PDHonline Course E536 (4 PDH)

Application of Capacitors on Electric Power Systems

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Application of Capacitors on Electric Power Systems

Table of Contents

This course is based on the United States Department of Agriculture, Rural Utilities Service Bulletin 1724D-112, "The Application of Capacitors on Rural Electric Systems", 1981.

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 (more or less, 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 fairly 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 far in excess of connected inductive loading and they are allowed to 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, as long as 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:

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

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

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

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

Solution:

Using the Power Factor equation previously presented,

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

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

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

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 have to 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 for the solid dielectric.

A capacitor is built by layering conductive aluminum foil between sheets of insulating polyethylene film. This compilation of foil and film is known as a *capacitor pack*. Capacitor packs are then connected in series together to obtain the desired voltage rating of the capacitor.

The capacity of a capacitor is dependent on the size and spacing of the conducting metal plates and the type of dielectric medium between the plates. Dielectrics can be paper, film, mica, glass, and even air. The value of capacitance varies directly with the area of the metal plates and inversely with the thickness of the dielectric. Figure 1 shows the internal layout of a capacitor.

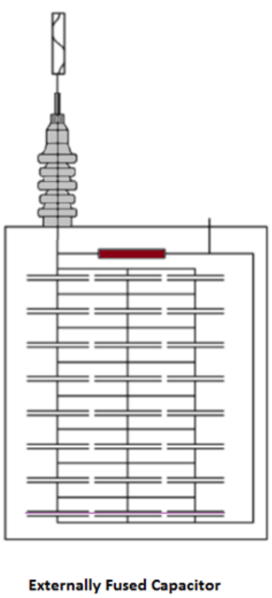


Figure 1

The series capacitor packs are installed in a hermetically sealed tank, which is filled with an insulating oil (usually mineral oil). The oil provides dielectric strength and cooling for the capacitor. The leads are connected 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.

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.

Capacitors contribute slightly to the losses in a circuit. Newer capacitors, which use an all film dielectric, have loss values of 0.07 to 0.15 watts/kVAR. Older paper designs may have losses of 1.0 watts/kVAR or greater.

ANSI standards require that a discharge resistor be placed across the terminals of the capacitor to drain potentially harmful residual charges in the capacitor. After a capacitor is removed from operation it can retain a potentially dangerous charge for some time. ANSI standards state that the discharge resistor must be capable of reducing the charge to less than 50 volts within five minutes of removal from the electric circuit.

Capacitor Ratings

Capacitor ratings include voltage, kVAR ratings, BIL, and temperature constraints.

<u>Circuit Voltage</u>
Manufacturers can supply individual capacitor units in voltages ranging from 2.4 to 25 kV. Units of the same or of different voltage ratings can be mixed to obtain the required circuit voltage. Most utilities utilize capacitor equipment at or above 7.2 kV. The desired circuit voltage is obtained by connecting as many capacitor groups in series as necessary to obtain the required voltage. Usually, the best engineering choice is to use the fewest number of series groups as possible. Use of capacitors with the highest possible voltage rating results in fewer series groups. This generally provides the simplest and most economical bank design. However, inventory or other economic considerations may override this rule.

Another design characteristic is the discharge inception voltage. The initiation of corona discharge is known as the partial discharge inception voltage of the dielectric system. The *discharge inception voltage* (DIV) is the voltage at which electrical breakdown of a capacitor begins to occur. DIV is controlled by increasing the dielectric thickness. Capacitor design specifications will frequently state a safety factor as a ratio of DIV to operating stress and the safety factor should be 150% or more.

Capacitors are designed to operate at up to 135% of their nameplate rating. Operating a capacitor at other than nameplate rating will affect the kVAR output of the capacitor. The kVAR rating of a bank operating at other than nameplate voltage can found from the following formula:

$$\mathbf{kVAR_{system} = kVAR_{rating} * (V_{system} / V_{rating})^2}$$

What will be the kVAR output of a 300 kVAR, 7,620 volt capacitor if it is used on a 7,200 volt electric system?

$kVAR_{system} = 300 \times (7{,}200 / 7{,}620)^2$

$kVAR_{system} = 268$ kVAR.

This example shows that the kVAR output of a capacitor will be reduced by the square of the ratio of actual voltage to the rated voltage. Therefore, operating a capacitor at less than rated voltage will severely reduce its kVAR rating.

kVAR Rating

Capacitor unit ratings available from domestic manufacturers undergo frequent change in order to provide the most practical and economical sizes for existing conditions. In general, the trend is toward larger unit sizes. Standard capacitor units for shunt capacitor bank applications are 50, 100, 150, 200, 300, and 400 kVAR. No upper limits are defined for internally fused capacitor units. These units are typically sized based on minimizing the number of capacitor units to minimize the bank's physical size while avoiding overvoltage and unbalance conditions with a substantial loss of a capacitor unit's individually fused elements.

The capacitor manufacturer's recommendations should be considered in determining the optimum size of capacitor unit, number of series sections, number of units in parallel, and type of connection to make up the kVAR requirement for a given application.

Basic Insulation Level

Basic impulse insulation levels of individual capacitor units range from 75 to 200 kV. Table 1 summarizes typical basic impulse insulation levels by capacitor unit voltage rating.

Table 1
Capacitor Unit Voltage & BIL Ratings

Capacitor Voltage Rating (kV, RMS)	BIL (kV)
2.4-4.8	75
6.6-12.47	95
13.2-14.4	95 & 125
15.1-19.9	125
19.2 (single bushing)	125 & 150
19.9-24.9	150 & 200

Temperature

The maximum allowable ambient temperature for capacitor equipment installed outdoors with unrestricted ventilation is 40C based on the mathematical average of hourly readings during the hottest day expected at the site. Isolated, multiple row and tiers and metal-enclosed or housed units will have maximum ambient ratings of 46C, 40C, and 40C, respectively. Capacitors are designed for continuous operation at –40C. Where the expected in-service ambient temperatures are lower than –40C, the manufacturer should be consulted.

What Is Power Factor?

This chapter demonstrates the power relationships between watts, VARs, volt-amperes and power factor. The total power (Apparent Power) in kilovolt-amperes (kVA) delivered by a distribution line to a load consists of two parts, Real Power (kW) and Reactive Power (kVAR), as shown in the container analogy of Figure 2. Power factor is a mathematical representation of the amount of reactive power relative to the amount of real power or apparent power.

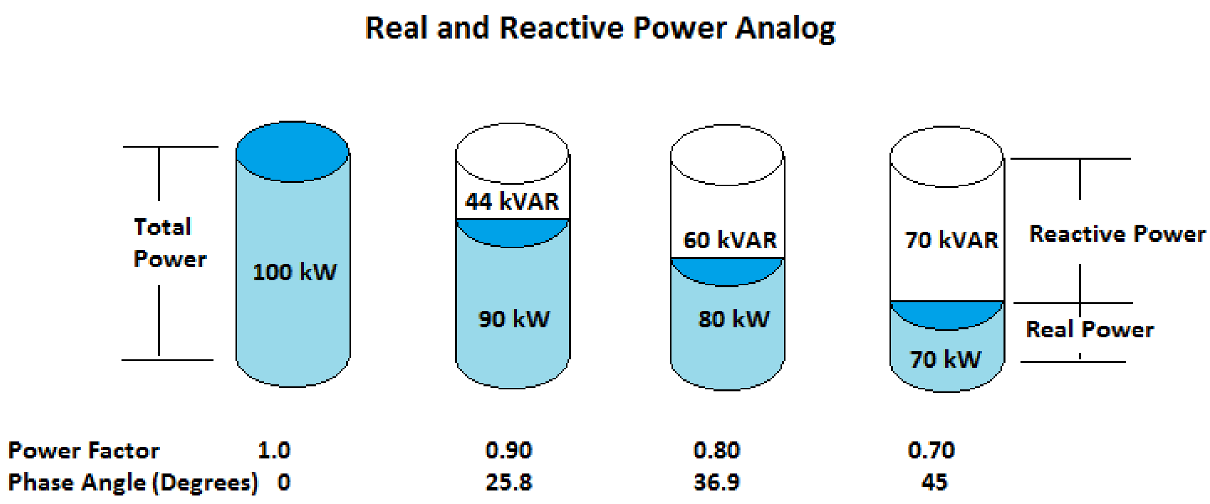


Figure 2

Figure 2 shows 100 kVA loads at various power factors. The usable power is in kW. As power factor increases, the useful power delivered is increased. As can be seen, lagging kilovars may form an appreciable component of the system load. In Figure 2, electricity required to serve a system may be thought of as a mug of beer where you have to purchase a whole mug to get what you really want. Liquid beer represents kW energy which can perform useful work and reactive kVAR is represented by the foam on top of the beer. One would prefer a mug full of liquid beer with little foam. The reactive component (or the foam in this analogy) of the total kVA, while it performs no useful work, has to be purchased.

Reactive energy is required because connected loads (motors, transformers, and other inductive type loads) and associated conductors demand this type of energy along with real energy to do work. As a result, in the absence of any other source, reactive energy has to be supplied by the generator at the power plant, be transformed and transmitted along the transmission grid, and finally be transformed again on the distribution system for delivery to the reactive load.

When the distribution system's reactive load can be canceled by a capacitor placed at the reactive load center, the entire power delivery system will be relieved of this kVAR burden originally supplied from the power supplier's generator; thereby making its full capacity available to serve real power loads. If a capacitor is connected to the distribution system either too far ahead of or too far beyond the system's inductive load center, the capacitor still provides reactive loading relief, but the system will not gain the full advantages of voltage and loss improvement which would be afforded by proper capacitor placement.

The inter-relationship between kilovolt-amperes (kVA), kilowatts (kW), kilovars (kVAR), and power factor (PF) is illustrated in Figure 3. The real power component in kilowatts (kW), which is capable of doing work, is what utilities sell, and it is measured using kilowatt-hour (kWh) meters. The inductive reactive power component, measured in lagging kilovars (kVAR), is required by and supplied to motors to magnetize motor-winding fields, transformers to magnetize transformer windings and cores, and phase conductors to sustain the magnetic fluxes associated with current flowing in the conductors. This reactive lagging power component (kVAR):

1. Performs none of the useful work,
2. Is not measured on kWh meters,
3. Has to be furnished to the loads, and
4. Is measured by kVAR meters.

The leading current developed by capacitors can effectively cancel the lagging current demanded by the reactive load components. The total power delivered to the load consists of a real and a reactive component. Total power is measured in kilovolt-amperes (kVA). *Power factor* is defined as the ratio of real power (kW) to total power (kVA).

Power and Power Factor Relationships

A useful way to show the power relationships is with the Power Triangle of Figure 3. Total Apparent Power (in kVA) is the vector sum (not arithmetic sum) of the Real Power (in kilowatts) and the Reactive Power (in kilovars). A vector has a length, or magnitude, and a direction. A vector diagram allows easy calculation of relationships within the Power Triangle using trigonometry. VAR means volt-ampere reactive, or more simply Volts times Amps (V*A or

VA) shown in the reactive relationship (90 degree out of phase with the Voltage and kW). Therefore, VARs lead or lag by 90 degrees the Real Power (kW) vector. The Real Power vector always lies along and is in phase with the Voltage vector. The Apparent Power vector always lies along and is in phase with the Current (Amperes) vector. Thus simple trigonometry explains the Power Triangle of Figure 3.

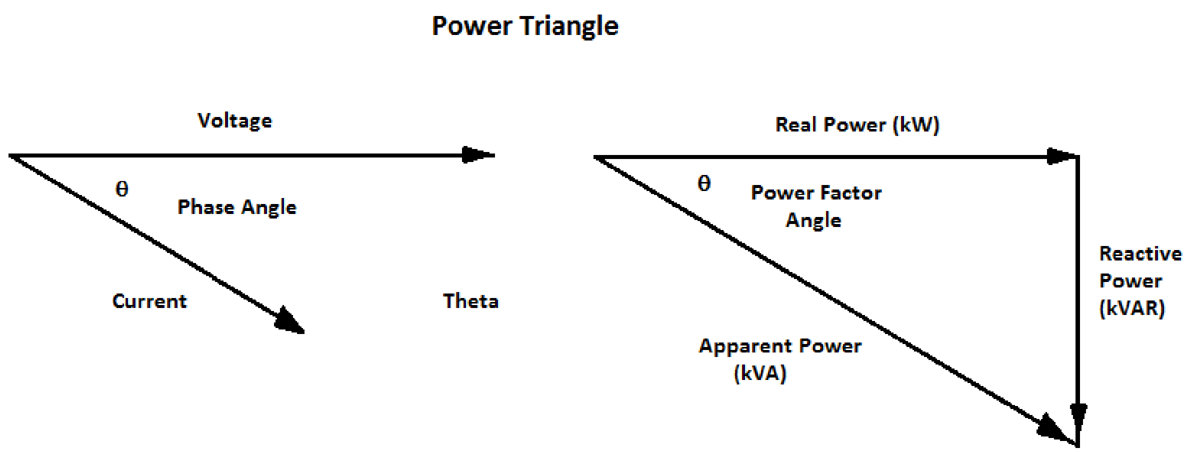


Figure 3

Power Triangle = A vector representation of time relationships where:

- Apparent Power (kVA) is the vector sum of Real Power (kW) and Reactive
- Power (kVAR) ;
- Real Power (kW) is in phase with the voltage vector;
- Apparent Power (kVA) is in phase with the current vector;
- Reactive Power is perpendicular to Real Power;
- Lagging Reactive Power is customarily shown pointing Down; and
- Leading Reactive Power is customarily shown pointing Up.

By definition, Power Factor equals kW divided by kVA. Power factor is also equal to the Cosine of the *Phase Angle* (theta) between the voltage and current vectors. Power Factor is the trigonometric Cosine of the angle between the Real and Apparent Power. This angle is identical to the angle between the voltage and current vectors.

$$\textbf{Phase Angle} = \cos^{-1}\frac{\textbf{kW}}{\textbf{kVA}}$$

Explained another way, the phase angle is equal to the angle whose Cosine is (kW / kVA).

Power Factor Effects

A complete understanding of capacitors and their effects on the power system begins with understanding that capacitors are an unusual load with unusual characteristics. Capacitors draw current that is advanced 90 degrees (or 1/240th of a second) ahead in time of the applied voltage wave. This leading current accomplishes several worthwhile purposes if applied with understanding and in moderation. The main benefits are that the leading current cancels lagging current which decreases kVAR losses and the voltage drop. Thus, capacitors actually cause a system voltage rise.

