Module-2

Subject: Flexible AC Transmission System (FACTS)

Content: Reactive Power Control in Power System (understanding of reactive power associated with power transmission networks is developed. To make transmission networks operate within desired voltage limits, methods of making up or taking away reactive power hereafter called reactive-power control

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2.0 Relationship between Reactive Power and Voltage

There is a strong relationship between voltage and reactive power flow, though real power flow on loaded circuits may further escalate the voltage problem. The voltages in a distribution system and to the consumers must be maintained within a certain plus–minus band around the rated equipment voltage, ideally from no load to full load, and under varying loading conditions.

Sudden load impacts (starting of a large motor) or load demands under contingency operating conditions, when one or more tie-line circuits may be out of service, result in short-time or prolonged voltage dips. High voltages may occur under light running load or on sudden load throwing and are of equal considerations, though low voltages occur more frequently. ANSI C84.1 specifies the preferred nominal voltages and operating voltage ranges A and B for utilization and distribution equipment operating from 120 to 34,500 V. For transmission voltages over 34,500 V only nominal and maximum system voltage is specified. Range B allows limited excursions outside range A limits. As an example, for a 13.8 kV nominal voltage, range A=14.49 – 12.46kV and range B = 14:5 – 13.11kV. Cyclic loads, e.g., arc furnaces giving rise to flicker, must be controlled to an acceptable level. The electrical apparatuses have a certain maximum and minimum operating voltage, range in which normal operation is maintained, i.e., induction motors are designed to operate successfully under the following conditions:

1. Plus or minus 10% of rated voltage, with rated frequency.
2. A combined variation in voltage and frequency of 10% (sum of absolute values) provided that the frequency variations do not exceed 5% of rated frequency.
3. Plus or minus 5% of frequency with rated voltage.

Motor torque, speed, line current, and losses vary with respect to the operating voltage, as shown in Table 2.1. Continuous operation beyond the designed voltage variations is detrimental to the integrity and life of the electrical equipment.

Characteristics of induction motor	Variation with voltage	Performance at rated voltage (1.0 per unit) and other than rated voltages				
		0.80	0.95	1.0	1.05	1.10
Torque	$= V^2$	0.64	0.90	1.0	1.10	1.21
Full-load slip	$= 1/V^2$	1.56	1.11	1.0	0.91	0.83
Full-load current	$\approx 1/V$	1.28	1.04	1.0	0.956	0.935
Full-load efficiency		0.88	0.915	0.92	0.925	0.92
Full-load power factor		0.90	0.89	0.88	0.87	0.86
Starting current	$= V$	0.80	0.95	1.0	1.05	1.10
No load losses (watts)	$= V^2$	0.016	0.023	0.025	0.028	0.030
No load losses (vars)	$= V^2$	0.16	0.226	0.25	0.276	0.303

Table 2.1 Effect of Voltage Variations on Induction Motor Performances

A certain balance between the reactive power consuming and generating apparatuses is required. This must consider losses which may be a considerable percentage of the reactive load demand.

When the reactive power is transported over mainly reactive elements of the power system, the reactive power losses may be considerable and these add to the load demand. This reduces the active power delivery capability of most electrical equipment rated on a kVA base. As an example, consider the reactive power flow through a 0.76 ohm reactor. For a 70Mvar input the output is 50 Mvar and 20 Mvar are lost in the reactor itself. If the load voltage is to be maintained at 1.0 per unit, the source side voltage should be raised to 1.28 per unit, representing a voltage drop of 28% in the reactor.

In a loaded transmission line, when power transfer is below the surge impedance loading, the charging current exceeds the reactive line losses and this excess charging current must be absorbed by shunt reactors and generators. Above surge impedance loading the reactive power must be supplied to the line. At 1.5 times the surge loading an increase of 150 MW will increase the reactive power losses in a 500- kV transmission line by about 95 Mvar, or about 50% of the line charging. At twice surge loading, approximately 1800 MW (surge impedance 277 ohms), a 100-MW load increase will increase reactive loses by 100Mvar. A V–Q control may necessitate addition of leading or lagging reactive power sources, which may be passive or dynamic in nature. Shunt reactors and capacitors are examples of passive devices. The SVC is an example of a dynamic device. It should be ensured that all plant generators operate within their reactive power capability limits and remain stable. The on-load tap changing transformers must be able to maintain an acceptable voltage within their tap setting range.

