Chapter 3
Reactive Power Role and Its Controllability in AC Power Transmission Systems

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Abstract This chapter is a general introduction to the reactive power role in the voltage control and the stability in power transmission systems. It starts with a brief overview of the potential limitations related to the transmission system loading and also different ways that the reactive power can affect the power system operation. Different reactive power generation technologies based on capacitors and power electronic converters are reviewed as possible sources for the reactive power compensation. Also, voltage and reactive power control methods of the mentioned technologies are briefly explained for use in AC power transmission systems.

3.1 Introduction

Reactive power is generated when the current waveform is not in phase with the voltage waveform because of inductive or capacitive components. Only the component of current in phase with voltage generates active power that does the real work. Reactive power is required for producing the magnetic and electric fields in capacitors and inductors. Power transmission lines have both capacitive and inductive properties. A typical transmission line can be presented by a PI equivalent model as shown in Fig. 3.1.

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N. Mahdavi Tabatabaei et al. (eds.), *Reactive Power Control in AC Power Systems*,
Power Systems, DOI 10.1007/978-3-319-51118-4_3

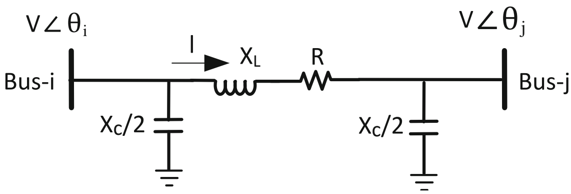

Fig. 3.1 Transmission line connecting two buses (*i*, *j*) presented by a PI equivalent model

The line capacitance supplies the reactive power ($Q_{produced}$) and the line inductance consumes the reactive power ($Q_{consumed}$), which can be calculated in an ideal line ($R = 0$) as:

$$Q_{produced} = \frac{V^2}{X_C} \tag{3.1}$$

$$Q_{consumed} = I^2 X_L \tag{3.2}$$

where V, X_C, X_L, and I are the bus voltage, the line's capacitive reactance, the line's inductive reactance and the line current, respectively. Therefore, the amount of reactive power consumed by a line is related to the current flow in the line; the amount of reactive power supplied by a line is related to the line voltage. At a Surge Impedance Loading (SIL), the supplied reactive power is equal to the absorbed reactive power:

$$Q_{Produced} = Q_{Consumed} \tag{3.3}$$

By substituting (3.1) and (3.2) in (3.3), the surge impedance (Z_0) can be obtained:

$$Z_0 = \frac{V}{I} = \sqrt{\frac{X_L}{X_C}} \tag{3.4}$$

The surge impedance loading (*SIL*) is equal to the voltage squared divided by the surge impedance:

$$SIL = \frac{V^2}{Z_0} \tag{3.5}$$

The above expression shows that an ideal line (with zero resistance) loaded at its surge impedance loading does not produce or consume reactive power, so it will have the same voltage at both ends. When a line is loaded above its *SIL*, it acts like a shunt reactor which are absorbing the reactive power from the system, and when a line is loaded below its *SIL*, it acts like a shunt capacitor which are supplying the reactive power to the system [1]. Balance of both consumption and production of reactive power at a particular loading level results into a flat voltage profile along the line.

The consumption of the reactive power by transmission lines increases with the square of current. Thus, reactive power is difficult to transport along long lines. In a power system, the goal is to maximize the utilization of the transmission system but some factors limit the loading capability of the transmission systems, which are as discussed in Sect. 3.2. Equation (3.5) shows that the transmitted power through a long transmission line can be increased by increasing the value of the line voltage (V) or by reducing the surge impedance (Z_0). This illustration demonstrates that there are two main variables that can be directly controlled for improving the performance of the power system. These are [2]:

- Voltage
- Impedance

Increasing the line voltage is the most common method for increasing the power limit under heavy loading conditions. But there are some economical and practical limitations. The surge impedance can be decreased by either increasing the capacitance of the line or by reducing the inductance of the line. With the establishment of "which" variables can be controlled in a power system, the next question is "how" these variables should be and can be controlled [2]. The answer is reactive power generation equipment, which is discussed in Sects. 3.3 and 3.4. For example, series capacitors or shunt capacitors can be used to reduce the value of the surge impedance.

