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SCHOOL OF ELECTRICAL AND ELECTRONICS ENGINEERING

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT - I

Flexible AC Transmission System – SEEA3004

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

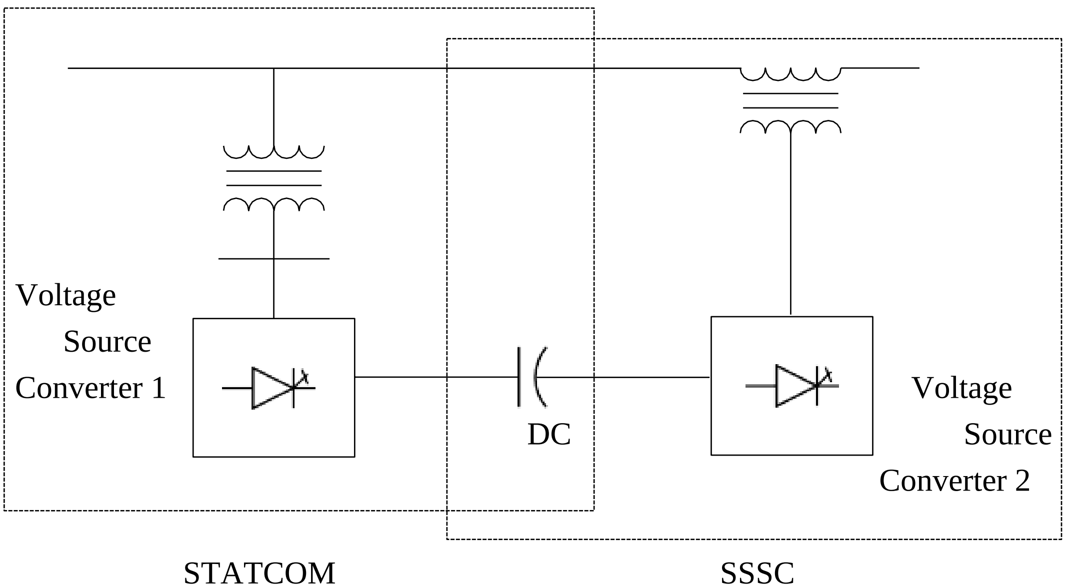


Figure 1.1 A 1-line diagram of a unified power-flow controller (UPFC).

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 opportunity-ties. 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.

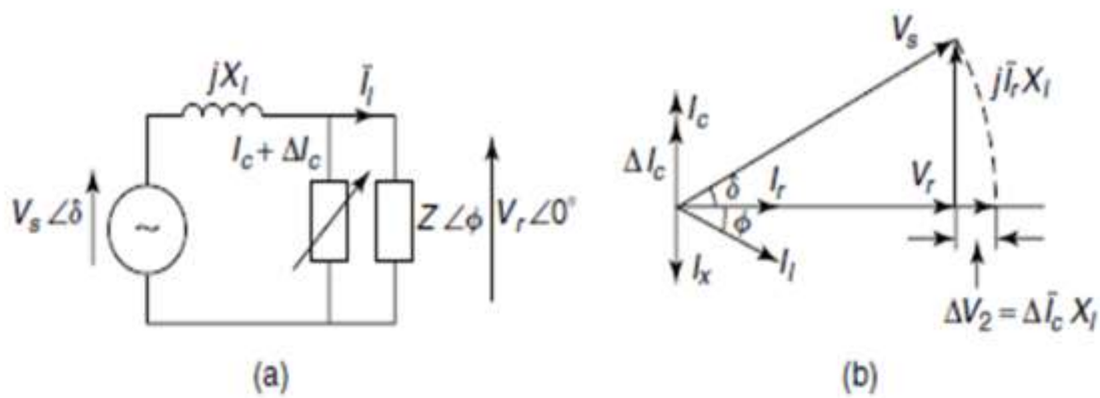


Figure 1.2 A short, lossless transmission line feeding a load.

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*

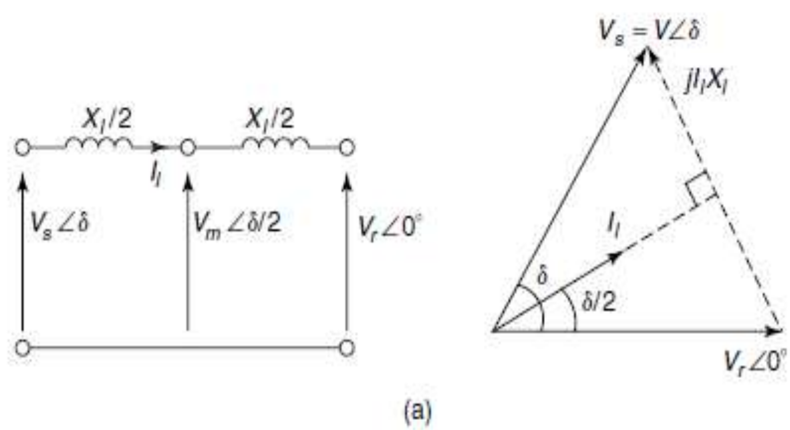


Figure 1.3 A short transmission line without compensation

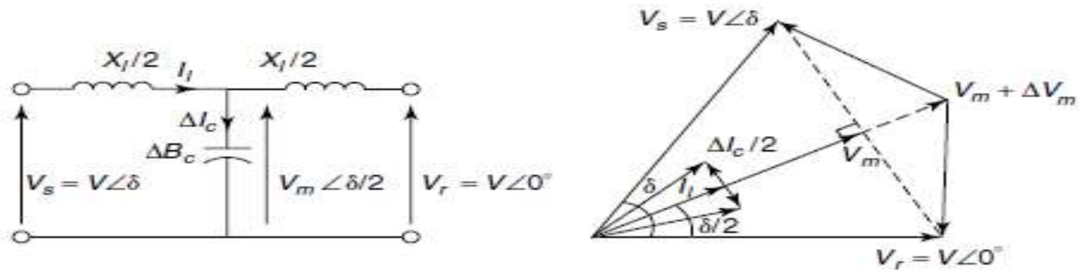


Figure 1.4 The midpoint-capacitor compensation of a short, symmetrical line.

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*

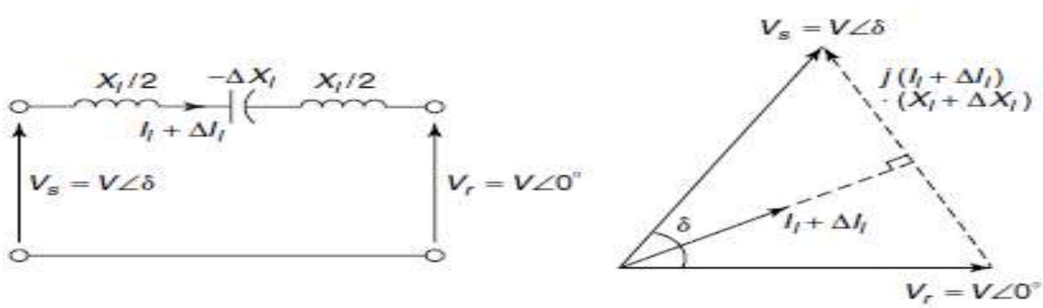


Figure 1.5 The series compensation of a short, symmetrical transmission line.

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 con- stitutes 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

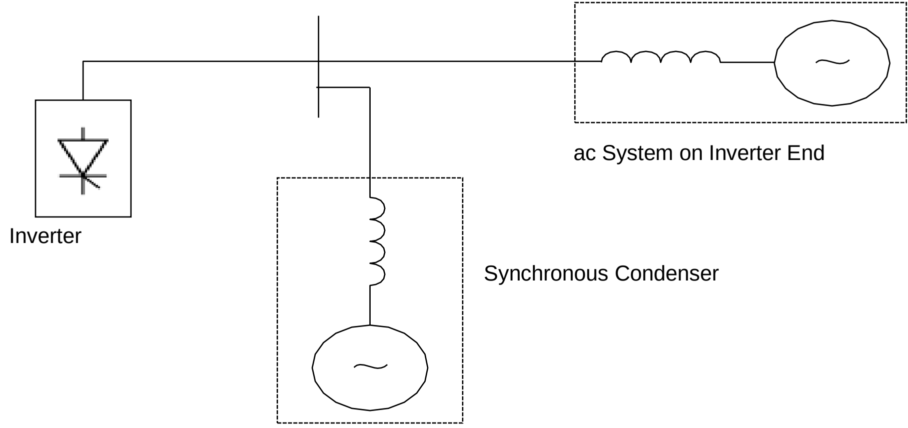


Figure 1.6 An equivalent circuit of a synchronous condenser connected at the inverter end of a dc link..

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.

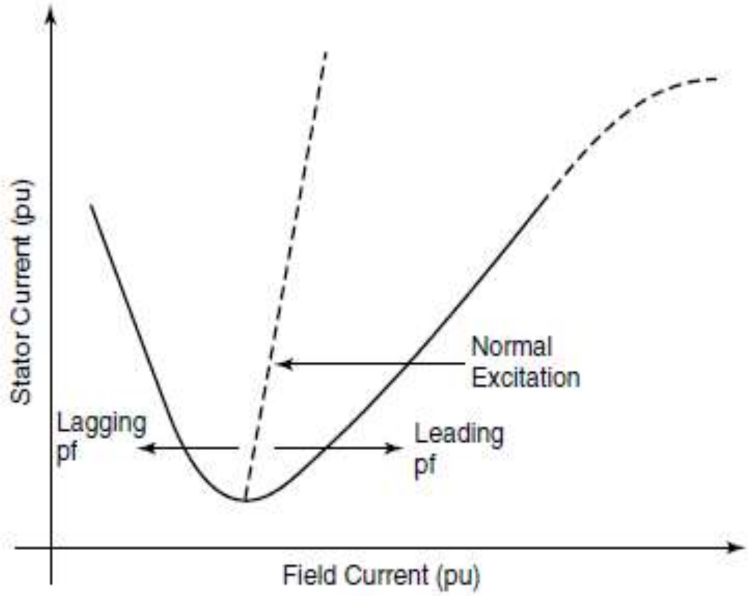


Figure 1.7 The relation between stator current and field current in the synchronous condenser.

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 reac- tive 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 con- denser 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

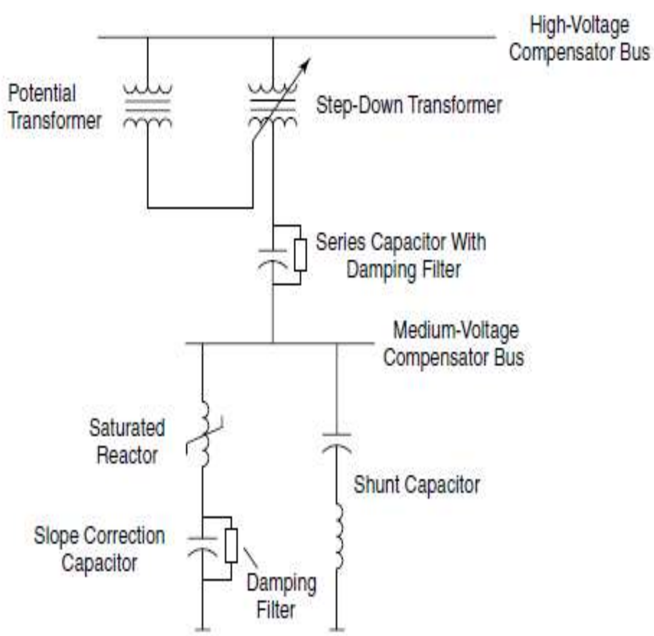


Figure 1.8 An SR compensator

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.

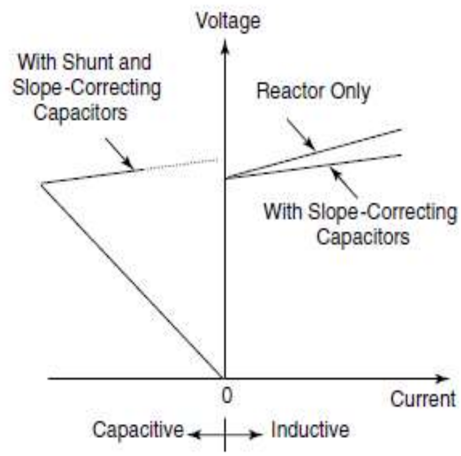


Figure 1.9 The operating characteristics of an SR compensator

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 reg- ulation at the HV bus.

