Unit-V Power factor & Voltage Control Improvement

BASIC DEFINITIONS

Capacitor element: an indivisible part of a capacitor consisting of electrodes separated by a dielectric material

Capacitor unit: an assembly of one or more capacitor elements in a single container with terminals brought out

Capacitor segment: a single-phase group of capacitor units with protection and control system

Capacitor module: a three-phase group of capacitor segments

Capacitor bank: a total assembly of capacitor modules electrically connected to each other

Capacitive compensation for power factor control

POWER CAPACITORS

At a casual look a capacitor seems to be a very simple and unsophisticated apparatus, i.e., two metal plates separated by a dielectric insulating material. It has no moving parts, but instead functions by being acted upon by electric stress. In reality, however, a power capacitor is a highly technical and complex device in that very thin dielectric materials and high electric stresses are involved, coupled with highly sophisticated processing techniques. Figure 8-1 shows a cutaway view of a power-factor-correction capacitor. Figure 8-2 shows a typical capacitor utilization in a switched pole-top rack.

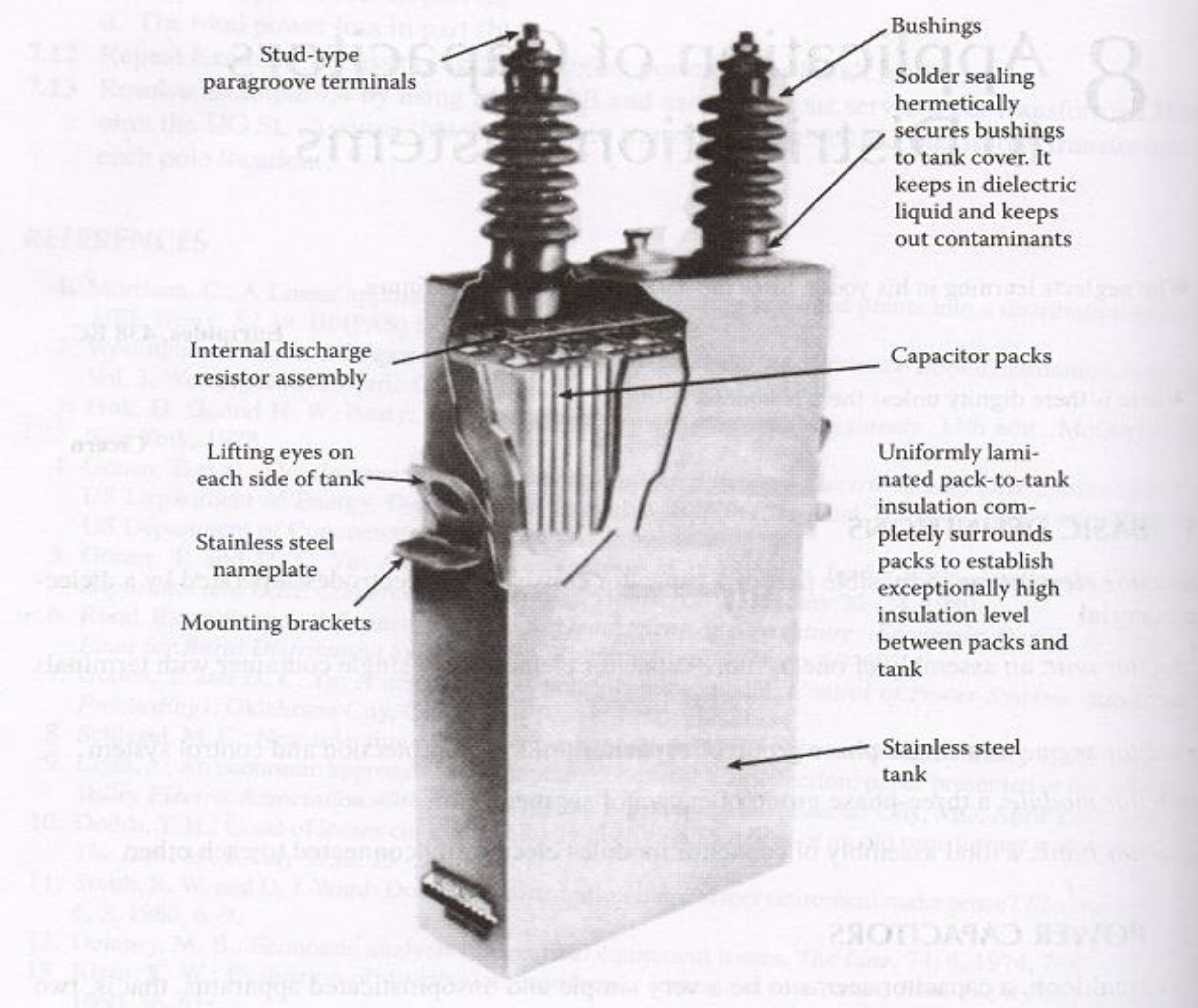


FIGURE 8.1 A cutaway view of a power factor correction capacitor. (From McGraw-Edison company *The ABC of Capacitors*, Bulletin R230-90-1, 1968.)

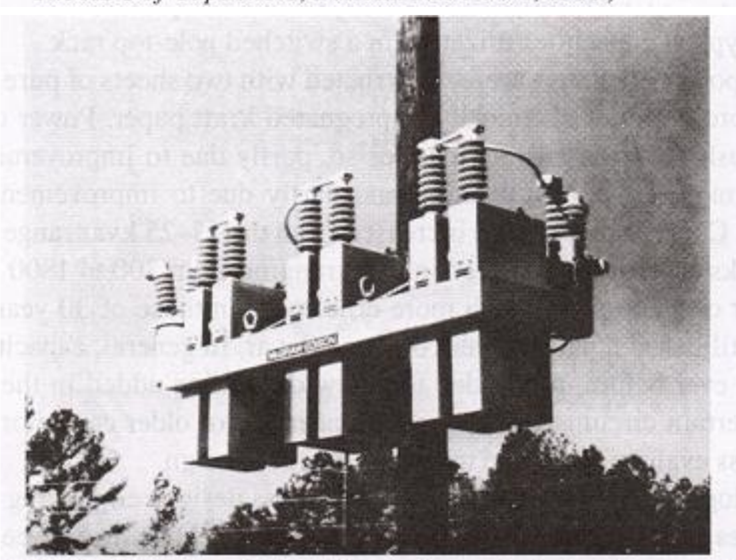


FIGURE 8.2 A typical utilization in a switched pole-top rack.

