31

Flexible AC Transmission Systems

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This chapter presents the basic operation principles of FACTS devices. Starting with a brief introduction on the concept and its origin, the text then focuses on the ideal behavior of each basic shunt and series FACTS device. Guidelines on the synthesis of the first generation of these devices, based on thyristors, are presented, followed by the newer generations of FACTS devices based on self-commutated semiconductor switches.

31.1 Introduction

In 1988, Hingorani [1] published a paper entitled "Power Electronics in Electric Utilities: Role of Power Electronics in Future Power Systems," which proposed the extensive use of power electronics for the control of AC systems [2]. The basic idea was to obtain AC systems with a high level of control flexibility, just as in high voltage direct current (HVDC) systems [3], based on the use of the thyristor, as well as on self-commutated (controllable turn-on and turn-off) semiconductor devices like gate turn-off thyristors (GTOs), insulated gate bipolar transistors (IGBTs), and integrated gate controlled thyristors (IGCTs) [4, 5], which were not developed at that time yet.

The switching characteristics of thyristors – controlled turn-on and natural turn-off – are appropriate for using in line-commutated converters, like in conventional HVDC transmission systems with a current source in the DC side. In this latter application, the technology for series connection of thyristors is very important due to the high-voltage characteristics of the transmission voltage. This is a well-known technology. Maximum breakdown voltage and current conduction capabilities are around 8 kV and 4 kA, respectively. These are some features that make thyristors important for very high-power applications, although they also present some serious drawbacks: the lack of controlled turn-off capability and low switching speeds.

Self-commutated switches are adequate for use in converters where turn-off capability is necessary. The device with highest ratings in this group was, for a long time, the GTO, with maximum switching capability of 6 kV and 6 kA. At present, there are IGBTs with ratings in the range of 6.5 kV and 3 kA and IGCTs with switching capability of about 6 kV and 4 kA. Other semiconductors switches – like the injection enhanced gate transistor (IEGT), faster than IGBTs and with high ratings – can be also found in the market. The GTOs and IGCTs are devices that need turn-on current rate of change (*di/dt*) limitation, normally achieved with a small inductor. Normally, GTOs also need a snubber circuit for voltage rate of change (*dv/dt*) limitation.

The GTOs, IGCTs, and IGBTs are the most used options for self-commutated high-power converters. Because the switching time of these devices is in the microsecond range (or below), their series connection is more complicated than in the case of thyristors. However, there are examples of series connections of various GTOs or IGCTs and, in the case of IGBTs, the number of series connected devices can go as high as 32 [6].

Because of the commutation nature of the thyristors, the converters used in HVDC systems are of the current source type [7]. On the other hand, the force commutated converters using the self-commutated devices are basically of the voltage source type. More details about current source and voltage source converters can be found in many power electronics text books, e.g. [3, 7].

31.2 Ideal Shunt Compensator

A simple and lossless AC system is composed of two ideal generators and a short transmission line, as shown in Fig. 31.1, is considered as basis to the discussion of the operating principles of a shunt compensator [8]. The transmission line is modeled by an inductive reactance X_L. In the circuit, a continuously controlled voltage source is connected in the middle of the transmission line. It is assumed that the voltage phasors V_S and V_R have the same magnitude and are phase-shifted by δ. The subscript "*S*" stands for "Source" and "*R*" stands for "Receptor." Figure 31.2 shows the phasor diagram of the system in Fig. 31.1, for the case in which the compensation voltage phasor V_M has also the same magnitude as V_S and V_R and its phase is exactly $(-\delta/2)$ with respect to V_S and $(+\delta/2)$ with respect to V_R.

In this situation, the current I_{SM} flows from the source and the current I_{MR} flows into the receptor. The phasor I_M is the resulting current flowing through the ideal shunt compensator, figure shows that this current I_M, in this case, is orthogonal to the voltage V_M, which means that the ideal shunt compensator voltage source does not have to generate or absorb active power and have only reactive power in its terminals.

From Fig. 31.2 and knowing that no active power flows to or from the ideal shunt compensator, it is possible to calculate the power transferred from V_S to V_R which is given by:

$$P_S = \frac{2V^2}{X_L} \sin(\delta/2) \tag{31.1}$$

where, P_S is the active power flowing from the source, V is the magnitude of the voltages V_S and V_R.

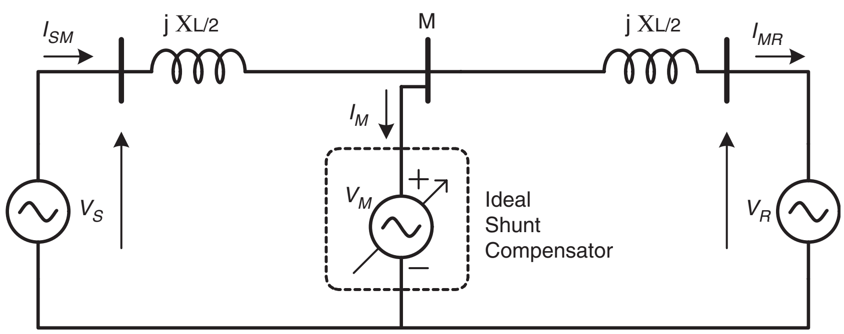


FIGURE 31.1 Ideal shunt compensator connected in the middle of a transmission line.

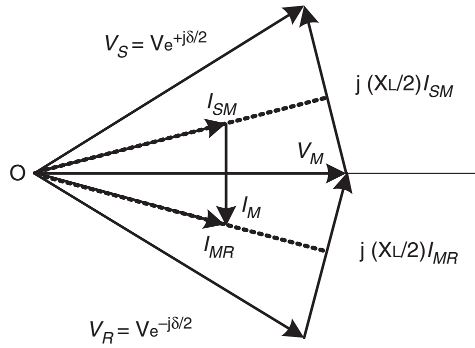


FIGURE 31.2 Phasor diagram of the system with shunt reactive power compensation.

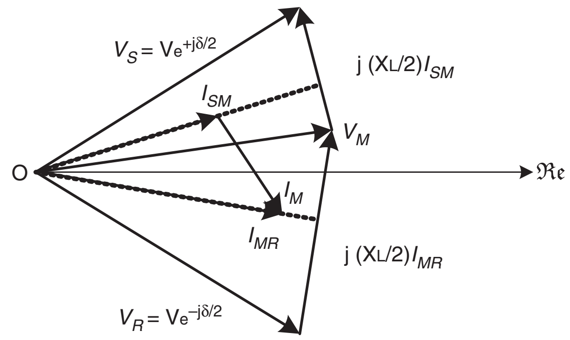


FIGURE 31.3 Phasor diagram of the system with shunt reactive and active power compensation.

If the ideal shunt compensator were not present, the transferred power would be given by:

$$P_S = \frac{V^2}{X_L} \sin\delta \tag{31.2}$$

Since $2\sin(\delta/2)$ is always greater than $\sin\delta$ for δ in the range of $[0, 2\pi]$, the ideal shunt compensator does improve the power transfer capability of the transmission line. This voltage source is in fact operating as an ideal reactive power shunt compensator.

If the phase angle between V_M and V_S is different from $\delta/2$ (as shown in Fig. 31.3), the power flowing through V_M has both active and reactive components.

With the characteristics of the ideal shunt compensator presented above it is possible to synthesize power electronics-based devices to operate as active or reactive power compensators. This is discussed in the following sections. It will be seen that the requirements of the device synthesis with actual semiconductor switches for the situations of reactive or active power compensation are different, due to the need of energy storage element or energy source if active power is to be drained/generated by the shunt compensator.

31.3 Ideal Series Compensator

Similar to the previous section, the ideal series compensator is modeled by a voltage source for which the phasor is V_C, connected in the middle of a lossless transmission line as shown in Fig. 31.4.

The current flowing through the transmission line is given by:

$$I = (V_{SR} - V_C)/jX_L \tag{31.3}$$

where $V_{SR} = V_S - V_R$.

If the ideal series compensator voltage is generated in such a way that its phasor V_C is in quadrature with line current I, this series compensator does not supply neither absorb active power. As previously discussed, power at the series source is only reactive and the voltage source may, in this particular case,

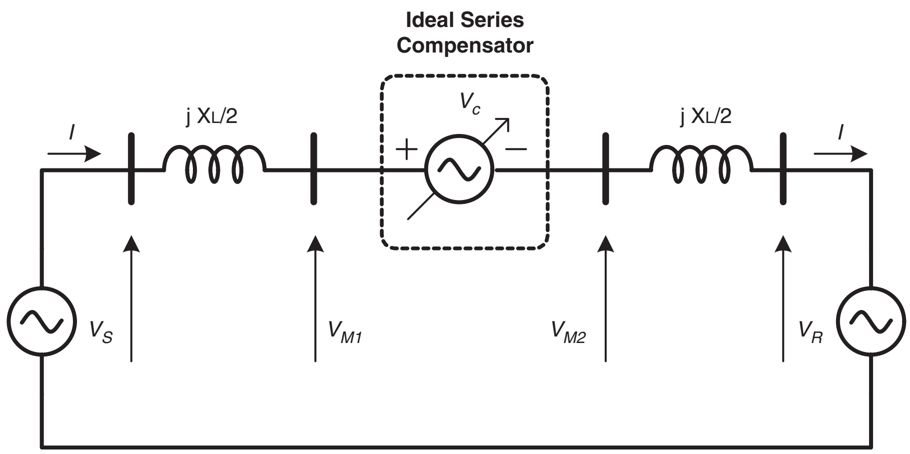


FIGURE 31.4 Ideal series compensator connected in the middle of a transmission line.

be replaced by capacitive or inductive equivalent impedance. The equivalent impedance would then given by

$$X_{eq} = X_L(1 + s) \tag{31.4}$$

where,

$$s = \frac{X_{Comp}}{X_L}; \quad (0 \leq |s| \leq 1) \tag{31.5}$$

is the compensation factor and X_{Comp} is the series equivalent compensation reactance, negative if capacitive and positive if inductive. In this case the compensation voltage is given by

$$V_C = I_L X_{eq} \tag{31.6}$$

and the transmitted power is equal to

$$P_s = \frac{V^2}{X_L(1 - s)} \sin\delta \tag{31.7}$$

Equation (31.6) shows that the transmitted power can be considerably increased by series compensation, choosing a proper compensation factor s. The reactive power at the series source is given by

$$Q_{CS} = \frac{2V^2}{X_L} \frac{s}{(1 - s)^2}(1 - \cos\delta) \tag{31.8}$$

The left-hand side of Fig. 31.5a shows the phasor diagram of the system in Fig. 31.4 without the ideal series compensator. The voltage phasor V_L on the line reactance X_L and the compensator voltage phasor V_C are shown for a given compensation level, assuming that this voltage V_C corresponds to a capacitive compensation. In this case, the line current phasor leads voltage phasor V_C by 90° and the total voltage drop in the line V_Z $(=V_S - V_R - V_C)$ is larger than the original voltage drop V_L. The current flowing in the line is larger after compensation than before. This situation shows the case where the series compensator is used to increase power flow.

The left-hand side of Fig. 31.5b shows the same non-compensated situation as in the previous case. In the middle is shown the case of inductive compensation. In this case, the compensation voltage V_C is in phase with the line drop voltage V_L, producing an equivalent total voltage drop V_Z smaller than in the original case. As a result, the current phasor I flowing in the line is smaller than before compensation. This kind of compensation may be interesting in the case that the power flowing through the line has to be decreased. In either capacitive or inductive compensation modes, no active power is absorbed or generated by the ideal series compensator.

Figure 31.6 shows an AC system with an ideal generic series compensation voltage source V_C for the general case where it may not be in quadrature with the line current. In this case, the compensator is able to fully control the phase difference between the two systems, thus controlling also the active and reactive power exchanged between them. However, in this case, the compensation source V_C may have to absorb or generate active power (P_C), as well as to control the reactive power (Q_C).

