads, and hence generate reactive power under all operating conditions.

Transformers always absorb reactive power regardless of their loading; at no load, the shunt magnetizing reactance effects predominate; and at full load, the series leakage inductance effects predominate.

Loads normally absorb reactive power. A typical load bus supplied by a power system is composed of a large number of devices. The composition changes depending on the day, season, and weather conditions. The composite characteristics are normally such that a load bus absorbs reactive power. Both active power and reactive power of the composite loads vary as a function of voltage magnitudes. Loads at low-lagging power factors cause excessive voltage drops in the transmission network and are uneconomical to supply. Industrial consumers are normally charged for reactive as well as active power; this gives them an incentive to improve the load power factor by using shunt capacitors.

Compensating devices are usually added to supply or absorb reactive power and thereby control the reactive power balance in a desired manner. In what follows, we will discuss the characteristics of these devices and the principles of application.

11.2.2 Methods of Voltage Control

The control of voltage levels is accomplished by controlling the production, absorption, and flow of reactive power at all levels in the system. The generating units provide the basic means of voltage control; the automatic voltage regulators control field excitation to maintain a scheduled voltage level at the terminals of the generators. Additional means are usually required to control voltage throughout the system. The devices used for this purpose may be classified as follows:

(a) Sources or sinks of reactive power, such as shunt capacitors, shunt reactors, synchronous condensers, and static var compensators (SVCs).

(b) Line reactance compensators, such as series capacitors.

(c) Regulating transformers, such as tap-changing transformers and boosters.

Shunt capacitors and reactors, and series capacitors provide *passive* compensation. They are either permanently connected to the transmission and distribution system, or switched. They contribute to voltage control by modifying the network characteristics.

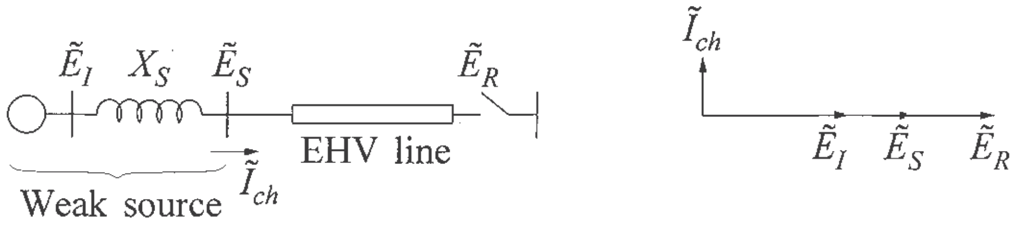
Synchronous condensers and SVCs provide *active* compensation; the reactive power absorbed/supplied by them is automatically adjusted so as to maintain voltages of the buses to which they are connected. Together with the generating units, they establish voltages at specific points in the system. Voltages at other locations in the system are determined by active and reactive power flows through various circuit elements, including the passive compensating devices.

The following is a description of the basic characteristics and forms of application of devices commonly used for voltage and reactive power control.

11.2.3 Shunt Reactors

Shunt reactors are used to compensate for the effects of line capacitance, particularly to limit voltage rise on open circuit or light load.

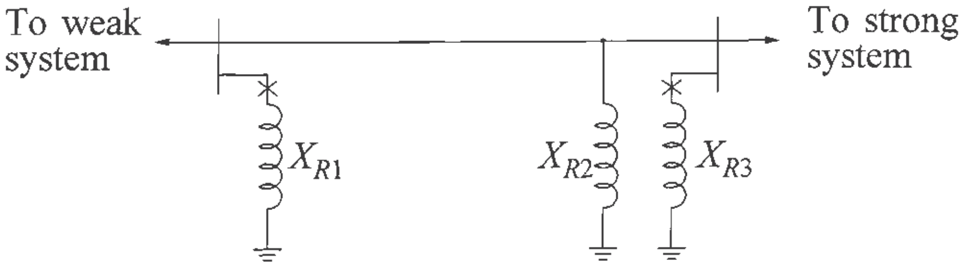
They are usually required for EHV overhead lines longer than 200 km. A shorter overhead line may also require shunt reactors if the line is supplied from a weak system (low short-circuit capacity) as shown in Figure 11.32. When the far end of the line is opened, the capacitive line-charging current flowing through the large source inductive reactance (X_S) will cause a rise in voltage E_S at the sending end of the line. The "Ferranti" effect (see Chapter 6, Section 6.1) will cause a further rise in receiving-end voltage E_R.



(a) System diagram (b) Phasor diagram

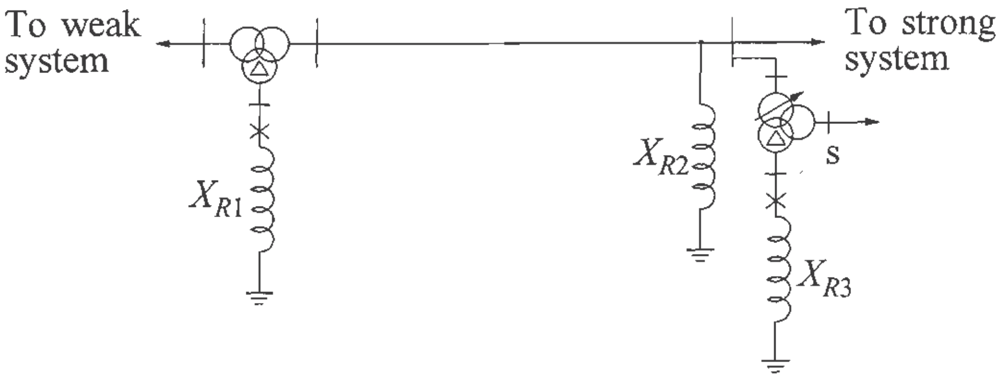
Figure 11.32 EHV line connected to a weak system

A shunt reactor of sufficient size must be permanently connected to the line to limit fundamental-frequency temporary overvoltages to about 1.5 pu for a duration of less than 1 second. Such line-connected reactors also serve to limit energization overvoltages (switching transients). Additional shunt reactors required to maintain normal voltage under light-load conditions may be connected to the EHV bus as shown in Figure 11.33, or to the tertiary windings of adjacent transformers as shown in Figure 11.34. During heavy loading conditions some of the reactors may have to be disconnected. This is achieved by switching reactors using circuit-breakers.



X_{R2} – permanently line-connected reactor
X_{R1}, X_{R3} – switchable bus-connected reactor

Figure 11.33 Line and bus-connected EHV reactors



X_{R2} – permanently line-connected reactor
X_{R1}, X_{R3} – switchable reactors connected to tertiary windings of transformers

Figure 11.34 Line and transformer-connected reactors

For shorter lines supplied from strong systems, there may not be a need for reactors connected to the line permanently. In such cases, all the reactors used may be switchable, connected either to the tertiary windings of transformers or to the EHV bus. In some applications, tapped reactors with on-voltage tap-change control facilities have been used, as shown in Figure 11.35, to allow variation of the reactance value.

Shunt reactors are similar in construction to transformers, but have a single winding (per phase) on an iron core with air-gaps and immersed in oil. They may be of either single-phase or three-phase construction.

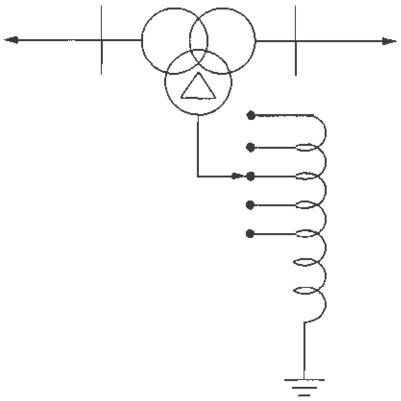


Figure 11.35 Tapped shunt reactor

11.2.4 Shunt Capacitors

Shunt capacitors supply reactive power and boost local voltages. They are used throughout the system and are applied in a wide range of sizes.

Shunt capacitors were first used in the mid-1910s for power factor correction. The early capacitors employed oil as the dielectric. Because of their large size and weight, and high cost, their use at the time was limited. In the 1930s, the introduction of cheaper dielectric materials and other improvements in capacitor construction brought about significant reductions in price and size. The use of shunt capacitors has increased phenomenally since the late 1930s. Today, they are a very economical means of supplying reactive power. The principal advantages of shunt capacitors are their low cost and their flexibility of installation and operation. They are readily applied at various points in the system, thereby contributing to efficiency of power transmission and distribution. The principal disadvantage of shunt capacitors is that their reactive power output is proportional to the square of the voltage. Consequently, the reactive power output is reduced at low voltages when it is likely to be needed most.

Application to distribution systems [25,26]

Shunt capacitors are used extensively in distribution systems for power-factor correction and feeder voltage control. Distribution capacitors are usually switched by automatic means responding to simple time clocks, or to voltage or current-sensing relays.

The objective of *power-factor correction* is to provide reactive power close to the point where it is being consumed, rather than supply it from remote sources. Most loads absorb reactive power; that is, they have lagging power factors. Table 11.1 gives typical power factors and voltage-dependent characteristics of some common types of loads.

Table 11.1 Typical characteristics of individual loads

Type of load	Power factor (lag)	Voltage dependence	
		P	Q
Large industrial motor	0.89	$V^{0.05}$	$V^{0.5}$
Small industrial motor	0.83	$V^{0.1}$	$V^{0.6}$
Refrigerator	0.84	$V^{0.8}$	$V^{2.5}$
Heat pump (cool/heat)	0.81/0.84	$V^{0.2}$	$V^{2.5}$
Dishwasher	0.99	$V^{1.8}$	$V^{3.5}$
Clothes washer	0.65	$V^{0.08}$	$V^{1.6}$
Clothes dryer	0.99	$V^{2.0}$	$V^{3.3}$
Colour TV	0.77	$V^{2.0}$	$V^{5.0}$
Fluorescent lighting	0.90	$V^{1.0}$	$V^{3.0}$
Incandescent lighting	1.00	$V^{1.55}$	-
Range, water or space heat	1.00	$V^{2.0}$	-

Power-factor correction is provided by means of fixed (permanently connected) and switched shunt capacitors at various voltage levels throughout the distribution systems. Low voltage banks are used for large customers and medium voltage banks are used at intermediate switching stations. For large industrial plants, as shown in Figure 11.36, power factor correction is applied at different levels: (i) individual motors, (ii) groups of motors, and (iii) the overall plant.

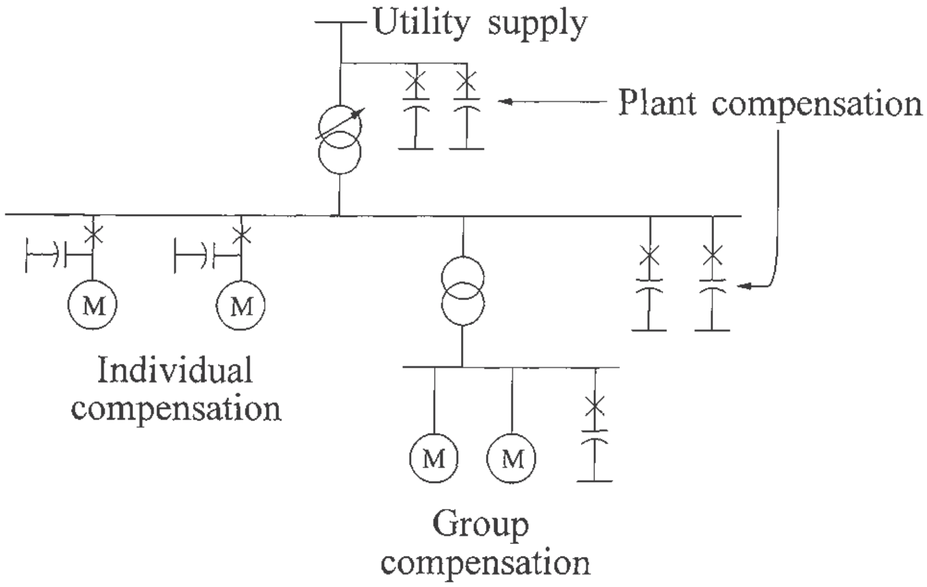


Figure 11.36 Power factor correction in industrial plants [26]

Switched shunt capacitors are also used extensively for *feeder voltage control.* They are installed at appropriate locations along the length of the feeder to ensure that voltages at all points remain within the allowable maximum and minimum limits as the loads vary. As discussed in Section 11.2.10, the application of shunt capacitors is coordinated with that of feeder voltage regulators or booster transformers.

Application to transmission system

Shunt capacitors are used to compensate for the XI^2 losses in transmission systems and to ensure satisfactory voltage levels during heavy loading conditions. Capacitor banks of appropriate sizes are connected either directly to the high voltage bus or to the tertiary winding of the main transformer, as shown in Figure 11.37. They are breaker-switched either automatically by a voltage relay or manually. Switching of capacitor banks provides a convenient means of controlling transmission system voltages. They are normally distributed throughout the transmission system so as to minimize losses and voltage drops. Detailed power-flow studies are performed to determine the size and location of capacitor banks to meet the system design criteria which specify maximum allowable voltage drop following specified contingencies. Procedures for power-flow analysis are discussed in Section 11.3.

The principles of application of shunt capacitors and other forms of transmission system compensation are presented in Section 11.2.8.

(a) Tertiary connected capacitor banks

(b) HV capacitor bank

Figure 11.37 Capacitor bank connections

11.2.5 Series Capacitors

Series capacitors are connected in series with the line conductors to compensate for the inductive reactance of the line. This reduces the transfer reactance between the buses to which the line is connected, increases maximum power that can be transmitted, and reduces the effective reactive power (XI^2) loss. Although series capacitors are not usually installed for voltage control as such, they do contribute to improved voltage control and reactive power balance. The reactive power produced by a series capacitor increases with increasing power transfer; a series capacitor is self-regulating in this regard.

Application to distribution feeders

Series capacitors have been applied to improve voltage regulation of distribution and industrial feeders since the 1930s. Welders and arc furnaces are typical of loads with poor power factor and intermittent demand. A series capacitor not only reduces voltage drop in the steady state, but it responds almost instantaneously to changes in load current. The series capacitor, by reducing the impedance between the bulk power source and the fluctuating load, is effective in solving light-flicker problems.

There are a number of problems associated with the application of series capacitors to industrial feeders that need careful attention [27-29]:

- Self-excitation of large induction and synchronous motors during starting. The motor may lock in at a fraction of synchronous (subsynchronous) speed due to resonance conditions.

  The most common remedy is to connect, during starting, a suitable resistance in parallel with the series capacitor.

- Hunting of synchronous motors (in some cases induction motors) at light load, due to the high R/X ratio of the feeder.

- Ferroresonance between transformers and series capacitors resulting in harmonic overvoltages. This may occur when energizing an unloaded transformer or when suddenly removing a load.

Because of the above problems and the difficulty in protecting the capacitors from system fault currents, series capacitors are not very widely used in today's distribution systems. They are, however, used in subtransmission systems to modify load division between parallel lines and to improve voltage regulation.

Application to EHV transmission system

Because series capacitors permit economical loading of long transmission lines, their application to EHV transmission has grown. They have been primarily used to improve system stability and to obtain the desired load division among parallel lines.

Complete compensation of the line is never considered. At 100% compensation, the effective line reactance would be zero, and the line current and power flow would be extremely sensitive to changes in the relative angles of terminal voltages. In addition, the circuit would be series resonant at the fundamental frequency. High compensation levels also increase the complexity of protective relaying and the probability of subsynchronous resonance. A practical upper limit to the degree of series compensation is about 80%.

It is not practical to distribute the capacitance in small units along the line. Therefore, lumped capacitors are installed at a few locations along the line. The use of lumped series capacitors results in an uneven voltage profile.

Series capacitors operate at line potential; hence, they must be insulated from ground. A widely accepted practice is to mount the capacitors on platforms insulated from ground. Alternatively, ground-base capacitor banks consisting of capacitor cans placed inside oil-insulated tanks may be used.

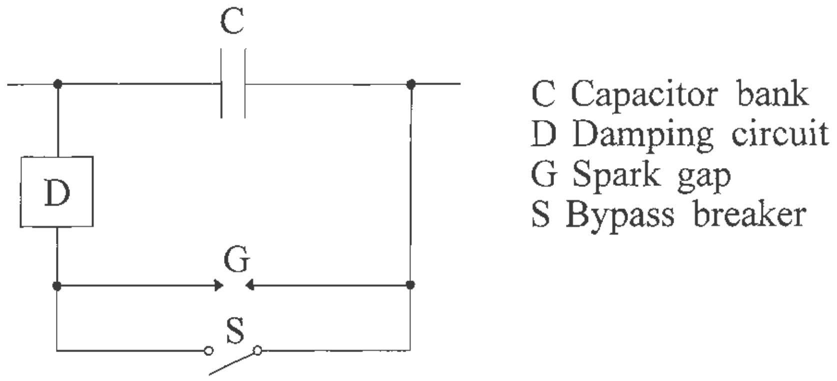
The following are some of the key considerations in the application of series-capacitor banks:

(a) *Voltage rise due to reactive current.* Voltage rise on one side of the capacitor may be excessive when the line reactive-current flow is high, as might occur during power swings or heavy power transfers. This may impose unacceptable stress on equipment on the side of the bank experiencing high voltage. The system design must limit the voltage to acceptable levels, or the equipment must be rated to withstand the highest voltage that might occur.

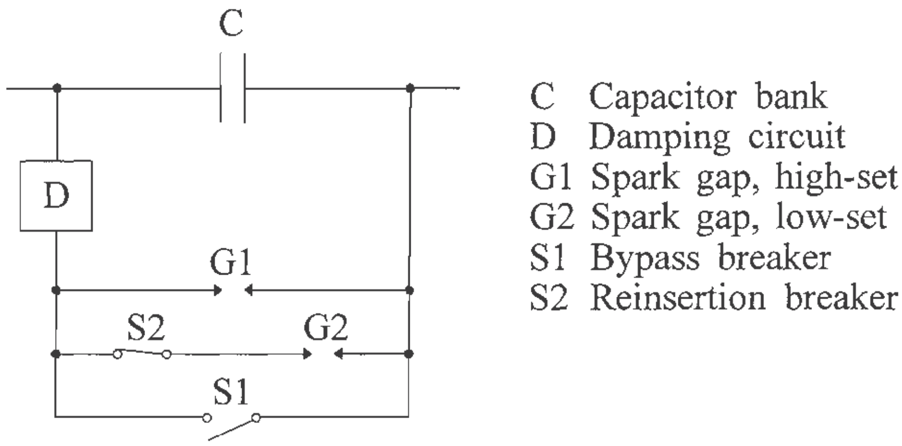
(b) *Bypassing and reinsertion.* The series capacitors are normally subjected to a voltage which is on the order of the regulation of the line, i.e., only a few percent of the rated line voltage. If, however, the line is short-circuited by a fault beyond the capacitor, a voltage on the order of the line voltage will appear across the capacitor. It would not be economical to design the capacitor for this voltage, since both size and cost of the capacitor increase with the square of the voltage. Therefore, provision is made for bypassing the capacitor during faults and reinsertion after fault clearing. Speed of reinsertion may be an important factor in maintaining transient stability.

    Traditionally, bypassing was provided by a spark gap across the bank or each module of the bank. However, the present trend is to use nonlinear resistors of zinc oxide which have the advantage that reinsertion is essentially instantaneous. Figure 11.38 shows alternative bypass schemes [30]. The scheme shown in Figure 11.38(a) consists of a single spark gap (G) which bypasses the capacitor bank when the capacitor voltage exceeds a set value, usually about three to four times the capacitor rated voltage. The damping circuit (D) limits the discharge current and absorbs the capacitor energy. Upon detection of gap current, the bypass breaker (S) is closed, diverting the current from the gap. When the current returns to normal, the breaker is opened, thereby reinserting the capacitor into the line. This scheme is designed to provide a reinsertion time of 200 to 400 ms.

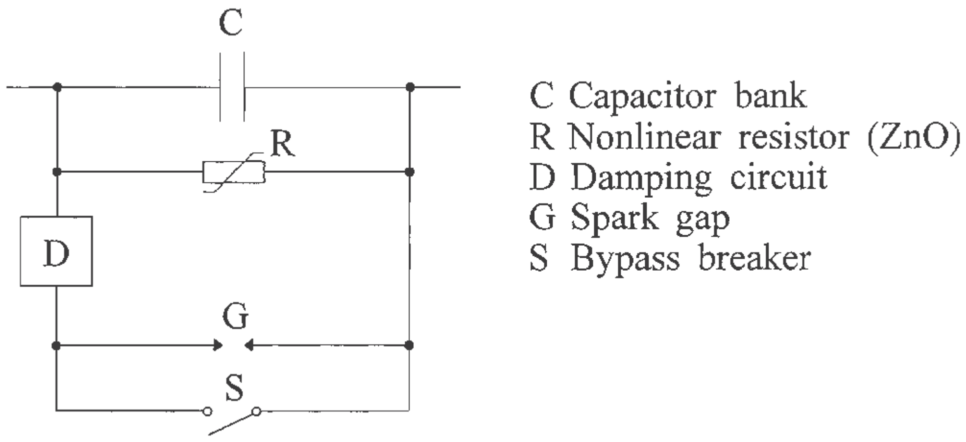
    A dual-gap scheme with reinsertion time on the order of 80 ms is shown in Figure 11.38(b). It has an extra spark gap (G2) which is set low so that it will spark over first. Breaker S2 is normally closed. In the event of a fault, gap



(a) Single-gap protective scheme



(b) Dual-gap protective scheme



(c) Zinc-oxide protective scheme

Figure 11.38 Series capacitor bypass protective schemes [30]

G2 bypasses the capacitor bank. Breaker S2 opens immediately after the line fault has been cleared and reinserts the capacitor bank into the line. As a result, reinsertion is not delayed due to the de-ionization time. The other gap G1, which is high-set, and the bypass breaker S1 serve as backup protection.

