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SCHOOL OF ELECTRICAL AND ELECTRONICS ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT - I

Flexible AC Transmission System – SEE1601

I. Introduction

Electrical Transmission Network – Emerging Transmission Network – Concept of Reactive Power – Load and System Compensation – Midpoint Voltage – Passive Compensation – Synchronous Condenser – Saturated Reactor – Classification of FACTS controllers

1.1 EMERGING TRANSMISSION NETWORKS

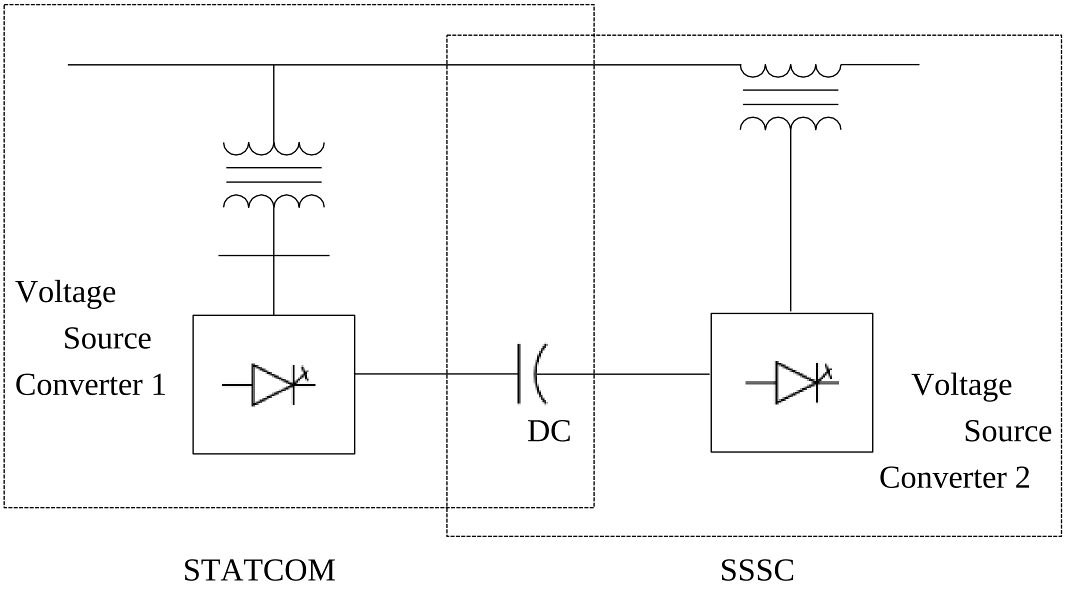


Figure 1.1 A 1-line diagram of a unified power-flow controller (UPFC).

A historic change is overtaking electrical power utility businesses. Customers are demanding their right to choose electrical energy suppliers from competing vendors—a movement that has arisen from the benefits of lower costs of such services as long-distance telephone calls, natural-gas purchases, and air travel. The industries embracing these activities have been recently deregulated, and in these sectors, competition has been introduced. The basic belief is that compe- tition leads to enhanced efficiency and thus lower costs and improved services. For nearly 100 years, electrical power utilities worldwide have been verti- cally integrated, combining generation, transmission, distribution, and servic- ing loads. Also, most such utilities have operated as monopolies within their geographic regions. Their method of operation has been "power at cost," and their principal financers have been governments. Therefore, to many people the pressure of electrical power utilities to operate efficiently has been missing.

Operating the electrical energy sector competitively requires the unbundling of generation, transmission, and distribution. Competition is expected to exist among generators as well as retailers. The transmission and distribution (i.e., the controlling wires) must, out of necessity, be regulated. The new order requires new agencies taking the responsibility to link customers (loads) with generators (market operators) and, at the same time, to clearly understand the limitations and capabilities of power-transmission and -distribution networks [22], [23].

On becoming responsible for its own business, a power-transmission com- pany must make the best use of its transmission capacity and ensure that trans- mission losses are reduced to their lowest values. Also, any loss of transmission capacity means loss of income for the company; therefore, all actions must be taken to ensure that unwanted circulating power is not clogging the available transmission capacity. In addition, energy congestion in critical transmission corridors must be avoided to eliminate the risk of missed business opportunityties. Finally, to offer the greatest flexibility to market operators, a transmission company must create the maximum safe operating limits to allow power inject- tion and tapping from its buses without risking stable operation. The success of a transmission company depends on offering the maximum available trans- mission capacity (ATC) on its lines.

From the foregoing discussion, it is evident that in the emerging electric- cal energy business, transmission companies have a greater need to make their networks more flexible. Fortunately, advances in power-electronics technology now offer new fast, controllable FACTS controllers to secure the needed flexi- bility [15], [22], [23].

The subject matter contained in this book is intended to assist engineers seek- ing FACTS knowledge and help utilities meet the energy challenge.

1.2 Electrical Transmission Network

The rapid growth in electrical energy use, combined with the demand for low- cost energy, has gradually led to the development of generation sites remotely located from the load centers. In particular, the remote generating stations include hydroelectric stations, which exploit sites with higher heads and significant water flows; fossil fuel stations, located close to coal mines; geothermal stations and tidal-power plants, which are site bound; and, sometimes, nuclear power plants purposely built distant from urban centres. The generation of bulk power at remote locations necessitates the use of transmission lines to connect generation sites to load centers. Furthermore, to enhance system reliability, multiple lines that connect load centers to several sources, interlink neighboring utilities, and build the needed levels of redundancy have gradually led to the evolution of complex interconnected electrical transmission networks. These networks now exist on all continents.

An electrical power transmission network comprises mostly 3-phase alternating-current (ac) transmission lines operating at different transmission voltages (generally at 230 kV and higher). With increasing requirement of power-transmission capacity and□ or longer transmission distances, the trans- mission voltages continue to increase; indeed, increases in transmission voltages are linked closely to decreasing transmission losses. Transmission voltages have gradually increased to 765 kV in North America, with power transmission reaching 1500 MVA on a line limited largely by the risk that a power utility may be willing to accept because of losing a line.

An ac power transmission network comprises 3-phase overhead lines, which, although cheaper to build and maintain, require expensive right-of-ways. How- ever, in densely populated areas where right-of-ways incur a premium price, underground cable transmission is used. Increasing pressures arising from eco- logical and aesthetic considerations, as well as improved reliability, favor under- ground transmission for future expansion.

In a complex interconnected ac transmission network, the source-to-a-load power flow finds multiple transmission paths. For a system comprising multiple sources and numerous loads, a load-flow study must be performed to determine the levels of active- and reactive-power flows on all lines. Its impedance and the voltages at its terminals determine the flow of active and reactive powers on a line. The result is that whereas interconnected ac transmission networks

provide reliability of power supply, no control exists on line loading except to modify them by changing line impedances by adding series and□ or shunt-circuit elements (capacitors and reactors).