A capacitor is a leading reactive power load whose leading VAR requirements cancel an equal portion of the system's lagging VAR requirements thereby reducing the overall load on the system. The leading current required by the capacitor, which flows through the lagging impedance of the system conductors and transformers, causes a voltage rise. The addition of capacitors at the system's inductive load center results in a decrease in VARs required from the generator. This reduction in overall VAR flow brings about lower losses in the system and better voltage at the load due to the resulting lower line currents. In many cases, the system can then deliver more useful power with the same investment in equipment. This type of operation provides better utilization of existing investment in equipment and may make possible the deferral of costly system improvements.

To see how a capacitor affects a power system, look first at the sine-wave-shaped instantaneous voltage wave generated by a rotating generator. Applied to a purely resistive load, the current wave is "in-phase" with the voltage wave as shown in Figure 4.

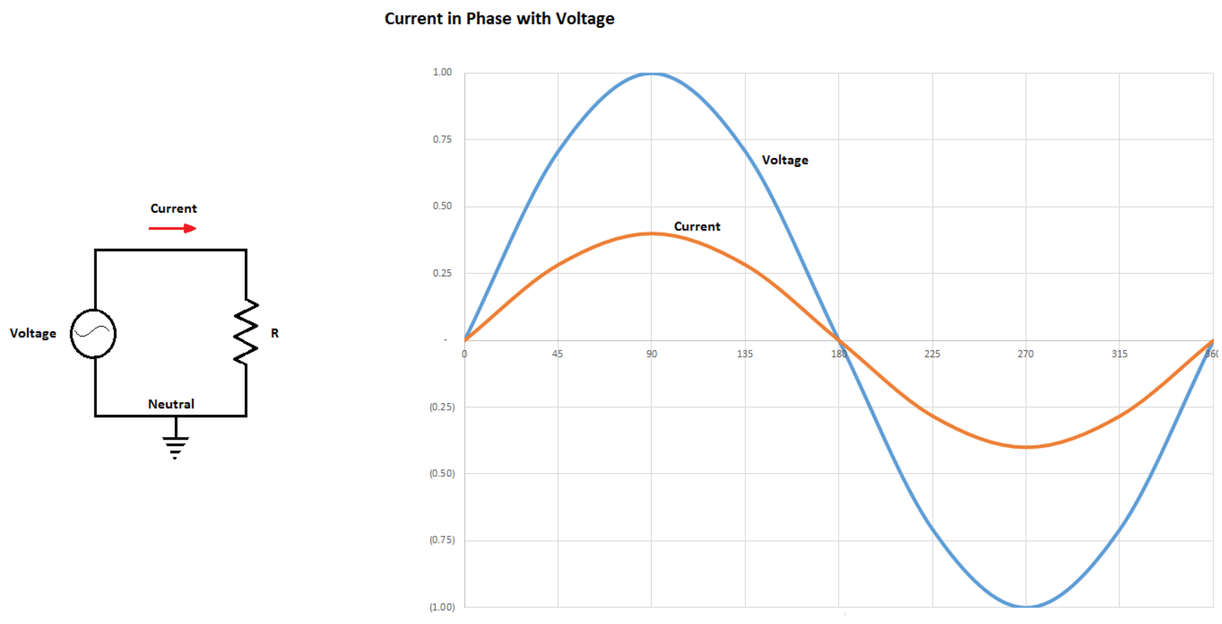


Figure 4

“In Phase” means that the current wave starts "positive" at exactly the same time as does the voltage wave. The current wave also crosses the zero-amplitude axis going the same direction (positive or negative) at the same time as the voltage wave and this action repeats itself at all zero amplitude crossings. The current wave is usually not the same magnitude (height at peak) as the voltage wave but it does have the same frequency. The current magnitude is determined by the load using Ohm’s Law, which for resistive loads, follows the rise and fall of the voltage wave exactly, and so current is called "in-phase" with the voltage.

Inductive loads, such as motors, cause the current wave to “slow down” or *lag* with respect to the voltage wave as shown in Figure 5. The degree of slowness in time is measured as an electrical phase angle difference (assuming 360 degrees for one cycle) between the voltage and current waves. The frequency of power systems in the United States is 60 hertz (60 cycles per second), so one cycle represents 1/60th of a second. The voltage wave makes one complete revolution, completing both a positive and negative cycle, during a period of time that is also defined as 360 electrical degrees. So 1/2 cycle, or the positive (or negative) half cycle for instance, takes 180 degrees. The time to rise from zero to a peak value is 1/4 cycle or 90 degrees.

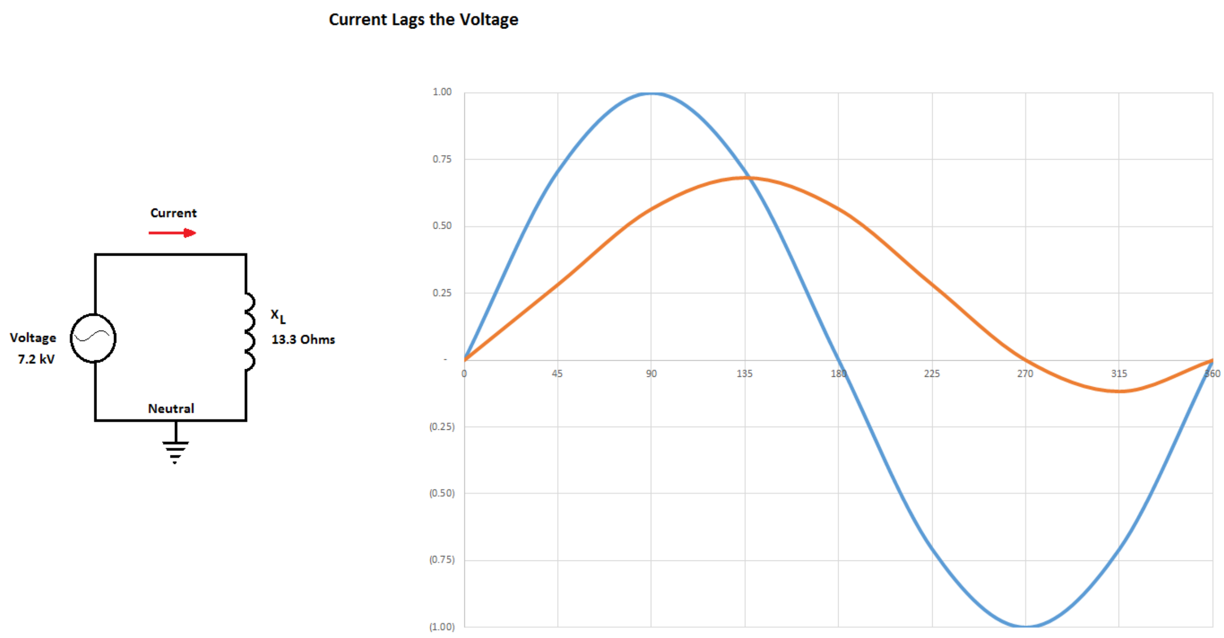


Figure 5

The time to fall back to zero is another 1/4 cycle or a second 90 degrees. By describing time in terms of degrees, simple trigonometry can be used to solve relationships between the sinusoidal waves.

Likewise, capacitive loads cause the current wave to "get ahead" of or *lead* the voltage wave in time as shown in Figure 6. A pure capacitor with no resistance will cause the current wave to lead the voltage wave by exactly 90 degrees. A pure inductance with no resistance will cause the current wave to lag the voltage wave by exactly 90 degrees. But in actuality, inductors have some resistance and a small amount of capacitance. Capacitors also have some resistance and a small amount of inductance. So a full 90 degrees of lead or lag never is actually achieved.

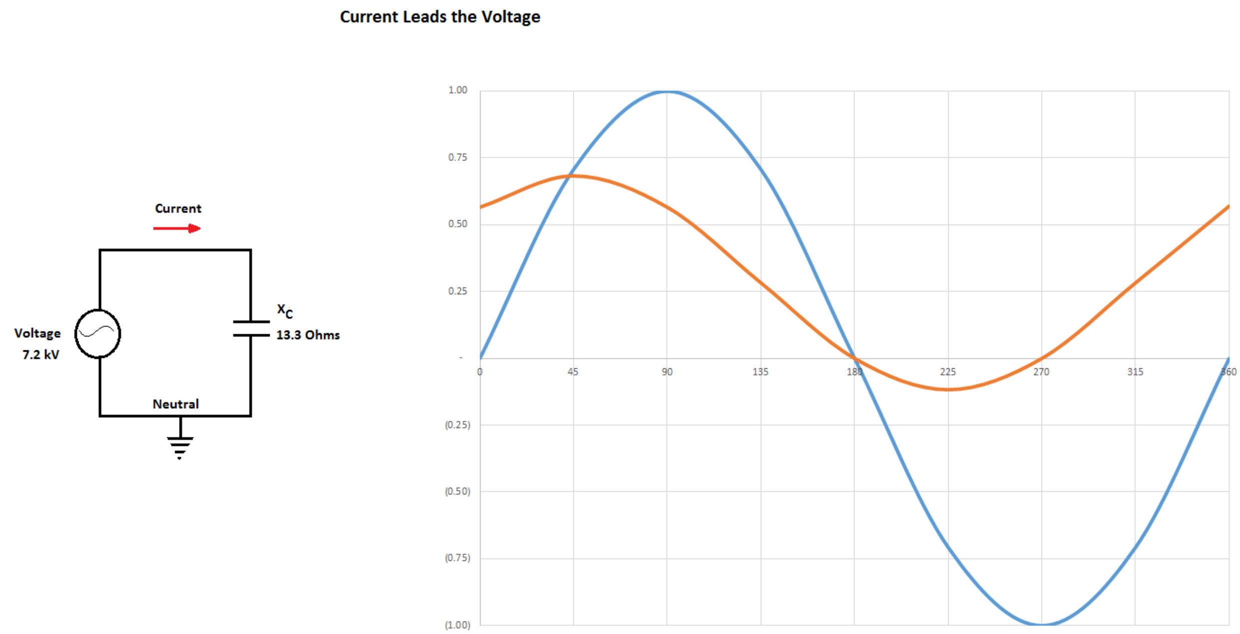


Figure 6

Our goal on the power system is to cancel out as much of the effects of the line inductance and capacitance as possible to allow the most efficient power transfer from the source to the load. Motor loads and system conductors and service drop wires are inductive causing the current to "slow down" in time and lag the voltage waves by 30 to 40 degrees.

The lead or lag phase angle can also be expressed by the system Power Factor. From the previous section, Power Factor has also been defined as the Cosine of the phase angle between the voltage and current waves. It may be a leading power factor or a lagging power factor.

Example: For an inductive phase angle of 30 degrees, the Power Factor equals Cosine (30 degrees) or 0.866 lagging (meaning inductive). This can be further expressed as Power Factor of 86.6 percent (0.866 * 100) when expressed as a percentage of unity (100%) power factor. For a 40-degree lagging phase angle, the Cosine (Power Factor) is 0.766 or 76.6 percent lagging. The following table is provided for reference purposes.

Table 2
Trigonometric Power Factor Conversion Table

Phase Angle (Degrees)	Cosine	Power Factor (%)

0.0	**1.00**	**100.0**
18.2	**0.95**	**95.0**
25.8	**0.90**	**90.0**
31.8	**0.85**	**85.0**
36.9	**0.80**	**80.0**
41.4	**0.75**	**75.0**
45.6	**0.70**	**70.0**
49.5	**0.65**	**65.0**

The greater the phase angle between the voltage and current waves, the poorer or lower the Power Factor (PF). Unity Power Factor occurs when the voltage and current waves are in phase with each other and is designated as 100 percent power factor.

Loads on a distribution power system are usually inductive as are the phase conductors and drop wires serving these loads. Capacitors are added to compensate for the tendency of the inductance to "slow" the current wave down with respect to the voltage wave. If sized properly, most of the effects of the inductance can be nullified. Unfortunately, because of continuous load variation and available capacitor sizes, continuous optimization is not feasible.

Load Factor Effects on Power Factor

Typical billing demand data of electric power systems show a steady downward trend in average power factor. This decrease is almost directly proportional to the rising trend in kilowatt-hours used. The decrease can be attributed largely to the addition of industrial-type loads and increased usage of motors as residential consumers install more and more inductive loads (larger freezers, heat pump, etc.,) which lower the power factor and operate intermittently over a 24 hour period. On a daily basis, the load distribution of these devices is comparatively uniform. The load factor of the reactive component is much higher than the load factor of the real component (that portion of load that is in phase with the voltage) because the real load component fluctuates widely on a daily basis.

$$\textbf{Load Factor} = \frac{\textbf{Average Demand}}{\textbf{Maximum Demand}}$$

or,

$$\textbf{Load Factor} = \frac{\textbf{kWh}}{\textbf{Peak kW} * \textbf{Billing Hours}}$$

Load Factor variations help to explain why VAR requirements are significantly greater during peak load times than off peak. Motor driven devices that set the peak require additional VARs over the base load, which is more resistive and less inductive.

The following figures show the relationships between load factor and power factor during peak and off peak periods.

Figure 7 illustrates typical kilowatt and kilovar load curves. Notice that while the kW load almost doubles on this peak summer day, the KVAR requirement only increases about one third and remains constant while the kVA rises from 90 percent to 100 percent of peak. Figure 7 indicates that for a residential feeder on a peak air conditioning summer day, any capacitors needed should be on line from 2:00 to 10:00 pm for this utility.

