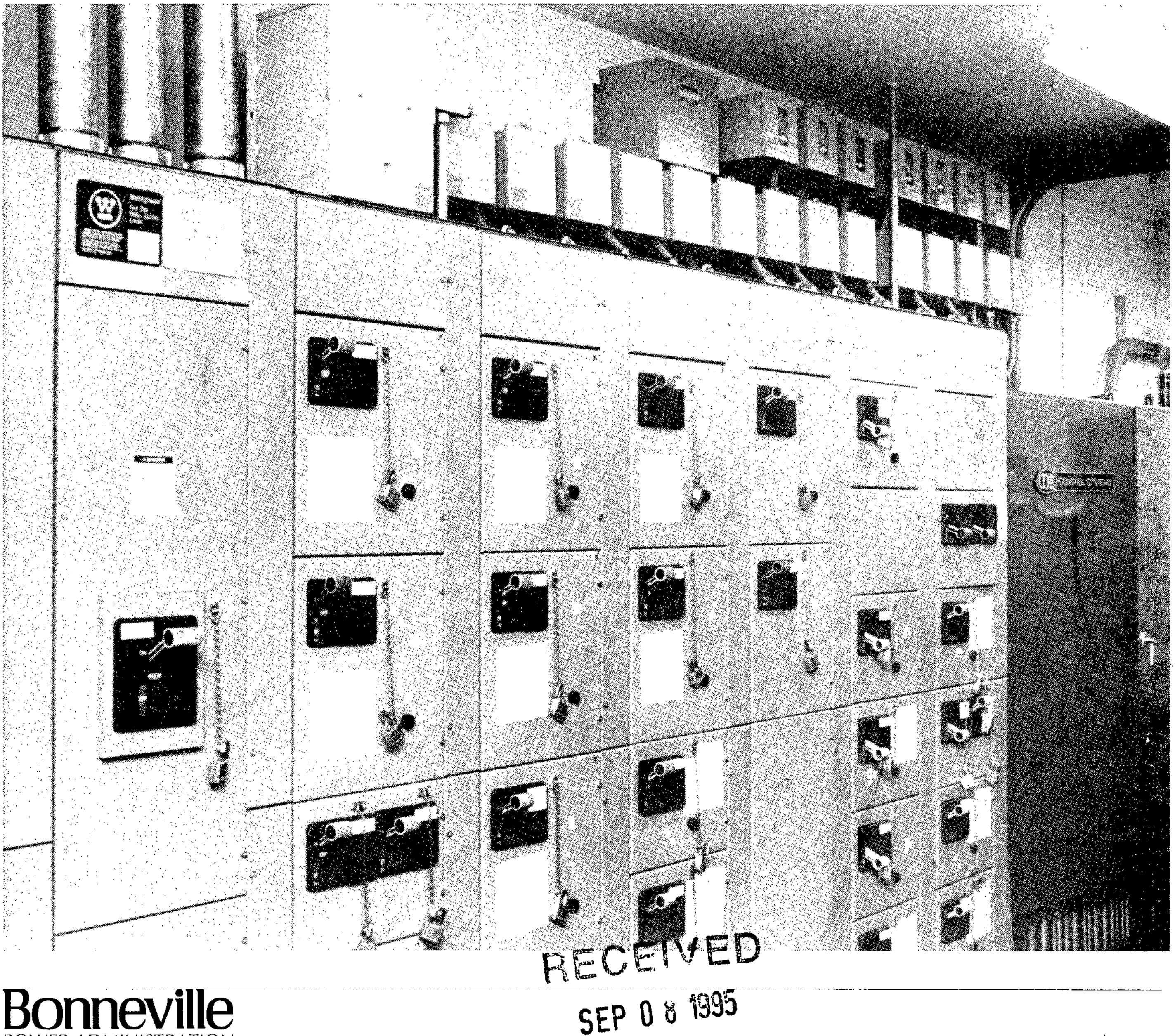
Industrial Power Factor Analysis Guidebook



Bonneville
POWER ADMINISTRATION

March 1995

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INDUSTRIAL POWER FACTOR ANALYSIS

GUIDE BOOK

March 1995

MASTER

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Submitted to:
Bonneville Power Administration
US Department of Energy

Prepared by:
Electrotek Concepts, Inc.

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REPORT SUMMARY

TITLE	**INDUSTRIAL POWER FACTOR ANALYSIS GUIDE BOOK**
SUMMARY	Improving system power factor can reduce reactive and active power losses for both industry and utilities through the addition of shunt capacitors. This Guide Book gives electric utility technical staff, industrial end-users, consultants and BPA employees a step-by-step method for evaluating the cost effectiveness of installing power factor correction capacitors in an industrial plant.
BPA PERSPECTIVE	Raising power factor to 95 percent and above is a proven way of increasing the efficient use of electricity by utilities and end-users. Economic benefits for end-users result from reduced power bills, lower line and transformer losses, and improved voltage conditions, while utilities benefit from released system capacity. Most of the cost savings for end-users are obtained by eliminating the power factor penalty charges. Improving the power factor to unity will ensure even greater economic benefits.
BACKGROUND	Power factor is a way of measuring the percentage of reactive power in an electrical system. Reactive power represents wasted energy-- electricity that does no useful work because the electrical current is out of phase with the voltage. Reactive power is used by inductive loads (such as, motors, transformers, fluorescent lights, arc welders and induction furnaces) to sustain their magnetic fields. Electric systems with many motors exhibit low power factors, increased conductor and transformer losses, and lower voltages. Utilities must supply both active and reactive power and compensate for these losses. Power factor can be improved by the addition of shunt capacitors. Capacitors act in opposition to inductive loads, thereby minimizing the reactive power required to serve them. In raising the power factor, shunt capacitors release energy to the system, reduce system losses, and ultimately decrease power costs.
OBJECTIVE	Provide utility customers and industrial end users a guidebook of procedures, methods and analysis tools which can be used to analyze how to improve the power factor in industrial plants.
APPROACH	The Guide Book was developed in three phases over a period of 2 years. In Phase I, industrial sites were selected, loads characterized and inventoried, and baseline data collected. In Phase II, shunt capacitors were purchased and installed, post-installation measurements were taken and a power factor improvement procedure was established. In Phase III, a guidebook with two case studies was written.

RESULTS

The process of installing capacitors is presented in a flow chart comprised of the following blocks: preliminary evaluation, design phase, capacitor selection, and capacitor installation. The preliminary evaluation determines if the application of capacitors is economical. It includes worksheets to evaluate the costs and benefits of the capacitors. If the capacitor application is economical, the user continues with the design phase, including plant survey and capacitor selection. The harmonic evaluation procedure is then applied. Finally, post installation measurements are required to determine if the installation process is complete or further modifications are needed.

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Executive Summary

Purpose

A high power factor is a key to obtaining the best possible economic advantage from electric power for both utilities and industrial end users. Industrial plants typically have a large number of motors, which draw a certain amount of current just to provide their magnetic fields. Therefore, besides the *active* power (measured in watts) that does the real work, the power delivery system must also supply *reactive* power (measured in vars). As shown in Figure 1, capacitors can help supply the reactive power closer to the loads, reducing the amount that must be supplied by the utility generation and, therefore, reducing the associated losses and voltage drop in the lines and transformers. The power system then provides mainly the active power (watts).

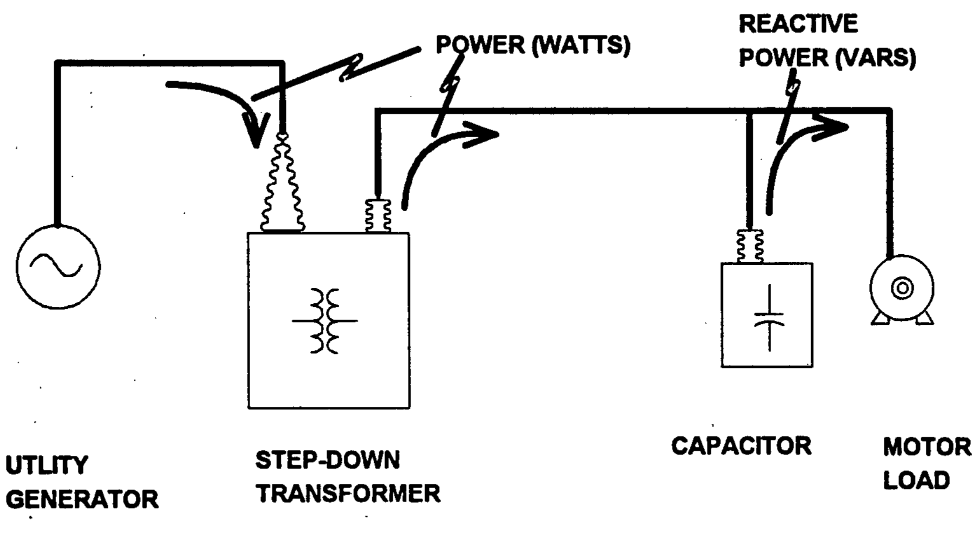


Figure 1. Capacitors Supply Some of the Reactive Power (vars) Needed by Motor Load Locally so that Losses and Voltage Drop in the Power System are Reduced

Capacitor installations are generally straightforward, but occasionally there will be problems that may discourage industrial users from installing them. This Guide Book has been prepared to assist industrial energy consumers in the selection of power factor correction capacitors and to help avoid some of the common pitfalls.

Cost/Benefit

Utilities frequently increase the monthly demand charge because of poor power factor. This penalty is to provide economic incentive for the customer to correct the power factor. The utility must provide excess capacity in transformers, lines, and generators to accommodate the poor power factor. To eliminate the power factor penalty, one need only place the capacitors at the main plant bus. However, this gives no additional benefit to the customer. Distributing the capacitors throughout the system decreases the losses in the cables and step-down transformers, and releases capacity in the main feeders to allow the addition of new loads without expensive additions to the plant electrical system.

It is common to distribute capacitors on motors throughout an industrial plant. This is a good strategy when capacitors must be switched to follow a changing load due to motors being switched. Depending on the size of the motors, it may be more economical to place the capacitors in larger banks at, or near, the motor control centers. Except for lightly loaded plants, the bulk of the benefit to losses and capacity release is accomplished in the feeder circuits leading up to the motor control centers. If the motors themselves are relatively small, placing the capacitors on the motor may lead to high unit cost ($ per kvar) due to fixed charges for labor and material.

Most of the economic justification for capacitors comes from the penalty that utilities assess. This is usually assessed for average monthly power factors less than 0.95. The lower the power factor, the more incentive there is. Reducing the losses contributes to the justification, but is generally not sufficient by itself to justify the cost of installing capacitors. Energy savings achievable from distributing the capacitors over the plant power system will generally be in the range of 0.5 - 1.5 % of the average kW demand. One of the additional benefits of placing capacitors farther out into the system is that they allow more of the natural resistance of the cables to contribute to damping of harmonics, thus reducing the effects of harmonic resonance. Of course, this is of little consequence in plants with compact, lightly loaded power systems.

At current price levels, the average installed cost of 480-volt capacitors is about $30 per kvar. Automatic power factor controllers or capacitors with harmonic filters cost at least twice this amount. Both tend to be applied on larger capacitors, 100 kvar and larger. The cost per kvar for small capacitors on motors can also be substantially higher because of labor and materials costs. Likewise, costs for large banks can be lower on a per kvar basis because of the economy of scale. When capacitors are to be installed at higher voltage levels (2400 V and up) the unit costs are generally much lower -- about $6 - $12 per kvar installed.

Harmonics

Harmonic resonance is probably the single largest problem facing industrial end users who install capacitors. Adding capacitance to the fundamentally inductive power system always creates at least one potential resonant frequency. In an industrial plant with many capacitors and many circuits, there could be several. Problems arise when sources of harmonics in the plant excite these resonances. These sources are on the increase because many of the energy efficient devices such as adjustable-speed motor drives that are being added to plant processes in large numbers are significant sources of harmonics. Studies (measurement and analysis) should be performed on most industrial plant capacitor installations for this reason. If the resistive loads are insufficient to damp out the resonance, failure of capacitors could result. If harmonic resonance becomes a problem, the two most common solutions are to change the capacitor sizes or convert some of the capacitors into filters by adding a reactor in series. It is sometimes possible to program automatic power factor controllers to avoid steps that cause high harmonic distortion. Harmonic problems may be easily found upon installation by monitoring the rms current in the capacitors while the load is running. Capacitor current levels exceeding 135% could be indicative of harmonic problems and should be evaluated by a harmonics specialist.

Case Studies

Two case studies are presented to demonstrate the principles described herein. For the first case savings were estimated to be more than $600 per month as the power factor was corrected from 78% to 96%. In the second case savings of over $1900 per month are achieved in correcting the power factor from 55% to 95%. Loss savings vary widely with plant structure. In the first case, losses account for 1% of the savings, while they account for 20% in the second case. The payback in each case was between 1.5 and 2.0 years. This is expected to be typical of many 480 V industrial systems with substantial motor loads.

1. Introduction

To obtain the best possible economic advantage from electric power, both the utility system and the end users should operate their facilities at high efficiency. A key to accomplishing this is to have a high power factor (near 1.0) throughout the system.

Certain alternating current (ac) machines appear to draw more power than they actually convert into useful work. This translates into extra current that the system must carry to supply the load. All connecting cables and transformers must carry this extra current, which results in inefficiencies and a higher cost of electricity. Most utilities offer rates to industrial consumers that encourage a higher power factor by reducing the rates for better power factor. This is commonly expressed in terms of a penalty for poor power factor that provides sufficient economic incentives for consumers to improve their power factor.

Any installation containing the following types of machinery or equipment is likely to have a low power factor. If a penalty rate is in force, end users may achieve a substantial savings on the monthly power bill by adding power factor correction capacitors:

- Induction motors of all types (the greatest industrial loads on utility systems)
- Power electronic power converters
- Power transformers and voltage regulators
- Welding machines
- Electric arc and induction furnaces
- Fluorescent and various types of arc lightning

Some typical power factors encountered in industry are listed in Table 1.1. These are selected data from ANSI/IEEE Std 141-1986 (Red Book) and from studies performed by the authors.

Table 1.1.
Typical Power Factors Encountered in Industry

Industry	Power Factor
Textile	0.65 - 0.75
Chemical	0.65 - 0.75
Machine Shops	0.4 - 0.65
Arc Welding	0.35 - 0.6
Arc Furnaces	0.7 - 0.9
Coreless Induction Furnaces and Heaters	0.15 - 0.4
Cement Works	0.78 - 0.80
Breweries	0.75 - 0.80
Foundries	0.5 - 0.8
Printing	0.55 - 0.7
Quarries	0.5 - 0.7

Many utilities begin to assess a power factor penalty when the power factor drops below 0.95 (lagging). The amount of the penalty is then proportional to the difference between actual power factor and 0.95. From Table 1.1, it is obvious that several classes of industries could be subject to substantial penalties. The cost of capacitors can be recovered quickly simply by eliminating the power factor penalty. Typical break-even times range from 1.5 to 2.0 years, depending on the size of load and how far the power factor is from the target value.

Once an end user decides that capacitors are an economical option, the main issues become the size, type, and location of the capacitors. The power factor metered by the utility can be corrected simply by placing all the capacitors at the service entrance. However, this does nothing for losses and freeing up capacity farther down into the plant. By dispersing the capacitors throughout the plant, end users can take optimal advantage of the benefits of power factor correction. Not only is the power factor penalty eliminated, but energy demand is reduced by reducing the losses and capacity is released so that the system may be expanded (new loads added) without increasing the size of existing cabling.

This Guide Book is the result of an 18-month study of power factor correction of industrial loads. It describes procedures, methods, and analysis tools that industrial power consumers can use to systematically improve the power factor and efficiency of their plants. Two case studies are documented. Software has also been developed that will enable users to perform many of the procedures described in this book more easily. Some short-cut methods are described, but short-cut methods are not applicable to all situations. The software, designed for the Microsoft®

Windows™ 3.1 operating environment, is intended to make the process as painless as possible. Economic costs and other benefits of power factor improvement are explained.

The Guide Book provides both introductory and advanced material on power factor and energy efficiency to meet the diverse needs of a wide spectrum of readers. It describes the procedures to follow for correcting power factor and avoiding the common pitfalls. Among other things, the Guide Book explains the following:

- How to tell if your plant could benefit from capacitors.
- How to select capacitor schemes to eliminate the power factor penalty and minimize losses.
- How to perform detailed plant surveys to collect sufficient data to determine where to put capacitors.
- Why the power system must be built with extra capacity to supply the power.
- How reactive power contributes to extra losses.
- Why the power system must be built bigger to supply the power.
- How capacitors, synchronous machines, static (adaptive) power compensators correct the power factor.
- When to use switched and fixed capacitors.
- How and when capacitors contribute to harmonic distortion problems and how to predict this.
- How capacitors can fall prey to harmonics and switching transients and what to do about it.

2. Overview of Power Factor Concepts

Beer Analogy

Power factor often seems like a complicated subject because of the mathematics used to describe it. However, the basic concept is actually quite simple: Power Factor essentially measures the percentage of the current that is actually doing useful work. One of the simplest ways to understand this is to compare it to beer and the size of mug needed to hold it.

Consider the pair pictured in Figure 2.1. The individual on the left has purchased a brand that has a lot of foam and needs a much larger mug to hold it. This is analogous to *poor* power factor because most of the volume of the container is wasted. The gentleman on the right has made better use of the capacity of his container by purchasing a brand that does not foam as much. This gives him the choice of either choosing a much smaller mug to hold the desired quantity, or getting more quantity out of a mug of the same size.

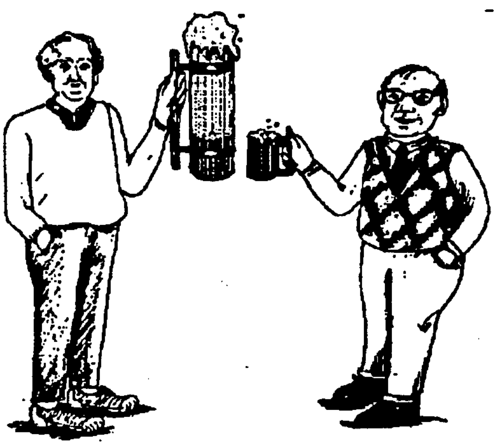


Figure 2.1. The mug must be sized to hold both the foam and the beer.

Electrical current also contains some "foam" - a portion which does no useful work because it is out of phase with the voltage. And, just as the mug must hold the foam, the electrical system must be sized to accommodate the additional current. This "foam" is called *reactive power.*

Capacitors Reduce the Reactive Power

Some types of electrical loads demand more reactive power than others. As shown on the left side of Figure 2.2, most motors are "pigs" in this regard. The owners of the motor pay for non-productive current through increased equipment costs (larger cables), higher losses (cable and transformer heating), and monthly utility surcharges. The alternative is to reduce the amount of unproductive current flowing through the meter and feeder circuits. This has been done on the right of Figure 2.2 by adding a capacitor close to the motors. The capacitor reduces the current required, permitting smaller cables and the addition of a new motor. Cable heating is reduced and the utility surcharge is eliminated.

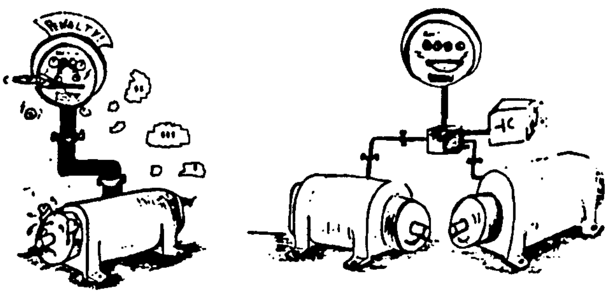


Figure 2.2. Capacitors reduce load current, which increases system efficiency and capacity.

How Capacitors Work

Capacitors are two parallel metal plates separated by insulation (Figure 2.3). In commercial capacitors, the plates are generally thin metal foil separated by a sheet of polymer material. These are tightly wound into a compact roll, placed in a hermetically sealed can, and impregnated with an insulating fluid. The greater the total area of the plates, the greater the capacitance.

As a battery is connected to the two plates as shown, a current flows until the plates of the capacitor are charged up to the same voltage of the battery. The current is initially limited only by the resistance of the battery and wires connecting the battery to the capacitor. Therefore, it starts off as a large value and tapers off to zero as the capacitor charges. This is exactly the opposite of what happens with an inductive device, such as in motors.

The capacitor doesn't actually *consume* the energy it takes from the battery, it just *stores* it in the form of opposite charges on the two plates until it is discharged. In an alternating current circuit, this charging and discharging is repeated with each half cycle of voltage. This results in a current that *leads* the voltage in phase angle by 90 degrees. Again, this is exactly the opposite of the inductive component of the current going into motors, which *lags* the voltage by 90 degrees. The capacitor stores up the energy used for magnetization of the motor over each half cycle and gives it back at precisely the time the motor needs it. This gives capacitors the physical properties needed to supply the inductive portion of the current required by the motors near the motor site.

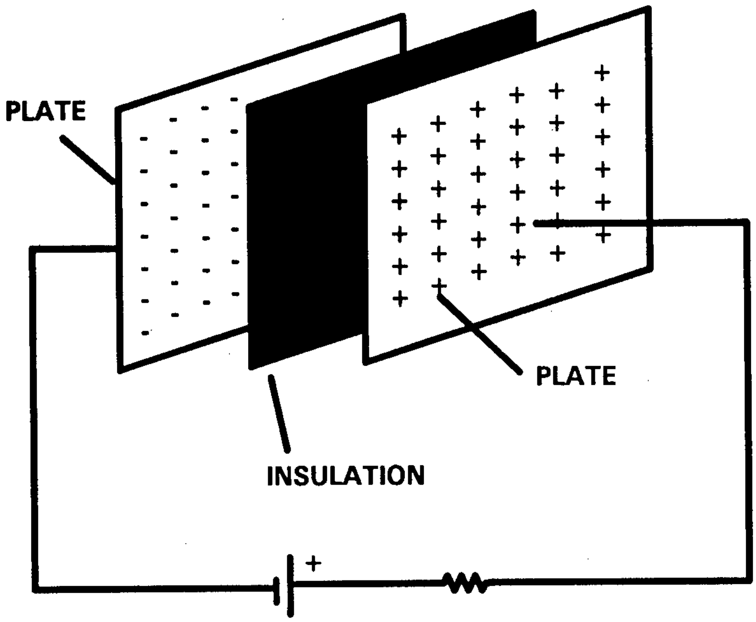


Figure 2.3. Physics of Capacitors.

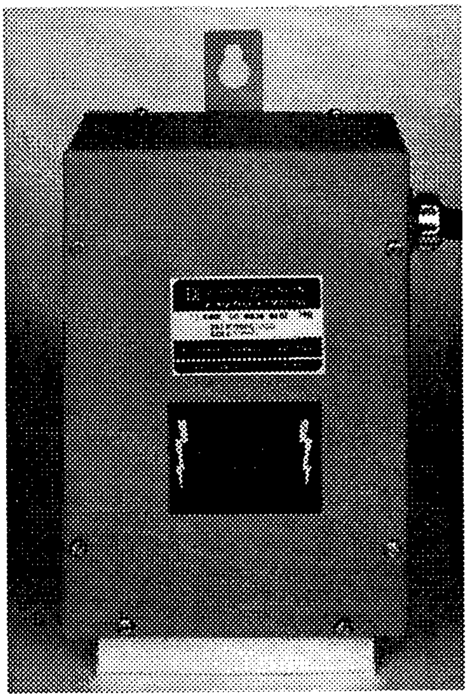
Typical Capacitor Configurations

Capacitors come packaged in a variety of ways. Figure 2.4 shows common configurations for 480-volt capacitors that would typically be found in industrial facilities:

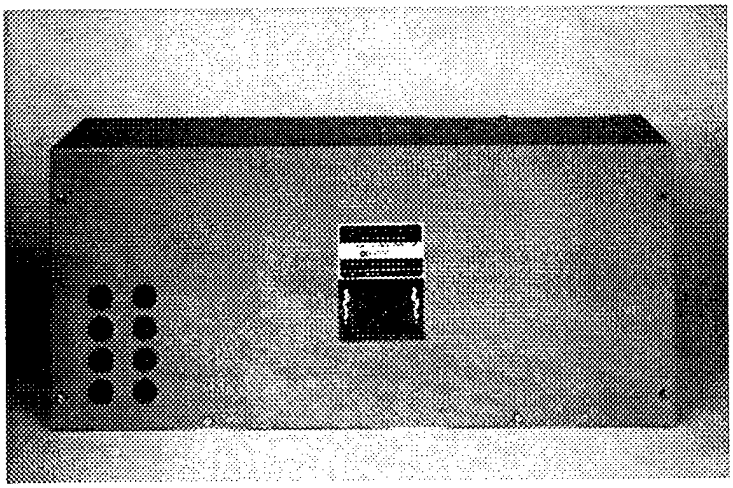
(a) A small unit (7.5 kvar) that is commonly mounted on a motor.

(b) A 50-kvar unit packaged in a single box for convenient mounting. Note the lamps for indicating blown fuses.

(c) A large unit consisting of two 75-kvar capacitors mounted in a rack.