The long-distance separation of a generating station from a load center requiring long transmission lines of high capacity and, in some cases in which a transmission line must cross a body of water, the use of ac□ dc and dc□ ac converters at the terminals of an HVDC line, became a viable alternative many

years ago. Consequently, beginning in 1954, HVDC transmission has grown steadily to the current □600 kV lines with about 4000 A capacity. Also, direct current (dc) transmission networks, including multiterminal configurations, are already embedded in ac transmission networks. The most significant feature of an HVDC transmission network is its full controllability with respect to power transmission [1]–[5].

Until recently, active- and reactive-power control in ac transmission networks was exercised by carefully adjusting transmission line impedances, as well as regulating terminal voltages by generator excitation control and by transformer tap changers. At times, series and shunt impedances were employed to effectively change line impedances.

1.3 Concept of Reactive Power

Reactive power associated with power- transmission networks is developed. To make transmission networks operate within desired voltage limits, methods of making up or taking away reactive- power—hereafter called reactive-power control—are discussed. Before proceeding further, however, a thorough understanding of the reactive power in ac systems is necessary.

Upon energization, the ac networks and the devices connected to them create associated time-varying electrical fields related to the applied voltage, as well as magnetic fields dependent on the current flow. As they build up, these fields store energy that is released when they collapse. Apart from the energy dissipation in resistive components, all energy-coupling devices, including transformers and energy-conversion devices (e.g., motors and generators), operate based on their capacity to store and release energy.

The reactive power is essential for creating the needed coupling fields for energy devices. It constitutes voltage and current loading of circuits but does not result in an average (active) power consumption and is, in fact, an important component in all ac power networks. In high-power networks, active and reactive powers are measured in megawatts (MW) and MVAR, respectively.

Electromagnetic devices store energy in their magnetic fields. These devices draw lagging currents, thereby resulting in positive values of Q; therefore, they are frequently referred to as the absorbers of reactive power. Electrostatic devices, on the other hand, store electric energy in fields. These devices draw leading currents and result in a negative value of Q; thus they are seen to be sup- pliers of reactive power. The convention for assigning signs to reactive power is different for sources and loads, for which reason readers are urged to use a consistent notation of voltage and current, to rely on the resulting sign of Q, and to not be confused by absorbers or suppliers of reactive power.

Reactive power is essential to move active power through the transmission and distribution system to the customer. Reactive power is required to maintain the voltage to deliver active power (watts) through transmission lines

1.4 UNCOMPENSATED TRANSMISSION LINES

To develop a good, qualitative understanding of the need for reactive-power control, let us consider a simple case of a lossless short-transmission line con- necting a source Vs to a load Z/–f. (For simplicity, the line is represented only by its inductive reactance Xl.) Figure 1.2 shows such a network with its param- eters, as well as a phasor diagram showing the relationship between voltages and currents. From Fig. 1.2(b), it is clear that between the sending- and the receiving-end voltages, a magnitude variation, as well as a phase difference, is created. The most significant part of the voltage drop in the line reactance (DV1j IxXl) is due to the reactive component of the load current, Ix. To keep the voltages in the network at nearly the rated value, two control actions seem possible:

load compensation, and

system compensation.

1.4 *.1* *Load Compensation*

It is possible to compensate for the reactive current Ix of the load by adding a parallel capacitive load so that Ic   Ix. Doing so causes the effective power factor of the combination to become unity. The absence of Ix eliminates the voltage drop DV1, bringing Vr closer in magnitude to Vs; this condition is called load compensation. Actually, by charging extra forsupplying the reactive power, a power utility company makes it advantageous for customers to use load compensation on their premises. Loads compensated to the unity power factor reduce the line drop but do not eliminate it; they still experience a drop of DV2 from j IrXl.

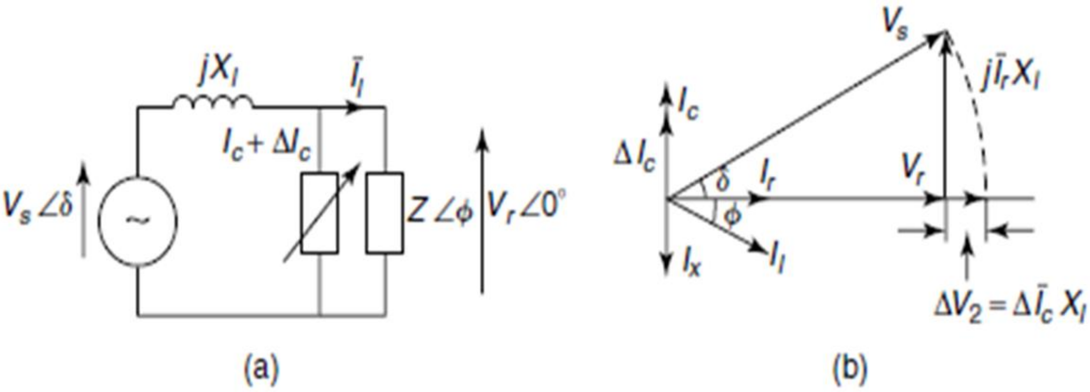


Figure 1.2 A short, lossless transmission line feeding a load.

1.4 .2 *System Compensation*

To regulate the receiving-end voltage at the rated value, a power utility may install a reactive-power compensator as shown in Fig. 2.3. This compensator draws a reactive current to overcome both components of the voltage drop DV1 and DV2 as a consequence of the load current Il through the line reactance Xl. To compensate for DV2, an additional capacitive current, DIc, over and above Ic that compensates for Ix, is drawn by the compensator. When DIcXl   DV2, the receiving-end voltage, Vr, equals the sending-end voltage, Vs. Such compensators are employed by power utilities to ensure the quality of supply to their customers [1].

1.5 PASSIVE COMPENSATION

In the foregoing discussion, a lossless line was analyzed, and the case study presented in Section 2.2 provided many numerical results and highlighted the problems of voltage control and the need to exercise reactive-power control to make a system workable. Reactive-power control for a line is often called reactive-power compensation. External devices or subsystems that control reactive power on transmission lines are known as compensators. Truly speaking, a compensator mitigates the undesirable effects of the circuit parameters of a given line.

The objectives of line compensation are invariably

1. to increase the power-transmission capacity of the line, and□ or
2. to keep the voltage profile of the line along its length within acceptable bounds to ensure the quality of supply to the connected customers as well as to minimize the line-insulation costs.

Because reactive-power compensation influences the power-transmission capacity of the connected line, controlled compensation can be used to improve the system stability (by changing the maximum power-transmission capacity), as well as to provide it with positive damping. Like other system components, reactive-power compensators are dimensioned, and their types are selected on the basis of both their technical and cost effectiveness.