In the scheme shown in Figure 11.38(c), a nonlinear resistor of zinc oxide (ZnO) limits the voltage across the capacitor bank during a fault and reinserts the bank immediately on termination of the fault current. The energy is absorbed by the ZnO resistor without the need to fire the spark gap (G). The spark gap is provided as a backup overvoltage protection for the resistor. The capacitor bank and the ZnO resistor remain in circuit during the fault, with the resistor bypassing most of the current; reinsertion takes place automatically without delay when the fault is cleared.

(c) *Location.* A series-capacitor bank can theoretically be located anywhere along the line. Factors influencing choice of location include cost, accessibility, fault level, protective relaying considerations, voltage profile and effectiveness in improving power transfer capability.

The following are the usual locations considered:

- Midpoint of the line
- Line terminals
- 1/3 or 1/4 points of the line

In practice all of the above arrangements have been used.

The midpoint location has the advantage that the relaying requirements are less complicated if compensation is less than 50%. In addition, short-circuit current is lower. However, it is not very convenient in terms of access for maintenance, monitoring, security, etc.

Splitting of the compensation into two parts, with one at each end of the line, provides more accessability and availability of station service and other auxiliaries. The disadvantages are higher fault current, complicated relaying, and higher rating of the compensation.

The effectiveness of the compensation scheme depends on the location of the series capacitors and the associated shunt reactors. References 31 and 32 present results of comprehensive studies evaluating the effectiveness of different capacitor locations.

The choice of configuration of the compensation scheme for any particular application requires a detailed study with regard to the overall economy and system reliability. The study should take into account voltage profiles, compensation effectiveness, effect on transmission losses, overvoltages, and proximity to an attended station. References 33 and 34 provide details of engineering considerations related to series-capacitor applications on two power systems.

Adding a capacitor in series with the inductance of a transmission line forms a series-resonant circuit. The natural frequency of the resonant circuit so formed, for the usual range of compensation (20 to 70% of line reactance), is below the power frequency. The transmission network thus has a natural frequency in the subsynchronous range. Consequently, transient current components of subharmonic frequency are excited during any disturbance and are superimposed on the power-frequency currents. The subharmonic currents are usually damped rapidly within a few cycles, due to the resistances of the line and of any connected equipment such as loads. Therefore, the subharmonic natural mode introduced by the use of a series capacitor is rarely troublesome. One notable exception is the possible interaction with a natural frequency of the shaft mechanical system of nearby steam turbine generating units. It may lead to a buildup of torsional oscillations, either spontaneously or after a disturbance. This phenomenon is known as *subsynchronous resonance* (SSR). A detailed discussion of the SSR problem and measures available to counter it are presented in Chapter 15.

11.2.6 Synchronous Condensers

A synchronous condenser is a synchronous machine running without a prime mover or a mechanical load. By controlling the field excitation, it can be made to either generate or absorb reactive power. With a voltage regulator, it can automatically adjust the reactive power output to maintain constant terminal voltage. It draws a small amount of active power from the power system to supply losses.

Synchronous condensers have been used since the 1930s for voltage and reactive power control at both transmission and subtransmission levels. They are often connected to the tertiary windings of transformers. They fall into the category of *active shunt compensators*. Because of their high purchase and operating costs, they have been largely superseded by static var compensators (discussed next). Recent applications of synchronous condensers have been mostly at HVDC converter stations connected to weak systems [35]. There are many old synchronous condensers still in operation, and they serve as an excellent form of voltage and reactive power control devices.

Synchronous compensators have several advantages over static compensators. Synchronous compensators contribute to system short-circuit capacity. Their reactive power production is not affected by the system voltage. During power swings (electromechanical oscillations) there is an exchange of kinetic energy between a synchronous condenser and the power system. During such power swings, a synchronous condenser can supply a large amount of reactive power, perhaps twice its continuous rating. It has about 10 to 20% overload capability for up to 30 minutes. Unlike other forms of shunt compensation, it has an internal voltage source and is better able to cope with low system voltage conditions.

Some combustion turbine peaking units can be operated as synchronous condensers if required. Such units are often equipped with clutches which can be used to disconnect the turbine from the generator when active power is not required from them.

11.2.7 Static Var Systems [36-38]

Terminology [36]

Static var compensators (SVCs) are shunt-connected static generators and/or absorbers whose outputs are varied so as to control specific parameters of the electric power system. The term "static" is used to indicate that SVCs, unlike synchronous compensators, have no moving or rotating main components. Thus an SVC consists of static var generator (SVG) or absorber devices and a suitable control device.

A static var system (SVS) is an aggregation of SVCs and mechanically switched capacitors (MSCs) or reactors (MSRs) whose outputs are coordinated.

Types of SVC

The following are the basic types of reactive power control elements which make up all or part of any static var system:

- Saturated reactor (SR)
- Thyristor-controlled reactor (TCR)
- Thyristor-switched capacitor (TSC)
- Thyristor-switched reactor (TSR)
- Thyristor-controlled transformer (TCT)
- Self- or line-commutated converter (SCC/LCC)

A number of different SVS configurations made up of a combination of one or more of the basic types of SVC and fixed capacitor (FC) banks (i.e., capacitors not switched via local automatic control) have been used in practice for transmission system compensation.

We will first discuss the general principle of SVS operation in an HVAC system using a somewhat idealized compensator and then examine the characteristics of specific configurations.

Static var systems are capable of controlling individual phase voltages of the buses to which they are connected. They can therefore be used for control of negative-sequence as well as positive-sequence voltage deviations. However, we are interested here in the balanced fundamental frequency performance of power systems and therefore our analysis will consider only this aspect of SVS performance.

Fundamental frequency performance of an SVS [36,38]

Characteristic of an ideal SVS:

From the viewpoint of power system operation, an SVS is equivalent to a shunt capacitor and a shunt inductor, both of which can be adjusted to control voltage and reactive power at its terminals (or a nearby bus) in a prescribed manner (see Figure 11.39).

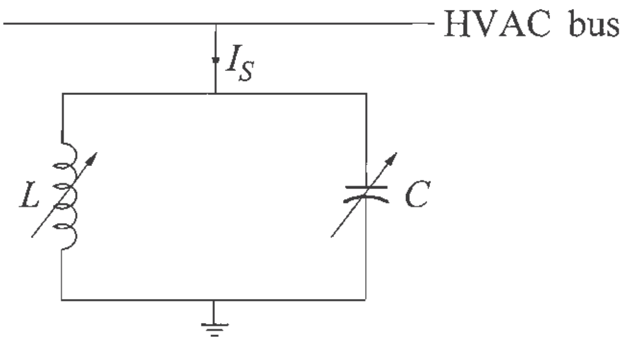


Figure 11.39 Idealized static var system

Ideally, an SVS should hold constant voltage (assuming that this is the desired objective), possess unlimited var generation/absorption capability with no active and reactive power losses and provide instantaneous response. The performance of the SVS can be visualized on a graph of controlled ac bus voltage (V) plotted against the SVS reactive current (I_S). The V/I characteristic of an ideal SVS is shown in Figure 11.40. It represents the steady-state and quasi steady-state characteristics of the SVS.

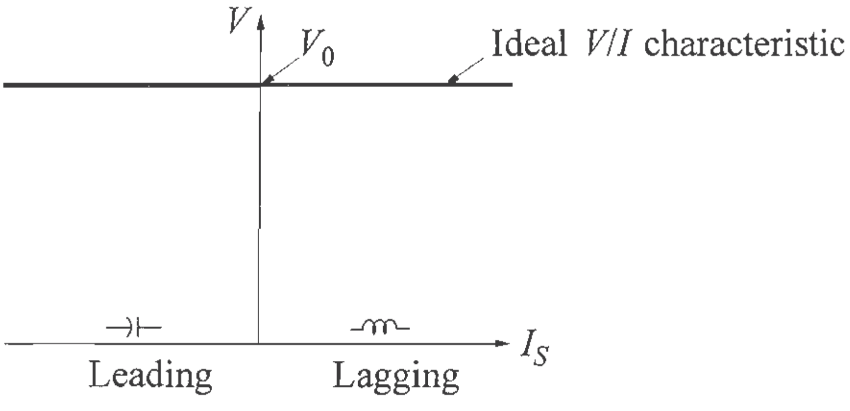
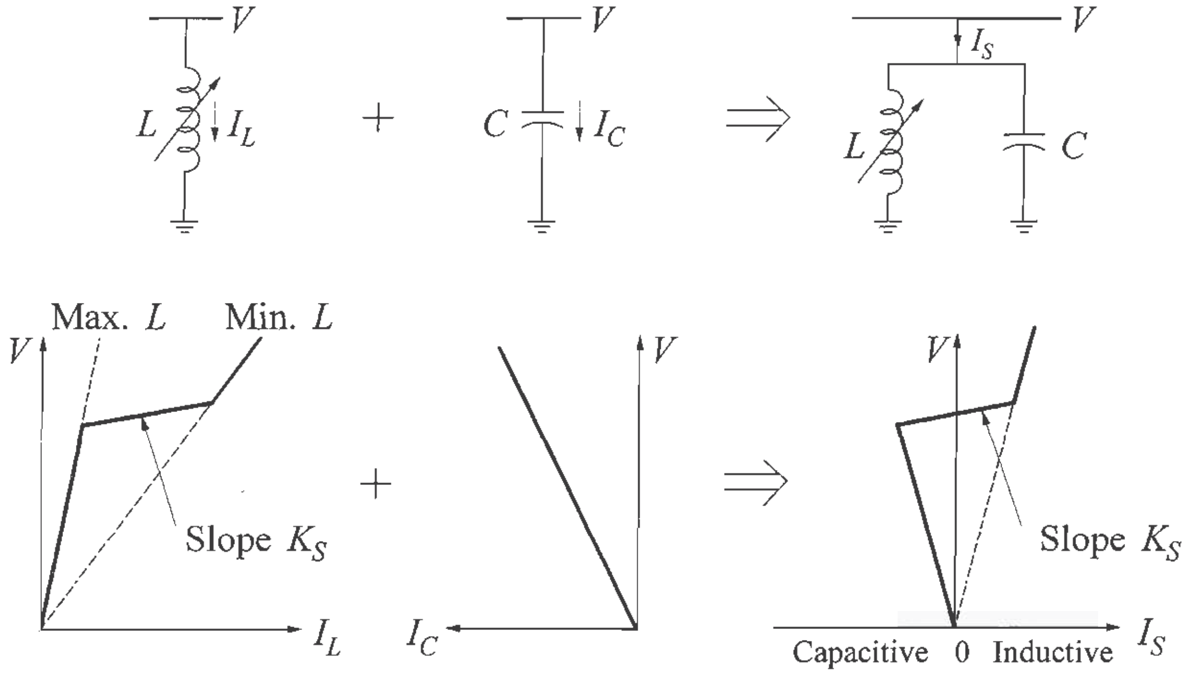


Figure 11.40 V/I characteristic of ideal compensator

Characteristic of a realistic SVS:

We consider an SVS composed of a controllable reactor and a fixed capacitor. The resulting characteristics are sufficiently general and are applicable to a wide range of practical SVS configurations.

Figure 11.41 illustrates the derivation of the characteristic of an SVS consisting of a controllable reactor and a fixed capacitor. The composite characteristic is derived by adding the individual characteristics of the components. The characteristic shown in Figure 11.41(a) is representative of the characteristics of practical controllable reactors.

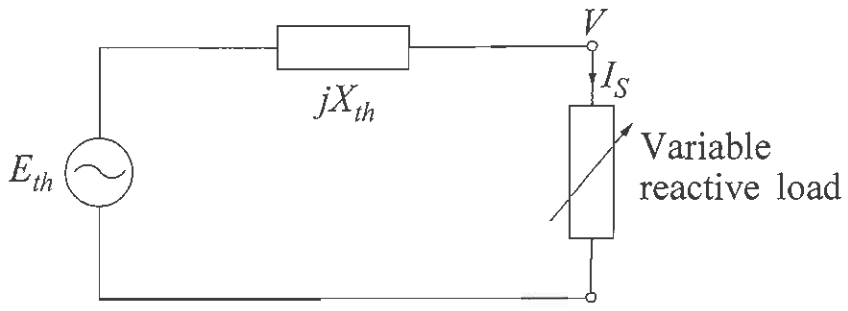


(a) Controllable reactor (b) Fixed capacitor (c) SVS

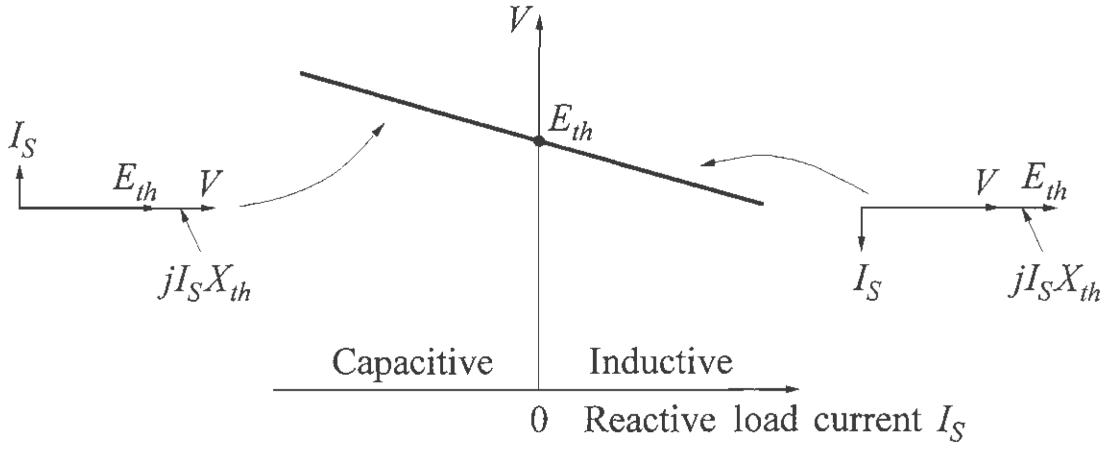
Figure 11.41 Composite characteristics of an SVS

Power system characteristic:

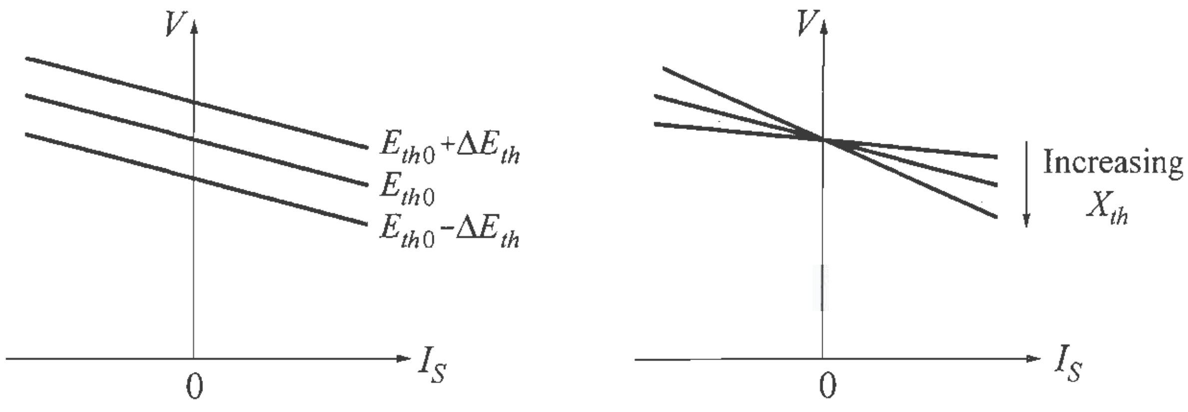
In order to examine how the SVS performs when applied to a power system, the characteristics of the SVS and the power system need to be examined together. The system *V/I* characteristic may be determined by considering the Thevenin equivalent circuit as viewed from the bus whose voltage is to be regulated by the SVS. This is illustrated in Figure 11.42. The Thevenin impedance in Figure 11.42(a) is predominantly an inductive reactance. The corresponding voltage versus reactive current characteristic is shown in Figure 11.42(b). The voltage V increases linearly with capacitive load current and decreases linearly with inductive load current.



(a) Thevenin equivalent circuit of HVAC network



(b) Voltage-reactive current characteristic



(c) Effect of varying source voltage E_{th}

(d) Effect of varying system reactance X_{th}

Figure 11.42 Power system voltage versus reactive current characteristic [38]

For each network condition, an equivalent circuit such as that shown in Figure 11.42(a) can be defined. Figures 11.42(c) and (d) show how the network *V/I* characteristic is affected by changes in source voltage E_{th} and the system equivalent reactance X_{th}, respectively.

Composite SVS - power system characteristic:

The system characteristic may be expressed as

$$V = E_{th} - X_{th} I_S \tag{11.31}$$

The SVS characteristic, within the control range defined by the slope reactance X_{SL}, is given by

$$V = V_0 + X_{SL} I_S \tag{11.32}$$

For voltages outside the control range, the ratio V/I_S is equal to the slopes of the two extreme segments of Figure 11.41(c). These are determined by the ratings of the inductor and capacitor.

The solution of SVS and power system characteristic equations is graphically illustrated in Figure 11.43. Three system characteristics are considered in the figure, corresponding to three values of the source voltage. The middle characteristic

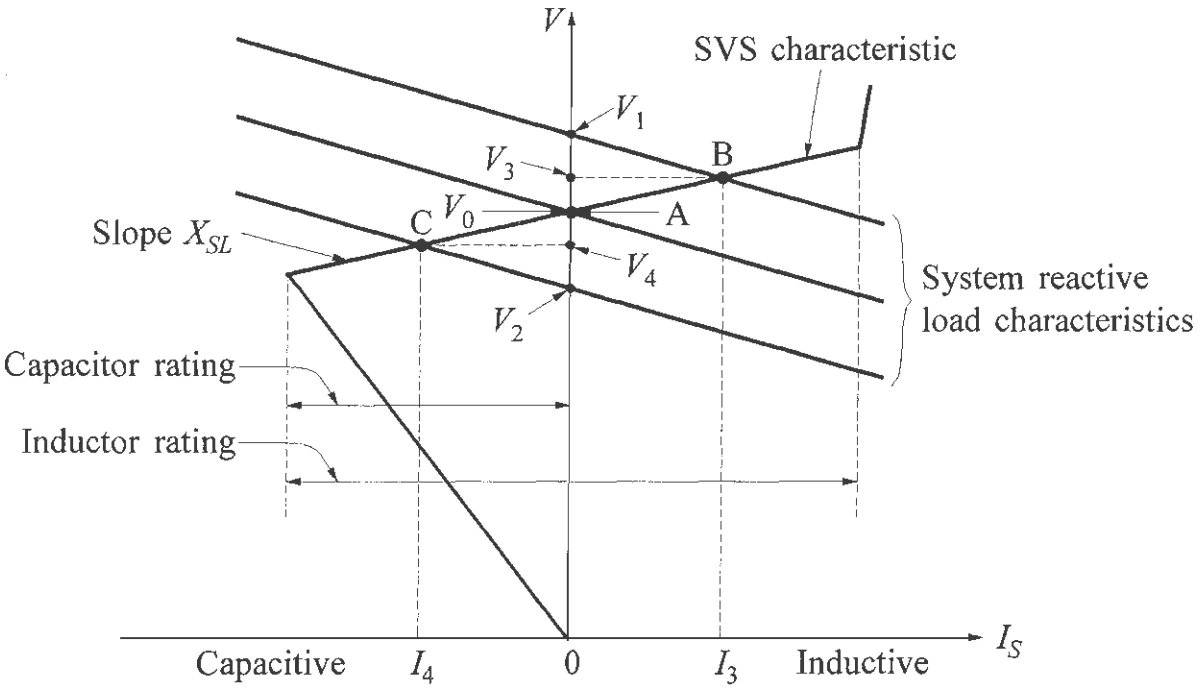


Figure 11.43 Graphical solution of SVS operating point for given system conditions

represents nominal system conditions, and is assumed to intersect the SVS characteristic at point A where $V=V_0$ and $I_S=0$.

If the system voltage increases by ΔE_{th} (for example, due to a decrease in system load level), V will increase to V_1, without an SVS. With the SVS, however, the operating point moves to B; by absorbing inductive current I_3, the SVS holds the voltage at V_3. Similarly, if the source voltage decreases (due to increase in system load level), the SVS holds the voltage at V_4, instead of at V_2 without the SVS. If the slope K_S of the SVS characteristic were zero, the voltage would have been held at V_0 for both cases considered above.

Effect of using switched capacitors:

In the example considered in Figure 11.43, the SVS control range would be exceeded for larger variations in system conditions. The use of switched capacitor banks can extend the continuous control range of the SVS. This is illustrated in Figure 11.44, which considers three capacitor banks, two of which are switchable. Either thyristors or mechanical switches may be used for switching the capacitors in and out automatically by local voltage-sensing controls. In the figure the unswitched capacitor includes a reactor for filtering harmonics.

We see that an SVS is not a source of voltage as is a synchronous condenser. Instead, it alters the system voltage at the point of connection by varying the reactive current drawn or supplied to the system. In effect, the SVS acts as a variable reactive load which is adjusted so as to keep the ac voltage nearly constant.