Figure 31.7 shows the phasor diagram for the case of this ideal generic series compensator. This figure shows also a dashed-line circle with the locus of all the possible position

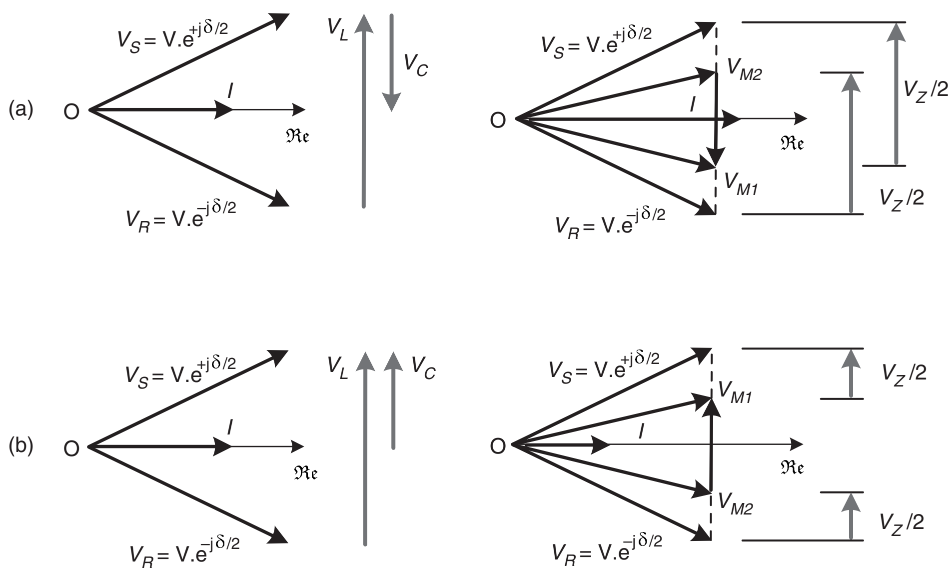


FIGURE 31.5 Phasor diagram of the series reactive compensator: (a) capacitive and (b) reactive mode.

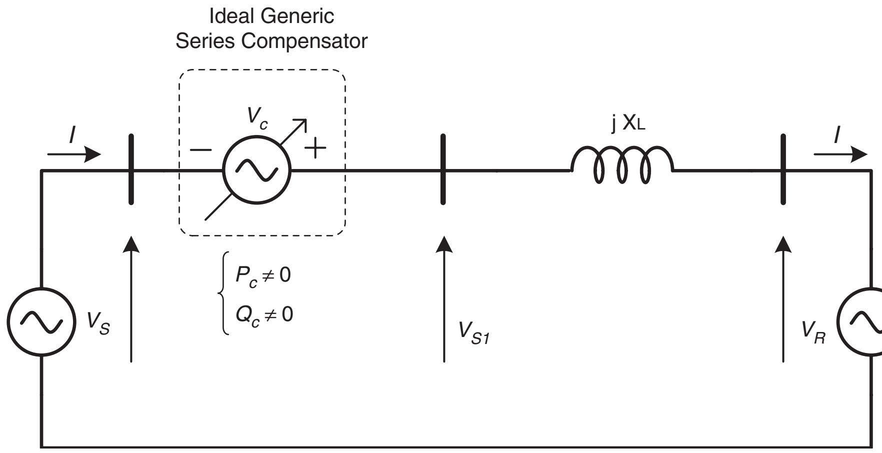


FIGURE 31.6 Ideal generic series compensator.

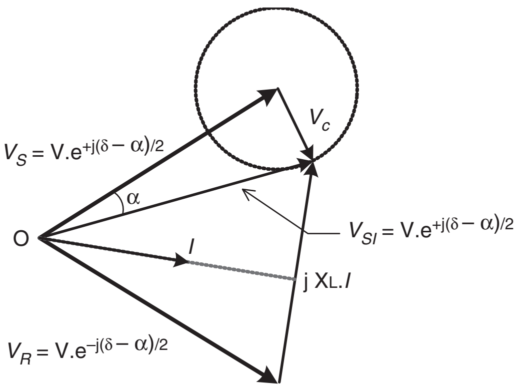


FIGURE 31.7 Phasor diagram of the AC system compensated with an ideal generic series compensator.

that the compensation voltage V_C could take, assuming that the magnitude shown for this voltage is its maximum. Naturally, if the sum of the compensation voltage and the source voltage V_S is on the circle, the magnitude of V_{S1} may be smaller or larger than the magnitude of V_S.

If the compensation voltage V_C added in series with V_S produces a voltage V_{S1} that has the same magnitude as V_S but is phase-shifted by an angle α, the power flowing through the transmission line in Fig. 31.6 is given by:

$$P_S = \frac{V^2}{X_L} \sin(\delta - \alpha) \tag{31.9}$$

Equation (31.8) shows that transmitted power increases as the phase difference $(\delta - \alpha)$ reaches 90°. However, its maximum value is the same as in the case of no compensation. The difference is that with this compensator the angle between the two voltage sources at the terminals of the line can be controlled.

In Fig. 31.7, voltage V_C may have any phase angle with respect to line current. Therefore, it may have to supply or absorb active power, as well as control reactive power. As in the case of the shunt device, this feature must also be taken into account in the synthesis of the actual devices. As a first approximation, when the goal is to control active power flow through the transmission line, compensator location seems to be just a question of convenience.

Figure 31.8 summarizes the active power transfer characteristics in a transmission line as a function of the phase difference δ between its sending and receiving ends, as shown in Figs. 31.1 and 31.2, for the cases of the line without compensation, line with series or shunt compensation, as well as line with a phase-shift compensation. These characteristics are drawn on the assumption that the source voltages V_S and V_R (see Fig. 31.2) have the same magnitude, which is a conventional situation. A 50% series compensation ($s = 0.5$ as defined in Eq. (31.4) presents a significant increase in the line power transfer capability.

In general, series compensation is the best choice for increasing power transfer capability. The phase-shifter compensator is important to connect two systems with excessive or uncontrollable phase difference. It does not increase power transfer capability significantly; however, it may allow the adjustment of large or highly variable phase differences. The shunt compensator does not increase power transfer capability in a significant way in its normal operating region, where the angle δ is naturally below 90° and in general around 30°. The great importance of the shunt compensator is the increase in the stability margin, as explained in Fig. 31.9.

Figure 31.9 shows the power transfer P_δ characteristics of a transmission line, which is first assumed to be transmitting power P_{S0} at phase angle δ_0. If a problem happens in the line (a fault, for example) the turbine that drives the generator cannot change its input mechanical power immediately even if there is no power transmission for a short time. This situation

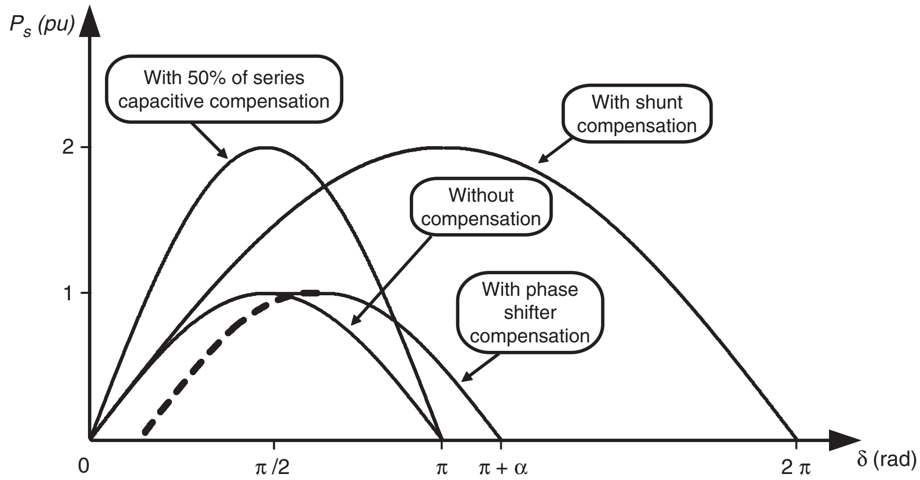


FIGURE 31.8 Power transfer characteristics for the case of shunt, series, and no compensation.

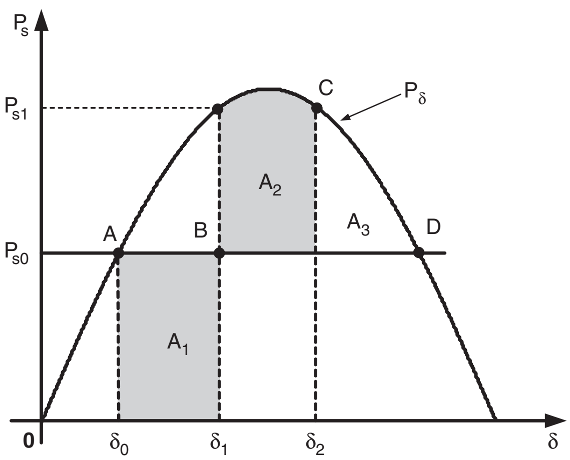


FIGURE 31.9 Stability margin characteristics – stable situation.

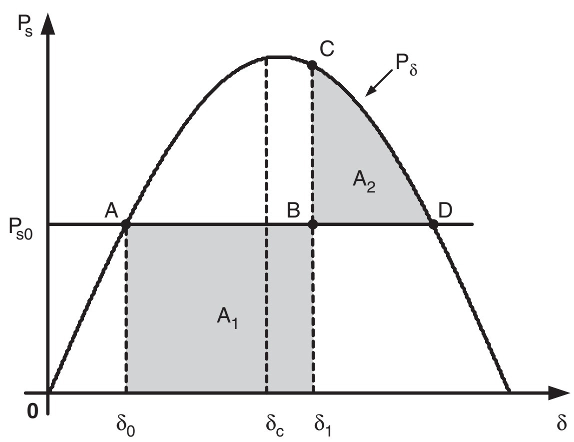


FIGURE 31.10 Stability margin characteristics – unstable situation.

accelerates the generator, increasing its frequency and leading to an increase of the phase angle δ to δ_1. If the line restarts operation at the instant corresponding to this phase angle δ_1, the transmitted power will be P_1, which is larger than P_0 and decelerates the turbine/generator. The area A_1 corresponds to the energy that accelerated the turbine. As the frequency gets higher than the rated frequency at (P_{S1}, δ_1), the phase angle will increase up to δ_2, where the area A_2 is equal to the area A_1. If the area given by the A_2 plus A_3 is larger than A_1, the system is said to be dynamically stable. On the contrary, if it is not possible to have an area A_2 equal to A_1, the system is said to be unstable. An unstable situation is shown in Fig. 31.10, where the system is the same as in Fig. 31.9 but with a longer interval with no power transmission. In this case, the turbine/generator accelerates more than in the case in Fig. 31.9 and the phase angle δ goes over its critical value δ_c reaching δ_1. Therefore, the area below the P_δ curve to decelerate the system is not enough leading to an unstable system because A_2 is smaller than A_1.

Looking at Fig. 31.8 it is possible to see that, depending on the operating point, all three compensation methods increase the stability margin as the area under the curve of transmitted power P_δ versus phase angle δ is increased. However, the ideal shunt compensator is the one that most increases this area, this is the reason why it is said to be the best option to increase the stability margin.

31.4 Synthesis of FACTS Devices

It has been stated that the synthesis of the compensators presented in Sections 31.2 and 31.3 may be achieved with thyristors or self-commutated switches like GTO, IGBT, or IGCT. Each type of switches leads to devices with different operating principles and synthesis concepts, and that is a reason why they should be discussed separately. Terms and definitions for most of the FACTS devices are given in [9].

Thyristor-based FACTS devices use line or natural commutation together with large energy storage elements (capacitors or reactors). On the other hand, devices based on self-commutating switches like GTOs, IGCTs, or IGBTs uses gate-controlled commutation. In general, it is said that the first generation of FACTS devices is based on conventional line commutated thyristors and the subsequent generations are based on gate-controlled devices. The most important FACTS devices based on thyristors and self-commutating devices are presented in the next sections.

31.4.1 Thyristor-based FACTS Devices

31.4.1.1 Thyristor-controlled Reactor

The most used thyristor-based FACTS device is the thyristor-controlled reactor (TCR) shown in Fig. 31.11a. This is a shunt compensator which produces an equivalent continuous variable inductive reactance by using phase-angle control. Figure 31.11b shows the voltage and current waveforms of the TCR. The current is controlled by the firing-angle α – its fundamental component can be larger or smaller depending on the angle α which may vary from 90 to 180°, measured from the zero-crossing of the voltage. At $\alpha = 90°$, the reactor is fully inserted in the circuit and for $\alpha = 180°$, the reactor is completely out of the circuit. Figure 31.12 shows the equivalent admittance of the TCR as function of the firing-angle α. Naturally, this admittance is always inductive.

31.4.1.2 Thyristor-switched Capacitor

Figure 31.13 shows the thyristor-switched capacitor (TSC). In this device the word "controlled" used in the case of the reactor is substituted by "switched," because the thyristor is turned-on only when zero-voltage switching (ZVS) condition is achieved. This means that the voltage across the thyristor terminals has to be zero at the turn-on instant. In practical cases, it may be slightly positive, since thyristors need positive anode–cathode voltages to be triggered (large anode–cathode voltage during turn-on, however, may produce a large current spike that may damage the thyristors). Therefore, due to this switching characteristic, the thyristors can only connect the capacitor to the grid or disconnect it. Consequently, only step-like control is possible and, therefore, a continuous control is not possible. The capacitor connection to or disconnection from the grid is normally done at very low frequencies and the harmonics, when they appear, are not a serious concern.