(a)



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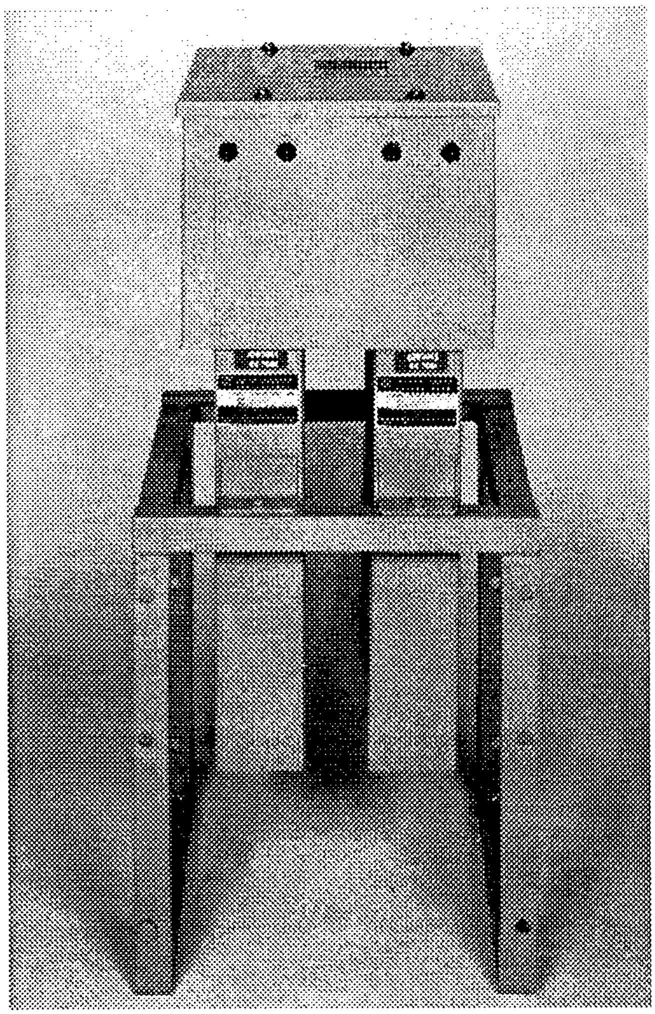


(c)

Figure 2.4. Typical 480-volt Capacitor Configurations (Courtesy Square D Corporation)

3. Capacitor Application Procedure

The overall capacitor application procedure is illustrated in the flow chart in Figure 3.1. The next few chapters are devoted to providing more detail on each major section of the flow chart.

The first step is to perform a preliminary evaluation to judge whether the application of capacitors to improve the power factor is likely to be successful and economical. First, perform a preliminary plant survey and economic screening. This will include such things as analyzing the monthly bills to estimate the amount of capacitors needed and the savings that might be achieved. Also, measure several convenient bus voltages and load currents with an instrument capable of measuring true rms values and detecting harmonic distortion. Scan the facilities looking for such things as adjustable speed drives that might suggest harmonic problems for the capacitor installation. If there is a significant potential for harmonic problems, plan on performing some sort of harmonics study and include this cost in the economic screening.

Next, we enter the design phase of the process. The first step in this phase is to perform a detailed plant survey, monitoring the loads on major subfeeds within the plant. This information will be useful when determining where to locate capacitors to achieve the optimal loss reduction and released circuit capacity. The entire plant can be surveyed including individual motors. It may be a good idea to document the electrical components in the plant if this has not been done before. However, it is a time-consuming process and it is usually sufficient for power factor correction purposes to monitor only the loads going into the major motor control centers and other larger subpanels.

Next, select an economical capacitor scheme that meets operational constraints such as harmonic distortion and voltage. This can be the most difficult part of the process. While most cases will be relatively straightforward, some will require modifications to meet the constraints. Generally, the most economical installation is acomplished with all fixed capacitor banks distributed proportionately to the load. However, leaving the capacitors on continuously may result in the voltage being too high at times when the system is lightly loaded. The usual upper voltage limit at no load is 110%. If the constraints are not met, make some changes and try again. Typical changes include increasing or decreasing capacitor sizes, adding switches on some or all of the capacitors.

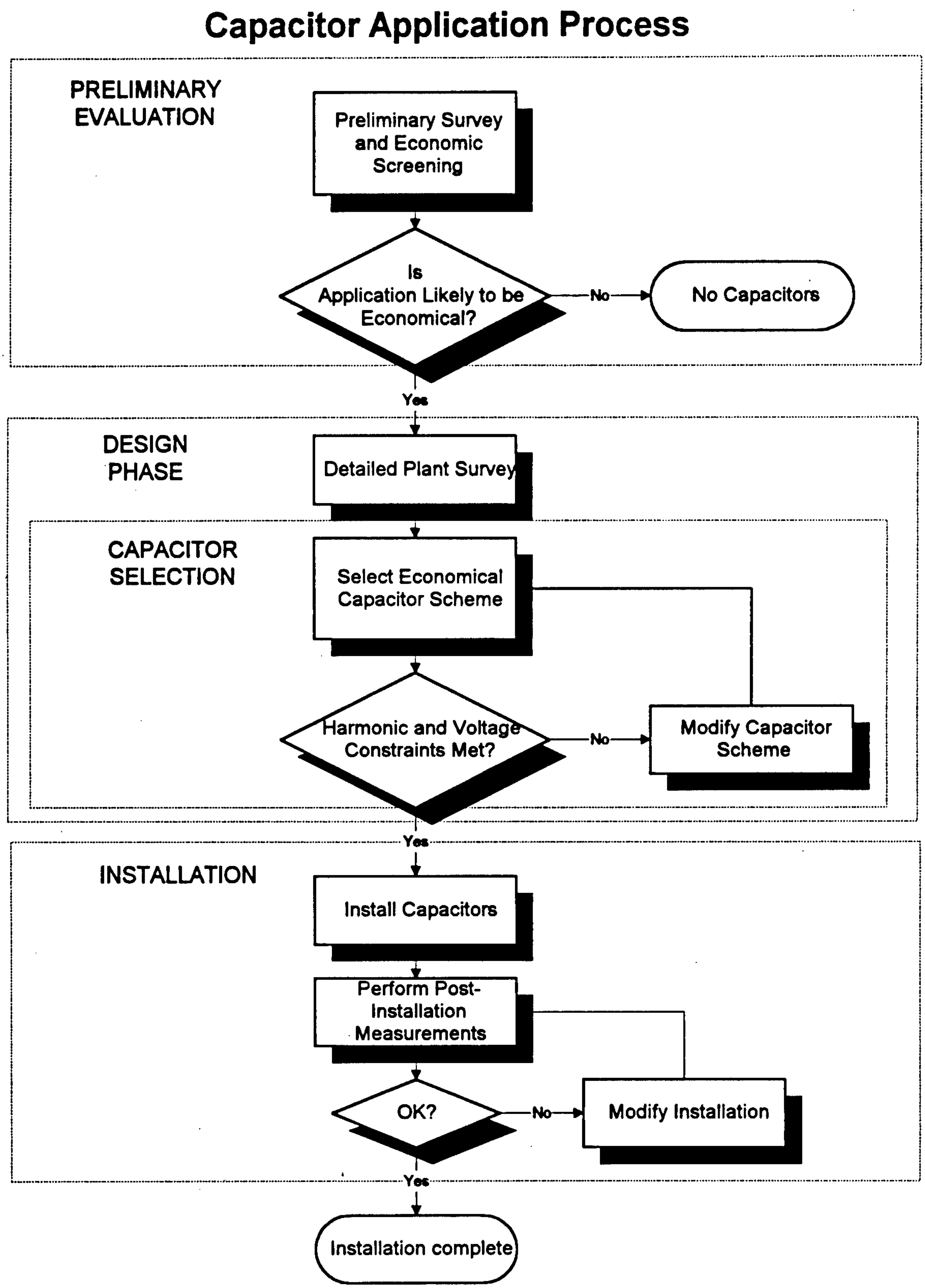


Figure 3.1 Basic Capacitor Application Process Flowchart

Harmonic limits typically are 5% total harmonic distortion (THD) in the voltage and 135% rms for the capacitor currents. Filters may have to be added to keep the harmonic distortion within limits.

Finally, install the selected capacitor scheme. After the capacitors are installed, measure the voltages and the currents at various load conditions to confirm desired operation. If there are unexpected problems, it will be necessary to modify the installation. Of course, you want to avoid this because it is generally very costly to retrofit modifications to an installation after it has been completed.

4. Preliminary Evaluation

The preliminary evaluation is performed to determine if the application of capacitors is likely to be economical. Figure 4.1 shows a typical flow chart for this procedure.

The first step in this procedure is to collect monthly billing data and make some preliminary measurements. The data collected are used for the Economic Screening Worksheet in the second major step of this procedure. The monthly billing data are used to estimate how many capacitors are needed and what the likely savings will be. The measurements are used to get a rough idea of how heavily loaded the plant cables and transformers are so that the loss savings can be better estimated. The measurements are also used to help identify potential harmonic problems.

The next step is to work through the Economic Screening Worksheet. This is a series of four worksheets that are used to determine the approximate savings possible through power factor penalty reduction and loss reduction. Then the savings are compared with the probable cost of capacitors to determine if it is economical. The worksheets are explained in detail later in this chapter.

On the first pass, assume that you will be able to achieve a simple capacitor installation with low capacitor costs. Requesting a bid from capacitor vendors will give you a good idea of what the costs will be. If even a simple installation is not economical, then it is probably reasonable to abort the process at this point because it is unlikely that a capacitor installation will be economical unless much lower cost capacitors can be acquired. Fortunately, in most cases where there is a significant power factor penalty, capacitors will be economical.

After doing this, you should evaluate contingencies that might increase the cost of the installation. One of the most important contingencies is harmonic problems. A substantial percentage (perhaps 20%) of industrial plants cannot operate capacitors without some careful attention to the harmonics. While this means that most industrial plants will not have problems, it is wise to prepare for that possibility in the initial evaluation. Scan the plant for large sources of harmonics such as adjustable-speed drives and arc furnaces. Also, the instrument used to make the preliminary measurements should have the capability to report harmonics as well. Assume that a harmonics study will be required if any of the following conditions are found:

1. Harmonic-producing devices are a large portion of the load,

2. The main bus voltage distortion is greater than 2%,

3. The distortion of the total plant current is greater than 10%.

Include the cost of studies and harmonic mitigation in the cost of the capacitors and repeat the economic screen. If the installation is still economical with these considerations, you may proceed with reasonable confidence that an economical and effective capacitor installation can be achieved. If the potential installation is no longer economical with the harmonic considerations, you have two options:

1. Abandon the process if you feel certain that harmonic mitigation will be needed and not economically justifiable.

2. Proceed into the design phase with the hope that the harmonic problems will not severely impact the installation, which happens frequently, and with the understanding that it may not be possible to find a capacitor scheme that is economical according to your criteria.

Many times, only a fraction of the capacitors are affected by the mitigation technique and the total installation costs are increased only marginally. Also, it is sometimes possible to achieve mitigation without resorting to expensive means as we will explain with respect to the Design Phase of the overall procedure.

Preliminary Evaluation

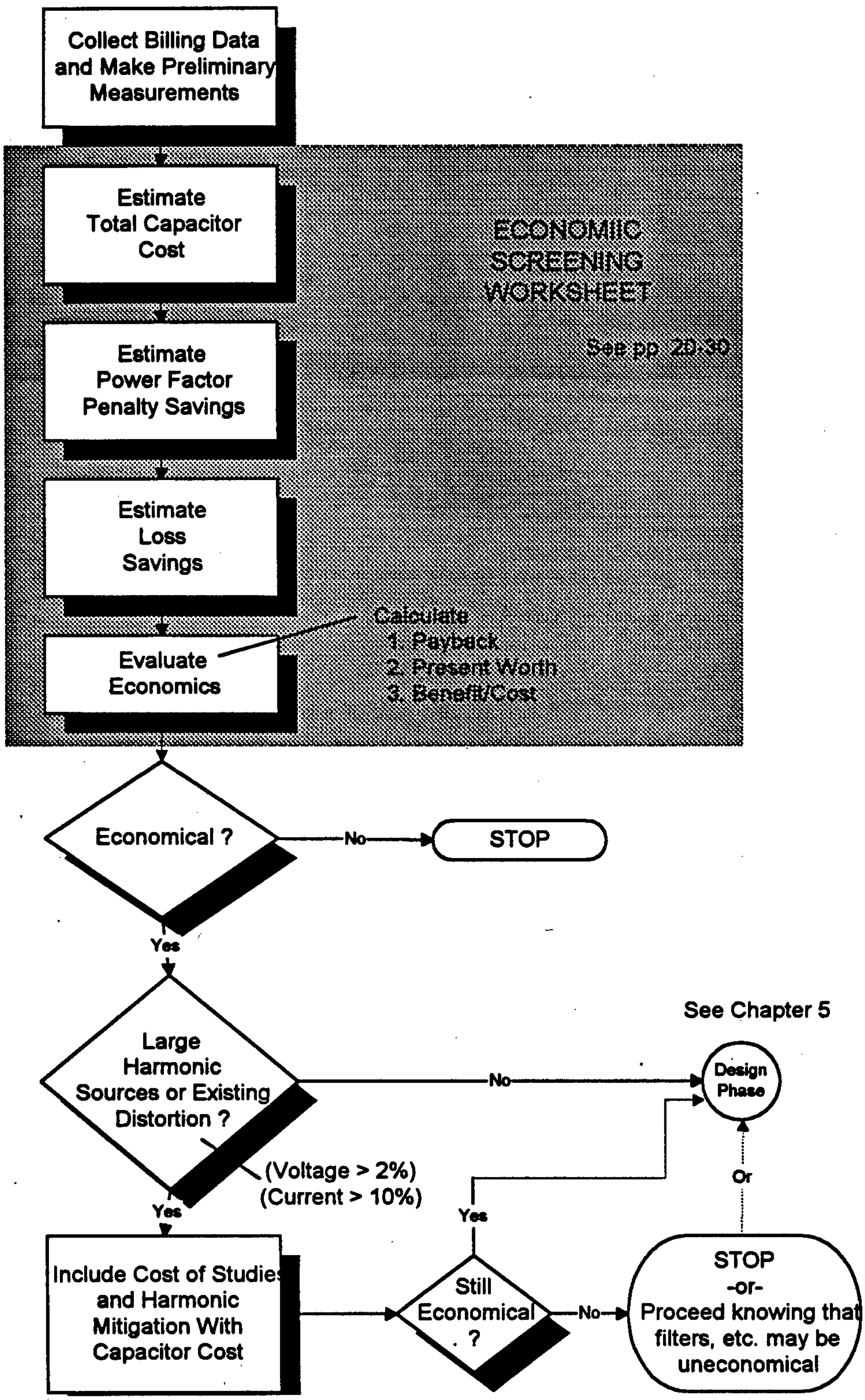


Figure 4.1 Flow Chart for Preliminary Evaluation

Preliminary Measurements

Measure the currents on several of the more significant feeds within the plant. Compare the current measurements to the ampacity of the cables and estimate a typical loading factor for the plant's cables. The ratio of measured current to ampacity is the cable capacity factor needed for the Loss Savings Worksheet.

If the plant has step-down transformers on the load side of the utility meter, the average load kVA flowing through these may also have to be determined. Transformers can account for a large percentage of the losses. This can be done by measuring the rms current flowing into the transformer from either the primary or secondary side of the transformer, depending on which is the most convenient. Remember to compare your measurement with the rated current on the side you measured. The formula for computing the three-phase kVA is

$$kVA_{3-phase} = \sqrt{3}\, kV_{line-line}\, I_{line}$$

where the line-line voltage is given in kV (rms) and the current, I, is the rms line current reading on the same side of the transformer.

Consider only transformers for which capacitors will be placed on the secondary side. For example, it is not common to place capacitors on 120/208 circuits, so these transformers would not be included. Capacitors don't help losses unless they are placed on the secondary side to reduce the current.

Measure at least the main bus voltage and the total load current with an instrument capable of measuring both total harmonic distortion (THD) and true rms values. It is not uncommon to measure bus voltages with approximately 1% distortion. Thus, a reading in that range is not necessarily an indication that there are harmonic sources to be concerned about. However, if the voltage at the main bus is distorted by more than 2%, there is a strong possibility that there are significant harmonic sources in the area that could impact a capacitor installation. This is not to be confused with the 5% upper limit set by some standards. While it is often acceptable by standards to have a voltage distortion of as much as 5%, lower values of distortion can cause problems with capacitors if the conditions are right. In fact, there is a possibility of problems for low values of voltage distortion less than 2% if the system gets into resonance, particularly, if the predominant harmonics are higher than the fifth. At this point in the process, we are simply interested in determining if there is sufficient cause to include harmonic studies in the cost justification and we are looking for symptoms of harmonic sources in the vicinity of the plant, either within the plant or in neighboring plants.

Likewise, the total plant current having a significant distortion (10% or more) indicates the presence of harmonic sources that could conflict with capacitor installation.

If there are any existing capacitors, a good predictor of potential harmonic problems is the current in the capacitors. If the rms current exceeds 120-130% of the rated capacitor current, it is likely that there are significant harmonic sources. At this point, we are not necessarily interested in characterizing the sources, but only wanting to know of their existence so that we can take them into account in the economic screening by assuming extra costs will be incurred.

Interpreting Utility Bills

Utility bills must be analyzed to obtain the data necessary for determining the total amount of capacitance needed and the savings possible. Preferrably, all bills for the previous year should be collected in order to observe seasonal variations and long term trends in electric consumption. Usually, you will be more interested in the typical high-usage months. The key data are maximum demand, power factor, typical energy usage, and power factor penalty or demand charge. Use the highest demand month unless there is reason to believe that it is an anomaly and will not be repeated. You may want to plot out these factors for a year of usage, or more, to better understand the trend in the load.

Industrial end user bills generally have two main parts:

1. The energy charge,

2. The demand charge.

There are also taxes and other miscellaneous charges, but these do not have a significant impact on the economic justification of power factor correction capacitors.

The energy charge is determined by multiplying the number of kilowatthours (kWh) of energy consumed in the month times the energy rate ($/kWh). The demand charge is more complicated. It is typically based on the peak kW demand over a given 15-, 30-, or 60-minute interval during the month. This is nominally multiplied by the demand charge rate ($/kW). In addition, many utilities assess a penalty to the demand if the power factor is lower than a predetermined value (typically 0.95 in the Pacific Northwest). There are two common formulae in use for determining the billed demand when the power factor, PF, is lower than 0.95, lagging:

$$kW_{Billed} = kW_{Actual} \cdot \left(\frac{0.95}{PF}\right)$$

or

$$kW_{Billed} = kW_{Actual} \cdot (1 + 0.95 - PF)$$

Both of these are applied only when PF is less than 0.95, lagging. Otherwise, the billed demand is the same as the actual demand.

The difference between the amount paid for the billed demand and the amount that would be paid for the actual demand is often termed the *power factor penalty*. This quantity is generally responsible for the bulk of the justification for capacitors:

$$Penalty = (kW_{Billed} - kW_{Actual}) \cdot \$ / kW$$

Some billing schedules are more complicated than this. For example, it is also common for the demand charge to be included with the first block of energy, which is charged at a different rate than the remaining energy usage. Compute the bill with the normal power factor, then recompute the bill assuming the power factor has been corrected sufficiently to avoid an extra charge. The difference is the power factor penalty.

You do not necessarily want to use the actual demand recorded on the bill to determine the amount of capacitors. Many loads peak sharply a few times per day for a brief time period then settle down to about 80% of that value. Determining the amount of capacitors based on the absolute peak will generally result in too many capacitors. If you, or your utility, have demand interval data, use that to determine the average demand at heavy load. You may also use a value from the preliminary measurements taken during a heavy load period. You may choose to use the peak demand during the preliminary screening. If that shows that the installation is likely to be economical, then it will certainly be economical for fewer capacitors. Then, when you design the actual installation, use the average maximum demand determined from the detailed plant survey.

The power factor used in billing is generally an average power factor determined over the entire month, although a few utilities bill interval-by-interval. The usual procedure for determining the power factor is to meter the kilovarhours (kvarh) as well as the kilowatthours (kWh). This may be done by two separate meters or may be contained within one electronic meter. The kvarh are then combined with the kWh to obtain an equivalent kilovoltamperehours (kVAh):

$$kVAh = \sqrt{kWh^2 + kvarh^2}$$

The average power factor is then:

$$PF = \frac{kWh}{kVAh}$$

The kvarh meter is usually "detented" so that it only records lagging vars; that is, the vars drawn by motors. No credit is given for leading vars.

[*It should be noted that many utilities are now considering billing for kvarh similarly to kWh. Existing meter technology can separately track leading and lagging kvarh. This provides the opportunity to have flexible rate structures to create more incentives for industrial end users to control var consumption and production.*]

Economic Screening Worksheet

The economic screening worksheet is actually made up of four smaller worksheets. The worksheets follow the sequence in the flow chart in Figure 4.1. Line-by-line instructions follow in the next section.

The worksheets assume that the capacitors will completely eliminate the monthly power factor penalty and that they will be distributed throughout the plant in such a manner that the maximum possible loss savings is achieved. Then, using the desired breakeven time period and interest rate (selected by the purchaser), the annual power factor penalty savings and loss savings are converted to their equivalent present value for comparison with the capacitor installation cost. To be economical, the equivalent savings must exceed the cost of the capacitors.

Loss savings are included in the worksheet. Losses are estimated by summing estimates of the transformer and cable losses. Transformer losses are straightforward. The impedance can be determined from the nameplate and the current magnitude can be determined by measurements or existing panel meters. The cable losses are difficult to accurately quantify because cable sizes and lengths vary widely. The cable loss formula used in the worksheet is based on the empirical observation that with cable sizes and lengths typical of industrial systems, cable losses would be about 2% if all cables were operated near rated cable ampacity. This was determined by calculating the cable losses for the two example cases in this project assuming that the cables were loaded to ampacity. Then the losses are referred to the total load that this current would yield. In both cases, the losses would have been approximately 2%. Thus, this was chosen as a round number for estimating purposes. Multiplying this by the square of the actual average per unit loading yields a number close to the actual losses.

These assumptions make the estimated cable loss savings very approximate, but a more precise calculation would be too cumbersome for a hand calculation and require a detailed plant survey. At this point in the process, we are interested only in ballpark estimating numbers.

The worksheet is designed to be used with data that can be obtained through relatively simple measurements. The percent loading of the cable is designed to be estimated from rms current measurements of the main feeder cables. The recommended procedure is to measure the average current flowing in several important cables and compare that to the ampacity of the cable. The ratio of average current to ampacity is entered into the Loss Savings Worksheet on line (b). Obviously, some cables will be more heavily loaded than others. The worksheet is intended to use an average loading level for the plant. It should be possible to make this judgment by determining the currents in a few of the main cables.

Transformers *within* the plant should also be accounted for in the loss calculation. However, the facility service entrance transformer should not be included if it is on the utility side of the meter because reductions in transformer losses would not benefit the end user. Include only those stepdown transformers on which *load-side capacitors* will be installed. A primary-side capacitor will not reduce the transformer's currents and, therefore, does not affect the losses. The average kW losses are estimated for each transformer that fits the criteria and then multiplied by 730 (avg. no. of hours in a month) to determine the monthly kWh losses.

Capacitor Costs Worksheet

(over)

Capacitor Costs Worksheet

Determine the approximate amount of capacitance needed to correct the power factor to the desired value.

a. Average Power Factor, *PF*:___________
(From utility bill; If greater than desired PF, no capacitors needed)

b. Compute $\sqrt{\frac{1}{PF^2}-1}$ .... =___________

c. Desired Power Factor, $PF_{Desired}$:_________________

d. Compute $\sqrt{\frac{1}{PF^2_{Desired}}-1}$ $(= 0.3286\ for\ 0.95\ PF)$ .... =___________

e. Subtract (b - d) ....=___________

f. Max Metered Demand from bill .... ___________kW

g. Capacitors Required (e x f)....................................... =___________kvar

h. Assumed Cost/kvar .... ___________$/kvar

i. Capacitor Cost (g x h) .... = $___________

j. Study Cost .... $___________

k. Total Capacitor Cost (i + j).................................... = $___________

Capacitor Costs Worksheet Instructions

This worksheet determines the amount of capacitors needed to correct the power factor to 0.95 and estimates the cost of the capacitor installation. Line-by-line instructions are:

a. Inspect the utility bills and insert the average power factor for a typical high demand month. If greater than the desired power factor, no capacitors are needed.

b. Use the power factor (PF) and compute the formula shown.

c. Enter the desired power factor.

d. Compute the formula using the desired power factor. To correct to .95 power factor, the value will be .3286

e. Subtract line (d) from line (b).

f. Insert on this line the maximum metered demand, kW, when the plant is heavily loaded.

g. Multiply lines (e) and (f) and put the result in line (g). This is the approximate amount of capacitive kvar needed to correct the power factor. If line (a) is the average monthly power factor, this is the average amount of capacitors that must be on line. More capacitors may be required if they are to be installed on intermittent duty motors.

h. Insert on this line the estimated installed cost of the capacitors. A typical average value for 480 volt capacitors as of this writing is $30 per kvar. If you anticipate using automatically switched capacitors or are required to use a filter, you might assume for a portion of the capacitors that the cost will be at least double the base cost for estimating purposes. Capacitors at higher voltage levels such as 4160 V or 12.47 kV are typically purchased and installed for $6 - $10 per kvar. A vendor can supply a more precise quotation.

i. Multiply line (g) by line (h). This is the estimated cost of the capacitors.

j. Include anticipated study costs on this line. On the first pass through, you may choose to ignore this. Then, if there are significant harmonic sources or existing distortion, come back to this worksheet, add in the estimated study cost here, and recompute the economics. Harmonic studies range from $3000 to $7000 for smaller industrial plants. Studies for large plants might typically be $15000 and up.

k. The sum of lines (i) and (j) is the Total Capacitor Cost used in the Economic Evaluation Worksheet.

Loss Savings Worksheet

Cable Loss Estimate

a. Monthly energy usage: .... ____________kWh

b. Multiply (a) by average cable capacity used ....= ____________kWh
(from measurements; typically 0.2 - 0.4)

c. Multiply (b) by .02 (empirical cable loss factor).............= ____________kWh

d. Divide (c) by the average power factor, PF (c / PF) .....= ____________kWh

This (d) is a rough estimate of the monthly kWh losses in the cables for a typical industrial facility.

Transformer Loss Estimate

For each transformer compute an estimate of the total monthly losses by filling in the table. Sum all transformers to get a total loss (right hand column).