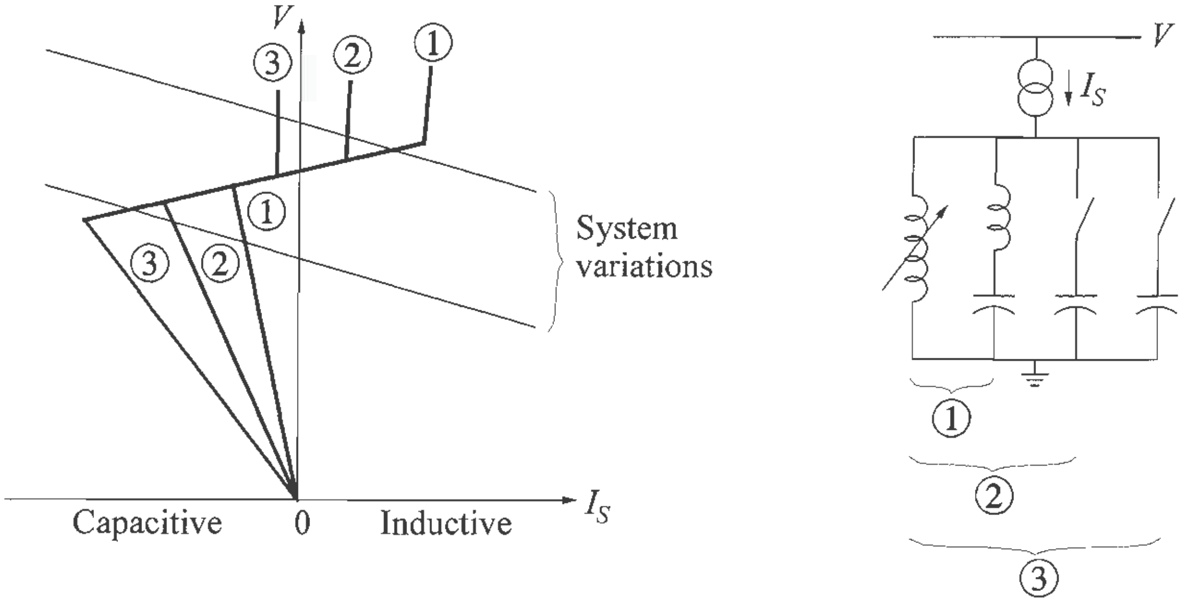


Figure 11.44 Use of switched capacitors to extend continuous control range

In general, the elements of an SVS operate on the principle of adjustable susceptance. The controlled susceptance is either a reactor or a capacitor. We will discuss next the operation of the more commonly used elements: TCR, TSC, and MSC. For a description of other forms of static compensators readers may consult references 36 and 37.

Thyristor-controlled reactor (TCR) [36,37]

Principle of operation:

The basic elements of a TCR are a reactor in series with a bidirectional thyristor switch as shown in Figure 11.45(a).

The thyristors conduct on alternate half-cycles of the supply frequency depending on the firing angle α, which is measured from a zero crossing of voltage. Full conduction is obtained with a firing angle of 90°. The current is essentially reactive and sinusoidal. Partial conduction is obtained with firing angles between 90° and 180°, as shown in Figure 11.45(b). Firing angles between 0 and 90° are not allowed as they produce asymmetrical currents with a dc component.

Let σ be the conduction angle, related to α by

$$\sigma = 2(\pi - \alpha) \tag{11.33}$$

The instantaneous current i is given by

$$i = \begin{cases} \dfrac{\sqrt{2}V}{X_L}(\cos\alpha - \cos\omega t) & \text{for } \alpha < \omega t < \alpha + \sigma \\ 0 & \text{for } \alpha + \sigma < \omega t < \alpha + \pi \end{cases} \tag{11.34}$$

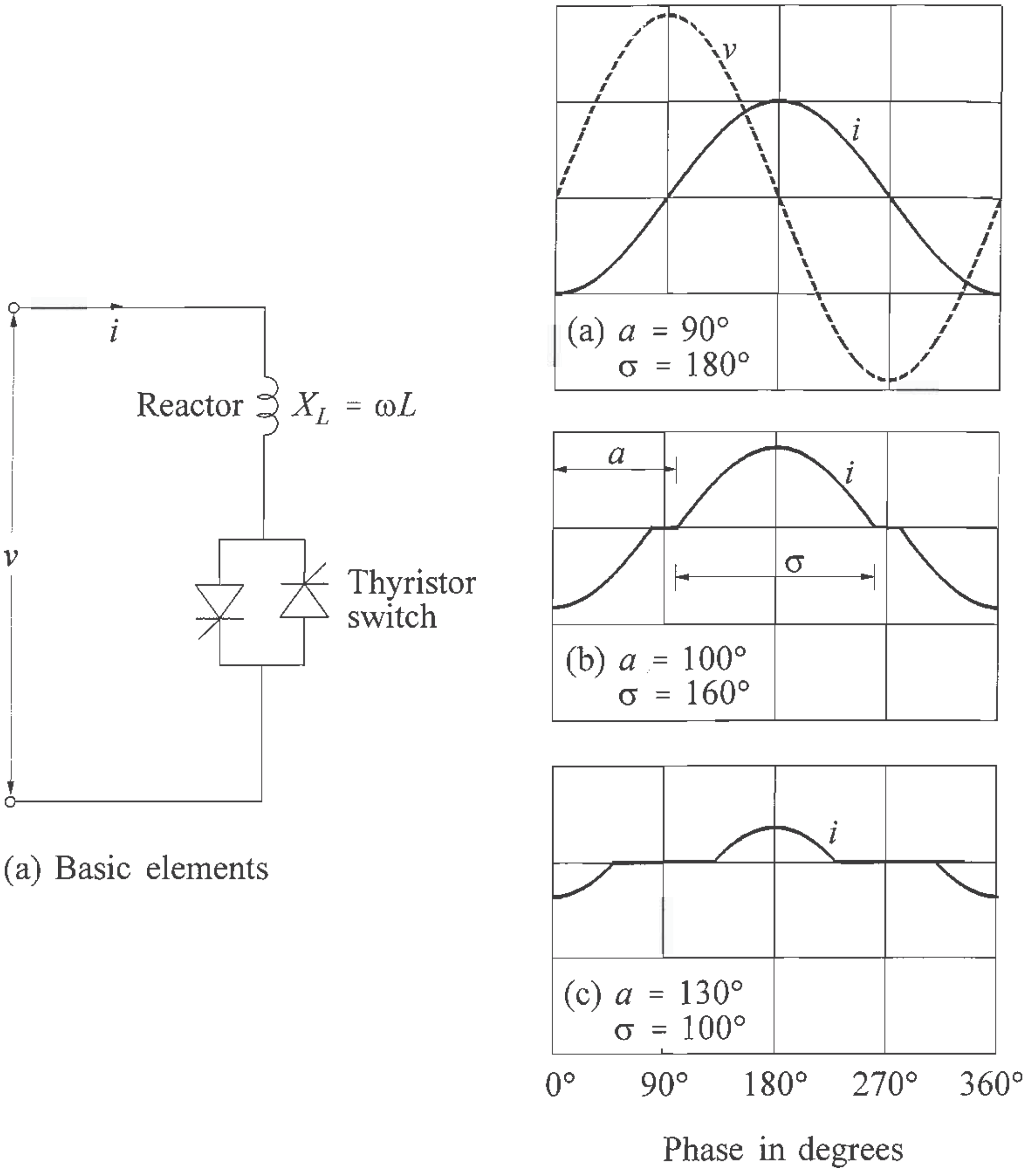
Fourier analysis of the current waveform gives the fundamental component:

$$I_1 = \frac{V}{X_L}\frac{\sigma - \sin\sigma}{\pi} \tag{11.35}$$

where I_1 and V are RMS values, and X_L is the reactance of the reactor at fundamental frequency.

The effect of increasing α (i.e., decreasing σ) is to reduce the fundamental component I_1. This is equivalent to increasing the effective inductance of the reactor.

In effect, so far as the fundamental frequency current component is concerned, the TCR is a controllable susceptance. The effective susceptance as a function of the firing angle α is



(a) Basic elements

(b) Current waveform

Figure 11.45 Thyristor-controlled reactor

$$
\begin{aligned}
B(\alpha) &= \frac{I_1}{V} = \frac{\sigma - \sin\sigma}{\pi X_L} \\
&= \frac{2(\pi - \alpha) + \sin 2\alpha}{\pi X_L}
\end{aligned}
\tag{11.36}
$$

The maximum value of the effective susceptance is at full conduction ($\alpha = 90°$, $\sigma = 180°$), and is equal to $1/X_L$; the minimum value is zero, obtained with $\alpha = 180°$ or $\sigma = 0°$.

This susceptance control principle is known as *phase control.* The susceptance is switched into the system for a controllable fraction of every half cycle. The variation in susceptance as well as the TCR current is smooth or continuous.

The TCR requires a control system which determines the firing instants (i.e., firing angle α) measured from the last zero crossing of the voltage (synchronization of firing angles). In some designs the control system responds to a signal that directly represents the desired susceptance. In others, the control responds to error signals such as voltage deviation, auxiliary stabilizing signals, etc. The result is a steady-state V/I characteristic shown in Figure 11.46, which can be described by

$$V = V_{ref} + X_{SL} I_1 \tag{11.37}$$

where X_{SL} is the slope reactance determined by the control system gain.

As illustrated in Figure 11.44, the TCR voltage control characteristic can be extended into the capacitive region by adding in parallel a fixed capacitor bank or switched capacitor banks.

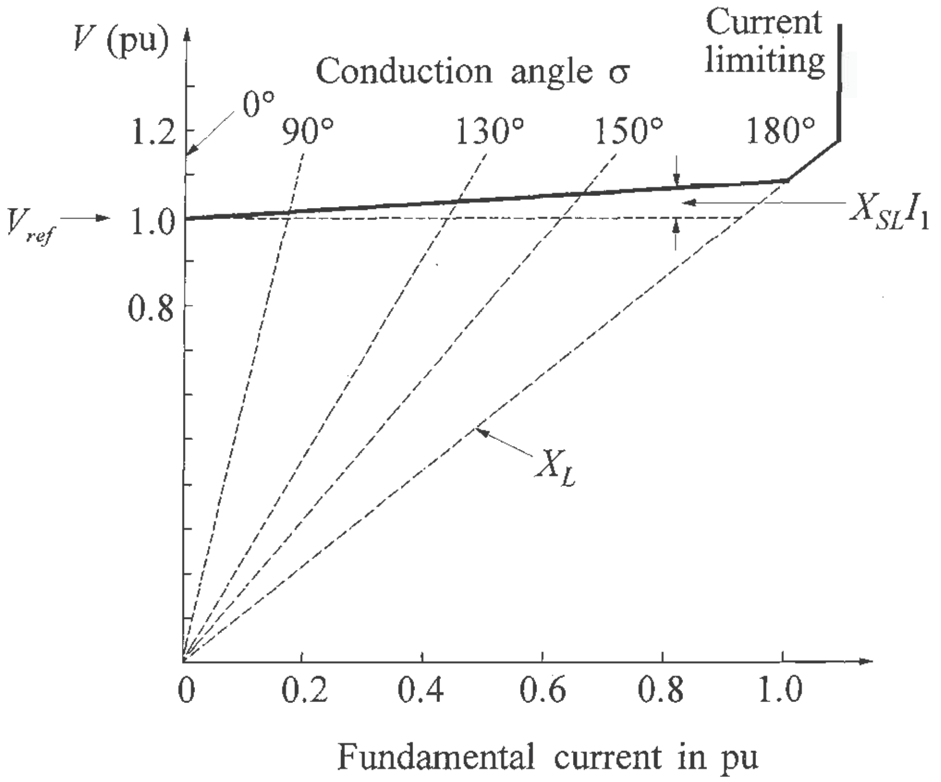
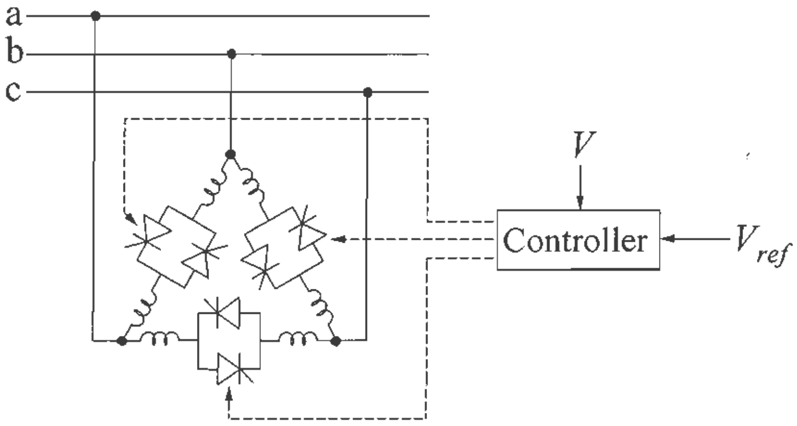


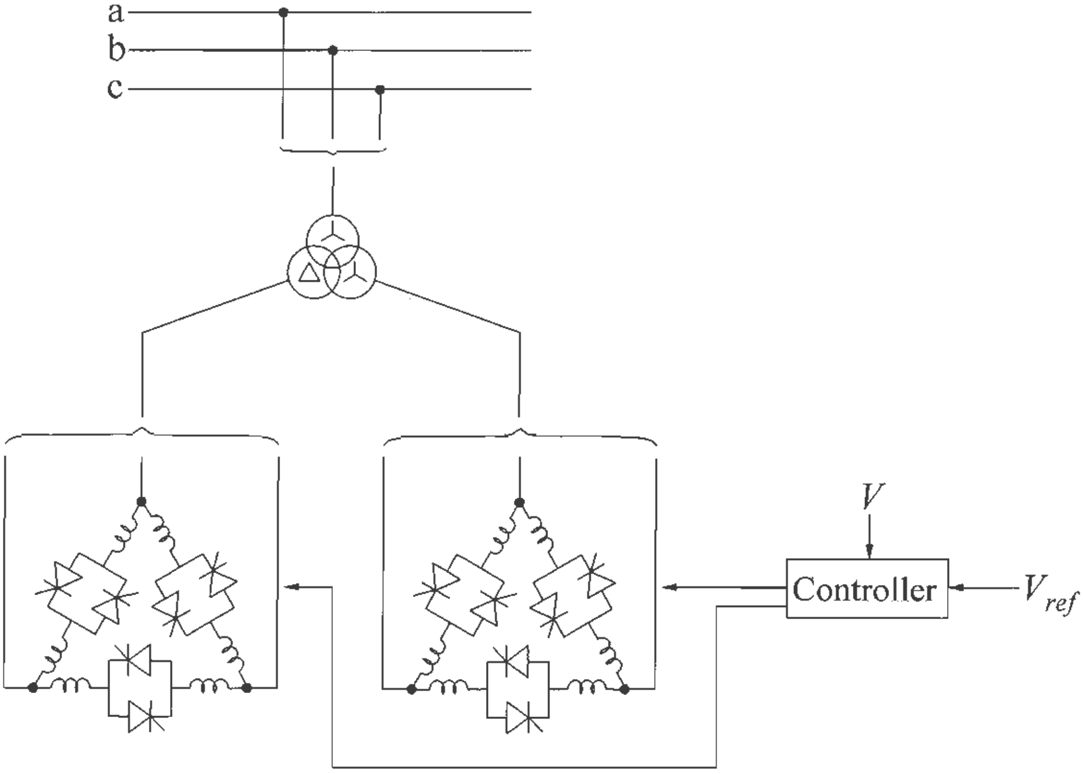
Figure 11.46 Fundamental voltage-current characteristic of TCR

Harmonics:

As α is increased from 90° to 180°, the current waveform becomes less and less sinusoidal; in other words, the TCR generates harmonics. For the single-phase device considered so far, if the firing of the thyristors is symmetrical (equal for both thyristors), only odd harmonics are generated. For a three-phase system, the preferred arrangement is to have the three single-phase TCR elements connected in delta (6-pulse TCR) as shown in Figure 11.47(a). For balanced conditions, all triple (3, 9, ...) harmonics circulate within the closed delta and are therefore absent from the line currents. Filters are often used to remove harmonic currents.



(a) 6-pulse TCR



(b) 12-pulse TCR

Figure 11.47 Three-phase TCR arrangements

Elimination of 5th and 7th harmonics can be achieved by using two 6-pulse TCRs of equal rating, fed from two secondary windings of the step-down transformers, one connected in Y and the other in Δ as shown in Figure 11.47(b). Since the voltages applied to the TCRs have a phase difference of 30°, 5th and 7th harmonics are eliminated from the primary-side line current. This is known as a 12-pulse arrangement because there are 12 thyristor firings every cycle of the three-phase line voltage. With the 12-pulse scheme, the lowest-order characteristic harmonics are the 11th and 13th. These can be filtered with a simple capacitor bank.

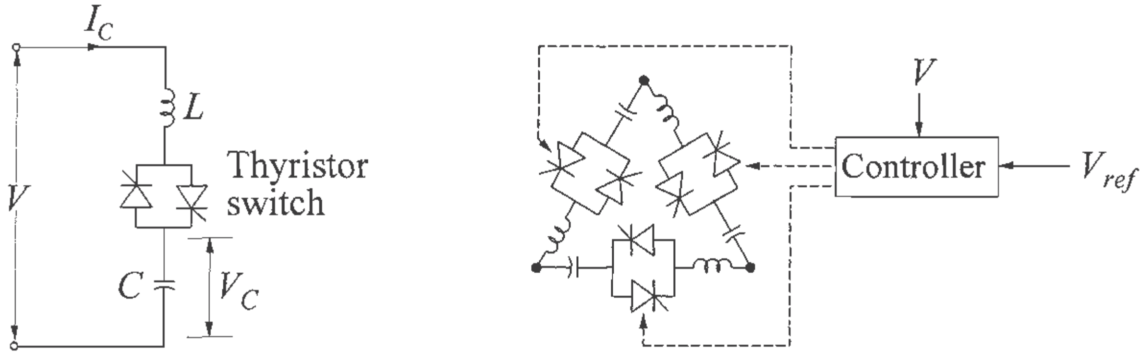
Dynamic response:

The TCR responds in about 5 to 10 ms, but delays are introduced by measurement and control circuits. To ensure control loop stability the response rate may have to be limited. For these reasons response times are typically around 1 to 5 cycles of supply frequency.

Thyristor-switched capacitor (TSC) [26,36,37]

Principle of operation:

A thyristor-switched capacitor scheme consists of a capacitor bank split up into appropriately sized units, each of which is switched on and off by using thyristor switches. Each single-phase unit consists of a capacitor (*C*) in series with a bidirectional thyristor switch and a small inductor (*L*) as shown in Figure 11.48(a). The purpose of the inductor is to limit switching transients, to damp inrush currents, and to prevent resonance with the network. In three-phase applications, the basic units are connected in Δ as shown in Figure 11.48(b).



(a) Single-phase unit (b) Three-phase unit

Figure 11.48 Thyristor-switched capacitor (TSC)

The switching of capacitors excites transients which may be large or small depending on the resonant frequency of the capacitors with the external system. The thyristor firing controls are designed to minimize the switching transients. This is achieved by choosing the switching instant when the voltage across the thyristor switch is at a minimum, ideally zero. Figure 11.49 illustrates the operating principle. The switching-on instant (t_1) is chosen so that the bus voltage V is at its maximum and of the same polarity as the capacitor voltage; this ensures a transient-free switching. The switching-off instant (t_2) corresponds to a current zero. The capacitor will then remain charged to a peak voltage, either positive or negative, ready for the next switch-on operation.

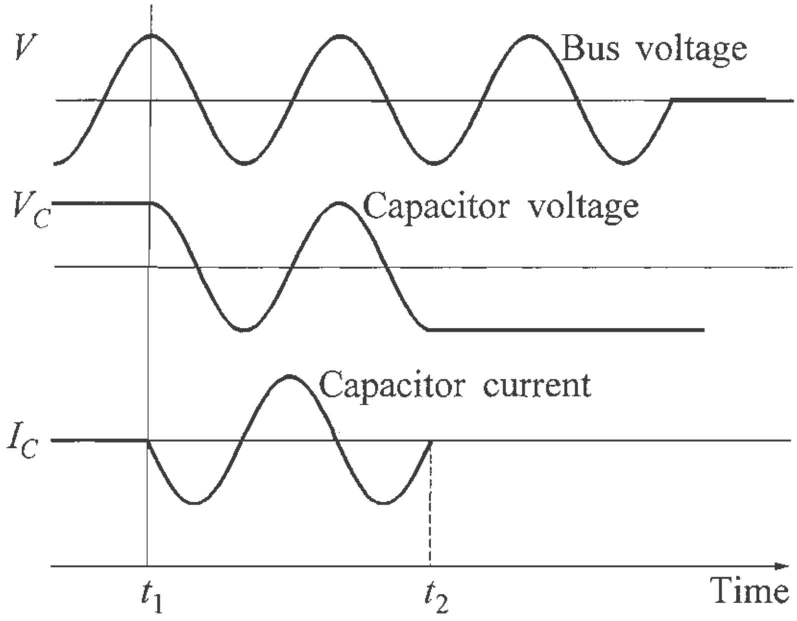


Figure 11.49 Switch operation of a TSC

The susceptance control principle used by a TSC is known as the *integral cycle control*; the susceptance is switched in for an integral number of exact half cycles. The susceptance is divided into several parallel units, and the susceptance is varied by controlling the number of units in conduction. A change can be made every half cycle. This form of control does not generate harmonics.

Figure 11.50 shows the basic scheme of a TSC consisting of parallel Δ connected TSC elements and a controller. When the bus voltage deviates from the reference value (V_{ref}) beyond the dead band in either direction, the control switches in (or out) one or more capacitor banks until the voltage returns inside the dead band, provided that not all the banks have been switched in (or out).