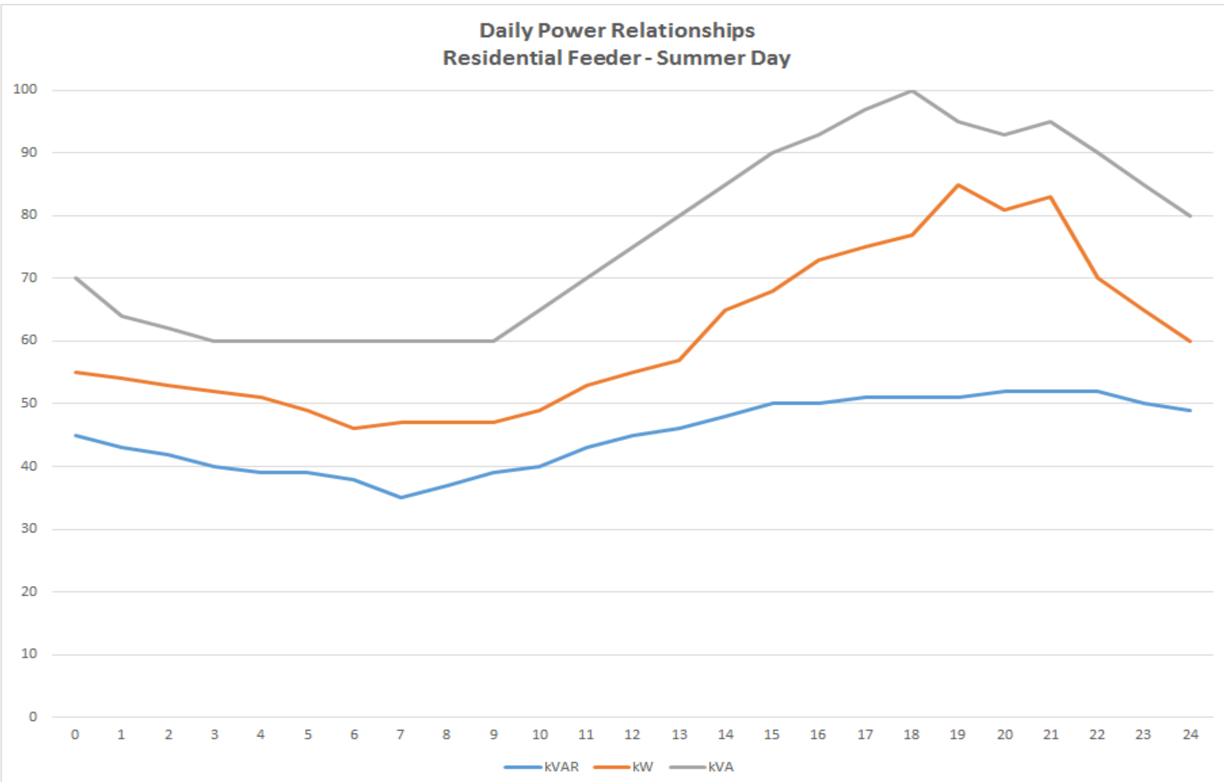


Figure 7

Figure 8 shows how kVAR varies on a system as a 300 kVAR switched capacitor bank operates.

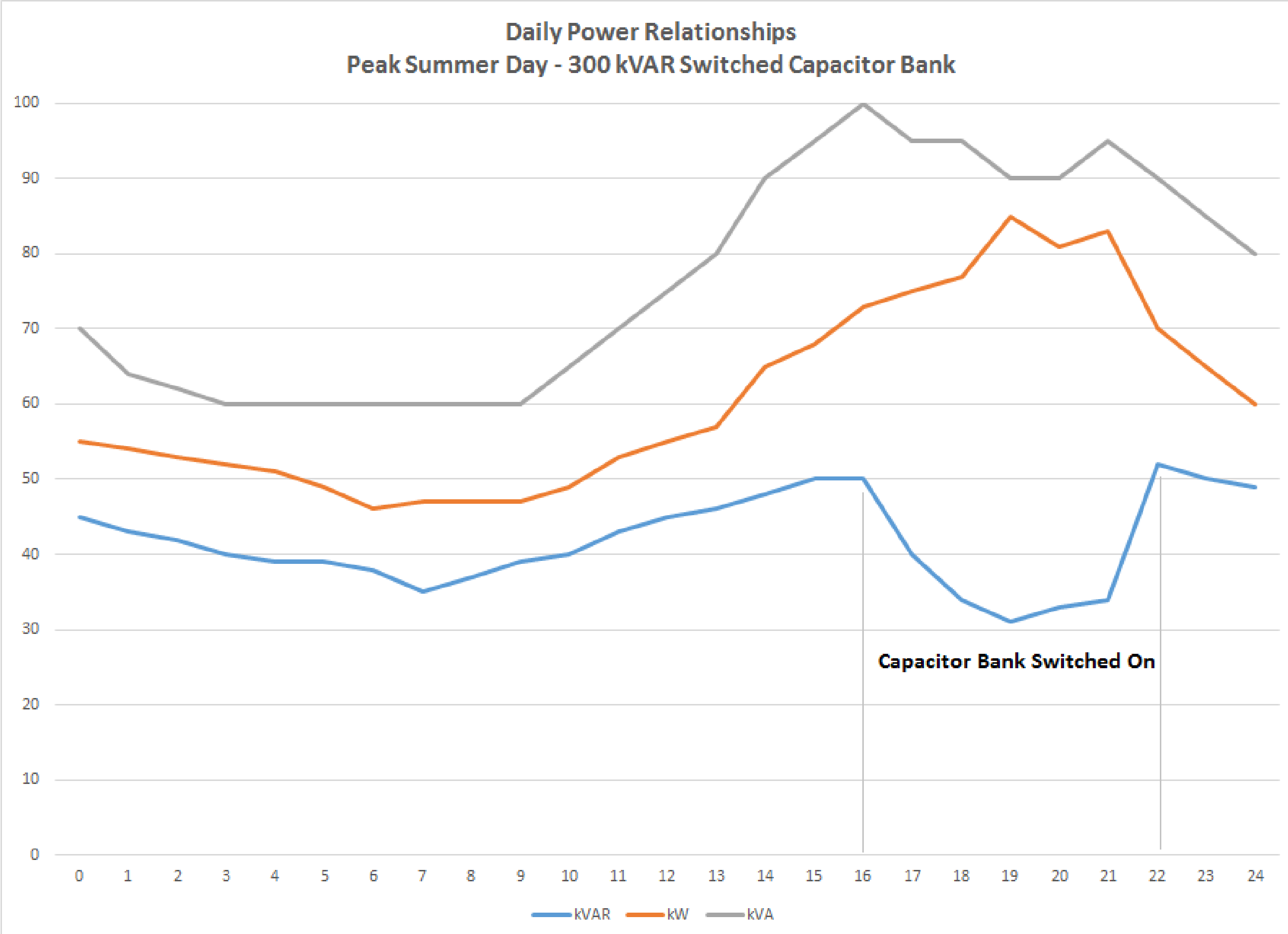

Daily Power Relationships
Peak Summer Day - 300 kVAR Switched Capacitor Bank
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Capacitor Bank Switched On
kVAR
kW
kVA

Figure 8

Figure 9 shows the same circuit for an off peak day.

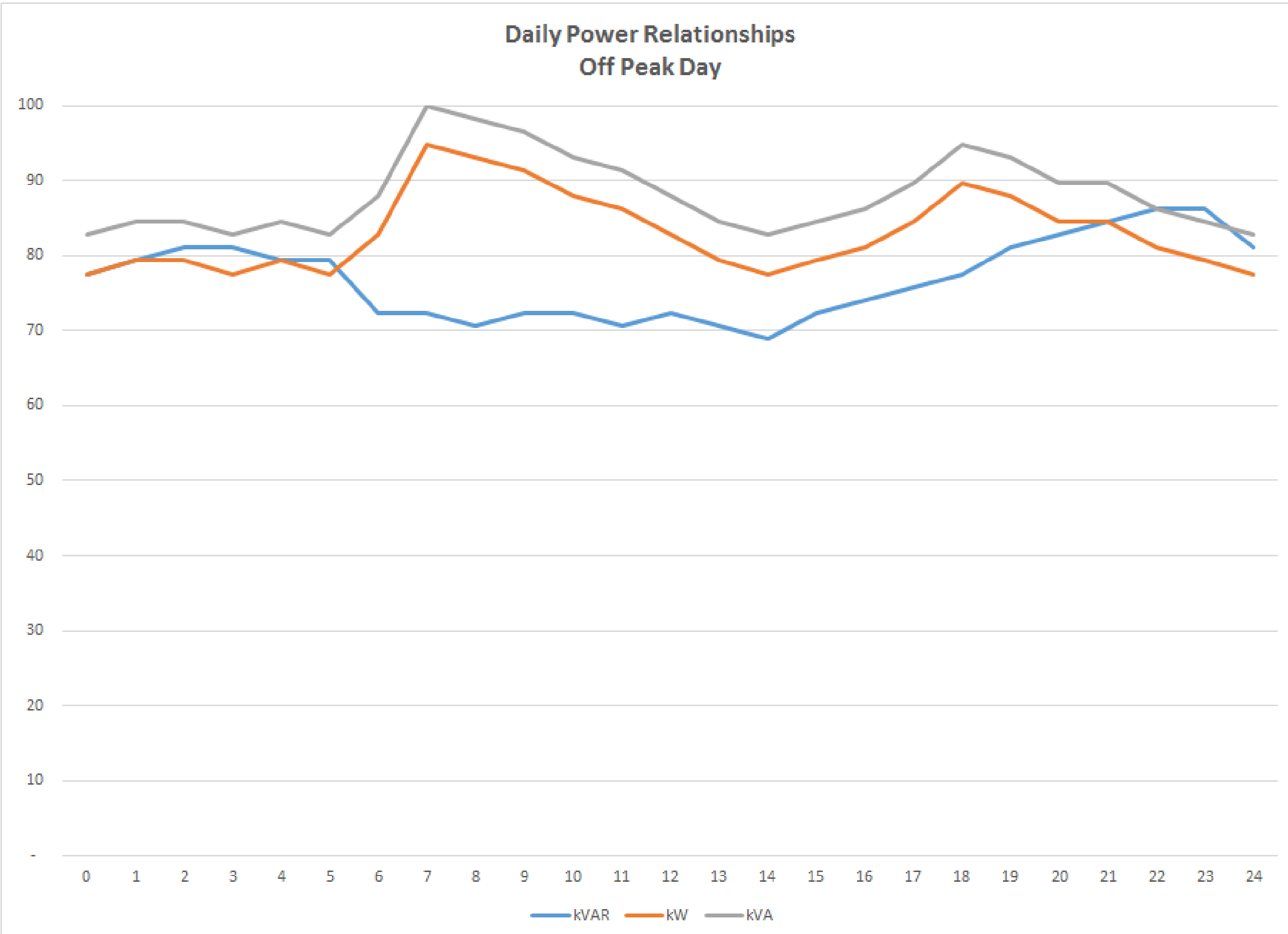


Figure 9

The uncorrected load factor on electric power systems at the time of peak may be about 0.40, while the average reactive load factor is about 0.70. A fairly constant kVAR load factor simplifies the problem of power factor correction. If the power factor of such a system is corrected to near unity at light load, it will remain nearer unity at peak load.

The flattening of the power factor curve at peak load in Figures 6 and 7 is not intuitive, but understandable. As air conditioning (A/C) loads come on the system early in the peak day, when the ambient temperature is 20-30 degrees below the afternoon peak, the A/C motors are not fully loaded and cycle off for extended periods of time. Their power factor approximates 80 percent. But as the temperature rises and all A/C units are on the system, they cycle off less and the motors become more fully loaded. At peak temperature, with all A/C units fully loaded and with little cycling, their power factor improves to near 95 percent. This helps correct the circuit power factor without additional capacitors.

Capacitor Sizing

Quick approximations of capacitor kVARs needed are fairly simple to make because the power factor angles of most uncorrected loads are around 30 degrees (a PF of approximately 87 percent). In a 30-60 degree right triangle, the side opposite the 30 degree angle is 1/2 the hypotenuse. As a "rule of thumb," this means that the reactive power (kVARs) is approximately half the apparent power (kVA) at 87 percent power factor. As discussed above, it is prudent to install less capacitor kVAR than one half the kVA because residential air conditioning load power factor actually improves near peak load

Graphically, the base of the triangle is the real power (kW) side and is always in phase with the voltage. The hypotenuse (kVA) is in phase with the current. As the reactive power is reduced, the phase angle decreases and the current moves closer to being in phase with the voltage. This improves the power factor.

Example: For a load of 1200 kVA at 87 percent power factor, about 600 kVAR of reactive power is required. If we provide 600 kVARs of capacitors, the leading 600 kVARs added would cancel 600 kVARs of the system's lagging inductive reactance.

V = Voltage Reference
I = Current

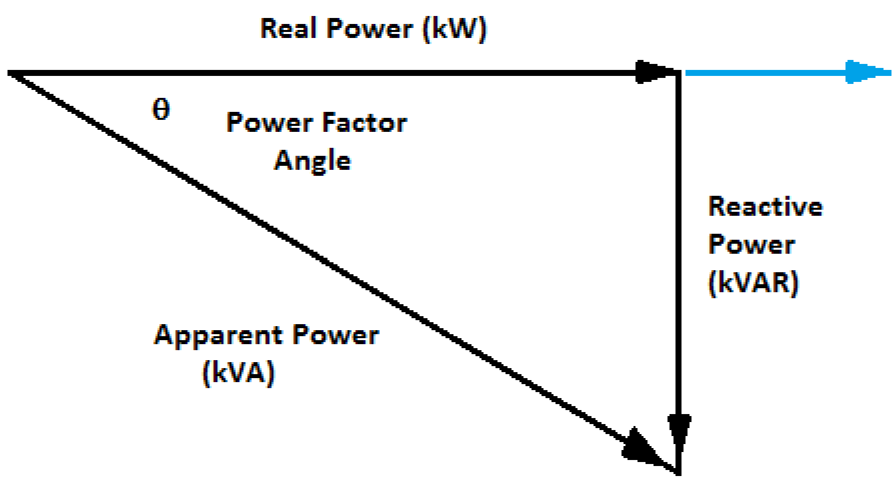


Figure 10

Example: For 1200 kVA at 87 percent power factor, find kW and kVAR.

Solution:

Power factor (Phase) Angle = $\cos^{-1}(0.87) = 29.54$

kW = 1200 kVA * 0.87 PF = 1044 kW

kVAR = 1200 kVA * sin (29.54 degrees) = 592 kVAR

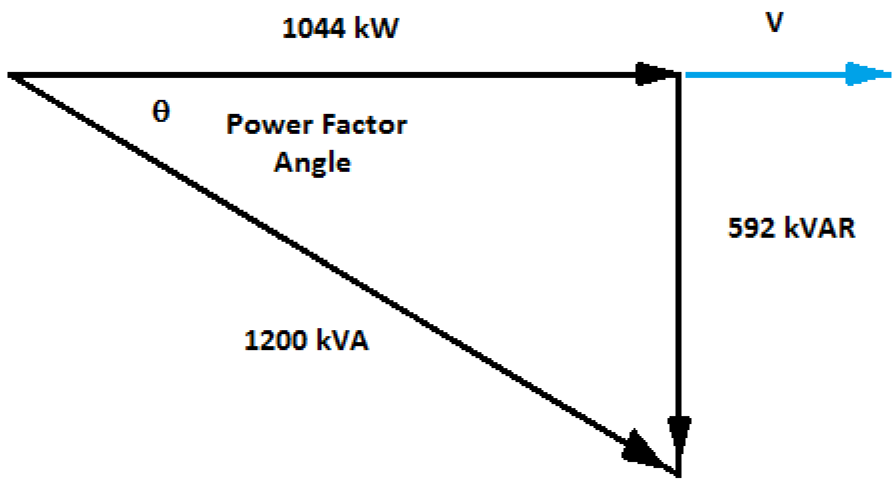


Figure 11

The difference in the 600-kVAR "rule of thumb" sizing method and the true answer of 592 kVAR is due to an 87 percent PF not being exactly equal to 30 degrees. Considering that capacitors are available in 50, 100, 150 or 200 kVAR sizes, the 8 kVAR difference is not a significant difference.