1.5 .1 *Shunt Compensation*

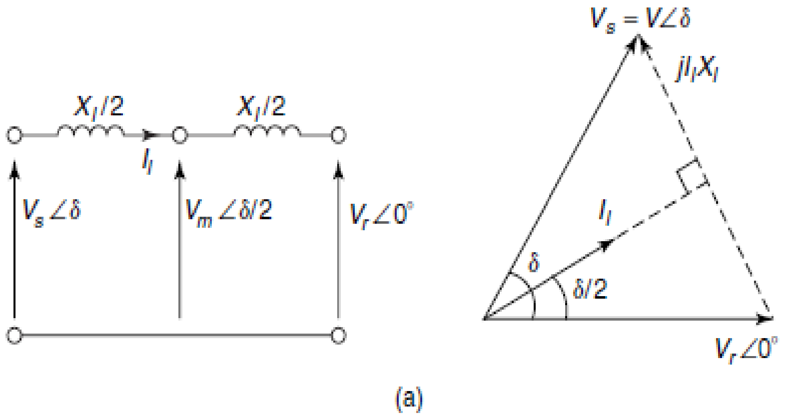


Figure 1.3 A short transmission line without compensation

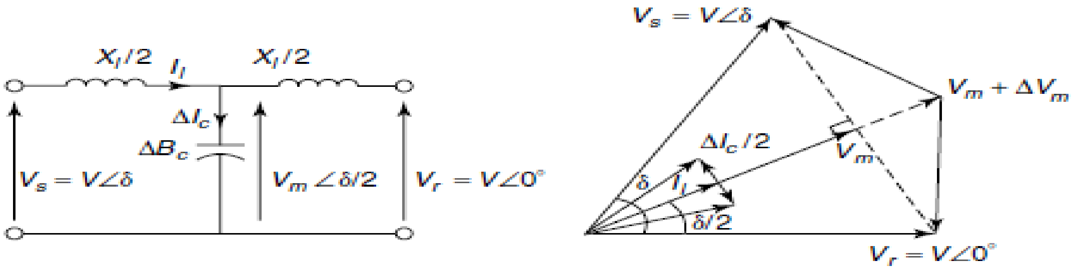


Figure 1.4 The midpoint-capacitor compensation of a short, symmetrical line.

Passive reactive-power compensators include series capacitors and shunt-connected inductors and capacitors. Shunt devices may be connected permanently or through a switch. Shunt reactors compensate for the line capacitance, and because they control over voltages at no loads and light loads, they are often connected permanently to the line, not to the bus. Figure 1.4 shows the arrangements of shunt reactors on a long-distance, high-voltage ac line. Many power utilities connect shunt reactors via breakers, thereby acquiring the flexibility to turn them off under heavier load conditions. Shunt reactors are generally gapped-core reactors and, sometimes, air-cored.

Shunt capacitors are used to increase the power-transfer capacity and to compensate for the reactive-voltage drop in the line. The application of shunt capacitors requires careful system design. The circuit breakers connecting shunt capacitors should withstand high-charging in-rush currents and also, upon dis- connection, should withstand more than 2-pu voltages, because the capacitors are then left charged for a significant period until they are discharged through a large time-constant discharge circuit. Also, the addition of shunt capacitors creates higher-frequency–resonant circuits and can therefore lead to harmonic over voltages on some system buses.

1.5 .2 *Series Compensation*

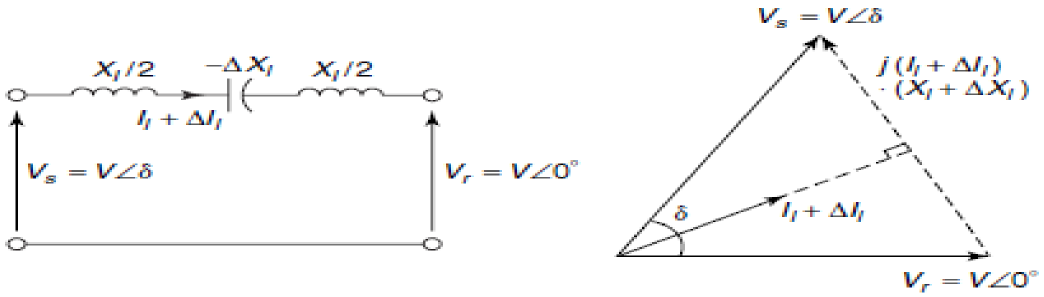


Figure 1.5 The series compensation of a short, symmetrical transmission line.

Series capacitors are used to partially offset the effects of the series induc- tances of lines. Series compensation results in the improvement of the maximum power-transmission capacity of the line. The net effect is a lower load angle for a given power-transmission level and, therefore, a higher-stability margin. The reactive-power absorption of a line depends on the transmission current, so when series capacitors are employed, automatically the resulting reactive-power compensation is adjusted proportionately. Also, because the series compensation effectively reduces the overall line reactance, it is expected that the net line-voltage drop would become less susceptible to the loading conditions.

In an interconnected network of power lines that provides several parallel paths, for power flow between two locations, it is the series compensation of a selected line that makes it the principal power carrier. Series compensation is defined by the degree of compensation; for example, a 1-pu compensation means that the effective series reactance of a line will be zero. A practical upper limit of series compensation, on the other hand, may be as high as 0.75 pu.

One impact of the passive compensation of lines is that whereas the shunt-inductive compensation makes the line electrically resonant at a super- synchronous frequency, the series compensation makes the line resonant at a sub synchronous frequency. The sub synchronous resonance (SSR) can lead to problematic situations for steam turbine–driven generators connected to a series-compensated transmission line. These generators employ multiple tur- bines connected on a common shaft with the generator. This arrangement constitutes an elastically coupled multi mass mechanical system that exhibits several modes of low-frequency torsional resonances, none of which should be excited as a result of the sub synchronous-resonant electrical transmission system.

The application of series compensation requires several other careful considerations. The application of series capacitors in a long line constitutes placing a lumped impedance at a point. Therefore, the following factors need careful evaluation:

1. The voltage magnitude across the capacitor banks (insulation);
2. The fault currents at the terminals of a capacitor bank;
3. The placement of shunt reactors in relation to the series capacitors (resonant over voltages); and
4. The number of capacitor banks and their location on a long line (voltage profile).

1.6 SYNCHRONOUS CONDENSER

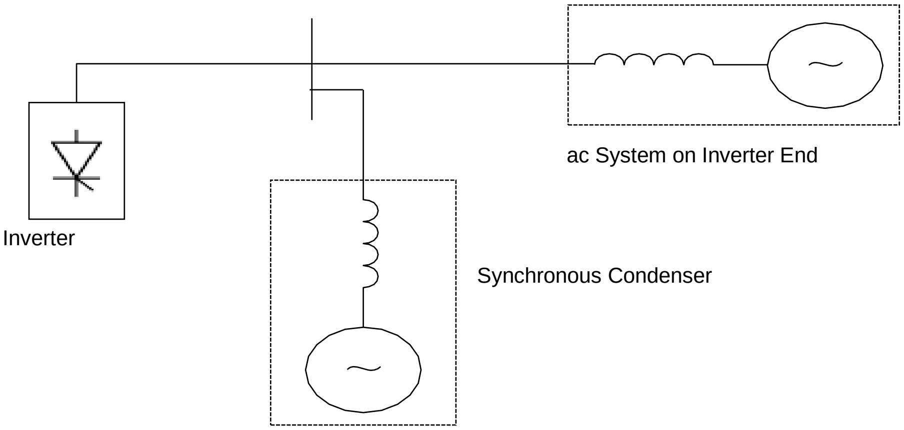


Figure 1.6 An equivalent circuit of a synchronous condenser connected at the inverter end of a dc link..