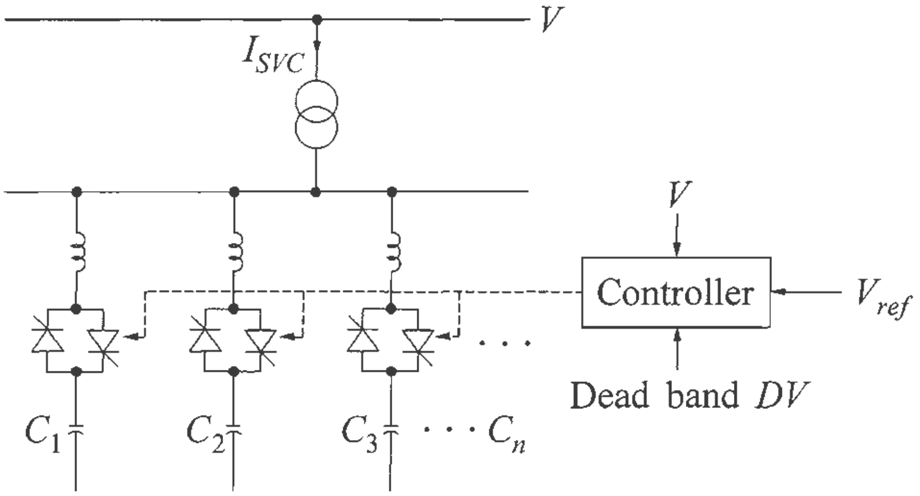


Figure 11.50 TSC scheme

Dynamic response:

The *V/I* characteristic of a TSC compensator is shown in Figure 11.51. We see that the voltage control provided is discontinuous or stepwise. It is determined by the rating and number of parallel connected units. In high voltage applications, the number of shunt capacitor banks is limited because of the high cost of thyristors. The power system *V/I* characteristics, as system conditions change, intersect the TSC *V/I* characteristics at discrete points. The bus voltage V is controlled within the range $V_{ref} \pm DV/2$, where DV is the dead band. When the system is operating so that its

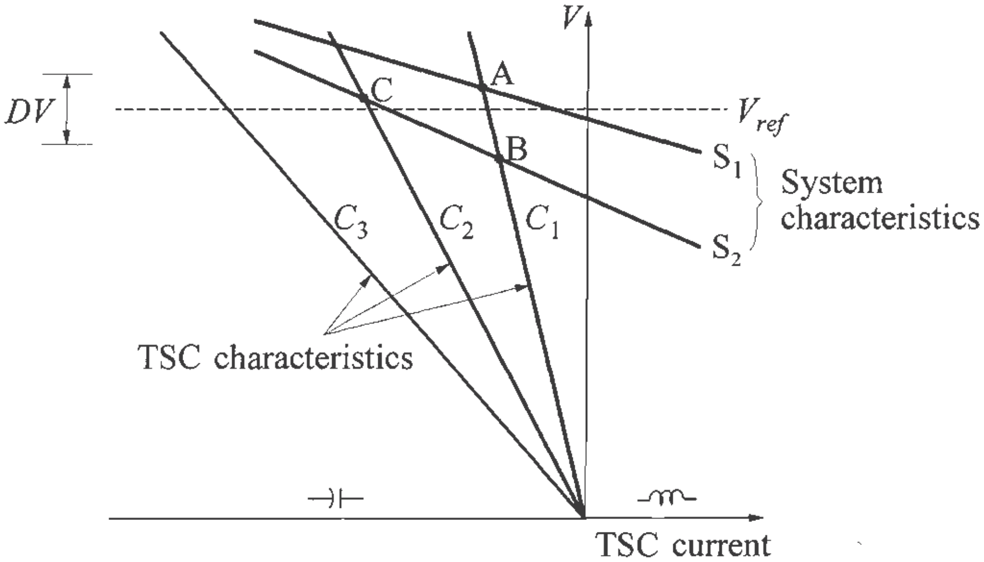


Figure 11.51 *V/I* characteristics of a TSC and power system

characteristic is represented by line S_1, then capacitor C_1 will be switched in and operating point A prevails. If the system characteristic suddenly changes to S_2, the bus voltage drops initially to a value represented by operating point B. The TSC control switches in bank C_2 to change the operating point to C, bringing the voltage within the desired range. Thus the compensator current can change in discrete steps. The time taken for executing a command from the controller ranges from one-half cycle to one cycle.

Mechanically switched capacitor (MSC)

Typically, an MSC scheme consists of one or more capacitor units connected to the power system by a circuit-breaker. A small reactor might be connected in series with the capacitor to damp energizing transients and reduce harmonics. Prestrike and restrike-free circuit-breakers have to be used to avoid system overvoltages due to capacitor-switching transients.

The *V/I* characteristic is linear and similar to that of a TSC. The response time is equal to the switching time of the circuit-breaker arrangement which is on the order of 100 ms following the initiation of switching operation instruction. Frequent switching is not possible unless discharge devices are provided.

Practical static var systems

A static var compensation scheme with any desired control range can be formed by using combinations of the elements described above. Several SVS configurations have been successfully applied to meet differing system requirements. The required speed of response, size range, flexibility, losses, and cost are among the important considerations in selecting a configuration for any particular application.

Figure 11.52 shows a typical SVS scheme consisting of a TCR, a three-unit TSC, and harmonic filters (for filtering TCR-generated harmonics). At power frequency, the filters are capacitive and produce reactive power of about 10 to 30% of TCR MVAr rating. In order to ensure a smooth control characteristic, the TCR current rating should be slightly larger than that of one TSC unit; otherwise dead bands arise (see reference 37, Chapter 4).

The steady-state *V/I* characteristic of the SVS is shown in Figure 11.53(a), and the corresponding *V/Q* characteristic is shown in Figure 11.53(b). The linear control range lies within the limits determined by the maximum susceptance (B_{LMX}) of the reactor, the total capacitive susceptance (B_C) as determined by the capacitor banks in service and the filter capacitance. If the voltage drops below a certain level (typically 0.3 pu) for an extended period, control power and thyristor gating energy can be lost, requiring a shutdown of the SVS. The SVS can restart as soon as the voltage recovers. However, the voltage may drop to low values for short periods, such as during transient faults, without causing the SVS to trip.

Within the linear control range, the SVS is equivalent to a voltage source V_{ref} in series with a reactance of X_{SL}. As is evident from Figure 11.43, the slope reactance

X_{SL} has a significant effect on the performance of the SVS. A large value of X_{SL} makes the SVS less responsive, i.e., changes in system conditions cause large voltage variations at the SVS high voltage bus. The value of X_{SL} is determined by the steady-state gain of the controller (voltage regulator). It may also be effected by a current feedback (with PI controller). Its choice should be based on detailed power-flow and stability studies. Typically, the slope is set within the range of 1 to 5%, depending on the ac system strength.

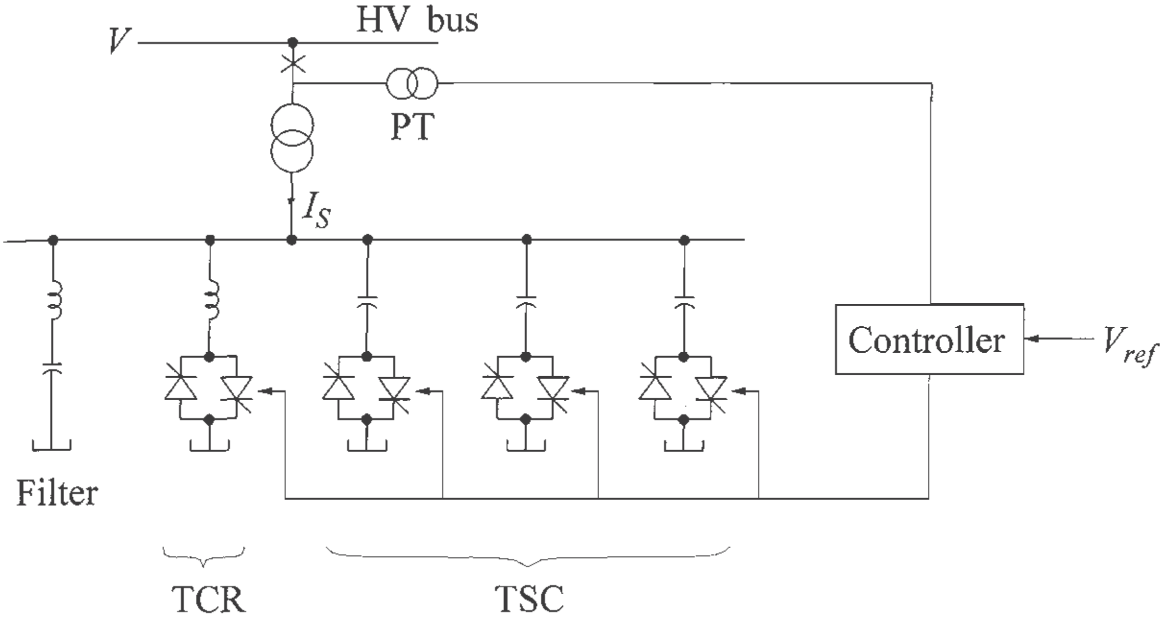
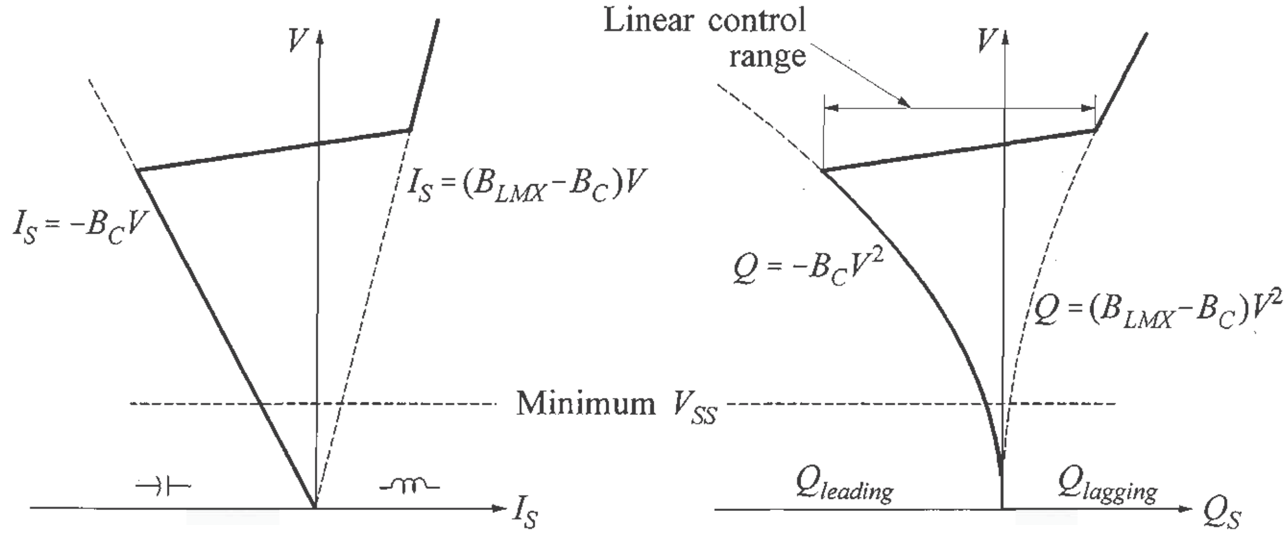


Figure 11.52 A typical static var system



(a) Voltage-current characteristic

(b) Voltage-reactive power characteristic

Figure 11.53 SVS steady-state characteristics

Application of static var compensators

Since their first application in the late 1970s, the use of SVCs in transmission systems has been increasing steadily. By virtue of their ability to provide continuous and rapid control of reactive power and voltage, SVCs can enhance several aspects of transmission system performance. Applications to date include the following:

- Control of temporary (power frequency) overvoltages
- Prevention of voltage collapse
- Enhancement of transient stability
- Enhancement of damping of system oscillations

References 39 to 42 provide details of SVC applications on a number of power systems.

At the subtransmission and distribution system levels, SVCs are used for balancing the three phases of systems supplying unbalanced loads. They are also used to minimize fluctuations in supply voltage caused by repetitive-impact loads such as dragline loads of mining plants, rolling mills, and arc furnaces.

Arc furnaces are a special case of impact loads. They cause voltage fluctuations with frequencies randomly varying between 2 and 10 Hz. These result in flicker of filament lamps in the adjacent load areas. Some electronic equipment and television receivers may also be adversely affected. The term “voltage flicker” is used to describe such rapid fluctuations in voltage. To minimize the adverse effects on the adjacent load areas, the voltage fluctuations must be kept below the acceptable minimum level (typically 0.3%). SVCs provide an effective and economical means of eliminating the voltage flicker problems and have been widely used for such applications since the early 1970s.

11.2.8 Principles of Transmission System Compensation

In the previous sections we have described various devices used for reactive compensation of transmission systems. A well-planned and coordinated application of these devices is essential for the economical design and operation of a reliable system. As reactive compensation affects the steady-state as well as the dynamic performance of the system, detailed power-flow and stability studies are required for establishing appropriate compensation schemes. We will describe the power-flow studies in Section 11.3. Stability studies will be covered in Chapters 12 to 17 in which we consider different aspects of system stability.

In addition to detailed simulations, an understanding of the principles of reactive compensation in transmission systems is invaluable for proper selection and application of the compensating devices. This subject is covered very well by T.J.E.

Miller in reference 37. Here we will briefly review these principles by considering how different forms of compensation affect the performance of a transmission line.

We will first consider the ideal cases of uniformly distributed compensation as they lead to simple relationships which help us to understand the fundamental nature of each type of compensation. We will then consider specific configurations of lumped or concentrated compensation to see how they compare with the ideal cases.

Uniformly distributed fixed series and shunt compensation

In Chapter 6 (Section 6.1) we saw that the line performance is determined by the characteristic impedance Z_C and the electrical length (also referred to as line angle) θ. The objective of compensation is to modify these parameters so as to result in the desired voltage and power transfer characteristics.

Without compensation, assuming a lossless line, the expressions for the two line parameters are

$$Z_C = \sqrt{\frac{L}{C}} = \sqrt{\frac{x_L}{b_C}} = \sqrt{\frac{X_L}{B_C}} \tag{11.38}$$

$$\theta = \beta l \tag{11.39}$$

with the phase constant β given by

$$\beta = \omega\sqrt{LC} = \sqrt{x_L b_C} = \frac{\sqrt{X_L B_C}}{l} \tag{11.40}$$

where

L = series inductance per unit length
C = shunt capacitance per unit length
x_L = series inductive reactance per unit length
b_C = shunt capacitive susceptance per unit length
X_L = total series inductive reactance
B_C = total shunt susceptance
l = line length

Let us designate the corresponding quantities *with compensation* by using a superscript prime (').

With a uniformly distributed *shunt compensation* having a susceptance of b_{sh} per unit length, the effective shunt susceptance is given by

$$b_C' = b_C - b_{sh} = b_C(1-k_{sh}) \tag{11.41}$$

where k_{sh} is the *degree of shunt compensation* defined as follows:

$$k_{sh} = \frac{b_{sh}}{b_C} \tag{11.42}$$

It is positive for inductive shunt compensation and is negative for capacitive shunt compensation.

The effective values of the characteristic impedance and phase constant with shunt compensation are related to the uncompensated values as follows:

$$Z'_C = \sqrt{\frac{x_L}{b'_C}} = \frac{Z_C}{\sqrt{1-k_{sh}}} \tag{11.43}$$

and

$$\beta' = \beta\sqrt{1-k_{sh}} \tag{11.44}$$

Shunt capacitive compensation in effect decreases Z_C and increases β, whereas shunt inductive compensation increases Z_C and decreases β.

With a uniformly distributed *series capacitive compensation* of C_{se} per unit length, the effective series reactance is

$$\begin{aligned} x'_L &= x_L - \frac{1}{\omega C_{se}} = x_L - x_{Cse} \\ &= x_L(1-k_{se}) \end{aligned} \tag{11.45}$$

where k_{se} is the *degree of series capacitive compensation* defined as follows:

$$k_{se} = \frac{x_{Cse}}{x_L} \tag{11.46}$$

It is positive for capacitive series compensation.

The effective values of characteristic impedance and phase constant with series compensation are given by

$$Z'_C = \sqrt{\frac{x'_L}{b_C}} = Z_C\sqrt{1-k_{se}} \tag{11.47}$$

and

$$\beta' = \beta\sqrt{1-k_{se}} \tag{11.48}$$

Series (capacitive) compensation decreases both Z_C and β.

With *both shunt and series compensation*, the combined effects are as follows:

$$Z_C' = Z_C\sqrt{\frac{1-k_{se}}{1-k_{sh}}} \tag{11.49}$$

$$\beta' = \beta\sqrt{(1-k_{sh})(1-k_{se})} \tag{11.50}$$

The effective line angle (θ') and natural load (P_0') are given by

$$\theta' = \theta\sqrt{(1-k_{sh})(1-k_{se})} \tag{11.51}$$

$$P_0' = P_0\sqrt{\frac{1-k_{sh}}{1-k_{se}}} \tag{11.52}$$

Effect of compensation on line voltage:

Under light load conditions, a flat voltage profile is achieved by inductive shunt compensation. For example, with k_{sh}=1 (100% inductive compensation), θ' and P_0' are reduced to zero and Z_C' is increased to infinity; this results in a flat voltage at zero load.

Under heavy load conditions, a flat voltage can be achieved by adding shunt capacitive compensation. For example, in order to transmit $1.4P_0$ with a flat voltage profile, a shunt capacitive compensation of $k_{sh}=-0.96$ is required.

Series capacitive compensation may, in theory, be used instead of shunt compensation to give a flat voltage profile, under heavy loading. For example, a flat voltage profile can be achieved at a load of $1.4P_0$ with a distributed series compensation of k_{se}=0.49. In practice, lumped series capacitors are not suitable for obtaining a smooth voltage profile along the line. Obviously, step changes in voltage occur at points where the series capacitors are applied. They do, however, improve voltage regulation at any given point, i.e., voltage changes with load are reduced.

Effect of compensation on maximum power:

In Chapter 6 we developed the expression (Equation 6.51) for power transferred by a line. With compensation, this expression becomes

$$P_R = \frac{E_S E_R}{Z_C' \sin\theta'} \sin\delta \qquad (11.53)$$

The maximum power (corresponding to δ=90°) can be increased by decreasing either Z_C', or θ', or both.

The characteristic impedance Z_C' can be decreased with capacitive shunt compensation, but it is accompanied by an increase in the electrical length θ'. On the other hand, inductive shunt compensation decreases θ', but increases Z_C'. Only series capacitor compensation contributes to the decrease of both Z_C' and θ'.

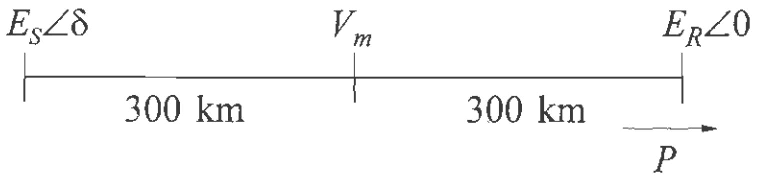
We should, however, recognize that compensation is not required in all cases to satisfy both objectives: (i) increasing P_0', the power level at which the voltage profile is flat, and (ii) decreasing electrical length in order to improve stability. Short lines may require voltage support, i.e., an increase in P_0', even though the inherent electrical length is small. This may be achieved by shunt capacitors, provided that θ' does not become excessive as a result. On the other hand, as we saw in Chapter 6 (see Figure 6.13), lines longer than about 500 km cannot be loaded even up to P_0 because of excessive θ; in such cases, reduction of θ' is the first priority.

Illustrative example

For purposes of illustration, we will consider a lossless 500 kV line having the following parameters:

β = 0.0013 rad/km $\qquad$ Z_C = 250 Ω (P_0 = 1,000 MW)
x_L = 0.325 Ω/km $\qquad$ b_C = 5.2 μS/km

The line is 600 km long and transfers power between two sources as shown in Figure 11.54. The magnitudes of the source voltages are held at 1.0 pu. Our objective is to examine the line performance without and with compensation. We will consider shunt capacitor and series capacitor compensations chosen so as to maintain 1.0 pu midpoint voltage when the power transferred (P) is equal to $1.4P_0$.



$$E_S = E_R = 1.0 \text{ pu}$$
$$\theta = \beta l = 0.0013\times600$$
$$= 0.78 \text{ rad} = 44.7°$$

Figure 11.54

(a) With *no compensation*, the power-angle relationship is

$$P = \frac{E_S E_R}{Z_C \sin\theta} \sin\delta$$

With E_S and E_R at rated values,

$$\frac{P}{P_0} = \frac{1}{\sin\theta} \sin\delta = \frac{1}{\sin 44.7°} \sin\delta = 1.42 \sin\delta$$

Also, considering one half of the symmetrical line, P may be expressed in terms of V_m as

$$P = \frac{E_S V_m}{Z_C \sin(\theta/2)} \sin(\delta/2)$$

$$= P_0 \frac{V_m \sin(\delta/2)}{\sin(44.7°/2)}$$

Hence, the per unit value of midpoint voltage as a function of P is given by

$$V_m = \frac{P}{P_0} \frac{0.38}{\sin(\delta/2)}$$

(b) With *uniformly distributed fixed shunt compensation*, to maintain V_m at 1.0 pu when $P=1.4P_0$, we have

$$1.4P_0 = P_0' = P_0\sqrt{1-k_{sh}}$$

Therefore, $k_{sh}=-0.96$. This will, in fact, result in 1.0 pu voltage throughout the line length at $P=1.4P_0$. The corresponding values of Z_C' and θ' are

$$Z_C' = \frac{Z_C}{\sqrt{1-k_{sh}}} = \frac{250}{\sqrt{1+0.96}} = 178.57 \quad \Omega$$

$$\theta' = \theta\sqrt{1-k_{sh}} = 10.92 \quad \text{rad} = 62.57°$$

The power transferred is given by

$$P = \frac{E_S E_R}{Z_C' \sin\theta'} \sin\delta$$

Hence,

$$\frac{P}{P_0} = \frac{Z_C \sin\delta}{Z_C' \sin\theta'} = 1.58\sin\delta$$

The midpoint voltage is now given by

$$V_m = \frac{P}{P_0}\frac{Z_C'}{Z_C}\frac{\sin(\theta'/2)}{\sin(\delta/2)} = \frac{P}{P_0}\frac{0.371}{\sin(\delta/2)}$$

(c) With *uniformly distributed fixed series compensation*, to maintain V_m at 1.0 pu when $P = 1.4P_0$, we have

$$1.4P_0 = P_0' = P_0/\sqrt{1-k_{se}}$$

Therefore, $k_{se} = 0.49$. The line parameters change to

$$Z_C' = Z_C\sqrt{1-k_{se}} = 250\sqrt{1-0.49} = 178.57 \quad \Omega$$

$$\theta' = \theta\sqrt{1-k_{se}} = 0.557 \quad \text{rad} = 31.92°$$

The power transfer and midpoint voltage equations now become

$$\frac{P}{P_0} = \frac{Z_C \sin\delta}{Z_C' \sin\theta'} = 2.65\sin\delta$$

and

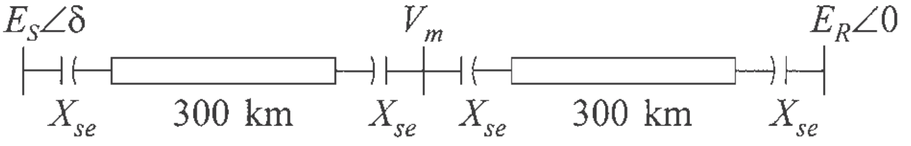
$$V_m = \frac{P}{P_0}\frac{Z_C'}{Z_C}\frac{\sin(\theta'/2)}{\sin(\delta/2)} = \frac{P}{P_0}\frac{0.1964}{\sin(\delta/2)}$$

Next, we consider the performance of lumped shunt capacitor and series capacitor compensations. With lumped compensation, the expression for P-δ and V_m-P relationships cannot be obtained by a simple modification of the corresponding equations for an uncompensated line. We will, therefore, use a power-flow program to analyze the performance of the compensated line.