31.4.1.3 Static Var Compensator

The use of the TCR shown in Fig. 31.11 or the TSC shown in Fig. 31.13 allows only continuous inductive compensation or capacitive discontinuous compensation. However, in most applications, it is desirable to have continuous capacitive or inductive compensation. The static var compensator (SVC) is generally designed to operate in both inductive and capacitive continuous compensation [10, 11]. The TCR serves as the controller basis for the conventional SVC used for reactive power compensation, for either voltage regulation or power factor correction.

Figure 31.14 shows a single-line diagram of a SVC, where the TCRs are Δ connected and the capacitors are Y connected.

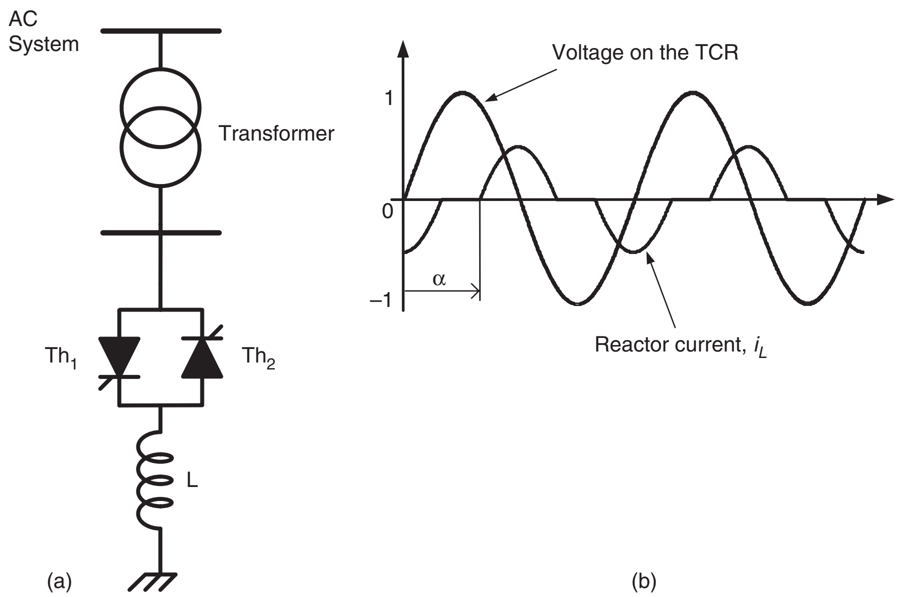


FIGURE 31.11 (a) TCR and (b) its voltage and current waveforms.

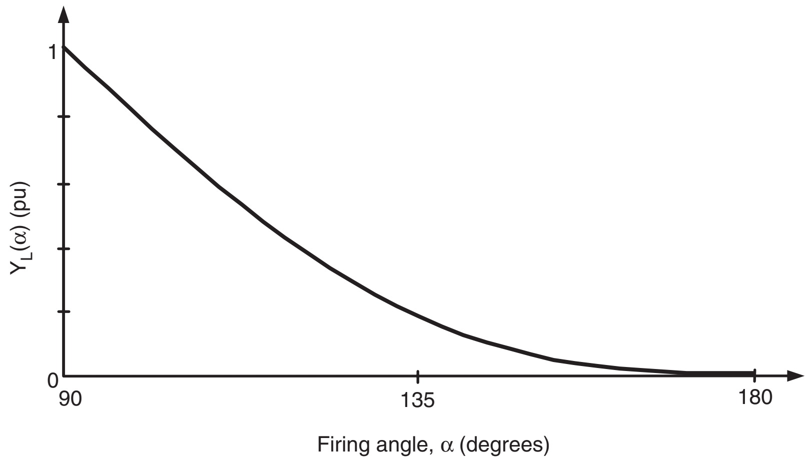


FIGURE 31.12 Equivalent admittance of a TCR as function of the firing-angle α.

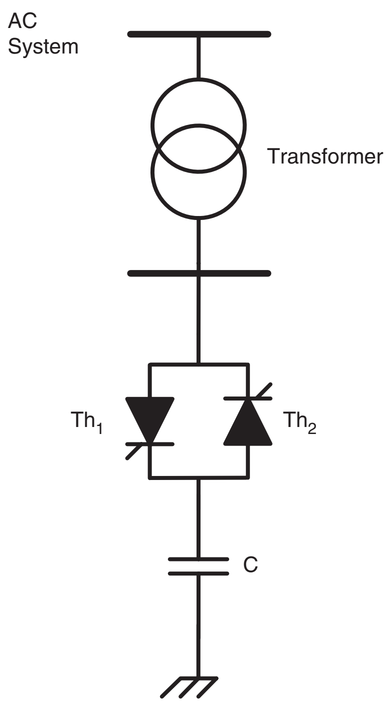


FIGURE 31.13 Thyristor-switched capacitor.

The circuit does not show the filters that are normally needed due to the switching-generated harmonics. In some cases, the fixed capacitor can be replaced by a TSC to get more flexibility in terms of control range.

The capacitor of the SVC is calculated in such a way as to generate the maximum capacitive reactive power that it has to control. This condition is achieved when the thyristors are turned-off ($\alpha = 180°$). On the other hand, the TCR inductor maximum reactive power has to be greater than the reactive power of the capacitor bank. In this way, the SVC is able to control the reactive power from capacitive to inductive. The maximum inductive reactive power is given for the case when the thyristors are turned-on at minimum firing-angle ($\alpha = 90°$). Thus, the SVC can control reactive power from maximum capacitive for $\alpha = 180°$ to maximum inductive for $\alpha = 90°$. In this sense, the SVC represents an adjustable fundamental frequency susceptance to the AC network, controlled by the firing-angle of the TCR thyristors ($90° < \alpha < 180°$).

The SVC is well-known and many examples of successful applications can be found around the world.

Due to the once-per-cycle thyristor firing with phase-angle control, current with low-order harmonic components appears and Y–Δ transformers and passive filters may be needed to eliminate them. Three sets of TCRs connected in the Δ side of Y–Δ transformers form a conventional 6-pulse TCR. To minimize harmonic generation, it is common to have two sets of transformers connected in Y–Δ and Δ–Δ with the TCR connected in the Δ side forming a 12-pulse TCR.

31.4.1.4 Thyristor-switched Series Capacitor

Figure 31.15 shows the thyristor-switched series capacitor (TSSC). In this device, the thyristors should be kept untriggered so as to connect the capacitors in series with the transmission line. If the thyristors are turned-on, the capacitor is bypassed. Thyristors turn-on must be at a zero-voltage condition (ZVS), as it occurs in the case of the TSC, to avoid current spikes in the switches. An example of an application based on this concept is presented in [12].

This compensation system has the advantage of being very simple. However, it does not allow continuous control. If the connection/disconnection of the capacitors is to be made at sporadic switching, no harmonic problem occurs. Depending on the frequency the thyristors are switched, harmonic or sub-harmonics may appear. In this arrangement, it is interesting to choose the value of the capacitors in such a way that many different combinations can be achieved. For example, if the

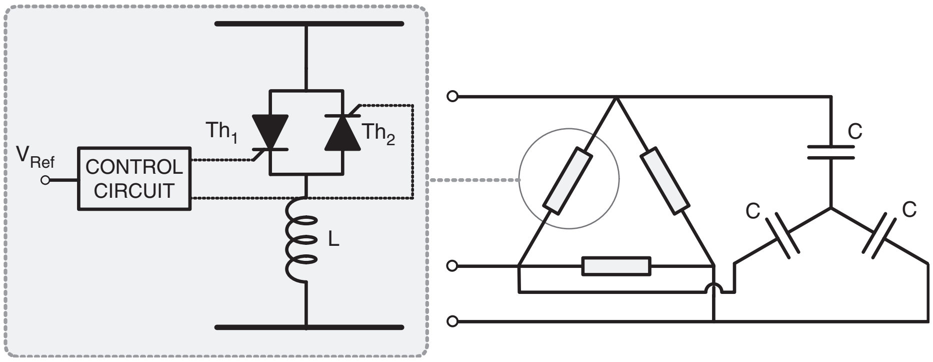


FIGURE 31.14 6-Pulse SVC.

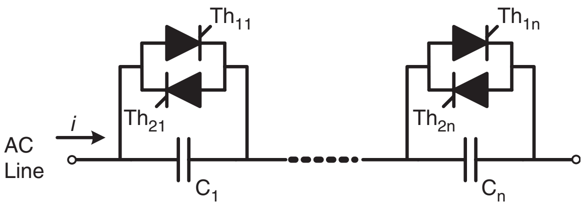


FIGURE 31.15 Thyristor-switched series capacitors.

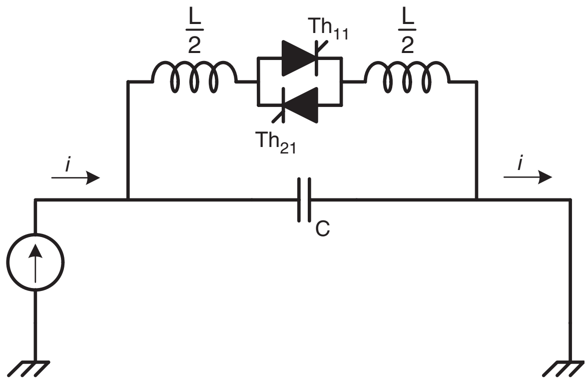


FIGURE 31.16 Thyristor-controlled series capacitors.

total number of capacitors is three, they could have values proportional to 1, 2, and 3. Therefore, by combining these values it is possible to obtain equivalent capacitor proportional to 1, 2, 3, 4, 5, and 6.

31.4.1.5 Thyristor-controlled Series Capacitor (TCSC)

Figure 31.16 shows the thyristor-controlled series capacitor (TCSC). In this figure, the transmission line and the voltage sources in its ends are represented by a current source because this is the actual behavior of most of the transmission system. This compensator is also based on the TCR which was first developed for shunt connection. When the TCR is used connected in series with the line, it has to be always connected in parallel with a capacitor because it is not possible to control the current if the equivalent of the transmission line and the sources is a current source. This circuit is similar to the conventional SVC, with the difference that the TCSC is connected in series with the line. In this compensator, the equivalent value of the series connected reactor can be continuously controlled by adjusting the firing-angle of the thyristors. As a consequence, this device presents a continuously controllable series capacitor. Various practical system based on this concept is under operation around the world [12–14]. This device has been used for power flow control and power oscillation damping.

Figure 31.17 presents the current and voltage waveforms in the TCSC, showing that although there is a large amount of harmonics in the capacitor and reactor currents, capacitor voltage is somehow almost sinusoidal. In actual applications, these harmonics are not a serious concern and they are filtered by the capacitor itself and the transmission line impedance.

Figure 31.18 shows the equivalent impedance of the TCSC as a function of the firing-angle α. This figure shows that this device has both capacitive and inductive characteristic regions. It also has a resonance for α around 145°, in this example. In normal operation, the TCSC is controlled in the capacitive compensation region where its impedance varies from its minimum value $Z_{\min}$ for firing-angle $\alpha = 180°$ and its maximum safe value $Z_{\max}$ for α around 150°. Operation with α close to the resonance region is not safe. This device can operate also in the inductive region, but in this case, normally it is used only with $\alpha = 90°$ to decrease power transfer capability of the transmission line.

31.4.1.6 Thyristor-controlled Phase Angle Regulator

The thyristor-controlled phase angle regulator (TCPAR), shown in Fig. 31.19 as an example, may improve considerably the controllability of a utility power transmission system. In this figure, only control of phase "a" is detailed. The series

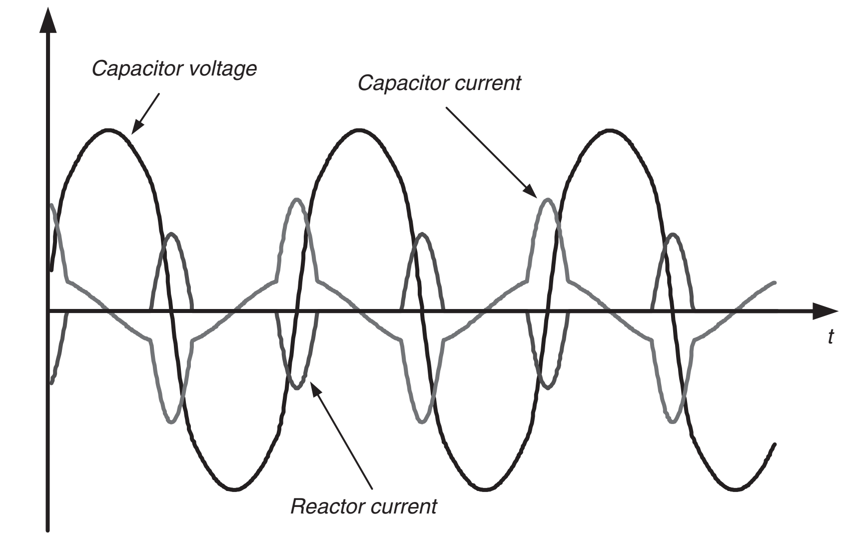


FIGURE 31.17 TCSC voltage and current waveforms.