Transf.	Rated kVA (a)	Aver. kVA (b)	per unit Resistance (R)	Loss = $730\ b^2R/a$ kWh
1	________	________	________	________
2	________	________	________	________
3	________	________	________	________

e. Monthly Losses:__________

f. Total losses: (d) + (e) .... = ____________kWh

g. Energy Rate .... ____________$/kWh

h. Total Cost of Monthly Losses: (f) x (g)................. = $____________

i. Fraction Saved by Capacitors: $\left[1-\left(\frac{PF_{old}}{PF_{new}}\right)^2\right]$ = ... ____________

j. Monthly Loss Savings (h) x (i) .... = $____________

Loss Savings Worksheet Instructions

The purpose of this worksheet is to estimate the amount of energy savings possible by distributing the capacitors over the plant in such a way as to minimize the losses.

a. From the utility bill, enter the monthly energy usage in kWh.

b. Multiply the amount on line (a) by the cable capacity factor determined by the preliminary measurements. This is the ratio of the average rms current in the main cables to the ampacity of those cables. This is typically somewhere in the range of .2 to .4, but could be higher or lower depending on the specific plant.

c. Multiply the amount on line (b) by 0.02. This is based on an estimate that the typical plant will have 2% losses in the cables if the cables are loaded to full ampacity. If you have data that indicate that your plant is substantially different, use a multiplier based on that data.

d. Divide the result on line (c) by the average power factor from the Capacitor Costs Worksheet. The result is a rough estimate of the monthly kWh losses in the cables. (We will account for the fraction saved by the capacitors in line (i).)

Transformer Loss Estimate: Follow instructions on the worksheet. Fill in the table for each transformer being considered. Use additional paper if necessary. Consider only those transformers that will benefit from power factor correction. Exclude transformers on the utility side of the meter and transformers that will not have capacitors installed on their secondary circuits. The table computes the monthly kWh losses expected in the transformers. The average kVA is determined from the preliminary measurements by multiplying the measured rms current by the voltage, in kV, and then by 1.732 (square root of 3).

e. Sum the kWh values in the rightmost column of the transformer table.

f. Sum the transformer losses and the cable losses (lines (d) and (e)).

g. Insert the energy rate charged by the utility in $/kWh.

h. Multiply lines (f) and (g) to obtain the estimated cost of losses per month.

i. Compute the fraction of the losses that might be saved by the capacitors using the formula shown. This assumes that the capacitors will be distributed throughout the plant. Otherwise, no loss savings are achievable. PF_{old} is the original power factor; PF_{new} is the corrected power factor, typically 0.95. Insert the result of the formula in this line.

j. Multiply lines (h) and (i). This is the estimate of the monthly costs that capacitors are likely to save. Include this value in the appropriate location in the Economic Evaluation Worksheet.

Power Factor Penalty Savings Worksheet

a. Billed Demand .... ____________ kW

b. Actual Demand .... ____________ kW

c. Difference (a - b) .... = ____________ kW

d. Demand Charge .... ____________ $/kW

e. Monthly Power Factor Penalty Savings (c x d)....... = $____________

Power Factor Penalty Savings Worksheet Instructions

The purpose of this sheet is to estimate the monthly savings possible by eliminating the power factor penalty.

a. From the monthly bill for a typical high demand month, enter the billed kW demand after the power factor has been taken into account.

b. Enter the actual kW demand that corresponds to line (a).

c. Subtract line (b) from line (a). This is the amount of kW demand for which you are being penalized for having a poor power factor.

d. Enter the utility's demand charge, ($/kW). While this is clearly stated on some bills, it may be buried in a complicated calculation on other bills. In those cases compute the equivalent demand charge rate by dividing the amount charged by the stated kW demand. Keep in mind that we are simply trying to determine how much lower the bill will be after correcting the power factor.

e. Multiply lines (c) and (d). The result is the Monthly Power Factor Penalty Savings that will be used in the Economic Evaluation Worksheet.

Economic Evaluation Worksheet

a. Monthly Power Factor Penalty Savings .... $__________

b. Monthly Loss Savings .... $__________

c. Total Monthly Savings (a) + (b) .... = $__________

d. Convert to Annual Savings (c) x 12 .... = $__________

e. Present Worth Factor .... __________
(From Present Worth Table, below)

f. Present Worth of Savings (d) x (e) .... = $__________

Value of Capacitors:

g. (Present Worth of Saving - Cost of Capacitors) .... = $__________ > $0

h. Benefit/Cost Ratio= $\frac{\text{Present Worth of Savings}}{\text{Cost of Capacitors}}$ .... =__________ > 1.0

i. Simple Payback = $\frac{\text{Cost of Capacitors}}{\text{Annual Savings}}$ .... =__________years

Present Worth Factor Table

Select a factor for the number of years and the interest rate you would use for the evaluation of capital equipment such as aapccitors

No. Years	5%	6%	7%	8%	10%
1	0.952	0.943	0.935	0.926	0.909
2	1.859	1.833	1.808	1.783	1.736
3	2.723	2.673	2.624	2.577	2.487
4	3.546	3.465	3.387	3.312	3.170
5	4.329	4.212	4.100	3.993	3.791

Economic Evaluation Worksheet Instructions

a. Insert monthly power factor penalty savings from Power Factor Penalty Savings Worksheet.

b. Insert monthly loss savings from Loss Savings Worksheet.

c. Add lines (a) and (b). This is the total monthly savings possible by adding capacitors.

d. Multiply line (c) by 12 to convert to annual savings. Insert results here.

e. Select a present worth factor from the Present Worth Factor Table corresponding to the number of years you wish to make this evaluation and the interest (discount) rate you wish to use.

f. Multiply lines (d) and (e). This result is the present worth of the savings for the number of years you chose for line (e).

g. Subtract the cost of the capacitors from line (i) of the Capacitor Cost Worksheet from the value on line (f). If the application is economical for the number of years you have chosen, this number will be greater than $0.

h. Another way of comparing the economics is to compute the benefit/cost ratio. For the application to be economical, this ratio must be greater than 1. The higher the number, the more economical the application. This is a good measure for comparing two capacitor schemes with widely varying costs and savings. Some prefer to invest in terms of the greater ratio rather than the higher absolute cost savings.

i. The simple payback indicates approximately how many years it will take to recover the investment in the capacitors. Divide the cost of the capacitors by the value in line (d). Typically, industrial facilities prefer to see this number no higher than 2-3 years for simple capacitor installations and 3-5 years for more complex installations with automatic controllers and filters.

Present Worth Factor Table

Select a factor for the number of years and the interest rate you would use for the evaluation of capital equipment such as capacitors. The interest rate reflects the cost of money, the desired rate of return, inflation, and other factors that may be pertinent to a particular industry. The length of the evaluation selected depends on how quickly the end user would like to see investments of this type pay off. For example, many industrial plant managers prefer to have capacitor investments achieve economic break even in less than three years. Thus, you would use a factor from the 3-year row. Most simple capacitor installations will easily achieve this. It may be necessary to stretch the evaluation period to 4 or 5 years for more complicated installations that involve filters and automatic switching.

5. Design Phase

Performing a Detailed Plant Survey

A detailed plant survey is conducted to collect sufficient data about the plant to determine the optimal size of capacitor to place in each location. It is also for determining if there will be any detailed studies required to avoid some of the pitfalls associated with capacitor application.

The ideal candidate for power factor correction would be a facility with a high power factor penalty, high utilization of system capacity so that there can be significant loss savings, and no harmonic sources or voltage distortion. These factors would ensure sufficient economic incentives and ease in application.

Systems with potential harmonic problems, frequently-switched major loads, greatly varying loads, and the like, often require more sophisticated engineering studies to ensure successful application of power factor correction capacitors. Studies typically cost several thousand dollars and additional costs may be incurred for filters or other specialized equipment necessary for proper operation. Thus, more economic incentive is required. Fortunately, many systems will have sufficient economic justification or less expensive alternatives can be found.

One-Line Diagram

The first step in the survey is to make a simple one-line diagram of the electrical system. This will be used throughout the design phase to help make judgments about the most appropriate form of power factor correction. If one is not readily available, a simple sketch may be made. This sketch should note the main structure of the electrical system from the utility interconnection up to at least the main motor control centers and larger sub panels. You may go into greater detail if you desire.

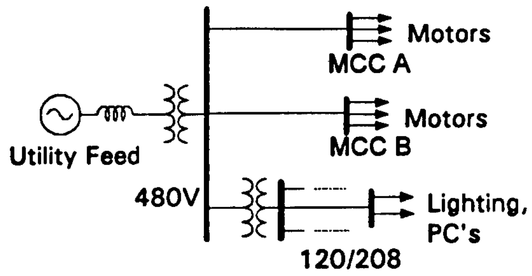


Figure 5.1. A simple one-line diagram

Major types of loads, step-down transformers, and approximate locations for existing capacitor banks should be noted. Figure 5.1 shows an example of a simple one-line diagram. The main buses are indicated by the heavy bars and are labeled with the rated bus voltage. All significant transformers and loads (particularly nonlinear loads) should be indicated.

Complete the one-line diagram as you proceed with the detailed load inventory. Supply the diagram to contractors and engineers you may choose to assist with the application. This will enhance communications considerably.

Potentially Troublesome Loads

Several different kinds of loads can interfere with power factor correction efforts. The most notable are those that produce harmonics or have sophisticated electronic controls. Some of the more critical types of loads to try to identify are:

- Adjustable speed drives
- Variable frequency drives
- DC Drives
- Arc furnaces
- Large amounts of fluorescent or sodium-vapor lighting
- Large UPS systems

If these loads exist in significant quantities in comparison to the size of the electrical system, a detailed harmonics study should be performed. This is why it is a good idea to obtain a meter capable of showing harmonic distortion for the initial plant survey. A quick scan of the bus voltages and a few load or capacitor currents will provide a good idea of the existence of harmonic-producing loads even if there is no specific knowledge of any.

Detailed Load Inventory

The objective of the detailed inventory is to collect sufficient data to understand how the system behaves so that optimal capacitor configurations may be determined. Sufficient data should be collected to enable a detailed computer analysis. Figure A-2 in the Appendix contains a checklist of specific items to collect.

Standard utility meters typically accumulate only kWh and kvarh over a month with a "drag hand" function that records the maximum demand interval. For more informed capacitor application, you should have more detailed demand interval data. For the purposes of the detailed load inventory, you should obtain an instrument capable of recording kW and kvar by a demand interval of, for example, 15 or 30 minutes. One type of portable power profiling instrument is shown in Figure 5.2. Many utilities have adopted electronic meters which can provide you with this data for the whole plant.

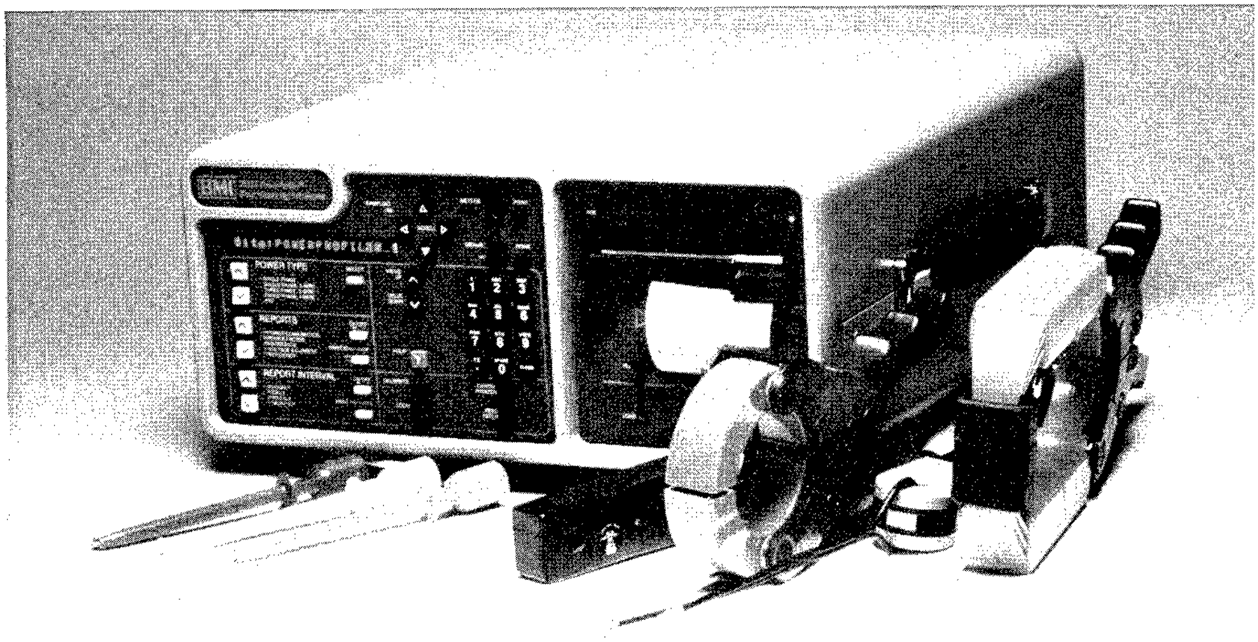


Figure 5.2. Typical power profiling meter. (Photo courtesy of BMI).

Some meters not only record the kW and kvar but can also differentiate between leading and lagging vars, reporting each for the interval. This is very useful for determining the amount of capacitance needed and for verifying the effectiveness of capacitors after installation.

The utility metering typically collects only average data for the whole plant. While this gives some general idea of how much total capacitance is needed, it provides little help in determining where to put it. For that, you will need to profile the loads on each major feeder and branch circuit for at least several demand intervals during typical loads. Figure 5.3 shows a modified version of the one-line diagram of Figure 5.1 with the minimum number of metering points required for a detailed plant survey. Meter at least each of the main feeds to the motor control centers (MCC) as well as other major sections of the plant, such as the office load. You may extend the metering farther out into the plant, to obtain the level of detail desired, as your time and budget allow. It is usually sufficient for the placement of power factor correction capacitors to meter just the major feeds within the plant.

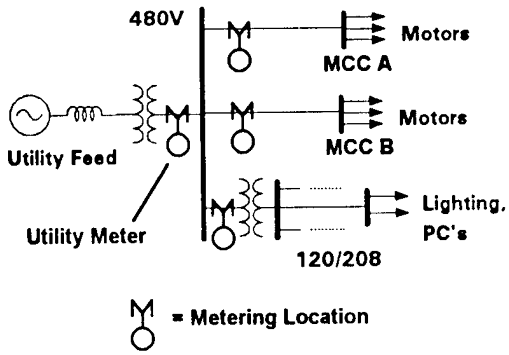


Figure 5.3. Metering locations for minimum power profiling for power factor correction.

It would be ideal to collect all this data simultaneously. While there are some permanently-installed instrumentation systems with this capability, it is available only in a few industrial facilities. Therefore, you are usually constrained to using portable instruments that are moved from circuit-to-circuit.

You may connect the metering at any convenient place along a feed. This is usually at the panel termination on either end. A power profiler must be connected to the three-phase bus voltages and three-phase line currents. This requires access to terminal lugs for voltage and an unobstructed access to the cables to install the current transformers. Refer to instructions with the instrument concerning voltage limitations and current limitations.

Follow safe practices for installing the probes. When in doubt, de-energize the circuit to install the probes. If the instrument must be left in place for several hours or days, it should be located so that passersby cannot easily disturb it or come in contact with leads. Mark off the area to keep unauthorized personnel out.

Permanently-mounted monitoring devices may be used, but it is generally sufficient to use portable meters with clip-on probes. On smaller cables, the clip-on probes are usually sufficient. For large cables, you must rely on existing CT's or be satisfied with clipping a probe on one cable in a parallel bundle and assuming the others are the same.

The sequence of taking the measurements is generally of secondary importance unless there are particular load behaviors you are trying to capture. The most important thing is that you set up a system for keeping track of what measurements were made, when they were made and what was going on in the plant at the time. Keep a detailed log book. Use features of the profiling instrument for labeling any output. Do not try to keep track of the measurements by memory. You will be amazed at how quickly you will forget what you did.

Leave the instruments in place for several demand intervals -- whatever it takes to properly characterize a load. For some loads, this may be as short as one hour or one duty cycle. For others, it may be necessary to monitor kW and kvar demand for several days to obtain definitions of the reactive power demand so that power factor correction can be properly defined. Generally, most individual loads are sufficiently consistent that the measurements need only be made through a few typical duty cycles. The main feeds should be monitored for at least a full typical working day. If practical, a full cycle of normal days and idle days (a week, 10 days, or whatever) should be monitored. This could be important later for determining whether or not to switch capacitors.

The data collected are time interval data expressed as either kW and power factor or kW and kvar demand for that interval, depending on the capabilities of the instrument. The monitoring should be sufficient to determine at least the load going into each significant motor control center or subpanel. It is generally not necessary to monitor each individual motor load. The exception might be for a case where a few large motors comprised the bulk of a load at a particular motor control center.

Simplified Load Inventory Methods

After you do the initial economic screening, you should have a good idea of what you can afford to spend on studies, inventories, and the like. When the budget for power factor correction does not justify a detailed inventory and analysis, the following are suggestions for less extensive load measurements:

1. Monitor only the main feeds.

2. Measure, at least, snapshots of the rms currents in the main cables to get an idea of how the load inside the plant divides.

3. Assume the overall plant load shape for all loads.

4. In lieu of demand interval data, several snapshots at different times will suffice.

Obviously, the more data collected, the more likely it is that the capacitors will be added to portions of the plant where they will do the most good. The greatest benefits will be achieved on lines that have high current with respect to ampacity, poor power factor, and long cable runs. Therefore, make special note of loads and cables with these characteristics.

Instrumentation Capabilities

The power profiling instrument for performing a detailed plant survey should have the following recording capabilities:

- kW, kvar, PF by demand interval.

- Voltage and Current snapshots

- Voltage and Current harmonics; snapshots and trends.

For examples of the types of data recorded, refer to the case studies in Chapters 7 and 8.

Measuring Harmonics

While there are numerous instruments available for measuring harmonics, proper harmonic measurements and the proper interpretation of the results will generally require someone with special training in this field.

For the plant survey, the key things to determine with respect to harmonic distortion are:

1. Main bus voltage distortion. Measure the THD including all harmonics and, also, individual harmonic magnitudes in percent of fundamental.

2. Harmonic content of load currents, particulary those in suspected harmonic-producing loads such as adjustable-speed motor drives.

The THD and rms values are needed as well as magnitudes of individual harmonics.

3. Representative harmonic current in existing capacitor banks, at least the THD and rms values.

As you take the power intervals, take periodic harmonic samples. If the load varies considerably, such as rolling mills, veneer lathes, etc., take several measurements to try to capture the worst case.

If practical, measure the distortion of currents in existing capacitor banks. Existing capacitors are the best locations to find harmonic currents that might indicate that there is a harmonics problem. Unfortunately, capacitor leads are not always easily accessible. However, it is strongly recommended that you open one or two cabinets and measure the current. If you do not have a meter capable of showing the individual harmonic, measure the rms current with a suitable true rms ammeter. If the rms current measured is much higher than the expected rated current, there is likely to be a harmonics problem.

Lack of high current in capacitors does not, however, indicate that there will be no problems after the addition of capacitors -- only that there are none now.

The instruments for monitoring harmonics range from permanently-installed 3-phase monitors to hand-held single-phase devices. Most of the modern ones are capable of transmitting data to a computer for further analysis.

Observing Abnormalities

Throughout the inventory of the load, it is important to keep a watchful eye for things that might be a clue to potential problems installing capacitors. For example, an existing capacitor bank that cannot be used because it either blows fuses or interferes with some process is almost a certain indication of harmonic problems. It could also be an indication that the capacitor and/or the associated load is switched often and might require some special considerations.

Listen for motors or transformers making unusual high-pitched sounds and check for lightly-loaded transformers running much hotter than other similarly-loaded transformers. These are often symptoms of harmonics problems. Sometimes your ear and hand are sufficient instruments for detecting them.

Selecting a Capacitor Scheme

Figure 5.4 shows a detailed flow chart on one capacitor scheme selection process that works well for many industrial facilities. The flow chart is an expansion of the Capacitor Selection portion of the overall Capacitor Application Process flowchart presented earlier. It is not claimed that this is the only valid strategy for determining a capacitor scheme and if you are more familiar with another, please feel to use it.

The objective is to find the lowest cost capacitor scheme that will adequately correct for the power factor while minimizing the losses. The lowest cost installations are generally fixed capacitors with few additional accessories such as automatic switches and harmonic filters. Therefore, the philosophy of this process is to start with a suitable fixed capacitor scheme and then modify it until the voltage and harmonic constraints are met. In many cases, it will be possible to meet the constraints without resorting to these additional items.

There is no single path through this flow chart if modifications are necessary to the basic scheme. You may choose from more than one path at certain decision blocks and these are denoted with numbered choices. It is also beneficial to start with more than one fixed capacitor scheme and see if it leads to a more economical outcome. Since we are encouraging placing capacitors throughout the plant, a multitude of alternatives arise and there is no one "right" answer. Several schemes will work adequately. The challenge is to find one that is acceptably close to optimal.

Develop a Fixed Capacitor Scheme

There are several stategies you may employ for developing a fixed capacitor scheme:

1. Lump the required amount of capacitors at the main bus. This will eliminate the power factor penalty, but will not reduce the losses within the plant. Instead, we are encouraging the investigation of options for distributing capacitors throughout the plant to achieve more energy savings. One lumped bank is also the configuration most susceptable to harmonic resonance because there is less damping than when the capacitors are distributed throughout the plant.

2. Distribute the capacitors to the motor control centers and sub panels proportionally to average load. Lacking better information, this will generally achieve a good capacitor scheme with respect to losses, although, perhaps, not optimal.

3. Use a computer program to distribute the capacitors to minimize losses. A model of the plant and its load is constructed and the computer program will determine where to place each capacitor to achieve minimum losses. Such a computer program was developed in conjunction with this Guide Book to suupport this procedure.

4. Distribute the capacitors using motor sizes and the ANSI/NEMA tables (see Chapter 6.) as a guide. This procedure is acceptable, but does not reflect the need for more released capacity or loss reduction in another part of the plant. Capacitors sized for small motors are often proportionately much more expensive than larger fixed capacitors because of installation costs. We found in the case studies that for moderately to heavily loaded systems, most of the loss savings are achieved in the cables and transformers feeding the motor control centers. Therefore, the procedure here begins with a fixed capacitor installation at the motor control centers. Then, if there is a need to switch the capacitors, we will consider installing them on motors. Of course, capacitors on larger motors are often as economical as fixed banks of similar sizes.

Choose one, or a mixture of all the techniques above to select a capacitor scheme. Determine the total amount of capacitance required to correct the power factor to a desired target at average peak load and then distribute the capacitors over the plant. If you have access to a computer program for this purpose, it can do this for you while taking into account different loss densities in the plant. At this point, you may wish to go out for bids on the different schemes to get an idea of the costs. Because of the competitive nature of the capacitor market, there can be a wide range in prices. Generally, small capacitors are more expensive on a $/kvar basis than larger ones.

Capacitor Selection Detail

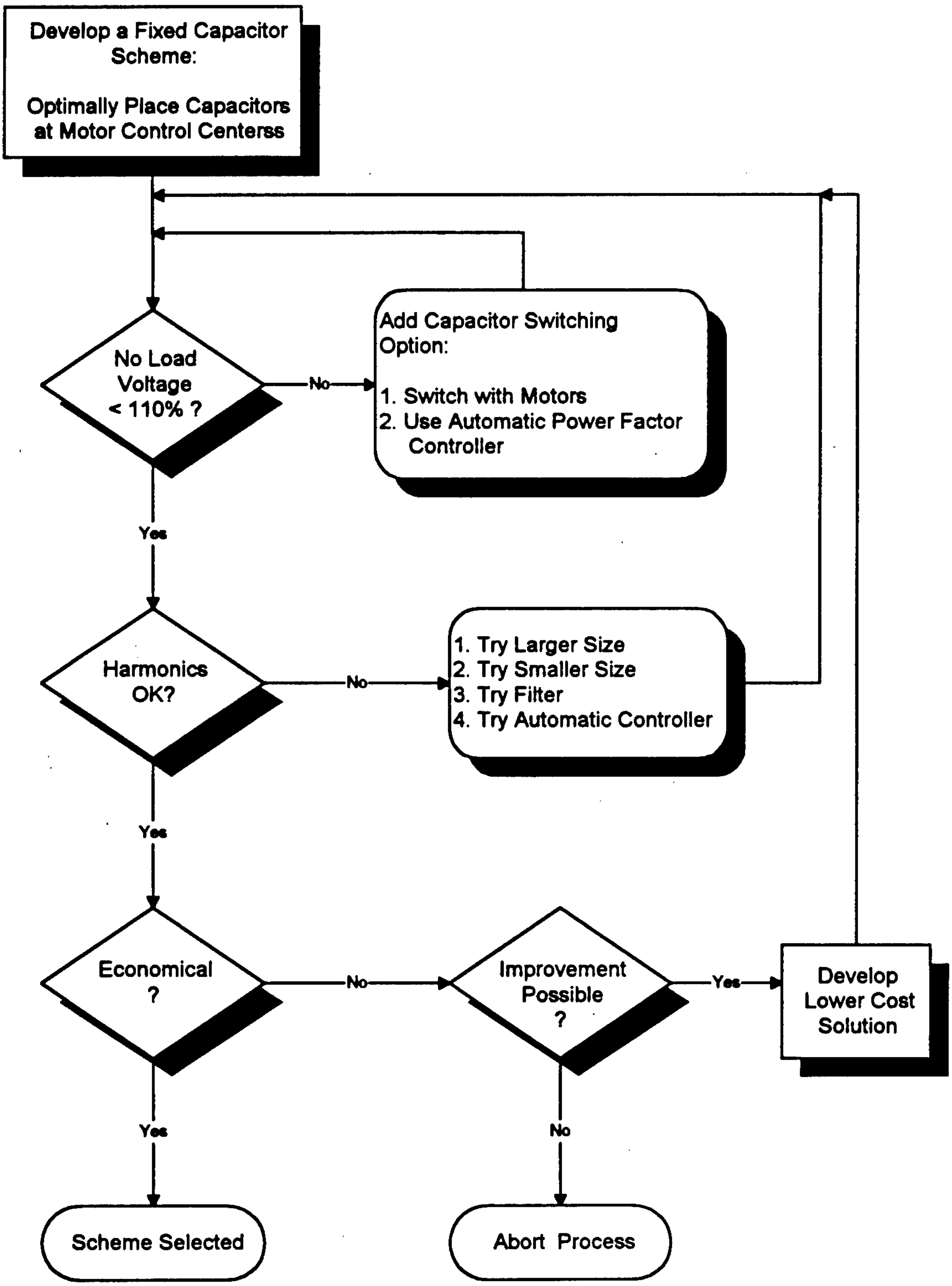


Figure 5.4 Flow Chart for Capacitor Scheme Selection Process.