(d) With *lumped midpoint shunt compensation*, a capacitor bank of 412 MVAr is required to maintain V_m at 1.0 pu when the power transferred is $1.4P_0$.

A distributed shunt compensation of -0.96 represents a total MVAr of about 749. This is nearly twice the MVAr rating of the lumped shunt compensation. The two sources at the ends of the line supply about half of the reactive power compensation required when lumped compensation is used.

(e) With *lumped series compensation*, split into four units (two at the ends and two in the middle of the line), as shown in Figure 11.55, the degree of compensation k_{se} required is 0.505 to maintain V_m at 1.0 pu when the power transferred is $1.4P_0$.



$$X_{se} = 24.625 \ \Omega \qquad k_{se} = \frac{4\times 24.625}{600\times 0.325} = 0.505$$

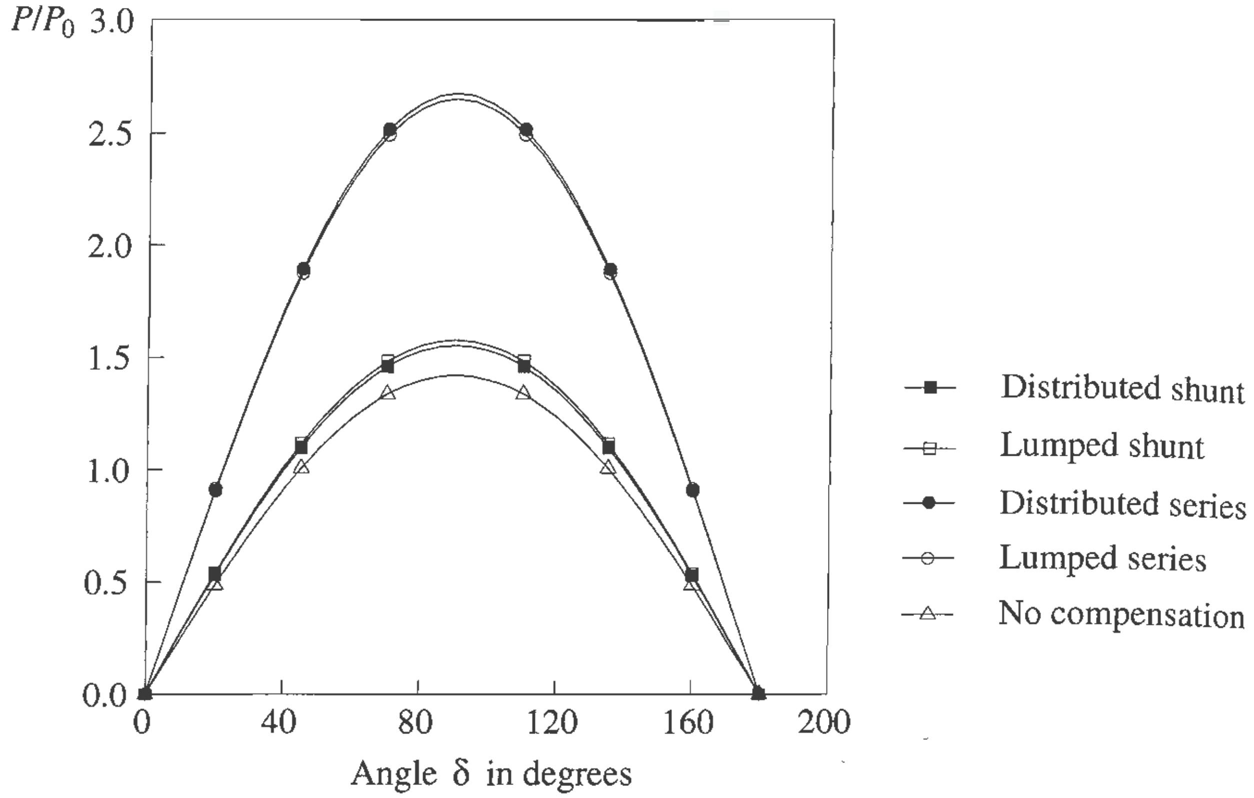
Figure 11.55 Lumped series compensation

Figure 11.56(a) shows plots of power transferred as a function of transmission angle δ for all the five cases we have considered: (a) no compensation, (b) distributed shunt compensation, (c) distributed series compensation, (d) lumped shunt compensation, and (e) lumped series compensation. Plots of midpoint voltage as a function of power transferred for the five cases are shown in Figure 11.56(b). We have considered here a 500 kV line. With line losses neglected and power expressed in per unit of natural power (P_0), the only parameter that has an impact on line performance is β. As noted in Chapter 6, β is practically the same for lines of all voltage levels. Hence, the results presented are generally applicable to a 600 km line of any voltage level.

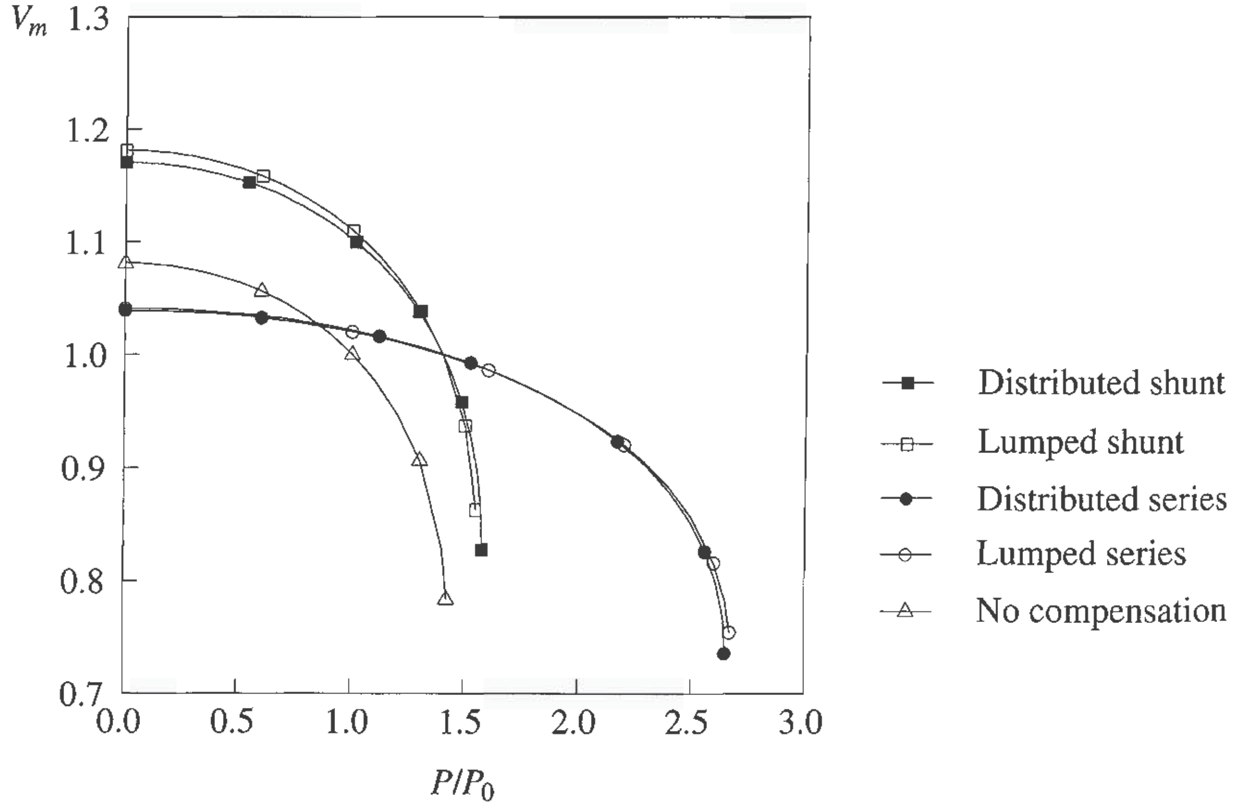
The P-δ and V_m-P characteristics with each type of lumped compensation, for the system considered, are practically identical to the characteristics computed with the corresponding uniformly distributed compensation.

From the results presented in Figure 11.56, we can make some general observations:

1. The shunt capacitor compensation (chosen to keep midpoint voltage at 1.0 pu when P=$1.4P_0$) increases the maximum power capability to 1.58 pu of natural power. This represents an increase of 0.16 pu over the limit of 1.42 pu for the uncompensated case.



(a) Power transfer as a function of transmission angle δ



(b) Midpoint voltage as a function of power transfer

Figure 11.56 Performance of 600 km line with and without compensation

While the shunt compensation has helped maintain the midpoint voltage at the rated values when P is equal to 1.4 pu, the voltage magnitude is very sensitive to variations in power transfer level. For example, when the shunt compensated line is operating near the effective natural load ($1.4P_0$), a small change in power changes the voltage magnitude significantly.

We also see that, when operating at a power transfer level corresponding to V_m of 1.0 pu, the shunt compensated line is much closer to the stability limit than the uncompensated line. Thus, shunt compensation has increased the effective natural load at the expense of stability margin and voltage regulation.

2. The series capacitor compensation (chosen so as to keep midpoint voltage at 1.0 pu when $P=1.4P_0$) increases the maximum transfer capability to 2.65 pu. In addition to nearly doubling the stability limit, the voltage regulation is significantly improved; for example, at $P=1.4P_0$, a large variation in P causes a very small change in V_m.

Uniformly distributed regulated shunt compensation

Consider a shunt compensation in which k_{sh} is continuously *regulated* so that the effective natural load (P_0') is equal to the power transmitted (P) at all times. From Equation 11.53,

$$P = \frac{P_0'}{\sin\theta'}\sin\delta$$

Therefore, when a line is operating at natural load, the transmission angle is equal to the line angle (see Chapter 6, Section 6.1.9). As a result, with continuously regulated shunt compensation, $\theta'=\delta$ at all times. Hence,

$$\frac{P}{\delta} = \frac{P_0'}{\theta'} = \frac{P_0\sqrt{1-k_{sh}}}{\theta\sqrt{1-k_{sh}}} = \frac{P_0}{\theta} = \text{constant} \tag{11.54}$$

We thus have a *linear* relationship between P and δ, instead of the sinusoidal relationship with fixed or no compensation. This means that the small-signal (steady-state) stability limit with the regulated compensation is infinite. With V_0 denoting the rated line voltage, the slope of the P-δ characteristic is given by

$$\frac{P_0}{\theta} = \frac{V_0^2}{Z_C\theta} = \frac{V_0^2}{X_L} \tag{11.55}$$

This is equal to the peak of the sinusoidal P-δ characteristic with 100% shunt inductive compensation ($k_{sh}=1$).

Let us consider the 600 km, 500 kV line for illustration. From Equation 11.54, with δ and θ expressed in radians,

$$\frac{P/P_0}{\delta} = \frac{1}{\theta} = \frac{1}{0.78} = 1.282 \quad \text{pu/rad}$$

This is illustrated in Figure 11.57, which shows P-δ characteristics with uniformly distributed regulated compensation and with fixed distributed shunt compensation of $k_{sh}=1.0$.

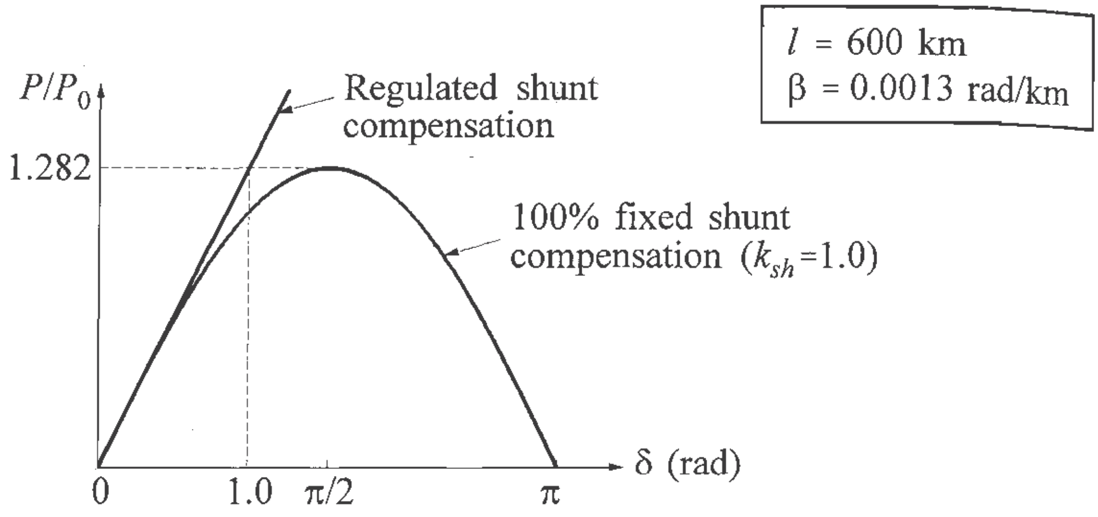


Figure 11.57 Power-angle characteristics of a 600-km line with regulated and shunt inductive compensation

The regulated shunt compensation effectively changes k_{sh} continuously so that $P_0' = P$. For each value of k_{sh}, there is a sinusoidal P-δ characteristic. As the transmitted power P changes, the regulator effectively adjusts k_{sh} so that the operating point shifts from one curve to another in such a way that it lies on a straight line with a positive slope. For satisfactory operation at high power transfer levels, the regulator must be rapid and continuous to prevent movement along the sinusoidal characteristic corresponding to the current value of k_{sh} before moving to the new characteristic.

In practice, this form of compensation can be nearly achieved by placing active compensators, such as synchronous condensers or static var systems, at discrete intervals along the line. The compensators would hold constant voltage equal to V_0 at many points along the line for all load levels; this nearly satisfies the requirement for the effective natural load (P_0') to be equal to the current value of power (P) being transmitted.

The regulators must, however, have sufficient capacity to satisfy the reactive power requirements for maintaining constant voltage at all possible load levels. For the ideal case, the total reactive power supplied or absorbed by the constant voltage regulators is given by

$$\begin{aligned} Q_V &= (V^2\omega C - I^2\omega L)l \\ &= P_0\theta\left[1-(P/P_0)^2\right] \end{aligned} \tag{11.56}$$

For P greater than P_0, the reactive power required is capacitive. The reactive power increases as the square of the power transmitted.

Satisfactory performance of such a scheme depends on the ability of all regulators to maintain constant voltage along the line. If one regulator fails or if it reaches a reactive power limit, the stability of the entire system may be affected.

Hydro Quebec's James Bay transmission system [39] uses this form of compensation. It is of historical interest to note that the concept of long distance ac power transmission using distributed regulated shunt compensation was proposed by F.G. Baum as far back as 1921 [43]. He envisioned a 220 kV line having its voltage maintained by synchronous condensers at intervals of about 100 mi. He showed that with equal voltage (within 3%) at all compensator stations, there was virtually no limit to transmission distance.

Regulated compensation at discrete intervals

We will now examine how regulated compensation applied at discrete intervals approximates the performance of uniformly distributed compensation. We will first consider a midpoint compensator as shown in Figure 11.58, and then we extend the analysis to an arbitrary number of compensators.

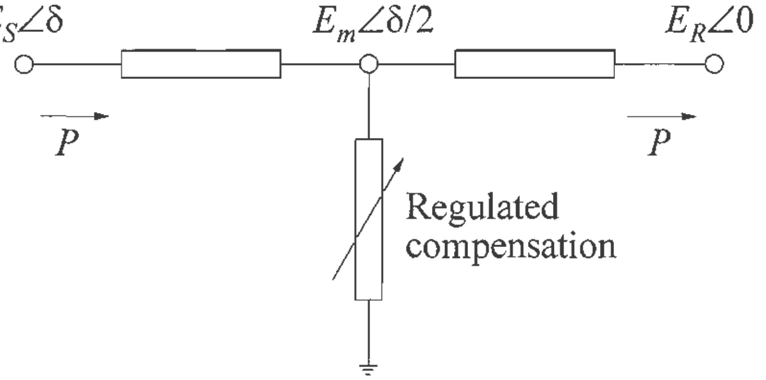


Figure 11.58 Line with midpoint regulated compensation

Midpoint regulated compensation:

The compensating susceptance is continuously varied such that E_m is constant. For simplicity, we will assume that $E_S = E_R = E_m = E$. The line may be considered to be made up of two *independent sections*, each section having a line angle of $\theta/2$, where θ is line angle of the entire line. By applying Equation 11.53 to each section, the expression for power transmitted is

$$P = \frac{E^2}{Z_C \sin(\theta/2)} \sin(\delta/2) \tag{11.57}$$

If E is equal to rated voltage, the expression for P may be expressed in terms of the natural power P_0 of the uncompensated line as follows:

$$P = \frac{P_0}{\sin(\theta/2)} \sin(\delta/2) \tag{11.58}$$

For an uncompensated line, the power transmitted is given by

$$P = \frac{P_0}{\sin\theta} \sin\delta \tag{11.59}$$

The ratio of maximum power that can be transmitted with and without midpoint regulated compensation is

$$\frac{P'_{max}}{P_{max}} = \frac{\sin\theta}{\sin(\theta/2)} \tag{11.60}$$

Table 11.2 lists the values of the above ratio for different line lengths (assuming $\beta = 0.0013$ rad/km).

Figure 11.59 shows plots of power versus angle characteristics with and without midpoint regulated compensation for a line length of 600 km ($\theta = 44.7°$).

If the regulated compensation has unlimited reactive power capability, it will hold the midpoint voltage through any load level as seen above. On the other hand, if it has a finite size, it can regulate only up to its maximum capacitive output. Its performance beyond this limit depends on the type of device.

Table 11.2

Line Length l (km)	Line Angle θ (degrees)	P'_{max}/P_{max}
200	14.9	1.98
400	29.8	1.93
600	44.7	1.85
800	59.6	1.73
1000	74.5	1.59
1200	89.4	1.42

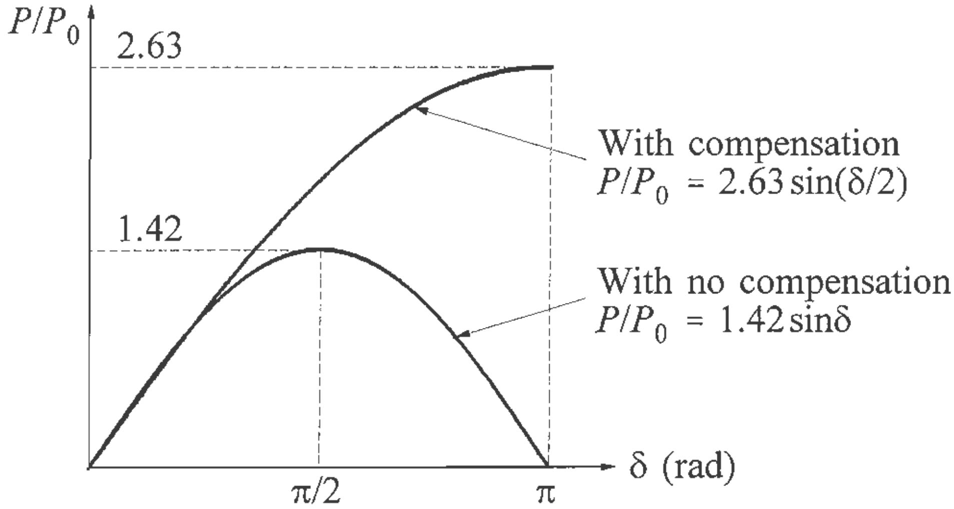


Figure 11.59 Power-angle relationship with and without midpoint regulated compensation

As an example, let us consider an SVS applied to the midpoint of the 600 km line considered above. The SVS performs as a regulated compensation until the reactive power output limit is reached. If the SVS has unlimited capacity, the P-δ characteristic is shown as curve 1 in Figure 11.60. If the SVS has a maximum capacitive rating of 750 MVAr at rated voltage, when the capacitive limit is reached the SVS behaves as a simple capacitor. Thus point A in Figure 11.60 represents the transition from a variable susceptance voltage control operation to a constant-B_{sh} operation represented by curve 2.