Assessment of voltage problems in a distribution system under normal and contingency load-flow conditions, therefore, requires investigations of the following options:

- Location of reactive power sources, i.e., series and shunt capacitors, synchronous condensers, voltage regulators, overexcited synchronous motors, and SVCs with respect to load.
- Control strategies of these reactive power sources.
- Provision of on-load tap changing equipment on tie transformers.
- Undervoltage load shedding.
- Stiffening of the system, i.e., reduction of system reactance which can be achieved by bundle conductors, duplicate feeders, and additional tie lines.
- Redistribution of loads.

2.1 Reactive Power

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

For the ac circuit shown in Fig. 2.1(a), instantaneous power from the voltage source to the load $Z\angle\phi$, in terms of the instantaneous voltage *v* and current *i*, is given as

$$p = vi \tag{2.1}$$

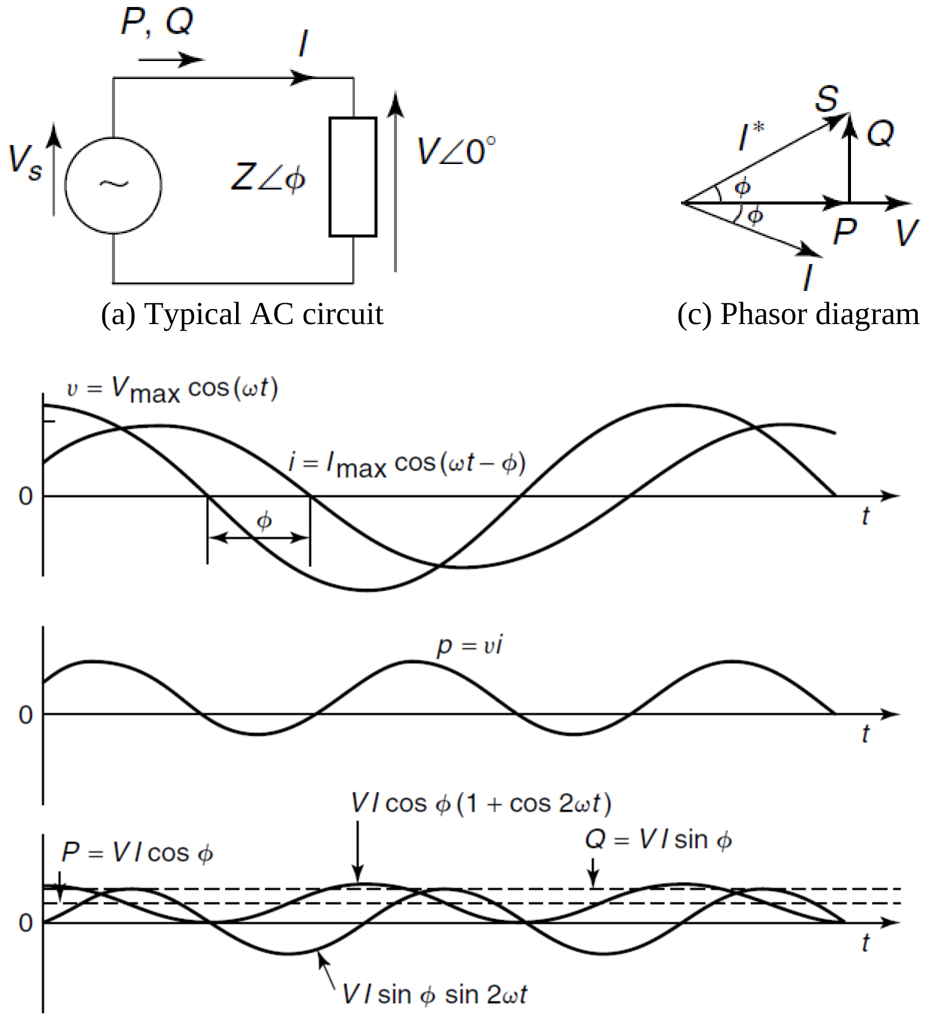
In the steady state, where $v = V_{\max}\cos(\omega t)$ and $i = I_{\max}\cos(\omega t - \phi)$

$$\begin{aligned} p &= \frac{V_{\max} I_{\max}}{2}\,[\cos\phi + \cos(2\omega t - \phi)] \\ &= VI\cos\phi(1 + \cos 2\omega t) + VI\sin\phi\sin 2\omega t \end{aligned} \tag{2.2}$$

where *V* and *I* are the respective root mean square (rms) values of *v* and *i*. Equations (2.1) and (2.2) are pictorially represented in Fig. 2.1(b). Equation (2.2) comprises two double-frequency (2q) components. The first term has an average value as well as a peak magnitude of *VI* cos wt. This average value is the active power, *P*, flowing from the source to the load.