Checking the "No Load" Voltage Rise

The basic reason why many plants cannot leave fixed capacitors energized continuously is that the voltage increases too much when the load is low. At this point in the process, compute the no-load voltage rise for the present capacitor scheme. For more details on how to compute the percent voltage rise, see Chapter 12. When using a computer program, simply set the load to a very low value and observe the computed voltage.

The limit on the steady state voltage is generally about 110%. Above this transformers will saturate and become overheated. Of course, the life of incandescent lamps is also drastically reduced. If we assume that the normal system voltage could be a 105%, then the capacitors should cause no more than a 5% rise at no load. For simple cases, the percent voltage rise, ΔV, can be estimated from the kvar of the capacitor and the percent impedance, Z, and kVA ratings of the main transformer as follows:

$$\%\Delta V \approx \frac{(kvar) \times (\%Z)}{kVA}$$

Fortunately, at many plants where this could be a problem, the load seldom drops low enough. Or, if the load is de-energized the capacitors are also deenergized. However, if these conditions can't be guaranteed, some or all of the capacitors will have to be switched.

Leading Power Factor

A leading power factor condition occurs when the capacitors overcompensate for the lagging power factor of the motor load. Some engineers also prefer to switch capacitors off if the power factor at the bus goes leading. While there is a certain negative stigma associated with leading power factor, the mere fact that power factor is leading is not necessarily a cause for concern. A fair amount of leading power factor can be tolerated in an industrial power system without ill effects, particularly if the leading power factor is localized to an entire bus or last for a relatively short period of the load cycle.

The main issues with leading power factor are:

1. An excessive voltage rise may accompany the leading power factor condition,

2. If the leading power factor condition persists for a large percentage of the time, there may be significant additional losses just like for lagging power factor. While you may not need to switch capacitors to control voltage, if the plant is at a low load level for extended

periods, you may want to switch some capacitors off to reduce current levels during those periods,

3. The excitation fields on generators supplying the load must be set lower than acceptable for stability concerns. This is a big concern for utilities, should their whole system become leading. It is also a concern for operating cogeneration in industrial plants. Some of the capacitors may have to be de-energized to operate a plant totally from cogeneration or stand-by generation so that the fields may be set to proper levels.

The decision on whether a leading power factor for the entire plant is of concern is largely up to the local utility. Some utilities are in such great need of var support, that they might welcome a leading power factor. Other utilities may have so many extra vars from transmission line charging that they would prefer that most larger industrial end users not go into a leading condition, at least with significant var levels. Consult with your local utility representative on this issue.

Capacitor Switching Options

The first switching scheme to investigate is to switch a few of the capacitors with the larger motors. The capacitors may be physically installed either directly connected to the motor or through a contactor on the motor control center that is tied in with the motor control.

If the motors are large enough to use capacitors of the same size as were being considered for the fixed capacitor scheme, little additional cost is incurred for installing them on the motors. Where the economy is lost is when capacitors are placed on several small motors. There is relatively little difference in installation charges for large and small 480-volt units. Therefore, the relative $/kvar is quite high for a small capacitor.

One common pitfall associated with switching capacitors with motors is that the motors are not energized when the correction is needed. Intermittent duty motors are not good candidates for capacitors. Having a mixture of fixed and motor-switched capacitors helps guard against this by having a base amount of capacitors continuously energized.

The second switching option to consider is an automatic power factor controller. This will switch large capacitor banks in small steps to follow the load. These are considerably more expensive compared with fixed capacitors, but can be an excellent alternative when the capacitors must be switched and capacitors switched with motors is impractical. It may also be possible to do some harmonic control with them.

To achieve optimal loss reduction, the power factor controllers should be installed at the motor control centers rather than on the main bus so they can reduce the currents in the main feeder cables. While this is more costly than installing only fixed units, it can be cost competitive with distributing several small capacitors on motors throughout the plant.

Check the Harmonic Distortion

Once a capacitor scheme has been selected that meets the power factor and voltage criteria, the harmonic distortion must be estimated. The recommended method is:

1. Measure the maximum voltage distortion at the plant main bus without capacitors. This is done with a meter capable of reporting the individual harmonic values.

2. Apply the distorted source voltage to a model of the plant circuit and compute the currents in the capacitors.

For all but the simplest of cases, this will require a computer program. Techniques for doing this and a worksheet for the simple cases are described in Chapter 23.. The Power Factor Improvement and Energy Savings computer program developed with this Guide Book is also capable of computing the harmonic currents.

If the estimated current in the capacitors exceeds 135% rms or the bus voltage exceeds 5% THD, some form of mitigation is required.

Harmonic Mitigation Options

The first harmonic mitigation options to consider are those that have little incremental cost. Often, the harmonic currents are high simply because the optimal capacitor value with respect to power factor and losses exactly tunes the system to some undesirable harmonic. Therefore, the first thing to try is to add about 20% more capacitance to move the tuning frequency lower. This continues to meet power factor requirements. Then the no-load voltage and capacitor switching options must be reconsidered.

The second modification to check is to try a smaller amount of capacitance. This will also move the tuning frequency, but could result in not being able to completely eliminate the power factor penalty. Now the evaluation becomes an economic trade off between accepting a small power factor penalty versus investing in a filter.

For a number of reasons, selecting different capacitor sizes may not be a practical consideration. One common reason is that a number of capacitors are being switched at random and there are several combinations that could yield trouble. Filters are then considered to control the harmonic distortion.

The first filter design to attempt is to convert one of the larger banks into a filter for the lowest harmonic of interest. In most industrial plants, this is the fifth harmonic, but is sometimes the third. If additional filters are needed, they are added for the next highest odd harmonic of any significance. If there is a concentration of harmonic sources, the logical bus for the filter is the one supplying that portion of the plant. Since the filter must be sized sufficiently large for the bus capacity so that it doesn't burn up due to the bus distortion, some capacitors originally planned for other areas of the plant may have to be combined with the filter bank. This may sacrifice some of the loss reduction, but is the often the price that must be paid for achieving successful operation in the presence of harmonics.

After selecting a filter design, the new scheme must again be evaluated for no-load voltage rise and other harmonic problems that may crop up unexpectedly. Several iterations in this loop are sometimes necessary. For estimating purposes, filters may be assumed to double the cost of the capacitors incorporated with them. You may wish to obtain more exact costs by contacting vendors because costs do vary significantly.

Another harmonic mitigation alternative is to use an automatic power factor controller to avoid the resonant conditions. If the capacitor steps that cause resonance can be predicted ahead of time, the controller can simply be set up to avoid those steps. It is also possible that the vendor can supply an adaptive control scheme that watches the harmonic distortion and automatically changes capacitor values when the system distortion gets high.

Is it Economical?

Use the Economic Screening Worksheet described in the previous chapter to evaluate the economics. Of course, you can now use better estimates of cost values. The computer program developed in conjunction with this Guide Book will also perform the economic calculations and compare various alternatives. It is possible that after modifications for switching and harmonic control the capacitor scheme is no longer economical. That is, the cost of the capacitor scheme is greater than the expected benefit. If that occurs, one must evaluate whether it is possible to reduce the costs. If not, the plan must be abandoned unless you choose to compromise on the economic guidelines.

Is Improvement Possible?

This block is reached if the scheme under consideration is uneconomical. Since there are many ways of meeting the power factor criteria, one must at this point judge whether it is likely that sufficient reductions in the cost of the scheme are possible to make it economical. If not, then the process is stopped and the power factor correction plans abandoned.

Developing Lower Cost Solutions

Check with power factor capacitor and filter suppliers to learn if there are more economical combinations that have not been considered. It may be possible that by sacrificing some power factor correction or loss improvement, a much less costly installation may be achieved. For example, it may be economical to install a few large capacitor banks while it is not economical to install several smaller ones distributed throughout the plant. In another case, it may be possible to combine several capacitors under one power factor controller rather than having several controllers.

Consider putting the capacitors at a higher voltage level, if available. Many industrial plants have 4 to 15 kV circuits as well as 480 volt circuits. Of course, there is considerably more energy to be saved on the 480 volt circuits, but the capacitors and filters on the higher voltage systems are often much lower per unit cost. At least, the power factor penalty may be saved.

Look at the root cause of the problem. If it is harmonics, is it possible to mitigate the harmonics in some other way? Can the capacitors be tied in with other plant improvements that would make it economical to install a practical scheme? For example, step-down transformers that are too small may be the root cause of having to switch the capacitors because of the no-load voltage rise. Consider upgrading the transformer as well.

Cycle back through the voltage and harmonic checks before settling on a reduced cost scheme.

6. Installation

Installing the Capacitors

The following are general guidelines for installing capacitors.

Selecting the Configuration of the Capacitor Bank

- Use a delta connection on ungrounded systems to provide for a rapid fuse clearing of faulted capacitors. Use a delta connection at motors.
- Only use a grounded-wye configuration for four-wire systems. This connection allows the use of smaller fuse sizes and exposes the capacitors to lower fault currents than a delta system.
- Use an ungrounded-wye configuration only at locations where the fault current is excessive. This connection limits the fault current to about 300% normal operating current (but does cause fuse clearing times to be extremely long).

Selecting Fuses for a Capacitor Bank

There are two choices when fusing a capacitor bank, group fusing and individual unit fusing. Group fusing involves the use of one fuse per phase. Individual unit fusing has the advantage of easy identification of the faulty capacitor. Consult information from the capacitor manufacturer for fuse selection, normally this information is found on charts supplied with the capacitors. As a general rule, use a dual-element fuse with a continuous current capability of at least 165% of the normal capacitor current, or a single element fuse capable of supporting a 250% inrush current. Some capacitors are manufactured with an internal fuse to prevent the possibility of case rupture and damage to other units. If not, the time-current curve of the fuse used should coordinate with the case rupture curve of the capacitor - so as to avoid damage to adjacent units. Size molded case circuit breakers to at least 150% of the capacitor load current.

Wiring Considerations

Size the power cable for at least 135% of the capacitor full load current. Also, make sure that if the capacitor is connected to the terminals of a motor or to motor circuit conductors, the conductors shall have an ampacity no less than one third the ampacity of the motor circuit conductors themselves.

Lay out the wiring connections on a most direct basis with a minimum of bends, for ease of troubleshooting. Assure that the appropriate schematics are updated, and that all new conductoring is marked with appropriate wire numbers.

Installing Capacitors on Motors

These guidelines are for capacitors placed on motors. See the chapter on Capacitors on Individual Motors for additional details.

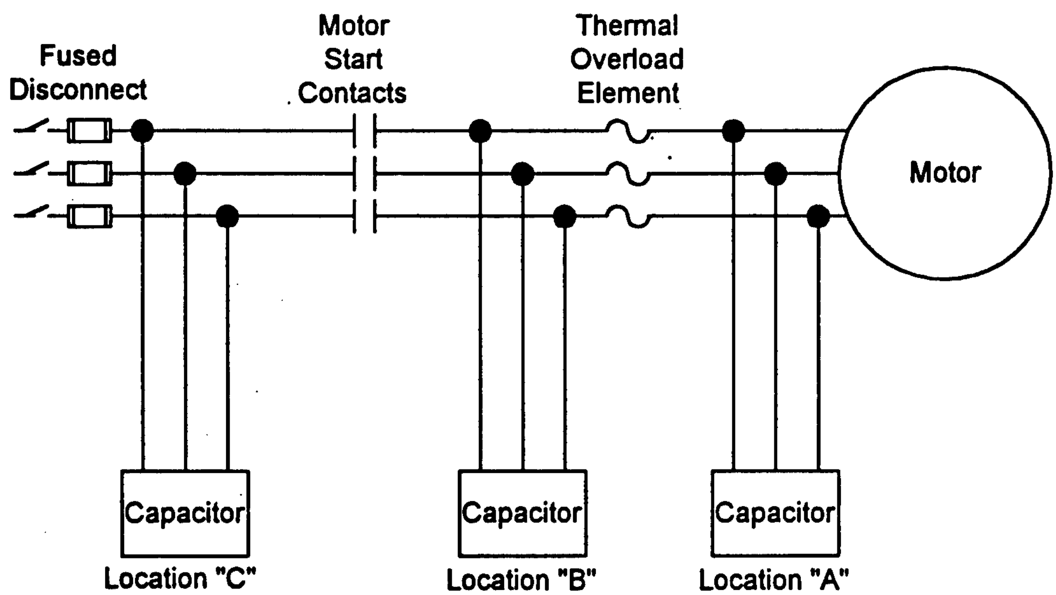


Figure 6.1. Possible Locations for Capacitors on Individual Motors

What Motors Should have Capacitors?

Switching capacitors with motors is generally the most cost effective means of switching the capacitors to follow the load. However, there are some pitfalls, both economic and technical to be aware of.

The best candidate motors are those that are energized most of the time and are sufficiently large for the $/kvar cost of installing capacitors to be nearly as low as simple fixed capacitors. Consult with capacitor vendors and installers regarding costs. Determine the cost per kvar for a range of sizes. For example, you may find that the per unit cost begins to climb steeply for 480 volt capacitor sizes smaller than 20 - 30 kvar . Therefore, you might select 20 kvar as the smallest capacitor you wish to install. According to the sizing table below, this would require that the smallest motor to consider would be approximately 60 to 75 hp, depending on type.

It is often easiest to physically install the capacitors at the location of the motor starting contactor. Usually this will be housed in a motor control center (MCC).

If you choose to install capacitors on motors that are not energized during the entire heavy load period, you must add proportionally more capacitors somewhere else in the system. Monitor the motors under consideration to determine their availability.

Where to Connect the Capacitors With Respect to Motors

Connect the capacitor on the secondary side of the overload relay (location "A") when:

- It is a new motor installation, and the motor overload element can be sized for the reduced current draw.

- It is an existing motor, but no overload element change is required.

Connect the capacitor between the contactor and the overload element (location "B") when:

- It is an existing motor when the overload element would exceed the code if the capacitor were installed on the motor side.

Connect the capacitor on the line side of the starter (location "C) when:

- The motor is used in jogging, plugging, reversing, multi-speed, and high inertia applications.

Sizing the Capacitor for Individual Motor Loads

To size capacitors for individual motor loads, use Table 6.1 below. Simply look up the type of motor frame, RPM and horsepower. The table indicates the maximum amount of kvar that you should switch with the motor without exceeding voltage restrictions. Do not oversize the capacitor.

Table 6.1

Sizing Guide for Capacitors on Individual Motors
Kvar to correct typical motor to 0.95 PF; motor and capacitor switched as single unit. (ANSI/NEMA MGI - 1978).

NEMA Code	B																		C		D	Wound Rotor
	Before 1955						U-Frame						T-Frame									
Poles	2	4	6	8	10	12	2	4	6	8	10	12	2	4	6	8	10	12	4 / 6	8	6	
RPM	3600	1800	1200	900	720	600	3600	1800	1200	900	720	600	3600	1800	1200	900	720	600	1800 / 1200	900	1200	
HP=3	1.5	1.5	1.5	2	2.5	3.5	1	1	1	2			1.5	1.5	2.5	3	3	4				
5	2	2	2	3	4	4.5	1	2	2	2			2	2.5	3	4	4	5				
7.5	2.5	2.5	3	4	5.5	6	1	2	4	4			2.5	3	4	5	5	6				
10	3	3	3.5	5	6.5	7.5	2	2	4	5	5	5	4	4	5	6	7.5	8				
15	4	4	5	6.5	8	9.5	4	4	4	5	5	5	5	5	6	7.5	8	10	5	5	5	5.5
20	5	5	6.5	7.5	9	12	4	5	5	5	10	10	6	6	7.5	9	10	12	5	6	6	7
25	6	6	7.5	9	11	14	5	5	5	5	10	10	7.5	7.5	8	10	12	18	6	6	6	7
30	7	7	9	10	12	16	5	5	5	10	10	10	8	8	10	14	15	23	7.5	9	10	11
40	9	9	11	12	15	20	5	10	10	10	10	15	12	13	16	18	23	25	10	12	12	13
50	12	11	13	15	19	24	5	10	10	15	15	20	15	18	20	23	24	30	12	15	15	18
60	14	14	15	18	22	27	10	10	10	15	20	25	18	21	23	26	30	35	18	18	18	20
75	17	16	18	21	26	33	15	15	15	20	25	30	20	23	25	28	33	40	19	23	23	25
100	22	21	25	27	33	40	15	20	25	25	40	45	23	30	30	35	40	45	27	27	30	33
125	27	26	30	33	40	48	20	25	30	30	45	45	25	36	35	42	45	50	35	38	38	40
150	33	30	35	38	48	53	25	30	30	40	45	50	30	42	40	53	53	60	38	45	45	50
200	40	38	43	48	60	65	35	40	60	55	55	60	35	50	50	65	68	90	45	60	60	65
250	50	45	53	58	70	78	40	40	60	80	60	100	40	60	63	82	88	100	54	70	70	75
300	58	53	60	65	80	88	45	45	80	80	80	120	45	68	70	100	100	120	65	90	75	85
350	65	60	68	75	88	95	60	70	80	80			50	75	90	120	120	135				
400	70	65	75	85	95	105	60	80	80	160			75	80	100	130	140	150				
450	75	68	80	93	100	110	70	100					80	90	120	140	160	160				
500	78	73	83	98	108	115	70						100	120	150	160	180	180				

General Purchase Requirements for a Fixed Bank

1. The installation shall meet all NEC standards and requirements, and individual capacitors and control units shall be UL listed.
2. The system shall include schematics and wiring diagrams.
3. All conductors should be numbered for identification within the schematic.
4. Recommended maintenance and spares list should be provided.

5. Blown fuse indicators should be visible for inspection and should include a push-to-test feature.

6. Power On indicators should be available.

Specific Capacitor Requirements

1. The capacitors shall be of welded construction and hermetically sealed. Any dielectric fluid should be non-flammable, non-PCB biodegradable.

2. Capacitor shall be provided with a means of draining stored charge per NEC requirements.

3. Each capacitor shall be tested and comply with the following parameters:

   a. The capacitor shall have a nominal voltage consistent with the application. It shall be able to withstand 135% of rated current continuously, and 110% of rated voltage continously.

   b. Capacitance (kvar) shall be 0 to +10% of specified value.

   c. Terminal to case dc hi-pot test - as appropriate for voltage class.

   d. Losses - not more than 0.5 watts per kvar.

   e. Leak test - 85° C, 10 hours

Specific Requirements for Harmonic Filter Reactors

1. The reactors shall be air cooled and suitable for the application.

2. The inductance values shall be tested and within 5% of the specified value.

3. The insulation BIL shall be appropriate (e.g., 30kV for 480V systems, 110kV for 12kV systems).

4. The reactors must be rated for both fundamental frequency and harmonic current duties as determined by a proper system analysis.

General Requirements for High Voltage Capacitor Banks

Since high voltage (HV: 2.4 kV - 35 kV) installations are often installed outdoors, the requirements for weather proofing and foundations must be taken into account. Harmonic filters installed on the HV generally use air core reactors, which have excellent linearity and fewer losses. In contrast, many low-voltage installations are iron-core reactors. However, you must take precautions with air-core reactors to limit the effect of stray flux in neighboring metallic parts, (e.g. the equipment frames and building structural steel). At the least, this contributes to losses and, at the worst, causes excessive heating.

Insure that switchgear is suitably rated for capacitor switching duty (ie. must withstand the inrush currents and open without restriking).

Provide suitable grounding equipment for maintenance purposes.

Performing Post Installation Measurements

As you install each capacitor unit, energize it and measure the current. Use a meter capable of reporting the true rms current with harmonics present. This measurement will indicate whether or not a unit is faulty and if the harmonic currents are larger than expected. If a harmonic study has indicated that a certain capacitor configuration should be avoided, develop an installation procedure to avoid that condition during installation.

The current should be close to the rated capacitor current unless some increase due to harmonic distortion is anticipated. If so, confirm that the measured values are within expected limits.

Next, observe the total plant load after the installation is complete to verify that the power factor has been improved as expected. An instrument capable of reporting kW demand and power factor is necessary for this. Consult with the utility representatives to confirm that the power factor for billing is proper.

Modifying the Installation

Hopefully, all will have gone well up to this point and there will be no need to modify the installation. However, not all problems can be anticipated. Three common problems encountered at this point are

1. Harmonics are higher than expected,
2. The power factor was not improved to the desired value,

3. Some loads cease to function properly after the capacitor installation.

The objective is to seek a solution at the minimum incremental cost. If harmonic distortion is the problem, the solutions are generally to first try a different size of capacitors. The easiest thing to do at this point is to disconnect one or two units to see if the problem disappears or gets worse. It is sometimes necessary to install a filter. Again, it is more desirable to predict this need ahead of time, because there may be space limitations that make a retrofit very expensive. Another condition that may occur is that an additional filter is needed. The first filter may have an adverse interaction with some system conditions (e.g., failing to account for cogeneration, non-characteristic harmonics, etc.) that was not anticipated, requiring additional filtering.

If the power factor needs further correction, it could be:

1. The capacitors are on motors that are not running when the correction is needed.

2. The capacitors are rated for the wrong voltage and are not producing the amount of kvar that was anticipated.

3. The automatic controllers are not programmed properly.

4. An error was made in the determination of the load characteristics.

The solution may be as simple as moving one or two capacitors to a different motor or connecting them as a fixed capacitor directly on a bus. Another possibility is that a few more capacitors need to be purchased. These are relatively inexpensive options that should not significantly impact the economy of the installation. Having to add such equipment as automatic power factor controllers could add considerable cost, but, of course, may be necessary in some cases.

If some loads begin to misoperate after installation, first try to determine why that is the case. It may be that switching transients involving the capacitors are affecting the operation. This can happen with adjustable-speed drives. This problem can be solved with line reactors or, in some cases, a different kind of capacitor switch. It may also be simply that there is slightly more harmonic distortion than before. While it may be within the recommended limits, some loads may be highly sensitive to harmonics. Monitor the voltage and current into the load with a power quality monitoring instrument to determine why the equipment is misoperating. Also, you might try moving capacitors near the load to another bus.

7. Case Study #1: Food Processor

Case study #1 involves a food processing facility fed at 480 V through a primary-metered 5 MVA transformer. The facility consists of three main processes which run independently. The kW level at each plant does not vary significantly. Thus, the overall kW level tends to be relatively constant for extended periods of time, with significant changes occuring only when a plant is started up or shut down.

The typical peak demand at present is 1000 kW, which is much less than the 5 MVA transformer capacity. The system originally had considerably more compressors than it currently does. Figure 7.1 shows a simplified one-line diagram of the facility. The capacitor locations selected are shown on the diagram.

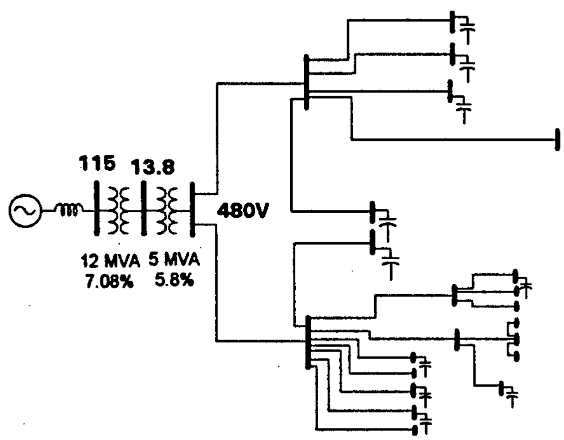


Figure 7.1. Case 1 plant diagram.

Preliminary Evaluation

The Economic Screening Worksheets for the preliminary evaluation of this site are filled out for this case as an example and included in the succeeding sections. The information known about the plant before the detailed plant survey was that the average power factor was about 78% and the typical demand was approximately 1000 kW. The worksheets indicate that a relatively simple fixed capacitor installation that costs approximately $30 per kvar should be quite economical based on a three year evaluation period. The simple payback is predicted to be about 1.8 years. Note that the losses were evaluated at the marginal energy rate of $0.007 per kWh, which is the lowest rate at the highest level of energy usage. This is the proper value for evaluating the effect of loss reduction because the losses are subtracted out at the margin. The billing schedule did not have a demand charge specifically identified, but an equivalent charge of approximately $2.90 per kW was derived from one of the bills by computing the bill assuming the power factor was corrected.

Capacitor Costs Worksheet

Determine the approximate amount of capacitance needed to correct the power factor to the desired value.

a. Average Power Factor, *PF*: **0.78**
(From utility bill; If greater than desired PF, no capacitors needed)

b. Compute $\sqrt{\frac{1}{0.78^2}-1}$ .... = **.8023**

c. Desired Power Factor, $PF_{Desired}$: **0.95**

d. Compute $\sqrt{\frac{1}{PF^2_{Desired}}-1}$ (= 0.3286 *for* 0.95 *PF*) .... = **.3286**

e. Subtract (b - d) .... = **.4737**

f. Max Metered Demand from bill .... **1000** kW

g. Capacitors Required (e x f) .... ≈ **475** kvar

h. Assumed Cost/kvar .... **30** $/kvar

i. Capacitor Cost (g x h) .... = $ **14250**

j. Study Cost .... $ N/A

k. Total Capacitor Cost (i + j) .... = $ **14250**

Power Factor Penalty Savings Worksheet

a. Billed Demand .... ***1240*** kW

b. Actual Demand .... - ***1020*** kW

c. Difference (Subtract Actual from Billed Demand) .... = ***220*** kW

d. Multiply by Demand Charge .... ***≈2.90*** $/kW

e. Monthly Power Factor Penalty Savings .... = $ ***≈640***

Loss Savings Worksheet

Cable Loss Estimate

a. Monthly energy usage: .... *482900* kWh

b. Multiply (a) by average cable capacity used *0.2 x 482900=* *96580* kWh
(from measurements; typically 0.2 - 0.4)

c. Multiply (b) by .02 .... *0.02 x 95680 =* *1932* kWh

d. Divide (c) by the average power factor, PF *1932 / 0.78 =* *2476* kWh

This (d) is a rough estimate of the monthly kWh losses in the cables for a typical industrial facility.