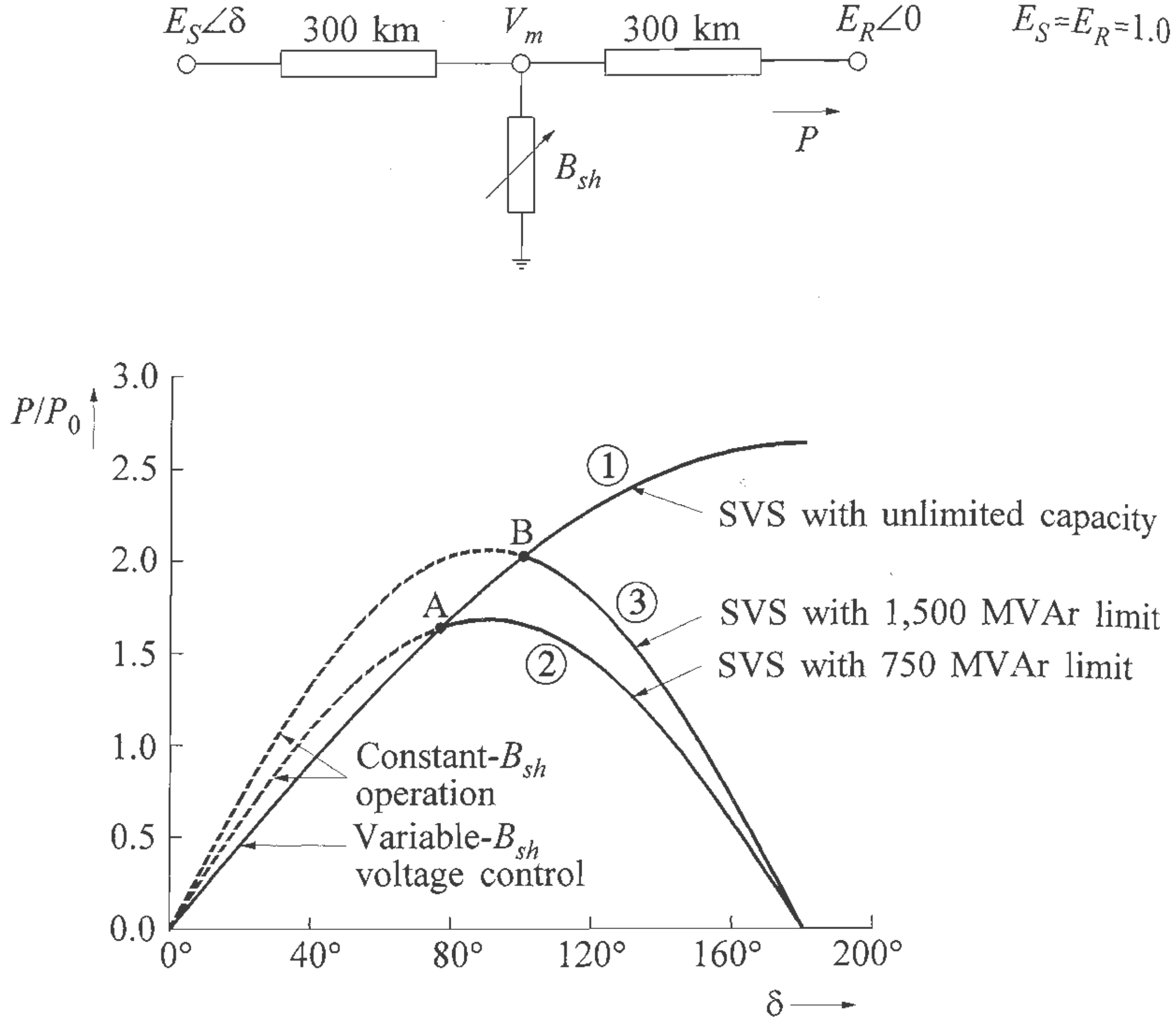


Figure 11.60 Performance of a 600 km line with an SVS regulating midpoint voltage

If the SVS capacitive limit is 1,500 MVAr, the corresponding constant-B_{sh} characteristic is represented by curve 3. In this case, the transition point (B) is on the unstable part (beyond δ=90°) of the power-angle curve. The operation would be unstable immediately following the transition from the variable susceptance mode to the fixed capacitor mode.

With an SVS of unlimited capacity, the maximum power that can be transmitted is $2.63P_0$. However, this is achieved by the SVS supplying very large amounts of reactive power at high values of P. Figure 11.61 shows a plot of the reactive power (Q) supplied (or absorbed) by the SVS to maintain 1.0 pu midpoint voltage as the transmitted power P is varied. The SVS absorbs Q when P is less than P_0, and supplies Q when P is greater than P_0. The Q supplied is not excessive for P less than about $1.4P_0$. Beyond a certain limit, it may not be economical to provide an SVS with the required reactive power capability; it may be cheaper to achieve the desired transmission capability by an alternative means.

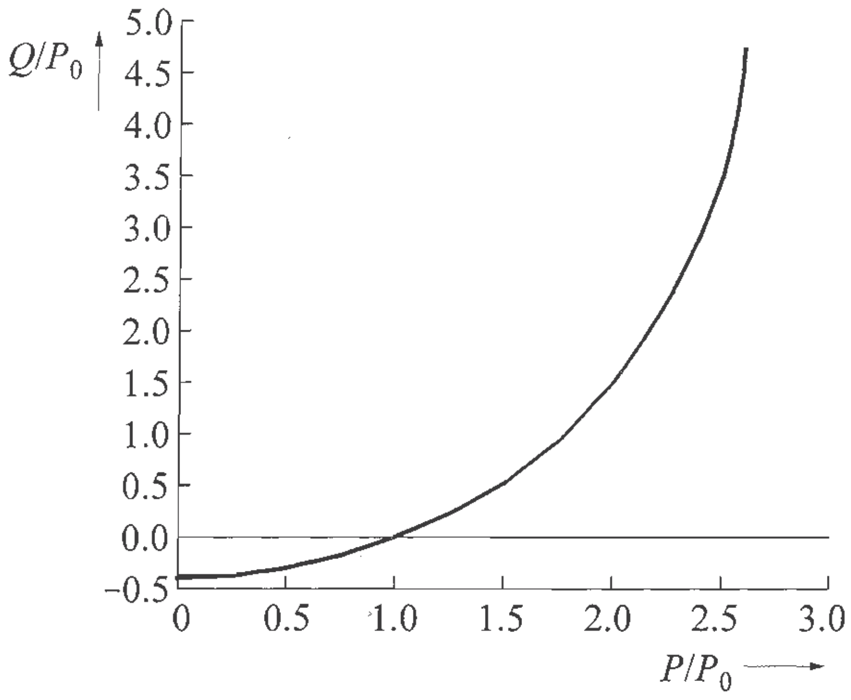


Figure 11.61 Reactive power supplied by SVS as a function of transmitted power

In our analysis, we have neglected the effect of the SVS droop characteristic; that is, we have assumed the slope reactance X_{SL} to be zero. The effect of a finite X_{SL} is to reduce the maximum power and the reactive power requirements.

Arbitrary number of regulated compensators:

We will next consider the general case where $n-1$ regulated compensators are applied to the line at regular intervals so that the line is divided into n independent sections. The power transmitted is now given by

$$P = \frac{P_0}{\sin(\theta/n)}\sin(\delta/n) \tag{11.61}$$

The ratio of maximum power that can be transmitted with and without the compensation is

$$\frac{P'_{max}}{P_{max}} = \frac{\sin\theta}{\sin(\theta/n)} \tag{11.62}$$

Table 11.3 lists the above ratio for different values of n for a line length of 600 km (assuming β=0.0013 rad/km).

Table 11.3

n	θ/n (degrees)	P'_{max}/P_{max}
1	44.70	1.00
2	22.35	1.85
3	14.90	2.74
4	11.17	3.63
6	7.45	5.42
8	5.59	7.22
10	4.47	9.03

Figure 11.62 shows plots of P-δ characteristics for different values of n.

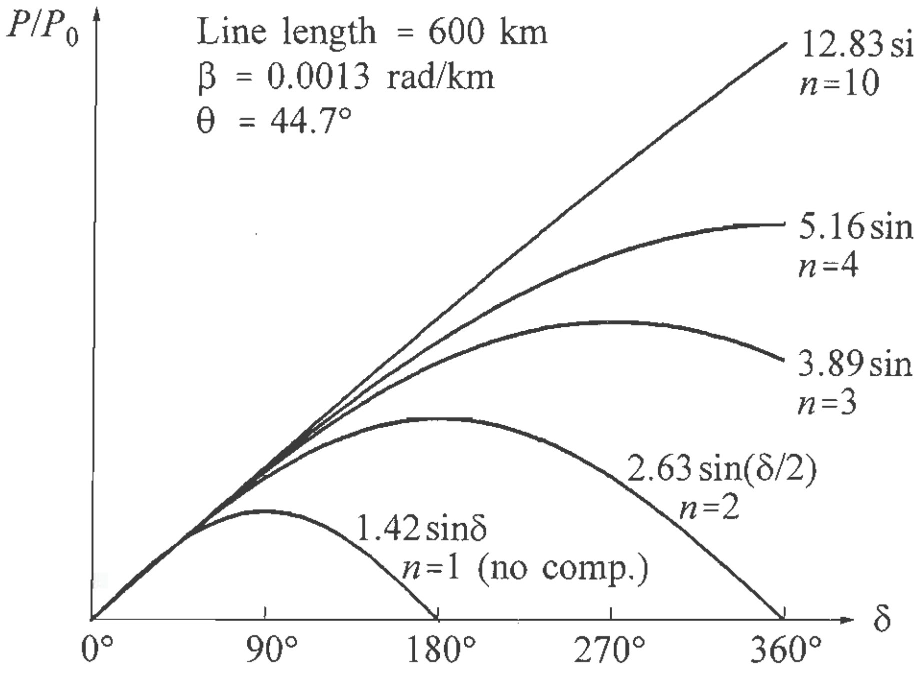


Figure 11.62 Power-angle relationships with regulated compensation at discrete intervals dividing line into n independent sections

Comparative summary of alternative forms of compensation [44-46]

1. Switched shunt capacitor compensation generally provides the most economical reactive power source for voltage control. It is ideally suited for compensating transmission lines if reduction of the effective characteristic impedance (Z'_C), rather than reduction of the effective line angle (θ') is the primary consideration.

   However, heavy use of shunt capacitor compensation could lead to reduction of small-signal (steady-state) stability margin and poor voltage regulation.

2. Series capacitor compensation is self-regulating, i.e., its reactive power output increases with line loading. It is ideally suited for applications where reduction of the effective line angle (θ') is the primary consideration. It increases the effective natural load as well as the small-signal stability limit and it improves voltage regulation. It is normally used to improve system stability and to obtain the desired load division among parallel lines.

   Series capacitor compensation could cause subsynchronous resonance problems requiring special solution measures. In addition, protection of lines with series capacitors requires special attention.

3. A combination of series and shunt capacitors may provide the ideal form of compensation in some cases. This allows independent control of the effective characteristic impedance and the load angle δ. An example of such an application is a long line requiring compensation which, in addition to increasing the effective SIL, causes the phase angle across the line to take a desired value so as not to adversely affect loading patterns on parallel lines.

4. A static var system is ideally suited for applications requiring direct and rapid control of voltage. It has a distinct advantage over series capacitors where compensation is required to prevent voltage sag at a bus involving multiple lines. Since shunt compensation is connected to the bus and not to particular lines, the total cost of the regulated shunt compensation may be substantially less than that for series compensation of each of the lines.

   When an SVS is used to permit a high power transfer over a long distance, the possibility of instability when the SVS is pushed to its limit must be recognized. When operating at its capacitive limit, the SVS becomes a simple capacitor; it offers no voltage control and its reactive power drops with the square of the voltage. Systems heavily dependent on shunt compensation may experience nearly instantaneous collapse when loadings exceed the levels for which the SVS is sized. The ratings of the SVS should be based on very thorough studies which define its total MVAr and the switched and dynamically controlled portions. An SVS has limited overload capability and has higher losses than series capacitor compensation.

11.2.9 Modelling of Reactive Compensating Devices

In power-flow and stability studies, the passive compensating devices (shunt capacitors, shunt reactors, and series capacitors) are modelled as admittance elements of fixed values. They are included in the network admittance matrix (see Chapter 6, Section 6.4.1) along with the other transmission network passive elements.

Synchronous condensers are modelled as synchronous generators but with no steady-state active power output. Except for the fact that there is no prime mover, the representation of a synchronous condenser and the associated excitation system is similar to that for a synchronous generator.

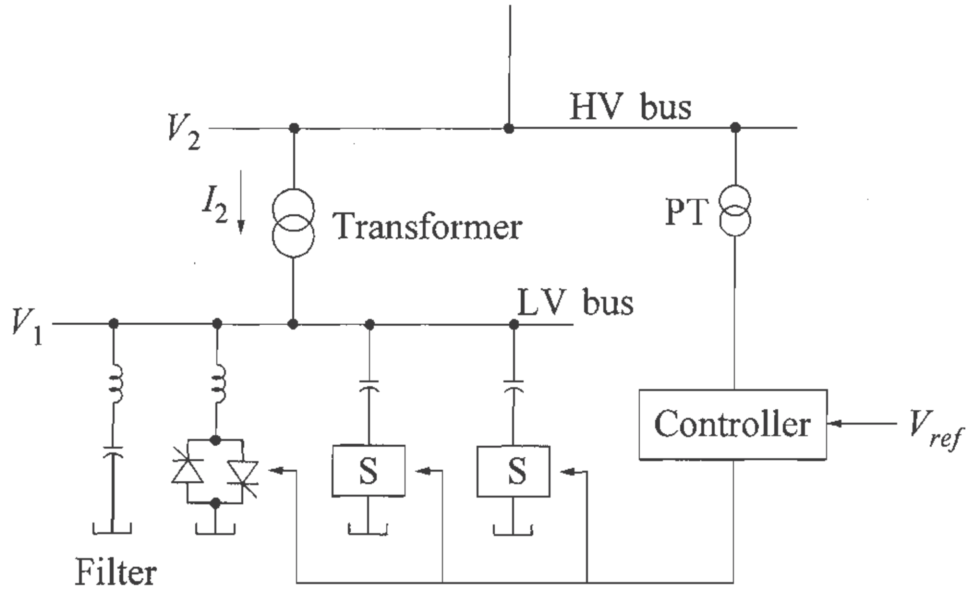
However, special models are required for representing static var compensators.

Modelling of static var systems [36,38,47]

Figure 11.63 shows the schematic diagram of a typical SVS. It consists of a TCR and switched (thyristor or mechanical) capacitors, and has the steady-state characteristic shown in Figure 11.64. The characteristics and modelling of SVSs with different configurations comprising other types of SVCs are conceptually the same.

Representation of SVS in power-flow studies:

From Figure 11.64 we see that the SVS has three possible modes of operation. The corresponding equivalent circuits of the SVS as seen from the HV bus are shown in Figure 11.65.



S = thyristor or mechanically controlled switch

Figure 11.63 Schematic of a typical SVS

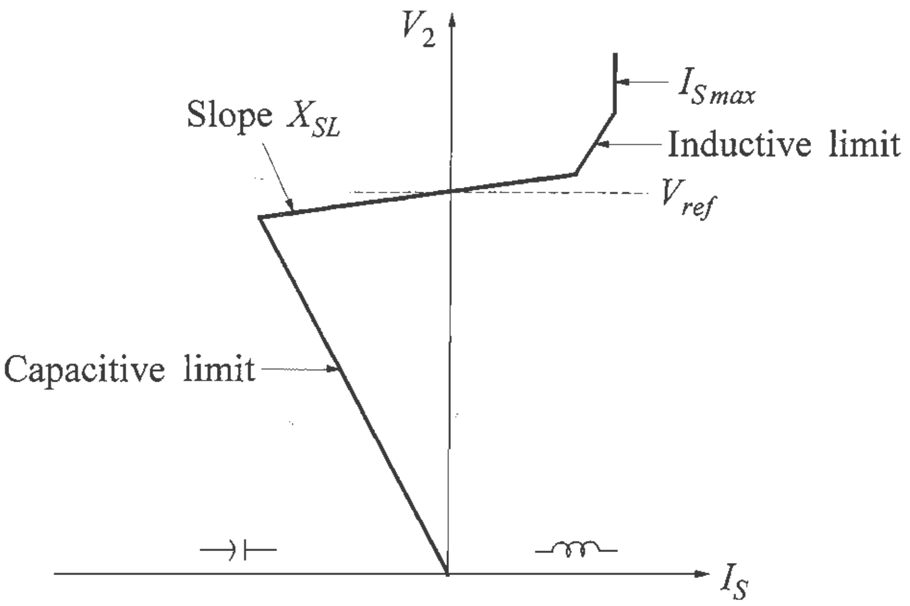
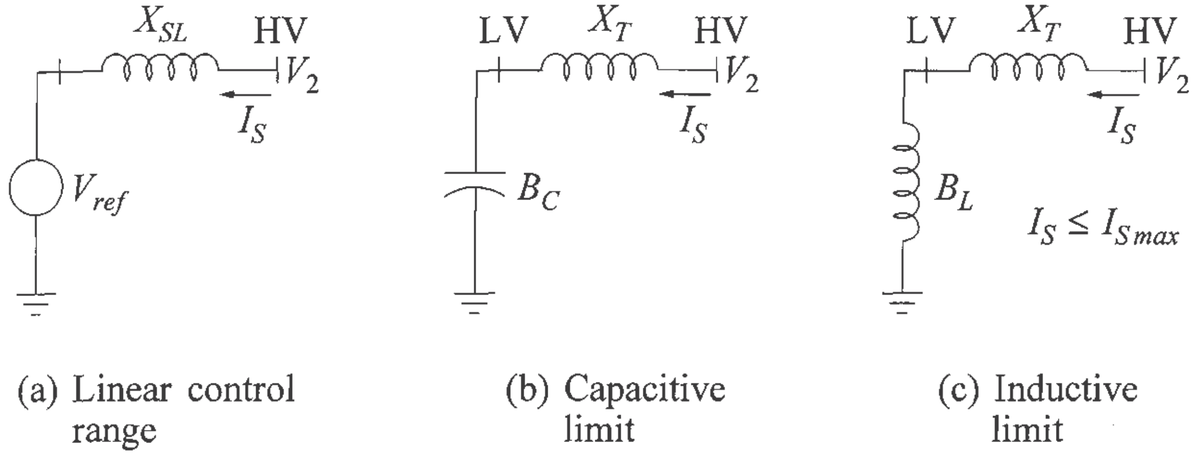


Figure 11.64 Steady-state *V-I* characteristic



(a) Linear control range (b) Capacitive limit (c) Inductive limit

Figure 11.65 Steady-state equivalent circuits of an SVS

The normal mode of operation is in the linear control range. In this mode, the SVS as seen from the HV bus is equivalent to a voltage source V_{ref} in series with the slope reactance X_{SL}. When the SVS operation reaches the capacitive limit, it becomes a fixed capacitive susceptance (B_C) connected to the LV bus. The reactance between the LV bus and the HV bus is the transformer leakage reactance X_T. Similarly, when the SVS operation hits the inductive limit, it becomes a fixed susceptance (B_L) whose net value is inductive. The maximum value of the SVS current is limited to I_{Smax}.

For power-flow analysis, the network configuration shown in Figure 11.66 may be used to represent the SVS. The transformer reactance X_T is split into X_{SL} and X_T-X_{SL}, thereby creating a phantom bus (M). This allows proper representation of the SVS while operating in the linear control mode, including the effect of the slope reactance. In this mode, the SVS is represented as a *PV* bus (with P=0) remotely controlling the bus M voltage equal to V_{ref}.

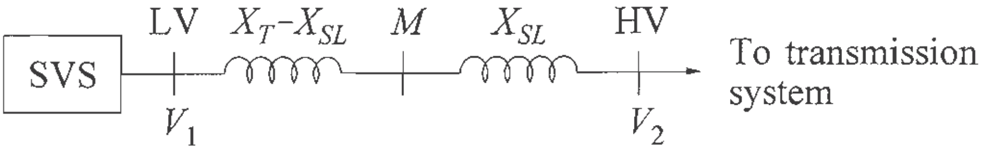


Figure 11.66 SVS representation in power-flow studies

When either of the reactive limits is reached, the SVS becomes a simple susceptance of fixed value connected to the LV bus; bus M voltage is no longer controlled. The SVS current is limited to $I_{S\,max}$.

The above representation accounts for the SVS performance appropriately in all three modes. In addition, it retains the identity of the LV bus to which the SVS is connected.

Representation in stability studies:

Static var systems are usually configured to meet individual system requirements. The control techniques used vary depending on the equipment suppliers and on the vintage of equipment. Therefore, standard stability models capable of representing in detail the wide range of SVSs in use have not been developed. Instead, basic models appropriate for general purpose studies have been recommended by CIGRE [36]. A new set of basic models covering recent developments has been prepared by the IEEE [47]. Such basic models are adequate for general purpose studies in which the special features specific to individual installations do not affect stability analysis. These models may also be used for preliminary studies involving new installations. For detailed studies, however, accurate models reflecting actual controls may be necessary.