In the past, most power capacitors were constructed with two sheets of pure aluminum foil separated by three or more layers of chemically impregnated kraft paper. Power capacitors have been improved tremendously over the last 30 years or so, partly due to improvements in the dielectric materials and their more efficient utilization and partly due to improvements in the processing techniques involved. Capacitor sizes have increased from the 15–25 kvar range to the 200–300 kvar range (capacitor banks are usually supplied in sizes ranging from 300 to 1800 kvar). Nowadays, power capacitors are much more efficient than those of 30 years ago and are available to the electric utilities at a much lower cost per kilovar. In general, capacitors are getting more attention today than ever before, partly due to a new dimension added in the analysis: changeout economics. Under certain circumstances, even replacement of older capacitors can be justified on the basis of lower-loss evaluations of the modern capacitor design. Capacitor technology has evolved to extremely low loss designs employing the all-film concept; as a result, the utilities can make economic loss evaluations in choosing between the presently existing capacitor technologies.

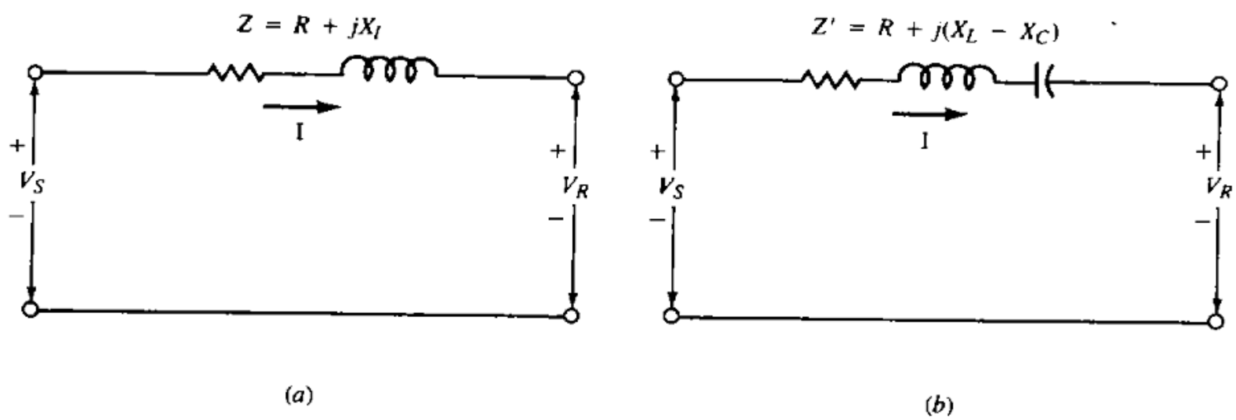
EFFECTS OF SERIES AND SHUNT CAPACITORS

As mentioned earlier, the fundamental function of capacitors, whether they are series or shunt, installed as a single unit or as a bank, is to regulate the voltage and reactive power flows at the point where they are installed. The shunt capacitor does it by changing the power factor of the load, whereas the series capacitor does it by directly offsetting the inductive reactance of the circuit to which it is applied.

Series Capacitors

Series capacitors, i.e., capacitors connected in series with lines, have been used to a very limited extent on distribution circuits due to being a more specialized type of apparatus with a limited range of application. Also, because of the special problems associated with each application, there is a requirement for a large amount of complex engineering investigation. Therefore, in general, utilities are reluctant to install series capacitors, especially of small sizes.

As shown in Fig. 8-3, a series capacitor compensates for inductive reactance. In other words, a series capacitor is a negative (capacitive) reactance in series with the circuit's positive (inductive) reactance with the effect of compensating for part or all of it. Therefore, the primary effect of the series capacitor is to minimize, or even suppress, the voltage drop caused by the inductive reactance in the circuit. At times, a series capacitor can even be considered as a voltage regulator that provides for a voltage boost which is proportional to the magnitude and power factor of the through current. Therefore, a series capacitor provides for a voltage rise which increases automatically and instantaneously as the load grows. Also, a series capacitor produces more net voltage rise than a shunt capacitor at lower power factors, which creates more voltage drop. However, a series capacitor betters the



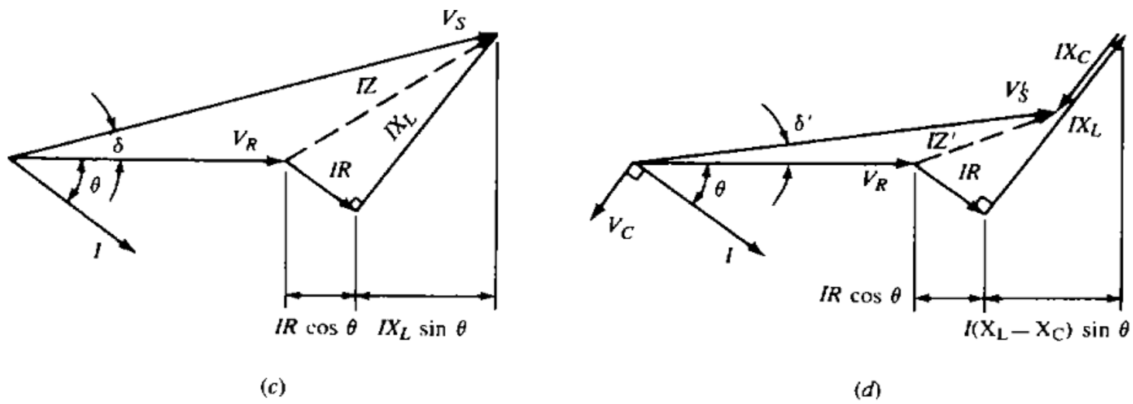


Figure 8-3 Voltage-phasor diagrams for a feeder circuit of lagging power factor: (*a*) and (*c*) without and (*b*) and (*d*) with series capacitors.

system power factor much less than a shunt capacitor and has little effect on the source current.