The second term has a zero average value, but its peak value is *VI* sin wt. Written in phasor domain, the complex power in the network in Fig. 2.1(a) is given by

$$\begin{aligned} S &= \overline{V} \cdot \overline{I}^* \\ &= P + jQ = VI\cos\phi + jVI\sin\phi \end{aligned} \quad (2.3)$$



(a) Typical AC circuit (c) Phasor diagram

(b) Waveforms

Figure 2.1 The electrical parameters in an ac network.

where *P* is called the active power, which is measured in watts (W), and *Q* is called the reactive power, which is measured in volt–ampere reactive (var). Comparing Eqs. (2.3) and (2.2), the peak value of the second component of instantaneous power in Eq. (2.2) is identified as the reactive power. The reactive power is essential for creating the needed coupling fields for energy devices. It constitutes voltage and current loading of circuits but does not result in an average (active) power consumption and is, in fact, an important component in all ac power networks. In high-power networks, active and reactive powers are measured in megawatts (MW) and MVAR, respectively.

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

2.2 UNCOMPENSATED TRANSMISSION LINES

2.2.1 A Simple Case

To develop a good, qualitative understanding of the need for reactive-power control, let us consider a simple case of a lossless short-transmission line connecting a source Vs to a load $Z\angle\phi$. (For simplicity, the line is represented only by its inductive reactance X_l.) Figure 2.2 shows such a network with its parameters, as well as a phasor diagram showing the relationship between voltages and currents. From Fig. 2.2(b), it is clear that between the sending- and the receiving-end voltages, a magnitude variation, as well as a phase difference, is created. The most significant part of the voltage drop in the line reactance $(\Delta V_1 = j\bar{I}_x X_l)$ is due to the reactive component of the load current, I_x. To keep the voltages in the network at nearly the rated value, two control actions seem possible:

1. load compensation, and
2. system compensation.

2.2.1.1 Load Compensation

It is possible to compensate for the reactive current I_x of the load by adding a parallel capacitive load so that $I_c = -I_x$. Doing so causes the effective power factor of the combination to become unity. The absence of I_x eliminates the voltage drop ΔV_1, bringing V_r closer in magnitude to V_s; this condition is called *load compensation*. Actually, by charging extra for supplying the reactive power, a power utility company

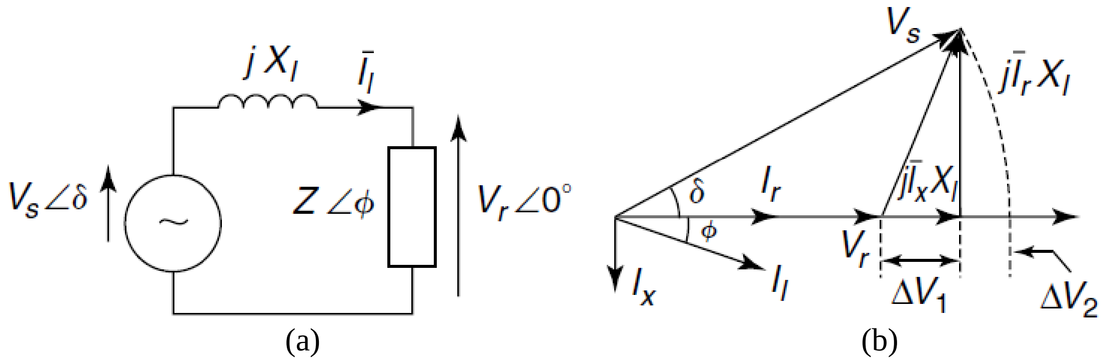


Figure 2.2 A short, lossless transmission line feeding a load.