Example: When a 600-kVAR capacitor bank is added, the resulting kVARs are: Resulting kVARs = 592 - 600 = -8 kVARs

New power factor = $\cos(\sin^{-1}(-8 / 1200)) = -0.9999$

This new Power Factor is virtually 1.00, but the power factor is slightly leading because the negative sign means the correction was greater than needed.

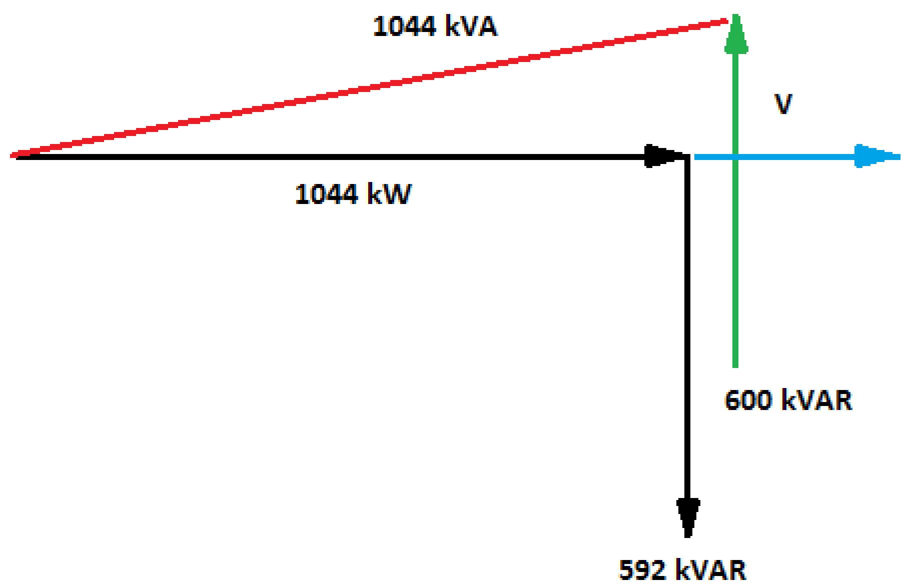


Figure 12

The 1200 kVA system load has now been reduced to 1044.1 kVA. See Figure 12. The current, on a 7200-volt system, would be reduced from 56 to 48 Amps. The VARs needed to correct any existing power factor and demand can be calculated by first determining the existing VARs using the method detailed in the solution related to Figure 10. Then using the same demand and the desired power factor, solve for the resulting VARs that should exist after Power Factor correction is achieved. The difference in the two VAR values is the maximum total VARs of capacitors to be added.

Voltage Improvement with Capacitors

In addition to improving the system Power Factor, capacitors also provide some voltage drop correction. Because of a capacitor's leading current which flows through the system's lagging inductance, capacitors cause a voltage rise on the system. It is not uncommon to experience a two to three volt rise (on a 120-volt base) with 300 kVAR of capacitors on 7.2-kV systems. For the same kVAR amount of capacitors, the rise would be half of that on a 14.4-kV system.

Voltage rise is determined by multiplying the capacitor's leading current by the inductive reactance (X_L) of the portion of the distribution system between the distribution voltage source and the capacitor location. The resistive (R) portion of the impedance involved causes a voltage drop in-phase with the voltage and, thus, does not play a role with the capacitor in creating voltage rise.

Voltage rise from the power source to the location of a shunt capacitor (or anywhere on the line between the capacitor and the power source) is calculated as follows:

Voltage Rise = Capacitor Current * Conductor Reactance

where:

$$\textbf{Capacitor Current} = \frac{\textbf{kVAR}_{\textbf{phase}}}{\textbf{kV}_{\textbf{Line to neutral}}}$$

And

Conductor Reactance = R + jX
(system component impedance near capacitor's location).

This voltage rise equation provides the total voltage rise from the generator to the capacitor, but since most of the impedance is on the distribution system, that is where most of the rise occurs. The calculated voltage rise is the actual rise on the primary system. To make it a usable and understandable number, voltage rise should be referred to the delivery voltage (120 volt) base.

Calculated primary voltage rise is thus divided by the primary line's potential transformer ratio. This is the primary line-to-neutral voltage divided by 120 volts (which is 60 for 7200 volt systems and 120 for 14.4 kV systems).

Example: Find the voltage rise caused by a three-phase, 300 kVAR, capacitor station located on a 12.47/7.2 kV feeder whose impedance at the node point nearest the capacitor station is:

Z = R + j X ohms = 13.4 + j 13.3 ohms. (See Figure 13).

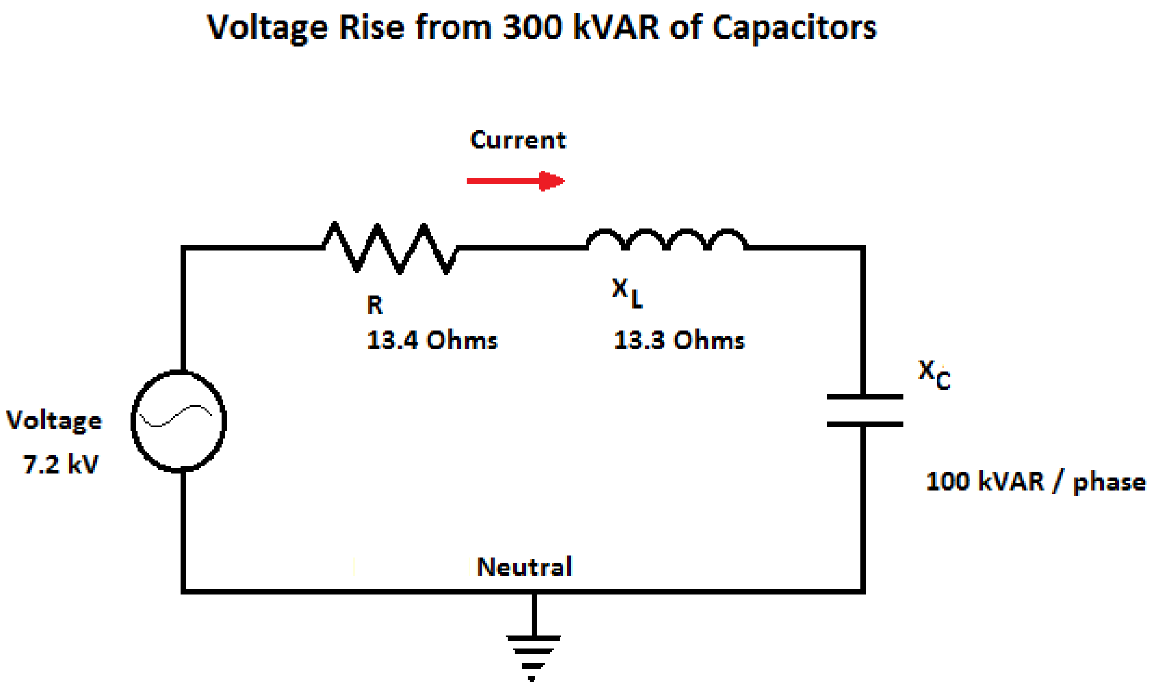


Figure 13

Solution: Capacitor current calculations use capacitor kVAR per phase divided by line-to-neutral voltage.

$$\text{Capacitor Current} = \frac{300\ \text{kVAR}}{3 * 7.2\ \text{kV}} = 13.9\ \text{amps}$$

(Note: Each 100 kVAR capacitor draws 13.9 Amps on a 7.2 kV system.)

Voltage Rise = 13.9 Amps * 13.3 ohms = 184.7 volts (7.2 kV base).

Referred to the delivery base voltage or 120-volt base, divide true volts rise on the primary by the transformer ratio.

7.2 kV / 120 V = 60 (60:1 ratio)

Voltage Rise on a 120 volt base then = 184.7 / 60 = 3.08 volts rise.

This means that the leading 13.9 amperes per phase capacitor current flowing through the 13.3 ohms of reactive system impedance causes the voltage to rise from the distribution voltage source to the capacitor. This results in a 3.08-volt rise at the capacitor location.

Adding a second 100-kVAR capacitor per phase will double the voltage rise to 6.16 volts on each phase.

This voltage rise starts at near zero at the source and uniformly rises to a peak of 3.08 volts at the capacitor location. The capacitor voltage rise can be calculated at any point between the distribution voltage source and the capacitor (the line section along which the capacitor's current flows) by the same method as above. The voltage rise caused by the capacitor levels out at the capacitor location (the capacitor current has reached its maximum effect), but the effect of the 3-volt rise is seen over the entire feeder proportionately, originating at the capacitor.

The percent voltage improvement due to a shunt-connected capacitor installation, at the capacitor location, is calculated as follows:

$$\%\,\mathbf{Voltage\ Rise} = \frac{\mathbf{Voltage\ Rise}}{\mathbf{Voltage\ Base}} * \mathbf{100}$$

$$\%\,\text{Voltage Rise} = \frac{3.08}{120} * 100 = 2.57\%$$

The textbook solution is:

$$\%\,\mathbf{Voltage\ Rise} = \frac{\boldsymbol{KVAR_C * X * d}}{\mathbf{10} * \boldsymbol{kV^2}}$$

Where:

D = length of line, circuit-miles (from distribution voltage source to capacitors)

$KVAR_C$ = total capacitor kVAR (1ϕ and 3ϕ lines, delta-connected capacitors), or
= 1/2 total capacitor kVAR (Vϕ lines), or
= 1/3 total capacitor kVAR (3ϕ lines, Y-connected capacitors)

X = reactance, ohms per circuit-mile (1ϕ and 3ϕ lines), or
= 1/2 single-phase reactance, ohms per circuit-mile (Vϕ lines)

kV = line-to-ground kilovolts (1ϕ and Vϕ lines, and 3ϕ, Y-connected capacitors), or
= line-to-line kilovolts (3ϕ, Delta-connected capacitors)

In Example 6, note the closeness of the resistive (13.4 Ω) and the reactive impedance (13.3 Ω). This closeness is typical of conductor that has a resistance fairly equal to its reactance (1/0 through 4/0 ACSR). Smaller conductors have lower X/R ratios. Larger conductors have higher X/R ratios. Resistance decreases much faster than reactance as conductor size gets larger. Reactance is a function of conductor spacing.

Table 3 Conductor Impedance				
ACSR Conductor Size	**Conductor Impedance ACSR - Ohms per Mile Using 8-foot crossarm spacing**		**% Voltage Rise per Mile on 120 Volt Base with 100 kVAR per Phase Line-to-Neutral Voltage**	
	Resistance (R)	**Reactance (X)**	**7,200**	**14,400**
4	**2.47**	**0.655**	**0.126**	**0.0631**
2	**1.41**	**0.642**	**0.123**	**0.0619**
1/0	**0.888**	**0.656**	**0.126**	**0.0632**
4/0	**0.445**	**0.581**	**0.112**	**0.0560**
267 kcmil	**0.350**	**0.465**	**0.0896**	**0.0448**
477 kcmil	**0.196**	**0.430**	**0.0829**	**0.0414**

System operators should take advantage of the voltage rise associated with capacitors to help offset normal system voltage drop. However, caution should be exercised to prevent over application of capacitors for the purpose of raising voltage because the current drawn by capacitors can increase line losses, especially if capacitors drive the system into a leading power factor.

Capacitors can be an inexpensive short-term fix for a voltage problem but capacitors can significantly increase line losses and probability of harmonic influence (interference) on nearby telecommunications lines if their use is not designed wisely.

Chapter 2
Capacitor Concerns

Overcurrent and Overvoltage Protection

Lightning surges may cause damage to capacitors. Capacitor units connected line-to-neutral on a multi-grounded neutral system provide a low-impedance path for lightning surges. This low impedance characteristic makes capacitors susceptible to lightning surge events. Lightning strikes have damaged capacitor bushings as a result of severe instances of flashover. However, the more probable lightning damage to capacitors is the breakdown of the insulation between the capacitor's internal elements and the capacitor case.

A capacitor attempts to maintain constant voltage across its terminals and if the voltage begins to change, the capacitor conducts charging current through itself of sufficient amplitude to maintain the voltage constant. When lightning strikes a capacitor, the surge impresses a very high voltage across the capacitor. The capacitor then, in an attempt to maintain the impressed voltage, charges to the surge voltage magnitude by passing enormous charging current. This action can cause the unit to fail from the internal heat generated by the large charging current. Capacitor failure is usually indicated by a severely bulging tank case, ruptured tank case, other catastrophic physical evidence or no visible physical evidence on the capacitor but by simple observation that the fuse protecting the capacitor has blown. Slight bulging or blooming of a capacitor tank is not necessarily indicative of capacitor failure because capacitors can withstand considerable overcurrent conditions. Capacitors should conform to the IEEE *Standard for Shunt Power Capacitors* (Std 18-1992). This standard expects a capacitor to provide continuous operation provided that none of the following limitations are exceeded:

1. 135 percent of nameplate kVAR;,
2. 110 percent of rated RMS voltage and crest voltage not exceeding 2.83 times the rated root mean square voltage (including harmonics but not transients); and
3. 180 percent of rated root mean square current (including fundamental and harmonics).