Consider the feeder circuit and its voltage-phasor diagram as shown in Fig. 8-3*a* and *c*. The voltage drop through the feeder can be expressed approximately as

$$\mathrm{VD} = IR \cos \theta + IX_L \sin \theta \tag{8-1}$$

where R = resistance of feeder circuit
X_L = inductive reactance of feeder circuit
$\cos \theta$ = receiving-end power factor
$\sin \theta$ = sine of the receiving-end power-factor angle

As can be observed from the phasor diagram, the magnitude of the second term in Eq. (8-1) is much larger than the first. The difference gets to be much larger when the power factor is smaller and the ratio of R/X_L is small.

However, when a series capacitor is applied, as shown in Fig. 8-3*b* and *d*, the resultant lower voltage drop can be calculated as

$$\mathrm{VD} = IR \cos \theta + I(X_L - X_c) \sin \theta \tag{8-2}$$

where X_c = capacitive reactance of the series capacitor.

Overcompensation Usually, the series-capacitor size is selected for a distribution feeder application in such a way that the resultant capacitive reactance is smaller than the inductive reactance of the feeder circuit. However, in certain applications (where the resistance of the feeder circuit is larger than its inductive reactance), the reverse might be preferred so that the resultant voltage drop is

$$\text{VD} = IR \cos\theta - I(X_c - X_L)\sin\theta \tag{8-3}$$

The resultant condition is known as *overcompensation*. Figure 8-4*a* shows a voltage-phasor diagram for overcompensation at normal load. At times, when the selected level of overcompensation is strictly based on normal load, the resultant overcompensation of the receiving-end voltage may not be pleasing at all because the lagging current of a large motor at start can produce an extraordinarily large voltage rise, as shown in Fig. 8-4*b*, which is especially harmful to lights (shortening their lives) and causes light flicker, resulting in consumers' complaints.

Leading power factor To decrease the voltage drop considerably between the sending and receiving ends by the application of a series capacitor, the load current must have a lagging power factor. As an example, Fig. 8-5*a* shows a voltage-phasor diagram with a leading-load power factor without having series capacitors in the line. Figure 8-5*b* shows the resultant voltage-phasor diagram with the same leading-load power factor but this time with series capacitors in the line. As can be seen from the figure, the receiving-end voltage is reduced as a result of having series capacitors.

When $\cos\theta = 1.0$, $\sin\theta \cong 0$, and therefore

$$I(X_L - X_c)\sin\theta \cong 0$$

hence Eq. (8-2) becomes

$$\text{VD} \cong IR \tag{8-4}$$

Thus, in such applications, series capacitors practically have no value.

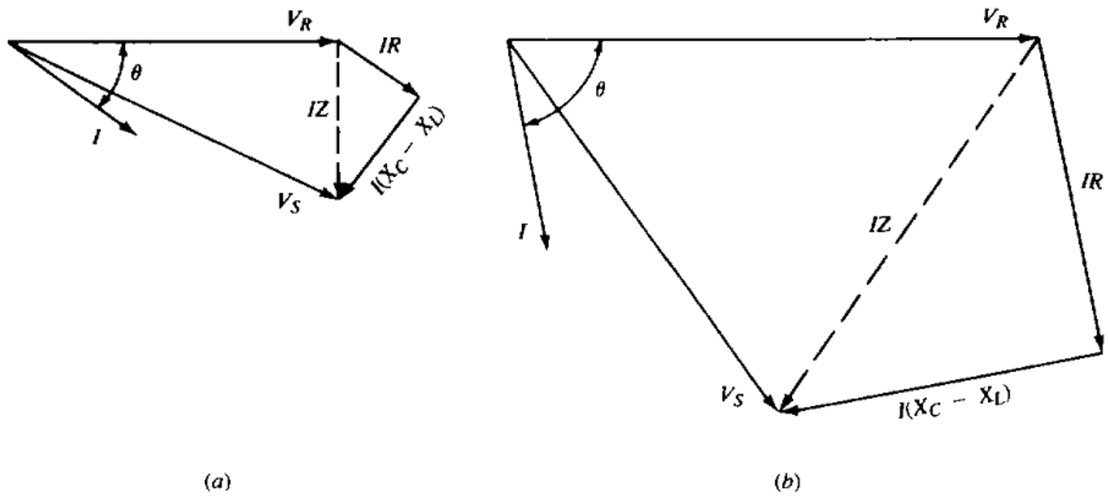


Figure 8-4 Overcompensation of the receiving-end voltage: (*a*) at normal load and (*b*) at the start of a large motor.

