



# Application of Capacitors on Electric Power Systems

An Online Continuing Education Course for Engineers

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# Application of Capacitors on Electric Power Systems

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## Introduction

An electrical capacitor is a device that can store electrical energy. In the electric utility industry, capacitors are used in electrical circuits to reduce the reactive demand on the circuit. Reducing the reactive demand on the circuit will release system capacity for other purposes, improve the voltage profile of the circuit, reduce  $I^2R$  losses in the circuit, and improve the power factor of the circuit.

In addition to offering better operating characteristics, capacitors offer economic benefits by reducing losses and possibly lowering power factor penalty billings from the power supplier.

Capacitors are simple static devices with no moving parts. They come in a variety of sizes and voltages for different applications. Most capacitors are installed in a fixed application, but controls can be added to the capacitor banks to switch them in and out of the circuit based on the real-time needs of the electric system.

The course explains how capacitors work, how they can be used to improve power factor and voltage profiles as well as how to apply capacitors in different situations.



## Why Power Factor Correction?

As power distribution system load grows, the system power factor usually declines. Load growth and a decrease in power factor leads to

1. Voltage regulation problems;
2. Increased system losses;
3. Power factor penalties in wholesale power contracts; and

#### 4. Reduced system capacity.

Capacitors offer a means of improving system power factor and helping to correct the above conditions by reducing the reactive kilovar load carried by the utility system. For optimum performance and avoidance of these undesirable conditions, prudent utility planners attempt to maintain as high a power factor as economically practical.

To gain optimum performance and advantage, power factor correction capacitors need to be effectively sized, efficiently located, and utilized on power circuits at times appropriate to the system's load cycle.

### **Voltage Regulation**

One of the greatest advantages gained by the proper sizing and location of distribution capacitors is voltage improvement. By placing leading volt-amperes reactive (VAR) loads (capacitors) near lagging VAR load centers (motors for example), the lagging VARs on a system basis are cancelled with an associated increase in voltage.

However, care is required not to exceed the lagging VAR requirement at any time. Capacitors that may be sized for peak load requirements, may need to be removed from the circuit as the load drops, usually through switched controls. Capacitors draw a specific leading current that generates a voltage rise through the reactive ohms of the system impedance. This voltage rise may be unneeded and even undesirable during low load conditions.

### **Capacitors or Voltage Regulators**

Care should be taken in choosing between capacitors and voltage regulators for voltage improvement. Often, both are necessary to have a well-balanced system operating at maximum efficiency. Shunt capacitors provide some voltage rise and can do so at a lower cost than a line regulator. Sample calculations are shown in the following Chapters. However, for some load conditions, the voltage rise offered by capacitors may be excessive and cause problems for customers' connected equipment. Higher cost regulators offer a means for maintaining more constant system voltage. The combination of regulators and capacitors provides the best of both worlds.

A small investment in 300 kilovolt-amperes reactive (kVAR) of fixed capacitors will provide about a 3-volt rise (depending on where the capacitors are located) when connected on a

distribution feeder. That rise is either on or off depending on whether the capacitors are on line or off. This capacitance provides power factor correction by canceling the effects of 300 kVAR of lagging reactive load.

A single-phase line regulator, which costs significantly more than a capacitor, can provide sixteen, 3/4 volt (5/8 percent) steps up or down (on a 120-volt base), depending on whether the regulator is raising or lowering the voltage. Although this step range approximates a 12-volt boost or buck capacity, effective voltage analysis has shown that the system operator should allow only an 8-volt variation per regulator. Moreover, from voltage analysis, the application of only two regulators in series along a feeder are recommended as a maximum in addition to the substation regulator or Load Tap Changing (L.T.C.) transformer. If more than two series regulators are boosting and there is a fault near the end of the line when an oil circuit recloser (OCR) opens, the line voltage can go up too high and damage customer owned equipment. This means that if any line regulator needs to raise to step 11 or greater, the incoming voltage, serving the last consumer prior to the regulator is below 118-volts, which is outside the Class A voltage limits.

Engineers should be wary of the temptation to install three times the needed capacitors instead of three regulators. A 12-volt voltage improvement can be gained inexpensively with capacitors, relative to voltage regulators. This gain may, however, be at the cost of higher losses and power factor penalty charges when the capacitors needed for the 12-volt voltage improvement are more than connected inductive loading and they can drive the power factor leading.

In general, voltage regulators should be used to maintain accurate control of voltage throughout the load cycle (control voltage fluctuation), and shunt capacitors should be used to correct low power factors.

### **Increased System Losses**

Distribution capacitors can reduce system line losses, if the system power factor is not forced into a leading mode. Line losses at 80 percent leading power factor are just as detrimental as line losses at 80 percent lagging power factor. Properly placed and sized capacitors can usually reduce system line losses sufficiently to justify the cost of their installation.