Transformer Loss Estimate

For each transformer compute an estimate of the total monthly losses by filling in the table. Sum all transformers to get a total loss (right hand column).

Transf.	Rated kVA (a)	Aver. kVA (b)	per unit Resistance (R)	Loss = $730\ b^2R/a$ kWh
1	5000	1000	.00966	1400
2				
3				

e. Monthly Losses: 1400

f. Total losses: (d) + (e) .... = *3876* kWh

g. Energy Rate .... (marginal rate) *0.007* $/kWh

h. Total Cost of Monthly Losses: (f) x (g)................. = $ *27.13*

i. Fraction Saved by Capacitors: $\left[1-\left(\frac{0.78}{0.95}\right)^2\right]$ = ... *.325*

j. Monthly Loss Savings (h) x (i) .... = $ *8.82*

Economic Evaluation Worksheet

a. Monthly Power Factor Penalty Savings	$	*640*
b. Monthly Loss Savings	$	*≈9*
c. Total Monthly Savings (a) + (b)	= $	*649*
d. Convert to Annual Savings (c) x 12 .... *649 x 12*	= $	*7788*
e. Present Worth Factor ....*(3 yrs, 7%)* (*From Present Worth Table, below*)		*2.624*
f. Present Worth of Savings (d) x (e)	= $	*20435*
Value of Capacitors:		
g. (Present Worth of Savings - Cost of Capacitors)	= $	*6185* > $0
h. Benefit/Cost Ratio= $\frac{\text{Present Worth of Savings}}{\text{Cost of Capacitors}}$	=	*1.43* > 1.0
i. Simple Payback = $\frac{\text{Cost of Capacitors}}{\text{Annual Savings}}$	=	*1.83* years

Plant Survey

The detailed plant survey was carried out using the utility's permanently-mounted metering and a BMI 3030A portable, three-phase monitoring instrument. Both instruments had demand interval recording capability. The 3030A was used to make measurements of the harmonics as well.

Each motor in the plant was identified and monitored. Also, the size and length of all cables in the plant were recorded for use in the computer simulation. The load in each cable was monitored for one or more 15-minute demand intervals to collect a sufficient amount of data to characterize the load. This time varies considerably. Some loads are constant while others are varying. We were interested in determining an average load under high load periods.

One of the first things learned was that the 1000 kW peak demand appears only briefly for one 15-minute demand interval each day. The remainder of the time the whole plant is operating, the load averages 800 kW. The three loading levels of the plant are plainly visible for the monthly loading characteristic shown in Figure 7.2. In this particular month, (not a peak usage month) the entire plant was operational only for about one week. The minimum load is about 200 kW and the second load level is about 400 kW. The capacitor sizing studies were performed using a load of 800 kW as being more representative of the typical load when the whole plant is operating, as is the case much of the rest of the year.

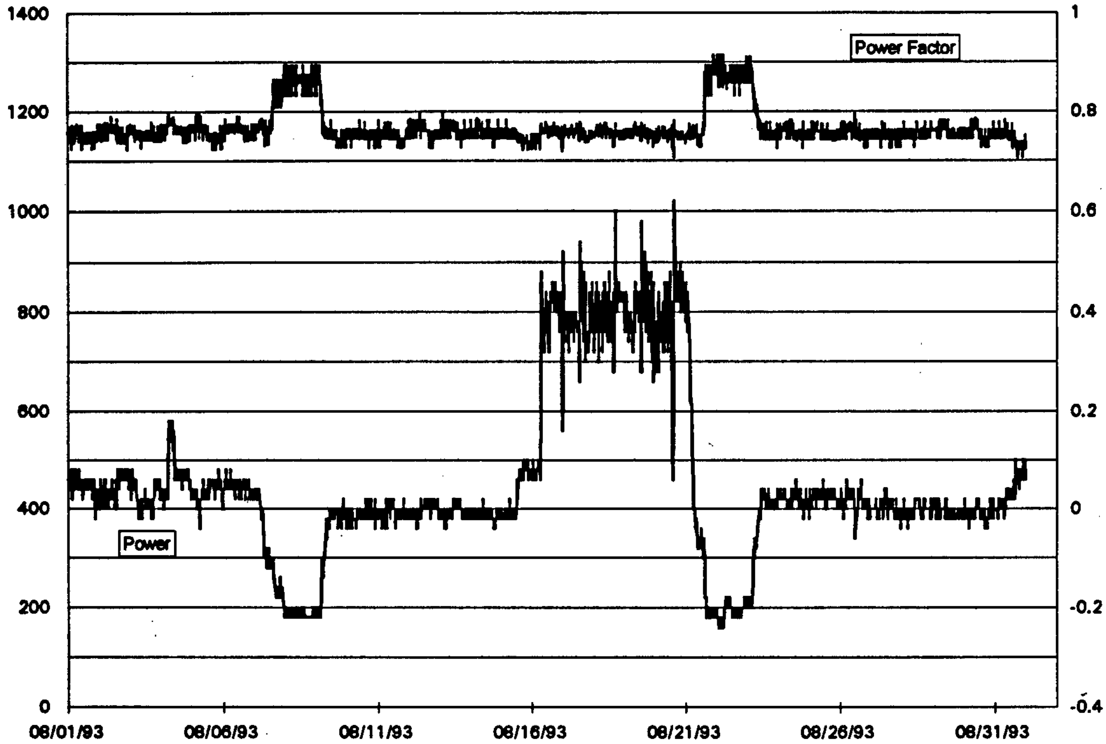


Figure 7.2. Load and power factor characteristic for one month.

Because of the research nature of this case study, we went into substantially more detail in the plant survey than is necessary to determine capacitor distributions within the plant. Except for large industrial plants, the amount of time spent would not be justifiable based on the cost savings. It would have been sufficient to determine loadings and cable characteristics in only the 20 circuits shown in the one-line diagram, which includes all circuits up to the motor control centers. Many of the loadings could have been determined by a single measurement snapshot because they were constant.

No appreciable harmonics were recorded during the survey.

The total losses in all the cables were calculated from measurement data to be 8.4 kW at 800 kW load. About 4 kW of these losses were in the main feeder cables shown in the one-line diagram. Assuming a duty cycle of 10 days at full load and 3 days idle (see Figure 7.3), this would yield about 2500 kWh in losses each month. This is quite close to the screening estimate of 2476 watts. To go after the remaining losses, one would have to put numerous capacitors on most of the small motors. This would dramatically increase the cost of the installation while achieving only a small increase in savings due to the low marginal energy rate.

Capacitor Scheme Selection

The scheme was selected by using a power flow computer program and a spreadsheet program to determine the optimal capacitor configuration to minimize losses at the 800 kW load level. The plant was modeled up the motor control centers. The model consisted of the resistances and reactances of the cables and transformers shown in the one-line diagram. The cable lengths were determined by measurement and the impedance values were determined from the conductor tables included in the Appendix. The loads simulated at the motor control centers corresponded to the measurements made in the detailed plant survey.

The programs provided a relatively easy means to try several different schemes. Each scheme required approximately 400 kvar to achieve 95% power factor. It was determined that 30 kvar banks were a convenient size for this facility based on breaker availability and cost. Fourteen (14) of these banks were dispersed over the system to achieve a total of 420 kvar.

Following the application of the capacitors, the load was set to a very low value in the power flow program to determine the no-load voltage rise. Since the system is so strong with respect to the present size of the load, the voltage increased only about 1%. Therefore, it was concluded that the capacitors did not need to be switched for voltage concerns.

The harmonics were analyzed using the Electrotek SuperHarm™ computer program. No problems were found, although conditions were such that there could be problems in the future if there are significant harmonic-producing loads added. No harmonic mitigation was deemed necessary.

Harmonic Considerations

The only nonlinear loads in the facility are two very small adjustable speed motor drives. The utility bus voltage was determined by measurement to be very clean Thus, harmonic distortion is negligible at present.

The source impedance seen at an industrial service entrance is dominated by the reactance of the service entrance transformer. When this is the case, the harmonic number at parallel resonance can be calculated with the simple formula shown in the harmonic estimation worksheet (Chapter 23.). In this case, there are two transformers in series feeding the plant and both must be considered (Figure 7.1). Therefore, the resonant frequency must be calculated with the more general formula given in Chapter 20.

Service entrance transformer reactance (5.8% @ 5 MVA) in ohms at 480 V:

$$X_T = .058 \cdot \frac{0.48^2}{5} = 0.00267$$

Utility substation transformer reactance (7.08% @ 12 MVA) referred to 480 V:

$$X_S = 0.0708 \frac{13.8^2}{12} \left(\frac{0.48}{13.8} \right)^2 = 0.00136$$

Capacitor reactance for 420 kvar, 480 V:

$$X_C = \frac{.48^2}{0.420} = 0.5486$$

Parallel resonant frequency:

$$h_{pk} = \sqrt{\frac{0.5486}{0.00136 + 0.00267}} = 11.66$$

Tuning the system so closely to the 11th harmonic often means serious trouble because ASDs and other power electronic equipment produce significant currents at this harmonic. This system is fortunate that there are no major harmonic sources and no significant utility bus distortion at the 11th harmonic. This was determined during the plant survey and was confirmed by follow-up measurements after the capacitors were installed. Such measurements should always be made in situations like this because of the potential for something to go wrong. If there is a change in the future such as the installation of large ASDs, modifications will likely have to be made to the capacitor installation.

If that were to happen one possible solution would be to increase the capacitor sizes to force system tuning safely below the 11th harmonic but above the 7th. This technique works well on a stiff system such as this because the resonant peak tends to be narrow. Another option is to install capacitors as close to individual loads as possible. This increases the length of cable in the resonant circuit, improving the damping. However, this system is relatively compact and not much damping can be achieved. It is likely that should harmonic distortion increase in the future, some sort of filtering will be required. Otherwise, the capacitors will be subject to failure or fuse blowing.

Installation

Fourteen 30 kvar capacitors were added at motor control centers throughout the facility to achieve 420 kvar of compensation. Most motors in the facility were too small to permit 30 kvar to be switched with the motors. Therefore, the capacitors were installed at motor control centers where spare circuit breakers were available or easily installed. The 30-kvar unit was chosen because it was a convenient size to install and was economical.

The capacitors are switched manually using the breakers and generally remain energized continuously. The total plant load goes leading when the load is at the 200 kW minimum level, but this is of little consequence.

Results

The installation of the capacitors was accomplished without incident. They remain energized all the time the motor control centers are energized. The no-load voltage rise and harmonic levels are very minor. Capacitor current distortion is only 7%, which causes an imperceptible increase in the rms current. Thus, all appears to be functioning as determined by calculation.

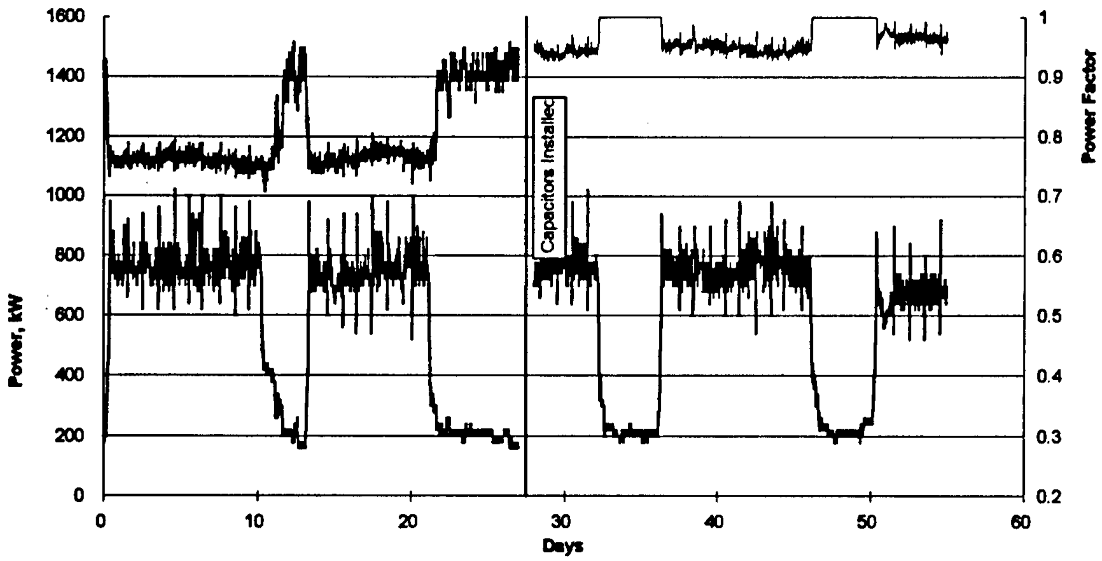


Figure 7.3. KW and power factor chart showing loads before and after capacitor installation.

Figure 7.3 shows the kW and power factor charts for several days immediately before and after capacitor energization. The power factor typically averages 96% and the power factor penalty has been eliminated, saving over $600 for a typical month. The amount of losses saved by the capacitors is not perceptible on this scale, but must be computed. A computer power flow simulation indicates the reduction in losses to average about 1.0 kW, which accounts for about $5 per month at the marginal energy rate.

8. Case Study #2: Wood Veneer Processing Plant

Case study #2 involves a lumber processing facility fed at 12.47 kV from the utility. As shown in Figure 8.1, the plant load is fed through three transformers within the plant at 480 V and 2400 V.

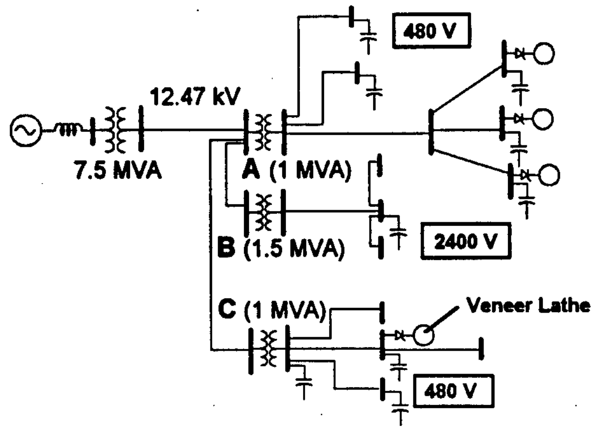


Figure 8.1. Case 2 plant diagram.

This plant was selected for a case study because it already had capacitors installed. Therefore, it was possible to obtain "before" and "after" measurements relatively quickly so that the computer models could be calibrated more quickly. The plant also offered an interesting challenge on two fronts:

1. The capacitors had failed to achieve the desired power factor. Instead of correcting to 95%, the power factor was typically 89-90%.

2. There were several significant harmonic sources, which would challenge our understanding of how capacitors and harmonic sources interact on such a large system.

Preliminary Evaluation

Because of the unique situation of the plant, the preliminary evaluation as defined in the recommended capacitor application procedure of this guide book was not performed. In fact, this case study falls more into the category of modifying the installation at the bottom of the Capacitor Application Process flow chart because results fell short of expectations. The preliminary evaluation consisted of a fact-finding visit to the plant to determine what had been done and what metering would be required for the detailed plant survey.

Application Process flow chart because results fell short of expectations. The preliminary evaluation consisted of a fact-finding visit to the plant to determine what had been done and what metering would be required for the detailed plant survey.

At this point in the case study, there was much discussion about what had gone wrong and how we might detect various suspected causes by measurements. Initially, there were two chief suspects: harmonics and the impulse loading of the veneer lathe. Harmonics could have caused two problems:

1. Excessive harmonic currents could have caused some of the capacitors to fail, which might explain why the actual correction was less than expected,

2. Harmonics currents cause the true power factor to be lower than just considering power frequency currents. Capacitors will not correct for the harmonic reactive power component. If the utility metering was measuring the true power factor rather than just the displacement power factor, this might explain why the correction was less than expected.

The idea associated with impulse loading was that the capacitors might not correct for the instantaneous power factor during the several seconds that the veneer lathe was dispatching a log and the accumulation of this over the month was causing the average power factor to appear lower than expected.

As it turned out, there was a much simpler explanation than either of these two. Most of the capacitor were installed on motors. The detailed plant survey showed that many of the motors were not energized when the power factor correction was needed. There were a few failed capacitors found, but it is believed that they were associated with reversing motors and the frequent switching is a more likely cause of failure than harmonics.

Plant Survey

A detailed survey of plant load was conducted for this facility. A pulse recorder was added to the utility revenue meter to record load data for the total plant. Two electronic watthour meters were installed on lines A and C. These meters had the capability of recording demand interval data and for recording both leading and lagging reactive power separately. Two BMI 3030A instuments were used to monitor individual loads and take snapshots of the voltage and current waveforms. Nameplate data was collected from each transformer and motor. All cable sizes and lengths were recorded.

Figure 8.3 shows the kW load characteristic for one month. During heavy load conditions, which average around 1100 kW, the power factor was typically 0.55. The plant has a large number of induction motors and adjustable speed drives which operate in short duty cycles. Hand calculations are not practical in this case because of the large number of operating scenarios that must be evaluated and the complicated structure of the circuit with multiple voltage levels in the plant.

Using 0.55 power factor and 1100 kW, you would estimate from the Capacitor Costs Worksheet that approximately 1300 kvar are needed to correct to 0.95 power factor. The plant already had 1270 kvar of capacitors installed, but according to utility billing, the actual power factor averaged only 0.89. Reasons for this discrepancy have been explained above.

The survey showed that one could count on having an average of only 1092 kvar actually in service during the peak load conditions. Therefore, an equivalent additional 150-200 kvar were needed.

Capacitor Scheme Selection

The transformer and cable data recorded in the survey were entered into a power flow computer program. This includes the nameplate impedance data from the transformers and the cable impedance data. The size and length of each cable was used to determined the cable impedance from the conductor tables reproduced in the Appendix. The portion of the plant electrical system modeled is shown in the one-line diagram above. This includes all transformers, cables, and buses up to the motor control centers. The leads to individual motors were not represented in the analysis for determining the capacitor distribution. However, they were included in the computation of losses in the entire plant Analysis of the plant survey data showed that 78% of the total losses in the plant were in the portion of the system modeled. The existing capacitors were modeled by entering the average amount of capacitive kvar found to be active on each bus during peak load conditions when the total plant load was about 1100 kW.

The computer program determined that an additional 150 kvar would be needed to obtain 95% power factor at 1100 kW demand. Losses were minimized by placing 50 kvar at the ends of two of the feeders in the "A" line and 50 kvar near the veneer lathe motor drive in the "C" line. Unfortunately, it was found that there were no suitable places for capacitors in these specific locations. It was decided to switch the capacitors with motors, so large motors in similar locations that were running a significant amount of the time were sought. To achieve an average of 150 kvar, a total of 205 kvar in sizes ranging from 7.5 kvar to 30 kvar were installed on motors that were energized from 60% to 100%

of the time. At two locations units were banked to form a total of 50 kvar and 70 kvar, respectively. 185 kvar were installed on the "A" circuits because that had the greatest effect on the losses. 20 kvar were installed on a pump motor on the "C" line. Computer calculations of the losses for actual installation indicated that the losses were only 100 W higher than the optimal case. This is a trivial amount that is probably smaller than the accuracy of the simulation, so the two solutions are essentially identical from the loss viewpoint.

There is inadequate space here to describe all the details, but this discussion should give you an idea of the iterative process required to go from a suggested computer solution to a practical application.

Loss Savings

Rather than estimate the losses by a simple formula, the *average* cable and transformer losses for the plant were calculated by computer simulation to be:

- 25 kW without capacitors.
- 11.2 kW with existing capacitors.
- 8 kW with the 205 kvar additional capacitors.

Thus, the average plant losses can theoretically be cut to one-third the value without capacitors. This amounts to a savings of 1% to 1.5% of the peak load kW.

The losses were computed by following the load curve for one day. While this may seem a daunting task, it is not always necessary to enter an extremely detailed load curve to achieve satisfactory results. In fact, the load profile illustrated in Figure 8.3 can be approximated by a demand of 1100 kW for 5/6 of time, and 440 kW for 1/6 of the time. The plant had these two dominant load states. It is expected that many industrial plants will have similar characteristics with only a few disctinct load states. Using this approximation was sufficient for estimating the economic benefits. Of course, more detailed data may be used if available.

This case is, perhaps, a bit unusual due to the three transformers. These account for approximately two-thirds of the losses that could be reduced by capacitors. This should not be surprising. The transformers accumulate all of the currents from the loads served as opposed to cables which carry only part of the load. Since the losses vary by the square of the current, it should be expected that they will be proportionately higher in the transformers.

$$Loss\,Fraction = 1 - \frac{PF_{old}^2}{PF_{new}^2} = 1 - \frac{.55^2}{.95^2} = 66\%$$

The actual computed improvement is:

$$(25\text{-}8)/25 = 68\%$$

The two values agree closely, which suggests that the ideal loss reduction can be approximated by distributing the capacitors across the system in the locations of concentrated losses.

Economic Evaluation

Although this case study started with capacitors already installed, an economic analysis of the additional 205 kvar of capacitors was computed anyway. The additional capacitors save an average of 3.2 kW losses. Based on the marginal energy rate for this facility, this saves about $56 per month in energy charges and about $12 per month in demand charges. In addition the capacitors eliminated the remainder of the demand charge penalty, which was about $260 per month. Thus, the annual savings are expected to be about $3900. Assuming $30 per kvar, the capacitors would cost $6150, yielding a simple payback of 1.57 years.

Using the simple screening technique described earlier, a 3-year payback at 6% interest would have justified the expenditure of $10,682. The benefit to cost ratio for this is 1.7. On this basis, this installation should prove to be very economical.

It may be a bit unusual to achieve such good economics on the last 200 kvar out of 1500 kvar. Normally, there is a diminishing return as the power factor approaches 95%. There were two factors that contributed in this case:

1. The capacitors were placed where they were able to save considerably more losses than the average,

2. The power factor penalty is a linear function of difference in power factor from 95% while the power factor is being improved in diminishing proportion.

With no capacitors, the power factor penalty was determined to be $1600 per month. Cutting the losses by an average of 17 kW should save another $350 per month, yielding a total monthly savins of $1950. Thus, the loss savings amount to about 20% of the total savings in this case.

Retrospective

If we had been starting from no existing capacitors, the high load diversity suggests that a few 100-250 kvar automatic power factor controllers placed at some of the motor control centers might have been a good option. It is likely that the automatic controller would have been cost competitive with several of the smaller capacitor installations and would have avoided the problems of inadequate compensation when certain motors were not energized. However, it would not have been cost effective to remove the existing capacitors on the motors and retrofit an automatic controller.

Harmonic Concerns

The harmonics were analyzed both by measurement and computer simulation. There were several major adjustable-speed or dc motor loads as indicated on Figure 8.1. There was a large veneer lathe on the C line and several drives on the A line. The number of these loads was cause for concern for problems due to capacitor-induced resonance. Concern for harmonic problems was heightened by the fact that a few existing capacitors were found to have failed, or to have blown fuses. However, there is no conclusive evidence that harmonics contributed to this.

The harmonic impact of adding the new capacitors was analyzed using the SuperHarm™ computer program that is specifically designed for this task. Figure 8.2 shows the plot of the impedance vs. frequency associated with the case. This, too, suggested a possible harmonics problem because a parallel resonance peak shows up near the 5th harmonic (300 Hz). Since this is one of the largest harmonics produced by ASDs, this was particularly troubling.

Given these computations, one would be tempted to consider a filter. However, measurements taken during the detailed plant survey showed that while harmonics were present, there was not really a problem. Further investigation indicated that there were two effects occuring:

1. There was sufficient damping due to the cable resistance and loads to prevent resonance,

2. The relatively stiff 12.47 kV system tying the different parts of the plant helped isolate the harmonic currents in different parts of the plant, although it did not isolate completely.

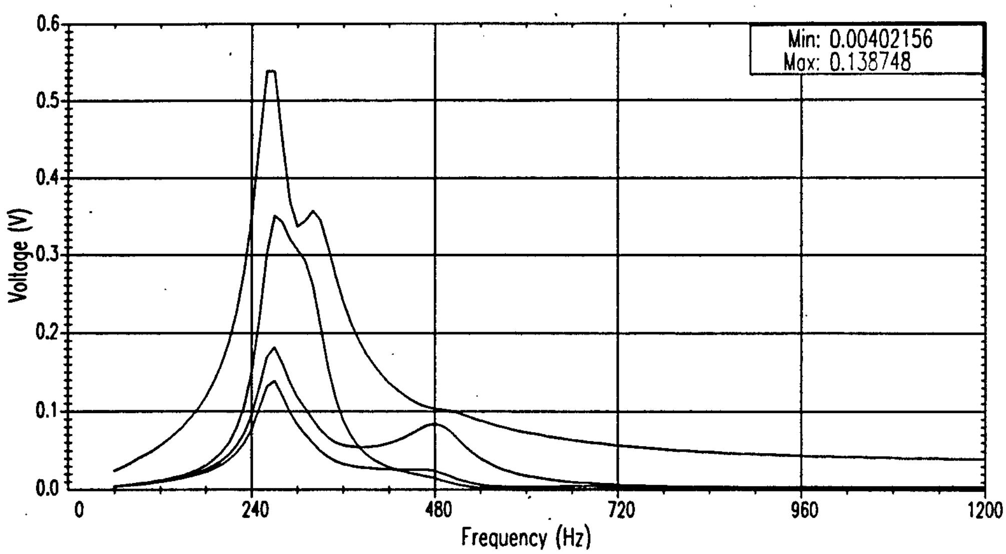


Figure 8.2. Harmonic impedance at various plant buses due to proposed capacitor configuration.