1.9 CLASSIFICATION OF FACTS CONTROLLER

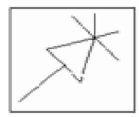
In general FACTS controllers can be classified into four categories.

Series controllers - TCSC , SSSC

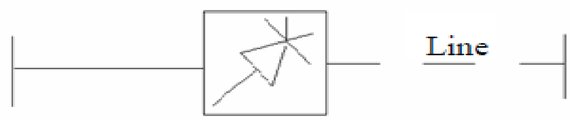
Shunt controllers – SVC, STATCOM

Combined series-series controllers - IPFC

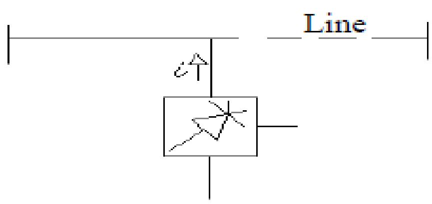
Combined series-shunt controllers - UPFC



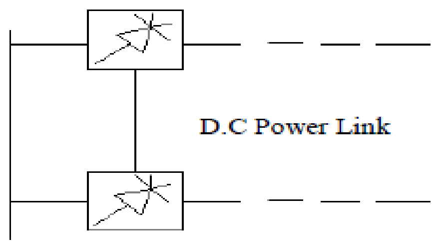
(a) General symbol of FACTS controller



(b) Series controller



(c) Shunt controller



(d) Unified Series controller

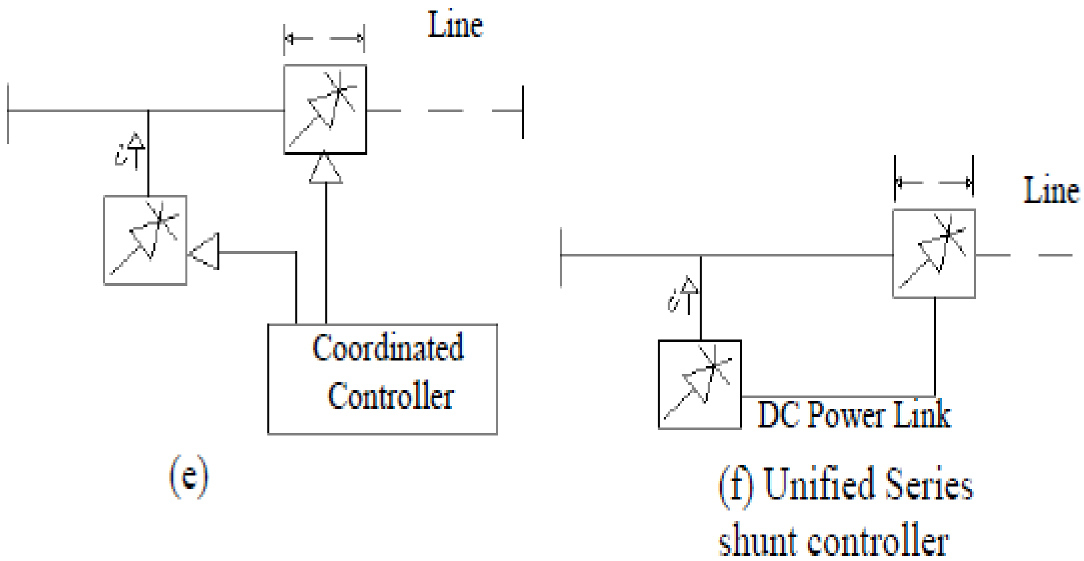


Figure 1.10 Classification of FACTS controller

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

S. No.	Question	Course Outcomes (Level)
	UNIT – I **Part – A**	
1.	Write the limits on loading capability of a Transmission system?	**CO1(2)**
2.	Classify the different types of FACTS controller.	**CO1(2)**
3.	List out the merits of FACTS Devices.	**CO1(4)**
4.	Define Reactive power.	**CO1(2)**
5.	List out the power electronics devices used in FACTS	**CO1(4)**
6.	Examine the necessity of compensation in Transmission line.	**CO1(4)**
7.	Justify how is reactive power controlled in the electrical network?	**CO1(5)**
8.	Interpret the term Saturated Reactor.	**CO1(5)**
9.	Why series compensation is advantage over shunt compensation?	**CO1(2)**
10.	List out the applications of synchronous condenser.	**CO1(4)**
	Part – B	
1.	(a) Explain the objectives of FACTS controllers in the power system network. (b) Describe the procedure to locate the FACTS devices in an electrical network.	**CO1(5)**
2.	Explain the load and system compensation.	**CO1(5)**
3.	Derive an Expression for midpoint voltage equation in the transmission line.	**CO1(4)**
4.	Briefly explain the concept of synchronous condenser with neat diagram.	**CO1(4)**
5.	Explain the configuration and operating characteristics of Saturated Reactor with neat diagram.	**CO1(5)**
6.	With a neat schematic diagram, explain the various basic types of FACTS controllers in detail.	**CO1(5)**

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UNIT - II

Flexible AC Transmission System – SEEA3004

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)

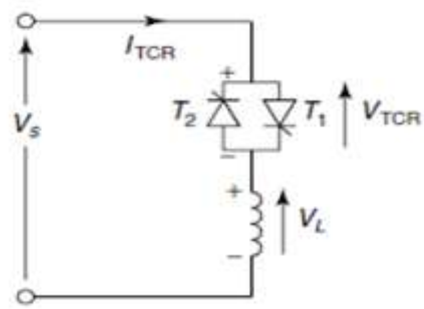


Figure 2.1 A TCR

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.

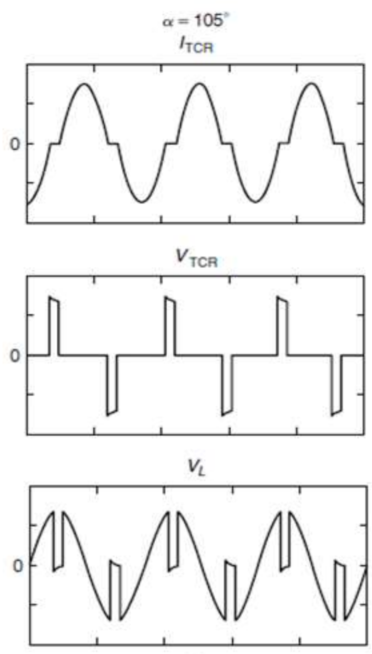


Figure 2.2 Current and voltages for different a in a TCR

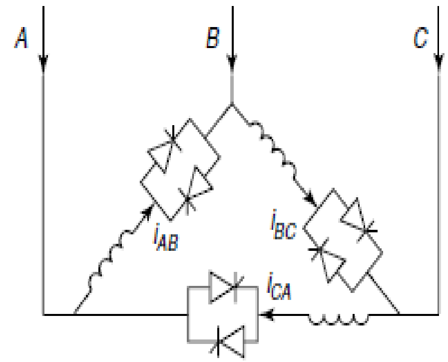


Figure 2.3 A 3 phase TCR

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 iden- tical, 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.

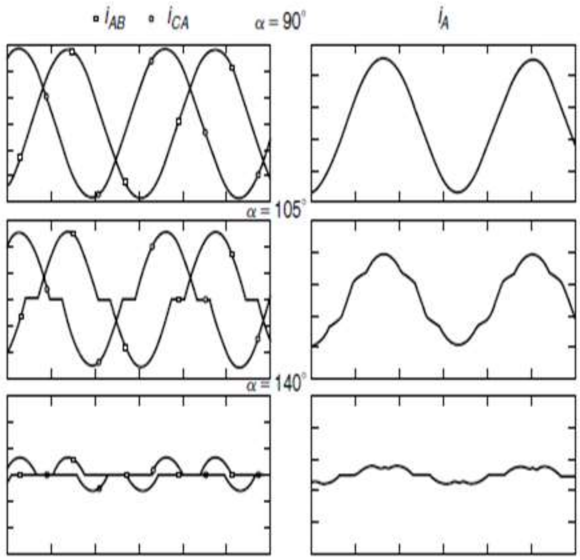


Figure 2.4 A delta-connected TCR and its phase and line currents for different a.

1.2 THYRISTOR SWITCHED REACTOR (TSR)

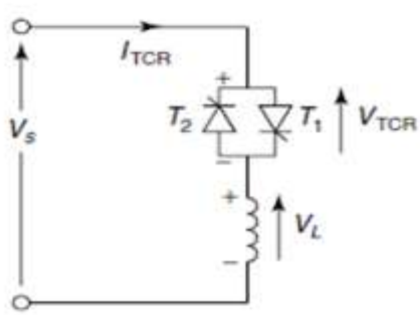


Figure 2.5 A TCR

1.3 THYRISTOR SWITCHED CAPACITOR (TSC)

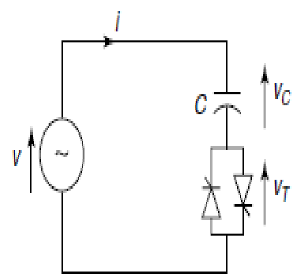


Figure 2.6 Switching of a capacitor at a voltage source of a circuit diagram

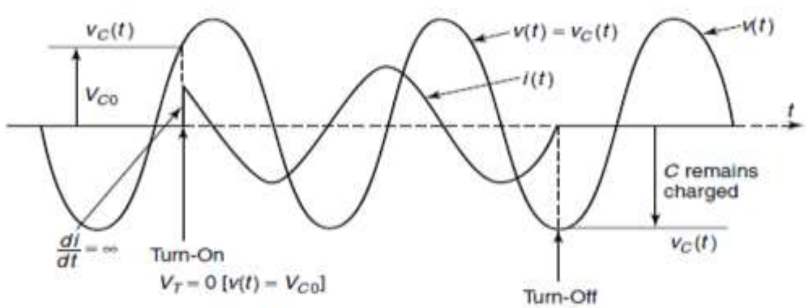


Figure 2.7 current and voltage waveforms

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)

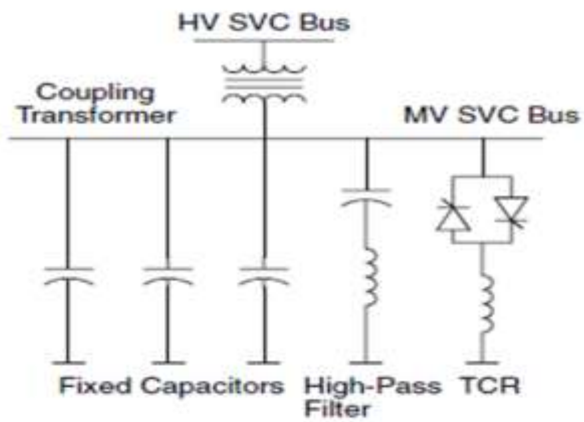
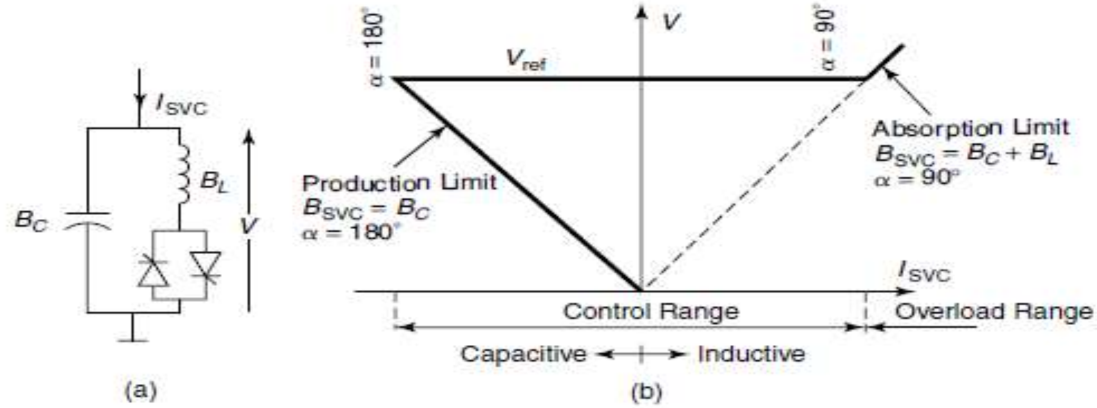


Figure 2.8 An FC–TCR SVC

Without Step down Transformer



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

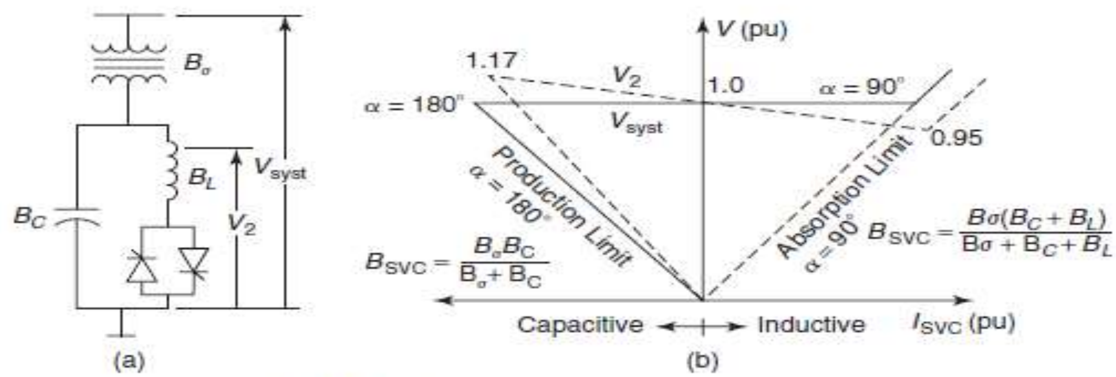
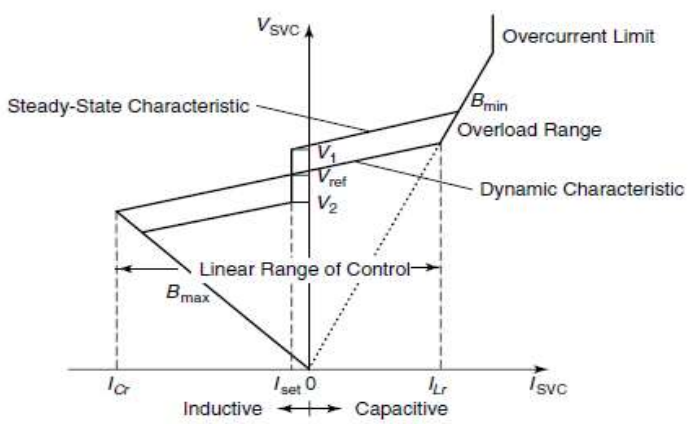


Figure 3.22 An FC–TCR with a step-down transformer and its V-I characteristics.

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

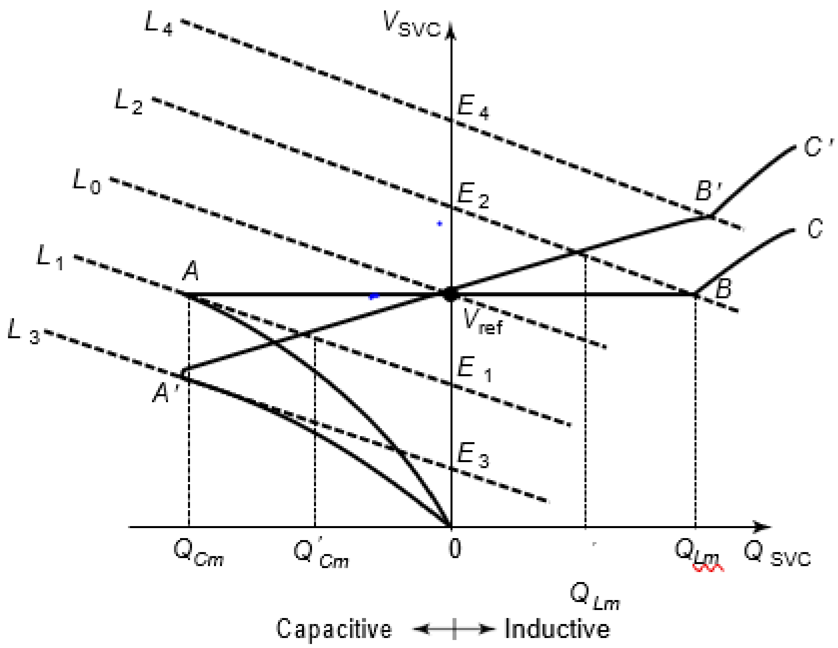
SVC slope

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.

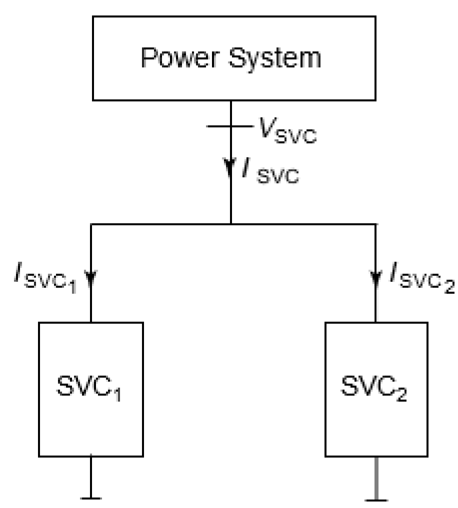
5.1.1.1 ***Reduction of the SVC Rating*** Figure 5.3 illustrates two dynamic *V-I* characteristics of an SVC. Characteristic $OA\square B\square C\square$ incorporates a finite slope, whereas characteristic *OABC* does not. The slope has been deliberately exaggerated to demonstrate its effect. Assuming 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.



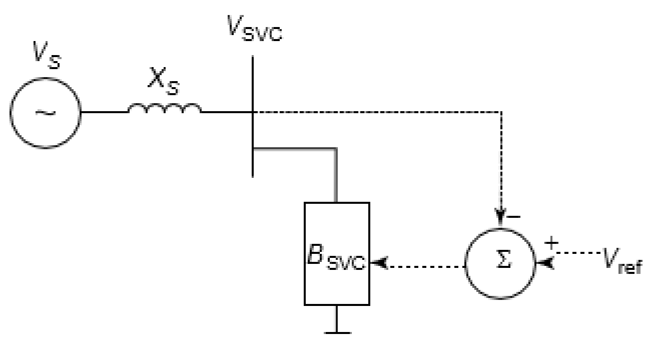
L 4
V SVC
E 4
L 2
E 2
C′
L 0
B′
C
L 1
A
B
V ref
L 3
E 1
A′
E 3
Q Cm
Q′ Cm
0
Q Lm
Q SVC
Q Lm
Capacitive
Inductive



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

S. No.	Question	Course Outcomes (Level)
	UNIT – II **Part – A**	
1.	What is firing angle limit of TCR?	**CO2(2)**
2.	Discuss TSC configuration and its operating characteristic	**CO2(2)**
3.	Write a short note on TSR	**CO2(2)**
4.	Construct the schematic diagram of Static Var Compensator	**CO2(6)**
5.	List out the applications of SVC	**CO2(4)**
6.	What is the best location of SVC? Justify.	**CO2(5)**
7.	Differentiate TCR and TSR.	**CO2(3)**
8.	Construct the V-I characteristics SVC	**CO2 (6)**
9.	Interpret the term Static VAR Compensators	**CO2 (5)**
	Part – B	
1.	Discuss the construction & operating principle of TCR with neat diagram	**CO2(4)**
2.	Explain the operating characteristic of Thyristor Switched Capacitor and its practical switching strategies	**CO2(5)**
3.	Explain the configuration and operating characteristic of fixed capacitor - thyristor controlled reactor (FC – TCR)	**CO2(5)**
4.	Explain the VI Characteristic of SVC in dynamic Characteristic and steady state Characteristic.	**CO2(5)**
5.	Elaborate the advantages of slope in the dynamic characteristics of SVC with neat diagrams?	**CO2(6)**
6.	Explain TSC – TCR compensator with its operating characteristic with neat diagram.	**CO2(5)**

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UNIT - III

Flexible AC Transmission System – SEEA3004

III. THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC)

Fixed Series Compensation – Need for Variable Series Compensation – TCSC: Basic principle – Modes of Operation – Advantages – Capability Characteristic – Variable Reactance Model – Application: Open loop & Closed loop Control

3.1 Fixed Series Compensation

Series capacitors offer certain major advantages over their shunt counterparts. With series capacitors, the reactive power increases as the square of line current, whereas with shunt capacitors, the reactive power is generated proportional to the square of bus voltage. For achieving the same system benefits as those of series capacitors, shunt capacitors that are three to six times more reactive- power–rated than series capacitors need to be employed. Furthermore, shunt capacitors typically must be connected at the line midpoint, whereas no such requirement exists for series capacitors.

3.2 Need for Variable Series Compensation

Compensation of transmission lines by series capacitors is likely to result in the following [4]:

1. enhanced base-power flow and loadability of the series-compensated line;
2. additional losses in the compensated line from the enhanced power flow; and
3. increased responsiveness of power flow in the series-compensated line from the outage of other lines in the system.

3.3 Advantages of TCSC

1. Rapid, continuous control of the transmission-line series-compensation level.
2. Dynamic control of power flow in selected transmission lines within the network to enable optimal power-flow conditions and prevent the loop flow of power.
3. Damping of the power swings from local and inter-area oscillations.
4. Suppression of subsynchronous oscillations. At subsynchronous frequen- cies, the

TCSC presents an inherently resistive–inductive reactance. The subsynchronous oscillations cannot be sustained in this situation and con- sequently get damped.

5. Decreasing dc-offset voltages. The dc-offset voltages, invariably resulting from the insertion of series capacitors, can be made to decay very quickly (within a few cycles) from the firing control of the TCSC thyristors.
6. Enhanced level of protection for series capacitors. A fast bypass of the series capacitors can be achieved through thyristor control when large overvoltages develop across capacitors following faults. Likewise, the capacitors can be quickly reinserted by thyristor action after fault clearing to aid in system stabilization.
7. Voltage support. The TCSC, in conjunction with series capacitors, can generate reactive power that increases with line loading, thereby aiding the regulation of local network voltages and, in addition, the alleviation of any voltage instability.
8. Reduction of the short-circuit current. During events of high short-cir- cuit current, the TCSC can switch from the controllable-capacitance to the controllable-inductance mode, thereby restricting the short-circuit cur- rents.

3.4 TCSC CONTROLLER

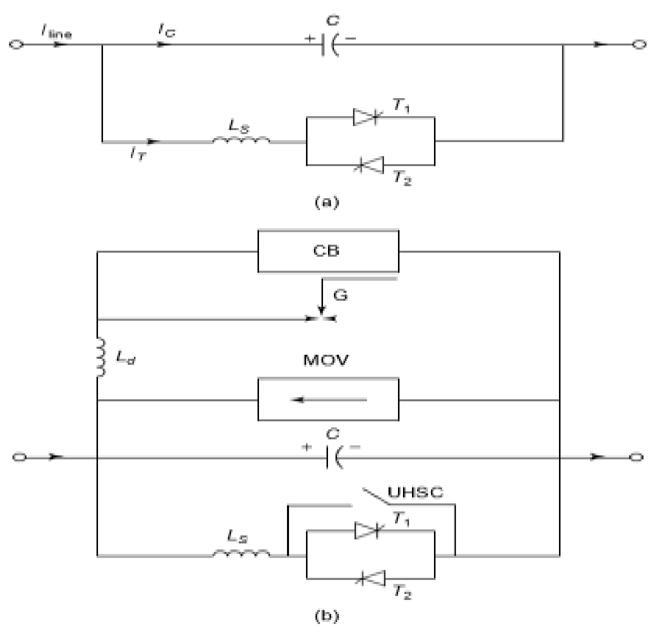

Figure 3.1 A TCSC module: (a) a basic module and (b) a practical module

The basic conceptual TCSC module comprises a series capacitor, *C*, in paral- lel with a thyristor-controlled reactor, L_S, as shown in Fig. However, a practical TCSC module also includes protective equipment normally installed with series capacitors, as shown in Fig.

A metal-oxide varistor (MOV), essentially a nonlinear resistor, is connected across the series capacitor to prevent the occurrence of high-capacitor over- voltages. Not only does the MOV limit the voltage across the capacitor, but it allows the capacitor to remain in circuit even during fault conditions and helps improve the transient stability.

Also installed across the capacitor is a circuit breaker, CB, for controlling its insertion in the line. In addition, the CB bypasses the capacitor if severe fault or equipment-malfunction events occur. A current-limiting inductor, Ld , is incorporated in the circuit to restrict both the magnitude and the frequency of the capacitor current during the capacitor-bypass operation.

If the TCSC valves are required to operate in the fully "on" mode for prolonged durations, the conduction losses are minimized by installing an ultra–high-speed contact (UHSC) across the valve. This metallic contact offers a virtually lossless feature similar to that of circuit breakers and is capable of han- dling many switching operations. The metallic contact is closed shortly after the thyristor valve is turned on, and it is opened shortly before the valve is turned off. During a sudden overload of the valve, and also during fault conditions, the metallic contact is closed to alleviate the stress on the valve.

3.5 MODES OF OPERATION

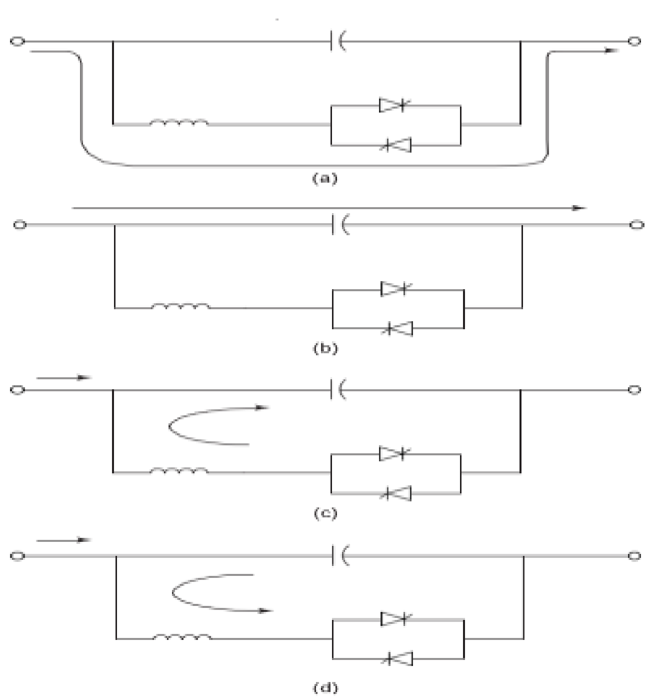

Figure 3.2 Different operating modes of a TCSC: (a) the bypassed-thyristor mode; (b) the blocked-thyristor mode; (c) the partially conducting thyristor (capacitive-vernier)

mode; and (d) the partially conducting thyristor (inductive-vernier) mode.

Bypassed-Thyristor Mode

In this bypassed mode, the thyristors are made to fully conduct with a conduction angle of 180 . Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous sinusoidal of flow current through the thyris- tor valves. The TCSC module behaves like a parallel capacitor–inductor com- bination. However, the net current through the module is inductive, for the sus- ceptance of the reactor is chosen to be greater than that of the capacitor.

Also known as the thyristor-switched-reactor (TSR) mode, the bypassed- thyristor mode is distinct from the bypassed-breaker mode, in which the circuit breaker provided across the series capacitor is closed to remove the capacitor or the TCSC module in the event of TCSC faults or transient overvoltages across the TCSC.

This mode is employed for control purposes and also for initiating certain protective functions. Whenever a TCSC module is bypassed from the violation of the current limit, a finite-time delay, Tdelay, must elapse before the module can be reinserted after the line current falls below the specified limit.

Blocked-Thyristor Mode

In this mode, also known as the wait- ing mode, the firing pulses to the thyristor valves are blocked. If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing. The TCSC module is thus reduced to a fixed-series capacitor, and the net TCSC reactance is capac- itive. In this mode, the dc-offset voltages of the capacitors are monitored and quickly discharged using a dc-offset control [9] without causing any harm to the transmission-system transformers.

Partially Conducting Thyristor, or Vernier, Mode

This mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. It is achieved by varying the thyristor-pair firing angle in an appropriate range. However, a smooth transition from the capacitive to inductive mode is not permitted because of the resonant region between the two modes.

A variant of this mode is the capacitive-vernier-control mode, in which the thyristors are fired when the capacitor voltage and capacitor current have opposite polarity. (Refer to Fig. 7.8, to be discussed later.) This condition causes a TCR current that has a direction opposite that of the capacitor current, thereby resulting in a loop-current flow in the TCSC controller. The loop current increases the voltage across the FC, effectively enhancing the equivalent-capac- itive reactance and the series-compensation level for the same value of line cur- rent. To preclude resonance, the firing angle a of the forward-facing thyristor, as measured from the positive reaching a zero crossing of the capacitor voltage, is constrained in the range amin □ a □ 180 . This constraint provides a continuous vernier control of the TCSC module reactance. The loop current increases as a is decreased from 1808 to amin. The maximum TCSC reactance permissible with a amin is typically two-and-a-half to three times the capacitor reactance at fundamental frequency.

3.6 Capability Characteristic

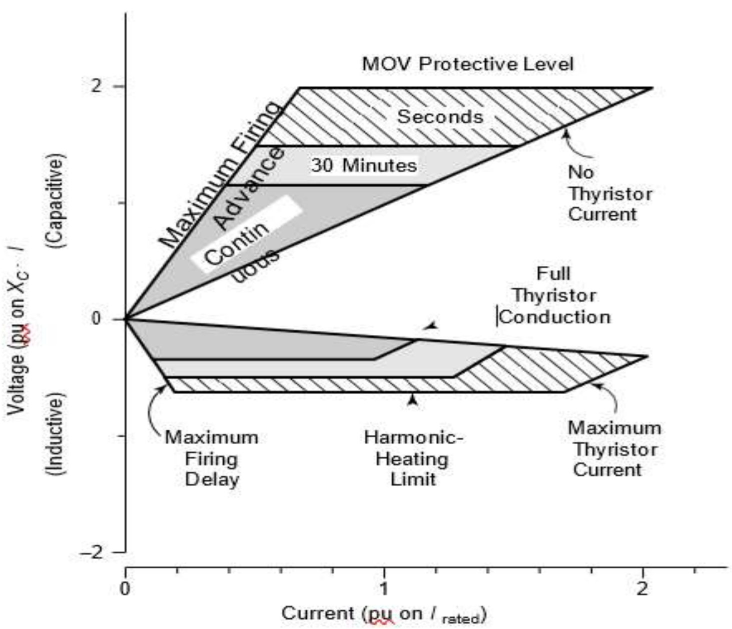

Figure 3.3 The V-I capability characteristics for a single-module TCSC

3.7 Variable Reactance Model

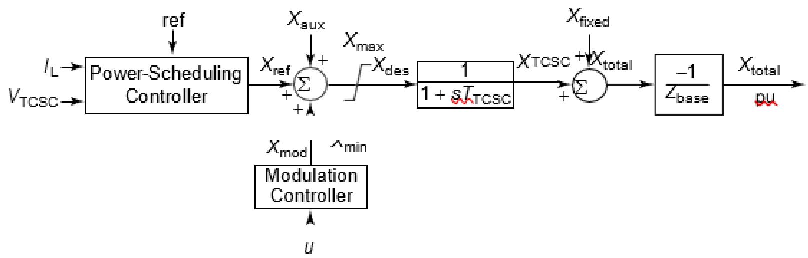

Figure 3.4 A block diagram of the variable-reactance model of the TCSC

A TCSC model for transient- and oscillatory-stability studies, used widely for its simplicity, is the variable-reactance model depicted in Fig.. In this quasi-static approximation model, the TCSC dynamics during power-swing frequencies are modelled by a variable reactance at fundamental frequency. The other dynamics of the TCSC model—the variation of the TCSC response with different firing angles, for example—are neglected.

It is assumed that the transmission system operates in a sinusoidal steady state, with the only dynamics associated with generators and PSS. This assump- tion is valid, because the line dynamics are much faster than the generator dynamics in the frequency range of 0.1–2 Hz that are associated with angular- stability studies.

3.8 Applications of TCSC

Constant-Current (CC) Control

In the constant-current (CC) control, the desired line-current magnitude is fed as a reference signal to the TCSC controller, which strives to maintain the actual line current at this value. A typical TCSC CC-controller model [2] is depicted in Fig. 8.2. The 3-phase current is measured and rectified in the measurement unit. The rectified signal is passed through a filter block that comprises a 60-Hz and a 120-Hz notch filter as well as a high-pass filter. The emanating signal is then normalized to ensure per-unit consistency with the reference-current signal.

The controller is typically of the proportional–integral (PI) type that outputs the desired susceptance signal within the preset limits, as discussed. A linearizer block converts the susceptance signal into a firing-angle signal.

An operation-mode selector unit is generally used for TCSC protection. During short-circuit conditions, at which time the current through the metal- oxide varistor (MOV) exceeds a threshold, the TCSC is made to switch to the bypassed-thyristor mode or the thyristor-switched reactor (TSR) mode. In this mode, the thyristors conduct fully (j c 1808), reducing both the TCSC volt- age and the current substantially and thereby reducing the stress on the MOV. During the clearance of faults, the “waiting mode” is implemented; when the capacitors are brought back into the circuit, a dc-voltage offset builds up that is discharged into this waiting mode.

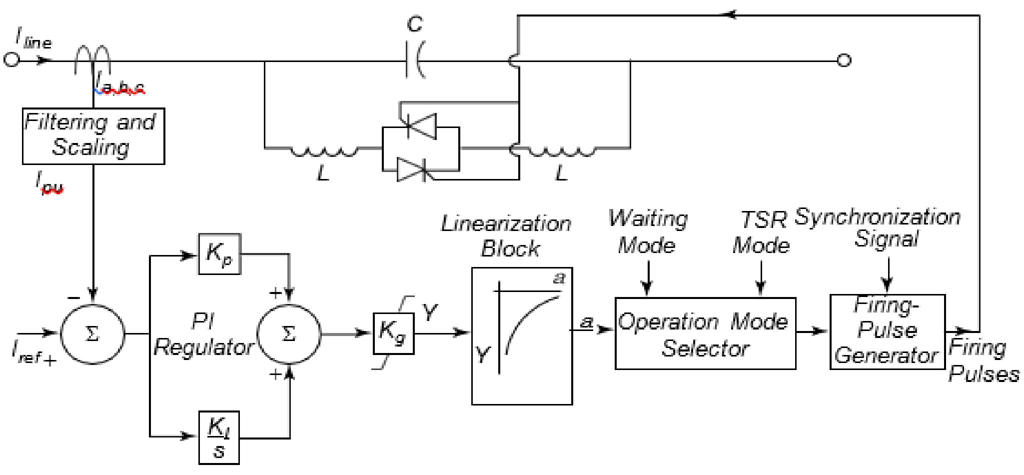

Figure 3.5 A TCSC constant-current (CC) controller model

Enhanced Current Control

To improve the damping of certain oscillatory modes, such as subsynchronous oscillations, an optimized, derivative line-current feedback is embedded in the TCSC controller, as depicted in Fig. In this control system, the volt- age regulator is a simple PI controller slightly different from the one depicted in Fig.The optimized current controller is shown to successfully damp sub- synchronous oscillations for all levels of line-series compensation, unlike a conventional controller, which provides very low damping to an SSR mode.

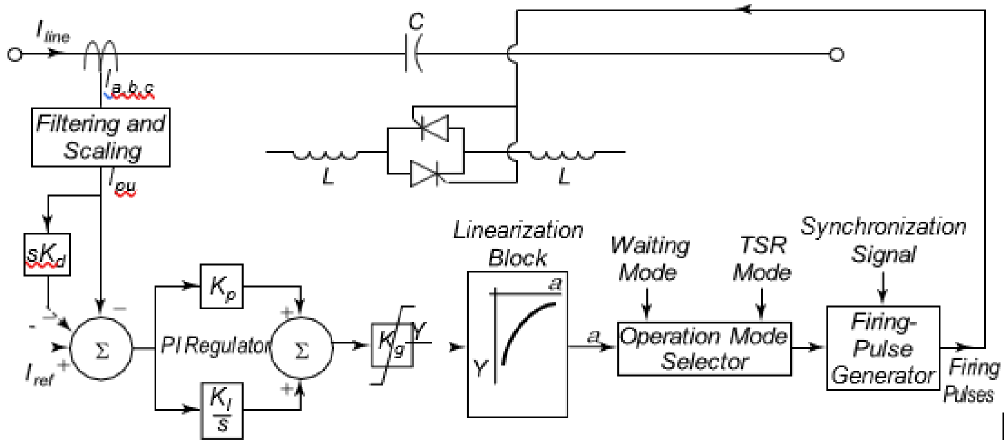

Figure 3.6 An optimized TCSC CC structure.

Constant Power Control

The block diagram of a typical TCSC power controller is depicted in Fig. The line power flow is computed from the measured local voltage and current signals after the *abc*–*ab*0 transformation. The calculated power signal is converted into a per-unit quantity and filtered, then fed to the summing junction of the power controller. The reference signal, P_{ref}, denotes the desired level of real-power flow in the TCSC-compensated line, and the power controller has a PI structure. The remaining control-system components were described previously

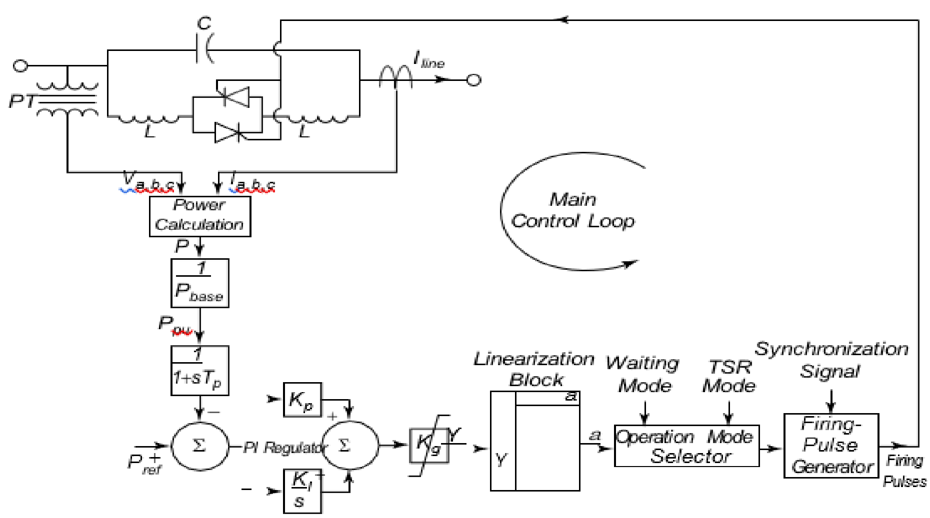

Figure 3.7 A conventional TCSC power-control structure

Enhanced Power Control

The need to keep TCSC power controllers slow is potentially detrimental to the power system, as it extends the post–fault system recovery period. A much- improved TCSC power controller that combines the beneficial influences of both power control and current control is depicted in Fig. 8.8 [2], [6]. It con- sists of two control loops—a fast, inner-current control loop and a slow, outer- power control loop. The power controller provides the current-reference signal for the current controller. Such a controller allows a fast TCSC response to sys- tem faults, yet it also allows a desired slow response to the electromechanical oscillations.

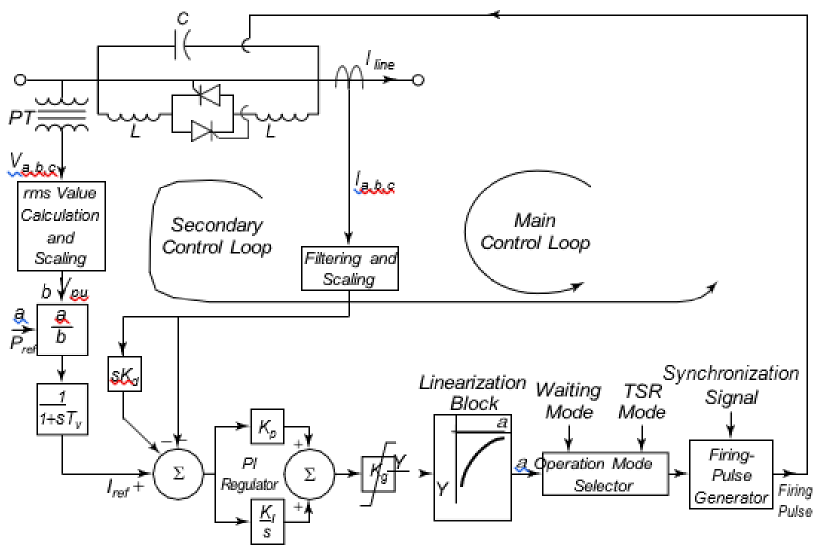

Figure 3.8 A Enhanced TCSC power-control structure

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

S. No.	Question	Course Outcomes (Level)
	UNIT – III **Part – A**	
1.	Define fixed series compensation.	**CO3(1)**
2.	Construct the basic module of TCSC.	**CO3(6)**
3.	Categorize the different modes of operation in TCSC	**CO3(4)**
4.	List out the advantages of TCSC.	**CO3(4)**
5.	Explain the need for variable series compensation.	**CO3(5)**
6.	Construct the VI capability characteristics for a single module TCSC.	**CO3(6)**
7.	Classify the closed loop control in TCSC applications.	**CO3(3)**
	Part – B	
1.	With neat block diagram explain the construction and working principle of TCSC controller.	**CO3(5)**
2.	Explain the different modes of operation of TCSC with neat diagrams.	**CO3(5)**
3.	Explain the capability characteristics of TCSC with neat graphs.	**CO3(5)**
4.	Elaborate the variable reactance model of TCSC with neat diagram.	**CO3(6)**
5.	Explain the different types of closed loop control of TCSC with neat diagram.	**CO3(5)**
6.	Explain the following closed loop control of TCSC with neat diagram (i) Constant current control (ii) Constant Angle control (iii) Enhanced power control.	**CO3(5)**
7.	Elaborate the function of enhanced constant power control in TCSC closed loop application with neat diagram	**CO3 (6)**
8.	Elaborate the function of enhanced constant current control in TCSC closed loop application with neat diagram	**CO3 (6)**

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UNIT - IV

Flexible AC Transmission System – SEEA3004

IV. EMERGING FACTS CONTROLLER

Static Synchronous Compensator (STATCOM): Introduction – Principle of Operation – V-I Characteristic. Multilevel VSC based STATCOM. SSSC: Principle of Operation. Unified Power Flow Controller (UPFC): Principle of Operation. Interline Power Flow Controller (IPFC): Principle of Operation.

4.1 Static Synchronous Compensator (STATCOM):

The STATCOM (or SSC) is a shunt-connected reactive-power compensation device that is capable of generating and or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. It is in general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. Specifically, the STATCOM considered in this chapter is a voltage-source converter that, from a given input of dc voltage, produces a set of 3-phase ac-output voltages, each in phase with and coupled to the cor- responding ac system voltage through a relatively small reactance (which is provided by either an interface reactor or the leakage inductance of a coupling transformer). The dc voltage is provided by an energy-storage capacitor.

A STATCOM can improve power-system performance in such areas as the following:

1. The dynamic voltage control in transmission and distribution systems;
2. the power-oscillation damping in power-transmission systems;
3. the transient stability;
4. the voltage flicker control; and
5. the control of not only reactive power but also (if needed) active power in the connected line, requiring a dc energy source.

Furthermore, a STATCOM does the following:

1. it occupies a small footprint, for it replaces passive banks of circuit ele- ments by compact electronic converters;
2. it offers modular, factory-built equipment, thereby reducing site work and commissioning time; and
3. it uses encapsulated electronic converters, thereby minimizing its envi- ronmental impact.

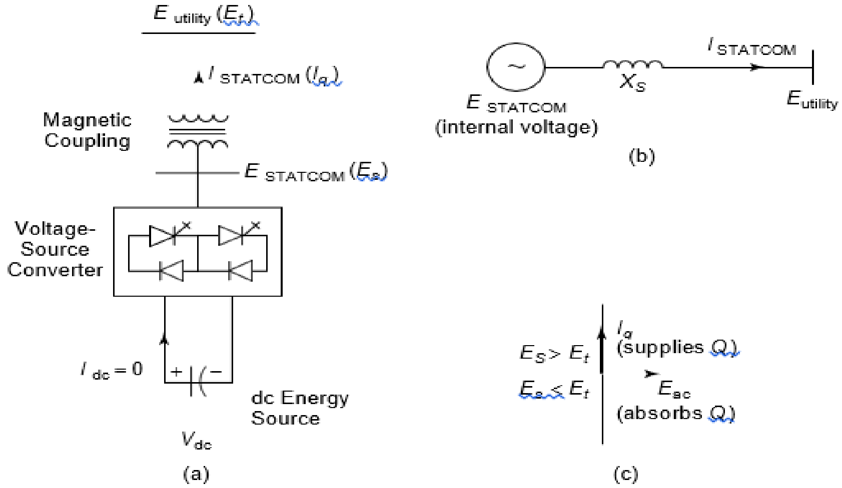

Figure 4.1 The STATCOM principle diagram: (a) a power circuit; (b) an equivalent circuit; and (c) a power exchange

A STATCOM provides the desired reactive power by exchanging the instantaneous reactive power among the phases of the ac system. The mechanism by which the converter internally generates and or absorbs the reactive power can be understood by considering the relationship between the output and input powers of the converter. The converter switches connect the dc-input circuit directly to the ac-output circuit. Thus the net instantaneous power at the ac- output terminals must always be equal to the net instantaneous power at the dc-input terminals (neglecting losses)

4.2 The V-I Characteristic

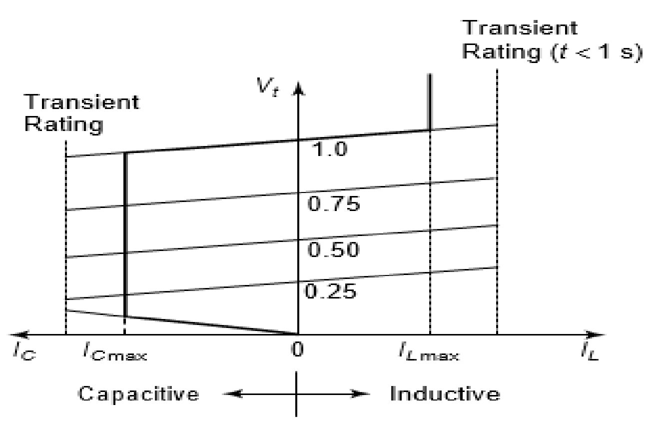

Figure 4.2 V – I Characteristics of STATCOM

A typical *V-I* characteristic of a STATCOM is depicted in Fig.. As can be seen, the STATCOM can supply both the capacitive and the inductive com- pensation and is able to independently control its output current over the rated maximum capacitive or inductive range irrespective of the amount of ac-system voltage. That is, the STATCOM can provide full capacitive-reactive power at any system voltage—even as low as 0.15 pu.

The characteristic of a STATCOM reveals another strength of this technol- ogy: that it is capable of yielding the full output of capacitive generation almost independently of the system voltage (constant-current output at lower voltages). This capability is particularly useful for situations in which the STATCOM is needed to support the system voltage during and after faults where voltage col- lapse would otherwise be a limiting factor.

4.3 THE SSSC

The SSSC, sometimes called the S^3C, is a series-connected synchronous-volt- age source that can vary the effective impedance of a transmission line by inject- ing a voltage containing an appropriate phase angle in relation to the line cur- rent. It has the capability of exchanging both real and reactive power with the transmission system. For instance, if the injected voltage is in phase with the line current, then the voltage would exchange real power. On the other hand, if a voltage is injected in quadrature with the line current, then reactive power—either absorbed or generated—would be exchanged. The SSSC emerges as a potentially more beneficial controller than the TCSC because of its ability to not only modulate the line reactance but also the line resistance in consonance with the power swings, thereby imparting enhanced damping to the generators that contribute to the power oscillations.

The SSSC comprises a multi-phase VSC with a dc-energy storage controller, as shown in Fig. Here, the controller is connected in series with the transmission line. The operating modes of the SSSC are illustrated graphically in Fig.

Principle of operation

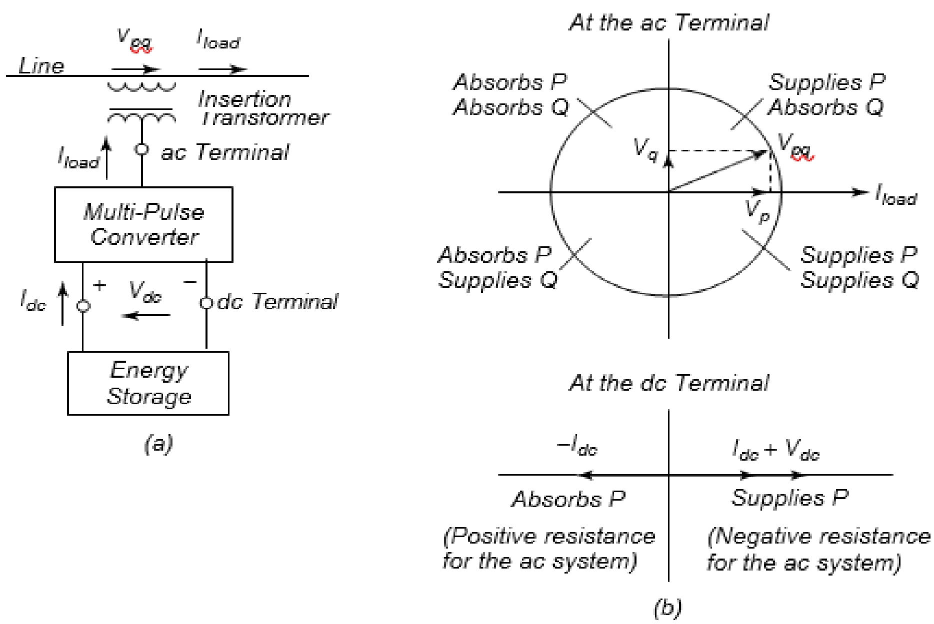

Figure 4.3 (a) Generalized series-connected synchronous-voltage source employing a multi-pulse converter with an energy-storage device; (b) the different operating modes for real- and reactive-power exchange.

A series-compensation scheme using the SSSC is depicted in Fig. 10.19. Normally, the SSSC-output voltage lags behind the line current by 90^8 to provide effective series compensation. In addition, the SSSC can be gated to produce an output voltage that leads the line current by 90^8, which provides additional inductive reactance in the line. This feature can be used for damping power swings and, if the converter has adequate rating, for limiting short-circuit currents.

4.4 THE UPFC

The UPFC is the most versatile FACTS controller developed so far, with all encompassing capabilities of voltage regulation, series compensation, and phase shifting. It can independently and very rapidly control both real- and reactive- power flows in a transmission line [1]–[8], [32]–[47]. It is configured as shown in Fig. 10.25 and comprises two VSCs coupled through a common dc terminal. One VSC—converter 1—is connected in shunt with the line through a coupling transformer; the other VSC—converter 2—is inserted in series with the transmis- sion line through an interface transformer. The dc voltage for both converters is provided by a common capacitor bank. The series converter is controlled to inject a voltage phasor, V_{pq}, in series with the line, which can be varied from 0 to $V_{pq\ \max}$. Moreover, the phase angle of V_{pq} can be independently varied from 0^8 to 360^8. In this process, the series converter exchanges both real and reactive power with the transmission line. Although the reactive power is internally generated□ absorbed by the series converter, the real-power generation□ absorption is made feasible by the dc-energy–storage device—that is, the capacitor.

The shunt-connected converter 1 is used mainly to supply the real-power demand of converter 2, which it derives from the transmission line itself. The shunt converter maintains constant voltage of the dc bus. Thus the net real power drawn from the ac system is equal to the losses of the two converters and their coupling transformers. In addition, the shunt converter functions like a STATCOM and independently regulates the terminal voltage of the intercon-nected bus by generating□ absorbing a requisite amount of reactive power

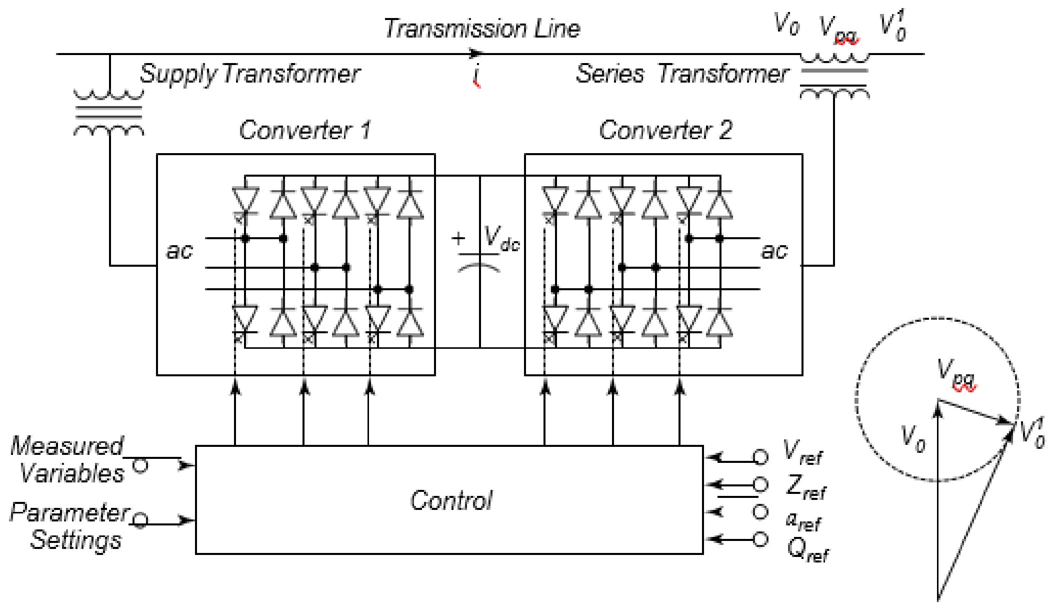

Figure 4.4 The implementation of the UPFC using two "back-to-back" VSCs with a common dc-terminal capacitor.

4.5 INTERLINE POWER FLOW CONTROLLER (IPFC)

In its general form the Interline Power Flow Controller employs a number of dc-to-ac converters each providing series compensation for a different line. In other words, the IPFC comprises a number of Static Synchronous Series Compensators. However, within the general concept of the !PFC, the compensating converters are linked together at their de terminals, as illustrated in Figure With this scheme, in addition to providing series reactive compensation, any converter can be controlled to supply real power to the common de link from its own transmission line. Thus, an overall surplus power can be made available from the under utilized lines which then can be used by other lines for real power compensation. In this way, some of the converters, compensating overloaded lines or lines with a heavy burden of reactive power flow, can be equipped with full two-dimensional, reactive and real power control capability, similar to that offered by the UPFC. Evidently, this arrangement mandates the rigorous maintenance of the overall power balance at the common de terminal by appropriate control action, using the general principle that the underloaded lines are to provide help, in the form of appropriate real power transfer, for the overloaded lines.

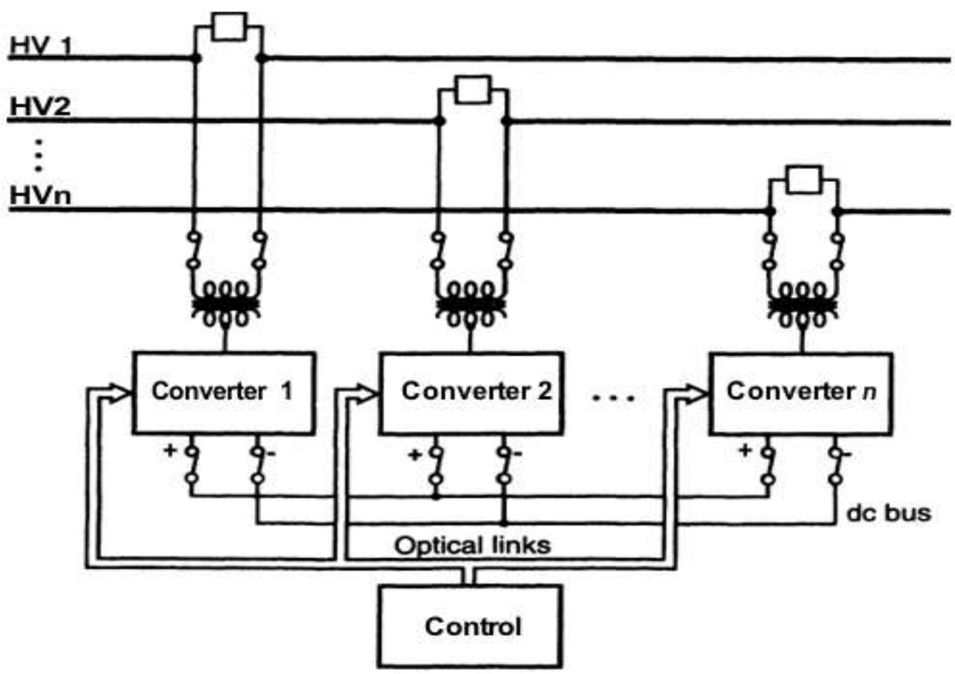

Figure 4.5 Interline Power Flow Controller comprising n converters.

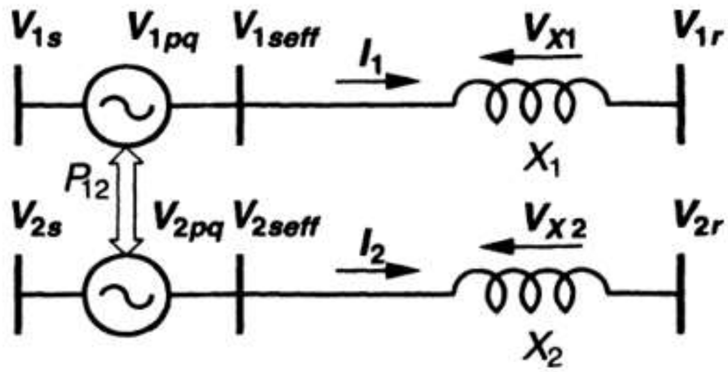

Figure 4.6 Basic two-converter Interline Power Flow Controller scheme.

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

[2] Narin G.Hingorani and Laszlo Gyugi "Understanding FACTS", IEEE Press Standard Publishers Distributors, 2001

S. No.	Question	Course Outcomes (Level)
	UNIT – IV **Part – A**	
1.	Interpret the function of STATCOM.	**CO4(5)**
2.	Construct the VI characteristics of STATCOM.	**CO4(6)**
3.	List out the advantage of STATCOM.	**CO4(4)**
4.	Explain the role of de link in UPFC.	**CO4(5)**
5.	State the salient features of UPFC.	**CO4(4)**
6.	What are the different types of converters used in UPFC	**CO4(2)**
7.	List out the application of UPFC device	**CO4(4)**
8.	Compare advantage of UPFC over TCSC	**CO4(3)**
9.	Construct the Schematic diagram for IPFC.	**CO4(6)**
10.	Construct the basic diagram of SSSC.	**CO4(6)**
	Part – B	
1.	Explain the principle and operation of STATCOM with a neat block diagram.	**CO4(5)**
2.	Describe the V-I characteristics of STATCOM.	**CO4(6)**
3.	Briefly explain the multilevel VSC based STATCOM with neat diagram,	**CO4(5)**
4.	Explain the working principle of SSSC with neat diagram.	**CO4(5)**
5.	Describe the implementation of the UPFC using two back to back VSCS with a common DC-terminal capacitor	**CO4(6)**
6.	Analyze the function of two back to back voltage source convertor in the transmission line with neat diagram.	**CO4(4)**

7.	Explain the principle of operation of IPFC with neat diagram.	**CO4(5)**
8.	Explain the concept FACTS device which is using to control the reactive power in multiple transmission lines with neat diagram.	**CO4 (5)**

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UNIT - V

Flexible AC Transmission System – SEEA3004

V. SUB SYNCHRONOUS RESONANCE (SSR)

Concept of SSR – NGH-SSR Damping scheme: basic concept – design and operation aspect. Thyristor Controlled Braking Resistor (TCBR), Advanced Series Capacitor (ASC): Basic concept – design and operation aspect

1.1 SUBSYNCHRONOUS RESONANCE

The question of subsynchronous resonance will arise in all FACTS applications, for brief or for in-depth consideration, for the basic reason that all high-speed, high-power Controllers have potential of enhancing or degrading subsynchronous phenomenon. This not only applies to the FACTS Controllers, but also HVDC, the Automatic Voltage Regulator (AVR), Power System Stabilizer, etc.

The subsynchronous problem is aggravated by series capacitor compensation and also high-speed reclosing of faulted lines with or without series capacitor compen- sation. It is therefore important for any power systems engineer to be familiar with this phenomenon, particularly those involved with the FACTS technology, because almost every FACTS Controller offers an opportunity for a SSR-neutral design and for value-added benefit in this area.

Electric power generation involves interaction between the electrical and me- chanical energies coupled through the generators. It follows that any change in the electric power system results in a corresponding reaction/response from the mechanical systems and vice versa. Slow-changing load translates into slow-changing mechanical torque on the rotor shafts, which in turn is matched by slow-changing rotor angles to new steady-state angles between the rotors and the stators along with adjustment in the mechanical power input to the rotors through the turbines. Major disturbances such as faults and fault clearing, etc. result in high-transient torques on the mechanical system and corresponding transient twisting of the rotor shaft couplings between tandem turbines and generators.

A large turbine-generator unit acting as a whole mass, has its resonance frequency below about 5 Hz with other nearby large turbine-generators. A cluster of turbo- generators closely coupled in a region representing a large collective rotating mass, would have a resonance frequency in the range of 0.2-3 Hz. These frequencies repre- sent the so-called power system stability swings, an issue of primary importance to the operation of a grid system.

Subsynchronous resonance has to do with the fact that internally, any turbine- generator mechanical system has inter-machine mechanical resonance frequencies between the masses along the shaft. These frequencies are below the main frequency, in the range of 10 Hz to 55 Hz for a 60 Hz system. The rotating shaft system of a large turbine-generator includes a number of large masses corresponding to several turbines, generators, and maybe even a coupled exciter, connected by rotor shafts which act like torsional springs.

For example, Figure 9.l(a) shows a representation of the high-pressure turbine generator unit of the Mohavi Power plant, the one damaged twice by the subsynchro- nous resonance, during 1970-71. This plant consists of two steam generating units. Each unit is made up of two turbine-generator units in cross-compound arrangement. One generator, 483 MVA high-pressure unit operates at 3600 rpm and the other generator 420 MVA low-pressure unit operates at 1800 rpm. The mechanical torsional frequencies are such that only the high-speed generators are subject to subsynchronous resonance problems. The low-pressure unit is hard to be excited by the SSR currents because it has relatively high mechanical damping at its own resonance frequencies and also provides damping at its companion high-pressure unit's resonance frequencies. Again by way of example, Figure 9.l(b) shows a diagram of mechanical gain versus frequency of the Mohavi high-pressure unit with four machines including two turbines, a generator and an exciter. Because the turbine-generator mechanical system comprises large masses connected by steel shafts, this rotating system has torsional resonance frequencies at which the adjacent masses tend to twist back and forth for any shock. Figure 9.l(b) shows three resonance modes with frequencies of approximately 26.7 Hz, 30.1 Hz, and 56.1 Hz, corresponding to the three couplings of four masses. Large masses coupled together have lower resonance frequency and the exciter being a little machine connected to the generator has the highest resonance frequency. The masses will experience relative motion when excited by a shock. The mechanical system has low but positive damping, which increases with load and without the impact of electrical system, these vibrations will die out slowly, with time constants in the range of ten or more seconds. The peak mechanical gains are limited by the amount of mechanical damping at each frequency and the lower the frequency the lower is the damping. It is worth noting that at low frequencies the three frequencies approach the response of a single inertia equal to the response of a single inertia of concern to the power system stability issues.

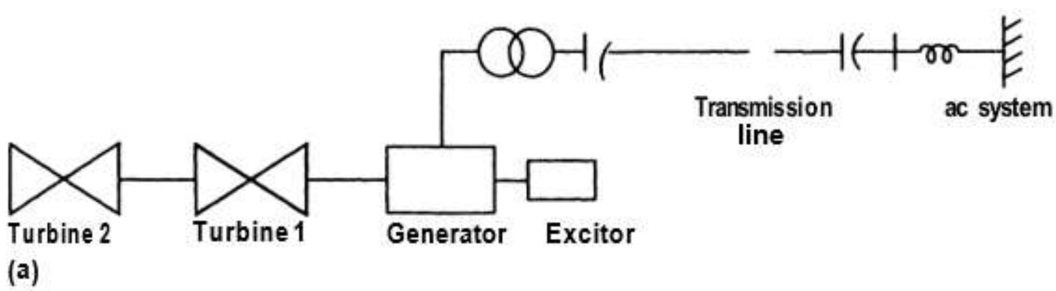

Figure 5.1 Representation of Mohavi Generator and Mohavi-Lugo line as an exam- ple of subsynchronous resonance: (a) Electrical-mechanical one-line dia- gram-Mohavi to Lugo

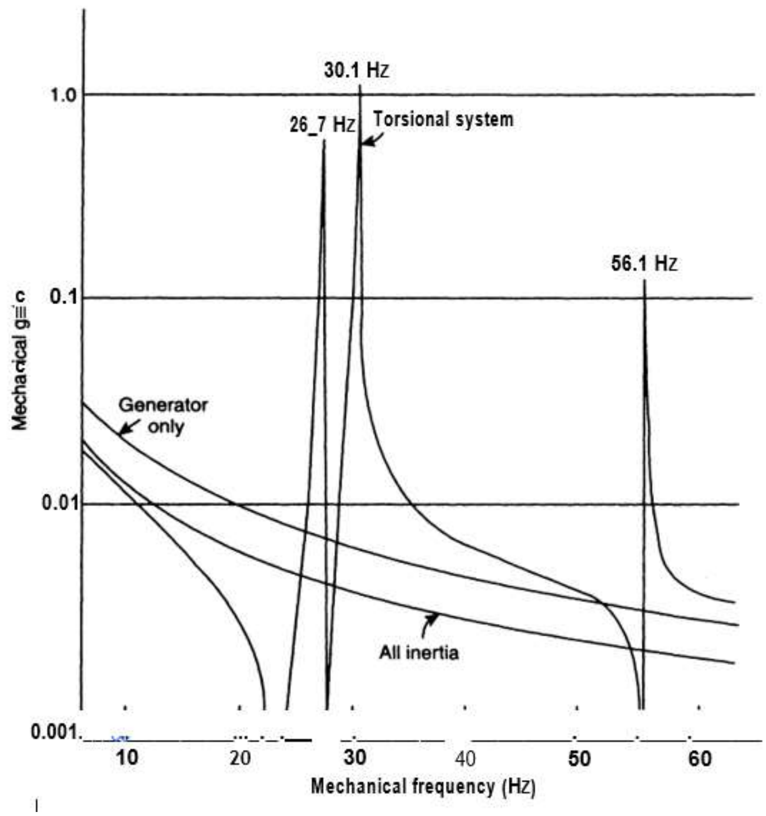

Figure 5.2 Mechanical frequency response of Mohavi high-pressure unit.

5.2 NGH-SSR DAMPING SCHEME

Series capacitor compensation of medium and long ac transmission lines has been recognized as a powerful and cost-effective tool for optimum/economical use of transmission lines, and improving system stability and power flow through the intended routes. This technique.is extensively used in Western United States, Canada, Brazil, and a number of other countries. However, technical issues of the protection of capacitors during line faults, subsynchronous oscillations, and consequent higher torque on the machine shafts have been a deterrent for many others. This section addresses one of the Controllers for active damping, referred to as the NGH-SSR scheme or just NGH Scheme, with NGH being the initials of its inventor, one of the authors of this book.

The NGH Scheme is intended to:

1 Minimize sub synchronous electrical torque and hence mechanical torques and shaft twisting.

2 Contain build up of oscillations due to steady state sub synchronous resonance.

3. Suppress the de offset of the series capacitor. De offset of a series capacitor occurs during faults, fault clearing, reclosing and other disturbances and this in turn feeds the sub synchronous electrical torques.

4. Protect series capacitors from over-voltages.

5. Reduce capacitor stresses, including over voltages and the rate of discharge current and eliminate oscillations associated with capacitor discharge during bypass, thereby reducing capacitor cost.

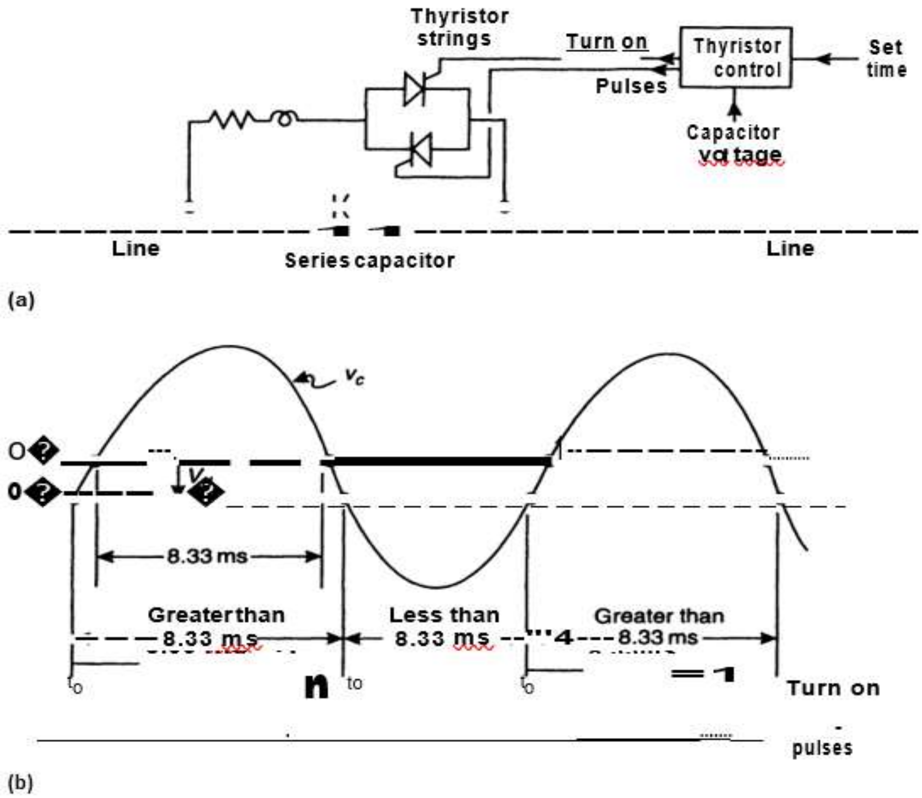

Figure 5.3 NGH-SSR Damping Scheme circuit diagram and principle of operation:

(a)Basic circuit diagram; (b) 60 Hz combined with de

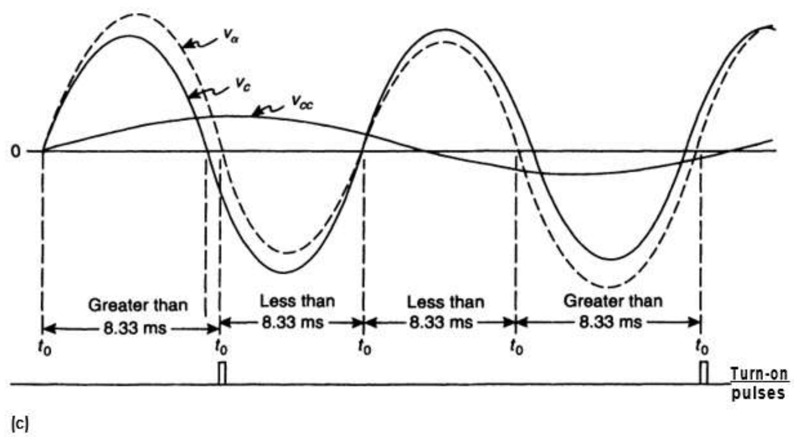

Figure 5.4 NGH-SSR Damping Scheme circuit diagram and principle of operation 60 Hz combined with sub synchronous.

The circuit diagram is shown in Figure 9.3, and the basic concept is described below with reference to the waveforms in Figures 9.3(b) and (c). In Figure 9.3(b), the 60 Hz voltage v, is combined with a de voltage and in Figure 9.3(c) the 60 Hz voltage is combined with a subsynchronous voltage Vee. It is seen in both cases that some half- cycles are longer than the nominal 60 Hz half-cycle period of 8.33 ms. Similarly, any combination of the de voltage, subsynchronous voltage, or voltage associated with any low-frequency stability-related oscillations, will result in some half-cycles being longer than the nominal half-cycle period. Conversely, if there were no de or any other low-frequency component combined with the main frequency, then each half-cycle would be equal to the nominal half-cycle period (8.33 ms for 60 Hz). For the present discus- sions these distorted voltage waveforms represent the voltage across a series capacitor. The hypothesis behind the NGH scheme is that the unbalanced charge in the series capacitor interchanges with the system inductance to produce oscillations. If this unbalanced charge is eliminated from the series capacitor, the system would be effec- tively detuned to any frequency other than the main frequency.

The basic scheme shown for one phase in Figure 9.3(a) consists of an impedance in series with an ac thyristor switch connected across the capacitor. This impedance may be an inductance or a resistance or a combination of the two. Essentially the impedance should be as small as possible, with the intent to discharge the capacitor with the thyristor bypass switch. In practical terms the best impedance is a combination of a small resistor, the size of which is essentially limited by the peak transient current capability of the switch and a small inductor, the size of which is limited by the di/dt limit of the thyristors. With an inductor in series, some of the charge will be transferred to the next half-cycle, which should generally be helpful since the half-cycle following the longer half-cycle will most likely be shorter. For this discussion we can assume that the switch can discharge and remove the capacitor charge when ordered to do so. Basically, the control of the thyristor switch is designed such that when zero crossing of the capacitor voltage is detected [t0 in Figure 9.3(c)], the succeeding half- cycle period is timed. As soon as the half-cycle exceeds the set time (e.g., 8.33 ms for 60 Hz), the corresponding thyristor is turned on to discharge the capacitor and bring about its current zero sooner than it would otherwise. The thyristor stops conducting when the thyristor current reaches zero soon after the capacitor voltage zero. At each capacitor voltage zero of each half-cycle, a new timing count starts with the intent to discharge the capacitor for the time that its half-cycle voltage exceeds the set period. There are a number of possible variations and/or improvisations of this basic concept in order to meet other functions. If the problem faced is only the transient torque problem (no steady-state resonance), the set period can be slightly larger than 8.33 ms, say 8.5 ms, so that the thyristors will not conduct at all during steady state, 60 Hz, and small changes. Yet the damping scheme will be effective in removing capacitor charge during large changes from steady state which may lead to de offset and significant subsynchronous components in the line current and capacitor voltage. On the other hand, if there is a likelihood of steady-state resonance, the set period may be slightly less than 8.33 MS. The thyristors will now conduct during steady state at the tail end of each half-cycle of the capacitor voltage, and provide detuning effect against any gradual build up of oscillations holding it to a low level. There will of course be a continuous power loss but this will be very small and of little consequence to the thyristor rating or the cost of losses.

5.3 THYRISTOR-CONTROLLED BRAKING

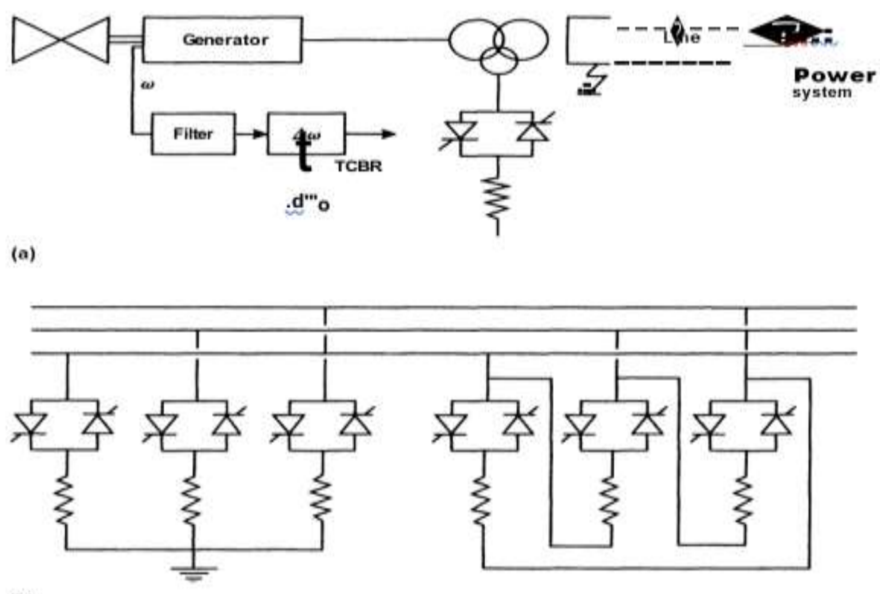

Figure 5.5 One-line diagram of Thyristor-Controlled Braking Resistor: (a) One line system diagram including TCBR; (b) Wye- and delta-connected TCBR.

5.4 WAPA'S KAYENTA ADVANCED SERIES CAPACITOR (ASC)

Advanced Series Capacitor (ASC) is the name given by the manufacturer, Sie- mens, to their total series capacitor system including a TCSC and a conventional series capacitor. Accordingly, in this section, this installation will be referred to as Kayenta ASC or just ASC, for the total system and TCSC for the thyristor-controlled module. Dedicated in 1992, this first of its kind ASC was installed at the Kayenta 230 kV Substation in Western Area Power Administration in Northeast Arizona.
Like the Slatt-TCSC, Kayenta-ASC is part of the WSCC regional system, charac- terized by a long transmission line, a large number of power plants both hydro and thermal, and many series capacitor compensated lines. This ASC was needed to increase the reliable transmission capacity of a 230 kV line between Glen Canyon aud Shiprock, as shown in Figure 10.1, and also to demonstrate this FACTS Controller as an accept- able planning option for future transmission capacity needs in the WAPA system. The Kayenta substation was selected for this unique project because of its location in the middle of 190 mile line. As can be seen from the one-line diagram, the sur- rounding system consists of many 500 kV and 230 kV lines connecting substations most of which are locations of large thermal power plants. There is a small local load of about 50 MW supplied from the Kayenta Substation.
The Glen Canyon-Shiprock 230 kV line was designed for an initial power transfer capability of 300 MW, but the line's effectiveness to carry scheduled power was diminished in the late 1960s due to the addition of parallel 345 kV and 500 kV paths. In 1977, a 230 kV phase-shifting transformer was installed at Glen Canyon Substation to reestablish effectiveness of the 300 MW path to Shiprock. With power transfers on the interconnected network approaching the transmission system's ability to reliably serve increasing loads, and with restrictions on building new lines, the economic benefits of adding series compensation became an attractive alternative to improve the line's power scheduling and transfer capability. An addition of 70% (110 0, 330 Mvar) of conventional series compensation was needed to increase the power schedul- ing capability by 100 MW, thus restoring its use to its full thermal rating. However, making part of this series compensation thyristor-controlled provided additional bene- fits, as described below.

Figure shows the simplified one-line diagram of the series compensation at Kayenta Substation. It consists of two 55 0 series capacitor banks each rated for 165 Mvar and 1000 amperes. One bank is operated in a conventional series compensation configuration with the second bank subdivided into a 40 !l, 120 Mvar conventional segment and a 15 !l, 45 Mvar TCSC. For completely conventional operation, the series compensation can be set to various levels by the fixed capacitors. These levels are established by 55 n, 40 !l, and 15 n conventional series capacitor segments. By using operation of circuit breakers and thyristor switches, a combination of O !l, 40 n, 55 !l, and 110 banks can be inserted into the transmission line based on operation needs. However, use of the 15 !l segment as a TCSC provides the following advantages:

- Continuous control of series capacitor compensation, all the way up to 100%, as against discrete step control up to 70% compensation.
- Direct and dynamic control of power flow.
- Short-circuit current reduction by rapidly changing from a controlled capacitive to inductive impedance.
- SSR mitigation. The ASC takes on an inductive-resistive impedance character- istic at SSR frequencies, thus detuning and damping SSR oscillations.
- Improved protection and rapid reinsertion of the series capacitors during sys- tem faults.
- Reduces de offset of the capacitor voltage within a few cycles.

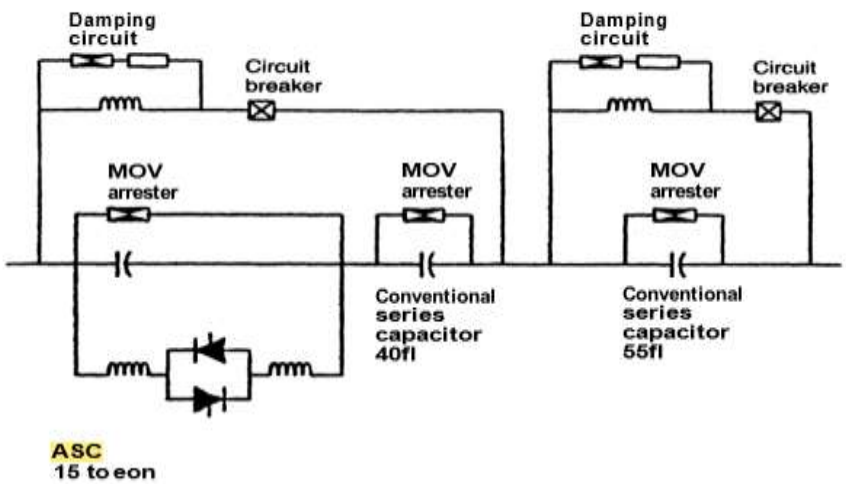

Figure 5.6 Single-line diagram of Kayenta ASC.

References

[1] Narin G.Hingorani and Laszlo Gyugi "Understanding FACTS", IEEE Press Standard Publishers Distributors, 2001

S. No.	Question	Course Outcomes (Level)
	UNIT – V **Part – A**	
1.	Examine the term SSR	**CO5(4)**
2.	Explain the NGH scheme.	**CO5(1)**
3.	Explain the operation of TCBR in a transmission line.	**CO6(5)**
4.	List out the effects of SSR problem,	**CO5(4)**
5.	Construct the NGH-SSR damping Scheme.	**CO5(6)**
6.	Explain the term ASC	**CO6(4)**
	Part – B	
1.	Explain the NGH – SSR damping scheme with neat diagram and waveforms	**CO5(5)**
2.	Draw electrical-mechanical one line diagram and mechanical frequency response and explain the sub-synchronous resonance problem	**CO5(5)**
3.	Briefly explain the concept of SSR.	**CO5(4)**
4.	Explain the design and operating aspects of Thyristor Controlled Breaking Resistor	**CO6(5)**
5.	Elaborate the function of ASC in the transmission system	**CO6(6)**