A synchronous condenser is a synchronous machine, the reactive-power out- put of which can be continuously controlled by varying its excitation current, as shown by the V-curves and performance characteristics of the machine in Fig. 1.6 & 1.7. When the synchronous machine is connected to the ac system and is under excited, it behaves like an inductor, absorbing reactive power from the ac system. However, when it is overexcited, it functions like a capacitor, inject- ing reactive power into the ac system. The machine is normally excited at the base current when its generated voltage equals the system voltage; it thus floats without exchanging reactive power with the system.

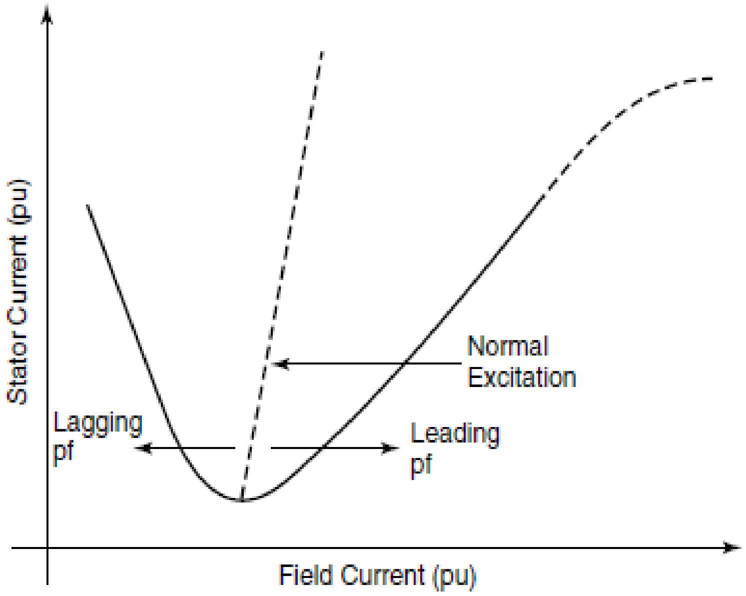


Figure 1.7 The relation between stator current and field current in the synchronous condenser.

The broken-line characteristic curve corresponds to loading beyond the machine’s rated stator current. A synchronous condenser is usually connected to the EHV ac system through a coupling transformer. For voltage-control applications, the desired slope in the steady-state voltage–current characteristics (see Section 5.2) is implemented through the reactance of the coupling transformer. The magnitude of the slope can be adjusted by excitation control.

Large, synchronous condensers are usually hydrogen-cooled. Ratings of up to 345 MVA have been reported in commercial use Various aspects of the design, operation, and starting methods of synchronous compensators are explained in ref.. Synchronous compensators are characterized by relatively slow control responses (100–500 ms) because of their large field-time constants. As they are rotating devices, they require regular maintenance and become more expensive than equivalent-rating static compensators.

1.7 APPLICATIONS

Synchronous condensers are currently used for the following main applications:

1. control of large-voltage excursions, and
2. dynamic reactive-power support at HVDC terminals.

1.7 .1 *Control of Large-Voltage Excursions*

Under sudden terminal- voltage changes, a synchronous condenser's operation switches sequentially to subtransient and transient modes, thus absorbing significant amounts of reactive power. For example, under severe overvoltage conditions, intrinsically a synchronous condenser absorbs a substantial amount of reactive power even when the field current remains unchanged. (In fact, the field control provides a slower follow-up control.) As the thermal time constant of the condenser is usually large, it can be safely overloaded for a short time by field control as well [3]. For example, should the terminal voltage degrade to 0.8 pu, the condenser may be used to supply 1.5-pu reactive power for about one minute to correct the voltage decline. The extent of capacitive overloading depends on the margin of the exciter-ceiling voltage.

1.7 .2 *Dynamic Reactive-Power Support at HVDC Terminals*

Synchronous condensers are connected at the inverter end of an HVDC line to provide the controllable part of the reactive-power requirement of the inverter station and also to help regulate the inverter ac voltage by increasing the short- circuit capacity of the ac system. More simply stated, a synchronous condenser can be modeled as a controlled voltage source behind a reactance, as shown in Fig.1.6. When it is viewed from the inverter terminals, the synchronous condenser reactance appears in parallel with the equivalent reactance of the ac system. The HVDC links are often connected to weak ac systems at the receiving end, which are susceptible to commutation failure if adequate control measures are not taken. Hence the compensation of ac system strength becomes an important consideration for utilities to adopt synchronous condensers instead of the much faster-acting SVCs, which do not contribute to the ac system fault level

1.8 SATURATED REACTOR

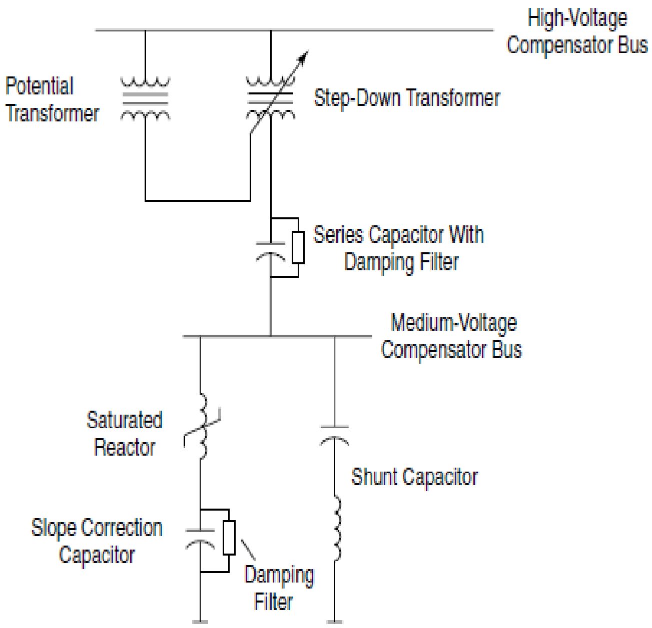


Figure 1.8 An SR compensator

The Saturated Reactor Provides the control of Reactive Power, Whereas the capacitor gives rise the leading power factor range. The SR Compensator has inherent voltage control capability. It directly responds the variation in the voltage terminal. It does not use any thyristor switches for voltage regulation. In EHV application (> 132 KV) SR compensator are connected to the transmission system buses by coupling Transformer.

The effective reactance corresponding to the slope of saturation characteristics of SR vary from 8 – 15 % on its own rating. Which will be occur residual inductance. For voltage regulation this slope has to reduced to 3 – 5 % . Therefore, a slope correction capacitor is installed in series with SR. To prevent the occurrence of sub harmonic oscillations, form the slope correction capacitor, a damping filter is provided across the slope correction capacitor. A capacitor with filter is installed in series with the coupling transformer to improve the voltage regulation at HV bus. The shunt capacitor extends the range of continuously controllable VAR to leading the power factor range.