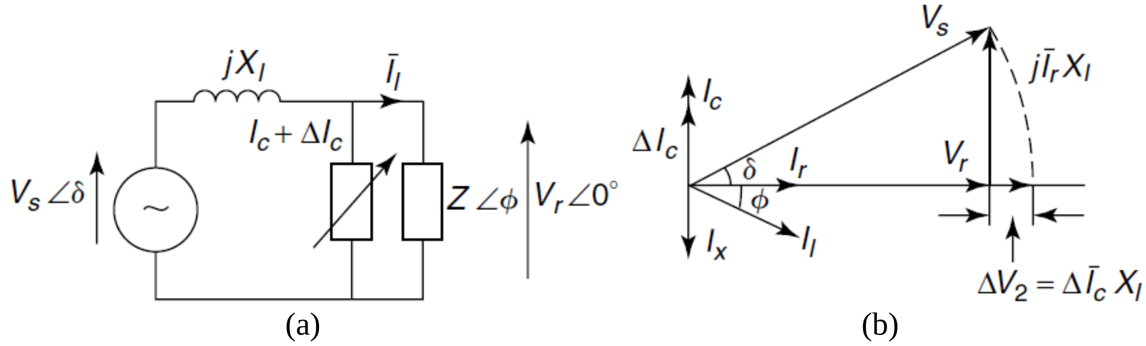


Figure 2.3 The reactive-power control for voltage regulations.

makes it advantageous for customers to use load compensation on their premises. Loads compensated to the unity power factor reduce the line drop but do not eliminate it; they still experience a drop of ΔV_2 from $j\ I_r X_l$.

2.2.1.2 System Compensation

To regulate the receiving-end voltage at the rated value, a power utility may install a reactive-power compensator as shown in Fig. 2.3. This compensator draws a reactive current to overcome both components of the voltage drop ΔV_1 and ΔV_2 as a consequence of the load current *Il* through the line reactance X_l. To compensate for ΔV_2, an additional
capacitive current, ΔI_c, over and above I_c that compensates for I_x, is drawn by the compensator. When $\Delta I_c X_l = \Delta V_2$, the receiving-end voltage, V_r, equals the sending-end voltage, V_s. Such compensators are employed by power utilities to ensure the quality of supply to their customers .

Active and Passive Var Control

When fixed inductors and□□ /or capacitors are employed to absorb or generate reactive power, they constitute passive control. An active var control, on the other hand, is produced when its reactive power is changed irrespective of the terminal voltage to which the var controller is connected.

2.3 PASSIVE COMPENSATION

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

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

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

2.3.1 Shunt Compensation

Passive reactive-power compensators include series capacitors and shunt-connected inductors and capacitors. Shunt devices may be connected permanently or through a switch. Shunt reactors compensate for the line capacitance, and because they control overvoltages at no loads and light loads, they are often connected permanently to the line, not to the bus. Figure 2.12 shows the arrangements of shunt reactors on a long-distance, high-voltage ac line. Many power utilities connect shunt reactors via breakers, thereby acquiring the flexibility to turn them off under heavier load conditions. Shunt reactors are generally gapped-core reactors and, sometimes, air-cored. Shunt capacitors are used to increase the power-transfer capacity and to compensate for the reactive-voltage drop in the line. The application of shunt

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

2.3.2 Series Compensation

Series capacitors are used to partially offset the effects of the series inductances of lines. Series compensation results in the improvement of the maximum power-transmission capacity of the line. The net effect is a lower load angle for a given power-transmission level and, therefore, a higher-stability margin. The reactive-power absorption of a line depends on the transmission current, so when series capacitors are employed, automatically the resulting reactive-power compensation is adjusted proportionately. Also, because the series compensation effectively reduces the overall line reactance, it is expected that the net line-voltage drop would become less susceptible to the loading conditions. In an interconnected network of power lines that provides several parallel paths, for power flow between two locations, it is the series compensation of a selected line that makes it the principal power carrier. Series compensation is defined by the degree of compensation; for example, a 1-pu compensation means that the effective series reactance of a line will be zero. A practical upper limit of series compensation, on the other hand, may be as high as 0.75 pu. One impact of the passive compensation of lines is that whereas the shunt-inductive compensation makes the line electrically resonant at a super synchronous frequency, the series compensation makes the line resonant at a subsynchronous frequency. The subsynchronous resonance (SSR) can lead
to problematic situations for steam turbine–driven generators connected to a series-compensated transmission line. These generators employ multiple turbines connected on a common shaft with the generator. This arrangement constitutes an elastically coupled multimass mechanical system that exhibits several modes of low-frequency torsional resonances, none of which should be excited as a result of the subsynchronous-resonant electrical transmission system. The application of series compensation requires several other careful considerations. The application of series capacitors in a long line constitutes placing a lumped impedance at a point. Therefore, the following factors need careful evaluation:

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

2.3.3 Effect on Power-Transfer Capacity

The consideration of series compensation invariably raises the issue of its comparison with shunt compensation. A simple system analysis can be performed to develop a basic understanding of the effect of shunt and series compensation on power-transmission capacity. Consider a short, symmetrical electrical line as shown in Fig. 2.4. For an uncompensated line, and assuming V_s -V_r -V, the power equation becomes

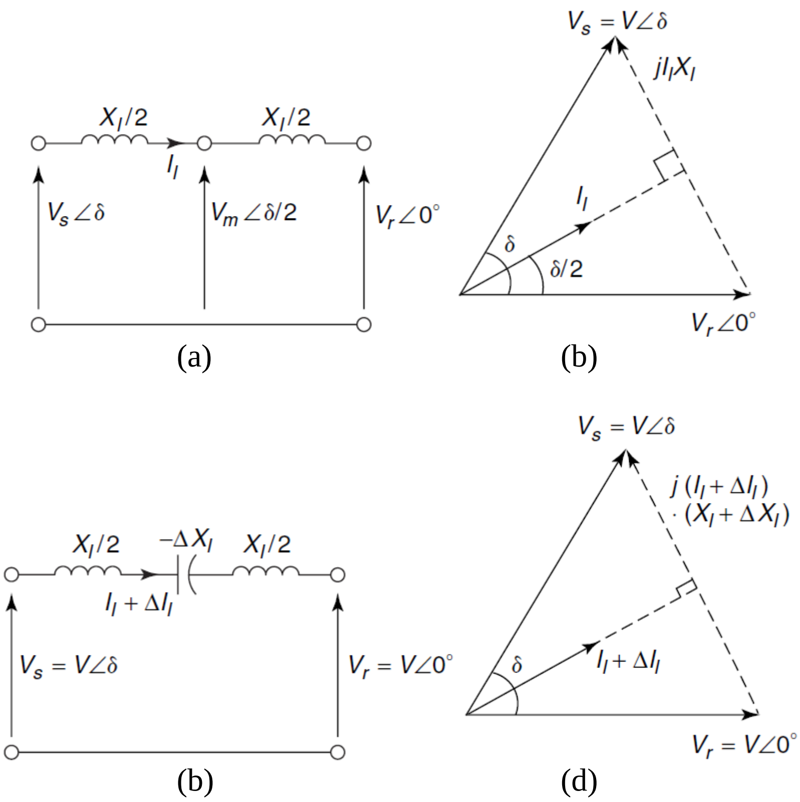


Figure 2.4 The series compensation of a short, symmetrical transmission line.

$$P = \frac{V^2}{X_l} \sin\,\delta = \frac{V^2}{X_l}\,2\sin\,\frac{\delta}{2}\,\cos\,\frac{\delta}{2} \tag{2.4}$$

From the voltage-phasor equations and the phasor diagram in Fig. 2.4(a),

$$I_l = \frac{2V}{X_l}\,\sin\,\frac{\delta}{2} \tag{2.5}$$

2.3.3.1 Series Compensation If the effective reactance of a line is controlled by inserting a series capacitor, and if the line terminal voltages are held unchanged, then a ΔX_l change in the line reactance will result in a ΔIl change in the current, where

$$\Delta I_l = -\frac{2V}{X_l^2}\,\sin\,\frac{\delta}{2}\,X_l = -I_l\,\frac{\Delta X_l}{X_l} \tag{2.6}$$

Therefore, from Eq. (2.4), the corresponding change in the power transfer will be

$$\Delta P = -\frac{V^2}{X_l^2}\,2\sin\,\frac{\delta}{2}\,\cos\,\frac{\delta}{2}\,\Delta X_l \tag{2.7}$$

Using Eqs. (2.5) and (2.6), Eq. (2.7) may be written as

$$\Delta P = \frac{1}{2\tan\frac{\delta}{2}}(-\Delta X_l I_l^2)$$

As $-\Delta X_l$ is the reactance added by series capacitors, $\Delta X_l I_{2l}$ - ΔQ_{se} represents the incremental var rating of the series capacitor. Therefore

$$\frac{\Delta P}{\Delta Q_{se}} = \frac{1}{2\tan\frac{\delta}{2}} \qquad (2.8)$$

2.3.3.2 Shunt Compensation Reconsider the short, symmetrical line described in Fig. 2.4(a). Apply a shunt capacitor at the midpoint of the line so that a shunt susceptance is incrementally added (ΔB_c), as shown in Fig. 2.5. For the system in this figure, the power transfer in terms of the midpoint voltage on the line is

$$P = \frac{V V_m}{\frac{X_l}{2}} \sin\frac{\delta}{2} \qquad (2.9)$$

The differential change in power, ΔP, as a result of a differential change, ΔV_m, is given as

$$\Delta P = \frac{2V}{X_l} \sin\frac{\delta}{2} \Delta V_m \qquad (2.10)$$

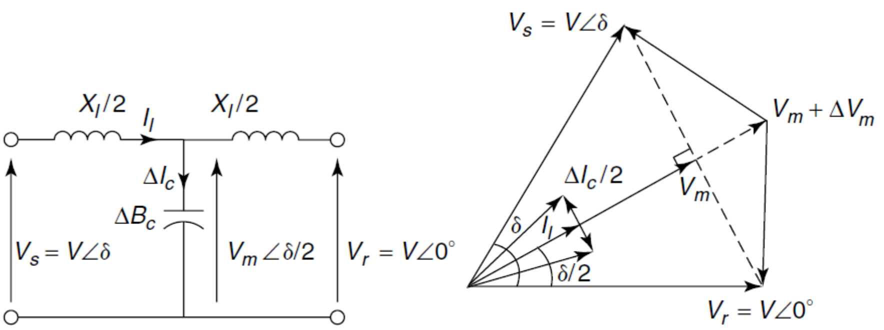


Figure 2.5 The midpoint-capacitor compensation of a short, symmetrical line.

Also as shown in Fig. 2.14,

$$\Delta I_c = V_m \Delta B_c$$

The current ΔI_c in the midline shunt capacitor modifies the line currents in the sending and receiving ends of the line to the following:

$$I_{ls} = I_l - \frac{\Delta I_c}{2} \quad \text{and} \quad I_{lr} = I_l + \frac{\Delta I_c}{2}$$

As $V_m = V_r + jI_{lr}X_l/2$,

$$\Delta V_m = \frac{\Delta I_c X_l}{4} = \frac{V_m X_l}{4} \Delta B_c \tag{2.11}$$

Substituting the results of Eq. (2.11) in Eq. (2.10), we get

$$\Delta P = \frac{V V_m}{2} \sin \frac{\delta}{2} \Delta B_c$$

If the midpoint voltage of the line is approximately equal to $V\cos \delta$□□2, then the incremental rating of the shunt-capacitor compensation will be ΔQ_{sh} - $V^2_m \Delta B_c$, or

$$\frac{\Delta P}{\Delta Q_{sh}} = \frac{1}{2} \tan \frac{\delta}{2} \tag{2.12}$$

By comparing Eqs. (2.8) and Eqs. (2.12), we deduce that for an equivalent power transfer on a short electrical line,

$$\frac{\Delta Q_{se}}{\Delta Q_{sh}} = \left(\tan \frac{\delta}{2}\right)^2$$

Assuming an operating load angle $\delta = 30°$, we get the ratio of the ratings of series (ΔQ_{se}) to shunt (ΔQ_{sh}) compensators to be 0.072, or 7.2%. From the foregoing discussion, it is clear that the var net rating of the series compensator is only 7.2% of that required of a shunt compensator for the same change in power transfer. Therefore, one concludes that the series-capacitive compensation is not only achieved with a smaller MVAR rating, but also that it is automatically adjusted for the entire range of the line loading. However, the

cost of the compensator is not directly related only to the MVAR-rating seriescapacitor costs increase because they carry full line current and also both their ends must be insulated for the line voltage. Practical application of series capacitors requires isolation and bypass arrangements as well as protection and monitoring arrangements.