If switched capacitors are used to help regulate voltage, the system operator will need to conduct frequent system studies to monitor the load growth and know when capacitors should

be switched on and off. Studies are especially important where loading is not uniform along the feeder. It is important to remember that costs to switch capacitor banks add several thousand dollars per bank, depending upon the control type used.

Capacitors energized at rated voltage always operate at their full load rating. Therefore, system load cycles have no effect on the losses of capacitors operating at rated voltage. Operating capacitors at voltages above their rated values can diminish capacitor life spans. Operation at voltages below their rated value reduces the effective (kVAR) size of the capacitor with a resulting decrease in their benefits.

### Power Factor Penalty Charges

Power factor correction may be initiated to reduce power factor penalty charges in purchased power rates. Most power purchase rates have penalties for power factor below a specified level or limit. Penalties take several forms, but the most common is an adjustment in Billing Demand. The Metered Peak Demand is increased by the ratio of the contract minimum allowed power factor over the actual metered power factor when the measured power factor is outside the allowed limit and is calculated as follows:

$$\text{Billing Demand} = \text{Metered Peak Demand} * \frac{\text{Contract Power Factor}}{\text{Measured Power Factor}}$$

Power Factor is either measured during the system peak or is calculated as an average power factor for the month as follows:

$$\text{PF} = \cos\left[\tan^{-1}\left(\frac{\text{kVar} * \text{Hours}}{\text{kWh}}\right)\right]$$

Example: Find the Power Factor for 244,300 kWh and 200,700 kVARh (Reactive) meter readings.

Solution:

Using the Power Factor equation previously presented,

$$\text{PF} = \cos\left[\tan^{-1}\left(\frac{\text{kVAR} * \text{Hours}}{\text{kWh}}\right)\right]$$

$$PF = \cos[\tan^{-1}\left(\frac{200,700}{244,300}\right)]$$

$$PF = \cos[\tan^{-1}(0.82153)]$$

$$PF = \cos(39.4) = 0.773$$

Low system power factor may result in higher demand charges because of calculated power factor penalty clauses. This situation becomes much worse if demand charges are ratcheted. For example, suppose the penalty for low power factor is applied when the power factor is lower than 90 percent (0.90). The penalty factor would become 1.1643 (power factor limit divided by actual power factor or 0.90 divided by 0.773). Metered Peak Demand would be multiplied by the penalty factor of 1.1643. This means the penalty for power factor below the allowable limit will increase demand charges by 16.43 percent in this case. The cost of poor power factor is then very tangible, but the true costs of poor power factor also includes increased losses, poor voltage, and wasted system capacity.

### Reduced System Capacity

The cause of increased system losses on the distribution system similarly affects the sub-transmission and bulk transmission system providing power to the distribution plant. These bulk power facilities must use some of their capacity to carry the inductive kVAR current to the distribution system. The resultant reactive current flow produces losses on the bulk facilities as well, introducing unnecessary costs. Generators provide the reactive needs of distribution plant inductive loads reducing the generator's capacity to produce real power.

As will be seen, capacitors will provide improvement on the bulk facilities as a by-product of the improvements they bring about on the distribution feeder.

# Chapter 1

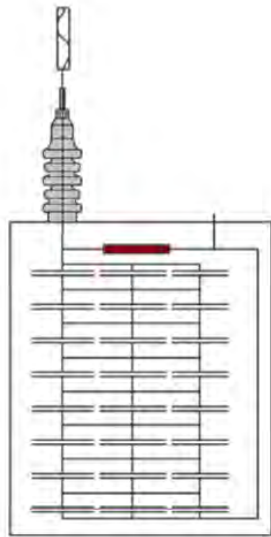
## How Capacitors Work

### Capacitor Design

The basic components of an electric capacitor include the tank, bushings, fixed metal plates, a solid dielectric between the plates, and an insulating fluid. The solid metal plates are usually some type of conducting foil and a polyethylene film is used as a solid dielectric.

A capacitor is built by layers of insulating polyethylene film. This film is used as a dielectric for the capacitor pack. Capacitor packs are then connected to the terminals of the capacitor. The rating of the capacitor.

The capacity of a capacitor is determined by the area of the conducting metal plates and the type of dielectric material used between the plates. Paper, film, mica, glass, and even air. The thickness of the metal plates is also a factor. Figure 1 shows



Externally Fused Capacitor

Figure 1

The unit of measure for a capacitor is the farad. This basic unit is quite large; so, most capacitor manufacturers refer to their capacitors in microfarads ( $10^{-6}$ ). For the power industry, capacitors are designated in kVAR, which takes their voltage rating into account.

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Figure 1 shows a capacitor pack that is electrically sealed (filled with mineral oil). The capacitor pack is mounted in a tank. The leads to the capacitor packs and are brought out of the tank through a bushing. Some capacitors bring both leads out through bushings and capacitors used exclusively in shunt banks may have one lead permanently grounded to the tank.

The American National Standards Institute (ANSI) has a standard for basic capacitor design and operation. The pertinent electrical characteristics of a capacitor are the kVAR rating, voltage rating, and frequency.