Here, we will describe the general approach to modelling of an SVS of the type shown in Figure 11.63. A functional block diagram representation of the SVS is shown in Figure 11.67. The stability model may be developed by identifying the mathematical model for each functional block.

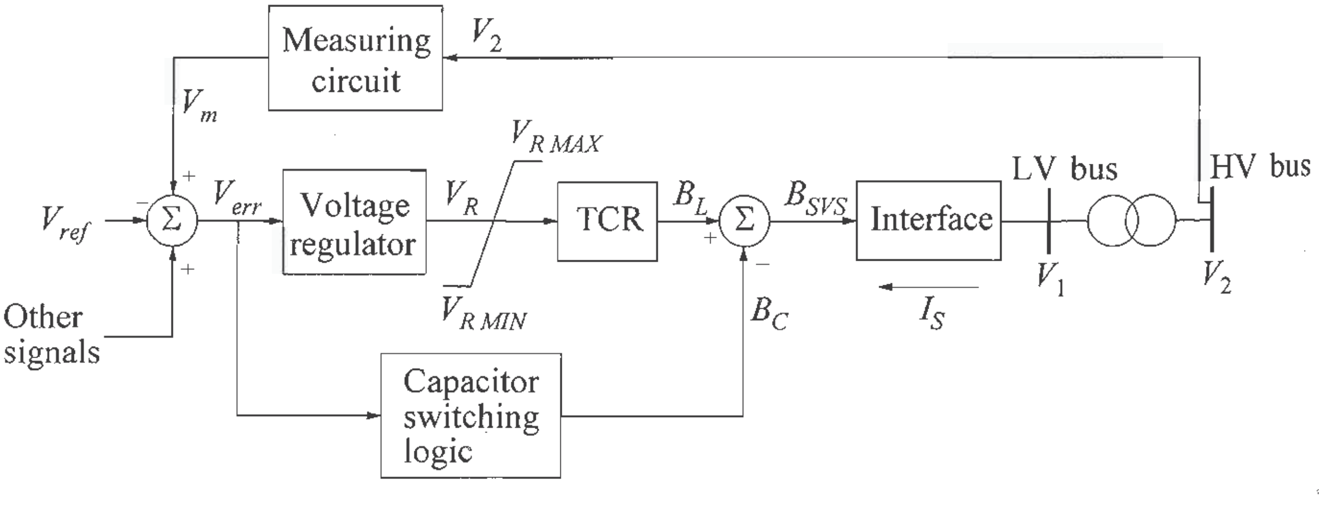
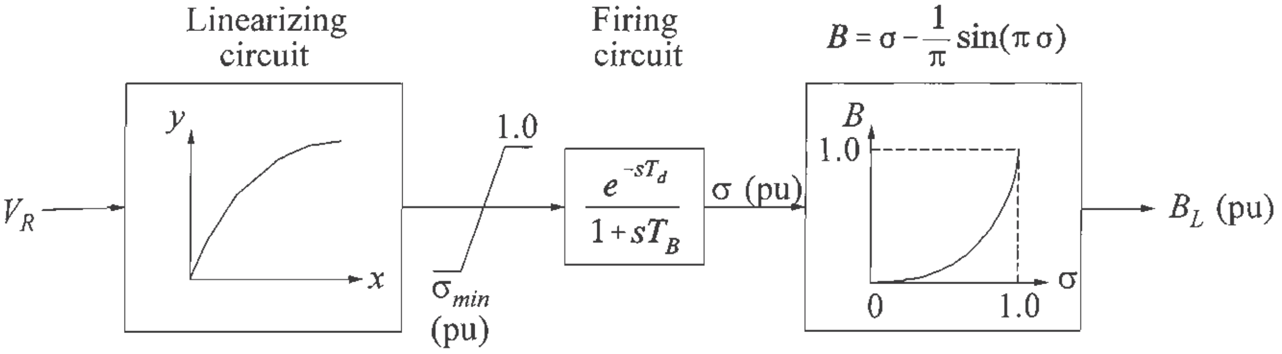


Figure 11.67 SVS functional block diagram

The *thyristor-controlled reactor* (TCR) block represents the variation of reactor susceptance as a function of the firing angle, thyristor firing circuits (Equation 11.36), and linearizing circuit used for compensating the nonlinear relationship between the susceptance B_L and the conduction angle σ. Figure 11.68 shows a model of the TCR block with parameters expressed in per unit with the MVA rating (Q_{TCR}) and kV rating of the TCR as base values. The conduction angle σ is in per unit on a base of 180°.



MVA base = Q_{TCR} = TCR MVAr rating σ base = 180°

Figure 11.68 Model of TCR block

The limits shown in the firing circuit block represent the limits on the conduction angle, which in turn determine the limiting values of B_L. In per unit, the maximum value of B_L is 1.0. Typically, the minimum value of B_L for a TCR is 0.02 pu; it may be assumed to be zero. The parameter T_d is the gating transport delay; it has a value of about 1 ms and is normally neglected, making $e^{-sT_d} \approx 1.0$. The time constant T_B associated with the thyristor firing sequence control has a value of about 5 ms; it may also be neglected for most studies.

If the nonlinear relationship between σ and B_L is assumed to be perfectly compensated and T_d and T_B are neglected, the TCR block may be represented by a unit gain with limits as shown in Figure 11.69.

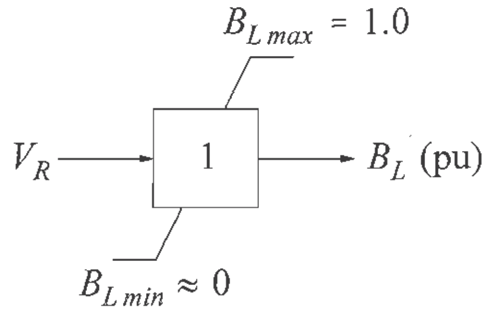
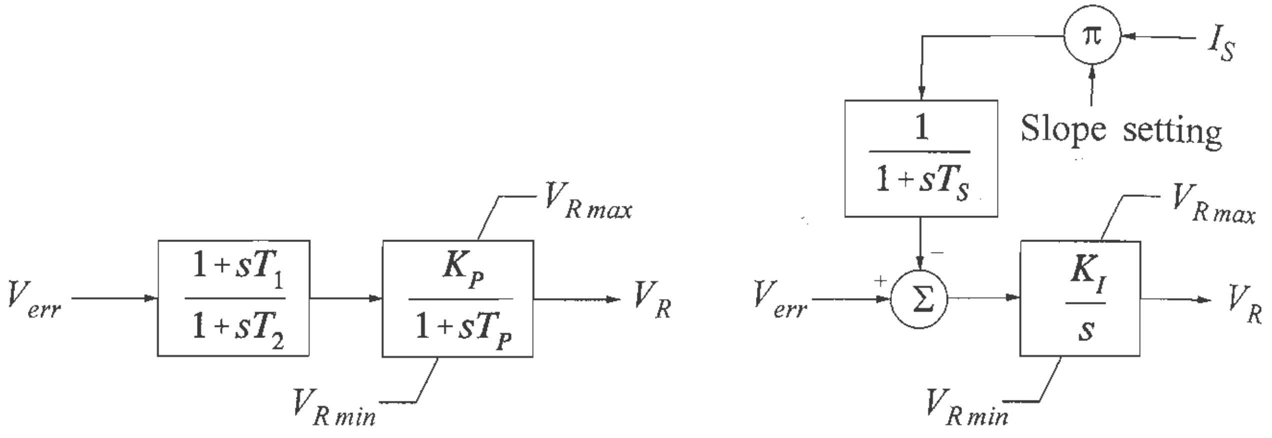


Figure 11.69 Simplified model of TCR block

The structure of the *voltage regulator* block in Figure 11.67 is very much dependent on the particular application as it provides a means of optimizing the SVS dynamic performance. Figure 11.70 shows models of two commonly used forms of regulators.



(a) Proportional type (b) Integral type

Figure 11.70 Voltage regulator models

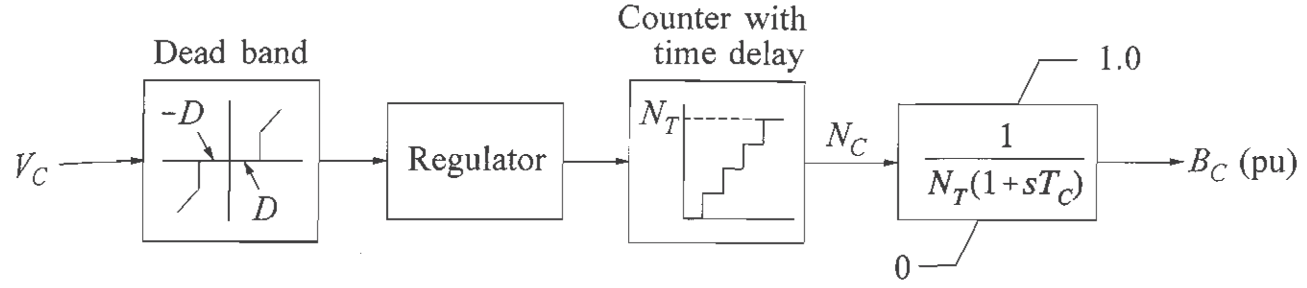
With the proportional type regulator shown in Figure 11.70(a), the gain K_P is the reciprocal of the droop characteristic, i.e., the slope reactance X_{SL}. The time constant T_P is usually in the range of 50 ms to 100 ms. Figure 11.70(b) shows an integral type regulator. The droop characteristic is obtained through feedback of SVS current. The limiters associated with both forms of regulators are of the non-windup type.

The *measuring circuit* block in Figure 11.67 includes instrument transformers, A/D converters, and rectifiers. It contains a transport delay and time constants which are very small. Consequently, the measuring circuit may be represented by a simple time constant on the order of 5 ms or as a unit gain.

The *capacitor-switching logic* may be represented by a switching sequence depending on the means used for switching, i.e., mechanical or thyristor switches. The intelligence used for switching depends on the requirements of the particular application.

Figure 11.71 shows a model suitable for representing a thyristor switched capacitor (TSC) with parameters expressed in per unit with the MVA rating (Q_{TSC}) and kV rating of the TSC as base values. In the model, T_C is the time constant associated with the thyristor sequence control.

In the model shown, N_T is the total number of individually switched capacitor bank units (assumed to be of equal size), N_C is the number of units switched in at any given time, and T_C is a time constant associated with the thyristor firing sequence control. The control signal V_C attempts to maintain V_2 within a narrow band, with the control action coordinated with that of the TCR.



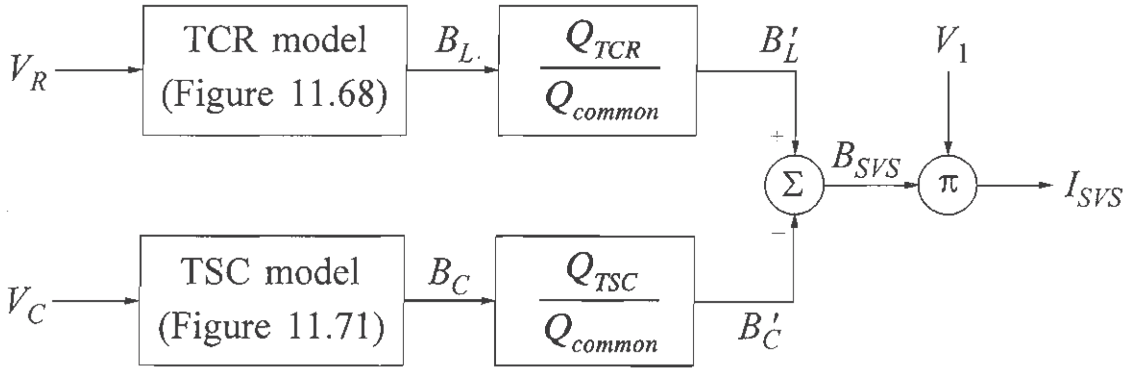
MVA base = Q_{TSC} = TSC MVAr rating

Figure 11.71 TSC model

Figure 11.72 shows the per unit representation of a combined TCR and TSC system. TCR and TSC are each modelled by using a per unit system with their respective MVAr ratings as base MVA. The susceptances B_L and B_C are converted to the common per unit system (usually with 100 MVA base) used to model the entire power system. In Figure 11.72, the net susceptance B_{SVS} and the total SVS current are expressed in the common per unit system. The net susceptance B_{SVS} is inductive if positive, and is capacitive if negative. The current into the SVS represented by I_{SVS} is positive when inductive (load convention). This is consistent with the convention commonly used for representing the *V-I* characteristic of the SVS (Figure 11.64).

For most system studies, it is not necessary to represent a TSC explicitly as shown in Figure 11.72. The TSC response may be assumed to be instantaneous, and the SVS is represented by a TCR and an FC with the MVAr ratings appropriately selected.

With a fixed capacitor there is no switching logic; the susceptance B_C has a fixed value. Figure 11.73 shows a simplified model of an SVC consisting of a TCR and a fixed capacitor. The TCR is assumed to have a proportional type regulator. The parameters are in per unit with TCR ratings as base values.



Q_{TCR} = MVAr rating of TCR
Q_{TSC} = MVAr rating of TSC
Q_{common} = common MVA base
V_1 = LV bus voltage

Figure 11.72 Combined TCR and TSC representation

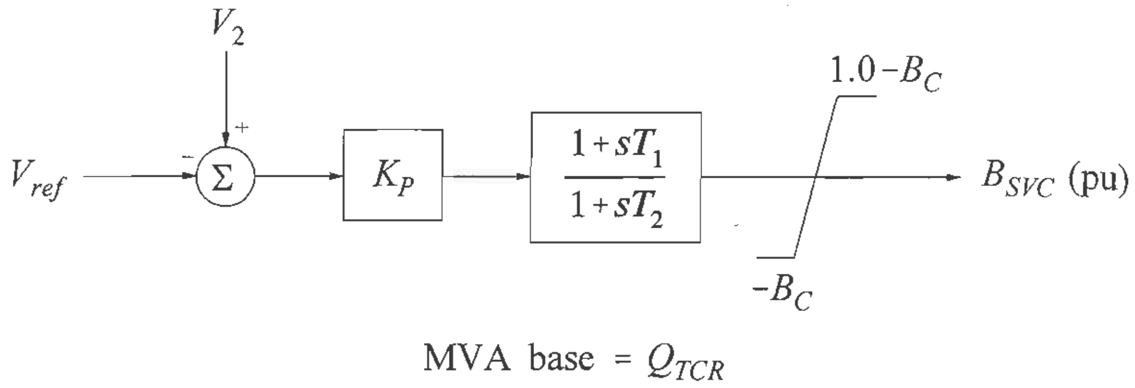


Figure 11.73 Simplified model of an SVC comprising a TCR and an FC

In addition to the feedback of HV bus voltage to control the SVS, additional signals may be used to enhance system stability.

11.2.10 Application of Tap-Changing Transformers to Transmission Systems

Transformers with tap-changing facilities constitute an important means of controlling voltage throughout the system at all voltage levels. In Chapter 6, we discussed the principle of operation and modelling of tap-changing transformers. Here we will consider how they are used to control voltage and reactive power at the transmission system level.

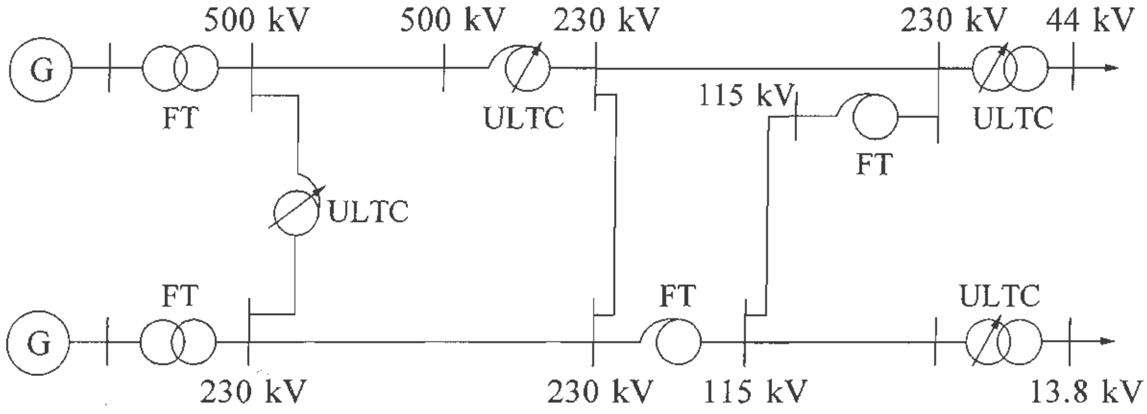
Autotransformers used to change voltage from one subsystem to another (for example, 500 kV to 230 kV) are often furnished with under-load tap-changing (ULTC) facilities. These may be controlled either automatically or manually. Usually there are many such transformers throughout the network interconnecting transmission systems of different levels. The taps on these transformers provide a convenient means of controlling reactive power flow between subsystems. This in turn can be used to control the voltage profiles, and minimize active and reactive power losses.

The control of a single transformer will cause changes in voltages at its terminals. In addition, it influences the reactive power flow through the transformer. The resulting effect on the voltages at other buses will depend on the network configuration and load/generation distribution. Coordinated control of the tap changers of all the transformers interconnecting the subsystems is required if the general level of voltage is to be changed.

During high system load conditions, the network voltages are kept at the highest practical level to minimize reactive power requirements and increase the effectiveness of shunt capacitors and line charging. The highest allowable operating voltage of the transmission network is governed by the requirement that insulation levels of equipment not be exceeded, taking into consideration possible switching operations and outage conditions. During light load conditions, it is usually required to lower the network voltages to reduce line charging and avoid underexcited operation of generators.

Transformers with off-load tap-changing facilities can also help maintain satisfactory voltage profiles. While transformers with ULTC can be used to take care of daily, hourly, and minute-by-minute variations in system conditions, settings of off-load tap-changing transformers have to be carefully chosen depending on long-term variations due to system expansion, load growth, or seasonal changes. Optimal power-flow analysis provides a convenient method of determining appropriate tap settings with either type of tap-changing facility [49-51].

Utility practices with regard to application of ULTC transformers to transmission systems vary widely. For example, Ontario Hydro's practice is to provide ULTC facilities on most 500/230 kV autotransformers and on all "area supply" transformers stepping down from 230 kV or 115 kV to 44 kV, 27.6 kV, or 13.8 kV. All 230/115 kV autotransformers and generator step-up transformers are provided with off-load tap-changing facilities. Figure 11.74 illustrates the general arrangement.



FT = Fixed tap or off-load tap changing
ULTC = Under-load tap changing

Figure 11.74 Single-line diagram of transmission network illustrating transformer tap change facilities

As an additional example, the practice in the United Kingdom is to provide ULTC on all generator step-up transformers and on autotransformers connecting a 400 kV or 275 kV "supergrid network" to a 132 kV or 66 kV "secondary network." Autotransformers connecting the 400 kV and 275 kV networks have fixed ratios.

Many utilities, on the other hand, do not provide for under-load tap changing of transmission network autotransformers.

11.2.11 Distribution System Voltage Regulation [25,48]

Automatic voltage regulation of distribution systems is provided by using one or more of the following methods:

- Bus regulation at the substation
- Individual feeder regulation in the substation
- Supplementary regulation along the feeders

Substation bus regulation

A distribution substation transformer is usually equipped with ULTC equipment that automatically controls the secondary voltage. Alternatively, the substation may have a separate voltage regulator that regulates the secondary side bus voltage.

Bus regulation generally employs three-phase units, although single-phase regulators could be used in applications where phase voltages have a significant unbalance.

Feeder regulation

Feeder voltage regulators control the voltage of each feeder. Either single-phase units or three-phase units may be used, the former being more common. Single-phase regulators are necessary when the individual phases serve diverse forms of loads. Three-phase regulators can provide the same high quality performance as the single-phase regulators, when the phases are similarly loaded and when the supply voltage is balanced.

If there are several feeders supplied by a substation, feeders with similar characteristics may be grouped, and a common regulator may be used to control the voltages of each group of feeders.

In applications where the feeders are very long, additional regulators and shunt capacitors located at selected points on the feeders provide supplementary regulation.

Feeder regulators are also sometimes referred to as booster transformers. A conventional transformer with ULTC performs two functions: voltage transformation and voltage control. Feeder voltage regulators perform only the latter function; that is, they buck or boost the voltage without changing the basic voltage level.

Types of feeder regulators

There are two basic types of feeder voltage regulators: the induction type and the step type. The following is a brief description of their operating principles.

Induction voltage regulator:

Figure 11.75 shows a schematic of an induction voltage regulator. It consists of two sets of windings: (a) primary winding wound on the rotor and connected across the line, and (b) regulating winding wound on the stator and connected in series with the line.

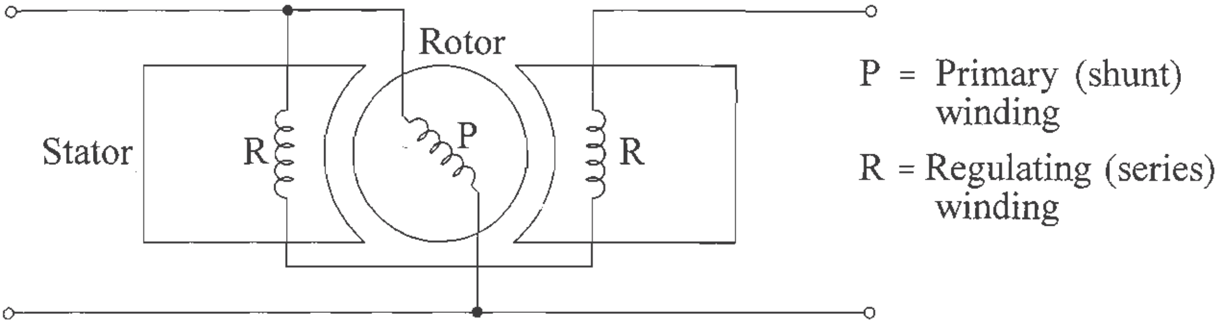


Figure 11.75 Schematic of an induction regulator

The voltage induced in the regulating series winding is added to the primary winding to give the output voltage. The magnitude and polarity of the induced voltage depend on the relative orientation of the regulating winding with respect to the primary winding. By changing the rotor position, the output voltage can be varied between the maximum and minimum limits. The position of the rotor is controlled by an electric motor which responds to a control signal.