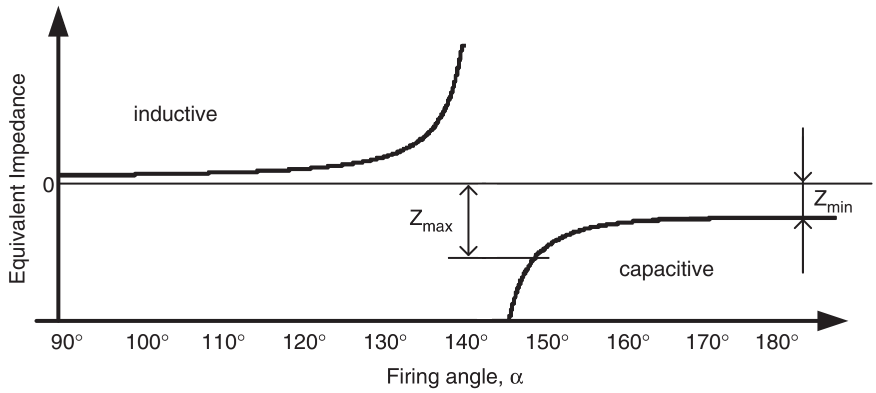


FIGURE 31.18 TCSC equivalent reactance.

voltage generated in phase "a" comes from three secondary windings of a transformer whose primary side is connected between phases "b" and "c." Each of the three secondary windings can be connected in series with the line through the thyristors switching. The thyristors are connected in anti-parallel, forming bidirectional naturally commutated switches. By turning on a set of thyristors, a voltage whose magnitude can be controlled by phase control is connected in series with the transmission line. The number of secondary windings is chosen as to decrease harmonic content of the series compensation voltage.

The TCPAR in Fig. 31.19 has some peculiarities that should be pointed out. One of them is that active power can only flow from the shunt to the series windings – therefore reverse power flow is not possible. The compensation voltage phasor, as shown in Fig. 31.20, has a limited range of variation: in the case of phase "a," its locus is along a line orthogonal to V_a, because the injected voltage is in phase with the voltage $(V_b - V_c)$. As a consequence, it is not possible for the TCPAR to generate a compensating voltage phasor whose locus is a circle, as shown in Fig. 31.7, for the case of an ideal generic series compensator.

Other configuration of phase-shifters can be found in the literature, e.g. [15, 16].

31.4.2 FACTS Devices Based on Self-commutated Switches

There are various different types of FACTS devices based on self-commutated switches and the names used here are in accordance with the names published in [9]. Some of them are newer devices and are not in that reference. In this case, the name used is as it appears in the literature. In [2] it is possible to find most of the details of FACTS devices.

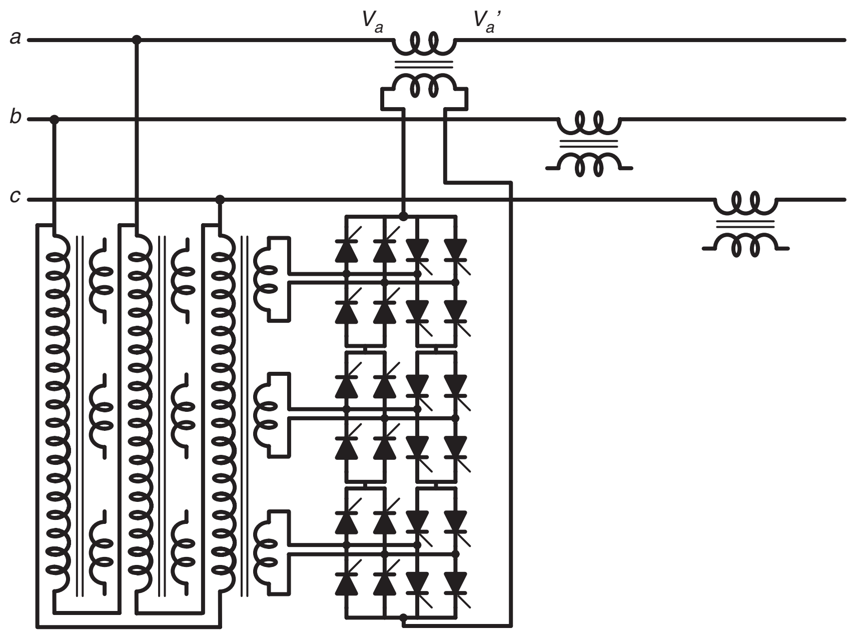


FIGURE 31.19 Thyristor-controlled phase angle regulator (TCPAR).

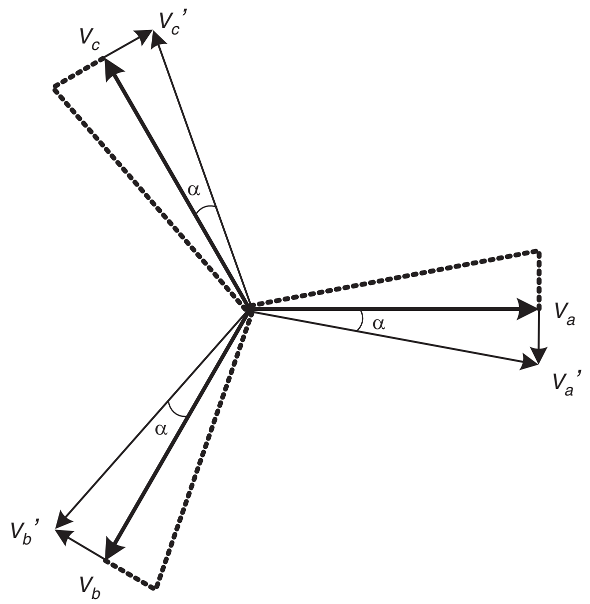


FIGURE 31.20 Phasor diagram of the TCPAR in Fig. 31.19.

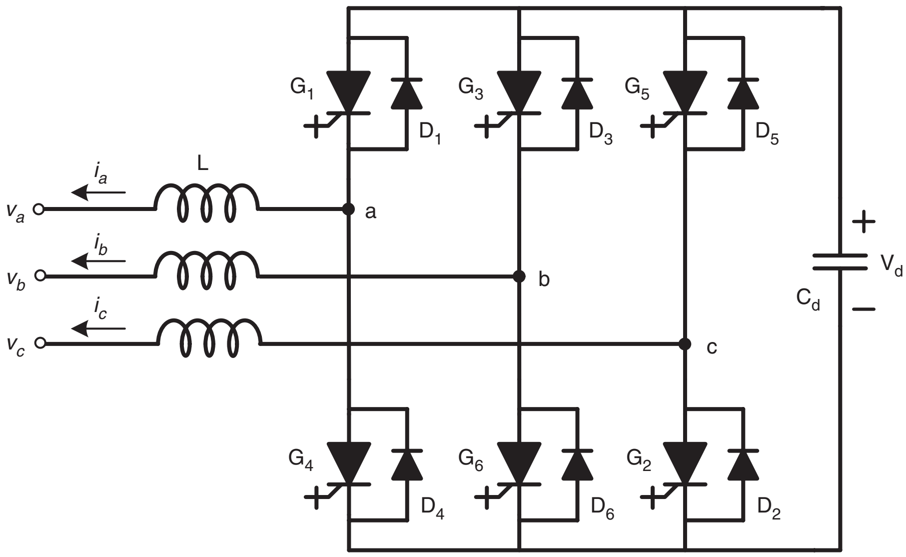
31.4.2.1 The Static Synchronous Compensator

The development of high-power self-commutated devices like GTOs, IGBTs, and IGCTs has led to the development of high-power voltage source inverters (VSI), as the 6-pulse 2-level VSI shown in Fig. 31.21a [4] or the 3-level neutral point clamped VSI shown in Fig. 31.21b [17]. In the figure, the switches are GTOs (they could be IGBTs, IGCTs, or other self-commutating switches) with an anti-parallel-connected diode, which operates with a unidirectional voltage blocking capability and a bidirectional current flow. In contrast, the current source inverters (CSI) used in HVDC transmission systems use switches (thyristors) operating with unidirectional current flow and bidirectional voltage blocking capabilities.

In a conventional VSI, for industrial applications, a voltage source is connected at the inverter DC side. However, in the case that only reactive power has to be controlled, the DC voltage source may be replaced by a small capacitor. If active power has to be absorbed or generated by the compensator, an energy storage system has to be connected at the DC side of the VSI.

In practical applications, small reactors (L) are necessary to connect the VSI to the AC network. This is necessary to avoid currents peaks during switching transients. In most cases, these small reactors are just the leakage inductance of the coupling transformers.

The first high rating STATCOM is under operation since 1991 [18] in Japan and uses three single-phase VSI to form one 3-phase, 6-pulses, 10 MVA converter. To guarantee low losses, the switching frequency is equal to the line frequency and a total of eight sets of 3-phase converters are used to form a 48-pulse converter. All the converters have a common DC capacitor in their DC side. In the AC side, the converters are connected in series through a zigzag transformer to eliminate low frequency voltage harmonics. The device, whose compensation capability is 80 MVA, was developed to increase the transient stability margin of a transmission line and has allowed a 20% increase of the transmitted power above the previous stability limit. Since it was developed for improving



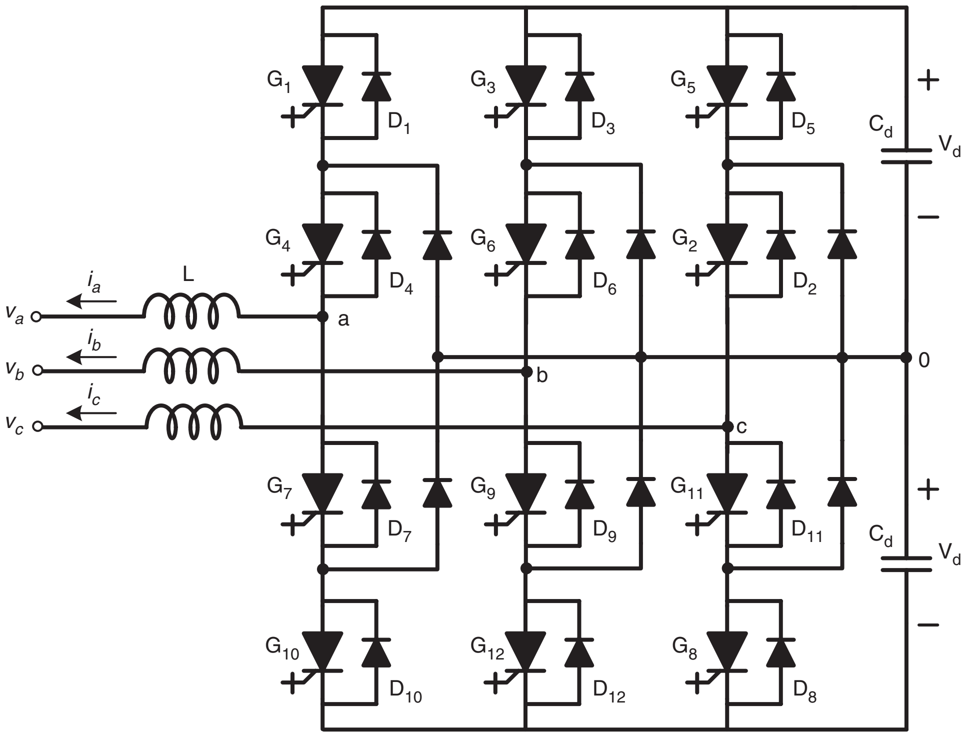


FIGURE 31.21 (a) Basic 6-pulse VSI 2-level var compensator and (b) basic 3-level var compensator.

transient stability margin, it normally operates in standby mode, without reactive compensation and, consequently, low losses. During transient situation, this STATCOM operates for a short time until the system is stable.

The development of a ± 100 Mvar STATCOM, in USA, was reported in [19]. It is based on eight sets of 3-phase bridge converters, similar to that shown in Fig. 31.21b and was developed for reactive power control, so it can operate continuously with acceptable losses. The switching frequency is equal to line frequency and the number of pulses is 48 and, therefore, the output voltage waveform is almost sinusoidal and harmonic filters are not used in both cases referred in [18] and [19].

31.4.2.1.1 Basic Switching Control Techniques In FACTS applications the power ratings of the converters are in the range of some MW to hundreds of MW and the switching frequency is lower, if compared to the switching frequency used in industrial application converters, to avoid excessive switching losses. However, there are various switching control types, being the most known so far:

- Multi-pulse converters switched at line frequency, as in [18] and [19];
- Pulse width modulation (PWM) with harmonic elimination technique [20];
- Sinusoidal PWM [6];
- Cascade converters [21].