Placing the capacitors toward the ends of the feeders close to the load provides more resistance to reduce resonance.

As a result of this series of events, a new harmonic evaluation procedure was developed from this case study for complex systems. This is described in chapter 23. This method predicts almost precisely the distortion levels measured in this case study. A typical capacitor current was distorted 25-30%, yielding an rms current of about 104%. The worst single measurement showed a THD in the current of 50% with an rms of 125%. As expected, the 5th harmonic was generally the highest. The measured values were well below typical capacitor fusing levels, which indicates that the application is likely to be successful.

The importance of measurements in harmonic analysis must be emphasized. In both cases studies reported here, a cursory calculation of the resonant frequency indicated that trouble was possible, but measurements confirmed subsequent detailed calculations that indicated that the applications were possible without problems.

If we had not been so fortunate, the best option was to convert a large capacitor bank (250 kvar) on the "C" bus into a 5th harmonic filter. Of course, this would have increased the cost of the installation quite significantly and it was fortunate from the economical point of view that it was not needed.

Results

Figure 8.3 shows the kW and power factor characteristic without capacitors compared to after installation. There is a dramatic improvement

Results

Figure 8.3 shows the kW and power factor characteristic without capacitors compared to after installation. There is a dramatic improvement in the power factor. The average monthly power factor is currently 95%, which eliminates the power factor penalty. This confirms that we were able to locate the capacitors on the correct motors to achieve proper correction. Harmonic levels are within expectations. There is some noticeable distortion in the bus voltages and capacitor currents, but it is well within limits.

Although the percentage losses are much higher in this case study than the previous case study, it is still impractical to discern the difference by these measurements. In fact, you will notice that the average kW load is higher after the installation of the capacitors. This is due to changes within the plant and to different characteristics of the logs being processed. Because the load changes so rapidly, it is impractical to find two before and after intervals that are sufficiently identical to compare. Thus, we have to rely on using the computer to sum the losses in each branch of the circuit, which indicates that the capacitors save 1 - 1.5% of the total energy consumed when compared to the case without capacitors.

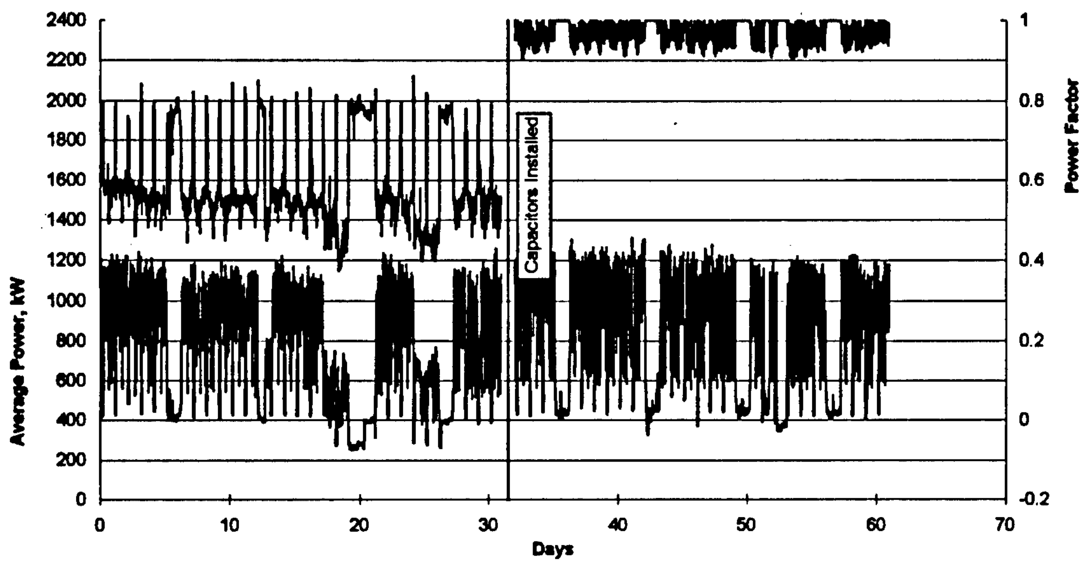


Figure 8.3. 30 day variation in plant load without capacitors (left) and with capacitors (right). Leading power factor goes off scale at the top.

9. Using the Power Factor Improvement Computer Program

The Power Factor Correction and Energy Savings computer program was developed to support the capacitor application procedure described in this guide. This chapter contains a brief description of how to make use of the computer program in the capacitor selection process.

While some simple installations can be easily analyzed manually, a computer program can be quite handy in power factor correction for most industrial plants. A power flow program, a spreadsheet program, and a harmonics analysis program were extensively used for the two case studies. This computer program combines some of the essential features of each to provide a tool that can perform the calculations for the vast majority of industrial capacitor installations with as simple of a user interface as possible.

A computer program is particularly useful when trying to optimize for losses. There is no easy way to accurately determine the losses in a plant's power delivery system other than adding them up transformer-by-transformer and line-by-line. This would be quite tedious to do repeatedly by hand, but a computer can do this in milliseconds -- after the appropriate data are collected.

Figure 9.1 shows a sample screen from the program. The program is written for the Microsoft® Windows™ 3.1 operating environment.

The computer program has the following main capabilities:

1. Power flow calculation.
2. Optimal siting of capacitors for loss reduction.
3. Estimation of transformer and cable losses.
4. Estimation of a monthly bill.
5. Economic evaluation of capacitor alternatives.
6. Estimation of harmonic duties on capacitors.
7. Graphical display of daily load variations.

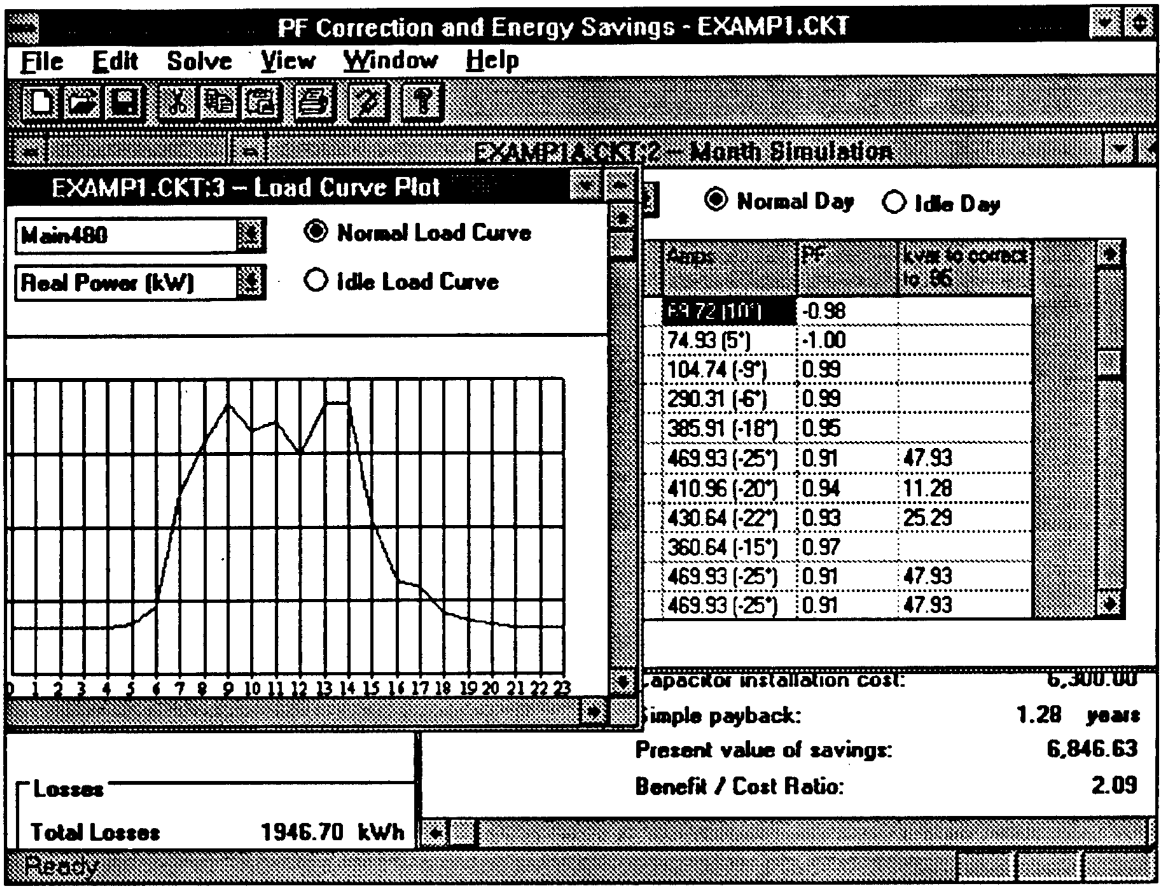


Figure 9.1. Sample screen from the Power Factor Correction and Energy Savings computer program

Collecting Data for the Computer Program

The basic data that must be collected are:

1. General topology of the circuit. Make a one-line diagram showing major buses and cables and transformers between them. Give each bus, transformer, and cable a name that you will be able to recognize.

2. Wire sizes and approximate lengths of major cables, at least up to the motor control centers. These are used to get the cable resistance and reactance, which is required by the program.

3. Impedance and kVA ratings from the nameplate of the transformers.

4. Load data consisting of kW and power factor. At a minimum, the peak load should be determined. Ideally, hourly demand curves should be obtained for each load. The program is able to accept

these. A good compromise is to monitor the main feeds to determine approximate load shapes.

5. Kvar and voltage rating of any existing capacitors.

Impedances of common industrial power cables are given in the cable impedance tables in the Appendix. Cable resistances and reactances must be entered in ohms per unit length, which are then multiplied by the length. Transformer impedances are entered in percent on the kVA rating of the transformer. This is usually given on the nameplate. Sometimes, the percent resistance is omitted from the nameplate, but this is an important quantity for this analysis because the losses in the transformers are significant for capacitor application and harmonic distortion calculation. A good estimate is to assume 10% of the reactance for larger transformers, 15% for medium-sized transformers, and 30% for small transformers.

Step-by-Step

The basic procedure for using the program to apply power factor correction capacitors is as follows:

1. Define the circuit configuration by entering the cable and transformer data into the program.

2. Define the loads at the buses. Specify the kW of each load. Also, define load curves for different classes of loads, both normal and idle days.

3. Fine-tune the base case model loading so that the calculations approximately match the measurements.

4. Save the base case before proceeding!

5. Make a new copy of the base case and add capacitors.

6. Compare the economics of the new case with capacitors to the base case.

7. Repeat steps 5 and 6 with different capacitor and load configurations to determine if more economical solutions are achievable by other strategies.

8. Check the harmonic distortion in the capacitors. If too great, change the capacitor configuration or add filters and try again.

The default circuit in the program matches the basic structure of many industrial power systems. It is similar to the circuit shown in Figure 5.1.

The circuit can be expanded indefinitely from that basic circuit with the restriction that the circuit be radial. Add lines and transformers as necessary to approximate the structure of the circuit up to at least the main motor control centers. When a new line or transformer is added to an existing bus, a new bus is provided. You may go into as much additional detail as you wish.

There is a default load curve, but you may add more load curves as necessary to represent the behavior of the loads. Load curves are simply the hourly magnitude and power factor of the load for a day. Load magnitude is entered in percent. The kW size of each load is defined with the load definition. Each load has two load curves: normal day and idle day. When the monthly bill is estimated, it is assumed that there will be a certain number of each of these two types of days in month. This can be changed interactively on the bill screen. There can be as many individual loads at a bus as you wish, each with different characteristics.

The model is calibrated by adjusting the loads to duplicate observed conditions as closely as possible. Use the single snapshot load flow to duplicate measurements at particular time intervals. Then adjust the load curves and number of normal days vs. idle days to approximate the typical monthly bill. This is used for comparison purposes after the load is added.

You may add capacitors manually or allow the computer program to do it automatically. The Monthly Simulation screen shows the amount of capacitive kvar needed to correct to 0.95 pf at each bus for each hour of the day. The computer adds capacitors in small increments at the location offering the best loss improvement until it reaches an overall plant power factor specified by the user.

To determine the economics of a particular case, the capacitor costs and the monthly bill are compared to a base case of the user's choosing. When each capacitor is added its cost is specified. When the computer adds capacitors, they are assigned costs at a constant $/kvar value selected by the user. Afterward, you may modify the cost of any capacitor on the system. The monthly simulation is automatically performed and the monthly bill is computed if it has not already been done.

The program is designed to make "what if" analysis easy and fast. Thus, the user is encouraged to try different capacitor configurations. Simply make another copy of the base circuit and add capacitors in a different manner.

Using the Program's Optimized Capacitor Application

The program applies a number of small capacitors across the system to minimize the losses at peak load. The user is asked to specify the capacitor increment size. This can be either an arbitrary size or a size that the user would prefer to install. It is recommended that the size be approximately one-tenth of the total amount of kvar needed, or smaller. The amount needed can be determined from the Monthly Simulation screen for the main bus (where the meter is located).

The user is also asked to provide a cost per kvar for the capacitors. For 480 V capacitors, a good estimating cost based on current costs for the complete installation is about $30/kvar. Of course, this will vary by size and vendor. Since there is a fixed cost per bank for installation labor and materials, the small units will have a higher $/kvar value and the larger units will have a smaller value. You can save the results of preliminary calculations and then go back at any time and recompute the economics after you receive price quotations from vendors.

When the program has completed its task, there will usually be some buses with several capacitors of the size increment you chose. The user has the option of purchasing larger units that are the sum total of the individual banks or purchasing several smaller units. While the latter is generally a little more expensive, it will sometimes permit a more flexible configuration and reduces the chances that the failure of one unit will have a serious impact on the monthly bill.

Numerous small banks placed on a motor control center feeding many small motors may be an indication that an automatic power factor controller may be useful. Since these are more expensive, it is necessary to adjust the cost of the capacitors being considered and do the economic comparison again to determine if the installation is economical.

The cost of capacitors considered in the economic evaluation is only the cost of the "new" capacitors. All capacitors allocated by the automatic algorithm are given the "new" attribute. This may be changed for particular capacitors, if desired, by editing the capacitor properties.

Checking the Voltage Rise

It is a simple procedure to check the voltage rise caused by capacitors at low load conditions to determine if you need to switch the capacitors. If you have modeled the daily load curve, you will be able to see the voltage fluctuation with load when you do the Monthly Simulation. You can get a tabular listing of the voltages or a plot of the voltages. You can also do this analysis simply by deleting all the loads or setting them to zero while leaving the capacitors on. The program automatically computes the bus voltages that result.

If the program predicts a voltage rise that exceeds standards, you can start deleting capacitors until the voltage goes back in bounds. This will tell you the minimum number of capacitors that you need to switch. Of course you may choose to switch more than that.

Checking Harmonics

Once you've arrived at a capacitor configuration, you can easily make a simple, but effective evaluation of the potential for harmonic problems. First, edit the source voltage to reflect the proper voltage spectrum for the 5th, 7th, 11th, and 13th harmonics. These are the most common harmonics produced by industrial equipment such as adjustable-speed drives. The values to use should ideally be determined by measuring the main bus voltage. If these values are not available and you must make an estimate, the default values represent a high typical distortion level commonly found. This generally is conservatively high. One thing you have to be careful of is that it could lead to the conclusion that harmonic mitigation is required when it is not. That is one reason why actual measurements are well worth the extra effort and expense. Ideally, the measurements would be made with no capacitors present on the system.

The program then computes estimates of the harmonic currents in all the capacitors and reports these values in percent of rated current. It also reports the total harmonic distortion (THD) at each bus. If the capacitor currents exceed 135% or the bus THD exceeds 5%, something will have to be changed. It is a simple matter to try changing the capacitor sizes and locations to get away from the resonance point. If this fails, you may experiment with adding filters in place of the capacitors. Make your changes and then repeat the harmonics solution until a suitable solution is found.

If your system has harmonics other than the ones indicated, another computer tool will have to be used. This program is designed only to handle the more common factory floor cases. In particular, the program will not handle neutral overloading calculations caused by triple harmonics because there is insufficient data to construct the correct circuit model.

Reference Section

Definition of Power Factor

10. Definition of Power Factor

Electrical loads demand more power than they consume. Induction motors, for example, convert at most 80 - 90% of the delivered power into useful work or electrical losses. The remaining power is used to establish an electromagnetic field in the motor. The field is alternately expanding and collapsing, thus the power drawn into the field in one instant is returned to the electric supply system in the next instant. The *average power* drawn by the field is zero.

However, the action of the field increases the motor's current demand, which in turn, increases heating in cables and transformers supplying the motor. The additional current also increases voltage drop across these components. Cable and transformer capacities must be increased to keep heating and voltage drop within allowable limits, resulting in increased costs.

Demand power, or *apparent power*, is a measure of how big the system must be built in order to supply a given load. Apparent power is found by multiplying the load's rms voltage and current, and is measured in units of kilovolt amperes (kVA). Power consumed, or *active power*, is measured in kilowatts (kW).

Power factor is simply the ratio of active power to apparent power.

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

The highest possible power factor is 1.0, which means that 100% of the power delivered to the load is converted into useful energy. Anything less than 1.0 indicates that the power system must be built larger in order to serve the load.

Traditionally, concern for power factor has been almost exclusively linked with use of induction motors. Now, facility engineers are also confronted with nonlinear loads. Power electronic equipment (adjustable speed motor drives, uninterruptible power supplies, induction furnaces, and other electrotechnologies) are the most common type of nonlinear load. Arcing loads (arc furnaces, welders) are also nonlinear.

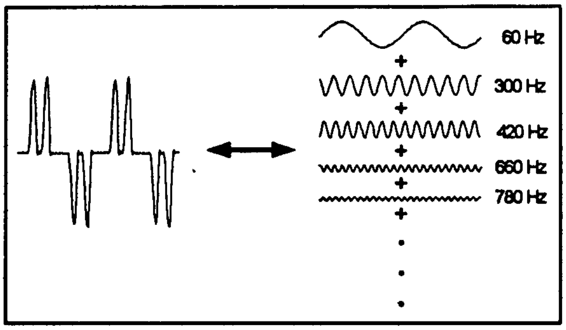


Figure 10.1 Distorted current can be regarded as a sum of sinusoidal currents of various frequencies.

Like inductive loads, nonlinear loads degrade power factor by "borrowing" and returning power to the power supply system. But there the similarity ends. The power system delivers current to a nonlinear load at the fundamental frequency (60 Hz in North America), and the load returns some of the current at higher frequencies(see Figure 10.1). Since the current waveform contains multiple frequencies, it appears distorted (nonsinusoidal) when viewed with an oscilloscope.

Distortion due to nonlinear loads is discussed in Chapter 19. The important thing to note here is that the traditional methods for analyzing power factor are not necessarily appropriate when dealing with nonlinear loads. The definition of power factor as the ratio of active power to apparent power, on the other hand, is always correct.

11. The Power Triangle

The power triangle is commonly used to describe power factor for motors and other linear loads. Although it doesn't apply as well to nonlinear loads such as adjustable-speed drives, it is still a useful concept to understand.

The power triangle can be illustrated using the R-X branch as shown below. If the branch voltage is perfectly sinusoidal, the current must also be sinusoidal, and will lag the voltage by some angle, θ, called the *displacement angle,* or the power factor angle.

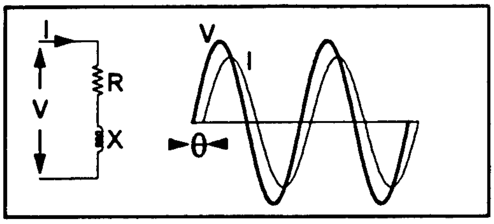


Figure 11.1. Displacement angle.

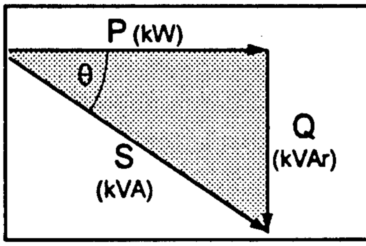
The formulas for apparent power *S*, and active power *P*, yield the well-known definition of power factor:

$$\begin{matrix} P = I^2 R \\ S = V \cdot I \end{matrix} \Rightarrow \frac{P}{S} = \cos\theta \equiv DPF$$

Here, the term *displacement power factor (DPF)* is used to emphasize that the power factor has been calculated using the displacement angle, as opposed to *true power factor (TPF)*, which is the ratio of *P* to *S*. This distinction is not normally made because when no harmonic sources are present *DPF* = *TPF*.

It is the DPF that most utilities currently measure, but there is a movement among some to measure TPF, which would include the effects of distortion. There are electronic meters capable of recording TPF properly.

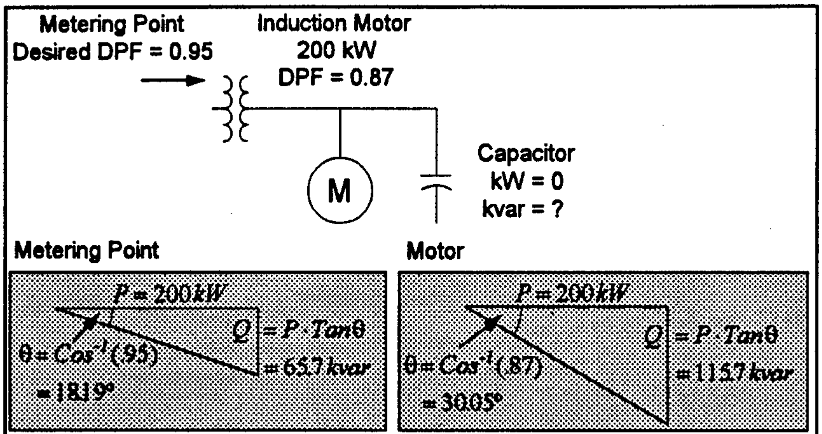
The formula $P = S \cdot \cos\theta$ suggests a right triangle relationship between *P* and *S* as shown in Figure 11.2. The third leg of the triangle, designated as Q, is called the *reactive power* and is measured in kvar (kilovolt amperes reactive).



$$P = S \cdot \cos\theta = S \cdot DPF$$
$$Q = S \cdot \sin\theta = P \cdot \tan\theta$$
$$S = \sqrt{P^2 + Q^2}$$
$$\theta = \arctan\frac{Q}{P}$$

Figure 11.2. Power triangle.

Q is actually a convenient mathematical contrivance, but is very useful because, *if there is no distortion*, it is conserved, just as active power is conserved. That is, the reactive power (vars) appears to flow around the system just like the active power (watts). In this concept, motors absorb vars while capacitors produce vars.



$$\begin{aligned} P_{Sources} &= P_{Loads} \\ P_{Meter} &= P_{Motor} + P_{Cap} \\ ? &= 200 + 0 \\ \Rightarrow P_{Meter} &= 200kW \end{aligned}$$

$$\begin{aligned} Q_{Loads} &= Q_{Sources} \\ Q_{Motor} &= Q_{Metered} + Q_{Cap} \\ 115.7 &= 65.7 + ? \\ \Rightarrow Q_{Cap} &= 50\,kvar \end{aligned}$$

Figure 11.3. Using the power triangle to find capacitor size.

Figure 11.3 illustrates how *P* and *Q* can be combined with the power triangle relationships to determine the amount of capacitor kvar that must be added to a circuit in order to obtain the desired power factor. These relationships will be simplified to a single, easy formula for determining capacitor size in Chapter 14.

12. Why Should Power Factor Be Improved?

Raising system power factor provides the following benefits:

- Lower utility charges
- Increased system capacity
- Less voltage drop
- Reduced losses

Reduced Electric Utility Charges

Thermal capacity considerations, discussed below, force the electric utility to overbuild its distribution system in order to serve a facility with low power factor. The utility may or may not charge the customer for the increased expense of larger system components. If it does, then adding capacitors is usually justifiable.

Increasing System Capacity

The thermal capacity of generators, transformers, and cables limit the kVA that can be supplied from the system. Reducing the net kvar demand from existing loads allows additional load to be added to the system.

Figure 12.1 can be used to calculate thermal capacity release. It assumes that the system is presently loaded to capacity, and that the present load and the new load have the same power factor. As an example, the figure shows that the capacity of a 1000 kVA, 0.8 PF system can be increased 150 kVA by adding a 300 kvar capacitor.

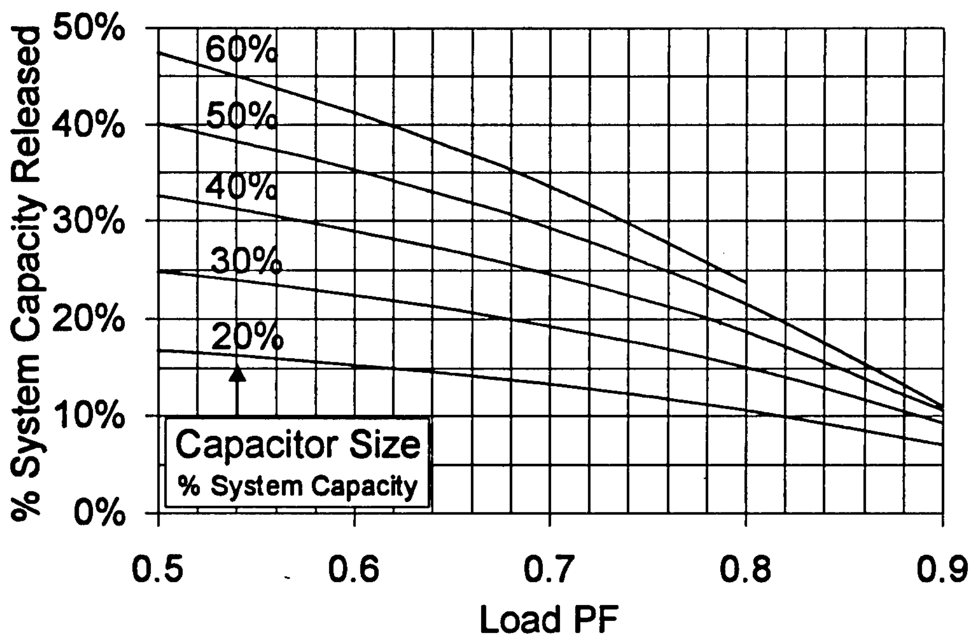


Figure 12.1. System capacity released by adding capacitors.