3.2 Basic Principles of Power Transmission Operation

A transmission system is a complicated network of the transmission lines which connect all power substations to the loads. The AC systems can be connected together by the transmission lines to create a large power system for exchanging electrical energy. In a power system, the goal is to use the transmission lines with the least possible power losses and to maximize its loading capability by considering emergency conditions all the time. But some factors limit the loading capability of transmission systems, which are as follows:

3.2.1 Thermal Limit

The thermal limit of an overhead transmission line is reached when the current flow heats the conductor material up to a temperature above which the conductor material gradually looses mechanical strength [3]. In fact, the thermal capability of an overhead transmission line is a function of environment temperature, wind conditions, conductor conditions and its distance from the ground. Excessive heat causes that the transmission lines loose its mechanical resistance and reduce its expected useful life time. Flowing current over the heat capability is allowed only for a short and limited time. According to the definition, normal and nominal current capacity of a transmission line is a current that can be flown over the line for an unlimited time.

The line current (I in Fig. 3.1) can be divided into two components:

$$I = I\,\cos\theta + I\,\sin\theta \tag{3.6}$$

where θ is the phase difference between the line voltage and the line current. So the line losses can be obtained as follow:

$$P = R(I\,\cos\theta + I\,\sin\theta)^2 \cong R(I\,\cos\theta)^2 + R(I\,\sin\theta)^2 = P + P' \tag{3.7}$$

where $P' = R(I\,\sin\theta)^2$ is the reactive power losses. Therefore, by reducing the reactive power, the line losses are decreased and consequently the loading capacity is increased. The following methods can potentially help to increase the loading capacity of a transmission line [4]:

- Phase shifting transformers
- Series capacitors or series reactors to adjust the impedances of the lines
- FACTS elements to control the reactive power flows using power electronics.
- The phase shifting transformers and series capacitors or series reactors are usually the less expensive options while FACTS are very flexible and also more costly.

3.2.2 *Voltage Limit*

Voltage limits normally require that the voltage level within a transmission system to be maintained within a specified interval, for instance ±5% of the nominal voltage. The voltage in the transmission line can be changed by the change of the load or occurrence of the fault in transmission and distribution lines or other equipment. In these cases, it should be noted that the dynamic and transient voltages should be remained within a given range. If the line voltage exceeds more than the maximum rated value, it can result in a short circuit and may cause damage to transformers and other equipment in the substations. The voltage in AC transmission line is almost related to the level of reactive current of the line as well as line's reactance. Capacitors and reactors can be installed on the lines to control the voltage changes along the line.

3.2.3 Stability Limit

According to the definition, power system stability is the ability of the power system to remain in a balanced condition during normal operation of the system and to bring back balanced conditions within minimum possible time after the occurrence of disturbance. In general, in the literature, four different types need to be dealt with the steady state stability, dynamic stability, transient stability and voltage stability [5].

3.2.3.1 Steady-State Stability

Steady state stability refers to system power stability in response to small disturbances and continuous changes in the load. Steady state stability can be improved by

- Increasing the voltage level of the network
- Adding new lines to the transmission systems
- Reducing the series reactance of the line with bundling the lines, with installation of series capacitors along the line.

3.2.3.2 Transient Stability

In a power system, transient stability is the ability of the system in damping the oscillations due to severe disturbances [6], for instance, the reaction of the voltage to faults in the transmission system caused by events such as lightning. Transient stability of the system can be improved by increasing the system voltage and increasing the *X*/*R* ratio of the power system. An increase in the system voltage profile and *X*/*R* ratio implies an increase in the power transfer ability. Thus it helps to improve the stability.

3.2.3.3 Dynamic Stability

The ability of a power system to maintain stability under sudden small disturbances is investigated under the name of dynamic stability (also known as small-signal stability) [7]. For instance, power oscillations occurring from disconnection of large amounts of generation or load, or switching of some of the lines.

3.2.3.4 Voltage Stability

Voltage Stability is the ability of the system to maintain steady state voltages at all the system buses when subjected to a disturbance [6]. The system voltage might be unstable, if the load demand suddenly increases, or a disturbance occurs. One of the important factors that plays a significant role in the voltage instability is the inability of the system to provide the required reactive power. Voltage instability causes voltage collapse in which the buses' voltage begins to drop progressively and uncontrollably [8, 9]. Placement of series and shunt capacitors and reactive power controllers can prevent voltage instability. Such compensation has the purpose of injecting reactive power to maintain the voltage magnitude in the buses close to the nominal values, as well as to reduce the line currents and therefore the total system losses.

In brief, reactive power generation technologies can provide remedies for all of the above voltage and stability issues, and create the possibilities to run the transmission system closer to its thermal limit by controlling two main variables of the power system: Voltage and impedance.

3.3 Equipment for Reactive Power Generation in Power System

Reactive Power can be generated by power plants, capacitors, static compensators and synchronous condensers. Reactive power generation by power plant has two problems: first, the reactive power generation capacity of a power plant is limited and secondly, this huge power occupies the capacity of transmission line, transformers, and imposes some losses in the system. The presence of reactive power sources near to the consumption not only reduce the costs, but also increase the capacity of the transmission line.