The connection of the shunt capacitor extends the range of continuously controllable vars to the leading power-factor range. The biasing shunt capacitor is equipped with small tuning inductors to provide filtering of the remnant harmonics generated by the SR. These inductors are designed to preclude the possibility of resonance with system impedance. The voltage reference, or knee point, of the V-I characteristic can be varied by adjusting the taps of the cou- pling transformer.

Because of its iron core, the SR compensator possesses an inherent current- overloading capability of 3–4 pu, which makes it very suitable for controlling temporary overvoltages. The overloading capability of the SR may become restricted from the slope-correcting capacitors, although it may, however, be restored by bypassing the slope-correcting capacitors with the use of spark gaps during severe overvoltage conditions, albeit at the expense of voltage regula- tion.

The SR in the absence of slope-correcting capacitor is the fastest of all com- mercially available SVCs. The slope-correcting capacitors reduce the response time to about one-and-a-half to two cycles, which is comparable to a thyristor- controlled reactor (TCR). The SR is more lossy (0.7–1% of its MVA rating) compared to TCR. Its high magnetostrictive noise usually forces its installa- tion in thick enclosures. The SR is a very reliable device, except for spark-gap protection and load tap-changer components, and it is generally employed for

1. the control of large-voltage excursions,
2. the alleviation of voltage flicker, and
3. the reactive compensation at a HVDC terminal.

The SR compensators are not amenable to external controls, which deprives the SR of its capability to introduce the much-needed damping in the ac system for stability enhancement. Commercial sizes of the SR compensator extend up to 270 MVAR.

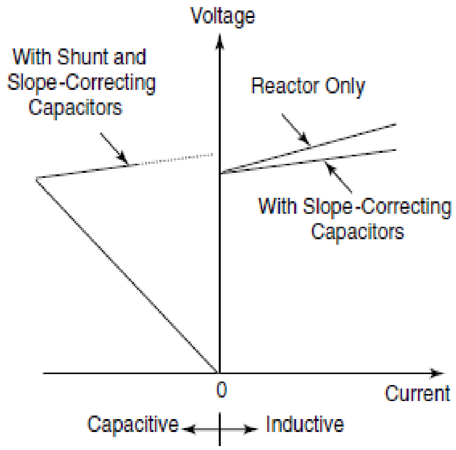


Figure 1.9 The operating characteristics of an SR compensator

The SR compensator has an inherent voltage-control capability. It directly responds to the variations in terminal voltage and does not use any thyristor switches or external control for voltage regulation. In EHV applications (usu- ally those above 132 kV), SR compensators are connected to transmission-sys- tem buses by means of a coupling transformer. A typical SR compensator is depicted in Fig. 3.4; its steady-state V-I characteristic is illustrated in Fig. 3.5. The effective reactance corresponding to the slope of saturation characteristic of the SR varies from 8 to 15% on its own rating, which is attributed to the residual inductance of saturated iron. For voltage regulation, however, this slope needs to be reduced to 3–5%. Because of the expense in achieving this slope reduction by improved reactor design, a slope-correcting capacitor is installed in series with a saturated reactor. To prevent the occurrence of subharmonic oscillations from the interaction of the slope-correcting capacitor, the saturated reactor, and the network reactance—especially in weak ac systems—invariably a damping filter is provided across the slope-correcting capacitor. Occasionally, a capacitor with an associated filter may be installed in series with the coupling transformer to offset its reactance and, consequently, improve the voltage regulation at the HV bus.

1.9 CLASSIFICATION OF FACTS CONTROLLER

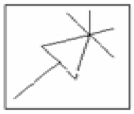
In general FACTS controllers can be classified into four categories.

Series controllers - TCSC , SSSC

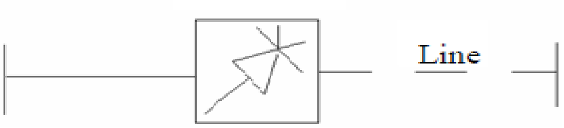
Shunt controllers – SVC, STATCOM

Combined series-series controllers - IPFC

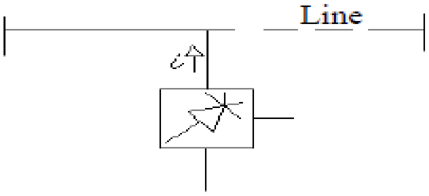
Combined series-shunt controllers - UPFC



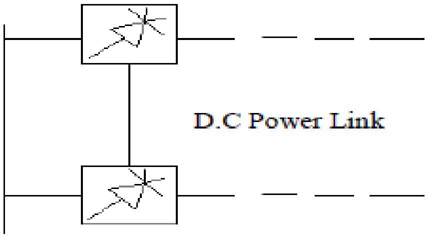
(a) General symbol of FACTS controller



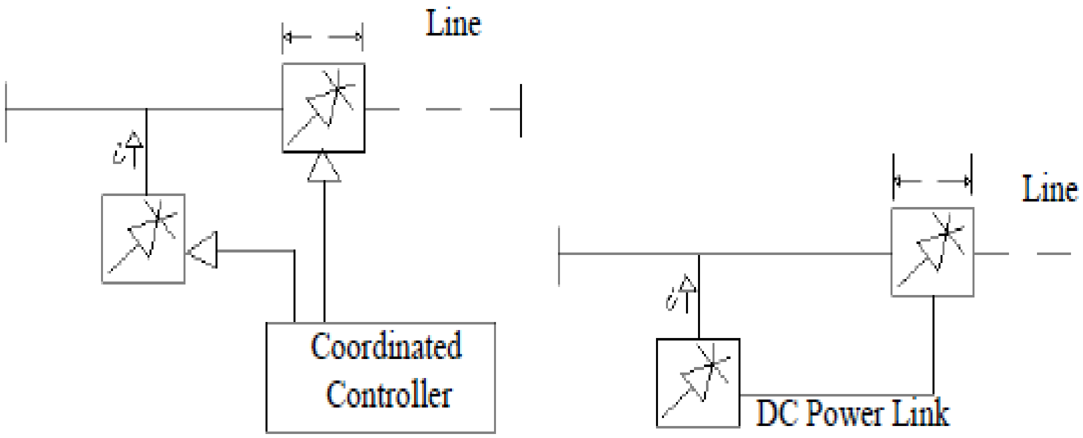
(b) Series controller



(c) Shunt controller



(d) Unified Series controller



(e)

(f) Unified Series shunt controller

Figure 1.10 Classification of FACTS controller

References

[1] R.Mohan Mathur and Rajiv K. Varma "Thyristor based FACTS controllers for electrical transmission systems", IEEE Press John Wiley & Sons Inc. Publication, 2002

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UNIT - II

Flexible AC Transmission System – SEE1601

II. Shunt Compensation

Thyristor Controlled Reactor (TCR) – Thyristor Switched Reactor (TSR) – Thyristor Switched Capacitor (TSC) – Fixed Capacitor- Thyristor Controlled Reactor (FC-TCR) – Thyristor Switched Capacitor-Thyristor Controlled Reactor (TSC -TCR) – V-I Characteristics of Static Var Compensator (SVC) – Advantages of slope in dynamic Characteristic – Voltage control by SVC.