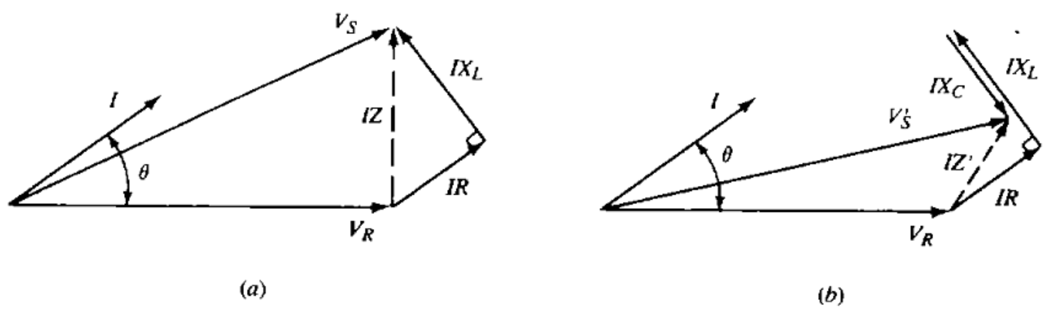


Figure 8-5 Voltage-phasor diagram with leading power factor: (*a*) without series capacitors and (*b*) with series capacitors.

Because of the aforementioned reasons and others (e.g., ferroresonance in transformers, subsynchronous resonance during motor starting, shunting of motors during normal operation, and difficulty in protection of capacitors from system fault current), series capacitors do not have large applications in distribution systems. However, they are employed in subtransmission systems to modify the load division between parallel lines. For example, often a new subtransmission line with larger thermal capability is parallel with an already existing line. It may be very difficult, if not impossible, to load the subtransmission line without overloading the old line. Here, series capacitors can be employed to offset some of the line reactance with greater thermal capability. They are also employed in subtransmission systems to decrease the voltage regulation.

Shunt Capacitors

Shunt capacitors, i.e., capacitors connected in parallel with lines, are used extensively in distribution systems. Shunt capacitors supply the type of reactive power or current to counteract the out-of-phase component of current required by an inductive load. In a sense, shunt capacitors modify the characteristic of an inductive load by drawing a leading current which counteracts some or all of the lagging component of the inductive load current at the point of installation. Therefore a shunt capacitor has the same effect as an overexcited synchronous condenser, generator, or motor.

As shown in Fig. 8-6, by the application of shunt capacitor to a feeder, the magnitude of the source current can be reduced, the power factor can be improved, and consequently the voltage drop between the sending end and the load is also reduced. However, shunt capacitors do not affect current or power factor beyond their point of application. Figures 8-6*a* and *c* show the single-line diagram of a line and its voltage-phasor diagram before the addition of the shunt capacitor, and Fig. 8-6*b* and *d* show them after the addition.

Voltage drop in feeders, or in short transmission lines, with lagging power factor can be approximated as

$$VD = I_R R + I_X X_L \qquad V \tag{8-5}$$

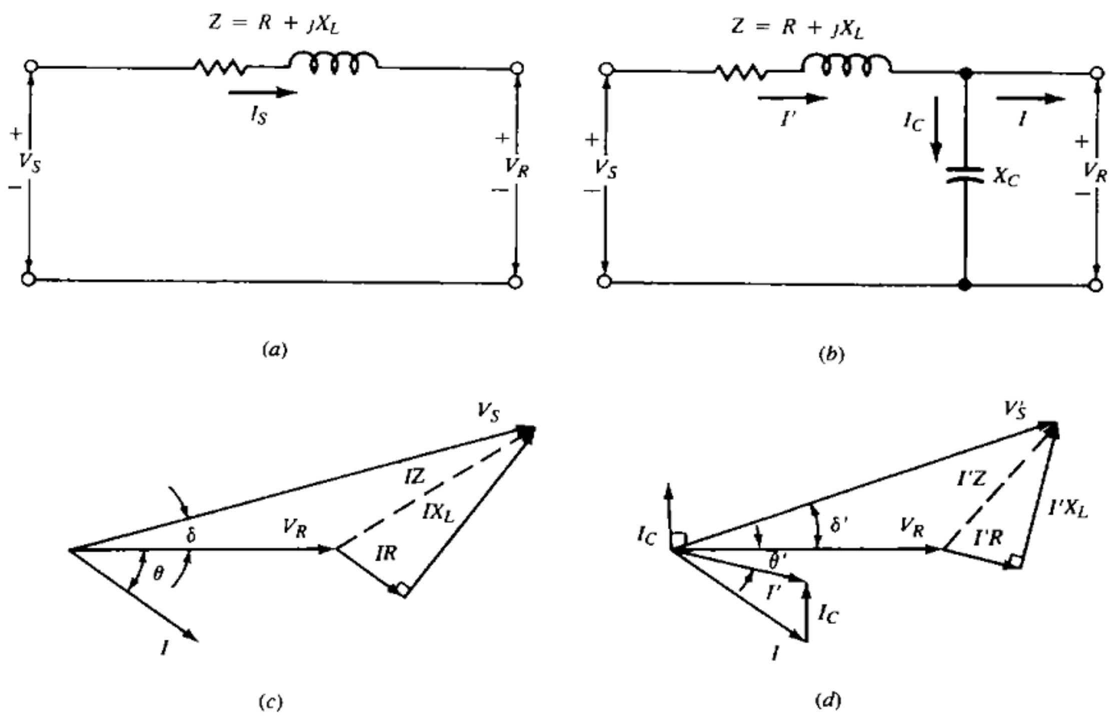


Figure 8-6 Voltage-phasor diagrams for a feeder circuit of lagging power factor: (*a*) and (*c*) without and (*b*) and (*d*) with shunt capacitors.

where R = total resistance of feeder circuit, Ω
X_L = total inductive reactance of feeder circuit, Ω
I_R = real power (or in-phase) component of current, A
I_X = reactive (or out-of-phase) component of current lagging the voltage by 90°, A

When a capacitor is installed at the receiving end of the line, as shown in Fig. 8-6*b*, the resultant voltage drop can be calculated approximately as

$$\text{VD} = I_R R + I_X X_L - I_c X_L \qquad \text{V} \tag{8-6}$$

where I_c = reactive (or out-of-phase) component of current leading the voltage by 90°, A.