Capacitors suspected of being damaged should be tested using a commercially available capacitor checker. Testing could also be conducted by using an audio oscillator, a voltmeter, a resistor and an inductor of known inductance. The resistor would be wired in series with the parallel connection of the capacitor and inductor and the circuit energized with the audio oscillator across this series parallel connected circuit. The voltmeter would be connected to measure the voltage across the capacitor or inductor and the frequency of the oscillator adjusted for a maximum voltage reading. At this frequency the capacitor and inductor should be in resonance where the inductive reactance should equal the capacitive reactance. The inductive

reactance of the inductor can be calculated by multiplying the known inductance value by the measured frequency and multiplying this value by 2π. The capacitance should be equal to 1 divided by the product of the calculated inductance multiplied by 2 times π times the resonant frequency. This calculated capacitance should be within the rated tolerances of the shunt capacitor's capacitance which is calculated according to the following formula:
Capacitance of a power shunt capacitor is equal to:

$$\mathbf{C = \frac{1000 * kVAR}{2 * \pi * f * V^2}}$$

Where:
C = capacitance in microfarads (μF) kVAR is the capacitor's rated kVAR
f = rated frequency of capacitor (60 Hz)
V = rated voltage of the capacitor in Volts

For example, plugging rated values for a 50 KVAR, 7200-volt, capacitor into the equation results in a capacitance of 2.56 μF.

If the capacitance calculated from the test varies significantly from the rated capacitance calculation, then the capacitor should be retired.

Power circuits can remain in operation with part or all of a capacitor bank out of service. But the portion of a capacitor bank that is not in service does not provide either voltage improvement (rise) or power factor correction. Wide voltage variations can occur on multi-phase systems that experience the loss of one or more but not all installed capacitors of a capacitor bank. Loss of some but not all capacitors on a multi-phase line can also cause shifting of phase angles, leading to system unbalance. Shifting phase angles away from the normal 120 degrees causes many problems on a three-phase power system, such as motor growling, motor overheating, difficulties in starting loaded three-phase motors, and blowing or tripping of motor protection devices. Thus single-or unbalanced phase capacitor use should be avoided. When one phase of a three-phase capacitor bank is out of service, the whole bank should be taken out of service.

In the event of capacitor failure, it is desirable to isolate the failure from the power system and minimize the damage, with no interruption in service. If the capacitor unit contains Polychlorinated Biphenyls (PCBs), extra care is required to clear the failed unit before tank rupture and an expensive cleanup of the affected area as is required by the Environmental Protection Agency (EPA). System operators would be prudent to remove all PCB capacitors from use and properly dispose of them in accordance with EPA regulations. Capacitors manufactured since 1978 should contain the statement "No PCBs" and do not contain PCBs. Newer non-PCB containing capacitors do not have the same health and disposal concerns as capacitors with PCBs. PCBs proved to be an excellent dielectric material for use in capacitors. However, scientific studies conducted raised concerns that PCBs may present a health hazard to humans, and PCBs were subsequently banned for use in the manufacture of capacitors and many other products. Locations allowing PCB containing transformers and capacitors are extremely limited. They may only be used in restricted access electrical substations or in a contained and restricted access indoor installation. They may not be used in areas which present a risk of exposure to food or feed. EPA promulgated these PCB product use regulations because PCBs will not readily decompose or break down and can be expected to retain their chemical composition for many years. These regulations include the proper method of disposal of products containing PCBs and PCB waste materials. EPA requires that certain PCB containing products (which includes capacitors) be properly contained and sent to a suitable approved PCB disposal facility. The location of the nearest facility can be obtained by contacting the capacitor manufacturer or the regional EPA office.

Capacitors need to be protected with surge arresters and proper fusing or short-circuit protection for reasons other than lightning. This protection is also needed to prevent capacitors from being damaged by transient overvoltage's caused by switching operations, arcing grounds, accidental conductor contact with higher voltages, disturbances caused by other arresters, and resonance or near resonance caused by motors while starting. Protection is best provided with maxi-block silicon carbide or metal oxide varistor (MOV) surge arresters. Connections to and from the arresters and capacitors and the arrester grounding provisions should be made using the shortest leads practical attempting to keep the leads as straight as possible. A capacitor should also be provided with a fuse or short-circuit protection that is designed to function under 135% of the capacitor's nameplate current rating.

Harmonics

Capacitors act as a path to ground for the harmonic currents of a power system's 60 Hz power wave. The impedance offered by a capacitor is calculated using the following formula:

$$\mathbf{X_I = \frac{1}{2 * \pi * f * C}}$$

Where:
X_I = Capacitor Impedance
π = 3.1416
f = Frequency (60 Hz for U.S. power systems)
C = Capacitance in Microfarads

As can be seen from the formula, a capacitor's impedance decreases as the frequency increases. Thus, higher order harmonic currents, or currents at multiple frequencies of the power system fundamental 60 Hz wave, can flow through a capacitor easily.

Non-linear loads such as transformers, especially transformers with poor quality cores, generate harmonics. The magnitude and number of harmonics generated by a transformer is directly related to the magnitude of the voltage used to energize the transformer. The higher the energizing voltage, especially as the energizing voltage exceeds the transformer's nameplate rating, the higher the magnitude and numbers of harmonics generated by the transformer. Harmonic currents travel down the lines looking for a low impedance path to ground.

Underground primary power cables are predominately capacitive and also provide this path. Any odd numbered triple (180, 540, 900 Hz, etc.) of the fundamental 60 Hz voltage wave is likely to cause problems because all three phases of the odd numbered triple harmonics are in phase with one another on a 3-phase system and, thus, add up rather than cancel one another where they flow to ground. The 9th harmonic, a triple harmonic, can have the greatest effect on capacitors because it is a common transformer-generated harmonic and capacitors offer low impedance at 540 Hz.

With a path to ground, harmonic currents can flow along the phase conductors and neutral conductors of a power line and can induce currents in parallel telecommunications cables. If high enough in magnitude, induced harmonic currents can render a telecommunications system unusable. The power system operator has to design electric facilities to minimize the possibility for harmonic induction. The primary frequency spectrum for wire-line telecommunications systems is from 40 Hz to 3000 Hz. But the frequencies from 100 to 2500 Hz are the most critical to causing objectionable harmonic interference. These same frequencies are within the range of typical harmonics generated on a power system. Capacitors can exacerbate normal power line harmonic current flow by providing them a lower impedance path thus causing their magnitudes to be higher than they otherwise would be without capacitors connected. In worst case situations, capacitors can also create resonant conditions on the power system that can cause extremely high magnitudes of harmonic current and voltage that can severely affect telecommunications operation.

Methods to alleviate harmonic problems associated with capacitors are discussed below.

Change Capacitor Location

Telecommunications noise problems created by capacitors can sometimes be remedied by moving the capacitors to a new location. This remedial solution involves moving the capacitor bank toward the substation to a location ideally where the power conductors between the capacitor bank and the substation do not parallel any telecommunications circuits. However, in many cases, moving the capacitor bank to a location where power conductors are no longer paralleled by telecommunications circuits would mean locating the capacitor bank very near the substation. In such cases, most of the capacitor benefits are lost. Thus a compromise has to be made, and the capacitor bank moved back toward the substation just far enough to detune a resonant condition and/or limit the parallel exposure enough to reduce harmonic coupling and unwanted telecommunications interference. Remedial success is typically high when the offending capacitors have caused a resonant condition on the power line and the two utilities parallel one another for a significant distance. Resonant conditions usually occur at a single frequency, often an odd multiple of 60 Hz, such as 300, 540, 900 Hz, etc. At the resonant frequency, the power circuit's inductive reactance (between the capacitor bank and the substation serving the bank) equals the power circuit's capacitive reactance. With the circuit impedance so drastically reduced to only a small resistive component, an abnormally high magnitude of current can flow at the resonant frequency, significantly improving the chances for induction and resulting objectionable harmonic noise in neighboring telecommunications circuits. At the resonant frequency, voltage on the power circuit can also become high and could lead to damage of connected power line equipment and/or system operating problems.

Moving the capacitor toward the distribution voltage source helps improve a noise situation in two ways. First changing the capacitor bank location can de-tune the resonance which, by itself, can help to reduce the noise. Moving the bank so there is limited parallel exposure of the two utilities' circuits between the capacitor location and the substation minimizes possible induction of harmonics into the telecommunications circuits and adds to the improvement.

Moving a capacitor bank is not necessarily a permanent solution. Noise problems could arise again as circuit loading and balance changes with time, possibly creating resonant conditions at different harmonics. In addition, future utility construction could result in new longer stretches of parallel exposure between the utilities and cause renewed noise problems. Joint utility planning and coordination can help to avoid such problems.

Change Capacitor Size

Adding capacitors at a capacitor bank suspected of causing a resonant condition can sometimes change the circuit capacitance enough to cancel the resonance and help alleviate a noise problem. Such a solution, however, needs to be addressed carefully to be certain that resonance is not moved to another critical power line harmonic frequency, resulting in continued or worsened telecommunications noise. Care is also needed to be certain the added capacitance does not cause the power circuit to have an objectionable leading power factor.

Because of the reduced power/telecommunications circuit exposure, moving capacitors as can be more effective in alleviating noise problems than adding capacitance.

Load growth, new utility construction, etc., can upset any success attained in adding capacitance to a capacitor bank to reduce a noise problem. Again, proper planning, design, and coordination with all neighboring utilities is extremely useful in minimizing problems.

Harmonic Filters

Another noise reducing remedy involves blocking the harmonic ground path by inserting a tuned filter in the capacitor ground connection. This filter would take the place of the grounding switch shown in Figure 14. The filter is a harmonic saturable reactor which during installation is experimentally tuned so that at the offending harmonic frequency it acts as a high impedance preventing current at that frequency from flowing on the power line. At 60 Hz the filter provides a low impedance connection to ground helping to maintain system grounding integrity.

A filter installation may need to be re-tuned as the loads and electric system changes. At some point the electric system could change to such an extent that the tuning needed for effective noise alleviation may be outside the range of the filter's core size installed and a new filter may be necessary.

Because saturable reactor filters involve non-standard construction and most line crews are not familiar with the connections, the use of this type of filter is not acceptable to some utilities.

Ungrounded Capacitor Banks

Another noise reducing remedy involves blocking the harmonic ground path by floating the wye point on the capacitor bank and denying harmonic current a path to ground. **However, because of the safety concerns, utility systems should consider this solution only as a last resort.** While the neutral is floated the ungrounded capacitor cases can become energized to primary line voltage levels and present a hazard to line crews who work on them.

If no other remedial effort is feasible and this solution is determined to be necessary then special operating procedures should be implemented and strictly observed. For safety reasons to assure the capacitor cases and the power system neutral are effectively grounded temporarily, the floating wye should be grounded, usually with a solid switch (solid blade cutout). This grounding switch would be used during manual switching or repairs on the capacitor bank or the power system within the vicinity of the capacitor bank location. For normal operation, after the capacitors are energized, the grounding switch is open and the wye-point of the capacitor bank is placed in the ungrounded mode.

It is recommended that a sign be added to the pole for electric line crews such as:

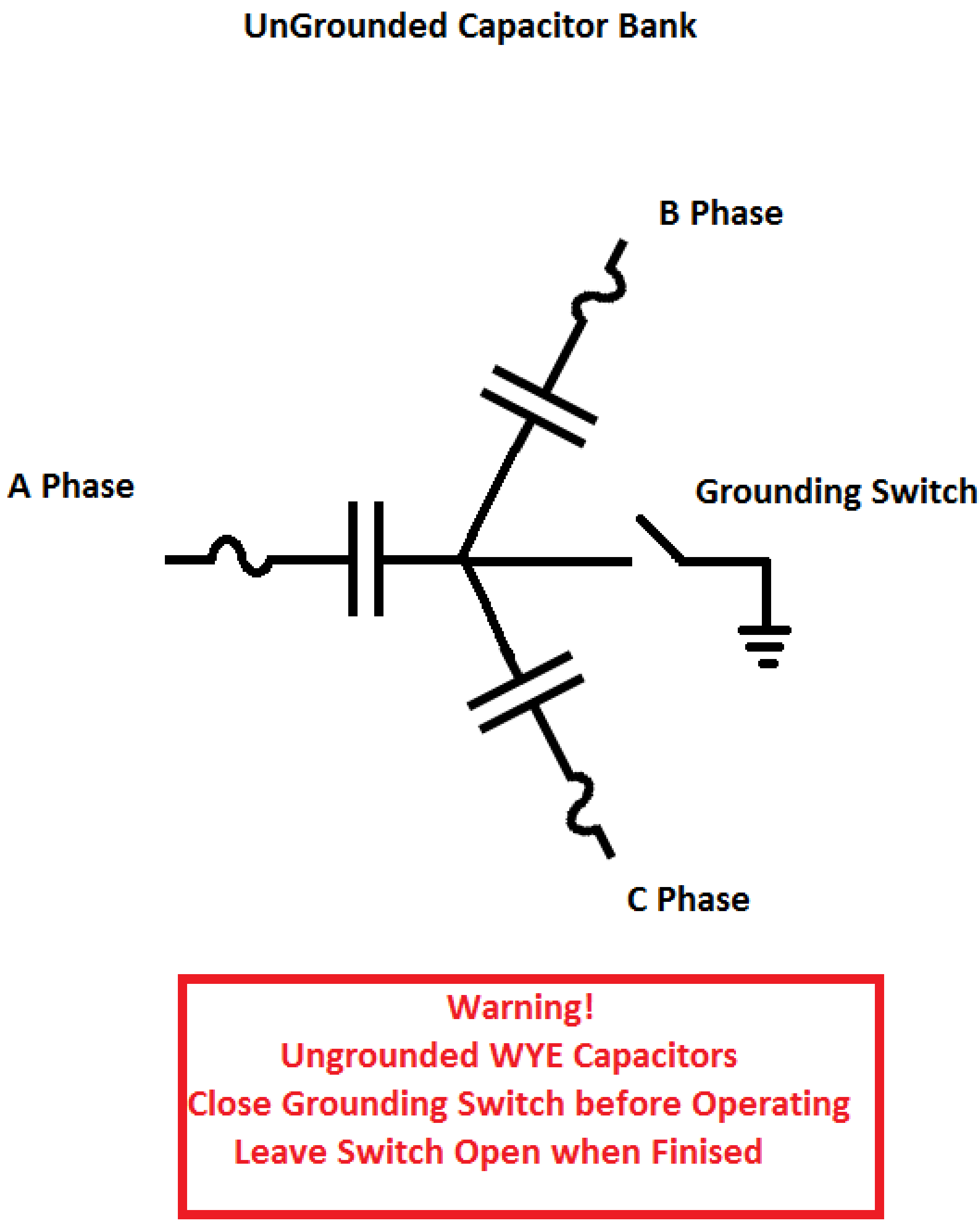


Figure 14

Map records should also show locations of non-standard capacitor connections.

Chapter 3
Capacitor Application

Light Load Conditions

The amount of capacitor kVARs needed at minimum load should be permanently connected fixed (un-switched) to the power system. Fixed capacitor banks should be installed on the system in amounts not exceeding the minimum kVAR demand, without causing leading power factor under light conditions on the respective feeders.