Because these curves are almost straight lines, capacity release can be estimated from this simple expression:

$$\%kVA = 100 \cdot \left(1 - \frac{PF_{Old}}{PF_{New}}\right)$$

Improving Voltage

High load kvar demand increases the voltage drops across transformers, cables, and other system components, resulting in decreased equipment utilization voltage. In a weak system, capacity can be limited by excessive voltage drop, rather than by component thermal ratings

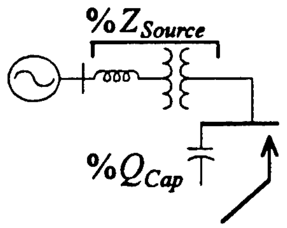
ANSI C84.1-1982, *American National Standard Voltage Ratings for Power Systems and Equipment (60 Hz)* establishes limits for minimum equipment utilization voltage. Strict "range A" (-10%, -8.3% for lighting) and more liberal "range B" (-13.3%, -11.7% for lighting) limits are defined. Prolonged operation outside of range A should be avoided; operation outside of range B should be corrected immediately.

Most facility systems are not limited by voltage drop, so power factor correction usually cannot be justified on this consideration alone. But improved equipment performance is a significant added benefit. For example, fully correcting a 5% undervoltage will (typically):

- Increase induction motor starting torque, running torque, and momentary overload capability by 10%. Decrease induction motor temperature rise by 5%.
- Provide the same benefits to synchronous motors. (The improvement will not be as great if the motor field is supplied from a DC generator driven by the motor.)
- Increase lighting intensity by 20% for incandescent lamps, 5% for fluorescent lamps, and as much as 15% for high intensity discharge lamps, depending on the type of ballast employed.

Of course, these benefits are highly dependent on the loading and design of specific equipment. It is possible that the increase of efficiency in certain processes will be substantial, although difficult to quantify.

Circuit current, and, therefore, circuit voltage drop, is reduced in direct proportion to the increase in power factor. This leads to the following equation for estimating the voltage improvement that will be obtained by applying capacitors:



$$\% \Delta V \approx \% Q_{Cap} \cdot \% Z_{Source}$$

where capacitor kvar, Q_{cap}, and source impedance, Z_{Source}, are expressed in percent of the transformer rated kVA. As an example, the voltage rise that will result from applying a 350 kvar capacitor at the secondary of a 1000 kVA transformer with an impedance of 7% is:

$$\% \Delta V \approx 35\% \cdot 7\% \approx 2.5\%$$

neglecting all impedances but the transformer.

__Reducing Circuit Losses__

Since circuit current is reduced in direct proportion to the increase in power factor, the I^2R loss, or resistive loss, in the circuit is inversely proportional to the square of the power factor. The loss reduction resulting from power factor improvement is:

$$\% \Delta P_{Loss} = 100 \cdot \left[1 - \left(\frac{PF_{Old}}{PF_{New}} \right)^2 \right]$$

It is first necessary to know what the system losses (kW) are in order to use this formula to calculate actual loss savings. The most accurate way is to make measurements of the current in each line and sum up the losses in the individual cables and transformers. Lacking this information, a rough estimate can be determined using the technique described in the Loss Savings Worksheet in Chapter 4.

By itself, loss reduction doesn't justify the cost of installing capacitors, but the added benefit can be substantial. For example, in the second case study, losses comprise nearly 20% of the total justification.

13. Methods of Reactive Compensation

Capacitors

By nature of its electrostatic field, the capacitor stores energy whenever the voltage applied across the capacitor is moving away from zero; it gives up energy after the voltage has crested. This sequence is opposite to that of the magnetic field, so the capacitor can be used to supply magnetizing current that would otherwise be drawn from the utility source.

Capacitors are generally the most economical source of reactive compensation. Other advantages include:

- low losses (less than ¼ Watt/kvar)
- essentially no maintenance
- light, compact units which can be combined as needed, make capacitors relatively easy to install and modify as reactive compensation needs change

Synchronous Machines

Both synchronous motors and generators can provide reactive power by increasing the excitation field sufficiently. The kvar available from a fully loaded machine depends on the rated kW and power factor:

$$kvar = kW \cdot \sin(\mathrm{acos}(pf))$$

More kvar is available if the machine is not fully loaded. For example, a 1.0 PF, 100 kW motor can provide 0 to 30 kvar from full load down to no load by operating in a leading mode.

A synchronous condenser is essentially an unloaded motor whose sole task is to provide reactive power. Synchronous condensers are continuously variable within wide limits to generate or consume kvar. Due to high initial costs, losses, and maintenance costs, synchronous condensers are not generally used for power factor correction unless their voltage stabilizing effects and influence on the system short-circuit capacity are needed. However, they do have the advantage that they do not cause harmonic resonance as capacitors sometimes do. Therefore, they are used in certain difficult situations where the extra costs are justifiable.

Static Var Systems

Loads such as arc furnaces and welders exhibit a rapidly changing current demand which may result in an unacceptable fluctuation of bus voltage, called flicker. One way to eliminate the flicker problem is to use a controller that can match the load's instantaneous reactive current demand. Only static var controllers employing semiconductor switches provide the speed required to accomplish this.

14. Capacitor Sizing and Location

This chapter provides reference material for the capacitor sizing and location discussions presented in earlier parts of this Guide Book.

Total Capacitor Kvar Required

The power triangle calculations of Figure 11.2 simplify to

$$kvar_{Cap} = M \cdot kW_{Load},$$

where M is calculated as shown in Figure 14.1.

$$M = \tan(\operatorname{acos} PF_{Old}) - \tan(\operatorname{acos} PF_{New}) = \sqrt{\frac{1}{PF_{Old}^2} - 1} - \sqrt{\frac{1}{PF_{New}^2} - 1}$$

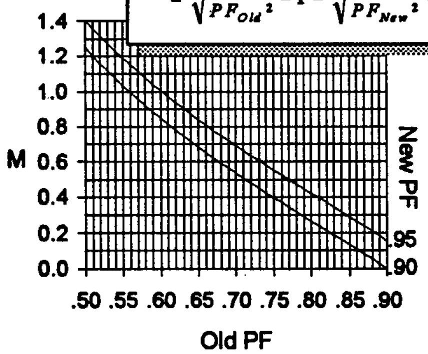


Figure 14.1. kW multipliers.

Capacitor Location

More difficult than determining total capacitance is deciding where the capacitance should be located. Should one large capacitor bank be used, or is it better to add small capacitors at individual loads? There are several factors to consider:

Cost. Adding fewer, larger banks is generally less expensive than smaller banks due to labor and materials costs for each bank. The costs per kvar are also less if the larger banks can be added at a higher voltage level. For example, capacitors applied at a 4.16 kV main bus might be less than half the cost per kvar than capacitors applied at 480 V buses. Of course, these will not provide loss reduction and capacity release at the lower voltage levels within the plant.

As pointed out several times in this Guide Book, automatic power factor controllers are generally at least double the cost per kvar of the lower cost fixed banks. They are generally economical only in the larger sizes (100 kvar, or more, for 480 V capacitors). Then they are cost competitive with several small capacitors distributed on motors. If capacitors are to be distributed for loss reduction and also need to be switched, an automatic power factor controller installed in a motor control center may be more economical than capacitors on each of the small motors fed from that control center.

Switched capacitors don't require switch control equipment if they are located on the load side of motor contactors. Thus, capacitors installed on the larger motors are nearly as economical as fixed banks installed at motor control centers. Therefore, the most economical capacitor installation, when some switching is required, is to install a base amount of fixed capacitors that are always energized and the remainder on the larger motors to be switched when the motors are switched. Load switching patterns must be observed to determine good candidate motors to receive capacitors.

Adding a reactor to convert a capacitor into a filter also approximately doubles the cost of the installation. To maintain the economics of the entire capacitor installation, a solution which requires only a small portion of the capacitors to be converted into filters is sought. Since filters must be designed to handle the capacity of the bus and not just the offending load, several smaller banks are generally combined into a large filter bank that is often placed more toward the main bus than toward the load buses. Some loss reduction is sacrificed, but that is the price paid to achieve successful operation.

Loss reduction favors distributing capacitance towards the loads. In the plant distribution circuit of Figure 14.2, motor *A* draws reactive current I_X from the capacitor at the main bus. This produces losses of $I_X^2 R_F$ and $I_X^2 R_B$ in the feeder and branch circuit supplying the motor. If motor *A* had a local capacitor like the one at motor *B*, this component of the losses would be eliminated.

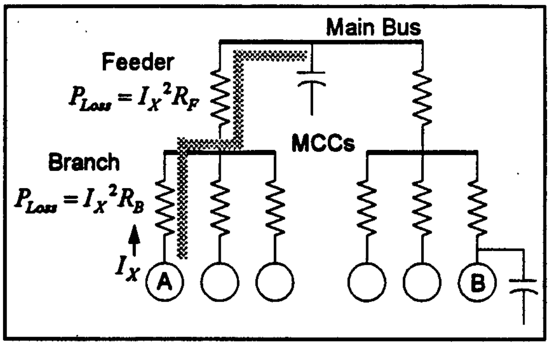


Figure 14.2. Reducing losses with motor capacitor.

Because of the power triangle relationship, the incremental improvement in losses obtained with each increase in the number of capacitors becomes progressively smaller.

The losses in feeders and transformers supplying a bus are typically much greater than those in branch circuits from motor control centers(MCC) to individual motors. Therefore, as Figure 14.3 illustrates, capacitors at the MCCs are typically almost as effective at reducing losses as capacitors at individual motors.

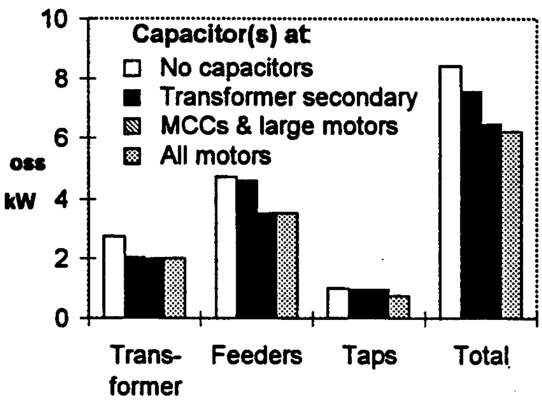


Figure 14.3. Effect of capacitor location on losses in service entrance transformer, feeders, and branch (taps) circuits.

Power factor improvement. Simply for overall power factor improvement, it would not matter how the added capacitors are distributed in the circuit. The capacitors simply must be energized when needed. The capacitors can be lumped at the main bus as is frequently done, but there is no energy conservation benefit because the losses in the lines are unchanged. Some installers will simply place capacitors on several of the convenient motors by consulting tables. However, it must be recognized that the capacitor is not available if the associated motor is off. It may not be possible to achieve the desired overall power factor solely with capacitors at motors.

Therefore, some fixed or switched capacitors at the MCCs or elsewhere in the circuit will be needed.

Voltage profile and release of system capacity. Two additional factors for sizing and placing capacitors are improvement to the voltage profile and the release of system capacity. Capacitors can help increase the voltage at the end of long cable runs or on the secondary of step-down transformers by both reducing the current and creating a voltage rise that counters the normal voltage drop of motor current. In fact, a voltage rise can be achieved if sufficient capacitors are placed on the system. This, of course, could present a problem at low loads if the voltage exceeds limits. If voltage improvement is the objective, the capacitance needs to be located as closely to the load as possible. If the load is to be intentionally overcompensated, keep in mind that there is a limit to the size of capacitor that may be switched with a motor.

Because of the action of reducing the current, capacitors may allow more load to be served from a bus without increasing conductor sizes on the incoming feed. Placing the capacitors at the MCCs will usually satisfy this requirement

15. Economic Evaluation

Economic analysis is used to determine which solution to a given problem is likely to be the best over a predetermined period of time. The essence of economic evaluation is to first identify the alternative technical solutions. Then all significant costs for each alternative are identified and assigned to specific time periods. The evaluation is carried out over the expected life of the equipment or a period of time determined by company financial guidelines.

In the case of power factor correction, the costs that must be considered are typically:

- cost of capacitors, switches, etc.
- installation costs
- operational and maintenance costs
- power factor penalty
- cost of losses

- study costs

For the plant with no existing power factor correction, the base case for comparison is generally the existing case with a high power factor penalty. Then alternative capacitor applications are developed and the costs estimated. Then it is simply a matter of determining the least cost solution considering the cost of money over time.

Electrical operational costs are generally negligible for capacitors, but there will be at least annual maintenance inspections, which might require the assignment of some costs.

The economic evaluation could include both the end user and the utility. Some analysts prefer this method because it tends to suggest solutions that are optimal for the whole electrical supply system. This is the so-called "value-based" economic evaluation that is popular today. However, it is generally assumed here that the power factor penalty reflects a fair representation of the utility costs and the economic evaluation is made strictly from the end user's point of view. While in some issues related to the quality of power, this can lead to decisions that are globally detrimental, decisions made by the end user for power factor correction are generally also beneficial to the utility as well.

Applying Discount Factors

Because the value of money is a function of time, costs in the future must be discounted before they can be appropriately included in the analysis. Thus, we cannot simply sum the costs directly. When capacitors are purchased, the costs of purchase and installation are generally in the beginning of year 1 of the evaluation period. However, maintenance costs as well as power factor penalty savings and loss savings continue to accrue over several years. All costs must be reflected to the same basis so that a correct evaluation may be made.

The discount factor generally reflects the cost of money that must be borrowed to purchase capital improvements. In larger corporations, this figure is usually dictated by the management and can reflect such things as a desired rate of return on investment and inflation.

Common evaluation techniques are described below.

Present Value Analysis

This is, perhaps, the most popular method of economic comparision employed today. The concept is simple: refer all costs to the present (year 0) and the lowest cost option will have the lowest present value. The entire cash flow series appears as a single purchase made at the present time. The present value (PV) of an arbitrary cost series $\{x_0, x_1, x_2, ...\}$ is:

$$PV = \sum_{k=0}^{n} \frac{x_k}{(1+i)^k}$$

where *i* is the interest rate corresponding to the time period and *n* is the total number of periods.

Annual Levelized Cost Analysis

This is similar in concept to present value analysis, except that the costs are converted to an equivalent annual cost that is the same for the entire period of the evaluation (i.e., the costs are levelized). This can be made equivalent to the present value analysis. This sometimes makes more sense for analyses that are dominated by continuing annual costs rather than by capital items that are purchased in the beginning.

The formula for converting a present value to a levelized annual cost series (A) is:

$$A = PW\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

where *i* is the annual interest rate and *n* is the total years. Economic evaluations made by industrial end users are typically no more than 3 to 5 years for electrical plant improvements, while utilities typically consider improvements for at least 10 years.

Benefit/Cost Analysis

This method is very simple and intuitive - if the benefits exceed the costs, the proposed solution is economical. The costs reflect the cash outlays for purchasing, installing and operating a capital improvement such as capacitors. The benefits are the cash savings achieved by installing the improvements, such as power factor penalty reduction and loss savings.

Both the benefits and the costs are referred to the same basis (e.g., present value or levelized annual costs). Then the benefits are divided by the costs. If this number is greater than 1 then the proposed alternative is potentially economical.

Payback Analysis

Another method preferred by many industrial facilities is to simply determine how long it will take to re-coup the investment in the improvement. In the simple payback analysis, the first cost is divided by the annual savings.

$$\text{Simple Payback} = \frac{\text{Investment}}{\text{Annual Savings}}$$

Industrial consumers are typically looking for a 1 to 3 year payback. Actual paybacks are typically easily within this range unless extra costs are incurred for switching or harmonic mitigation.

To make the analysis more correct, in many cases the annual savings should be levelized over the expected life rather than just the first year's savings. Likewise, all cash layouts in future years related to the investment should be referred to the present before making the calculation. This is particularly significant if the annual cash flow is not uniform or the savings do not begin to accrue immediately.

16. Capacitors at Individual Motors

The reactive power requirement of an induction motor (Figure 16.1) varies little throughout the range of loading. This makes it possible to obtain a nearly constant power factor with a fixed capacitor size. If capacitors throughout the facility are placed on the load side of motor contactors, the amount of reactive compensation is matched to the number of motors in service without the need for additional switchgear and control equipment.

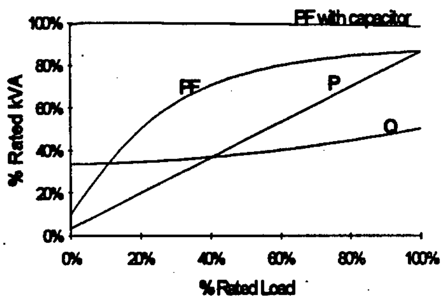


Figure 16.1. Variation in active and reactive power with motor load.

It is generally not economical to place capacitors at all motors, large and small. There is a temptation to add capacitors at motors that exceed the recommended size in order to maintain the desired kvar level. This practice may lead to overvoltages when motors are switched off with capacitors connected, due to a phenomenon known as *self-excitation.*

In Figure 16.2, the motor magnetization curve shows how the reactive current requirement of the motor field varies with the applied voltage; it represents a motor with no load. The straight lines shows capacitor current vs. voltage. At 480 V, the field requires 37 Amperes (31 kvar). A 50 kvar capacitor has been added so that a surplus of 19 kvar is available for other loads in the system.

In the moment after the motor is switched off, the still spinning machine becomes an unloaded induction generator. Without the rest of the system available to make up the difference, the kvar supplied by the capacitor must equal the kvar consumed by the field. Therefore, the voltage must rise to the intersection of the motor and capacitor curves.

The self-excitation problem usually does not result in voltages as high as possible, due to motor losses and the braking action of the load. Also, most motors have a flatter magnetization characteristic than the one pictured in Figure 16.2. A flatter curve reduces the rise in voltage after interruption.

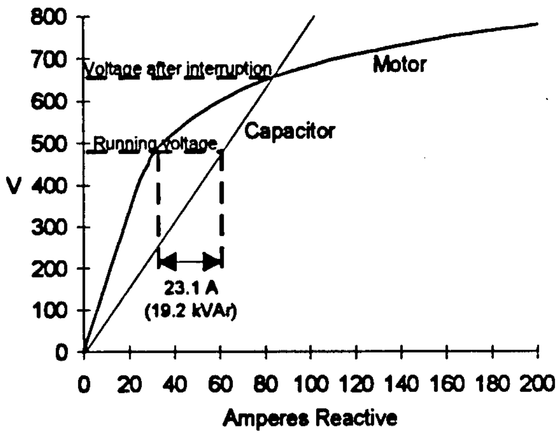


Figure 16.2. Momentary overvoltage when capacitor and motor are switched off.

Oversized capacitors have been applied at motors up to 50 HP without trouble. But without guidance from the manufacturer, the safest course of action is to limit the size of the capacitor to no more than the motor no-load kVA. This can be determined by measuring the line current with mechanical load disconnected:

$$kVAr_{Cap} \leq \sqrt{3} \cdot kV_{Bus} \cdot I_{No\,Load}$$

The fallback position is to use tables provided by NEMA (see Chapter 6.) or capacitor manufacturers. These tables reflect typical motor kvar requirements, so relying on them does not completely guarantee that trouble will always be avoided, but should be a good guide.

In the absence of a specific investigation or manufacturer recommendation, capacitors and motors should not be switched together in the following applications:

- motors that are subject to reversing, plugging, or jogging
- motors that are restarted while still spinning
- multispeed motors or motors that use open transition starters
- motors that can be driven by the load, e.g., cranes, submergible pumps

17. Fixed or Switched Capacitors

As noted in Chapter 12., applying capacitors causes voltage to rise. This leads to concern for overvoltage during periods of light load for capacitors that remain energized (fixed), rather than switched with the load. Transformer and capacitor standards limit the voltage rise, ΔV, to 10%. The limit determines the maximum amount of fixed kvar that can be added to the system. Any additional kvar must be switched, either by automatic power factor controllers, or by placement on the load side of the motor starters.

Figure 17.1 can be used to estimate if voltage rise will be a problem. It requires that the source impedance be expressed in percent on the transformer base. For example, if a system has a transformer rated 10 MVA, 7% Z, 480 V secondary, and the utility impedance at the primary is 1.3021 Ω, then:

$$\%Z_{Source} = 7\% + \left(\frac{.48^2}{10}\right) \cdot 1.3021 = 10\%$$

Figure 17.1 assumes that the transformer is loaded to maximum, and that power factor is to be corrected to either 0.90 or 0.95. If the intersection of the existing load power factor and the percent source impedance lies above the curve corresponding to the desired power factor, then the voltage rise is acceptable. For example, in a fully loaded system with 10% source impedance and a power factor of 0.7, (see indicated point on the curve) the power factor can be raised to 0.9 with a fixed bank. However, achieving 0.95 will require some switched capacitors.

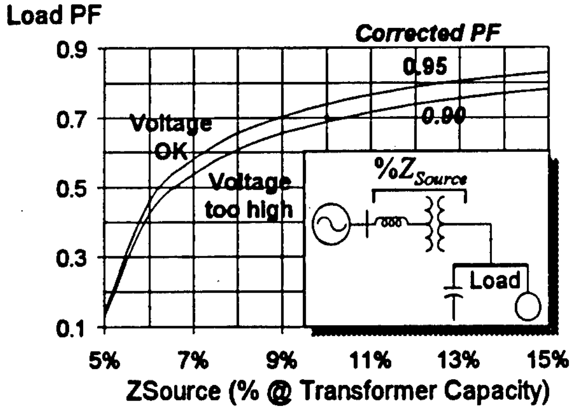


Figure 17.1. Check for excessive voltage rise.

<u>Switched Capacitors</u>

The most economical location for switched capacitors is at individual motors. Connecting the capacitors on the load side of the motor contactor eliminates the cost of an additional contactor. If this is not feasible due to motor size, duty cycle, etc., then banks switched by automatic controllers can be located at buses or motor control centers. Automatic controllers switch capacitance on and off in steps. They are quite useful for application where the kvar demand varies considerably due to numerous motors being switched frequently. The better controller designs will provide the flexibility to program any desired combination of capacitors at each step, e.g., to skip a kvar value that causes a resonance problem.

Controllers respond to system power factor (or reactive power demand) by continuously monitoring voltage and current. If there is only one controlled bank, its control signals must come from a location that sees the *entire* load current. One common error is to have the incorrect current signal so that the power factor controller doesn't follow the load correctly.

Another application which may or may not work well is placing two or more controlled banks on the same circuit. The concern here is "hunting" between controllers; that is, one bank adding a step causing another bank to de-energize a step, or vice versa. There should be no problem if the controllers are monitoring different currents (e.g., switched banks at each of the MCCs in Figure 14.2). However, if one controller is placed upline of another controller, then hunting is a possibility, particularly if there is an unfavorable combination of controller measurement tolerance. One solution is to keep the change in kvar between steps small. Another is to set the controllers for different target power factors (e.g., upline 0.93 ± 0.02, downline 0.97 ± 0.02).

18. Avoiding Lazy Capacitors

Some who apply power capacitors are surprised that they are not getting the amount of power factor correction that they had hoped for. There are two common reasons for this:

1. The capacitors were placed on motors that do not run a sufficient percentage of the time.

2. The capacitor have the wrong voltage rating.

The former is an easy trap to be lured into when a particular motor offers a convenient location for a capacitor. That is why it is important to perform a detailed plant survey to determine motor duty cycles when applying capacitors at individual motors.

The second item is due to a misunderstanding on how capacitors are rated. Unlike the reactance (Xc) or capacitance (μF) ratings, the rated kvar is *not* constant. Rather, it varies with the square of the applied voltage:

$$\text{kvar} = 1000 \cdot \frac{\text{kV}_{\text{Actual}}^{\;2}}{\text{Xc}}$$

where Xc is the capacitive reactance at 60 Hz, which is constant. This leads to the following formula:

$$\text{kvar}_{\text{Delivered}} = \text{kvar}_{\text{Rated}} \cdot \left(\frac{\text{kV}_{\text{Actual}}}{\text{kV}_{\text{Rated}}}\right)^2$$

One common error is apply 600 V capacitors on a 480 V system, paying heed only to the kvar rating. Unlike other devices, a higher voltage rating will not provide proper operation in this case. This formula shows that a 600 V capacitor will deliver 64% of its rated kvar if applied on a 480 V system, and that a 4.8 kV capacitor will deliver 75% of its rated kvar if applied on a 4.16 kV system.

19. Harmonic Considerations

What are Harmonics?

Nonlinear loads draw current which is distorted resulting in the presence of multiple frequencies. A nonlinear load can be visualized as a current source, drawing current from the system at the fundamental frequency, and injecting current back into the system at higher frequencies.

The current waveform, though distorted, is usually identical from one cycle to the next. This means that all frequencies in the waveform are ***harmonics*** (integer multiples) of the fundamental. For example, the harmonics contained in the waveform of Figure 10.1 are 1, 5, 7, 11, ... Why only these harmonics? The current waveforms with identically shaped positive and negative half cycles do not have any even harmonics (2, 4, ...). Triplen harmonics (odd multiples of 3: 3, 9, 15...) are usually negligible for the type of three-phase nonlinear loads that we generally encounter for industrial power factor correction. However, they can be quite significant for single-phase loads. Figure 19.1 shows the reason why. If the harmonic sources in each phase are balanced, any third harmonic components in the phase currents must be in phase. Therefore, they add directly into the neutral, if it exists. Summing currents at the neutral node, *N*, shows that if the circuit has a neutral wire and is serving single-phase loads, the third harmonic in the neutral current is three times the third harmonic in the phase current. On the other hand, if there is no neutral wire, as is the case for the larger 3-phase nonlinear loads in industrial plants, there will generally be no third harmonic current in the phase wires because there is no place for it to flow. Therefore, we commonly ignore these components for design of power factor capacitor installations unless we have special reasons to believe they exist.