The difference between the voltage drops calculated by using Eqs. (8-5) and (8-6) is the voltage rise due to the installation of the capacitor and can be expressed as

$$\text{VR} = I_c X_L \qquad \text{V} \tag{8-7}$$

Power factor correction

General

A typical utility system would have a reactive load at 80 percent power factor during summer months. Therefore, in typical distribution loads, the current lags the voltage, as shown in Fig. 8-7*a*. The cosine of the angle between current and sending voltage is known as the *power factor* of the circuit. If the in-phase and out-of-phase components of the current I is multiplied by the receiving-end voltage V_R, the resultant relationship can be shown on a triangle known as the *power triangle*, as shown in Fig. 8-7*b*. Figure 8-7*b* shows the triangular relationship that exists between kilowatts, kilovoltamperes, and kilovars. Note that, by adding the capacitors, the reactive power component Q of the apparent power S of the load can be reduced or totally suppressed. Figures 8-8 and 8-9 illustrate how the reactive power component Q increases with each 10 percent change of power factor. Note that, as illustrated in Fig. 8-8, even an 80 percent power factor of the reactive power (kilovar) size is quite large, causing a 25 percent increase in the total apparent power (kilovoltamperes) of the line. At this power factor, 75 kvar of capacitors is needed to cancel out the 75 kvar of lagging component.

As previously mentioned, the generation of reactive power at a power plant and its supply to a load located at a far distance is not economically feasible, but it can easily be provided by capacitors located at the load centers. Figure 8-10 illustrates the power-factor correction for a given system. As illustrated in the

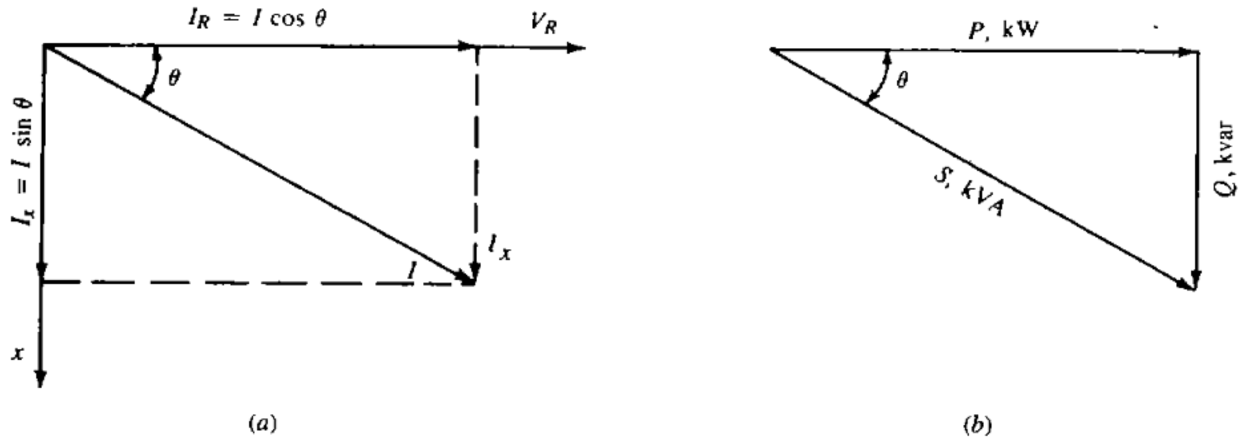


Figure 8-7 (*a*) Phasor diagram and (*b*) power triangle for a typical distribution load.

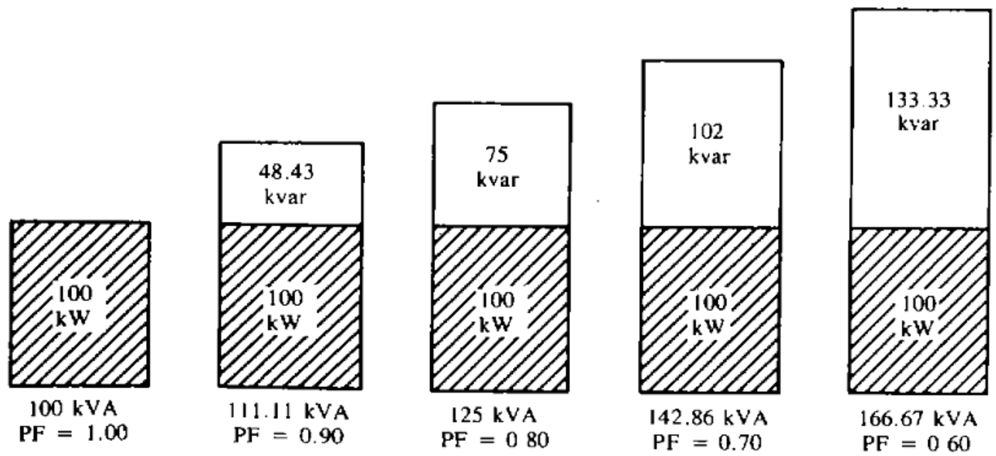


Figure 8-8 Illustration of the required increase in the apparent and reactive powers as a function of the load power factor, holding the real power of the load constant.