31.4.2.1.2 Multi-pulse Converters Switched at Line Frequency The multi-pulse converter was the first choice for STATCOM application as it presents low losses and low harmonic content [18, 19]. Figure 31.22 shows a 24-pulse converter based on 3-phase, 2-level 6-pulse converters. In this case, the zigzag transformers are connected in such a way as to produce phase differences of 15, 30, 45, and 60°. With this arrangement, the resulting output voltage and its harmonic spectrum are as shown in Fig. 31.23. The first two harmonics components are the 23rd and 25th order harmonics. Figure 31.24 shows the voltage waveform for a 48-pulse converter and its respective harmonic spectrum. In this case, the first two harmonic components are the 47th and 49th order harmonics. The total harmonic distortion (THD) for the 24- and 48-pulse converters are 7 and 3.3%, respectively. These converters can also be built by using 3-level converters. However, one drawback of the multi-pulse converter is the complexity of the transformers, which have to operate with high harmonic content in their voltage as well as various different turns ratio.

31.4.2.1.3 PWM (Pulse Width Modulation) with Harmonic Elimination Technique One way to avoid the complexity of the multi-pulse converters is to use PWM with harmonic elimination technique [20]. With this approach, it is possible to use relatively low switching frequency and, consequently, have low switching losses. The PWM modulation is obtained by offline calculation of the switches "on" and "off" instants in such a way as to eliminate the low frequency harmonics. Figure 31.25a shows an example of voltage waveform with "on" and "off" instants calculated in such a way as to eliminate the 5th, 7th, 11th, 13th order harmonics. This voltage corresponds to the voltage between one phase of the converter and the negative terminal of the DC side. Figure 31.25b shows the control angle as a function of the modulation index m_a. Figure 31.26 shows the harmonic spectrum for the phase-to-phase voltage waveform corresponding to that shown in Fig. 31.25a. Here it is considered that the RMS value of the fundamental component of the voltage in Fig. 31.25 is equal to unity. In Fig. 31.26 the magnitude of the fundamental component is equal to $\sqrt{3}$. The higher order harmonics in the voltage waveform can be eliminated by a relatively small passive filter, so the voltage and current at the converter terminals are practically harmonic-free and, therefore, the transformer to connect a PWM-controlled STATCOM to the grid may be a conventional transformer designed for sinusoidal operation.

31.4.2.1.4 Sinusoidal PWM The sinusoidal PWM control technique is possibly the simplest to implement and can be synthesized by comparing a sinusoidal reference voltage with a triangular carrier [4]. This switching control method needs a relatively high switching frequency which is in the range of 1–2 kHz and consequently produces higher switching losses if compared with multi-pulse STATCOM. The harmonic content at low frequencies is negligible; however, there is a relatively high harmonic content at the switching frequency which is eliminated by a passive filter.

31.4.2.1.5 Cascade Converter The basic cascade converter [21] topology is shown in Fig. 31.27. Only two single-phase full bridge converters are shown, the first and the *n*th. However, in actual application, several of them are connected in series and switched at line frequency. The resulting voltage waveform can be similar to the multi-pulse converter waveform with the advantage that there is no need of transformers to sum up the converters output voltage. Due to the line frequency switching, the switching losses are very low. The resulting voltage waveform can be almost sinusoidal depending on the number of series converters and the transformer used to connect them to the grid can be a conventional sinusoidal waveform transformer, if necessary. One drawback of this converter topology is that it is not possible to have a back-to-back connection. The need to have one DC capacitor for each single-phase converter has two consequences: the number of capacitors is equal to the number of single-phase converters; and the capacitance of each capacitor has to be much higher, if compared with three-phase converters. This is because the instantaneous power in the single-phase converter has a large oscillating component at double of the line frequency and it would force a large voltage ripple in the capacitor if they were small.

31.4.2.1.6 STATCOM Control Techniques The control of reactive power in the STATCOM is done by controlling its terminal voltage. Figure 31.28 shows a simplified circuit where the AC grid is represented by a voltage source V_S behind an impedance X_L and the STATCOM is represented by its fundamental voltage V_I. Figure 31.29a shows the case when the AC grid phasor voltage V_S is in phase with the STATCOM voltage V_I and both have the same magnitude. In this case, the line current I_L is zero. Figure 31.28b shows the case when V_S is a little larger than V_I. In this case, the line current I_L,

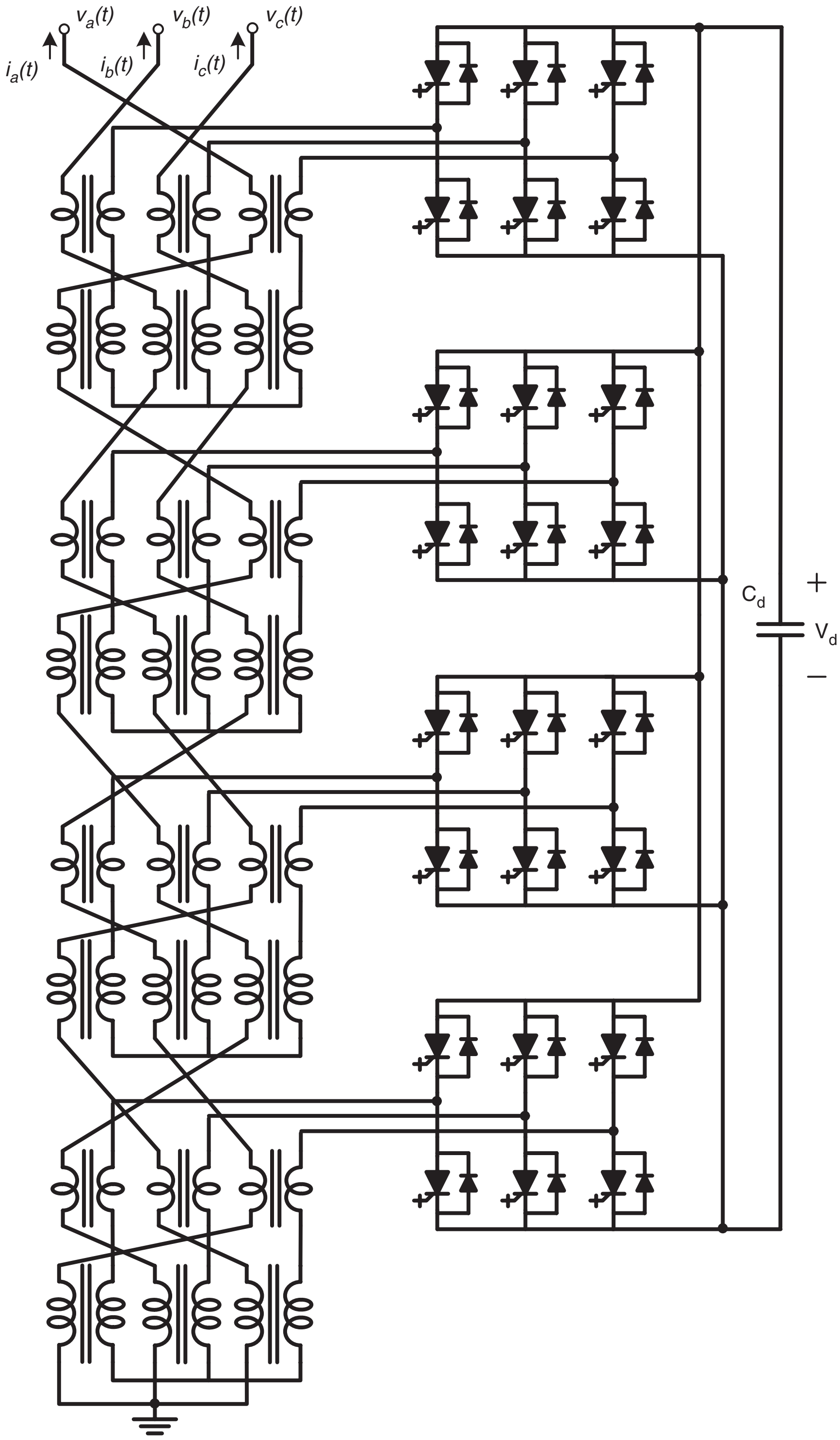


FIGURE 31.22 6-Pulse 2-level VSI-based 24-pulse var compensator.

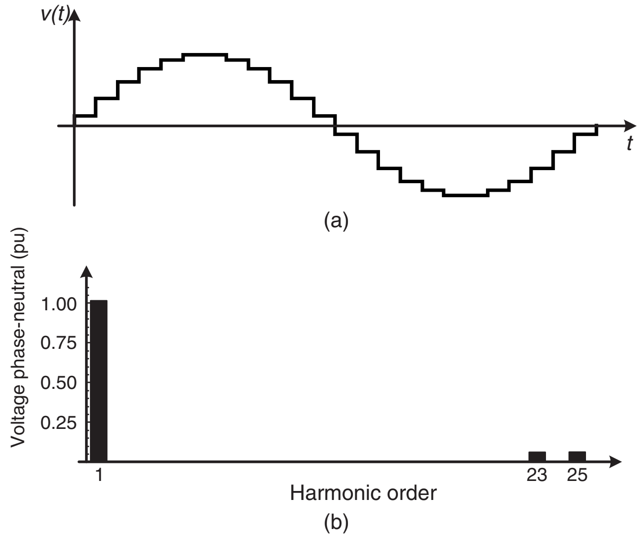


FIGURE 31.23 (a) 24-Pulse converter voltage waveform and (b) its harmonic spectrum.

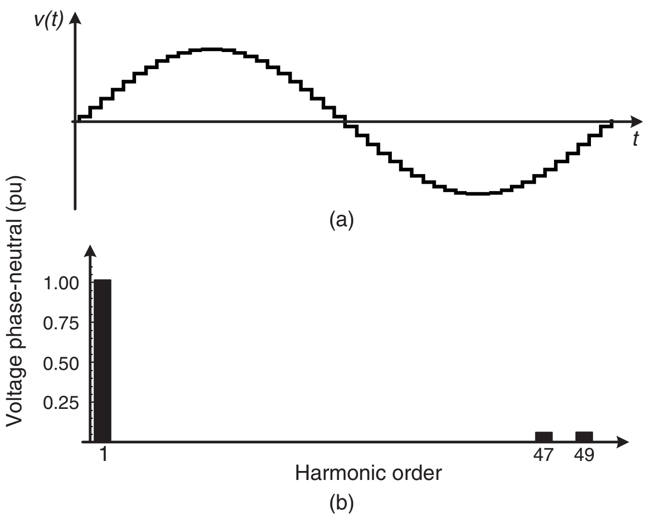


FIGURE 31.24 (a) 48-Pulse converter voltage waveform and (b) its harmonic spectrum.

which lags the voltage V_L by 90°, is also lagging the AC grid phasor voltage V_S, and therefore the STATCOM is producing an inductive reactive power. On the other hand, Fig. 31.29(c) shows the case when V_S is a little smaller than V_I. As a result, the line current I_L, which lags the voltage V_L by 90°, leads the voltage V_S, and therefore the STATCOM is producing a capacitive reactive power. In summary, the STATCOM reactive power can be controlled if the magnitude of its V_I voltage is controlled, assuming that it is in phase with V_S.

– if V_S is equal to V_I there is no reactive power and no active power in the STATCOM;
– if V_S is larger than V_I the STATCOM reactive power is inductive;
– if V_S is smaller than V_I the STATCOM reactive power is capacitive.

The reactive power control in a STATCOM is, therefore, a problem of how to control the magnitude of its voltage V_I. There are two basic principles: in the case of multi-pulse converters, the output voltage magnitude can only be controlled by controlling the DC side voltage that is the DC capacitor voltage; in the case of PWM control, the DC capacitor voltage can be kept constant and the voltage can be controlled by the PWM controller itself.

Figure 31.30a shows the phasor diagram for the case when a phase difference δ between V_S and V_I is positive. The resulting line current is in such a way that produces an active power flowing into the converter, charging the DC capacitor. Figure 31.30b shows the phasor diagram for a negative phase angle δ. In this case the DC capacitor is discharged. Therefore, by controlling the phase angle δ it is possible to control the DC capacitor voltage.

In general, STATCOM based on multi-pulse converter without PWM has to control its voltage by charging or discharging the DC capacitor and this voltage has to be variable. On the other hand, STATCOM based on a PWM-controlled converter has to control DC side capacitor voltage only to keep it constant. In both cases, the principle shown in Fig. 31.30 is valid.

The STATCOM control technique presented above illustrates the basic scalar control concepts. However, this compensator can be also controlled by a vector technique [22]. In this case, the three-phase voltages are transformed to a synchronous reference frame where they can be controlled in such a way as to regulate the quadrature component of the current, which controls reactive power. The direct component of the current are used to control the DC capacitor voltage as it represents the active power.

Another way to control the STATCOM is by using the instantaneous power theory [23, 24]. This theory was first proposed for controlling active power filters and is used in the design of the compensators operating with unbalanced systems. If a high frequency PWM converter is used, this theory allows the design of active filters to compensate for harmonic components or fundamental reactive component.