Experience shows that the minimum load is wholly dependent on the type of loads being served. Industrial loads may be fairly uniform all day and all year. However, most loads are cyclic in nature and most peaks are weather driven (either extreme hot or cold). Minimum loads for residential and small commercial loads may vary from 25 to 50 percent of peak. A utility system's monthly demand on the monthly power bill does not normally show the minimum load. The demand shown on a bill for an off-peak month is the maximum demand for that month. Selecting capacitor locations for the lightest load requires determining the expected minimum load from the lowest peak month's historical load data.

Capacitor or kVAR needs may also be determined by tracking minimum-maximum load readings from a feeder's bus-by-bus metering records or from SCADA (Supervisory Control and Data Acquisition) loading data. The preferred methods would be in the following order of priority:

1. SCADA system with archived load and kW/kVAR data,
2. Permanently-connected meter readings of amps, kilowatts, and kVARs or power factor, or
3. Temporarily-connected metering at buses during light-load periods to measure amperes and power factor.

Peak Load Conditions

The capacitor selection discussed so far has dealt only with applying capacitors to correct power factor at minimum load. In order to correct power factor during heavier loading periods, it is necessary to use switched capacitors. Switching of capacitors may be done manually or automatically. Automatic controls can become cost effective due to the cost incurred by personnel sent to manually switch them and because of the additional line losses incurred if not done in a timely manner. Automatic controls can track various parameters and switch the capacitor banks as needed to optimize the system power factor. The additional capacitors should be switched either as an entire bank or in steps in order to keep the power factor from becoming significantly leading at any time. In addition, proper switching prevents overvoltage, undesirable voltage flicker and helps the capacitors perform the task they were installed to do.

Voltage spikes or surges occur when switching capacitors because the switch usually closes when the system voltage is not at a zero voltage crossing point. Non-zero current switching causes a capacitor to abruptly charge to the system voltage and generally creates wide ranging over-swings. This transient will take several cycles to decay and can affect industrial loads with computer based controls. However, there are switches available now that switch only at the next zero crossing to minimize switching transients.

Capacitor bank size and location should be selected and designed in a manner that limits voltage change to 3 volts (on a 120-volt base) to eliminate customer complaints. For situations where limited switching is expected, customers on long, lightly loaded feeders may accept up to a 6 volt change.

Since switched capacitors are generally installed to supplement unswitched capacitors, they are located in the same manner as unswitched units. Results of computer load flow studies should be used to determine the optimum sizes and locations for capacitors. Fixed capacitor installations should be designed to appropriately accommodate the system's inductive reactance expected during expected minimum loading. The augmenting switched capacitor installations need to be designed to appropriately accommodate the system's inductive reactance expected during peak loading periods.

In lieu of load flow studies and computer calculated placement schemes, meter readings should be taken at load centers in the same manner as unswitched units, but now peak conditions should be investigated instead of minimum load conditions. Readings should be taken so that peak kVA and kW loading can be determined.

Since,

$$\textbf{Power Factor} = \frac{\textbf{kW}}{\textbf{kVA}}$$

Peak load power factor can then be determined along with peak kVAR load. Knowing that,

$$\textbf{kVAR}^2 = \textbf{kVA}^2 - \textbf{kW}^2$$

We can calculate,

$$\textbf{kVAR} = \sqrt{\textbf{kVA}^2 - \textbf{kW}^2}$$

Therefore, the magnitude of switched capacitor kVAR necessary to correct the peak load power factor to unity is the difference between the kVAR of the unswitched units and peak load kVAR. When selecting capacitors for switched units there are certain limiting factors that must be considered. The desired level of correction should be determined through economics. The cost of the switched capacitor installation should be less than the savings derived from the installation. Switching devices are expensive but the installed cost per kVAR of a capacitor installation generally decreases as the size of the installation increases.

On rural lines especially, the standard sizes of capacitors may be somewhat large for effective switching. The smallest standard unit for primary use is now 50 kVAR, and some manufacturers do not make a unit smaller than 100 kVAR. Since switched steps of capacitors have to be multiples of standard capacitor sizes, it is impossible to correct exactly to unity or to whatever value is desired. Besides, system load is dynamic and ever changing.

Choice of manual or automatic switching depends upon the benefits expected, the size of the capacitor bank, the amount of variation of kilowatt and kilovar load over a typical load period and fluctuation of voltage with load. Manual switching requires an attendant to make the necessary observations of voltage, power factor and kilovar demand. Therefore, automatic switching would almost always be chosen, in preference to manual switching.

Capacitor Location

Maximum benefits are obtained by locating the capacitors as near the inductive reactance kVAR loads as possible and by matching the magnitude of the inductive reactance kVAR requirement. Practical considerations of economics and availability of a limited number of standard kVAR sizes necessitate that capacitors be clustered near load centers. Computer modeling or rigorous evaluation of considerable load metering data are necessary to make the proper capacitor placement decision and keep line losses as low as possible. The loss reduction benefits possible with capacitor use can be significant enough to economically justify feeder metering or a large share of SCADA system costs.

A textbook solution assumes uniform distribution of consumers, and suggests that as the distance from the substation increases, the number of consumers per main line mile of feeder increases. To obtain maximum benefits in voltage improvement and reduction of loss on such a line, a permanently connected (fixed) capacitor bank should be located at a distance from the substation which is 1/2 to 2/3 of the total length of the line. This location method is used strictly as a "Rule of Thumb" because few circuits contain such uniformly distributed loads.

For industrial loads, it is best to correct the power factor at the load. It is important to remember that a capacitor bank draws considerable current, so the existing source-side protective equipment needs to be checked for adequacy. In an attempt to get the maximum voltage rise by placing a bank at the end of the 3-phase line, a bank of 15 Amp or 25 Amp circuit reclosers could be loaded to the point of tripping and could create unnecessary outage problems. Correcting lagging kVAR requirements at the point of use prevents the utility's primary line, transformer, and service lines, as well as the customer's internal wiring from unnecessary losses. Moreover, when corrected on the consumer side, the utility line never sees the consumer's kVARs. Appropriate effort should be made to encourage (perhaps through rate incentives) large consumers to correct their own power factor.

As previously stated, optimum benefits are derived by locating capacitors at industrial loads and at a feeder's consumer load density center for residential load. The residential load center is normally 1/2 to 2/3 the distance from the substation to the end of the line for uniformly loaded feeders. However, the installation of capacitors on all systems within the range specified above is not always feasible because of possible exposure of long lengths of the power line to telecommunications circuits, which may cause excessive noise interference.

Thus, the following methods are recommended for locating capacitors:

1. Using computer modeling allows the computer program to place the capacitors on the system in blocks of the largest size that can be used to limit the voltage changes to 3 volts per switched bank.

   Computer models calculate proper capacitor placement by trying the smallest size capacitor a system uses in each line section of every feeder and calculating the total circuit losses. In this way, the computer selects the line section with the lowest net losses and then places subsequent additional capacitors in the same manner. The individual effect on feeder losses is tabulated for each capacitor placed, with each subsequent unit having less benefit. At some point at less than unity power factor, an additional capacitor offers little additional benefit, and adding more actually increases losses. Capacitors should be located so as to reduce feeder losses as much as economically practical. The first capacitor placed provides the most improvement per unit cost because it is usually a fixed capacitor and it increases power factor the most. Each subsequent unit is less economically practical.

2. Feeder metering at the substation or point of delivery can provide the kW/kVAR information that is needed for both kVAR correction and engineering analysis. Additional kVAR information is available using new technology kVAR or power factor meters attached to hot sticks. No electrical connections to the line are

necessary. Placing the meter in contact with the primary wires will allow the necessary measurements to be recorded. Power factor and phase current data can be used to calculate kVA, kW, and kVAR flow. Example 7 that follows assumes that the system operator is using the "Rule of Thumb" method for locating an acceptable site for a capacitor bank. This means that the system operator travels 1/2 to 2/3 of the way out the line from the substation and conducts the sequence of measurements and determinations suggested in Example 7.

Example: At a given point on 12.5/7.2 kV feeder, the following is measured:

Currents: 25, 12, and 40 amperes (A, B, and C Phases, respectively)
Average Power Factor: 0.85

What do you know about the system at this point?

Calculations:

Average Current = (25 + 12 + 40) / 3 = 25.7 amperes

Circuit Balance =

A-Phase	Good Balance
B-Phase	13.7 Amps low
C-Phase	14.3 Amps high

$$kVA = 3 * \text{Average Current} * \text{Voltage}_{\text{line-to-neutral}}) / 1{,}000$$

$$= (3 * 25.7 * 7200) / 1{,}000$$

$$= 554 \text{ kVA}$$

$$\text{Phase angle} = \cos^{-1}(PF)$$

$$\text{Phase angle} = \cos^{-1}(0.85) = 31.8 \text{ degrees}$$

$$kW = kVA * PF = 554 * 0.85 = 471 \text{ kW}$$

$$kVAR = kVA * \sin(\text{phase angle})$$

$$= kVA * \sin[(\cos^{-1}(PF)]$$

= 554 * sin (31.8)

= 292 kVAR

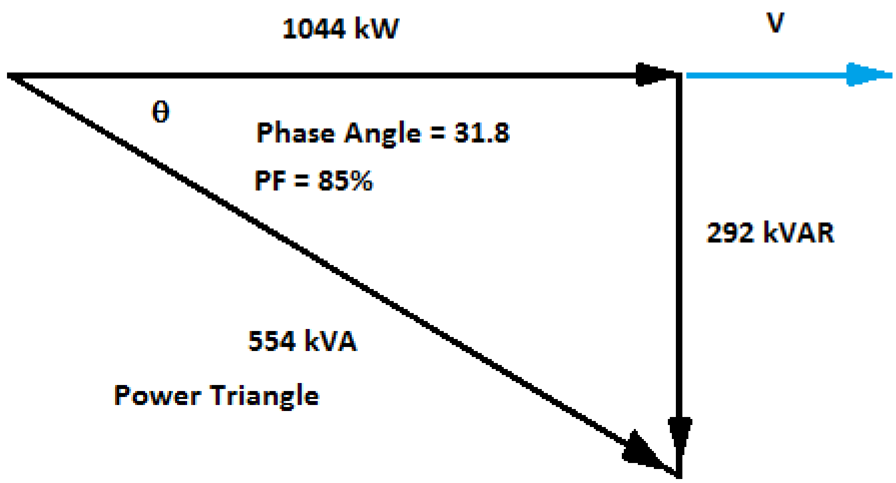


Figure 15

So with a few field measurements we know that almost 300 kVAR flows past this point. If capacitors were to be placed here, then 300 kVAR (three 100 kVAR, units) of capacitors located here (or beyond) would eliminate all lagging kVAR flow under these load conditions.

The addition of 300 kVAR of capacitors would change the kVAR flow from (292) - (300) = -8 kVAR. The new phase angle is:

New Phase Angle = $\tan^{-1}$(kVAR/kW)

= $\tan^{-1}$(-8 / 471)

= - 0.973 degrees (current leading)

New kVA = kW * cos (New Phase angle)

= 471 * 0.999

= 471 kVA

New Average current = (kVA/3) / (kV)

= (471 / 3) / 7.2

= 21.8 amperes

If you knew that the system impedance at this point (or near this point) was 14.5 + j 15.3 ohms, the voltage rise here from the 300-kVAR, three-phase, capacitor bank would be:

Voltage Rise = (Primary Capacitor Current) * (Inductive Reactance)

Voltage Rise = (100 kVAR/Phase / 7.2 kV) * 15.3 ohms Reactive

Voltage Rise = 212.5 volts at 7,200 volts or,

Voltage Rise = 212.5 / (7,200 / 120)

Voltage Rise = 3.54 volts on 120-volt base

So, by relieving the electric system of 292 lagging kVARs at this point, you have lowered the load from 554 to 471 kVA, reduced the average current from 25.7 to 21.8 amps, and gained 3.5-volts at this point and beyond.

Three-Phase Capacitor Banks

Capacitors to be installed on three-phase circuits should be installed in equal kVAR amounts per phase and not in proportion to the total connected transformer capacity on each phase. System loads should already be balanced within 20 percent (at peak load). In general, capacitors should not be installed on single-phase extensions of the main three-phase feeder. However, if it is absolutely necessary to install single-phase capacitor banks on a three-phase line, they should still be equally sized per phase and located close to each other so as to appear to be a Y-connected bank of capacitors.

This balance needs to be maintained to:

1. Minimize power factor phase unbalance, which translates into unbalanced voltages and unbalanced phase angles for three phase loads; and

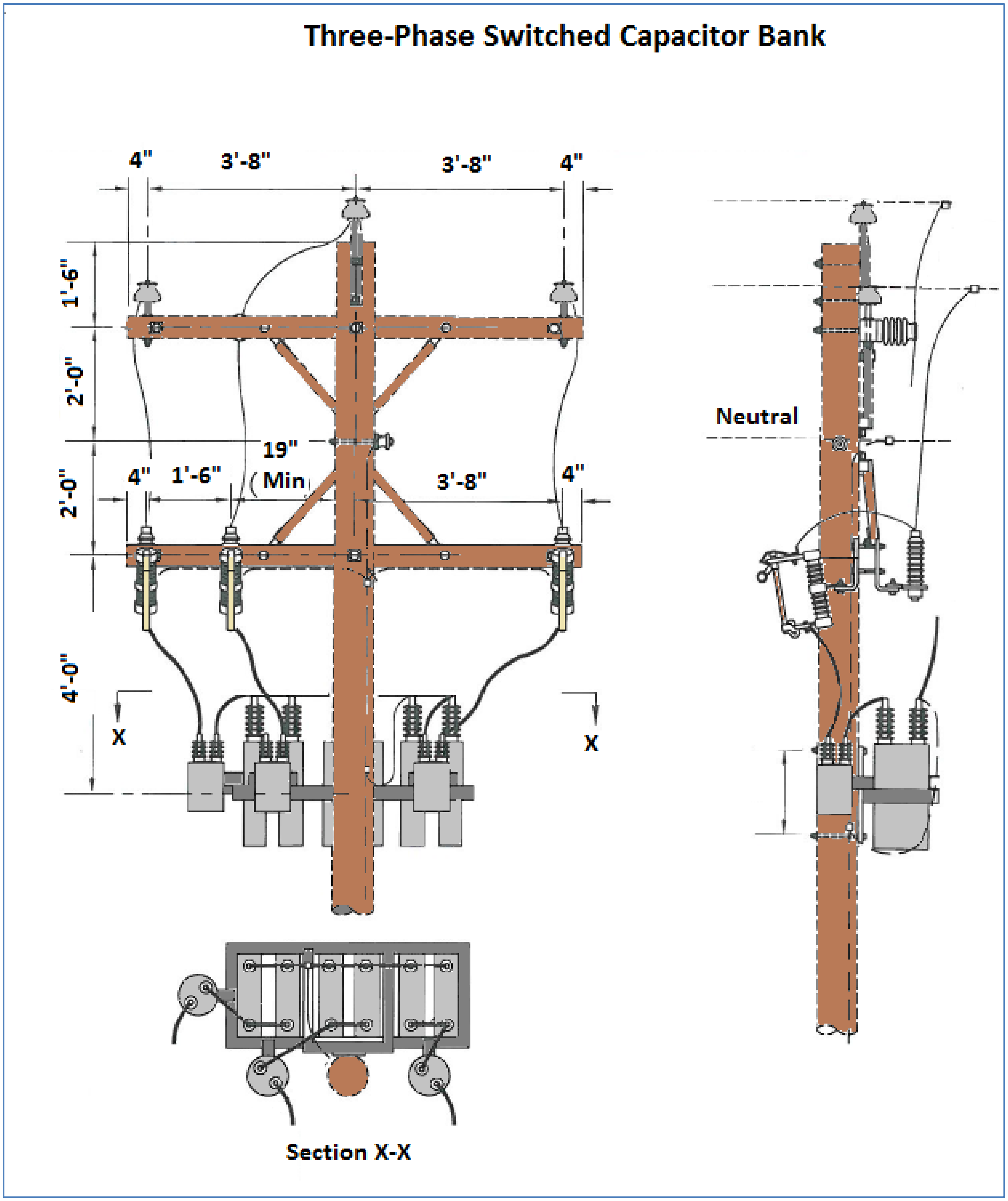
2. Minimize the effect of certain harmonic currents that would otherwise be produced and flow in the neutral conductor where it could cause interference in

nearby telecommunications circuits. Power factor unbalance causes more aggravating noise induction problems than does load unbalance, and these noise problems occur at higher and more troublesome frequencies.

3. When one phase of a capacitor bank is out of service, take the entire bank out of service. Capacitors should be inspected regularly, at least before and after peak seasons.

Capacitor Installation Drawings

Figure 16 shows a typical three phase switched capacitor bank installation drawing.



Three-Phase Switched Capacitor Bank
4"
3'-8"
3'-8"
4"
1'-6"
2'-0"
19"
(Min)
2'-0"
4"
1'-6"
3'-8"
4"
4'-0"
X
X
Neutral
Section X-X

Figure 16

Automatic Capacitor Switching

Additional material and equipment will be required when automatic capacitor switching is to be installed. In addition to the capacitors and protective equipment, a switched capacitor bank requires a switching device, control equipment, and a control power source.

The control equipment for automatic switching consists of a master element, a time delay device, and auxiliary devices such as an auto-manual switch and a close-trip switch. Some controls provide dual controls for Summer/Winter conditions or for dual conditions such as Thermal/Voltage. The master element is selected to suit the conditions of the system on which the control unit is to be used. Such stimuli as voltage, current, temperature, kilovar, power factor, or timing, or a combination may be used to actuate master elements. It is common to switch all three phases using one current sensor, so the designer should verify that all three phases have similar amount and types of load. The various types of master element control are as follows:

Voltage Control

Responds to objectionable voltage changes that occur with varying loads. One type of master element voltage control is essentially a contact-making voltmeter, which has a range of adjustment from 90 to 110 percent and a bandwidth adjustable from 3 to 7½ percent. Another type of master element voltage control incorporates a resistor inserted in series with a voltage-regulating relay, which enables the master element to sense a lower voltage during high load periods. (This type of master element sensing has to be coordinated with regulators for proper operation). Many new controls are electronic. Some controls allow dual sensing actuation or biasing, to allow control by temperature with voltage override so capacitors can be switched in during either high temperature or low voltage times.

Current Control

Responds to changes in load current by means of a current-sensitive relay. This means of control may be used on systems where the voltage is well-regulated and the power factor of the load remains substantially constant with variation in kilowatt loading, or on systems where the power factor of the circuit varies in a predictable manner with variation in kilowatt loading. Useful for recreational, seasonal, irrigation, or oil well pump-type loads when such loads constitute the bulk of the feeder load and are not dependent on time or temperature). Current sensing is usually located near the primary conductors inside the insulators supporting the conductors. Low voltage and current leads are neatly and safely trained down the supporting structure and connected to the master control.

Temperature Control
Responds to local air temperature for tracking such temperature-sensitive loads as air conditioning and electric heat. Controls include both wide range and narrow range settings. Wide range controls can be set to switch capacitors "ON" and "OFF" for various temperature ranges, for example, "ON" between 85 and 90 degrees Fahrenheit and "OFF" for temperatures between 75 and 80 degrees Fahrenheit. This feature allows a second tier of capacitors to act as fixed units during a long spell of hot or cold weather. Other capacitor banks can be controlled with narrow-range controls and be set to turn "ON" for temperatures between 90 and 92 degrees Fahrenheit and to turn "OFF" for temperatures between 85 and 88 degrees Fahrenheit, to handle system peak loads.

Kilovar Control
Responds to inductive loading and is used where load voltage is regulated and load power factor varies in an unpredictable manner with variation in kilowatt loading. KVAR type controls use an induction-directional or solid state relay for single-phase indication. Kilovar control presents a better approach to capacitor switching control but it has been rarely used in the past, due to its high cost. In recent years, electronic control costs have lowered making kVAR control now a consideration. KVAR control has been useful for improving system power factor in situations where one large industrial customer is served and the customer does not provide its own power factor correction.

Power Factor Control
Responds to changes in power factor and is similar to kVAR control in that it uses an induction-directional or solid state relay with a desensitizing adjustment to prevent hunting at light loads. The desensitizing adjustment is needed to account for the possible occurrence of the power factor bandwidth being less than the change in sensing caused by switching the capacitor.

Like kilovar control, power factor control has been rarely used because of its high cost. However, costs have been declining in recent years and several manufacturers offer good power factor controls, making this type of control also a consideration.

Time Switching Control
Responds by using a simple clock device to switch capacitors at some predetermined time. It is primarily used where the load characteristics are predictable and reasonably constant, as with industrial loads. Desirable added features are weekend and holiday blocking. This can be a low cost method. It is also recommended that the clock be capable of remaining accurate in case of a power outage.

Leading Power Factor

If the inductive kVAR load on the distribution system becomes less than the kVAR rating of the installed capacitors, a leading power factor will occur. Leading system power factor at the transmission system level can, in severe instances, cause generators to become unstable. This is typically only a concern in the case of small, isolated generating units. A leading power factor will cause the same losses as a lagging power factor of the same magnitude. If the power factor does go excessively leading, a system ends up spending money unnecessarily for capacitors (to reduce system losses) because it still incurs losses anyway. The solution is to either reduce the capacitors installed or switch them off when not needed. This can become a very serious problem if motor loads are disconnected due to a feeder recloser operation. Fixed capacitors may drive voltage beyond reasonable limits and cause equipment damage.

Because substation power transformers have predominately inductive (lagging) reactance, a slight distribution system leading power factor translates into a power factor closer to unity on the transmission system. In this case, the leading power factor helps the Transmission system.

Power Factor Penalty Rates

Most utilities have power factor clauses in their commercial and industrial retail rates that strongly encourage the customer to maintain a 90-95% power factor; otherwise the customer has to pay a penalty charge. Traditionally, these power factor penalty clauses were added into retail rates because the utilities purchased power rates included similar penalties. Lower power factors usually cause an increased billing demand by the ratio of the target PF divided by the metered PF, usually on peak.

A traditional method of applying a power factor penalty adjusts (raises) the billing demand in proportion to the metered power factor deviation from the desired power factor. This billing demand adjustment is expressed as:

$$\textbf{Billing Demand} = \textbf{Metered Peak Demand} * \frac{\textbf{Target Power Factor}}{\textbf{Measured Power Factor}}$$

For example, customers that have monthly bills with a metered PF of 0.83 and a target PF of 0.95 (minimum allowed by the utility in this example), the billing demand would be multiplied by 0.95 / 0.83 = 1.145. This 14.5 percent increase in billing demand should alert customers and encourage them to improve their power factors.

You may help persuade consumers to correct their own power factor by pointing out to them that capacitors help their system in the following ways:

1. Reduce their power factor penalties, if applicable;
2. Improve their in-plant voltage levels;
3. Reduce their in-plant line and transformer losses; and
4. Release (reclaim) substation, transformer, switchboard, and conductor capacity on their system.
5. A few utilities offer reduced billing demand if the actual power factor exceeds the desired power factor.

Capacitor Fusing

Fuse protection is necessary for each shunt capacitor installation, mainly to disconnect a faulted capacitor from the line before the capacitor causes other current protective devices to operate. Capacitor fuse protection has to be coordinated with any line sectionalizing devices that will be operated on the feeder. Fuses should be designed to blow before the capacitor case ruptures, in order to prevent personal injury, damage to adjacent equipment, or capacitor dielectric fluid leaks.

As previously noted, shunt capacitors are designed in accordance with IEEE Standard 181992 to operate temporarily at 135 percent of their rated kVAR. This 35 percent above rated tolerance is to allow for:

1. Additional kVARs (reactive power) that could be present as a result of operating the capacitors at voltages above their nameplate fundamental frequency voltage;

2. Additional kVARs that could be generated as a result of slightly higher than normal harmonic voltages that could be present along with the fundamental frequency voltage; and

3. Additional kVARs that could be present as a result of the capacitor's actual kVAR being on the high side of allowable manufacturing tolerances.

Capacitor current protection devices should have a nominal rating of 135 to 140 percent of the capacitor line current. Capacitor jumpers and switches need to have adequate capacity to handle capacitive currents at full rating of capacitors on a continuous basis.

Capacitor units are not normally fused individually, but by phase in a bank of one or more capacitors per phase. Banks should always contain the same amount of kVARs in each phase. Capacitor fusing is normally designed to operate at 120 to 135 percent of the capacitor's nameplate current rating, though such fusing is occasionally derated to no less than 108 percent for multiple units per phase.

In general, a fuse link should melt in 5 minutes at 150 to 300 percent of rated current. Fuses for small capacitors should have at least a 5-ampere rating to minimize the likelihood of fuse failure due to lightning or transient surges. In high lightning areas, fuses should be 15 amperes or larger, but no greater than 140 percent of the capacitor's nameplate current rating. The choice of fuse rating for a capacitor installation should always be based on a particular fuse's time-current characteristics. This individual design attention is needed because of the wide variation in fuse time-current characteristics and the different types and brands of fuses available.

The following table shows EEI/NEMA type T and K Link fuse applications for protecting capacitors.

Table 4
Capacitor Fusing Table

1-ϕ kVAR	Full Load Amps	12470/7200 Gnd Y	3-ϕ kVAR	Full Load Amps	24900/14400 Gnd Y
150	6.9	8T			
300	13.9	15T	300	6.9	8T
450	20.8	20T	450	10.4	10T
600	27.8	25T	600	13.9	15T
900	41.7	40T	900	20.8	20T

If lightning causes excessive fuse blowing but there is no capacitor damage, fuses should be replaced with the next larger size.

Safety Precautions

Capacitors require special precautions when they are taken out of service for repair or maintenance. Like a battery, a capacitor may retain a charge for an indefinite time after being disconnected; and the capacitor charge can be quite hazardous to an unsuspecting individual who encounters the charge. Generally, discharge resistors are manufactured into each capacitor unit to help dissipate charge when the unit is out of service. The discharging resistors should reduce the terminal voltage of a capacitor unit to 50-volts or less in one minute for units rated at 600 volts or less, and in five minutes for units rated higher than 600 volts.

Service Maintenance

Added precautions should be taken when working with delta and non-grounded, wye-connected, capacitors. A hazardous voltage may be present on a capacitor even when the phase conductor to which the capacitor is connected is open-circuited for work. Line voltage can feed back through the capacitor via the capacitor's common connection with capacitors connected to other phase conductors that are still energized. This is why it is important for line crews to always check phase conductors for the presence of voltage.

Before working on any part of a capacitor bank, completely de-energize the bank, and disconnect all line conductors from all terminals. It is not good practice to rely on a capacitor's internal discharging resistors to reduce the terminal voltage to a safe value after being disconnected from a power line. After disconnecting a capacitor and waiting for the discharging resistors to bleed voltage down, short-circuit the capacitor terminals and connect the shorted terminals and the cases to ground. Leave the capacitor shorted until all work is completed you are ready to re-energize.

Out of Service Repair/Storage

Prior to capacitors being removed from their racks, and waiting several minutes, during which time the discharging resistors should have reduced the capacitor terminal voltage practically to zero, the terminals should be simultaneously short-circuited and solidly connected to their cases. Permanent shorting connections should then be installed because capacitors tend to accumulate a residual charge, even when not connected to a power source, if not short-circuited. No. 6 copper wire can be used to make the capacitor terminal-to-terminal-to-case shorting connections. The connection should not be removed until the unit until is re-installed.

Load Breaking Considerations

It is important to note that a capacitor bank can be a formidable load as the kVAR size used increases. A 600 kVAR bank at 7,200V draws about 28 Amps. A bank drawing this much current cannot be "unloaded" without the use of a load-break tool. In cases where load-break cutouts have been installed, a load break tool is not required but recommended for continuity of service and safety during maintenance procedures.

Chapter 4
Power Supply Considerations

Capacitor Effects on Substations

In most cases, greatest efficiency of shunt capacitor use is achieved by placing capacitors out on the distribution line. In some cases, capacitors may have to be installed inside substations. This may be the case if the substation is located near a large industrial load, or the substation feeders are all underground where capacitors are more difficult and expensive to install.

The voltage improvement at a substation distribution bus with the substation transformer carrying full load, due to a shunt-connected capacitor installation at that location, may be calculated with the following formula:

$$\%\ \mathbf{Voltage\ Improvement} = \frac{\mathbf{KVAR_C * Z}}{\mathbf{kVA_t}}$$

Equation 10: Percent Voltage Improvement at Substation

Where:
Z = Percent transformer impedance
KVA_t = Transformer kVA rating, and
$KVAR_C$ = Total capacitor kVAR

Voltage rise at a substation is predominantly controlled by the reactance component of the transformer impedance. However, the impedance of most substation transformers is practically equal to the reactance. Thus, the percent impedance value that is provided on a substation transformer nameplate may be used to calculate voltage rise without appreciable error. If the transformer reactance is known, using the known value of reactance in lieu of total impedance will yield precise results.

The total voltage improvement brought about by the installation of shunt capacitors at a substation is the sum of the voltage improvements of all components of the system. When there are no regulators installed at the substation, the voltage improvement in the substation transformers is added to the voltage improvement on the distribution line to determine the total effect on the distribution line voltage. The voltage improvement due to the application of capacitors at a substation is neutralized at the distribution regulator within the operating range of the regulators.

The voltage rise on the distribution line or substation transformers, due to capacitors connected away from the substation out on the system, is not dependent on the system load. The capacitor's leading current flows through the lagging system reactance and creates the voltage rise. The benefits from this rise on a typical distribution system are usually less important than those from the reduction in system energy losses and the release (reclaiming) of kVA capacity for additional useful load.

Effects of Distribution Capacitors on Transmission Lines

In addition to the rise in feeder voltage due to a capacitor installation, the transmission circuit, as well as other substation transformers between the generating station and the capacitor location, will undergo some affects from the feeder voltage rise. Since the electrical characteristics of these parts of the system vary so widely with construction practices among power suppliers, their voltage rise cannot be readily reduced to chart form. When the total system impedance is known, the utility planner can easily calculate the voltage rise of any capacitor at any point on the system using the formulas and methods discussed previously for capacitors out on the distribution system.

Increase in Substation Capacity

An increase in power factor reduces the current drawn by a given load. The decrease in load current at a substation due to a capacitor installation on a feeder corresponds to released substation capacity. This released capacity is of particular value when the substation load approaches the substation design capability. Capacitors may also help to relieve overloaded substation conditions.

Chapter 5
Capacitors for Induction Motors

Switched Primary Shunt Capacitor Banks

Capacitors installed on primary circuits are commonly installed for the correction of the power factor of the system. These applications are usually accomplished without considering the benefits during starting and operation of large inductive motor loads.

Capacitors can be operated at voltages above their nameplate ratings for short times of no more than a few minutes, effectively increasing their available kVAR. The most common use of this short-term capacitor over-voltage capability is for helping to start large motors. This application also reduces the voltage drop during the starting condition, and this in turn reduces the voltage flicker condition impressed on all equipment connected to the feeder. For this purpose, a wye-connected capacitor bank is momentarily reconnected into a delta-connected, switched capacitor configuration which causes over-voltage on the capacitors in each delta leg by 1.732 times normal voltage (placing line-to-line voltage on a line-to-neutral unit). This over-voltage raises the effective kVAR to three times the capacitor's normal rating because:

$$\mathbf{kVAR} = \frac{\mathbf{V^2 * 2\pi f * C}}{\mathbf{1,000}}$$

Where:
V = Rated rms voltage
f = Frequency in hertz = 60 Hz for
C = Capacitance in farads

As switching methods become complex, motors may be controlled by Programmable Logic Controllers (PLC), which are small computers with rudimentary programming code for control used in manufacturing control systems. When a large motor's start button is pressed:

1. The PLC closes the primary switches on the capacitor bank and monitors capacitor inrush current or the system voltage to get full use of the capacitors, then
2. The PLC closes the motor contactor and monitors the motor starting current as the motor current falls from its starting high to near its running level, and
3. The PLC finally opens the capacitor primary switches to remove the starting capacitor bank from the circuit. All this happens within 10 to 20 seconds and allows a large motor to start with less impact on the distribution feeder.

Considerable coordination with the customer is required as the control is installed and tested.

Secondary Capacitors

Secondary capacitors are available for installation at a motor at somewhat higher costs than primary units. However, the benefits of the capacitor at the motor in decreasing starting and running current and the attendant losses are extended to the secondary and service wiring, as well as the supply transformer and the balance of the distribution system.

The motor starter is used to switch on the capacitor, which is wired directly to the large motor. The resulting load then behaves like a high power factor load on the system.

Certain limitations on the size of capacitor installations for various motor sizes and rotational speeds have to be imposed to avoid the possibility of self-excitation of the motor with its attendant problems. The maximum size of capacitor that can be used on an induction motor is one that is not large enough to augment magnetization current of the motor at any point on its starting and running curve. If this limitation is exceeded, the motor may run at a sub-synchronous speed and draw excessive current, which may damage the windings.

If the power source is disconnected momentarily, the motor will operate as an induction generator while it is coasting. Reconnection of the motor to the supply will have the same effect as closing the main switch on a generator that is not synchronized to the supply line.

Motor damage is possible when a motor is disconnected from its supply line. At the instant the motor is disconnected, current continues to flow in the circuit consisting of the motor winding inductance and the parallel connected capacitor. Resonance may occur at some point on the motor speed curve as the motor slows down. If this resonance occurs, voltage will rise on the motor windings and only the quality factor (Q) of the tuned circuit will limit the rise. The damping effect of the line resistance is no longer available to limit this voltage, and the motor insulation may be damaged.

Capacitor manufacturers can provide up-to-date information on suggested capacitor sizes for various motor sizes and loads. When capacitors are connected to motor terminals, the current flowing in the supply circuit is reduced. When the capacitors are connected on the motor side of an overload protective device, this device may no longer provide adequate protection if the protection device has been selected on the basis of the uncorrected full-load current. For effective protection, either the circuit breaker relay may need to be adjusted or a new fuse may need to be installed. The new fuse should have a rating that allows it to operate at a lower current consistent with the reduced line current.

A one-kVAR secondary capacitor at the load is equivalent to approximately a 1.04-kVAR capacitor installed on the primary, from the standpoint of reduction of losses in the transformer and on the service side of the installation. Secondary capacitors provide additional voltage rise through the service transformers and facility wiring. With this type of capacitor application where the load varies so widely, the secondary capacitor, which is switched with the load, is a practical and economical solution.

Series Primary Capacitors

Series-connected primary capacitors cause a voltage rise quite different than shunt-connected capacitors. Shunt-connected capacitors cause voltage rise when the leading current (I_c) they draw from the power source flows through the lagging impedance (X_L) of line conductors ($I_c * X_L$). Conversely, series-connected capacitors cause a voltage rise when the lagging load current (I_L) drawn by the inductive system impedance sources flow through the leading impedance (X_C) of the series-connected capacitors. ($I_L * X_C$). See Figure 17.

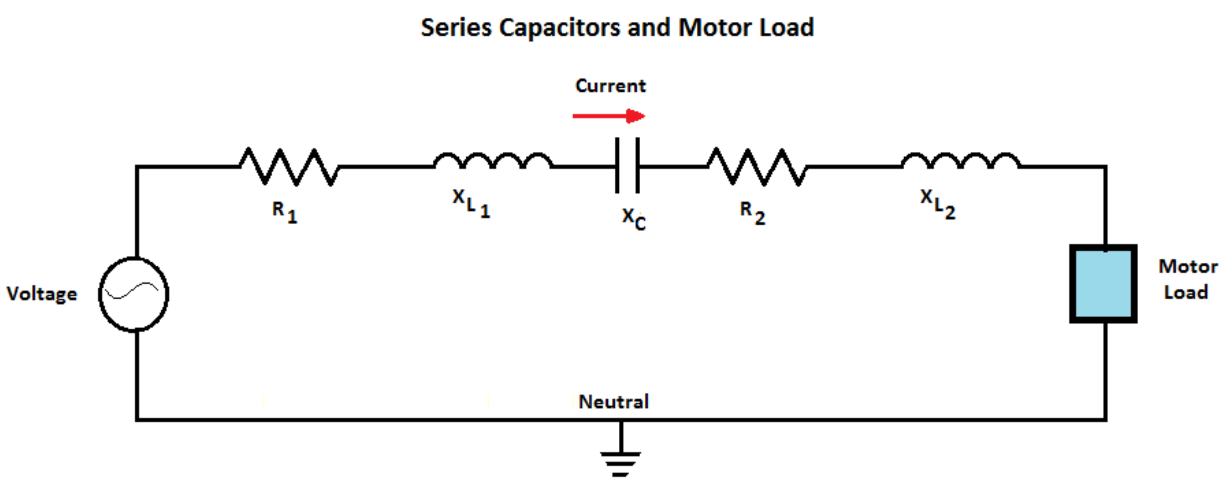


Figure 17

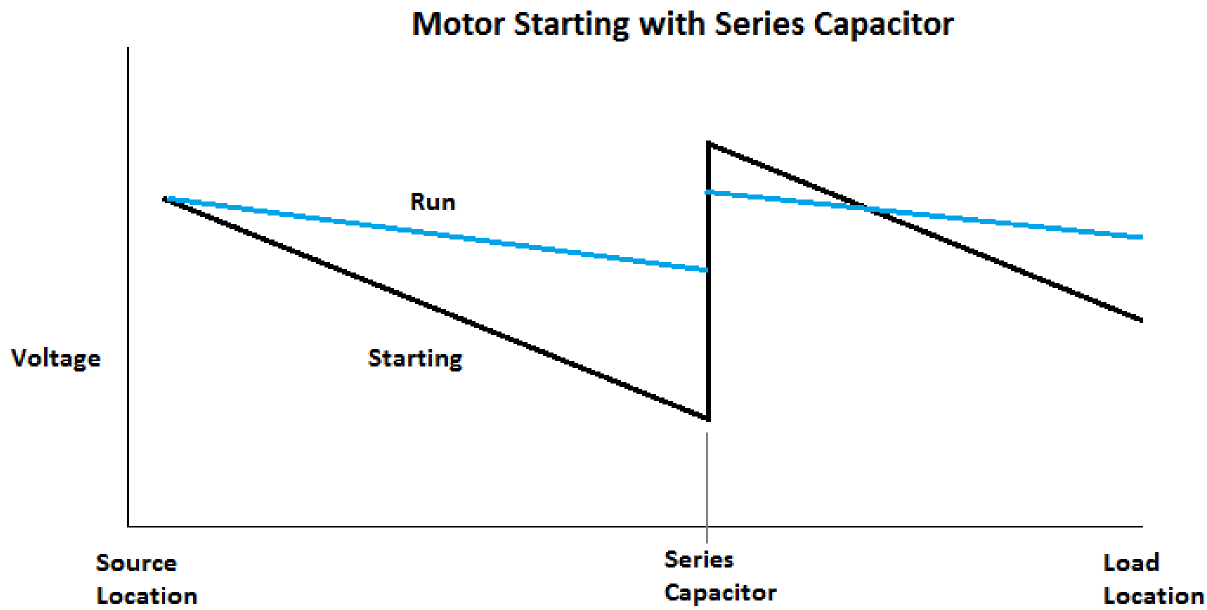


Figure 18

This rise through the series-connected capacitor is particularly useful in canceling voltage dips caused by large motors during starting, as shown in Figure 18.

A properly sized series capacitor could cancel the entire voltage drop of motor starting current and even add a voltage rise at the lower running current levels.

It sounds too good to be true. If series connected capacitors do all this, then why are most utilities not using them? Some utilities do use series capacitors, however, there are other inherent problems that usually outweigh the benefits.

The biggest problem is lightning. Since neither bushing of the capacitor is connected to ground, both ends have to be effectively protected with surge arresters. And because lightning current traveling down the phase conductor would pass through the capacitor and damage the capacitor, some current bypass method is also needed. Some utilities have tried installing surge arresters across the capacitor with limited success. Some utilities have developed solid state switching controls that either:

1. Switch the series capacitor into the circuit when a predetermined current level is sensed; or
2. Bypass the series capacitor when surge current is sensed.

Permanent series capacitor installations have proven to be impractical because of the considerable design problems. However, utilities have had some limited success with temporary series capacitor installations and have used them until major system improvements allow their removal.

Series capacitors are included here to provide a complete discussion of distribution capacitors.

Sizing Series Capacitors

In order to determine the size of a series connected capacitor to install on a system, the designer needs to know the system impedance at various points along the distribution feeder. A computerized fault current study can be used to provide the necessary impedance information. The magnitude of the feeder load current and the feeder's power factor also have to be known or calculated. The entire voltage rise appears and occurs across a series capacitor. A decision has to first be made to determine at what point on the system the lumped voltage rise is needed and whether nearby customers will be able to tolerate the resulting voltage fluctuations. Knowing the value of the voltage drop that needs to be cancelled and the prevailing feeder load current, the capacitive reactance necessary to accomplish the improvement can be calculated as follows:
The voltage drop through a feeder without the series capacitor connected is approximately:

$$V_{drop} = I_X * R_X * \cos(\theta) + I_X * X_L * \sin(\theta)$$

Where:
R_X = Feeder Resistance,
X_L = Feeder Reactance,
I_X = Feeder Current, and
θ = Feeder Power Factor Angle.

With a series capacitor installed, the voltage drop through a feeder becomes:

$$V_{drop} = I_X * R_X * \cos(\theta) + I_X * (X_L - X_C) * \sin(\theta)$$

$$V_{drop} = I_X * R_X * \mathrm{COS}(\theta), \qquad \text{when } X_L = X_C$$

Where:
R_X = Feeder Resistance,
X_L = Feeder Reactance,
X_C = Series Capacitor's Reactance,
I_X = Feeder Current, and
θ = Feeder Power Factor Angle

To avoid excessive voltage rise during normal load conditions and to avoid flicker during motor starts and stops, the capacitive reactance should be smaller than the feeder's inductive reactance. If the load power factor is near 100 percent, there will not be much capacitive rise. If the load power factor is leading, there will be a voltage drop. Voltage increases with series capacitors because the lagging load current produces a voltage rise through the leading capacitive reactance of the series capacitor. Voltage increases with shunt capacitors because the leading capacitive current drawn through the system by a shunt capacitor produces a voltage rise through the lagging conductor reactance.

$$\mathbf{X_C = \frac{1,000,000}{2 * \pi * f * C}}$$

Where:
f = Frequency in hertz, and
C =Capacitance in microfarads

Solving for Capacitance (C), we obtain:

$$\mathbf{C = \frac{1,000,000}{2 * \pi * f * \mathit{X_C}}}$$

And Capacitor kVAR is equal to:

$$\mathbf{kVAR = \frac{V^2 * 2\pi f * C}{1,000}}$$

Where:
V =rated rms Voltage of Capacitor units.

Summary

In this course we have reviewed the purpose of electrical capacitors on electric utility systems. The design and proper application of capacitors were covered. In addition the concepts of power factor correction and voltage improvement using capacitors was discussed.

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