1.1 THYRISTOR CONTROLLED REACTOR (TCR)

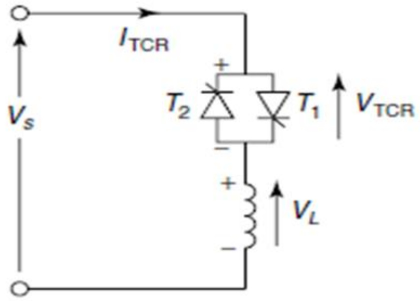


Figure 2.1 A TCR

A basic single-phase TCR comprises an anti-parallel–connected pair of thyristor valves, T1 and T2, in series with a linear air-core reactor, as illustrated in Fig.2.1. The anti-parallel–connected thyristor pair acts like a bidirectional switch, with thyristor valve T1 conducting in positive half-cycles and thyristor valve T2 conducting in negative half-cycles of the supply voltage. The firing angle of the thyristors is measured from the zero crossing of the voltage appearing across its terminals.

The controllable range of the TCR firing angle, a, extends from 90 to 180 . A firing angle of 90 results in full thyristor conduction with a continuous sinu- soidal current flow in the TCR. As the firing angle is varied from 90 to close to 180 , the current flows in the form of discontinuous pulses symmetrically located in the positive and negative half-cycles, as displayed in Fig. 3.7. Once the thyristor valves are fired, the cessation of current occurs at its natural zero crossing, a process known as the line commutation. The current reduces to zero for a firing angle of 180 . Thyristor firing at angles below 90 introduces dc components in the current, disturbing the symmetrical operation of the two antiparallel valve branches. A characteristic of the line-commutation process with which the TCR operates is that once the valve conduction has commenced, any change in the firing angle can only be implemented in the next half-cycle, leading to the so-called thyristor deadtime.

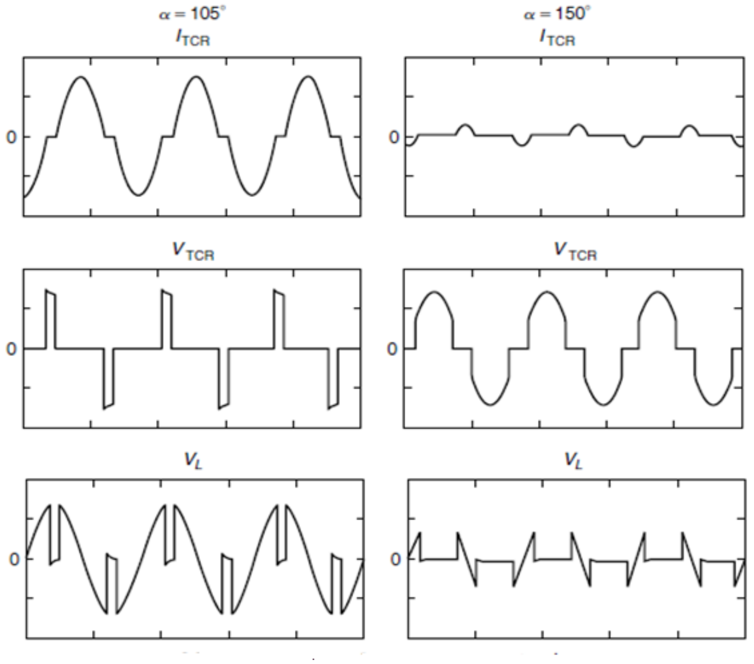


Figure 2.2 Current and voltages for different a in a TCR

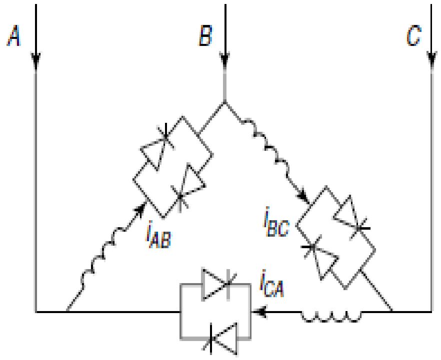


Figure 2.3 A 3 phase TCR

A 3-phase, 6-pulse TCR comprises three single-phase TCRs connected in delta, as shown in Fig. 2.3. The inductor in each phase is split into two halves, as shown in Fig. 2.3, one on each side of the anti-parallel–connected thyristor pair, to prevent the full ac voltage appearing across the thyristor valves and damaging them if a short-circuit fault occurs across the reactor's two end ter- minals. The phase- and line-current waveforms are also displayed in Fig. 2.4. If the 3-phase supply voltages are balanced, if the three reactor units are identical, and also if all the thyristors are fired symmetrically—with equal firing angles in each phase—then the symmetric current pulses result in both positive and negative half-cycles and the generating of only odd harmonics. The per- centage values of harmonic currents with respect to fundamental—both in the phases and in the lines—are the same.

The delta connection of the three single-phase TCRs prevents the triplen (i.e., multiples of third) harmonics from percolating into the transmission lines. The cancellation of its 3rd and multiple harmonics can be explained as follows: Let iABn, iBCn, and iCAn be the nth-order harmonic-phase currents in the respective delta branches, and let iAn, iBn, and iCn be the currents in the respective lines connected to the delta-configured TCR.

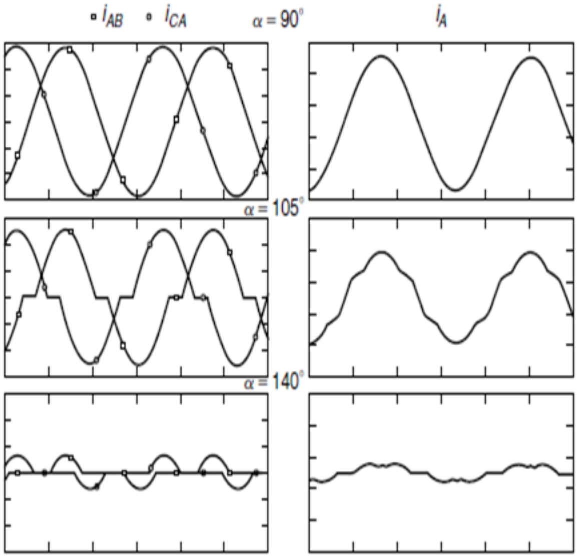


Figure 2.4 A delta-connected TCR and its phase and line currents for different a.