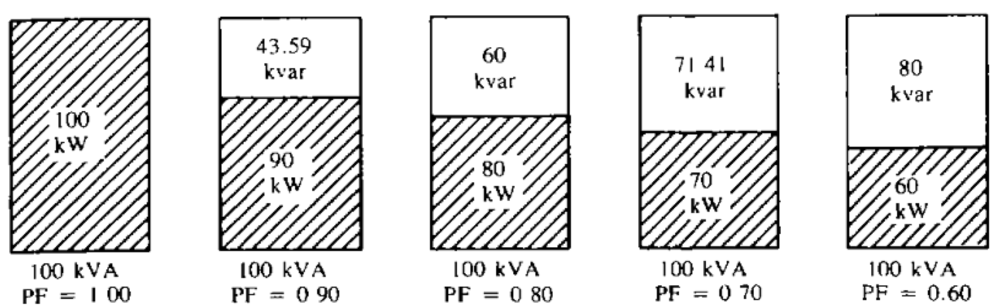


Figure 8-9 Illustration of the change in the real and reactive powers as a function of the load power factor, holding the apparent power of the load constant.

figure, capacitors draw leading reactive power from the source; i.e., they supply lagging reactive power to the load. Assume that a load is supplied with a real power P, lagging reactive power Q_1, and apparent power S_1 at a lagging power factor of

$$\cos \theta_1 = \frac{P}{S_1}$$

or

$$\cos \theta_1 = \frac{P}{(P^2 + Q_1^2)^{1/2}} \tag{8-8}$$

When a shunt capacitor of Q_c kVA is installed at the load, the power factor can be improved from $\cos \theta_1$ to $\cos \theta_2$, where

$$\cos \theta_2 = \frac{P}{S_2} = \frac{P}{(P^2 + Q_2^2)^{1/2}} = \frac{P}{[P^2 + (Q_1 - Q_c)^2]^{1/2}} \tag{8-9}$$

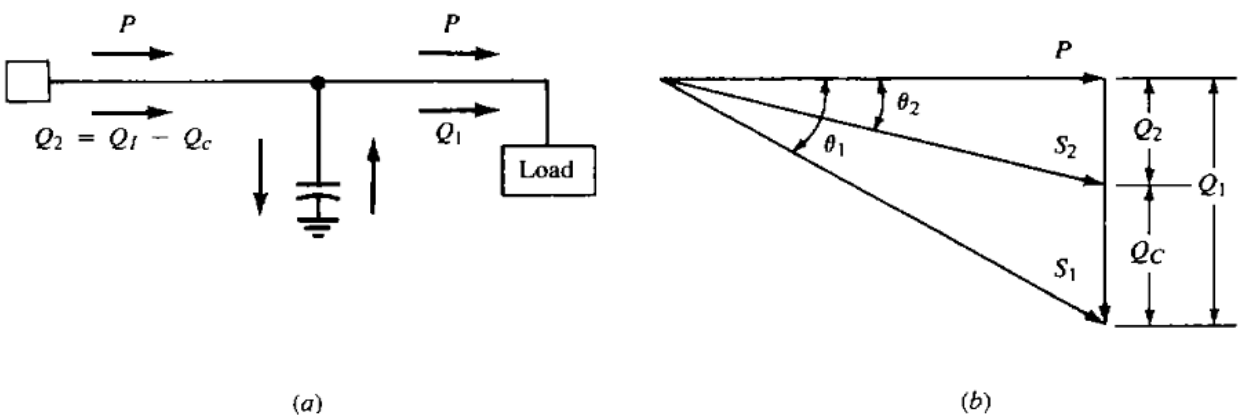


Figure 8-10 Illustration of power-factor correction.

Therefore, as can be observed from Fig. 8-10*b*, the apparent power and the reactive power are decreased from S_1 kVA to S_2 kVA and from Q_1 kvar to Q_2 kvar (by providing a reactive power of Q_c), respectively. Of course, the reduction of reactive current results in a reduced total current, which in turn causes less power losses. Thus the power-factor correction produces economic savings in capital expenditures and fuel expenses through a release of kilovoltamperage capacity and reduction of power losses in all the apparatus between the point of installation of the capacitors and the source power plants, including distribution lines, substation transformers, and transmission lines. The economic power factor is the point at which the economic benefits of adding shunt capacitors just equals the cost of capacitors. In the past, this economic power factor was around 95 percent. Today's high plant and fuel costs have pushed the economic power factor toward unity. However, as the corrected power factor moves nearer to unity, the effectiveness of capacitors in improving the power factor, decreasing the line kilovoltamperes transmitted, increasing the load capacity, or reducing line copper losses by decreasing the line current sharply decreases. Therefore the correction of power factor to unity becomes more expensive with regard to the marginal cost of capacitors installed.

Procedure to determine best capacitor location

In general, the best location for capacitors can be found by optimizing power loss and voltage regulation. A feeder voltage profile study is performed to warrant the most effective location for capacitors and the determination of a voltage which is within recommended limits. Usually, a 2-V rise on circuits used in urban areas and a 3-V rise on circuits used in rural areas are approximately the maximum voltage changes that are allowed when a switched-capacitor bank is placed into operation The general iteration process involved is summarized in the following steps:

1. Collect the following circuit and load information:
   a. Any two of the following for each load: kilovoltamperes, kilovars, kilowatts, and load power factor
   b. Desired corrected power of circuit

c. Feeder circuit voltage
d. A feeder circuit map which shows locations of loads and presently existing capacitor banks

2. Determine the kilowatt load of the feeder and the power factor.
3. From Table 8-1, determine the kilovars per kilowatts of load (i.e., the correction factor) necessary to correct the feeder-circuit power factor from the original to the desired power factor. To determine the kilovars of capacitors required, multiply this correction factor by the total kilowatts of the feeder circuit.
4. Determine the individual kilovoltamperes and power factor for each load or group of loads.
5. To determine the kilovars on the line, multiply individual load or groups of loads by their respective reactive factors that can be found from Table 8-1.
6. Develop a nomograph to determine the line loss in watts per thousand feet due to the inductive loads tabulated in steps 4 and 5. Multiply these line losses by their respective line lengths in thousands of feet. Repeat this process for all loads and line sections and add them to find the total inductive line loss.
7. In the case of having presently existing capacitors on the feeder, perform the same calculations as in step 6, but this time subtract the capacitive line loss from the total inductive line loss. Use the capacitor kilovars determined in step 3 and the nomograph developed for step 6 and find the line loss in each line section due to capacitors.
8. To find the distance to capacitor location, divide total inductive line loss by capacitive line loss per thousand feet. If this quotient is greater than the line section length:
   a. Divide the remaining inductive line loss by capacitive line loss in the next line section to find the location.
   b. If this quotient is still greater than the line section length, repeat step 8*a*.
9. Prepare a voltage profile by hand calculations or by using a computer program for voltage profile and load analysis to determine the circuit voltages. If the profile shows that the voltages are inside the recommended limits, then the capacitors are installed at the location of minimum loss. If not, then use engineering judgment to locate them for the most effective voltage control application.

Voltage and Reactive power control equipment

VAR generators are distinguished as either rotating electrical machines or static power electronics converters. The unique feature of VAR generators is their ability to deliver or absorb reactive power with continuity and in a repetitive way, without significant equipment fatigue on building materials or without internal losses. This happens until the generator's working point is maintained inside an operation within a field of continuity, bounded by capability curves that fix the maximum reactive power generation or absorption to be compatible with allowed thermal stresses, available cooling and/or design rating.

Among rotating electrical machines, the synchronous generator is not simply a megawatt generator but also a VAR generator: it allows the functional separation between the active and reactive power controls and the delivery or absorption of VARs up to limits without appreciable impact on the active power produced. Accordingly, as it is not able to deliver MW of power, a synchronous compensator is a pure VAR generator.

Considering power electronic converters, the main VAR generators are the so-called:

- Static VAR compensator (SVC);
- Static compensator (STATCOM);
- Unified power flow controller (UPFC).

Obviously, any VAR generator can, in principle, support voltages at its terminal edges or in the local grid buses.

Synchronous Generators

Synchronous generators are primary voltage control devices and they are primary sources of a spinning reactive power reserve. Through excitation controllability they allow continuous fast control of their stator voltages and of reactive power delivered to or absorbed by the grid. A closed-loop control scheme with an automatic voltage regulator (AVR), such as the basic one pictured in Fig. 2.7, is generally used for this purpose.

Excitation control systems (ECS) of synchronous generators can be classified as either "rotating" or "static". The first category comprises rotating machines such as DC power amplifiers that feed the synchronous generator field. Rotating types include:

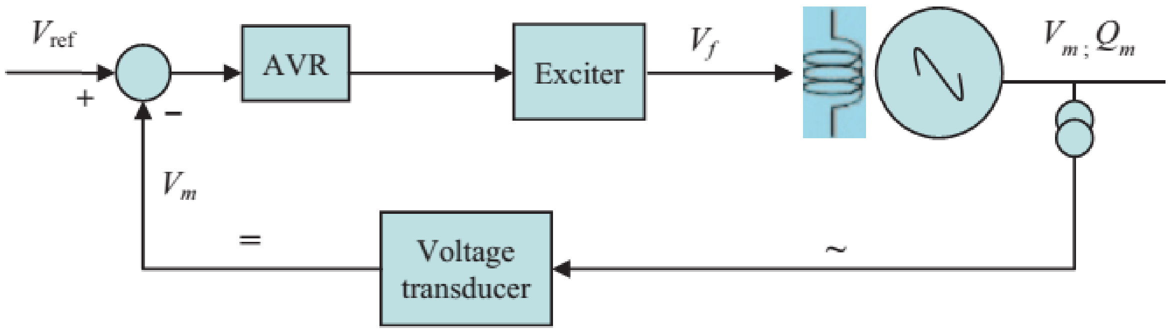


Fig. 2.7 Basic voltage control scheme of a synchronous generator

- ECS with exciting dynamo and electromechanical voltage regulator;
- ECS with exciting dynamo and electronic\microprocessor-based voltage regulator;
- ECS with alternator and rotating diodes, with electromechanical voltage regulator.

The second category considers as a DC power amplifier that feeds the synchronous generator field, a power electronic converter, typically thyristor-based. Static types include:

- ECS with static exciter and electronic/microprocessor-based voltage regulator.

Voltage Control Methods in Power System

Voltage ratings of the various buses in the power system which includes generating station buses, switching substation buses, receiving substation buses and distribution substation buses should be within the permissible limits for satisfactory operation of all electrical equipments. The task of voltage control is closely associated with fluctuating load conditions and corresponding requirements of reactive power compensation. Therefore several voltage control methods are employed in power system to keep the voltage levels within the desirable limits. In this article some of the voltage control methods in power system are discussed.

- Excitation control and voltage regulators at the generating stations:
- Use of tap changing transformers at sending end and receiving end of the transmission lines
- Switching in shunt reactors during low loads or while energizing long EHV lines
- Switching in shunt capacitors during high loads or low power factor loads
- use of series capacitors in long EHV transmission lines and distribution lines in case of load fluctuations
- Use of tap changing transformers in industries, substations, distribution substations
- use of static shunt compensation having shunt capacitors and thyristorized control for step-less control of reactive power
- Use of synchronous condensers in receiving end substations for reactive power compensation

All the above methods are suitably applied at different parts of the power system to maintain the voltage levels within the limits

Excitation Control and Voltage Regulation in generating Stations:

The induced emf of synchronous generator (E) depends upon the excitation current (field current). The terminal voltage V of synchronous generators are given by V = E – IX The generators have excitation and automatic voltage regulation systems (AVR). The function of this systems are:

- To control the load under steady state operating conditions for operating near steady state stability limit
- To regulate voltage under fault conditions (faults in the grid system beyond generator protection zone)
- To enable sharing of reactive power. The reactive power shared by a generator depends upon its excitation level The terminal voltage of the synchronous generator is held within the permissible limits by automatic voltage regulators (AVR) systems

Voltage Control by Tap changing in transformers:

The voltage control of transmission and distribution systems is obtained basically by tap-changing Tap changers are either on-load or off load tap changers. By changing the turns ratio of the transformer the voltage ratio and the secondary voltage is changed and voltage control is obtained. Tap changing is widely used voltage control method employed at every voltage level

The voltage control of the range + 15 to -15 % can be achieved by tap changing transformers

Off load tap changing voltage control:

Adjustment of voltage ratio can be made by off-circuit tap changing. These adjustments are usually for seasonal load variations of special operational requirement of local substations and adjusting the voltage in distribution transformer at consumer end.

On-Load tap changing voltage control:

Such an arrangement of on-load tap changing is employed for changing the turn-ratio of the transformer to regulate the system voltage while the transformer is delivering load.

Voltage Control by Shunt reactors:

Shunt reactors are provided at sending end and receiving end of the long EHV and UHV transmission lines. They are switched in when the line is to be charged or during line is on low load

When the line is on no load or low load, shunt capacitance predominates and receiving end voltage is higher than the sending end voltage. This phenomenon is called *Ferranti effect*.

The receiving end voltage of 400kV, 1000 km long line may be as high as 800kV. The shunt capacitance of such lines is neutralized by switching in the shunt reactor. During high loads, the series inductive reactance of the line produces IX_L drop and the receive end voltage drops, the shunt reactors are switched off Shunt treactors may be connected to the low voltage tertiary winding of a transformer via a suitable circuit breaker, EHV shunt reactors may be connected to the transmission line without any circuit breaker.

Voltage Control by Shunt Capacitors:

Shunt capacitors are usually switched in during high loads. Static shunt capacitors are installed near the load terminals, in industries, substations, … Most of the industrial loads (induction motors, transformers, welding sets, furnaces) draws inductive current of poor power factor (0.3 to 0.6 lag). The shunt capacitors provide leading VARs there by the total KVA loading of substation transformer and the current is reduced. Thereby IXl_L drop in the line is reduced and voltage regulation is improved. shunt capacitors are switched in when KVA demand on the distribution line goes up and voltage on the bus comes down. Switching in shunt capacitor should improve the bus voltage if the compensation is effective

Voltage Control by Static Shunt Compensation:

A step-less variable compensation is possible by thyristorized control of shunt capacitor and reactors. During heavy loads, the thyristors of the capacitor control are made to conduct for longer duration in each cycle. During low loads, the thyristors in reactor circuit are made to conduct for longer duration in each cycle. Thus a step-less variation of shunt compensation is achieved by means of static shut compensation

Voltage Control by Synchronous Condensers:

Synchronous condensers are over excited synchronous motors installed in the power system to deliver the reactive power. These synchronous phase modifiers are located near the load improves the voltage profile of the power system. The main advantage of synchronous phase modifiers are the ability to deliver the reactive power can be adjusted unlike static shunt capacitors.

Voltage Control by Series Capacitors:

In Extra High Voltage (EHV) or Ultra High Voltage System (UHV) systems series capacitors are connected in series with the transmission line to reduce the effect of inductive reactance XL between the sending end and receiving end of the line. One of the major drawbacks of series capacitors is that high over voltages are produced across the capacitor terminals under short circuit condition. Series capacitors are usually employed for increasing the power transfer capability of the transmission line and not for voltage regulation

Voltage Control by Flexible AC transmission (FACT) devices:

Very long high power transmission lines have high series reactance X_L and shut capacitance. It is difficult to control the voltage, power flow and stability by conventional manner. FACT devices play key role in high power interconnected systems. In every intermediate substation in transmission network FACT devices are installed

- Controllable Series Capacitor banks
- Controllable shunt compensation (SVS)

Thyristors are controlled by feedback control system. Voltage power flow and voltage angle is controlled

VOLTAGE CONTROL

To keep distribution-circuit voltages within permissible limits, means must be provided to control the voltage, i.e., to increase the circuit voltage when it is too low and to reduce it when it is too high. There are numerous ways to improve the distribution system's overall voltage regulation. The complete list is given by Lokay [1] as:

1. Use of generator voltage regulators
2. Application of voltage-regulating equipment in the distribution substations
3. Application of capacitors in the distribution substation
4. Balancing of the loads on the primary feeders
5. Increasing of feeder conductor size
6. Changing of feeder sections from single-phase to multiphase
7. Transferring of loads to new feeders
8. Installing of new substations and primary feeders
9. Increasing of primary voltage level
10. Application of voltage regulators out on the primary feeders
11. Application of shunt capacitors on the primary feeders
12. Application of series capacitors on the primary feeders

The selection of a technique or techniques depends upon the particular system requirement. However, automatic voltage regulation is always provided by (1) bus regulation at the substation, (2) individual feeder regulation in the substation, and (3) supplementary regulation along the main by regulators mounted on poles. Distribution substations are equipped with load-tap-changing (LTC) transformers that operate automatically under load or with separate voltage regulators that provide bus regulation.

Voltage-regulating apparatus are designed to maintain automatically a predetermined level of voltage that would otherwise vary with the load. As the load increases, the regulating apparatus boosts the voltage at the substation to compensate for the increased voltage drop in the distribution feeder. In cases where customers are located at long distances from the substation or where voltage drop along the primary circuit is excessive, additional regulators or capacitors, located at selected points on the feeder, provide supplementary regulation. Many utilities have experienced that the most economical way of regulating the voltage within the required limits is to apply both step voltage regulators and shunt capacitors. Capacitors are installed out on the feeders and on the substation bus in adequate quantities to accomplish the economic power factor. Many of these installations have sophisticated controls designed to perform automatic switching. Of course, a fixed capacitor is not a voltage regulator and cannot be directly compared to regulators, but, in some cases, automatically switched capacitors can replace conventional step-type voltage regulators for voltage control on distribution feeders.