31.4.2.1.7 STATCOM DC Side Capacitor Theoretically the DC side capacitor of a STATCOM based on three-phase converters operating in a balanced system and controlling only reactive power could have a capacitance equal to zero Farad. However, in actual STATCOMs, a finite capacitor has to be used with the objective of keeping constant or controlled DC voltage as it tends to vary due to the converter switching. One parameter commonly used in synchronous machine is

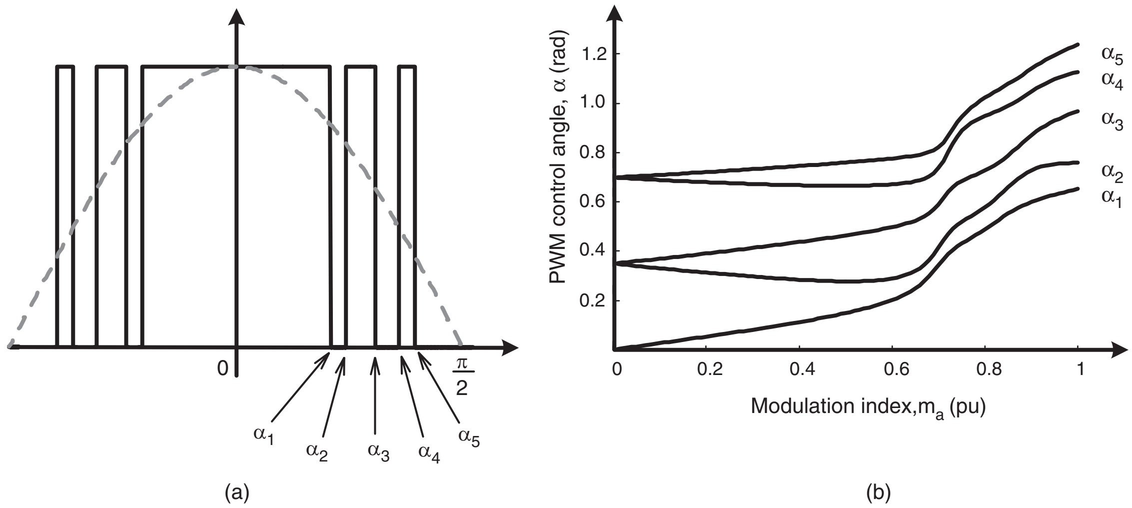


FIGURE 31.25 (a) Example of one-phase voltage with the harmonic elimination technique and (b) the control angle as function of the modulation index.

FIGURE 31.26 Line voltage harmonic spectrum for the voltage waveform in Fig. 31.25a.

the inertia constant H defined by

$$H = \frac{J\omega^2/2}{S} \tag{31.10}$$

where J and ω are the rotor moment of inertia and angular speed and S is the machine apparent power. A similar parameter for the STATCOM, H_{ST}, can be defined by

$$H_{ST} = \frac{CV_{DC}^2/2}{S} \tag{31.11}$$

where C and V_{DC} are the DC capacitance and its voltage and S is the STATCOM apparent power.

In both cases, the constants H and H_{ST} are values in time units corresponding to the relation of the amount of energy stored in the rotor inertia or in the capacitor and the machine or STATCOM apparent power. In the case of synchronous machines, the value of H is in the range of few seconds (generally, in the range of 1–3 s) and in the case of the STATCOM, H_{ST} is in the range of milliseconds or below (0.5–5 ms) if only reactive power is to be controlled. These numbers show that the STATCOM based on three-phase converters and designed for reactive power control only (which is the general case), has almost no stored energy in its DC capacitor. On the other hand, STATCOM based on single-phase converters without a common DC link may have larger capacitors, as in the case of

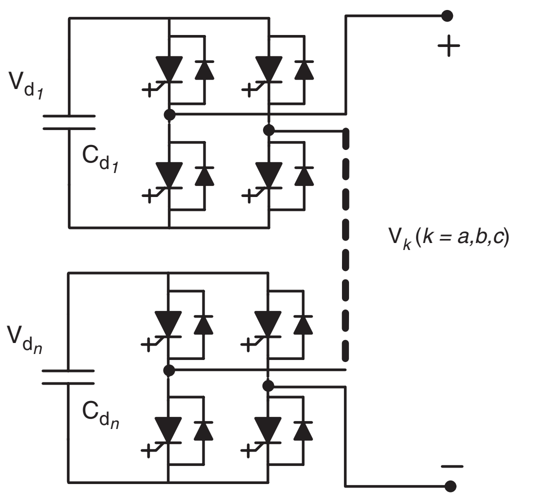


FIGURE 31.27 Cascade converter basic topology.

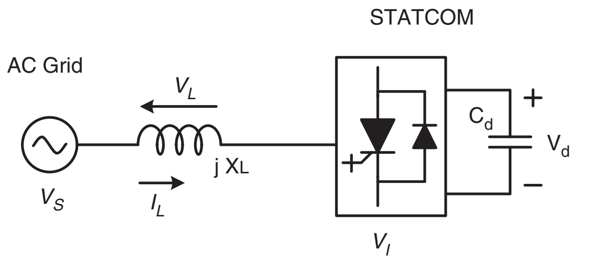


FIGURE 31.28 Simplified circuit for the AC grid and the STATCOM.

cascade converters due to the power oscillations at double of the line frequency.

There are STATCOMs (in some cases with different names) that are designed for operation with unbalanced loads. In this case, the DC capacitor has to be also much larger than in the case of balanced systems to avoid large voltage ripple

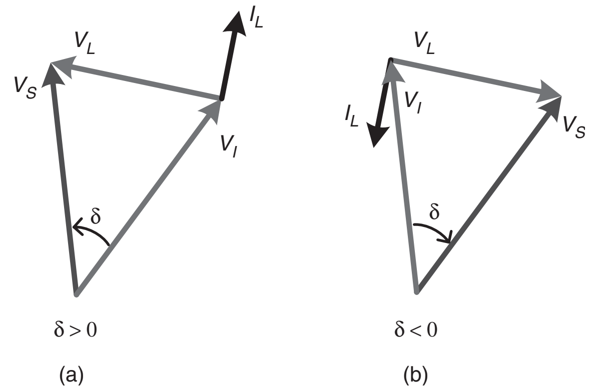


FIGURE 31.30 Active power control in a STATCOM.

on the DC voltage due to power oscillations at twice the line frequency, which appears naturally in unbalanced systems [25, 26] or unbalanced voltages [27] or system with flicker problem [28, 29]. In this case, the STATCOM compensates reactive power as well as the instantaneous oscillating active power due to the negative sequence currents components. In fact, this is an extension of the shunt active power filter application where the goal is the current harmonic compensation, which includes negative sequence currents even at the fundamental frequency. If sub-harmonics are present, the device is able to filter them out as well.

31.4.2.1.8 STATCOM with Energy Storage In general, the STATCOM is designed for reactive power compensation and it does not need large energy storage elements. However, there are some applications where it may be interesting to have some energy stored in the DC side, for example to compensate for active power for a short time. In these applications, the DC side capacitor has to be substituted by a voltage source energy storage device like a battery [30] or

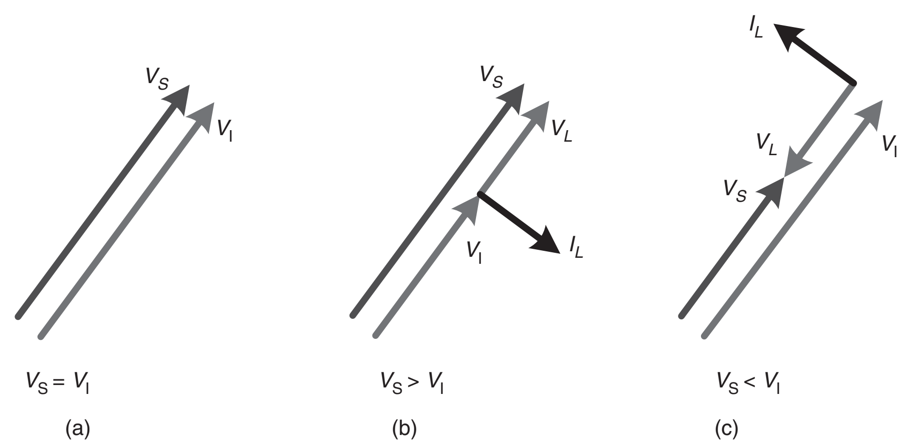


FIGURE 31.29 Reactive power control in a STATCOM.

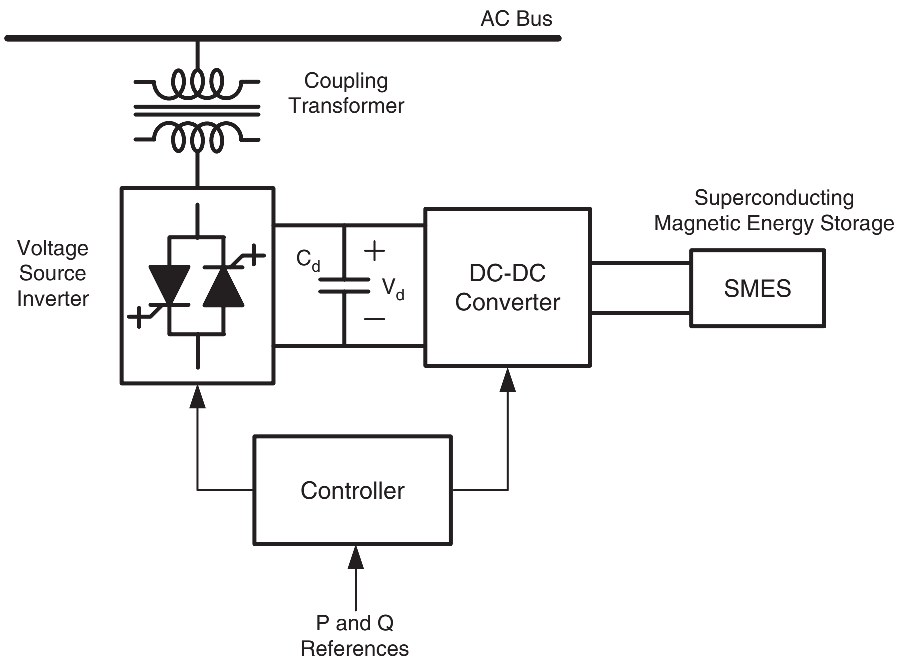


FIGURE 31.31 STATCOM with SMES.

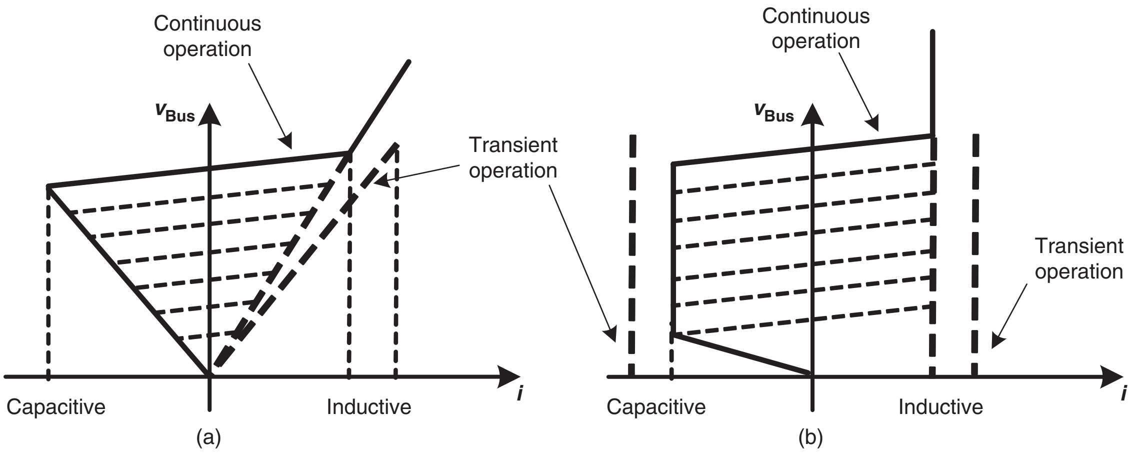


FIGURE 31.32 Comparison between SVC and STATCOM.

a double layer capacitor (super capacitor). Another possibility is to store energy in superconducting magnetic energy storage (SMES) systems [31, 32]. A natural solution for the use of the superconducting reactor would be the connection to the AC grid through a current source inverter (CSI) instead of the voltage source inverter. However, this has not been the case found in the literature. Figure 31.31 shows a block diagram of a typical STATCOM/SMES system, where the SMES is connected to the DC side of the STATCOM through a DC–DC converter which converts the direct current in the superconductor magnet to DC voltage in the STATCOM DC side and vice versa. This STATCOM is able to control reactive power continuously, as well as active power for a short time, depending on the amount of energy stored in the superconducting magnet.

31.4.2.1.9 Comparison between SVC and STATCOM Figure 31.32a shows the steady-state volt–ampere characteristics for the SVC shown in Fig. 31.14, while Fig. 31.32b shows the same characteristics for a STATCOM. For operation at rated voltage, both devices can present similar characteristics in terms of control range. However, SVC current compensation capability for lower voltages becomes smaller, while in the STATCOM it does not change significantly for voltages lower than rated (but approximately above 0.2 pu). This is explained by the fact that the SVC is based on impedance

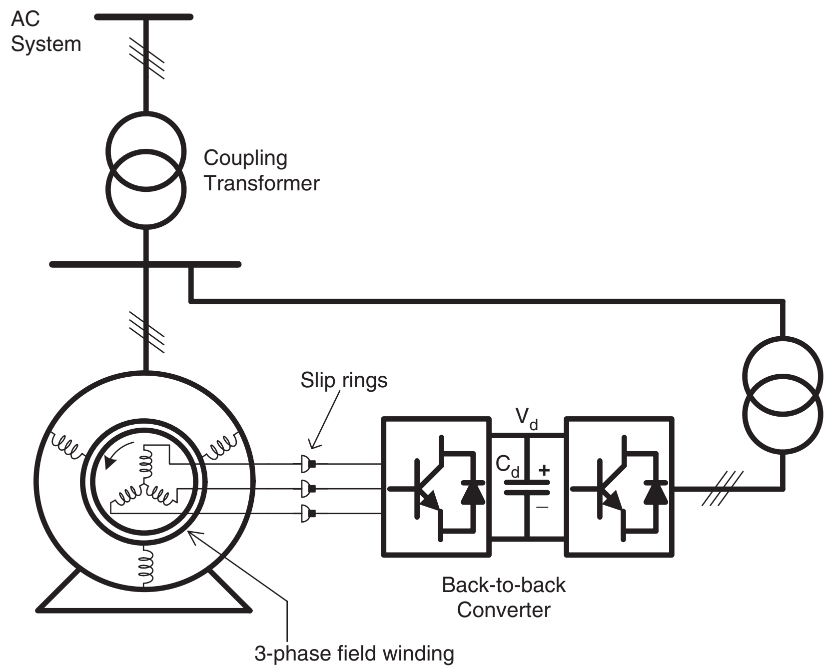


FIGURE 31.33 Adjustable speed synchronous condenser.

control, while the STATCOM is based on voltage source control. Therefore, while in the SVC the current decreases with a corresponding voltage decrease, in the STATCOM the current capability of the converters depends only on the switching device used, so the maximum current can be kept unchanged even for a low voltage condition. This is an important characteristic, especially in applications where the voltage may drop (as in most cases) where the STATCOM presents a better performance.

31.4.2.2 Adjustable Speed Synchronous Condenser

The adjustable speed synchronous condenser is not exactly a FACTS device, as it contains an electrical machine. However, it may be an interesting shunt device to compensate reactive power continuously and relatively large amounts of active power for a short time. The basic topology of this device is shown in Fig. 31.33. It is based on a double-fed induction machine with a conventional 3-phase winding in the stator and a 3-phase winding in the rotor. The latter is supplied by a 3-phase converter connected back-to-back to a second converter, which is connected to the grid.

This configuration allows the generation of a rotating magnetic flux in the rotor, which depends on the rotor converter frequency. When the machine is rotating at synchronous speed, the rotor converter operates at zero frequency, and the magnetic flux in the rotor is stationary, with respect to the rotor itself. In this case, the compensator operates as a conventional synchronous condenser.

However, when the rotor speed is lower or higher than the synchronous speed (normally during transients), the rotor converter generates a field current with the necessary frequency to keep the stator and rotor fluxes synchronized – if the synchronous frequency is 60 Hz and the rotor is running at 58 Hz, the rotor converter has to supply voltage or current at 2 Hz, so as to synchronize the fluxes. Naturally, it would be more interesting to use field-oriented control [33] instead of scalar control to get a better performance.

This hybrid compensator may supply energy to the AC system, if rotor speed is decreased. This machine is designed to have relatively large rotor inertia so as to present a large inertia constant (which may be in the range of more than 10 s). It is also called adjustable speed rotary condenser [34]. Operation at speeds higher than the synchronous speed is also possible, if it is necessary to absorb energy from the grid.

One of the advantages of this device is that a compensator with power in the range of 400 MVA may be synthesized with power electronics converter rated at a small fraction of this power and with a large capability to supply both active (for a few seconds) and reactive power (continuously) [34].

31.4.2.3 Static Synchronous Series Compensator

In contrast with the STATCOM, which is a shunt FACTS device, it is possible to build a converter-based compensator for series compensation. Figure 31.34 shows the basic diagram of a static synchronous series compensator (SSSC) based on voltage source inverter (VSI) with a capacitor in its DC side

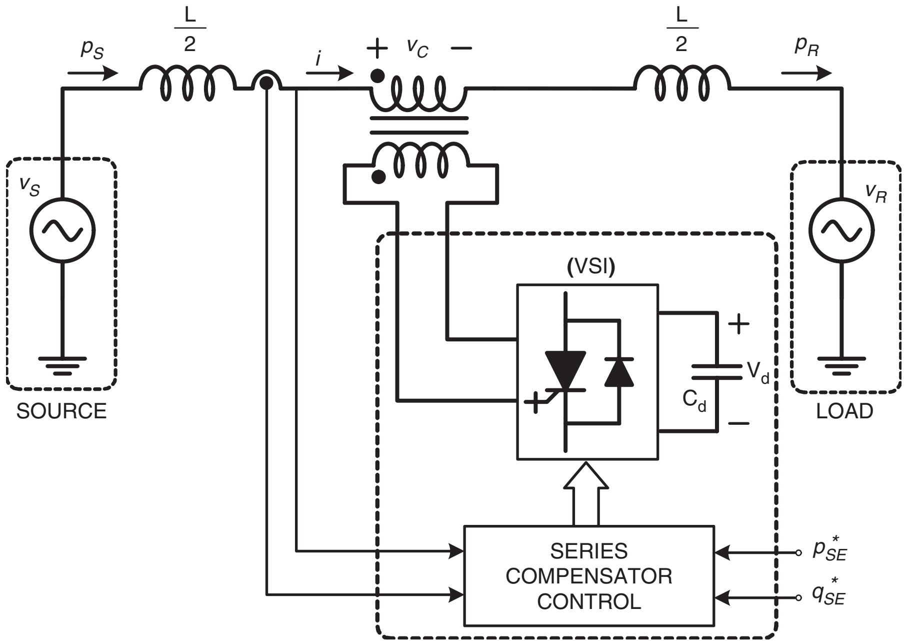


FIGURE 31.34 Static synchronous series compensator (SSSC).

and connected in series with the transmission line through a transformer [35]. The inputs to the SSSC controller shown are the line current and voltage, as well as the active and reactive power references p^*_{SE} and q^*_{SE}, respectively. In general, only reactive power is compensated and, in this case, the active power reference p^*_{SE} is zero and q^*_{SE} is chosen as to control power flow. Naturally, in the case of power flow control, it is necessary to have another control loop for this purpose and this is not shown in the figure.

One should note that if current is flowing in the transmission line, the SSSC controls reactive power by generating voltage v_C in quadrature with the line current. The device then behaves as capacitive or inductive equivalent impedance increasing or decreasing the power flow, respectively. The compensation characteristic is as shown in Fig. 31.8, for the case of series compensation where the transmitted power is always positive for $0 < \delta < 180°$. That is, with reactive power control it is only possible to transmit in one direction. However, if instead of controlling q^*_{SE} voltage v_C is controlled, it is possible to have power flow reversion. Figure 31.35 shows the power flow characteristics of a transmission line with an SSSC using constant voltage control. The voltage is in quadrature with the current and its magnitude is kept constant. The figure shows that it is possible to have power flow reversion for small values of δ with a constant compensation voltage v_C.

It should be noted that the discussion presented with respect to the converters for the case of the STATCOM is also valid for the case of the SSSC. The SSSC can be used for power flow control and for power oscillation damping as well.

31.4.2.4 Gate-controlled Series Capacitor

Figure 31.16 showed the TCSC, which is basically a TCR in parallel with a capacitor and both connected in series with a transmission line. The combination is effective in continuously controlling the equivalent capacitive reactance presented to the system, mainly for power flow control and oscillation damping purposes. It was also pointed out that the device has the disadvantage of a resonance area due to the association capacitor/TCR (see Fig. 31.18).

In [36], the continuously regulated series capacitor using GTO thyristors to directly control capacitor voltage is presented. Figure 31.36 shows the GTO thyristor-controlled series capacitor (GCSC) [37], hereafter renamed as the gate-controlled series capacitor, since it may also be built using other self-commutated switches such as IGBTs or IGCTs.

The GCSC circuit consists of a capacitor and a pair of self-commutated switches in anti-parallel. As the switches operate under AC voltage, they must be able to block both direct and reverse voltage, as well as allow current control in both directions.

Figure 31.37 shows the voltage and current waveforms for the GCSC, where the current in the transmission line is assumed to be sinusoidal. If the switches are kept turned-on, the capacitor is bypassed and does not present any compensation effect. If they are kept off, the capacitor is fully inserted in the line. On the other hand, if the switches are conducting and are turned-off at a given blocking angle γ counted from the zero-crossings of the line current, the capacitor voltage v_C appears as a result of the integration of the line current passing

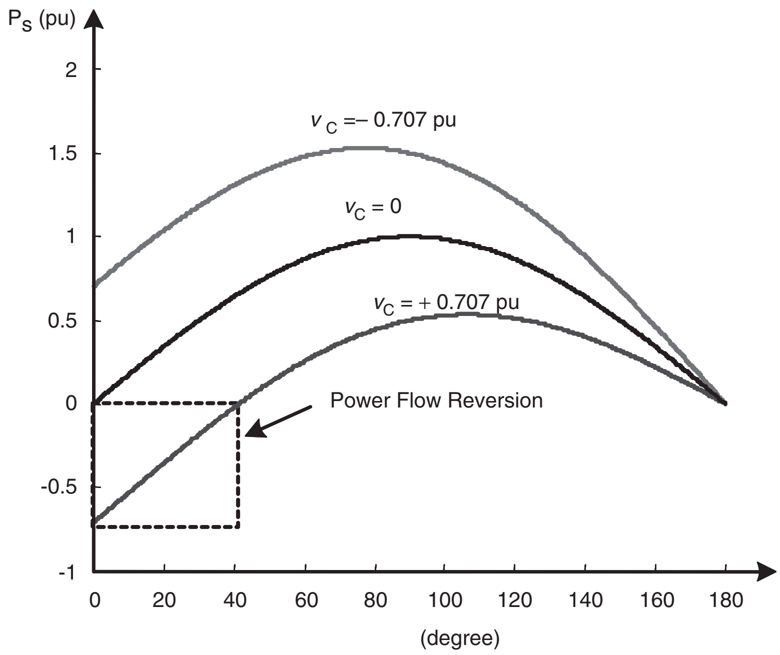


FIGURE 31.35 Power flow characteristics for voltage controlled SSSC.

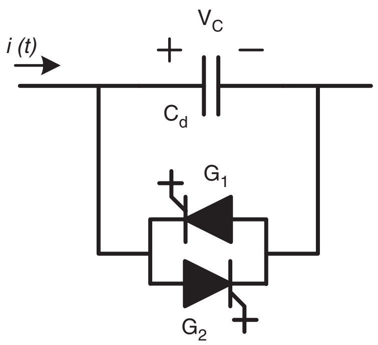


FIGURE 31.36 Gate-controlled series capacitor.

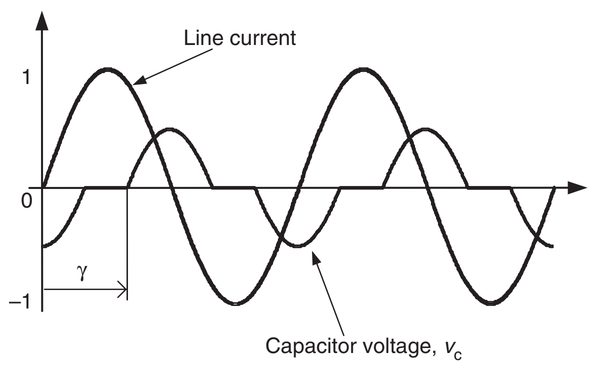


FIGURE 31.37 GCSC voltage and current waveforms.

through it. The next time the capacitor voltage crosses zero, the switches are turned-on again, to be turned-off at the next turn-off angle γ. With this switching control sequence, it must be clear that the switches always switch at zero voltage. This is an interesting feature for the series connection of the switches under high voltage operation [38].

The GCSC has some advantages when compared to the TCSC – the blocking angle can be continuously varied, which in turn varies the fundamental component of the voltage v_C. Also, it can be smaller than the TCSC [39]. Moreover, the dynamic response of the GCSC is generally better than that of the TCSC [40].

The fundamental impedance of the GCSC as a function of the blocking angle γ is shown in Fig. 31.38. A blocking angle of 90° means the capacitor is fully inserted in the circuit, while a value of 180° corresponds to a situation where the capacitor is bypassed and no compensation occurs.

31.4.2.5 Unified Power Flow Controller

The unified power flow controller (UPFC) is a more complete transmission line compensator [41], shown as a simplified block diagram in Fig. 31.39. This device can be understood as a STATCOM and an SSSC with a common DC link. The energy storing capacity of the DC capacitor is generally small, and so the shunt converter has to draw (or generate) active power from the grid in the exactly same amount as the active power being generated (or drawn) by the series converter. If this is not followed, the DC link voltage may increase or decrease

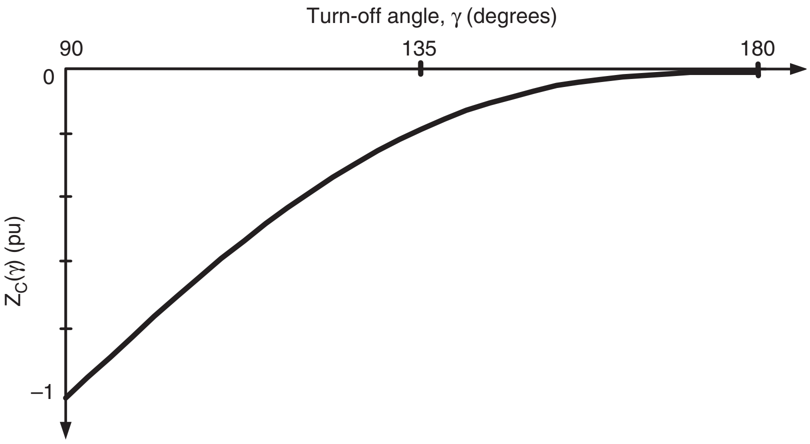


FIGURE 31.38 GCSC equivalent fundamental impedance.

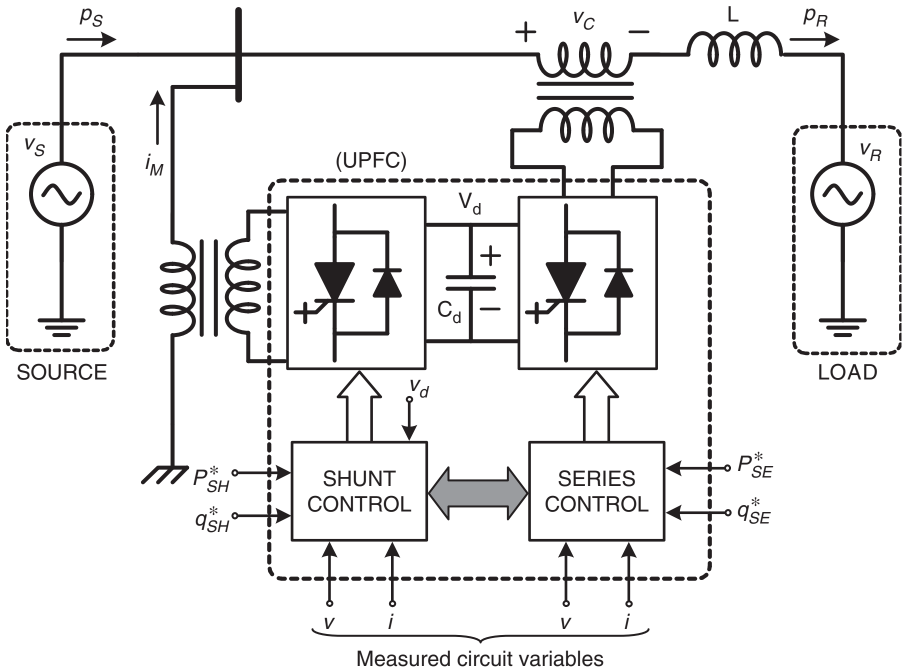


FIGURE 31.39 UPFC block diagram.

with respect to the rated voltage, depending on the net power being absorbed or delivered by both converters. On the other hand, the reactive power in the shunt or series converter can be controlled independently, giving a great flexibility to the power flow control.

The phasor diagram in Fig. 31.40 shows that the UPFC can be controlled in such a way as to produce any voltage phasor in series with the transmission line that fits inside the dashed line circle on top of the phase voltage phasors. The maximum radius of the circle is limited by the voltage limitation of the series converter. The fact that the locus of v_C is a circle is one of the greatest advantage of the UPFC when compared with the thyristor-based phase shifter. If the UPFC injects or absorbs reactive power in parallel with the system, the magnitude of voltage V_S will be increased or decreased, respectively. This extra-characteristic increases the locus of the series voltage v_C. Of course this effect is only possible if an inductive impedance is present in series with the voltage source V_S, which is normally the case.

The shunt compensator of the UPFC is normally used with two objectives. The first is to control the reactive power in the point of connection and therefore control the voltage at this point. The second is to control active power in such a way as to control the DC link voltage. The control technique to be used can be similar to the one used in STATCOM. The series compensator can be controlled in the same way as the SSSC,

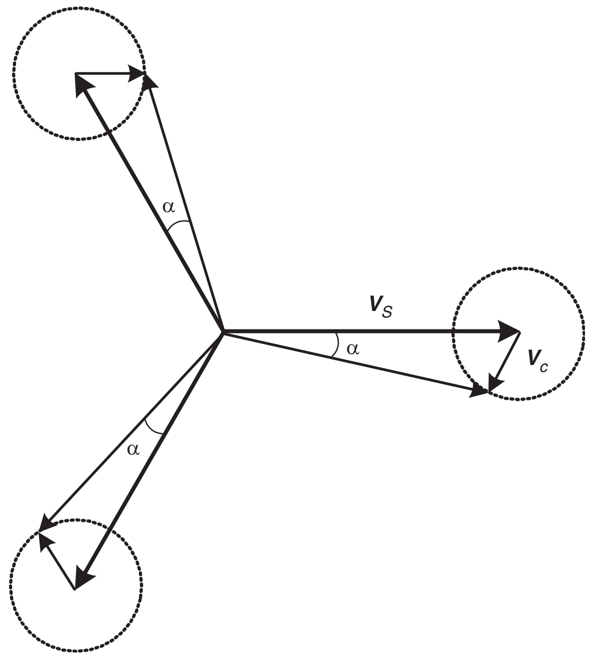


FIGURE 31.40 Phasor diagram for a system with a UPFC.

with the difference that in this case it may control active and reactive power. Naturally, the active power control in the series compensator would change the capacitor voltage that should be controlled by the shunt compensator.

31.4.2.6 Interline Power Flow Controller

The interline power flow controller (IPFC) [42] is a UPFC-derived device with the objective of controlling power flow between lines instead of one line as in the UPFC. Figure 31.41 shows a basic block diagram of an IPFC with two converters to control the power flow in lines 1 and 2. The minimum number of converters connected in back-to-back is two, but there may be more. Each converter should be connected in series with a different transmission line and should control power flow in this line with the following conditions:

- the reactive power control can be totally independent in each converter; and
- the active power flowing into or out of each converter has to be coordinated in such a way that the DC link voltage is kept controlled.

The DC link voltage control can be achieved in a similar way as in the case of the UPFC. In this case, one of the series converters can control the compensation voltage freely and it may produce active power flowing into or from the DC link, which would charge or discharge the DC link capacitor. Therefore, the other converter has to be controlled to regulate this DC voltage. If there are n converters with n greater than two, $(n-1)$ converters can absorb or generate active power while one converter has to control the DC link voltage. Anyway, all n converters can control reactive power freely. For instance, this concept allows the control of the power flow in n lines and it is possible to transfer active power from one line to another being an interesting device to balance power flow in n parallel transmission lines.

31.4.2.7 Convertible Static Converter

Following the IPFC, a more generic concept is the convertible static converter (CSC) [43, 44], which is based on the connection of a voltage source converter in various different topologies. Considering one simple case of two transmission lines and two converters with apparent power each equal to S, it is possible to have the following topologies:

- Two converters connected in shunt operating as a STATCOM rated at 2S apparent power;
- Two converters connected in series with one transmission line forming an SSSC with 2S apparent power;
- One converter connected in shunt and the other in series forming a UPFC;
- One converter connected in series with one line and the other connected in series with the other line forming an IPFC.

Other topologies are possible depending on how the converters are connected in the system. The basic control of each converter depends on how it is being used if, as a STATCOM, SSSC, UPFC, or IPFC.

31.4.2.8 Voltage Source Inverter-based HVDC Transmission

The VSI can be used for DC transmission with a circuit configuration exactly dual to the conventional HVDC transmission system, which is based on the thyristor-controlled CSI. The duality can be explained by the fact that the thyristor-controlled HVDC system controls the DC link current, while the system based on VSI controls the DC link voltage. The basic circuit configuration for a two converter VSI-HVDC system is shown in Fig. 31.42. This concept can be used for the connection of asynchronous systems, systems with different frequencies or located in places where cable transmission is more applicable than conventional transmission lines (as in congested urban areas or underwater transmission). The number of VSIs can be two for point-to-point transmission or more for multipoint transmission.

One great advantage of the VSI-HVDC system is that it allows independent active and reactive power control in each terminal. While the CSI-HVDC transmission can be synthesized for higher power as compared to the VSI-HVDC system, it can only control active power and may have large reactive power consumption, which means that reactive power compensation equipment is normally necessary.

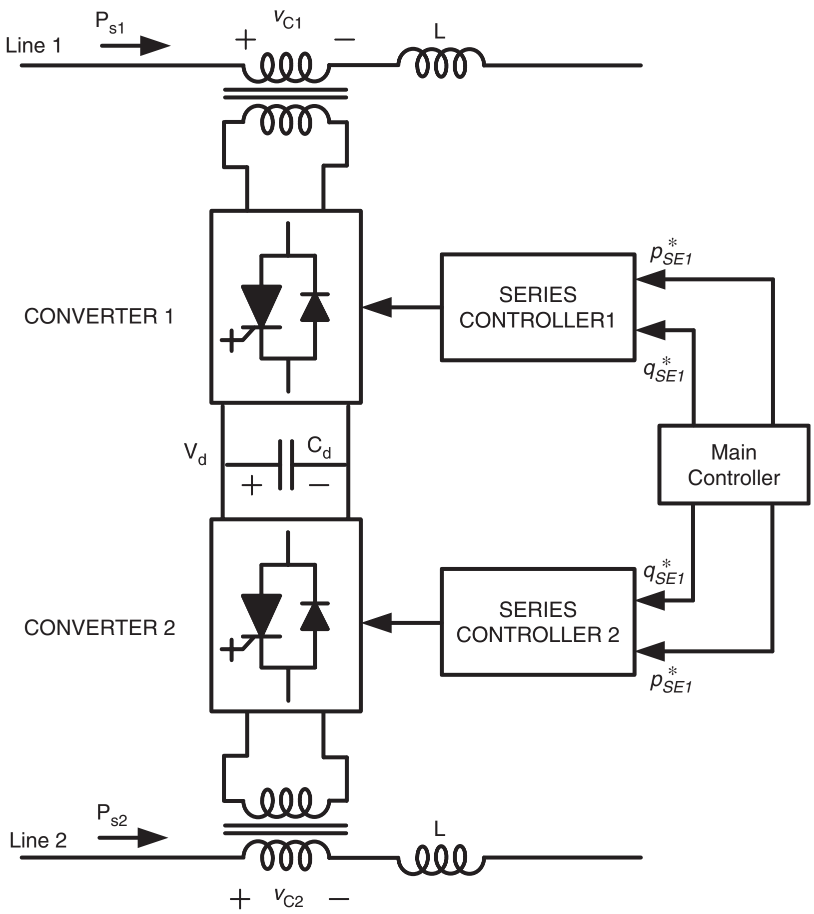


FIGURE 31.41 Block diagram of IPFC with two converters.

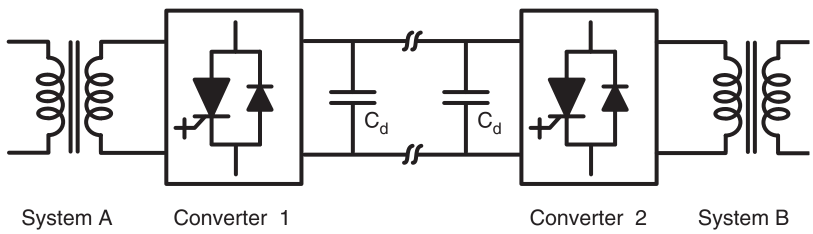


FIGURE 31.42 Voltage source inverter HVDC system.

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