The induction regulator provides accurate and continuous control, and performs reliably. Many of the older regulators in service are of this type. It is, however, costly and has been largely superseded by the step type regulator.

Step voltage regulator (SVR):

The step voltage regulator is basically an autotransformer with taps or steps in the series winding, as shown in Figure 11.76. However, it is purely a voltage control device; that is, it is not used for voltage transformation.

The voltage induced in the series winding is either added to or subtracted from the primary voltage depending on the polarity of the series winding. A reversing switch (RS) is provided to change this polarity. The series-winding output voltage magnitude is varied by changing the tap position, which can be done under load.

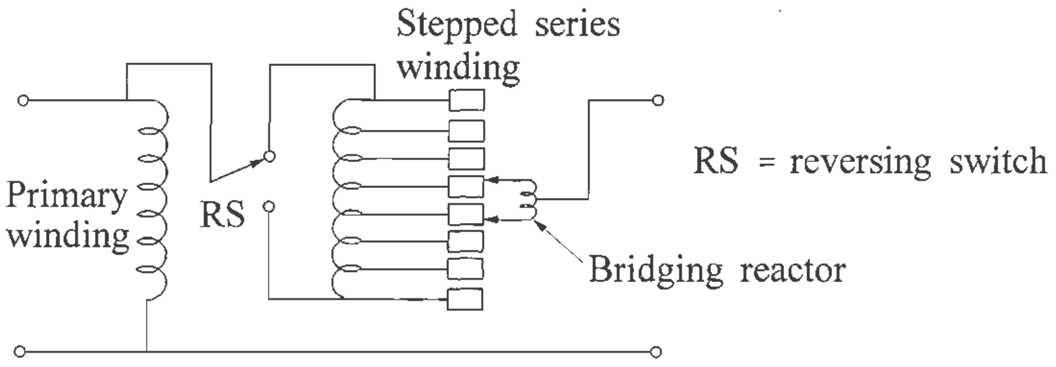


Figure 11.76 Schematic of a step voltage regulator

Typically, the SVR has provision for correcting the voltage by ±10% in 32 steps, each step representing a 5/8% change in voltage. This is achieved by tapping the series winding into eight equal parts, with each part providing one-eighth of the 10% change in voltage. The output terminal is connected to the centre tap of the bridging reactor associated with the tap-changing mechanism. This in effect further divides each step into two equal parts, giving a total of 16 steps of 5/8% each. The reversing switch allows the regulator to raise as well as lower the output voltage, covering a range of plus or minus 10% voltage regulation in a total of 32 steps.

Figure 11.77 shows the major elements of the SVR control mechanism. The SVR is set to hold a constant voltage (within a narrow range) at its secondary terminals or at some selected point out on the feeder as determined by the settings (R and X) of the *line drop compensator*. The voltage sensor compares the input voltage to a preset voltage level. If the input voltage deviates from the setpoint beyond a tolerance or spread for a certain time, the tap-changing motor operates the tap-changing mechanism in a direction so as to bring the voltage back to within a narrow range. This range is called the "bandwidth," and is typically ±2% around the setpoint. The time delay, which is adjustable, prevents the regulator from responding to temporary or self-correcting voltage variations. The time delay setting for the first tap movement can range from 30 to 60 seconds; a 30 seconds setting is typical [48].

The time taken by the tap-changing mechanism for each additional tap movement is in the 2 to 8 seconds range, with 6 seconds being a typical value. Thus, a change from the neutral tap position to full boost or buck takes about 2 minutes.

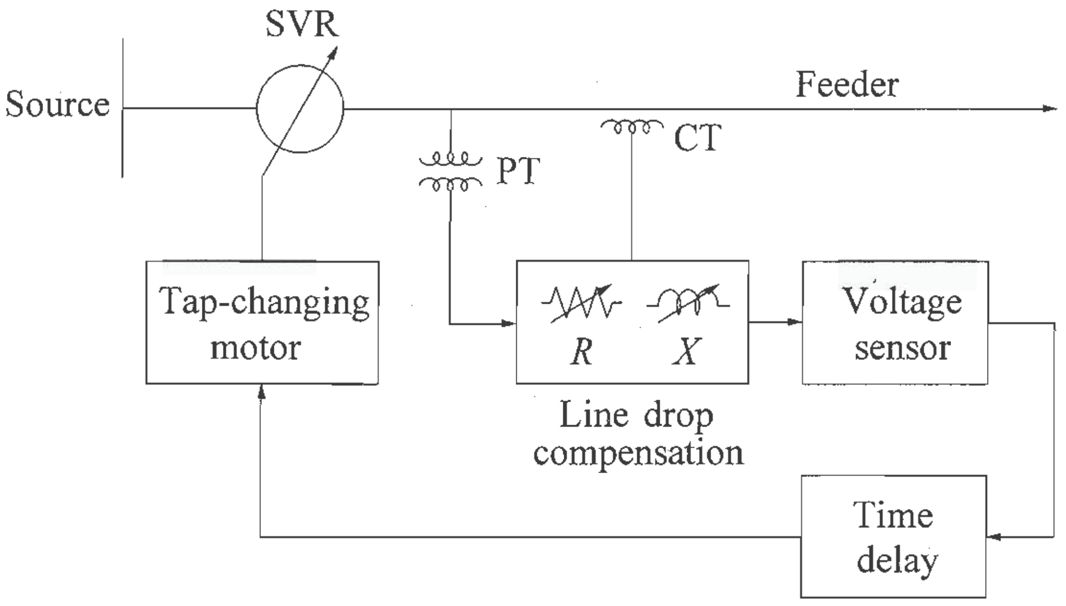
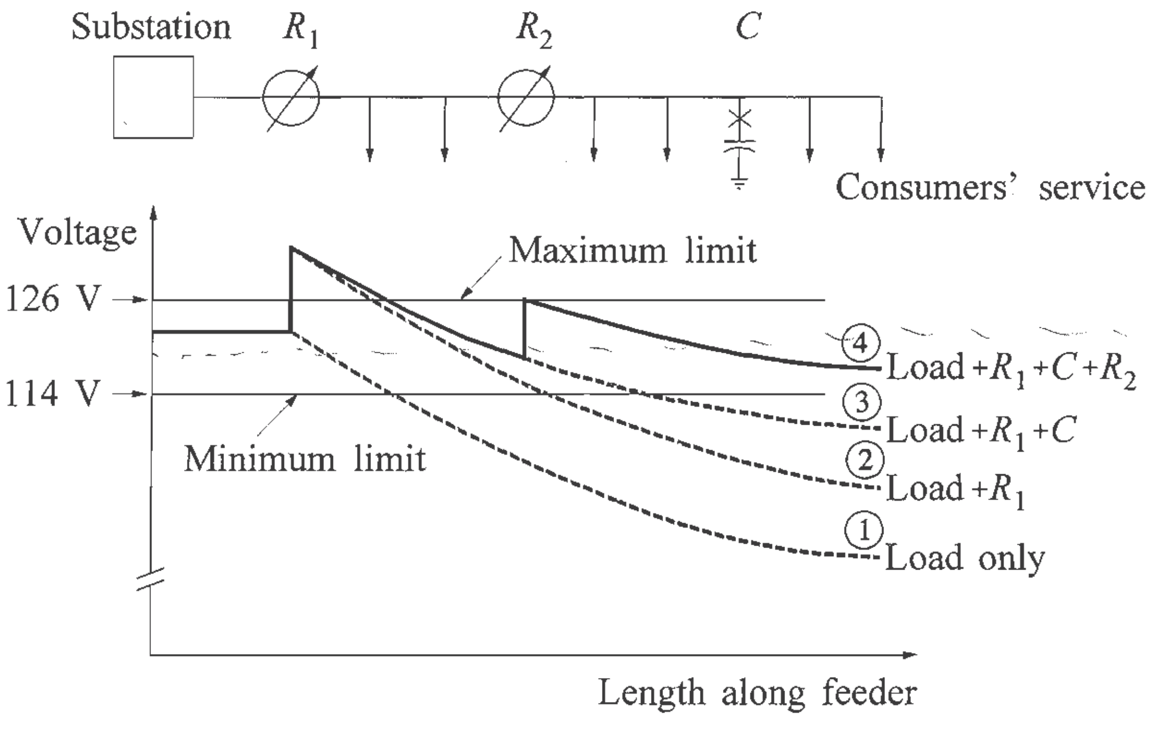


Figure 11.77 SVR control mechanism

Application of voltage regulators and capacitors

Figure 11.78 illustrates the application of regulators and shunt capacitors for control of voltage profile along a feeder. Curve 1 shows the voltage profile with a fairly evenly distributed load along the line, without any regulator or capacitor. The voltage for most parts of the feeder is seen to be below the permissible minimum value. The addition of a voltage regulator (R_1) moves the voltage profile up, as shown by curve 2. A capacitor bank (C), located at approximately two-thirds of the feeder length from the substation, moves the voltage profile to curve 3. The addition of a supplementary regulator (R_2) at approximately one-third of the feeder length from the substation will bring the voltage profile along the entire length of the feeder (from the first consumer to the last) to within the maximum and minimum permissible limits.

For very long feeders, it may be necessary to use two regulators in cascade. One regulator is placed at approximately the middle of the feeder and the other regulator at about one-fifth the distance from the station end. In such cases, it is necessary to ensure proper sequence of operation of the two regulators by setting the time delay of the regulator farther from the station longer than that for the closer regulator. Typical settings are 30 seconds for the regulator closer to the station and 40 seconds for the other regulator.



Vref

Figure 11.78 Voltage profile of a feeder with a station regulator (R_1), supplementary regulator (R_2) and a shunt capacitor bank (C)

11.2.12 Modelling of Transformer ULTC Control Systems

Modelling of transformers with tap-changing facilities is described in Chapter 6 (Section 6.2). Here we will focus on models for the control systems used for automatically changing transformer taps under load.

The functional block diagram of the control system is shown in Figure 11.79. It consists of the following basic elements [52]:

(a) Tap-changing mechanism driven by a motor unit

(b) Voltage regulator consisting of a measuring element and a time-delay element

(c) Line drop compensator

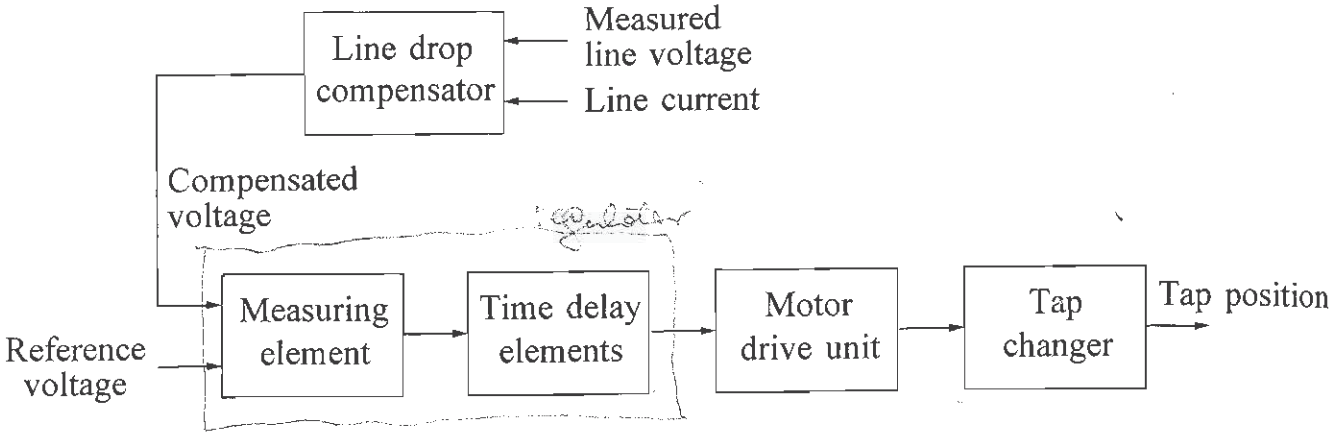


Figure 11.79 Functional block diagram of control system for automatic changing of transformer taps

Figure 11.80 shows the block diagram of the ULTC control system suitable for system studies.

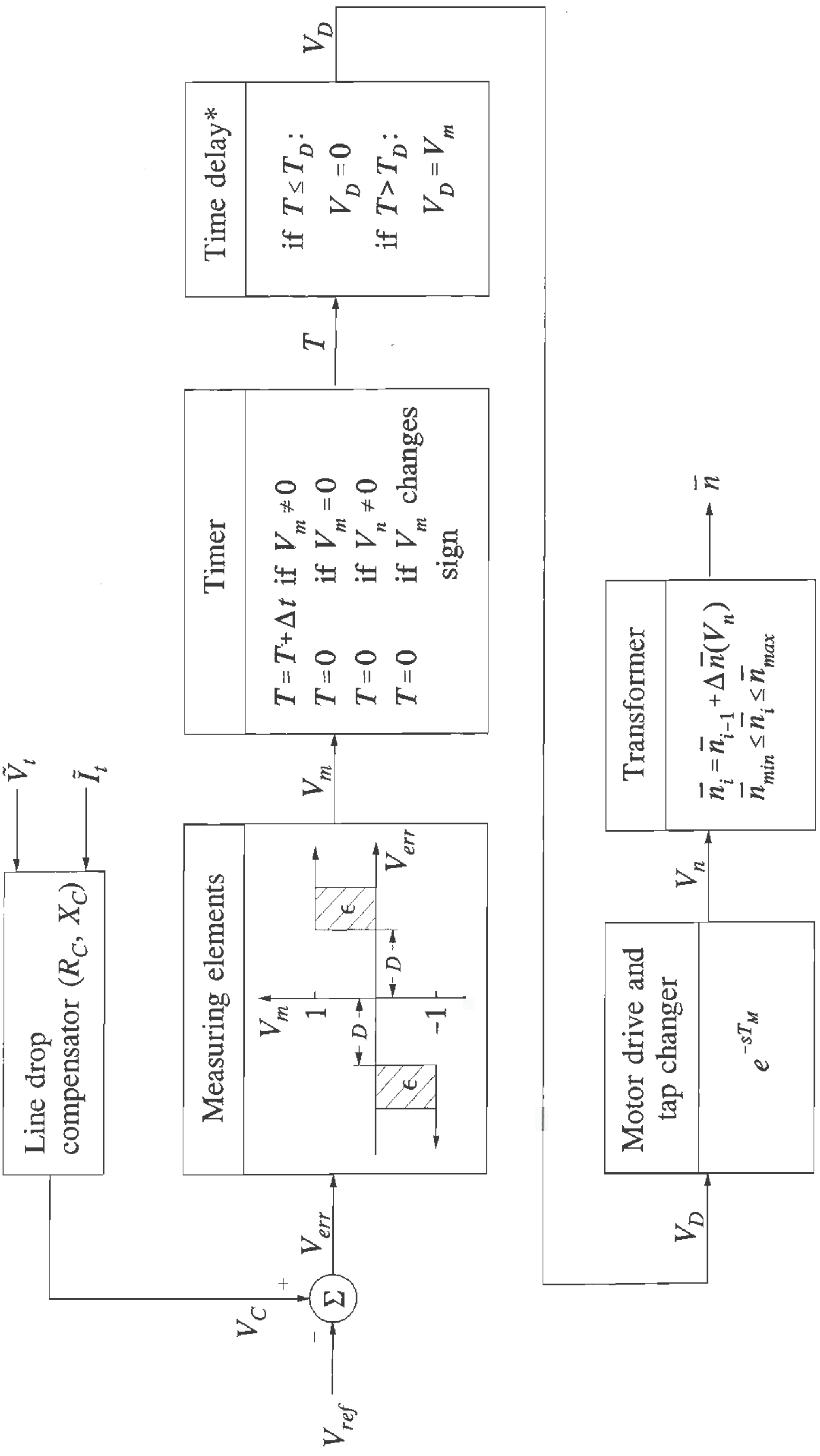
The function of the *line drop compensator*, as discussed in the previous section, is to regulate voltage at a remote point along the line or feeder. The voltage at the remote point is simulated by computing the voltage across the compensator impedance (R_C+jX_C). The magnitude of the compensated voltage is given by

$$V_C = |\tilde{V}_t+(R_C+jX_C)\tilde{I}_t|$$

where $\tilde{V}_t$ is the measured phasor voltage at the transformer secondary side.

The *measuring element* of the voltage regulator consists of an adjustable dead band relay with hysteresis. The input to the regulator is the voltage error.

$$V_{err} = V_{ref}-V_C$$



* $T_D = T_{D0}$ for first tap change
$\quad = T_{D1}$ for subsequent tap change

Figure 11.80 ULTC control system model

The output of the measuring element is V_m, which takes a value of 0, 1, or -1, depending on the input V_{err}. With a regulator dead band of D and a hysteresis band of ε, the output is

$$V_m = \begin{cases} 0 & \text{for } -D \le V_{err} \le +D \\ 0 & \text{for } D < V_{err} \le D+\epsilon; \quad V_{err} \text{ increasing} \\ 0 & \text{for } -D-\epsilon \le V_{err} < -D; \; V_{err} \text{ decreasing} \\ +1 & \text{for } V_{err} > D+\epsilon \\ +1 & \text{for } D < V_{err} \le D+\epsilon; \quad V_{err} \text{ decreasing} \\ -1 & \text{for } V_{err} < -D-\epsilon \\ -1 & \text{for } -D-\epsilon \le V_{err} < -D; \; V_{err} \text{ increasing} \end{cases}$$

The *time delay element* is used to prevent unnecessary tap changes in response to transient voltage variations and to introduce the desired time delay before a tap movement. The *timer unit* determines the time duration of the error voltage (V_{err}) exceeding the dead band. The timer is advanced if V_{err} is outside the dead band. It is reset if V_{err} is within the dead band, if there is a tap movement ($v_n \neq 0$), or if V_{err} oscillates above and below the dead band. The output V_D of the time delay unit is normally zero. If the accumulated time T of the timer exceeds T_D, then V_D is set to V_m (i.e., 1 or -1), thereby sending a signal to the tap-changer motor to move the tap up or down.

The time delay T_D is equal to T_{D0} for the first tap movement. Some regulators have an inverse time-delay characteristic, in which case the time delay is inversely proportional to the voltage error:

$$T_D = \frac{T_{D0}}{V_{err}/D}$$

For the second and subsequent tap movements the time delay T_D is equal to T_{DI}. This allows introduction of intentional time delay between consecutive tap movements, if so desired.

The *motor-drive unit and the tap-changer mechanism* may be represented by a simple time delay T_M inherent to the equipment. The output signal V_n represents an incremental change in tap position, and is equal to 0, 1, or -1.

A change in tap position is reflected in the *transformer* model (see Chapter 6, Section 6.2.1) as an incremental change in per unit turns ratio. The per unit turns ratio after the i^{th} operation is

$$\bar{n}_i = \bar{n}_{i-1} + \Delta\bar{n}(V_n)$$

where $\Delta\bar{n}$ represents the per unit turns ratio step corresponding to a change in tap position by one step.

The above assumes that the controlled bus is on the secondary side (see Figure 6.17 of Chapter 6). If the controlled bus is on the primary side, we have

$$\bar{n}_i = \bar{n}_{i-1} - \Delta\bar{n}(V_n)$$

The tap ratio is subject to the maximum and minimum limits ($\bar{n}_{max}$ and $\bar{n}_{min}$).

The following sample data apply to the ULTC control system of the 42 MVA, 110/28.4 kV two-winding transformer considered in Chapter 6, Section 6.2.1:

$\Delta\bar{n} = 0.0059524$	$\bar{n}_{max} = 1.04762$	$\bar{n}_{min} = 0.85714$
$T_M = 0.5$ s	$T_{D0} = 30.0$ s	$T_{D1} = 0$
$D = 0.00835$ (0.835%)	$\varepsilon = 0$	$R_C = X_C = 0$

11.3 POWER-FLOW ANALYSIS PROCEDURES

The main analytical tools used in the planning of reactive power resources are the power-flow and stability programs. The methods of analysis of various aspects of stability are discussed in Chapters 12 to 16.

For reactive power dispatching, in addition to conventional power flows, optimal power-flow programs are being increasingly used. *Optimal power-flow* (OPF) theory was first formulated by Carpentier in 1962 [53]. Since then much research work has been carried out on OPF analysis techniques [49-51,54]. A discussion of the OPF methods and their application is beyond the scope of this book.

In this section, we will limit our discussion to conventional power-flow analysis. Analytical techniques for the solution of the power-flow problem are covered in Chapter 6. We focus on practical considerations and modelling assumptions in power-flow studies of bulk transmission systems. In such studies, the distribution system is not usually represented and loads are represented at substation levels.

The purpose of power-flow analysis is to investigate equipment loadings, power losses, bus voltages and reactive power requirements for the possible range of system operating conditions and contingencies specified by the design criteria. For any given study, the network configuration, load level, and generation schedule are specified. Assumptions regarding equipment modelling depend on the type of power flow: prefault or postfault.

11.3.1 Prefault Power Flows

Prefault power flows generally consider normal system conditions. The basic assumption is that all control actions have taken place and the system is operating in a true steady-state condition. Consequently the system is represented as follows: