Module-5

Subject: Flexible AC Transmission System (FACTS)

Content: Voltage Source Converter based FACTS Controllers

Prepared by

Dr. Subhranshu Sekhar Dash, Professor
&
Dr. Sangram Keshori Mohapatra, Associate professor

Department of Electrical Engineering,
Government College of Engineering, keonjhar, Odisha, India

5.0 THE 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 corresponding 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 the following areas:

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 elements 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 environmental impact.

A STATCOM is analogous to an ideal synchronous machine, which generates a balanced set of three sinusoidal voltages—at the fundamental frequency—with controllable amplitude and phase angle. This ideal machine has no inertia, is practically instantaneous, does not significantly alter the existing system impedance, and can internally generate reactive (both capacitive and inductive) power.
The Tennessee Valley Authority (TVA) installed the first 100-MVA STATCOM in 1995 at its Sullivan substation. The application of this STATCOM is expected to reduce the TVA's need for load tap changers, thereby achieving savings by minimizing the potential for transformer failure. This STATCOM aids in resolving the off-peak dilemma of overvoltages in the Sullivan substation area while avoiding the more labor- and space-intensive installation of an additional transformer bank. Also, this STATCOM provides instantaneous control—and therefore increased capacity—of transmission voltage, providing the TVA with greater flexibility in bulk-power transactions, and it also increases the system reliability by damping grids of major oscillations in this grid.

To summarize, a STATCOM controller provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors or capacitor banks.

5.0.1 The Principle of Operation

A STATCOM is a controlled reactive-power source. It provides the desired reactive-power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC). A single-line STATCOM power circuit is shown in Fig. 5.1(a), where a VSC is connected to a utility bus through magnetic coupling. In Fig. 5.1(b), a STATCOM is seen as an adjustable voltage source behind a reactance—meaning that capacitor banks and shunt reactors are not needed for reactive-power generation and absorption, thereby giving a STATCOM a compact design, or small footprint, as well as low noise and low magnetic impact. The exchange of reactive power between the converter and the ac system can be controlled by varying the amplitude of the 3-phase output voltage, *Es*, of the converter, as illustrated in Fig. 5.1(c). That is, if the amplitude of the output voltage is increased above that of the utility bus voltage, *Et*, then a current flows through the reactance from the converter to the ac system and the converter generates capacitive-reactive power for the ac system. If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the ac system to the converter and the converter absorbs inductive-

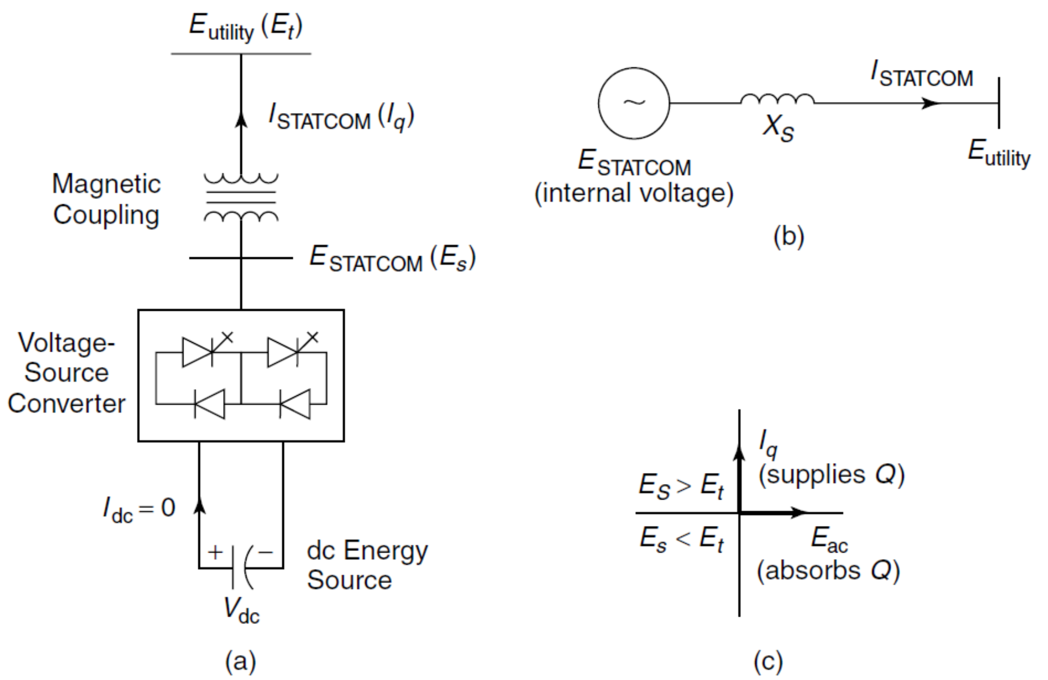

Figure 5.1 The STATCOM principle diagram: (a) a power circuit; (b) an equivalent circuit; and (c) a power exchange.

reactive power from the ac system. If the output voltage equals the ac system voltage, the reactive-power exchange becomes zero, in which case the STATCOM is said to be in a floating state. Adjusting the phase shift between the converter-output voltage and the ac system voltage can similarly control real-power exchange between the converter and the ac system. In other words, the converter can supply real power to the ac system from its dc energy storage if the converter-output voltage is made to lead the ac-system voltage. On the other hand, it can absorb real power from the ac system for the dc system if its voltage lags behind the ac-system voltage. 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).

Assume that the converter is operated to supply reactive-output power. In this case, the real power provided by the dc source as input to the converter must be zero. Furthermore, because the reactive power at zero frequency (dc) is by definition zero, the dc source supplies no reactive power as input to the converter and thus clearly plays no part in the generation of reactive-output power by the converter. In other words, the converter simply interconnects the three output terminals so that the reactive-output currents can flow freely among them. If the terminals of the ac system are regarded in this context, the converter establishes a circulating reactive-power exchange among the phases. However,

the real power that the converter exchanges at its ac terminals with the ac system must, of course, be supplied to or absorbed from its dc terminals by the dc capacitor.

Although reactive power is generated internally by the action of converter switches, a dc capacitor must still be connected across the input terminals of the converter. The primary need for the capacitor is to provide a circulating-current path as well as a voltage source. The magnitude of the capacitor is chosen so that the dc voltage across its terminals remains fairly constant to prevent it from contributing to the ripples in the dc current. The VSC-output voltage is in the form of a staircase wave into which smooth sinusoidal current from the ac system is drawn, resulting in slight fluctuations in the output power of the converter. However, not to violate the instantaneous power-equality constraint at its input and output terminals, the converter must draw a fluctuating current from its dc source. Depending on the converter configuration employed, it is possible to calculate the minimum capacitance required to meet the system requirements, such as ripple limits on the dc voltage and the rated-reactive power support needed by the ac system.

The VSC has the same rated-current capability when it operates with the capacitive- or inductive-reactive current. Therefore, a VSC having a certain MVA rating gives the STATCOM twice the dynamic range in MVAR (this also contributes to a compact design). A dc capacitor bank is used to support (stabilize) the controlled dc voltage needed for the operation of the VSC. The reactive power of a STATCOM is produced by means of power-electronic equipment of the voltage-source-converter type. The VSC may be a 2- level or 3-level type, depending on the required output power and voltage. A number of VSCs are combined in a multi-pulse connection to form the STATCOM. In the steady state, the VSCs operate with fundamental-frequency switching to minimize converter losses. However, during transient conditions caused by line faults, a pulse width–modulated (PWM) mode is used to prevent the fault current from entering the VSCs. In this way, the STATCOM is able to withstand transients on the ac side without blocking.

5.0.2 The *V-I* Characteristic

A typical *V-I* characteristic of a STATCOM is depicted in Fig. 5.2. As can be seen, the STATCOM can supply both the capacitive and the inductive compensation 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 technology: 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 collapse would otherwise be a limiting factor.

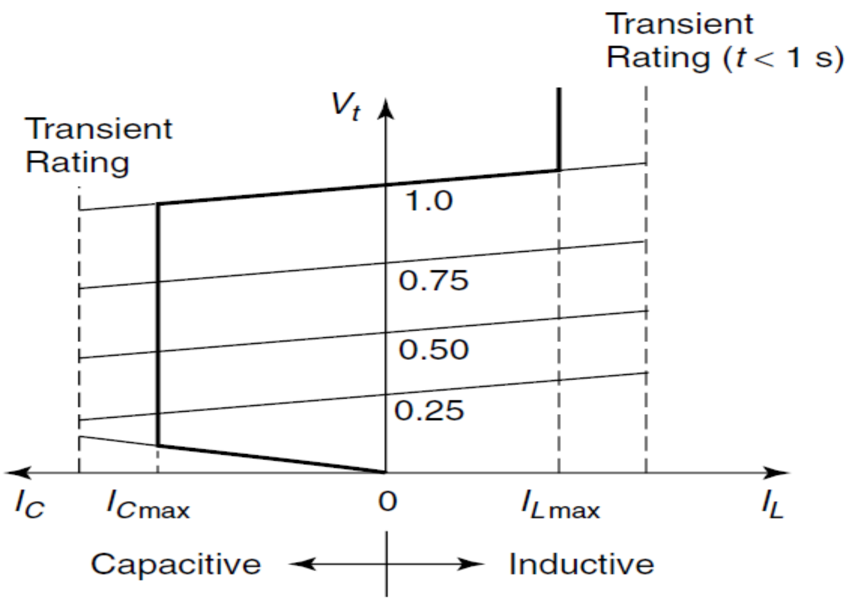

Figure 5.2 The *V-I* characteristic of the STATCOM.

Figure 5.2 also illustrates that the STATCOM has an increased transient rating in both the capacitive- and the inductive-operating regions. The maximum attainable transient overcurrent in the capacitive region is determined by the maximum current turn-off capability of the converter switches. In the inductive region, the converter switches are naturally commutated; therefore, the transient-current rating of the STATCOM is limited by the maximum allowable junction temperature of the converter switches.

In practice, the semiconductor switches of the converter are not lossless, so the energy stored in the dc capacitor is eventually used to meet the internal losses of the converter, and the dc capacitor voltage diminishes. However, when the STATCOM is used for reactive-power generation, the converter itself can keep the capacitor charged to the required voltage level. This task is accomplished by making the output voltages of the converter lag behind the ac-system voltages by a small angle (usually in the 0.18–0.28 range). In this way, the converter absorbs a small amount of real power from the ac system to meet its internal losses and keep the capacitor voltage at the desired level. The same mechanism can be used to increase or decrease the capacitor voltage and thus, the amplitude of the converter-output voltage to control the var generation or absorption.

The reactive- and real-power exchange between the STATCOM and the ac system can be controlled independently of each other. Any combination of real power generation or absorption with var generation or absorption is achievable if the STATCOM is equipped with an energy-storage device of suitable capacity, as depicted in Fig. 5.3. With this capability, extremely effective control strategies for the modulation of reactive- and real-output power can be devised to improve the transient- and dynamic system stability limits.

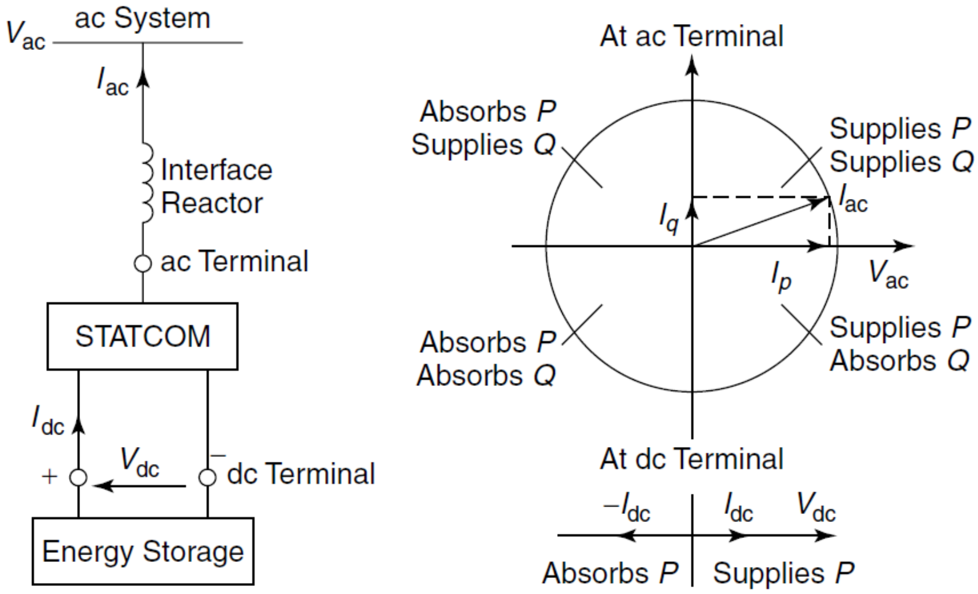

Figure 5.3 The power exchange between the STATCOM and the ac system.

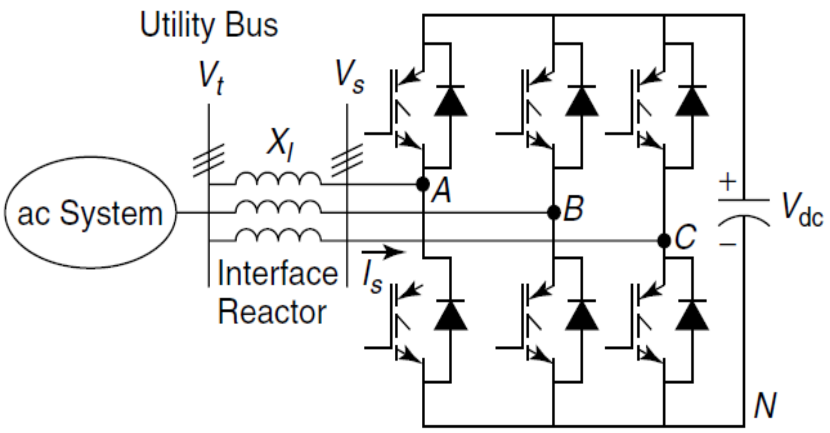

Figure 5.4 An elementary 6-pulse VSC STATCOM.

5.0.3 A Multilevel VSC–Based STATCOM The harmonic contamination of the power-system network by the addition of STATCOM into the power system can be reduced by employing multilevel VSC configurations. The multilevel converters usually synthesize a staircase-type voltage wave from several levels of dc-voltage sources (typically capacitor-voltage sources). The multilevel VSC schemes studied and tested so far include the *diode clamp*, the *flying capacitor*, and the *cascaded, separate dc-source converter* types.

Multilevel converters can reach high voltages and reduce harmonic distortion because of their structure. To increase the voltage rating, many single-phase full-bridge converters (FBCs) can be connected in series, automatically leading to a desirable reduction of harmonic distortion. However, the need to balance capacitor voltages, the complexity of switching, and the size of the capacitors all limit the number of levels that can be practically employed. Figure 5.5 shows the 3-phase star-connected arrangement of the separate dc-source, 3-level binary VSC commonly referred to as a BVSI. It consists of three single-phase FBCs, each with its own dc source, connected in series.

However, the magnitude of each dc source is in binary proportion of V_{dc}, $2V_{dc}$, and $4V_{dc}$, where V_{dc} is chosen to get the desired fundamental ac-voltage output for a normalized 1-pu modulation index. The switches are turned on and off to generate a 15-step ac-voltage output over one fundamental cycle. In general, n-level BVSI would produce a $(2^{n+1}-1)$–step ac-voltage output versus a $(2n+1)$–step output generated by a conventional n-level, separate dc-source VSC configuration.

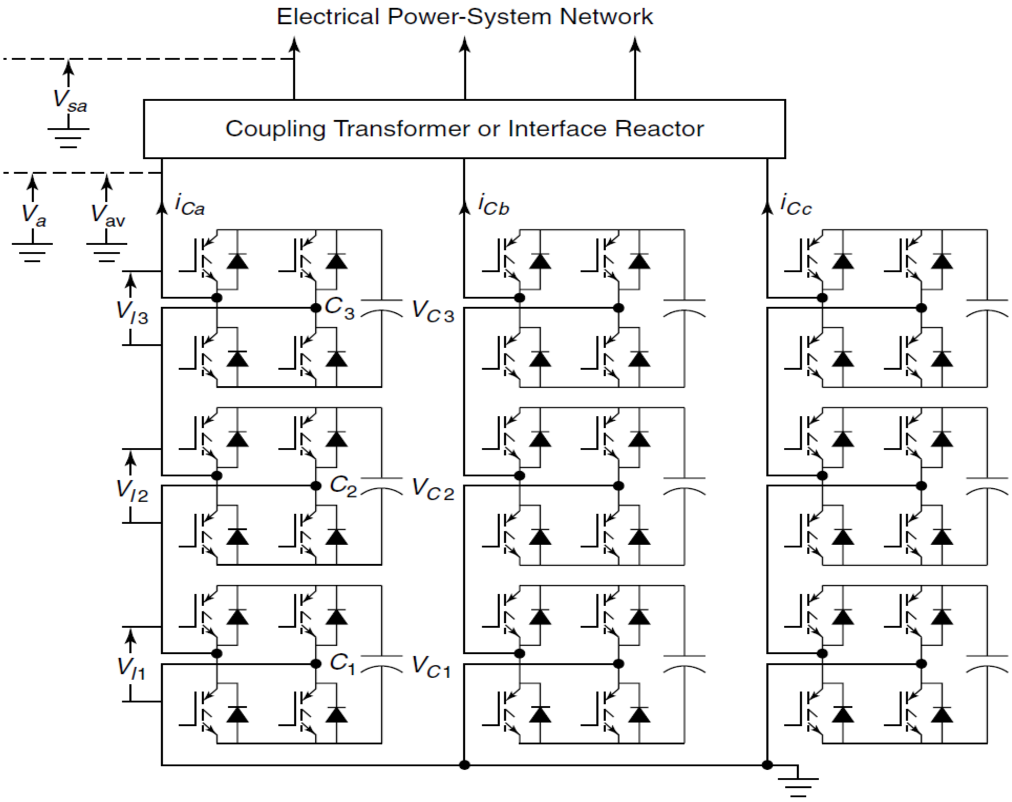

Figure 5.5 The 3-phase, star-connected 3-level BVSI

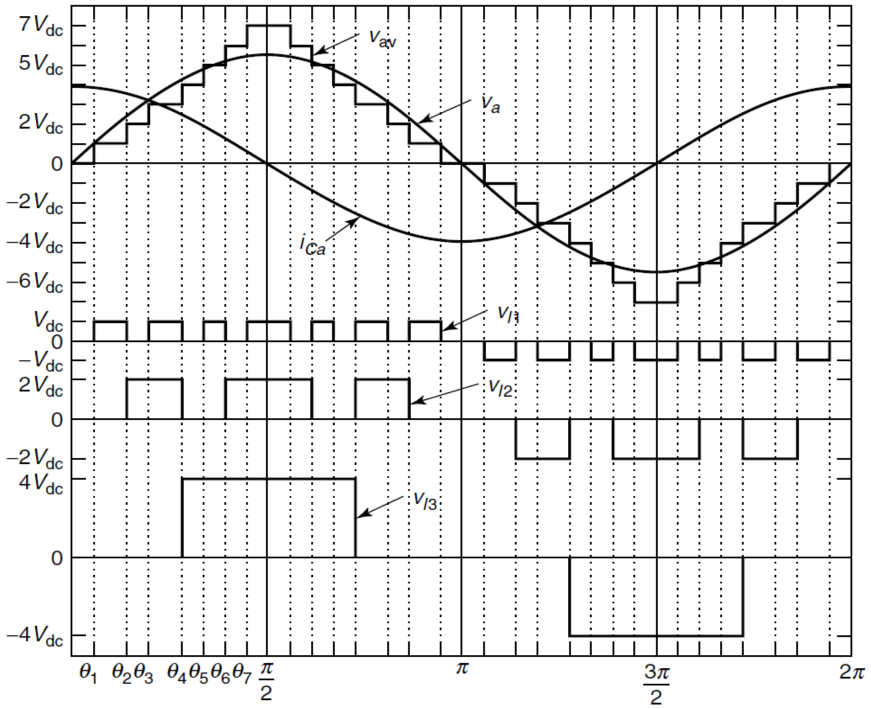

Figure 5.6 Typical voltages of the 3-level BVSI.

Figure 5.6 illustrates the various voltages in the 3-level BVSI STATCOM. The resulting ac-phase voltage, $v$av, and the fundamental-output voltage, v_a, of the 3-level converter are also shown in Fig. 5.6. The output-phase voltage is given by

$$v_{av} = v_{l1} + v_{l2} + v_{l3}$$

where

$$v_{l1} = +V_{C1}, 0, -V_{C1} \quad \text{and} \quad V_{C1} = V_{dc}$$

$$v_{l2} = +V_{C2}, 0, -V_{C2} \quad \text{and} \quad V_{C2} = 2V_{dc}$$

$$v_{l3} = +V_{C3}, 0, -V_{C3} \quad \text{and} \quad V_{C3} = 4V_{dc}$$

The phase voltage given by Eq. (10.16) is obtained by varying the voltage output of each FBC level in Eq. (10.17) by appropriately switching various devices and their combinations. From Fig. 5.6, the a-phase converter-output voltage for n-level BVSI is given by

$$v_{av} = \frac{4V_{dc}}{(2k-1)\pi} \sum_{k=1}^{\infty} \sum_{i=1}^{2^n-1} \cos[(2k-1)\theta_i] \sin[(2k-1)\omega t]$$

From Eq. (10.18), the fundamental root mean square (rms) voltage, V_a, the harmonic rms voltage, V_{2k-1}, and the maximum fundamental-phase voltage, $V_{a\,max}$, can be determined as

$$V_a = \frac{4V_{dc}}{\sqrt{2}\pi} \sum_{i=1}^{2^n-1} \cos\theta_i$$

and

$$V_{2k-1} = \frac{4V_{dc}}{\sqrt{2}(2k-1)\pi} \sum_{i=1}^{2^n-1} \cos[(2k-1)\theta_i]$$

and

$$V_{a\,max} = \frac{28V_{dc}}{\sqrt{2}\pi} \quad \text{for a 3-level BVSI}$$

Transient Simulation

The operation of the 3-level BVSI for distribution system dynamic compensation, described in Fig. 5.7, is evaluated using PSCAD / EMTDC for various disturbances and different system-operating conditions. This simulation illustrates the effectiveness of the BVSI in reactive power compensation, as well as the suitability of the capacitor-voltage controller in maintaining the capacitor voltages in binary proportion and the suitability of the voltage controller in regulating load-bus voltage during abnormal conditions and varied operating environments. Also, it shows that the power-quality impairment from STATCOM operation can be minimized by the proper configuration of STATCOM, that is, multilevel and/or high-pulse converter configurations. As an example case, Fig. 5.8 illustrates the operation of the BVSI when it generates leading var and absorbs lagging var. Initially, the capacitor voltages are maintained at 2, 4, and 8 kV levels, the BVSI is in a floating state, and the load-bus voltage is 1 pu.

At 0.12 s, a 10-MW, +j8 MVAR inductive load is added. To maintain the load-bus voltage at 1 pu, increased capacitive-reactive-power demand at the load bus is met by the converter. The voltage controller responds to the changed operating condition and adjusts the modulation index, and the converter generates 11-MVAR capacitive-reactive power. Figure 5.8 also shows the variations in the capacitor voltages, V_{C1}, V_{C2}, and V_{C3}; the rms load-bus voltage, V_l; the BVSI-bus voltage, V_s; and instantaneous load-bus line voltages, v_{ab}, v_{bc}, and v_{ca}. It is seen that after the initial disturbance, the capacitor voltages adjust to the predisturbance binary levels, and V_l is regulated to 1 pu. At 0.4 s, a 16-MVAR capacitor bank is switched in at the load bus, changing the load to 10 MW,−j8 MVAR capacitive. It is seen that the converter is able to switch successfully from capacitive to inductive operation and the load-bus voltage is regulated rapidly to 1 pu. However, the capacitor voltages are maintained at newly reduced steady-state values but still remain in a binary proportion. In principle, the variation in the dc-link voltages does not inherently affect the ability of the converter to produce the designated sinusoidal-output voltages at the desired single synchronous frequency by appropriately controlling the (instantaneous) magnitude of the converter-output voltage. Here, too, the reduced dc voltages do not affect the effectiveness of the BVSI in any manner as long as they remain in a binary proportion and are not reduced substantially. If the capacitor voltages drift from their binary proportions, the harmonic distortion would increase. The line-voltage harmonic spectrum is shown in Fig. 5.8. The total harmonic distortion (THD) with a 60-Hz base frequency and the first 100 harmonics considered is 0.3717% at 0.6499 s. The THD values at a different time instant are shown in Table 5.1. These very low THD values indicate that a SHEM algorithm with precomputed switching patterns improves the system harmonic profile significantly.

Figure 5.9 illustrates real-power flow from an ac system into the STATCOM to meet its losses. The real power drawn by the STATCOM is very low when there are no disturbances; the STATCOM draws more power to meet increased losses during transient conditions. This figure also shows $\Delta\theta_{1a}$, $\Delta\theta_{2a}$, and $\Delta\theta_{4a}$ angles used to modulate capacitor-switching periods to regulate their voltages, which vary from −1° to +1°. The STATCOM bus-phase voltages v_{av}, v_{bv}, and v_{cv} distinctly show the 15-step output.

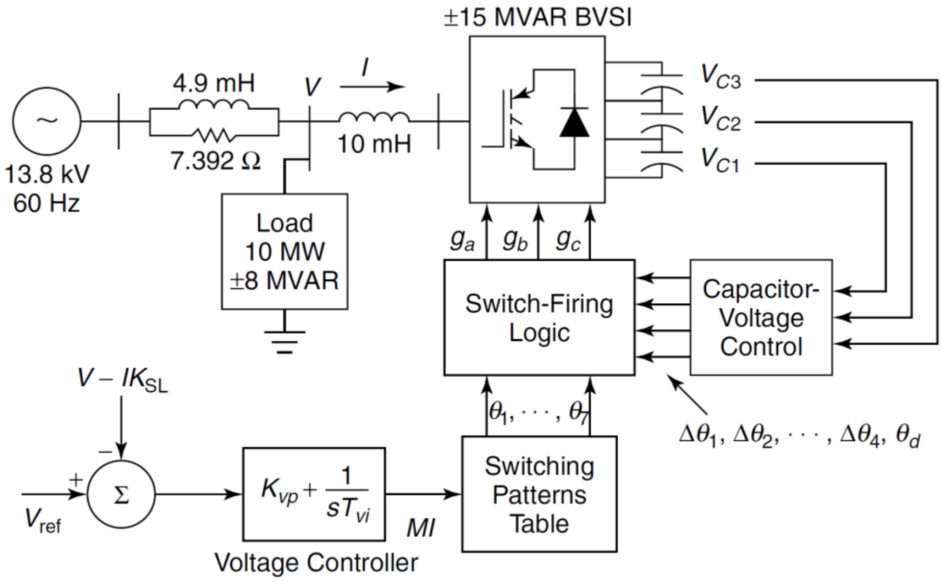

Figure 5.7 Distribution-system compensation using a BVSI STATCOM.

No. of Cycles After a Load Change at Which the THD Is Measured	Inductive/Capacitive Loads	
	Time	THD
5	0.2033 s	1.2496%
	0.4833 s	0.5488%
10	0.2866 s	1.0945%
	0.5666 s	0.2857%
15	0.3699 s	1.1043%
	0.6499 s	0.3717%

Table 5.1 The THD during STATCOM operation in the MVAR absorption supply modes

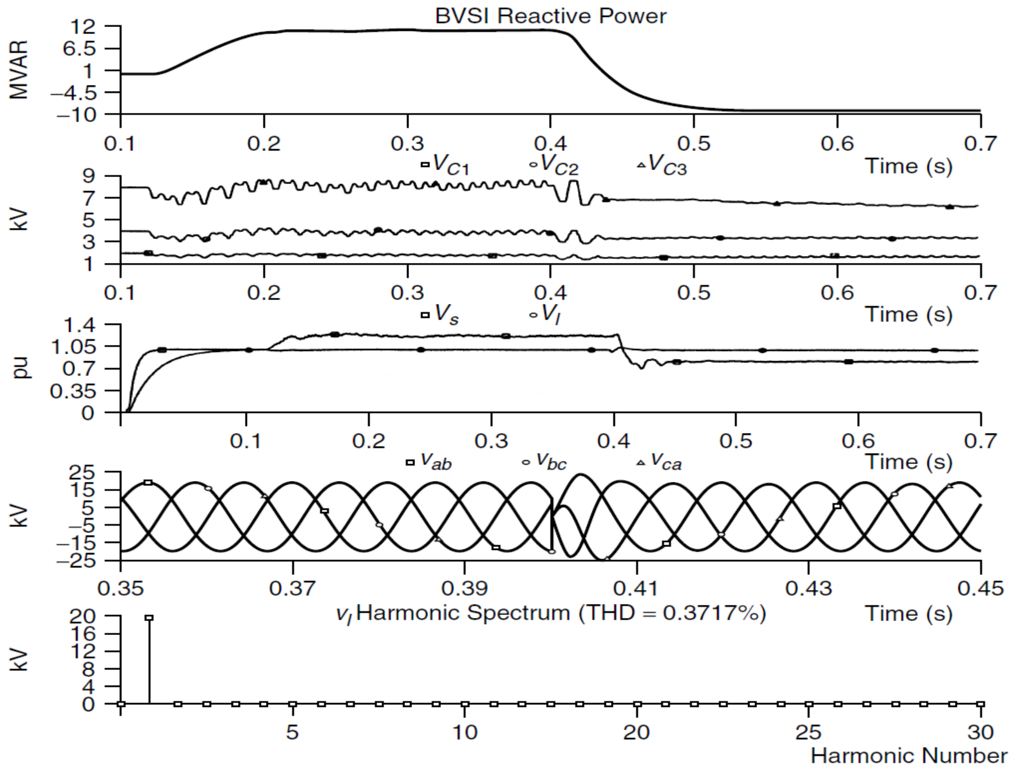

Figure 5.8 The addition of inductive (at 0.12 s) and capacitive (at 0.4 s) loads.

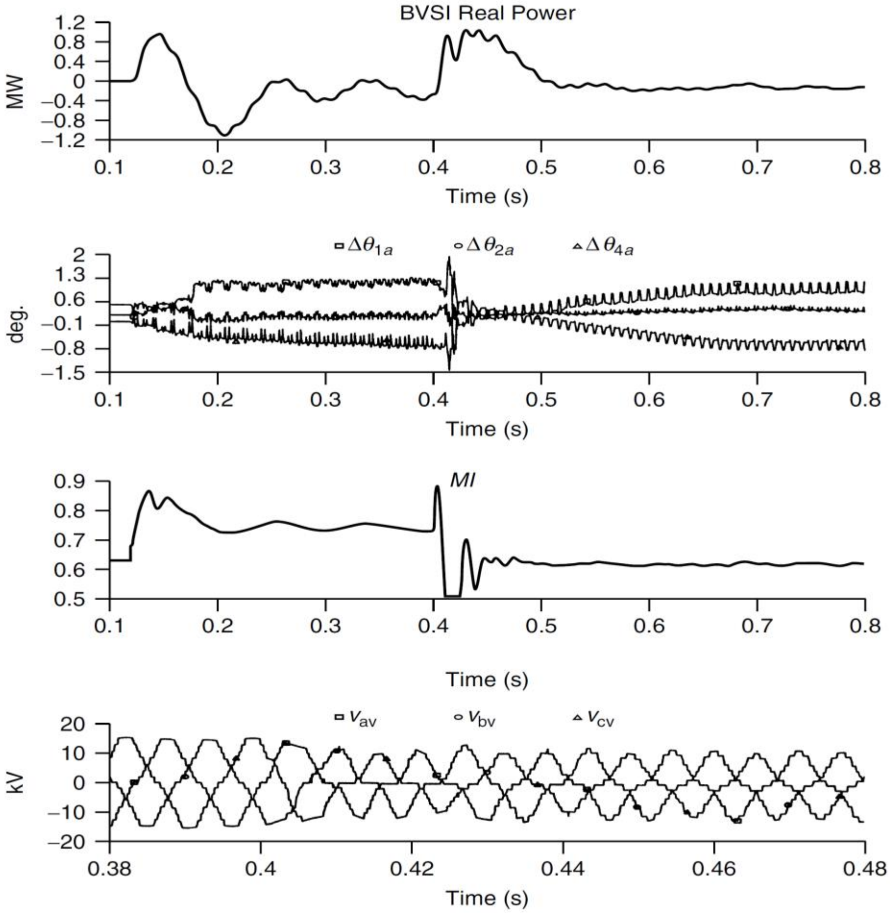

Figure 5.9 Typical STATCOM real-power consumption

5.1 THE SSSC

The SSSC, sometimes called the S3C, is a series-connected synchronous-voltage source that can vary the effective impedance of a transmission line by injecting a voltage containing an appropriate phase angle in relation to the line current. 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 not only to 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. 5.10(a). Here, the controller is connected in series with the transmission line. The operating modes of the SSSC are illustrated graphically in Fig. 5.10(b).

5.1.1 The Principle of Operation

A series capacitor compensates the transmission-line inductance by presenting a lagging quadrature voltage with respect to the transmission-line current. This voltage acts in opposition to the leading quadrature voltage appearing across the transmission-line inductance, which has a net effect of reducing the line inductance. Similar is the operation of an SSSC that also injects a quadrature voltage, *VC*, in proportion to the line current but is lagging in phase:

$$\overline{V_C} = -jkX\overline{I_L}$$

where VC =the injected compensating voltage
IL =the line current
X=the series reactance of the transmission line
K=the degree of series compensation

The current in a line compensated at its midpoint by the SSSC is expressed as:

$$I_L = \frac{2V \sin \delta/2}{X} + \frac{V_C}{X}$$

where V=the magnitude of voltage (assumed to be the same) at the two ends of the transmission line
δ=the angular difference across the line.

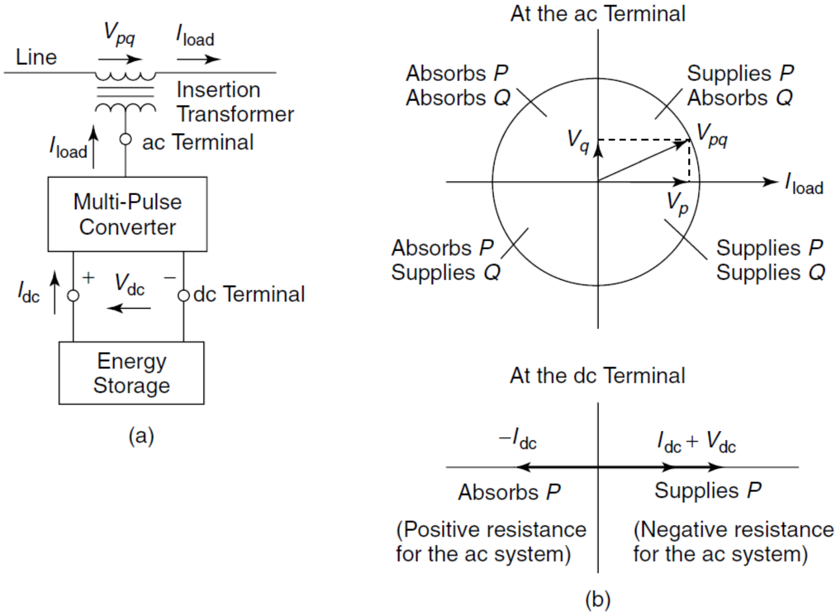

Figure 5.10 (a) Generalized series-connected synchronous-voltage source employing a multi-pulse converter with an energy-storage device; (b) the different operating modes for real- and reactive-power exchange.

The corresponding line-power flow is then expressed as

$$P = VI_L \cos(\delta/2)$$

Or

$$P = \frac{V^2 \sin \delta}{X} + \frac{VV_C}{X} \cos(\delta/2)$$

A series-compensation scheme using the SSSC is depicted in Fig. 5.11. Normally, the SSSC-output voltage lags behind the line current by 90^0 to provide effective series compensation. In addition, the SSSC can be gated to produce an output voltage that leads the line current by 90^0, 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. A typical SSSC controller connected in a transmission line is shown in Fig. 5.12. This controller comprises a VSC in which its coupling transformer is connected in series with the transmission line. The valve-side voltage rating is higher than the line-side voltage rating of the coupling transformer to reduce the required current rating of the gate turn-off (GTO) thyristor valves. The valve-side winding is delta-connected to provide a path for 3rd harmonics to flow. Solid-state switches are provided on the valve side to bypass the VSC during periods of very large current flow in the transmission line or when the VSC is inoperative. The basic dc voltage for conversion to ac is provided by the capacitor, and the dc/□□ac conversion is achieved by pulse width–modulation techniques. The dc-capacitor rating is chosen to minimize the ripple in the dc voltage. An MOV is installed across the dc capacitor to limit its voltage and provide protection to the valves.

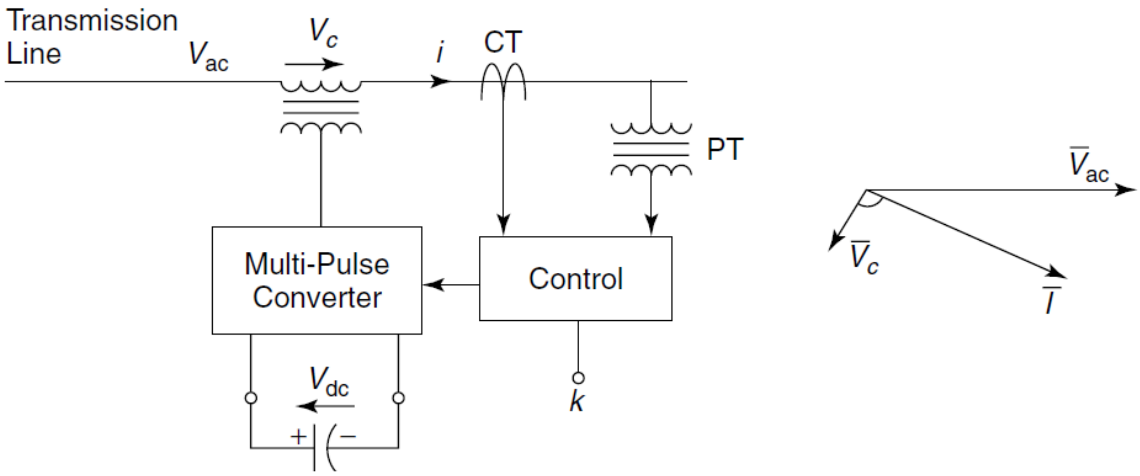

Figure 5.11 A synchronous-voltage source employing a multi-phase dc□□ac converter that is operated as a series-capacitive compensator.

5.1.2 The Control System

A typical SSSC control system is depicted in Fig. 5.13. It accomplishes the following functions:

- The introduction of desired series-reactive compensation (capacitive or inductive).
- The damping of power-swing oscillations and enhancement of transient stability.
- The control of current in the SSSC-compensated line.

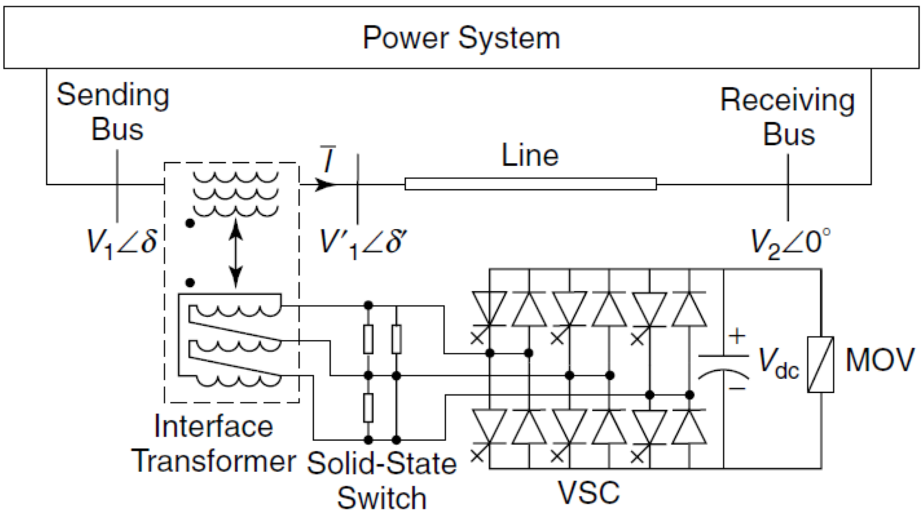

Figure 5.12 A line compensated with an SSSC.

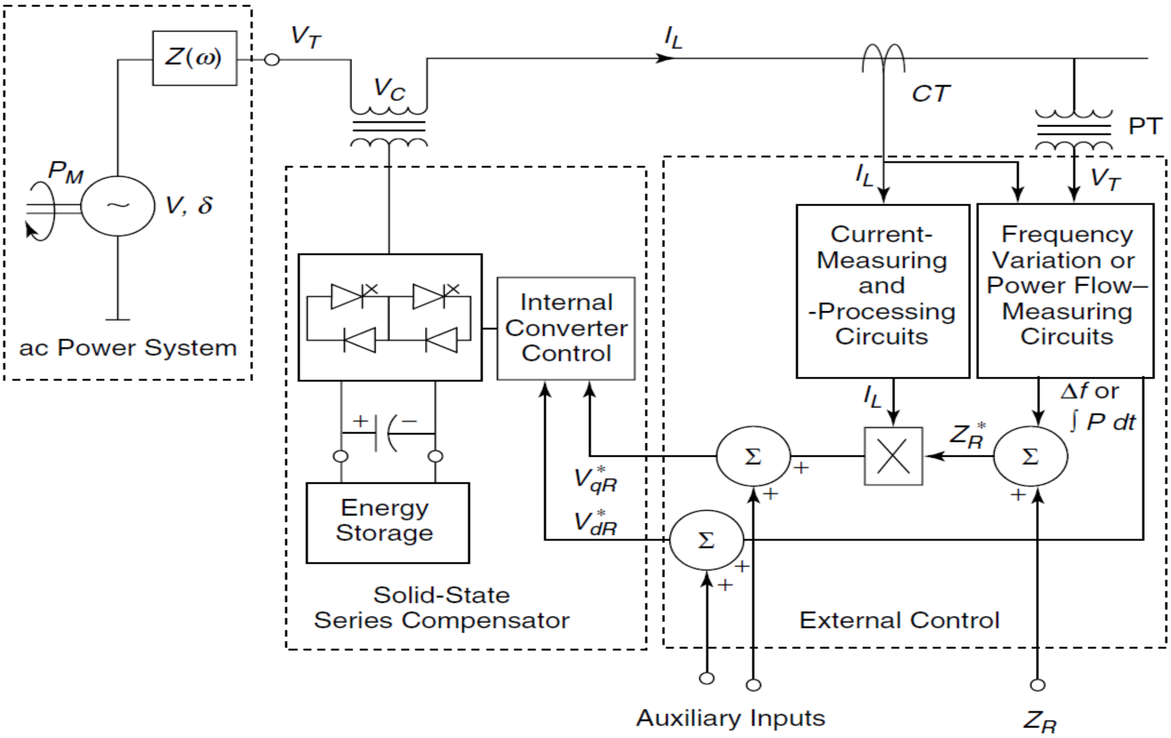

Figure 5.13 A basic control scheme for the solid-state series compensator to control (reactive and real) line impedance and improve system stability.

The line current, I_L, and the SSSC terminal voltage, V_T , are measured together with the bus frequency or the line-power flow, which can either be measured directly or calculated from I_L and V_T measurements. The desired SSSC reactance is set by a reactance reference, Z_R.
The SSSC acts as a voltage source in synchronism with the ac-system voltage—the magnitude and phase of which can be controlled by voltage reference inputs of V^*_{dr} and V^*_{qr}. The signal V^*_{qr} regulates the SSSC-output voltage component in quadrature with the line current. It thus determines the amount of reactive compensation (capacitive or inductive) introduced in the transmission line. The reactance reference Z_R is modulated with bus frequency or line-power signals to generate Z^*_R, which when multiplied with the rms line current I_L results in the signal V^*_{qr}. The bus frequency or line-power signals are representative of the generator-rotor oscillations, *(dδ□/dt)*, as follows:

1. If *(dδ□/dt)* >0—that is, the generators accelerate—the signal V^*_{qr} controls the SSSC output to increase the power drawn from the generator, thereby decreasing its kinetic energy. This action is achieved by enhancing the series-capacitive compensation provided by SSSC.
2. If *(dδ□/dt)* <□ 0—that is, the generators decelerate—the signal V^*_{qr}, effectively inserts an inductive reactance in the line to decrease the power transmitted from the generator.

The signal V^*_{dr} determines the magnitude of the SSSC-output voltage component that is in phase (or out of phase) with the line current. It thus controls the real-power exchange between the SSSC and the system and is particularly effective when the SSSC is equipped with an energy-storage device such as the one shown in the Fig. 5.13. To damp power swings, the modulation signal representing *(dδ□/dt)* is used to modulate V^*_{dr}, as follows:

1. If $(d\delta/dt) > 0$—that is, the generators accelerate—the signal V^*_{dr} controls the SSSC to absorb real power from the system. It effectively introduces a positive (apparent) resistance in the transmission network.
2. If $(d\delta/dt) < 0$—that is, the generators decelerate—the signal V^*_{dr} instructs the SSSC to inject real power into the system. This action is equivalent to the introduction of a negative (virtual) resistance in the transmission circuit.

The SSSC can also be used to balance the currents in parallel lines. This objective is attained by implementing an additional current loop in which the measured current is compared with the desired reference value. The error signal is then employed to modulate Z_R to effect the required current flow in the compensated line.

5.1.3 Power-Flow Control A case study that illustrates the effectiveness of the SSSC in providing line-power control is presented. Figure 5.14 depicts a two-area 500-kV test system interconnected by a 600-km double-circuit line. Each circuit is compensated by fixed capacitors to the extent of 70.5% line reactance, which translates to a net series compensation of 46.6% if the area impedances are also considered. The SSSC is inserted in series with the line. The coupling transformer is rated at 28.9 kV (line side) and 57.7 kV (valve side) per phase. The dc side of the GTO-based VSC is rated at 75 kV (which can be increased to 85 kV) by the MOV across the dc capacitor. The SSSC can thus inject a maximum phase voltage of 28.9 kV, corresponding to a line-to-line voltage of 50 kV. The SSSC response to changes in the line-power reference is shown in Fig.5.15. Initially, the SSSC is blocked and bypassed with the dc capacitor of the VSC uncharged. At this instant, the line-power flow is 2015 MW, corresponding to an angular difference of 308 between the two areas. At t=0.1 s, the SSSC is deblocked; the line-power reference setting is first increased to 2400 MW, then reduced in steps to a final value of 1600 MW. It is seen from Fig. 5.15 that even a small SSSC that is rated at 10% of the line voltage can provide effective control of 800 MW of line power, or 40% of the line power. The total harmonic distortion with the switching scheme of Fig. 5.15 is about 1.5%. Even in unbalanced-voltage scenarios, the SSSC is shown to operate satisfactorily.

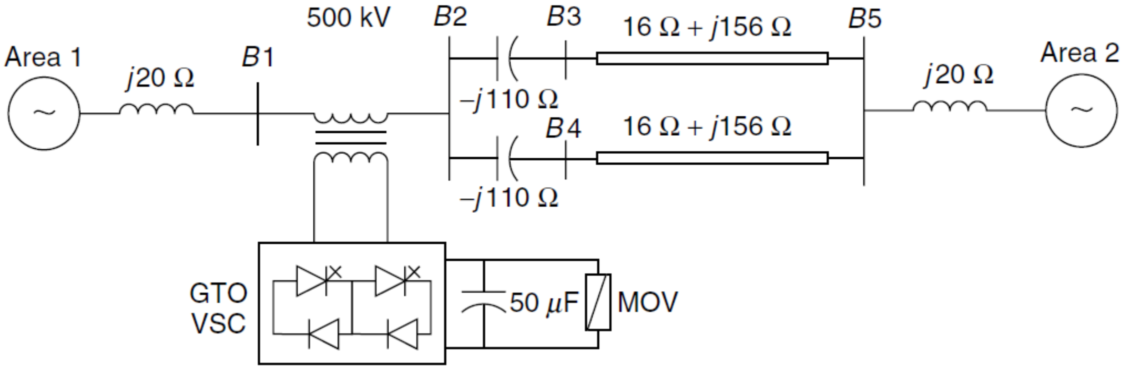

Figure 5.14 A test system.

5.1.4 SSR Mitigation An important aspect of the SSSC is that because it does not introduce a physical capacitor in the line, it does not cause SSR. However, it assists in the damping of subsynchronous oscillations caused by other series capacitors inserted in the transmission network. This damping is achieved by introducing subsynchronous voltages of appropriate magnitude, frequency, and phase to negate the effect of original subsynchronous currents. The subsynchronous voltages can be generated together with the fundamentalfrequency voltage.

The influence of the SSSC in suppressing SSR in a modified IEEE First Benchmark System is described. The line is assumed to be compensated by 50%. Three cases are considered for line compensation:

1. Total of 50% series compensation by the fixed capacitor.
2. Total of 35% compensation by a fixed capacitor and 15% by an SSSC.
3. Total of 50% compensation by an SSSC.

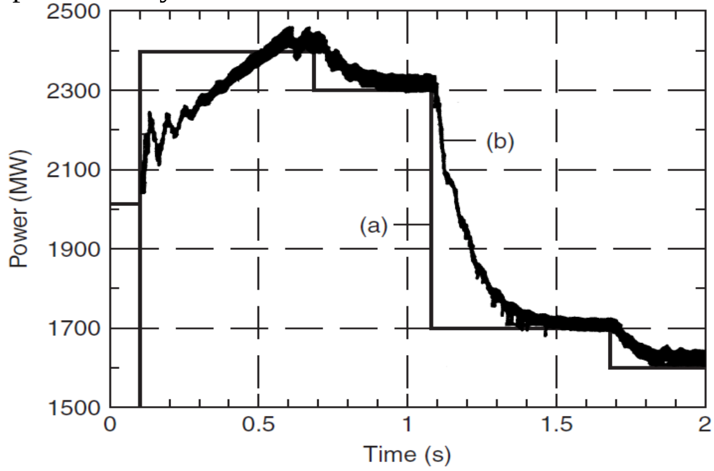

Figure 5.15 The system response to power-reference change: (a) line-power reference and (b) line power.

Eigenvalue analysis is used to show that both cases 1 and 2 of the preceding list reduce the undamping of the concerned torsional mode. The SSSC of case 2 damps the torsional oscillations effectively with a damping controller. It may be noted that the SSSC, as a very expensive controller, is not used alone to compensate the line. A practical compensating scheme involves the use of a relatively small-rating SSSC in conjunction with a fixed-series capacitor. For the case-study system, depicted in Fig. 5.16 is the response of the SSSC in case 2 to a step increase in the HP turbine's mechanical-torque output. The generator-rotor-angle oscillations decay very rapidly, and in the GEN–LP shaft torques, and the subsynchronous oscillations are also stabilized—although slowly. Moreover, the SSSC closely regulates the dc-capacitor voltage.

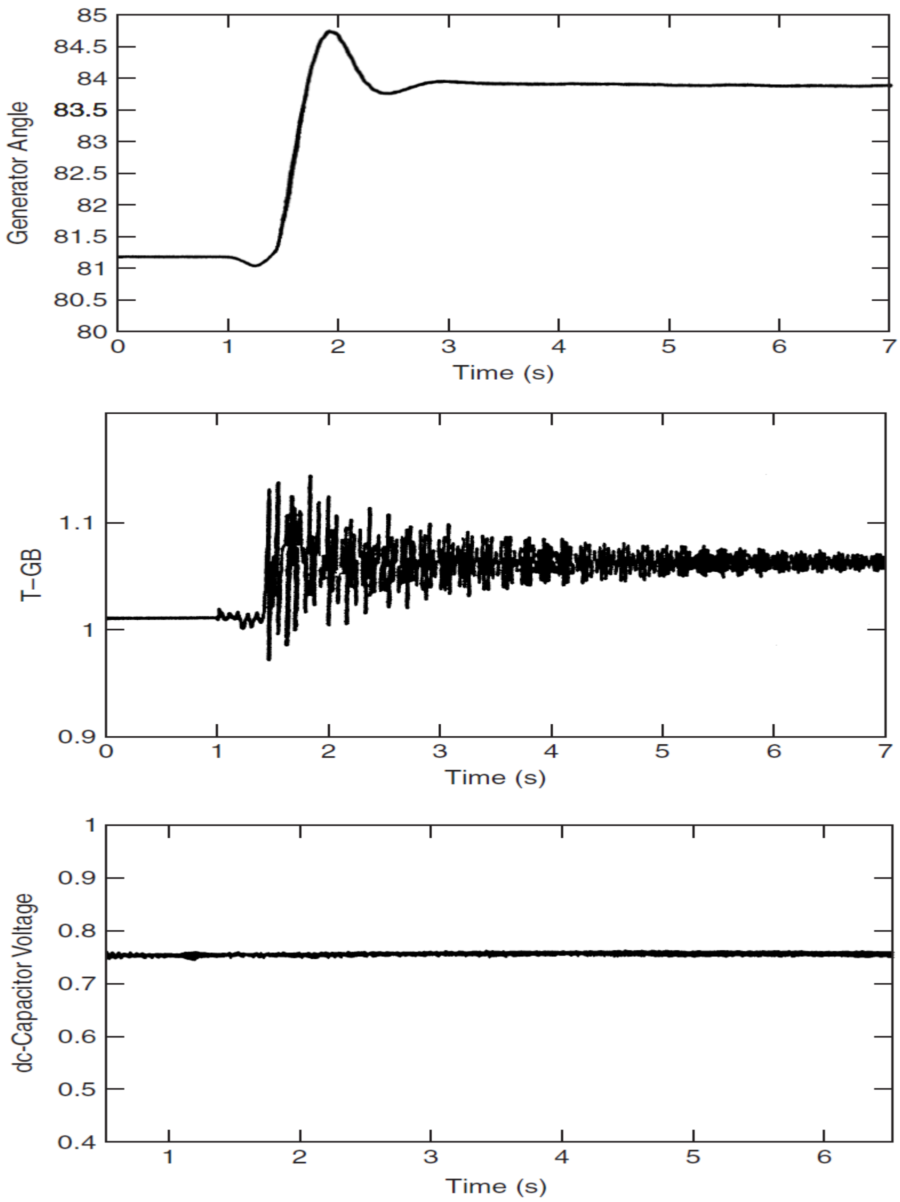

Figure 5.16 The SSSC response for a step change in the mechanical input of an HP turbine.

5.2 THE UPFC

5.2.1 The Principle of Operation

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. It is configured as shown in Fig. 5.17 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 transmission 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 0^0 to 360^0. 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 interconnected bus by generating/absorbing a requisite amount of reactive power.

The concepts of various power-flow control functions by use of the UPFC are illustrated in Figs. 5.18(a)–(d). Part (a) depicts the addition of the general voltage phasor V_{pq} to the existing bus voltage, V_0, at an angle that varies from 0^0 to 360^0. Voltage regulation is effected if V_{pq} (= ΔV_0) is generated in phase with V_0, as shown in part (b). A combination of voltage regulation and series compensation is implemented in part (c), where V_{pq} is the sum of a voltage regulating component ΔV_0 and a series compensation providing voltage component V_c that lags behind the line current by 90°.

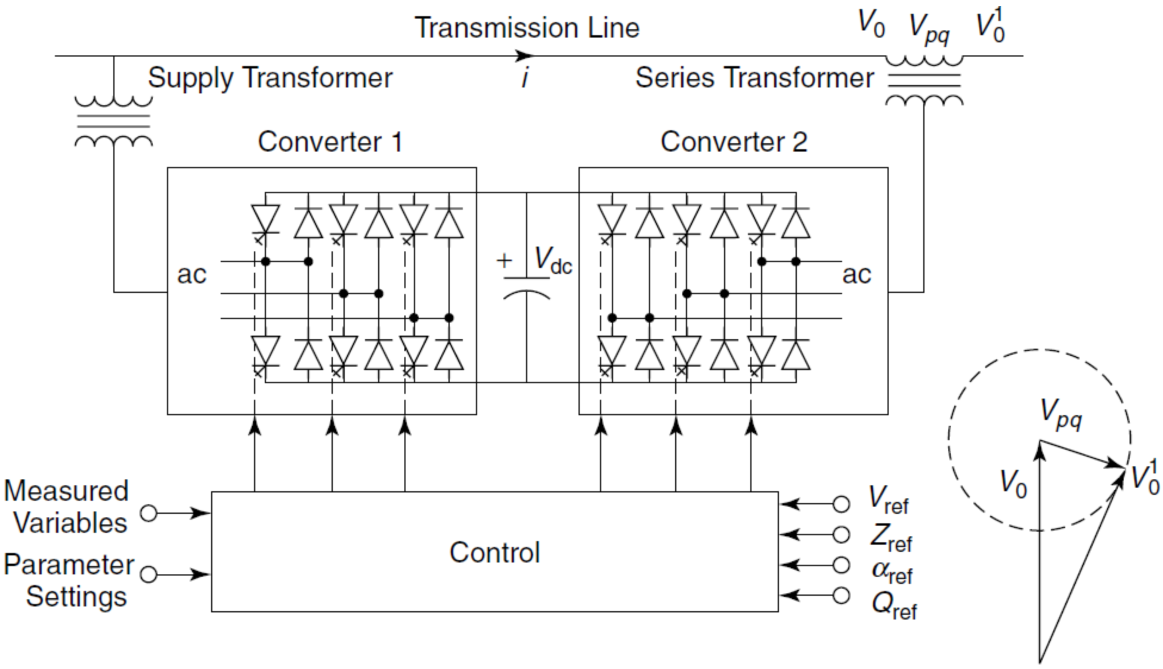

Figure 5.17 The implementation of the UPFC using two “back-to-back” VSCs with a common dc-terminal capacitor.

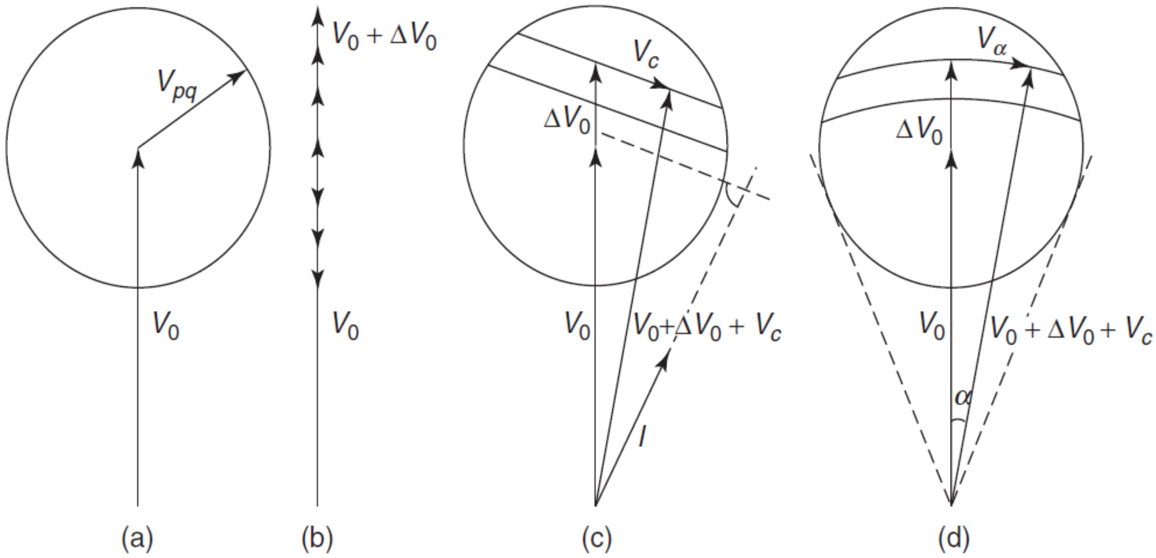

Figure 5.18 A phasor diagram illustrating the general concept of series-voltage injection and attainable power-flow control functions: (a) series-voltage injection; (b) terminal-voltage regulation; (c) terminal-voltage and line-impedance regulation; and (d) terminal-voltage and phase-angle regulation.

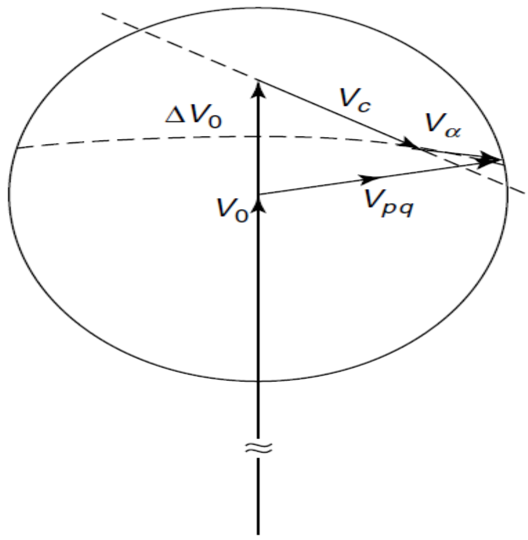

Figure 5.19 A phasor diagram illustrating the simultaneous regulation of the terminal voltage, line impedance, and phase angle by appropriate series-voltage injection.

In the phase-shifting process shown in part (d), the UPFC-generated voltage V_{pq} is a combination of voltage-regulating component ΔV_0 and phase-shifting voltage component V_a. The function of V_a is to change the phase angle of the regulated voltage phasor, $V_0 + \Delta V$, by an angle α. A simultaneous attainment of all three foregoing power-flow control functions is depicted in Fig. 5.19. The controller of the UPFC can select either one or a combination of the three functions as its control objective, depending on the system requirements.

The UPFC operates with constraints on the following variables:
1. the series-injected voltage magnitude;
2. the line current through series converter;

3. the shunt-converter current;
4. the minimum line-side voltage of the UPFC;
5. the maximum line-side voltage of the UPFC; and
6. the real-power transfer between the series converter and the shunt converter.

5.3 Interline Power Flow Controller (IPFC)

The combination of two or more Static Synchronous Series Compensators which are coupled via a common dc link to facilitate bi-directional flow of active power between the ac terminals of the SSSCs, and are controlled to provide independent reactive compensation for the adjustment of active power flow in each line and maintain the desired distribution of reactive power flow among the lines. The IPFC structure may also include a STATCOM, coupled to the IPFC's common dc link, to provide shunt reactive compensation and supply or absorb the overall active power deficit of the combined SSSC's.
The IPFC addresses the problem of compensating a number of transmission lines at a given substation. Series capacitive compensators are used to increase the transmittable active power over a given line but they are unable to control the reactive power flow in, and thus the proper load balancing of the line. With IPFC active power can be transferred between different lines. Therefore, it is possible to:

- equalize both active and reactive power flow between the lines,
- reduce the burden of overloaded lines by active power transfer,
- compensate against resistive line voltage drops and the corresponding reactive power demand,
- and increase the effectiveness of the overall compensating system for dynamic disturbances.

The general form of a IPFC is shown in Fig. 5.20. It employs a number of DC-to-AC converters, namely SSSC, each providing series compensation for a different line. With this scheme the converters do not only provide series reactive compensation but can also be controlled to supply active power to the common DC link from its own transmission line. Like this active power can be provided from the overloaded lines for active power compensation in other lines. This scheme requires a rigorous maintenance of the overall power balance at the common DC terminal by appropriate control action: the underloaded lines provide appropriate active power transfer for the overloaded lines.

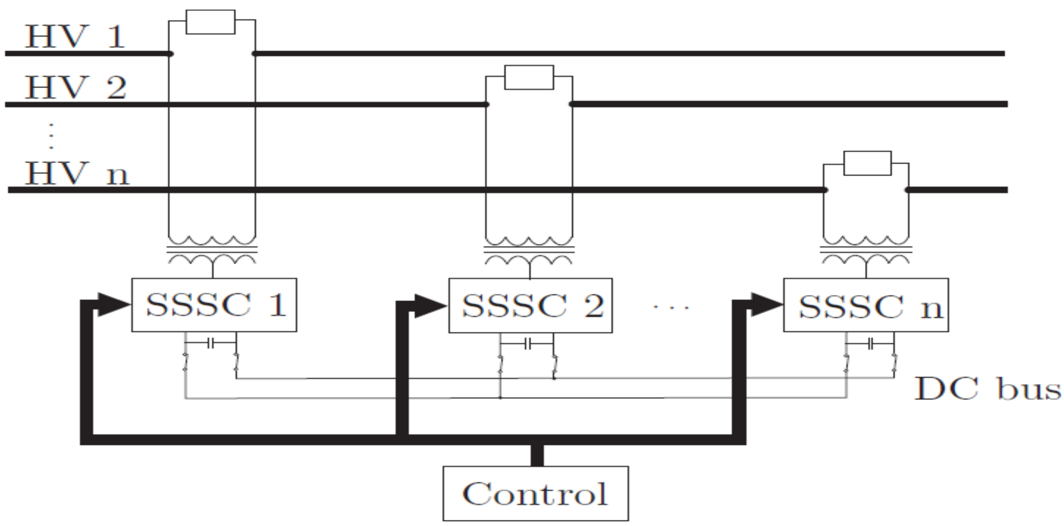

Figure 5.20 Interline Power Flow Controller

References

1. R. Mohan Mathur, Rajiv K. Varma, Thyristor-based facts controllers for electrical transmission systems, IEEE Press, USA, 2002.
2. N. G. Hingorani and L. Gyugyi, Understanding FACTS, IEEE Press, New York, 1999.
3. Y. H. Song and A. T. Johns, Eds., Flexible AC Transmission Systems (FACTS), IEEE Press, U.K., 1999.
4. IEEE Power Engineering Society, FACTS Applications, Publication 96TP116-0, IEEE Press, New York, 1996.
5. T. J. E. Miller, Ed., Reactive Power Control in Electric Power Systems, John Wiley and sons, New York, 1982.
6. E.Acha, V.G.Agelidis, O Anaya-Lara, TJE Miller, Power Electronic Control in Electric System, Newnes Power Engineering Series, UK, 2002
7. V.K.Sood,HVDC and FACTS controllers – Applications of Static Converters in Power System, APRIL 2004 , Kluwer Academic Publishers.
8. A.T.John, “Flexible A.C. Transmission Systems”, Institution of Electrical and Electronic Engineers (IEEE), 1999.
9. K.R.Padiyar,” FACTS Controllers in Power Transmission and Distribution”, New Age International(P) Limited, Publishers, New Delhi, 2008
10. J.Arrillaga, Y.H.Liu, Neville R Watson, Flexible Power Transmission: The HVDC options, John Wiley and Sons, UK, 2007
11. K. R. Padiyar and R. K. Varma, “Damping Torque Analysis of Static Var System Controllers,” IEEE Transactions on Power Systems, Vol. 6, No. 2, May 1991, pp. 458–465.
12. K. R. Padiyar and R. K. Varma, “Concepts of Static Var System Control for Enhancing Power Transfer in Long Transmission Lines,” Electric Machines andPower Systems, Vol. 18, No. 4–5, July–October 1990, pp. 337–358.
13. L. Gyugyi, “Fundamentals of Thyristor-Controlled Static Var Compensators in Electric Power System Applications,” IEEE Special Publication 87TH0187-5- PWR, Application of Static Var Systems for System Dynamic Performance, 1987, pp. 8–27.
14. P. Kundur, Power System Stability and Control, McGraw-Hill, New York, 1993.
15. P. K. Dash, S. Mishra, and A. C. Liew, “Fuzzy Logic Based Var Stabilizer for Power System Control,” IEE Proceedings on Generation, Transmission, and Distribution, Vol. 142, No. 6, November 1995. IEEE Power Engineering Society, FACTS Applications, Document 96TP116-0, IEEE Press, New York, 1996.
16. Noroozian.M, Angqyist.L, Ghandhari.G and Andersson.G, (1997), “Use Of UPFC For Optimal Power Flow Control” IEEE Transactions On Power Delivery, No.4, Vol.12