3.3.1 Parallel Capacitor

Based on the amount of voltage drop, some parallel capacitor banks are connected to the network and provide the required reactive power. It increases the load power factor and finally the active power capacity of transformers.

3.3.2 Series Capacitor

Series capacitors at the network are used to reduce the impedance of the transmission lines which increases the power transmission capacity and reduces the voltage drop. Nowadays, it is also used for dynamic stability and prevention of Sub-Synchronous Resonance (SSR). In other words, the series capacitor is used to compensate the series inductive effect of lines by creating a negative reactance. Capacitive reactance should always be less than inductive reactance, and this condition is considered to determine the capacity of the series capacitor. Lack of attention to this condition may result in over-compensation at the end of the line, which is not desired.

3.3.3 Reactor

Reactors are reactive power consumers which are mostly installed in substations and at the end of long transmission lines in parallel. Basically, a circuit breaker is installed with reactors to connect them to the network, when it is needed. Usually, the reactor is switched on when the network load is minimum, and it is switched off when the network load is high.

3.3.4 Synchronous Condenser

A synchronous condenser is a synchronous motor, which is running at no load and can be operated as an inductor or a capacitor by controlling its excitation current. The machine has three operating states, which are dependent on the power factor: under-excited state, normal-excited state, and over-excited state. An under-excited synchronous motor draws both active and reactive power from the network. An over-excited synchronous motor draws active power from the network, while delivers reactive power to the network. A normal-excited motor draws only active power.

Because of the energy storage capability, synchronous condensers with automatic control has faster and smoother response to reactive power consumers. Therefore they are more effective than the parallel capacitor banks. These reactive power suppliers improve the voltage and frequency stability and they are able to supply energy in transients caused by short-circuit fault. Automatic excitation control of synchronous condensers can improve the system stability by generating lagging kVar at low loads and leading kVar at high loads. Also, they can prevent over-voltage phenomena at low loads, which is called the Ferranti effect. Relatively high losses are the main disadvantage of this device.

3.3.5 Reactive Power Control Transformer

Reactive power control transformers adjust secondary voltage by tap changer and as a result, keep the reactive power within a specified range.

3.3.6 Static Reactive Power Generators with Variable Impedance

Static reactive power generators with variable impedance change the reactive power amount by switching the capacitor banks and reactors. The aim of the approach is to provide variable impedance for compensation of the transmission system.

3.3.6.1 Thyristor-Controlled Reactor (TCR)

A single-phase Thyristor-Controlled Reactor (TCR) is shown in the Fig. 3.2a. The device consists of a fixed reactor with inductance L and a thyristor based AC switch. The effective reactance of the inductor can be changed continuously by controlling the firing angle of the thyristor.

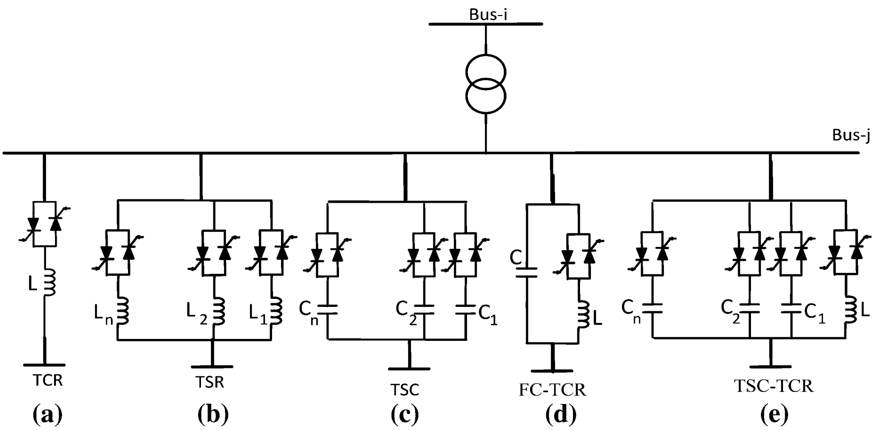

Fig. 3.2 Parallel compensators for reactive power control, **a** Thyristor-Controlled Reactors, **b** Thyristor-Switched Reactor, **c** Thyristor-Switched Capacitor, **d** Fixed Capacitor Thyristor-Controlled Reactor, **e** Thyristor-Switched Capacitor-Thyristor-Controlled Reactor

3.3.6.2 Thyristor-Switched Reactor (TSR)

A Thyristor-Switched Reactor (TSR) consists of several parallel inductors and switches which has no firing angle control and is shown in Fig. 3.2b. Using the switches without firing angle control leads to lower losses, but the control of reactive power is not continuous.

3.3.6.3 Thyristor-Switched Capacitor (TSC)

In a Thyristor-Switched Capacitor (TSC), thyristor based ac switches (without control of firing angle) are used to switch on or off the parallel capacitor units which provide the required reactive power of the system (Fig. 3.2c). Unlike the parallel reactors, the parallel capacitors cannot be switched based on the firing angle to control the reactive power continuously.

3.3.6.4 Fixed Capacitor Thyristor-Controlled Reactor (FC-TCR)

One of the main arrangements to provide reactive power is to use a Fixed Capacitor and a Thyristor-Controlled Reactor (FC-TCR), which is shown in Fig. 3.2d. The capacitive fixed reactive power along with variable reactive power of the TCR generates an output reactive power.

3.3.6.5 Thyristor-Switched Capacitor-Thyristor-Controlled Reactor (TSC-TCR)

A basic configuration of a single phase Thyristor-Switched Capacitor-Thyristor-Controlled Reactor (TSC-TCR) is shown in Fig. 3.2e. For a given range of the power output, the arrangement consists of n TSC branches and a TCR. The output capacitive reactive power is changed by the TSCs in steps and a relatively small output of the inductive reactive power is used to eliminate the excess reactive power for providing the required reactive power.

3.3.6.6 Thyristor-Switched Series Capacitor (TSSC)

The main element of a Thyristor-Switched Series Capacitor (TSSC) is a capacitor which is connected in parallel to a thyristor based ac switch as shown in Fig. 3.3a. A TSSC can only play a role of a discrete capacitor for compensation and there is no continuous control over it.

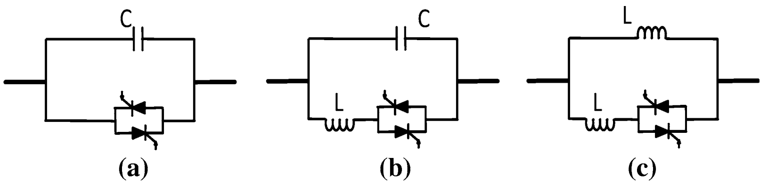

Fig. 3.3 Series compensators for reactive power control, **a** Thyristor-Switched Series Capacitor (TSSC), **b** Thyristor-Controlled Series Capacitor (TCSC), **c** Thyristor-Controlled Series Reactor (TCSR)

3.3.6.7 Thyristor-Controlled Series Capacitor (TCSC)

Thyristor-Controlled Series Capacitor (TCSC) consists of a capacitor bank in parallel with a thyristor-controlled reactor to provide the series capacitive reactance with the smoothly changes (Fig. 3.3b). The impedance of reactor is designed to be much less than the impedance of the series capacitor. At the firing angle of 90°, the TCSC helps to limit the fault current. The TCSC may consist of several smaller capacitors with different size in order to achieve a better performance.

3.3.6.8 Thyristor-Controlled Series Reactor (TCSR)

A Thyristor-Controlled Series Reactor (TCSR) is an inductive reactance compensator, which includes a series reactor along with a controlled-reactor as shown in Fig. 3.3c.

3.3.7 Static Reactive Power Generators Based on the Power Electronic Converters

More recently, interruptible (self-commutated) thyristors and other power semiconductors are used to generate and to absorb reactive power, without the use of ac capacitors or reactors, in which the output voltage is controlled for generating the required reactive power. So, a static reactive power compensator with a power electronic convertor is a system, which can provide controlled reactive current from an AC power source.

3.3.7.1 STATic Synchronous COMpensator (STATCOM)

A STATic synchronous COMpensator (STATCOM) is a static synchronous generator, which operates as a parallel reactive power compensator and can control the output capacitive or inductive current as shown in Fig. 3.4 [10].

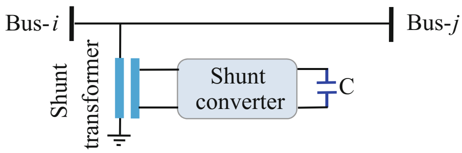

Fig. 3.4 STATic synchronous COMpensator (STATCOM)

3.3.7.2 Static Synchronous Series Compensator (SSSC)

Static Synchronous Series Compensator (SSSC) is a static synchronous generator based on power electronics without an external energy source, and works as a series compensator (Fig. 3.5) [11]. It is used to increase or to decrease the reactive voltage drop along the transmission line and consequently control the transferred electrical power.

3.3.7.3 Unified Power Flow Controller (UPFC)

A Unified Power Flow Controller (UPFC) is a combination of STATCOM and SSSC, which are connected through a dc link, to compensate active and reactive power simultaneously without external energy source (Fig. 3.6) [12]. It is a complete compensator for controlling the active and reactive power as well as the network voltage [13, 14].

3.3.8 Interline Power Flow Controller (IPFC)

An Interline Power Flow Controller (IPFC), as shown in Fig. 3.7, can draw the active power from one side of a line and injected to the other side of the line [15]. Therefore, unlike the SSSC, this compensator is able to control both the phase and amplitude of the injected voltage into the line.

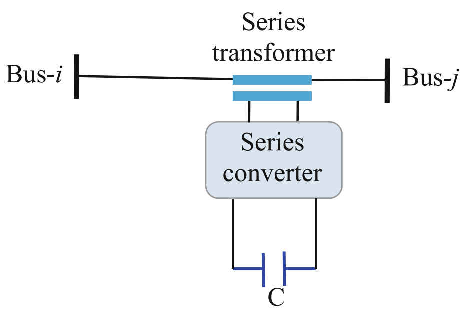

Fig. 3.5 Static Synchronous Series Compensator (SSSC)

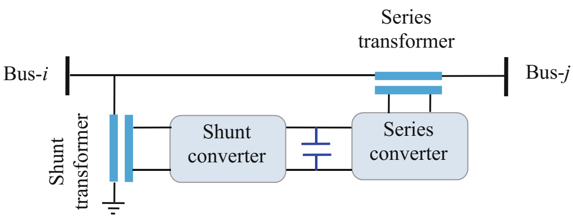

Fig. 3.6 Unified Power Flow Controller (UPFC)

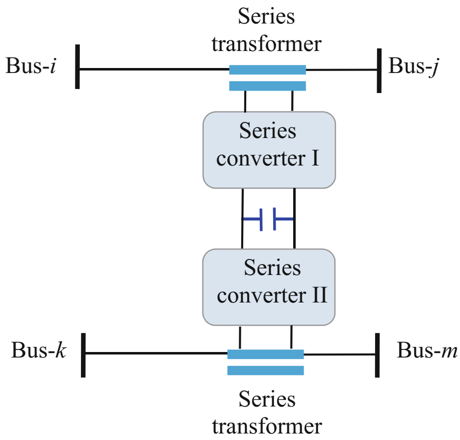

Fig. 3.7 Interline Power Flow Controller (IPFC)

Table 3.1 Comparison between reactive power sources for power system stability enhancement [16]

Reactive power controller	Stability enhancement	Load flow	Voltage control	Transient stability	Dynamic stability	Required time (s)
UPFC	Y	High	High	Medium	Medium	0.6
TCSC	Y	Medium	Low	High	Medium	1.5
FC-TCR	Y	Low	high	Low	Medium	7
SSSC	Y	Low	High	Medium	Medium	11

Table 3.1 shows a comparison between various reactive power sources for power system stability enhancement. It is found that UPFC is a more effective device for load flow, voltage control and stability enhancement of the power system, but it is also a more expensive solution.

3.4 Control of Reactive Power in a Power Transmission System

Figure 3.8 shows a simplified model of a power transmission system, where X_L is the reactance of the transmission line, $V_i \angle \theta_i$ and $V_j \angle \theta_j$ are voltage phasors of the grid buses. The purposes of the reactive power control in power transmission system are to

(a) transmit as much power as feasible on a line of the specified voltage and
(b) to control the voltage along the line within the limits [17].

The active and reactive power at buses *i* and *j* can be obtained by Eqs. (3.8) and (3.9), respectively:

$$P_i = \frac{V_i V_j}{X_L}\sin(\theta_i - \theta_j), \quad Q_i = \frac{V_i (V_i - V_j \cos(\theta_i - \theta_j))}{X_L} \tag{3.8}$$

$$P_j = \frac{V_i V_j}{X_L}\sin(\theta_i - \theta_j), \quad Q_j = \frac{V_j (V_j - V_i \cos(\theta_i - \theta_j))}{X_L} \tag{3.9}$$

It can be seen from (3.8) and (3.9) that the active and reactive power can be controlled by the voltages, phase angles and line impedance of the transmission system. Reactive power compensation can be implemented by reactive power generators, which are connected to the transmission line in parallel or in series [18]. The principles of shunt and series reactive power controllers are described below.

3.4.1 Shunt Compensation

Shunt reactive compensation is used in transmission systems to adjust the voltage magnitude, improve the voltage quality and the system stability. Shunt-connected reactors reduce the line over-voltages by consuming the reactive power, while shunt-connected capacitors maintain the voltage levels by compensating the reactive power. Instead of inductors or capacitors, there are reactive power generators based on the power electronic converters, which can generate the reactive power independent of the voltage at the point of connection.

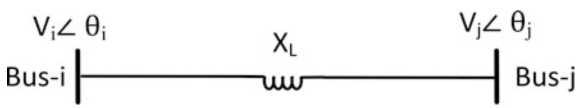

Fig. 3.8 Model of a lossless power transmission system

3.4.1.1 Shunt-Connected Capacitors

Figure 3.9 shows a simplified model of a compensated transmission line, in which the voltage magnitudes of the buses are assumed as $V \angle \theta_i$ and $V \angle 0$. An ideal controlled shunt-connected capacitor C is expected to regulate the voltage at the connection point as $V \angle \theta_i/2$ [19].

By using the above assumptions, (3.8) and (3.9), the reactive powers at buses i and j can be obtained as

$$Q_i = Q_j = 2\frac{V^2}{X_L}(1 - \cos(\frac{\theta_i}{2})) \tag{3.10}$$

Therefore, the injected reactive power by the capacitor to adjust the mid-point voltage can be calculated as:

$$Q_c = -(Q_i + Q_j) = -4\frac{V^2}{X_L}(1 - \cos(\frac{\theta_i}{2})) \tag{3.11}$$

3.4.1.2 Shunt Compensation Based on the Power Electronic Converters

Figure 3.10 depicts an equivalent circuit of the system, which is compensated by a shunt power electronic converter. There are different configurations available for the shunt compensator such as modular multi-level inverter, six-pulse three phase

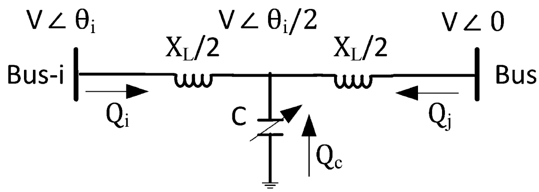

Fig. 3.9 Simplified model of a compensated transmission line by a shunt-connected capacitor

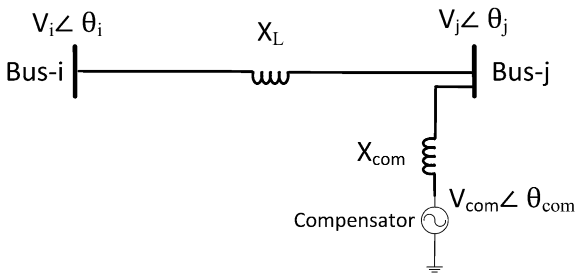

Fig. 3.10 Shunt compensation based on the power electronic converters

inverter, cascaded H-bridge converter, Neutral Point Clamped (NPC) inverter etc. [20].

Since the phase difference between the converter voltage and grid bus-j voltage (θ_{com}–θ_j) is small under normal operation, then sin (θ_{com}–θ_j) ≈ (θ_{com}–θ_j) and cos (θ_{com}–θ_j) ≈ 1 [21]. Therefore, based on (3.8) and (3.9), the active power P_{com} and reactive power Q_{com} flowing out of the parallel converter are

$$P_{com} = \frac{V_j V_{com}}{X_{com}} \sin(\theta_{com} - \theta_j) \approx \frac{V_j V_{com}}{X_{com}} (\theta_{com} - \theta_j) \tag{3.12}$$

$$Q_{com} = \frac{V_j V_{com}}{X_{com}} \cos(\theta_{com} - \theta_j) - \frac{V_j^2}{X_{com}} \approx \frac{V_j}{X_{com}} (V_{com} - V_j) \tag{3.13}$$

From (3.13), the reactive power Q_{com} can be controlled by changing the voltage difference between the converter and grid bus *(*V_{com}–V_j*)*. When the reactive power Q_{com} is changed, the voltage V_j changes slightly as well. This can be used to regulate the voltage at the PCC. Hence, a shunt reactive power controller mainly has two different operation modes: one is called the direct Q control mode, which provides the desired amount of reactive power, and the other is called the voltage regulation mode, which regulates the PCC voltage. Equation (3.12) shows the relationship between the active power P_{com} and the phase difference of the converter voltage and bus voltage. The real power flowing in or out forces the DC-link voltage to increase or decrease. As a result, it can be regulated by controlling the phase angle of the voltage generated by the converter. When the parallel compensator is operated in voltage regulation mode, it implements the following *V-I* characteristic [22].

Figure 3.11 shows as long as the reactive current stays within the minimum and maximum current values (–I_{max}, I_{max}) imposed by the converter rating, the voltage is regulated at the reference voltage V_{ref}.

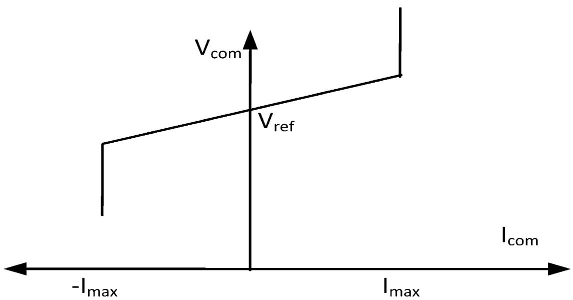

Fig. 3.11 *V-I* characteristic of the shunt compensator

3.4.2 Series Compensation

Series compensation controls the series impedance of the transmission line. Based on Eqs. (3.8) and (3.9), the AC power transmission is basically limited by the series reactive impedance of the transmission line. Series compensation with capacitors is the most common strategy to cancel the reactance part of the line. Like shunt compensation, series compensation may also be implemented with power electronic converters.

3.4.2.1 Series Capacitors

A simplified model of a series-compensated transmission line is shown in Fig. 3.12.

The transmission line is assumed ideal and it is represented by the reactance X_L. A series controlled capacitor is connected in the transmission line. The overall series inductance of the compensated transmission line is:

$$X_{total} = X_L - X \tag{3.14}$$

Therefore, a series capacitor can cancel the reactance part of the line. This increases the maximum power, reduces the transmission angle at a given level of power transfer, and increases the surge impedance loading. Based on Eq. (3.8), the transmitted active power in the compensated line is calculated as:

$$P_i = \frac{V_i V_j}{X_L - X} \sin(\theta_i - \theta_j) \tag{3.15}$$

3.4.2.2 Series Compensation Based on the Power Electronic Converters

Like shunt compensation, series compensation may also be implemented with voltage source converters. Under compensation conditions, the converter injects a voltage vector between two buses in series. The equivalent circuit to explain the injected voltage vector by the converter is shown in Fig. 3.13. As it can be seen, bus-j voltage vector can be expressed as follow:

$$\vec{V}_j = \vec{V}_{inj} + \vec{V}_i \tag{3.16}$$

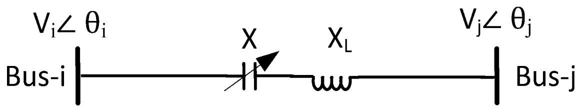

Fig. 3.12 Simplified model of a series compensated transmission line

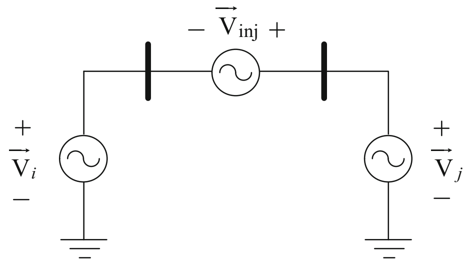

Fig. 3.13 Series compensation based on the power electronic converter

where $\overrightarrow{V}_i$, $\overrightarrow{V}_{inj}$ and $\overrightarrow{V}_j$ are bus-*i* voltage vector, injected voltage vector by the series converter and bus-j voltage vector, respectively. By injecting an appropriate voltage vector by the converter, the voltage can be regulated.

The control scheme is one of the important parts of the series compensator and has four basic functions:

- First, the grid buses voltages must be estimated
- After estimation, using an appropriate compensation method, the control scheme generates the voltage references.
- After producing the voltage references, the switching commands are generated by the appropriate modulation technique.
- When the current magnitude exceeds the rated converter range, the control scheme will generate the appropriate commands to the protection devices.

The two following methods have been usually used in the literature for compensation and voltage control:

1. After transformation of the three-phase voltages to the synchronous reference frame, dq-components of the voltages are controlled using PI controllers as shown in Fig. 3.14 [23, 24].
2. By using a phasor estimation method such as Kalman filter, Discrete Fourier Transform, or Least Error Squares, phasor parameters of the sensed voltages and currents are estimated separately for each phase. Then the control scheme generates the voltage references for each phase [25].

Figure 3.15a depicts the vector diagram of the voltages and current during the compensation and Fig. 3.15b shows the control scheme based on phasor estimation method. Here $\overrightarrow{V}_i = V_i\angle\theta_i, \overrightarrow{V}_j = V_j\angle\theta_j, \overrightarrow{V}_{inj} = V_{inj}\angle\theta_{inj}$ and $\vec{I} = I\angle\theta$ are the vectors of bus-i voltage, bus-j voltage, injection voltage by the converter and the line transmission current, respectively. V_{nom} is the compensated voltage magnitude. ϕ is the phase difference between the current and voltage of the bus-*j*. γ is phase difference between the injected voltage and bus-*i* voltage. According to the Fig. 3.15, the injected power is calculated as

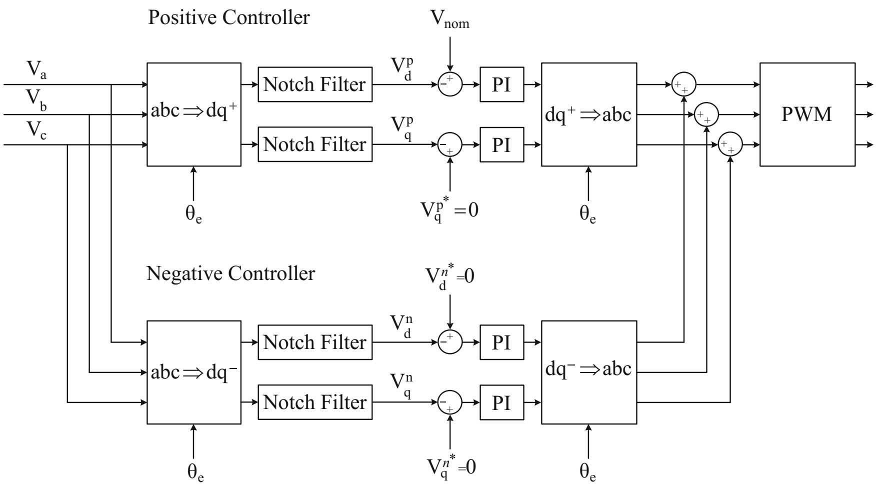

Fig. 3.14 Voltage control block diagram in dq reference frame

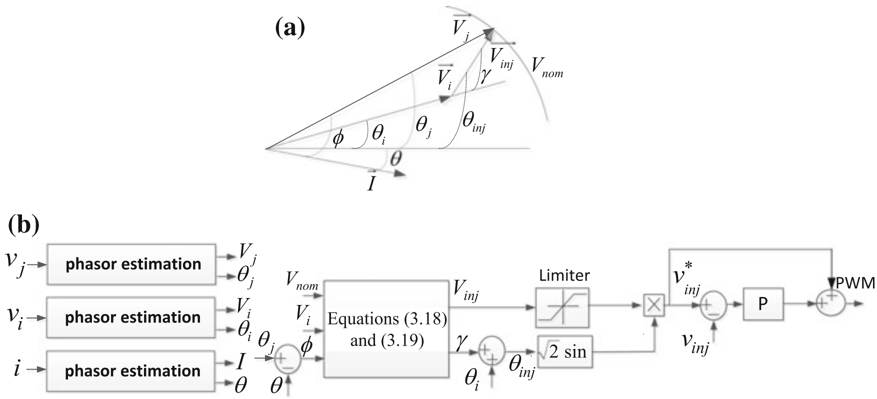

Fig. 3.15 Voltage control based on phasor estimation by series compensator, **a** vector diagram of the voltages and current during compensation, **b** block diagram of the control scheme

$$P_{inj} = P_{out} - P_{in} = V_j I \cos(\phi) - V_i I \cos(\phi - \theta_j + \theta_i) \tag{3.17}$$

where P_{out} is the output power and P_{in} is the input power. Since the compensation should be done by exchanging only reactive between the series converter and the network, so $P_{inj} = 0$ is assumed. In other words, the injected voltage should be perpendicular to the current, so no active power is exchanged between the converter and the network. By doing a small amount of computations and trigonometric relations, the injected voltage magnitude (V_{inj}) and γ are obtained as follows:

$$\gamma = \text{arc}\ \sin\left(\frac{V_{nom}\ \cos(\phi)}{V_i}\right) \tag{3.18}$$

$$V_{inj} = \sqrt{V_{nom}^2 + V_i^2 - 2V_{nom}\, V_i\ \sin(\gamma + \phi)} \tag{3.19}$$

After producing the voltage references, the inverter output voltages are injected in series by three single-phase transformers. To eliminate the switching frequency harmonics, a low-pass filter for each phase is used, which consists of the leakage inductance of the series transformer and the filter capacitor. Also, a parallel switch for each phase is used to bypass the series converter in fault conditions.

3.5 Conclusion

An overview of the basic principles of the power transmission operation and the reactive power role in the transmission system has been presented. The flow of reactive power causes additional heating of the lines and voltage drops in the network. High reactive power consumption by heavily loaded transmission line lead to voltage dips in the system and limit the generation of the active power. Voltage and reactive power control causes that a stable, efficient, and reliable operation of the power system is achieved and utilization of the transmission system is maximized.

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