1.2 THYRISTOR SWITCHED REACTOR (TSR)

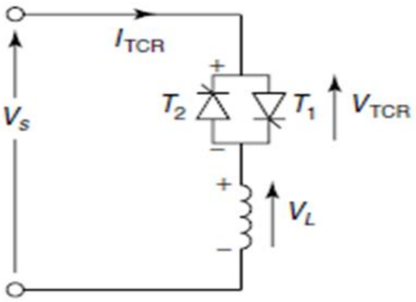


Figure 2.5 A TCR

1.3 THYRISTOR SWITCHED CAPACITOR (TSC)

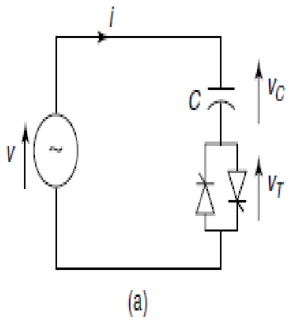


Figure 2.6 Switching of a capacitor at a voltage source of a circuit diagram

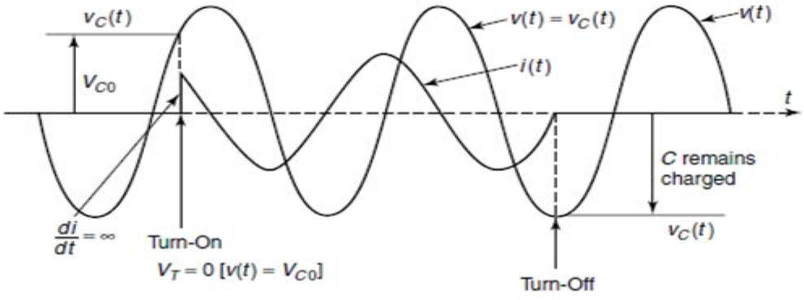


Figure 2.7 current and voltage waveforms

The circuit shown in Fig. 2.6 consists of a capacitor in series with a bidirec- tional thyristor switch. It is supplied from an ideal ac voltage source with nei- ther resistance nor reactance present in the circuit. The analysis of the current transients after closing the switch brings forth two cases:

1. The capacitor voltage is not equal to the supply voltage when the thyris- tors are fired. Immediately after closing the switch, a current of infinite magnitude flows and charges the capacitor to the supply voltage in an infinitely short time. The switch realized by thyristors cannot withstand this stress and would fail.
2. The capacitor voltage is equal to the supply voltage when the thyristors are fired, as illustrated in Fig. 3.26(b). The analysis shows that the current will jump immediately to the

value of the steady-state current. The steady- state condition is reached in an infinitely short time. Although the magni- tude of the current does not exceed the steady-state values, the thyristors have an upper limit of di□ dt values that they can withstand during the firing process. Here, di□ dt is infinite, and the thyristor switch will again fail.

1.4 FIXED CAPACITOR- THYRISTOR CONTROLLED REACTOR (FC-TCR)

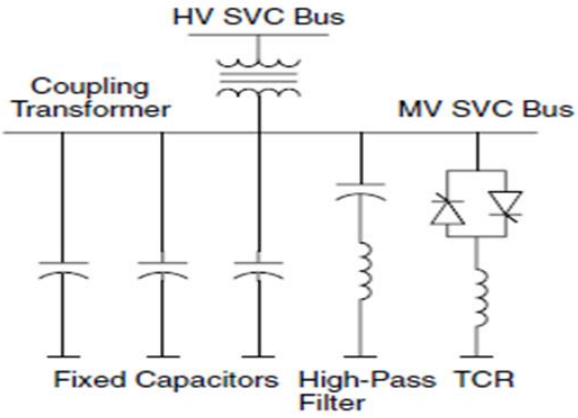
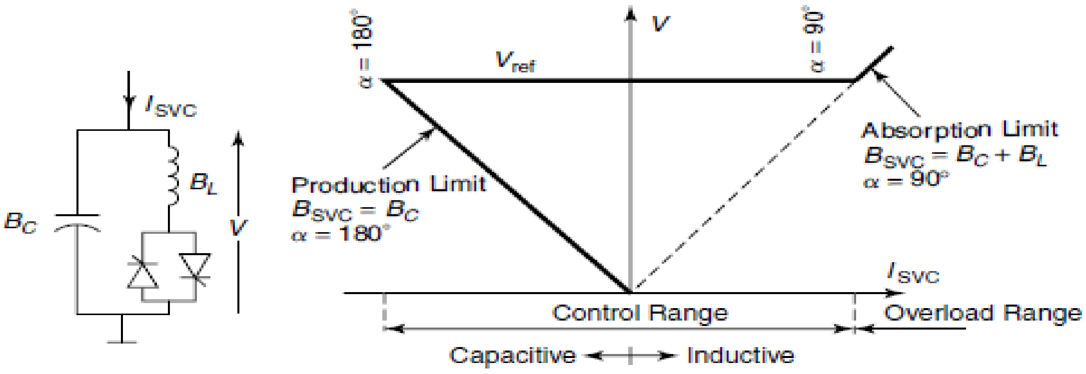


Figure 2.8 An FC–TCR SVC

Without Step down Transformer



(a) (b)

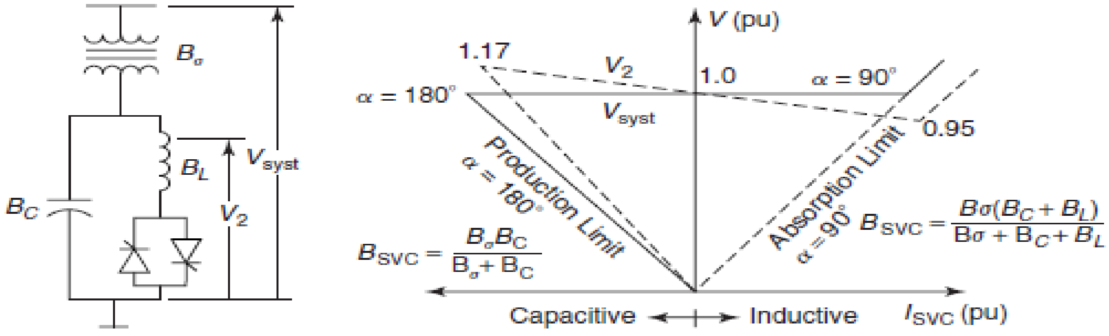
The SVC current, I_{SVC}, can be expressed as a function of system voltage, V, and compensator susceptance, B_{SVC}, as follows:

$$\overline{I}_{SVC} = \overline{V} j B_{SVC}$$

where

$$B_{SVC} = B_C + B_{TCR} \quad \text{and} \quad B_C = \omega C$$

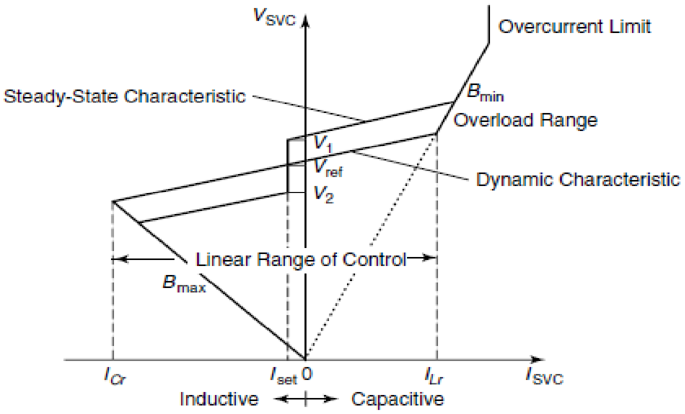
With Step down Transformer



(a) (b)

Figure 3.22 An FC–TCR with a step-down transformer and its V-I characteristics.

V-Characteristics of Static VAR Compensator (SVC)



(a)

Advantages of slope in dynamic Characteristic.

Although the SVC is a controller for voltage regulation, that is, for maintaining constant voltage at a bus, a finite slope is incorporated in the SVC's dynamic characteristic and provides the following advantages despite a slight deregula- tion of the bus voltage. The

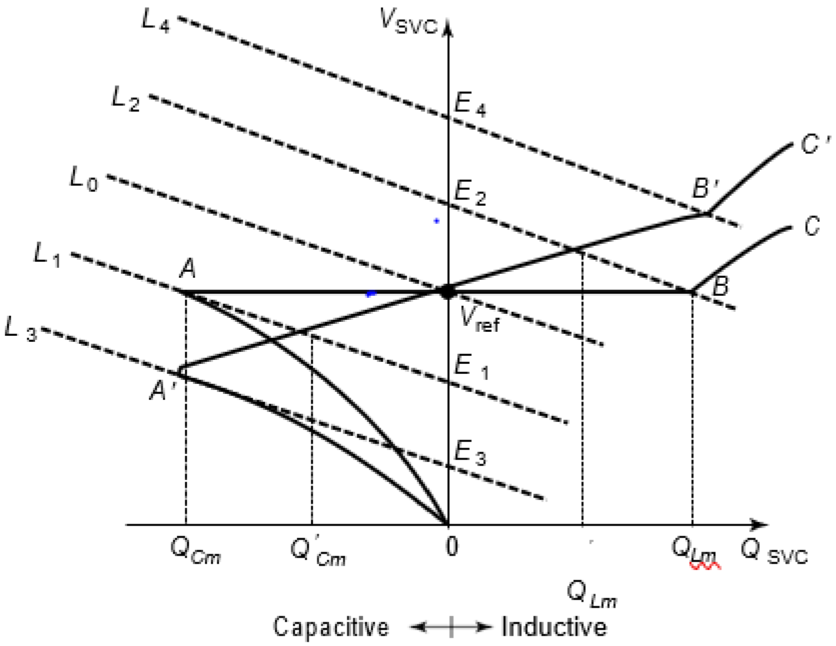
SVC slope

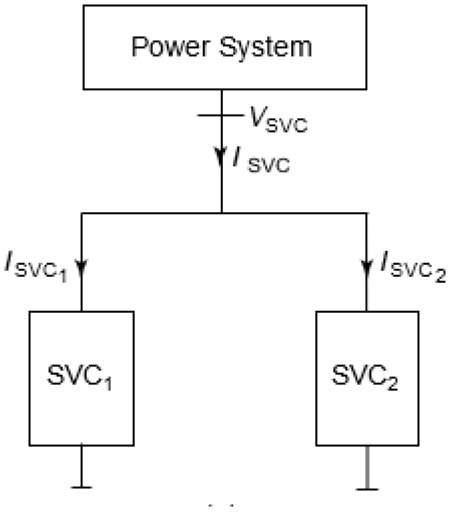
1. substantially reduces the reactive-power rating of the SVC for achieving nearly the same control objectives;
2. prevents the SVC from reaching its reactive-power limits too frequently; and
3. facilitates the sharing of reactive power among multiple compensators operating in parallel.

5.1.1.1 Reduction of the SVC Rating Figure 5.3 illustrates two dynamic *V-I* characteristics of an SVC. Characteristic $OA\square B\square C\square$ incorporates a finite slope, whereas characteristic *OABC* does not. The slope has been deliberately exaggerated to demonstrate its effect. Assuming that the system load line varies between L_1 and L_2, the reactive-power rating of the SVC needed for providing flat voltage regulation is Q_{Cm} capacitive to Q_{Lm} inductive, as determined from the characteristic *OABC*. However, if a small deregulation in the SVC bus volt- age is considered acceptable (as demonstrated by the characteristic $OA\square B\square C\square$), the maximum reactive-power rating of the SVC required for performing the voltage control corresponding to the same variation in the system load line is $Q\square_{Cm}$ capacitive to $Q\square_{Lm}$ inductive. Evidently, $Q\square_{Cm} \square Q_{Cm}$ and $Q\square_{Lm} \square Q_{Lm}$. Thus a much lower SVC reactive-power rating and, hence, a much lower cost is required for nearly the same control objective.

Load Sharing Between Parallel-Connected SVCs For reliabil- ity via redundancy, and also for minimizing the net harmonic generation, it is not uncommon to divide the net-required SVC range into several equal-sized compensators. When more than one compensator is used at one location, the control action must be coordinated. This section discusses such coordination

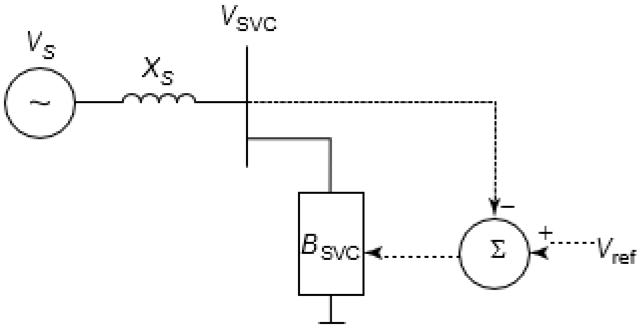
Consider two SVCs, SVC_1 and SVC_2, connected at a system bus as depicted in Fig. 5.4(a). The two SVCs have the same ratings but the reference voltages, V_{ref}, of the two control characteristics differ by a small amount, □. In practice,
□ is small, although it is not zero. Two cases are examined: one in which both the SVCs have a zero slope, as shown in Fig. 5.4(b), and the other in which the two SVCs have a finite slope, as illustrated in Fig. 5.4(c). The composite *V-I* control characteristic of the two SVCs is derived by summing up the individual currents of both SVCs for the same bus-voltage magnitude—procedure that is repeated over the entire range of SVC bus voltage. The composite characteristic is indicated by the thicker line.


L 4
V SVC
L 2
E 4
C ′
L 0
E 2
B′
C
L 1
A
B
L 3
V ref
E 1
A′
E 3
Q Cm
Q′ Cm
0
Q Lm
Q SVC
Q Lm
Capacitive
Inductive


Power System
V SVC
I SVC
I SVC1
I SVC2
SVC1
SVC2

Voltage Control by the SVC

The voltage-control action of the SVC can be explained through a simplified block representation of the SVC and power system, as shown in Fig. 5.2. The power system is modeled as an equivalent voltage source, V_s, behind an equiv- alent system impedance, X_s, as viewed from the SVC terminals. The system impedance X_s indeed corresponds to the short-circuit MVA at the SVC bus



References

[1] R.Mohan Mathur and Rajiv K. Varma “Thyristor based FACTS controllers for electrical transmission systems”, IEEE Press John Wiley & Sons Inc. Publication, 2002