The most common location for triplen harmonic problems in an industrial plant is on 120V/208V circuits where it is not common to place capacitors for power factor correction. They also appear commonly on utility 4-wire wye distribution feeders because there are several 3-phase loads. To model the effects of triplen harmonics, it is generally necessary to build a full 3-phase model of the power system. This is what computer programs such as the SuperHarm® program used in the case studies are designed to do. Since we do not have to concern ourselves with these for most industrial power factor correction studies, it is possible to get satisfactory models with a simpler positive-sequence model of the system. Therefore, only the latter is built into the computer program that supports this Guide Book.

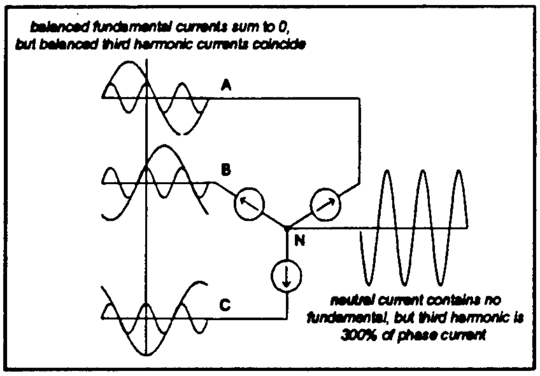


Figure 19.1. Flow of triple harmonic currents.

There may be some even harmonics and harmonics of triplen frequency (but not zero-seqence) due to circuit unbalances and equipment tolerances, but high values for 3-phase loads generally indicate an equipment malfunction or a transient loading condition.

Why the Concern for Harmonics?

Distorted currents, and the distorted voltages they create as they flow through system impedances, can reduce equipment operating reliability and service life. Potential problems include the following:

Failure of power factor correction capacitors. The presence of power factor correction capacitors in the building greatly increases the potential for harmonic problems. As described in Chapter 20., a capacitor can cause the system to resonate near a harmonic frequency, producing high voltage and/or current distortion that can destroy the capacitor or cause nuisance capacitor fuse/breaker operations.

Equipment misoperation. Circuit breakers, adjustable speed drives (ASDs), programmable logic controllers, and other equipment employ control circuits that may not operate correctly in a distorted environment. Distortion of the equipment supply voltage may cause inaccurate measurement of control input signals. It can produce multiple zero crossings per cycle of the input signal waveform, causing crossing detectors to malfunction. Typical problems include clocks running fast, hunting and oscillation in motor speed control systems, and circuit breaker failure to trip or nuisance trips. Voltage distortion can also reduce the ability of electronic equipment to withstand momentary voltage sags and interruptions.

Overheating of transformers. Winding eddy current losses and other stray losses vary roughly with the square of the frequency of the load current. Therefore, harmonic load currents significantly increase transformer heating. This problem is most severe in dry-type transformers.

Overloading of neutral conductors in three-phase 4-wire circuits serving single-phase electronic power supply loads. As with transformers, harmonic currents increase conductor heating. However, the neutral conductor is of special concern due to the phenomenon illustrated in Figure 19.1. Triplen harmonic currents from each phase add in the neutral. Though balancing loads among the phases will eliminate fundamental current in the neutral, this is not true for the triples. Neutral current can be approximately 70% higher than phase conductor current for circuits serving balanced computer loads.

Measures of Harmonic Distortion

There are several measures used for indicating the harmonic content of a waveform with a single number. One of the most common is *Total Harmonic Distortion (THD)*, which can be calculated for voltage or current:

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} M_h^2}}{M_1}$$

where M_h is the rms magnitude of harmonic component h. M_1 is the magnitude of the fundamental value. THD is related to the rms, or root mean square, value of the waveform as follows:

$$rms = \sqrt{\sum_{h=1}^{h_{max}} M_h^2} = M_1 \cdot \sqrt{1 + THD^2}$$

Power Factor and Harmonics

Transforming distorted voltage and current waveform into sums of harmonic sinusoids allows the definitions for P and S to be extended to cover nonlinear cases:

$$P = \sum_{h=1}^{h_{max}} V_h I_h \cos\theta_h \qquad Q = \sum_{h=1}^{h_{max}} V_h I_h \sin\theta_h$$

$$S = V_{RMS} \cdot I_{RMS} = \sqrt{\sum_{h=1}^{h_{max}} V_h^2} \cdot \sqrt{\sum_{h=1}^{h_{max}} I_h^2}$$

where θ_h is the angle between the voltage and current sinusoids at harmonic h, and V_h & I_h are the rms values of these sinusoids.

Q is not particularly useful when distortion is present. It is not conserved, nor is it directly related to the difference between S and P ($S^2 \neq P^2 + Q^2$). This mathematical contrivance would be completely useless in distorted systems if it were not for one fact - most utilities meter only fundamental frequency reactive power, Q_1. In other words, utility demand charges are based on displacement power factor (DPF), not the true power factor (TPF).

This presents a dilemma for the facility engineer: minimizing utility demand charges dictates that DPF be optimized, rather than TPF. However, adding capacitance to increase DPF may actually *decrease* TPF, which increases the costs associated with system capacity and losses. The reason: adding capacitance can increase harmonic distortion through the parallel resonance phenomenon described in Chapter 20. With certain nonlinear loads, the increase in distortion will outweigh the decrease in displacement angle.

20. Harmonic Interaction with Capacitors

Parallel Resonance

The voltage distortion that results from harmonic current injection is a function of how the system impedance varies with frequency. To visualize the response of the system when a capacitor is present, replace the nonlinear load with a current source that injects 1 Ampere over a wide range of frequencies. Calculating the voltage at the current source for each frequency allows the system impedance to be plotted against frequency, as shown in Figure 20.1.

The source voltage is zero at all frequencies above fundamental, so the source bus is grounded in the simplified circuit shown in part (b) of the figure. The simplified circuit illustrates that, from the perspective of a harmonic current source, the capacitor appears to be in parallel with the reactances of the transformer and utility source. Resonance occurs at the frequency where the impedance of this parallel combination approaches infinity.

If resonance occurs at or near a frequency excited by nonlinear loads in the system, high voltage distortion and large circulating currents will occur if the harmonic injection is high enough. The acceptable amount of nonlinear load depends on the damping provided by other loads in the system. Loads like electric heating and incandescent lighting act as resistors in parallel with harmonic current sources, reducing the height of resonant peaks. Motors, on the other hand, are primarily inductive at harmonic frequencies, and provide little damping.

The harmonic number at parallel resonance is:

$$h_p = \sqrt{\frac{X_C}{X_T + X_S}}$$

If the capacitor's rated kV is the same as the transformer secondary nominal kV, then:

$$h_p = \sqrt{\frac{kVA_{SC}}{kvar_{CAP}}}$$
$$\approx \sqrt{\frac{kVA_T}{X_{TPU} \cdot kvar_{Cap}}}$$

where kVA_T is the rated transformer kVA, and X_{TPU} is the transformer reactance per unit on kVA_T.

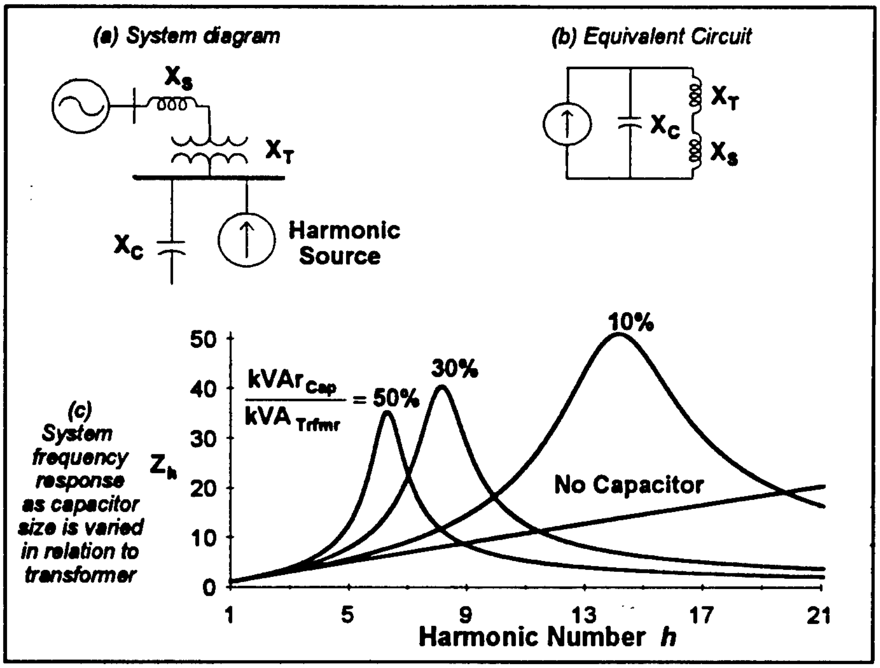


Figure 20.1. Effect of capacitor size on resonant frequency.

At what harmonic is resonance most likely to occur? If the supply transformer is heavily loaded with induction motor load, then the capacitive kvar required to correct power factor to 95% will be approximately 50% of the transformer kVA. As shown in Figure 20.1(c), this results in a resonance around the fifth and seventh harmonics. This is the worst possible situation because the current injected by most types of nonlinear loads is highest at these harmonics.

Series Resonance

Adding a capacitor to the system may also cause a *series resonance*. This occurs when, from the perspective of a harmonic source, an inductance and a capacitance appear to be in series. An example of this occurs when a capacitor is applied at an industrial facility's 480 V bus. To a harmonic source elsewhere on the utility system, the capacitive reactance X_C and the transformer inductive reactance X_L appear to be in series. The reactance of the series branch approaches zero at harmonic number:

$$h_S = \sqrt{\frac{X_C}{X_L}}$$

The problem with series resonance is that the capacitor will attract currents at a certain frequency from all over the system. The size of the capacitor is likely to be small in relation to the combined capacities of the harmonic sources, and the maximum allowable current or kvar duties could easily be exceeded. High overvoltages are not generally a problem, but the voltage THD could be excessive at the capacitor bus if the harmonic being attracted is one of the lower ones (3, 5 or 7). Higher frequencies mean lower capacitive reactance, X_C, so the voltage across the capacitor is lower even though the current is higher.

When the harmonic being attracted is one of the higher ones, series resonance has been known to cause electromagnetic interference problems if telephone or industrial control circuits are routed close to power conductors.

21.Harmonic Limits

Voltage distortion. The harmonic standard *IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems* (IEEE Std 519-1992) suggests that THD on low voltage buses be limited to 5%. With no capacitors in the system, this limit is typically exceeded when nonlinear load reaches 30% - 40% of system capacity.

Many systems operate successfully with load bus voltage THD in excess of 5%, but problems can be expected when values exceed 8% or so.

Harmonic current injected into the utility system. IEEE 519 also recommends limits on the level of harmonic current injection from an individual customer at the point of common coupling (PCC) with other customers. The limits are a function of the *Short Circuit Ratio* - the customer size relative to the system short circuit capacity:

$$SCR = \frac{I_{Short\ Circuit}}{I_{1max}}$$

where I_{1max} is the maximum customer fundamental demand current. Large end users face stricter limits because they have more impact on voltage distortion. The limits shown in Table 21.1, both for individual harmonics and for the RMS value of all harmonics (called *Total Demand Distortion* or TDD), are expressed in percent of I_{1max}.

SCR	Individual Harmonic Limits				TDD
	<11	18-23	24-35	>35	Limit
<20	4.0%	1.5%	0.6%	0.3%	5%
20-50	7.0%	2.5%	1.0%	0.5%	8%
50-100	10.0%	4.0%	1.5%	0.7%	12%
100-1000	12.0%	5.0%	2.0%	1.0%	15%
>1000	15.0%	6.0%	2.5%	1.4%	20%

Table 21.1 - IEEE 519 harmonic current limits at the PCC.

The limits shown above apply to odd harmonics. Even harmonics are limited to ¼ of the odd harmonic limit in the same group. Often when an even harmonic shows up, there is an equipment malfunction.

Capacitor limits. The first sign of a resonance problem is often nuisance fuse blowing or outright failure of capacitor banks. Capacitor duties should be limited as specified in ANSI/IEEE Std. 18-1980: *IEEE Standard for Shunt Power Capacitors*:

- Rms voltage should be less than 110% of the rated voltage, and the peak voltage should be less than 120% of the rated rms voltage $\cdot\sqrt{2}$. The rms and peak voltage limits are designed to prevent dielectric failure.

- The rms reactive power delivered by the capacitor should be less than 135% of the rated kvar, in order to prevent overheating of the capacitor.

- The capacitor rms current should be less than 180% of rated current. Exceeding this value could result in failure of internal capacitor connections.

Rms kvar and peak kV duties are usually the most restrictive when applying capacitors in a harmonic environment. Figure 21.1 illustrates just how severe the kvar limit can be. It assumes that the capacitor fundamental voltage is equal to the rated voltage, and that all harmonic current through the capacitor are due to the single harmonic shown on the X axis (approximately true if the capacitor is in resonance). The Y axis value is the voltage at that harmonic to achieve 135% of rated kvar. The top and bottom curves correspond to capacitor μF equal to 100% and 110%, respectively. (Standards allow capacitor μF to range from -0% to +15% of the nameplate value. Manufacturers usually restrict the maximum to +8% for economic reasons, so the bottom curve represents a worst case condition.)

Figure 21.1 suggests that a capacitor might fail with as little as a 10% fifth harmonic voltage. If the system is resonant at a higher harmonic, the voltage required for failure is even less. In many cases, there will be no noticeable equipment malfunctions with this level of voltage distortion. Thus, capacitor failure is often the first sign of a harmonic resonance problem.

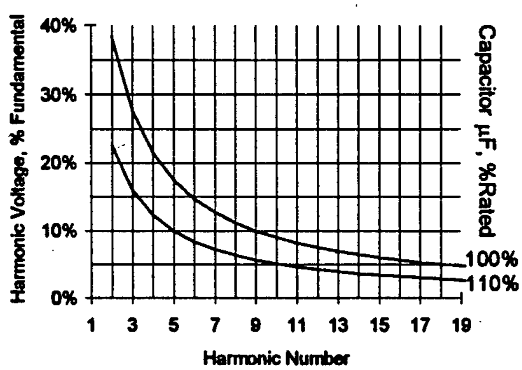


Figure 21.1. Harmonic voltage needed to exceed capacitor 135% current limit.

22. Harmonic Mitigation

Capacitor Sizing to Control Resonance

In many cases, harmonic problems can be eliminated by selecting capacitor size to avoid problem resonances. For an automatically switched bank, step sizes must be selected to skip over resonances, and the controllers programmed accordingly.

Unfortunately, this technique will not always work. First, the resonant peaks may be so high and broad that any capacitor size within the desired range of compensation is unacceptable. Second, if capacitors are automatically controlled or switched with motors, high diversity in plant load may make it impossible to avoid all resonant configurations.

Harmonic Filters

The most common type of filter is the bandpass ("notch") filter illustrated in Figure 22.1. The notch refers to the dip in the characteristic at the tuned frequency. Notch filters provide reactive compensation like a capacitor bank, but the inductors introduce a series resonance which diverts harmonic currents into the filter. Part *c* of the figure shows that the filter does not eliminate parallel resonance - it merely shifts the resonance to some frequency below the notch frequency. In order to prevent a second resonance problem, filters must be added starting with the lowest problem harmonic. For example, a fifth harmonic filter must be in service before a seventh harmonic filter can be energized.

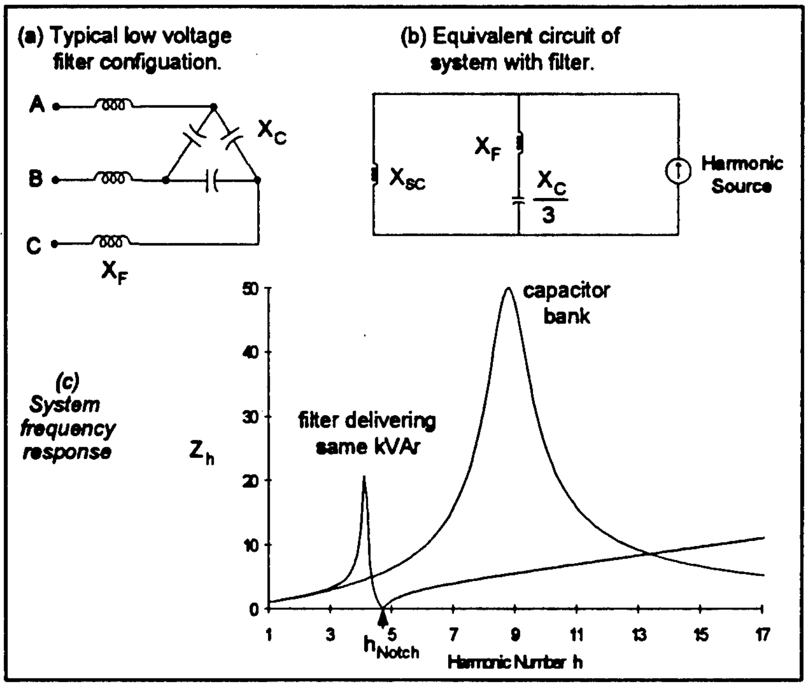


Figure 22.1. Effect of notch filter on system response.

Notch filters are generally tuned 3 - 10 % below the harmonic to be suppressed. For example, a fifth harmonic filter might be tuned to h = 4.7. Slightly detuning the filter in this way causes the impedance of the filter at the target harmonic to be not quite zero. This actually reduces capacitor and reactor current duty. The tuning is always *below* the target harmonic in order to insure that the parallel resonance is well below this harmonic.

(Tolerances in the capacitor and reactor ratings may result in the notch and peak frequencies being higher than calculated.)

Filter Pitfalls

Modular filters. Designing a filter for an individual load, without regard for the system that it is applied on, is asking for trouble. Overload is the most common problem, since the filter will attract harmonic currents from all nonlinear loads on the system. Using equipment with modular filters can create problems if capacitors are added to the system (see below).

Mixing filters and capacitors. The cost per kvar is much higher for filters than for capacitors. Thus, it is desirable for capacitor banks to provide the bulk of reactive compensation, using filters as needed to prevent excessive harmonic levels. Unfortunately, capacitors and filters somtimes cannot be applied from the same bus. As Figure 22.2 shows, the result is a broad, high-magnitude resonance occurring above the filter notch frequency. Any prospective capacitor-filter application should be evaluated very carefully by a harmonics specialist.

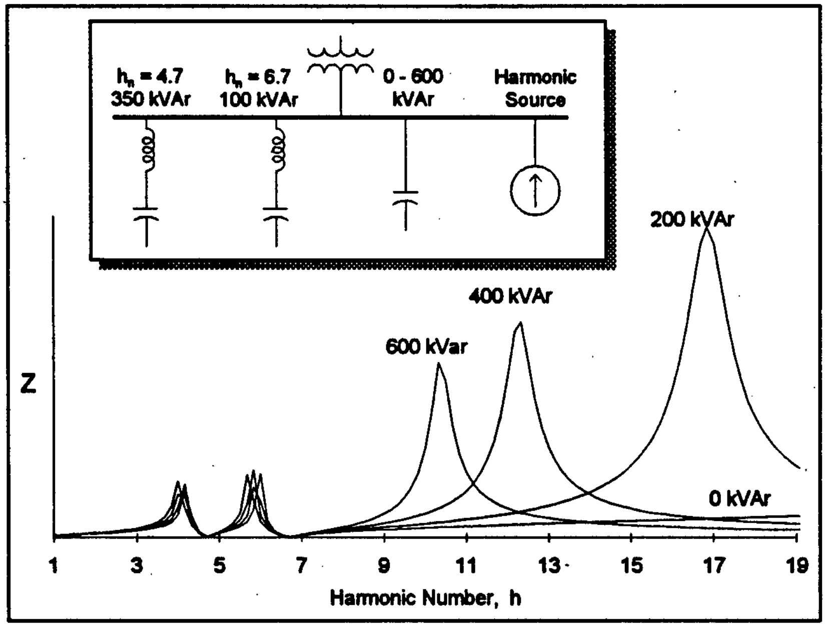


Figure 22.2 - Mixing capacitors and harmonic filters.

Other Forms of Mitigation

AC line chokes are series reactors used to reduce the harmonic injection from some types of adjustable speed drives(ASD). They are placed in series with the ASD. They are most effective when the capacity of the ASD is small relative to the transformer supplying it. They are also effective in reducing nuisance tripping of ASDs due to capacitor switching transients (Chapter 25.).

Active filters have been used in low power applications for some time. Units capable of delivering the high levels of harmonic compensation for industrial applications are becoming available, but are still relatively expensive.

23. Harmonic Estimation Procedures

Harmonic Estimation Worksheet for Simple Systems

The worksheet shown in Figure 23.1 provides a rough estimation of harmonic voltage distortion from six-pulse rectifiers such as adjustable speed motors drives (ASDs).

Hand calculations of harmonic levels are very cumbersome. For circuits larger than one major load bus and one capacitor, a computer program is a virtual necessity. Therefore, only the simple system illustrated in the worksheet is considered. The assumptions are:

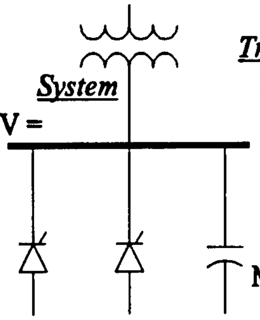
1. The service entrance transformer dominates the source reactance. In other words, the spreadsheet assumes that the utility capacity is much larger than the service entrance transformer, and that the impedance of cables within the facility are negligible.

2. The capacitor bank and all major harmonic loads are connected to the same bus.

3. The significant harmonics are 5, 7, 11, and 13. This is generally the case for industrial facilities with 3-phase loads. This worksheet is not applicable to the analysis of triplen harmonics due to line-to-neutral connected 1-phase loads.

Harmonic Estimation Worksheet

System Impedances and Load Currents



kV =

Transformer

MVA = ______

%Z = ______

Capacitor

MVAr = ______

6-Pulse Rectifiers

PWM ASD w/o chokes: kVA_U= ______

Other: kVA_O = ______

$$X_L \approx \frac{\%Z \cdot kV^2}{100 \cdot MVA} = \text{\_\_\_\_\_\_}$$

$$X_C = \frac{kV^2}{MVAr} = \text{\_\_\_\_\_\_}$$

$$Iu_{Fund} = \frac{kVA_U}{\sqrt{3} \cdot kV} = \text{\_\_\_\_\_\_}$$

$$Io_{Fund} = \frac{kVA_O}{\sqrt{3} \cdot kV} = \text{\_\_\_\_\_\_}$$

Harmonic Currents

	PWM ASDs w/o chokes		*Other 6-Pulse Rectifier Loads*		
h	Mu(h)	Iu(h) = $Iu_{Fund} \cdot Mu(h)$	Mo(h)	Io(h) = $Io_{Fund} \cdot Mo(h)$	$I_{Tot}(h)$ = Iu(h) + Io(h)
5	0.35		0.25		
7	0.18		0.10		
11	0.07		0.07		
13	0.05		0.05		

Harmonic Voltage Distortion

h	$I_{Tot}(h)$	$X_L(h) = X_L \cdot h$	$X_C(h) = X_C / h$	$X(h) = [X_L(h) \cdot X_C(h)] / [X_L(h) - X_C(h)]$	$V(h) = I_{Tot}(h) \cdot X(h)$	$V(h)^2$
5						
7						
11						
13						

$$THD = \frac{\sqrt{\sum_h V_h^2}}{V_1} = \text{\_\_\_\_\_\_}$$

Harmonic Standard IEEE 519-1992 recommends a THD limit of 5.0%

Harmonic Number at Parallel Resonance

$$H_{Peak} = \sqrt{\frac{100 \cdot MVA}{\%Z \cdot MVAr}} = \text{\_\_\_\_\_\_}$$

Even if THD is acceptable, there is potential for future harmonic problems if the system is tuned close to one of the significant harmonics (e.g., 5, 7, 11, 13, ...)

Figure 23.1. Harmonic estimation worksheet.

Worksheet Instructions

1. Divide the nonlinear loads in the facility into two classes:

   a. PWM adjustable speed drives that do not use AC line chokes, and

   b. All other 6-pulse drives.

   Consider a PWM ASD with rated kVA more than 50% of the service entrance transformer to have a choke.

2. Specify the kVA of PWM ASD without chokes (kVA_U) and the kVA of all other devices (kVA_O). These values are determined from the nameplate ratings of the devices.

3. Specify the transformer MVA and %Z.

4. Specify the capacitor Mvar.

5. Compute the system reactance, X_L, in ohms using the formula shown.

6. Compute the capacitor reactance, X_C, in ohms using the formula shown.

7. Compute the fundamental currents from the total kVA for each class of device.

8. Estimate the harmonic amperes for each class of device, $I_u(h)$ and $I_o(h)$, by multiplying each fundamental current by the typical harmonic magnitudes, Mu(h) and Mo(h), given on the worksheet. If actual measurements or manufacturer data is available, you may substitute these values instead.

9. Compute the total harmonic currents injected by the sources (rightmost column of the table).

10. Calculate the voltage at each harmonic by multiplying the corresponding harmonic current by the system impedance at that harmonic. This is done by filling out the Harmonic Voltage Distortion table:

    - Copy the total harmonic currents, I_{Tot} from the previous table.

    - Compute the new X_L for each harmonic by multiplying by the harmonic number, h.

- Compute the new X_c for each harmonic by dividing by the harmonic number, h.
- Compute the total parallel reactance, X(h), seen looking into the bus by using the formula shown.
- Compute the voltage at each harmonic by multiplying the total current by the total reactance, as shown.
- Compute the square of each harmonic voltage in preparation for computing the THD.

11. Compute the THD of the voltage as shown. Divide the sum of $V(h)^2$ by the fundamental voltage. If the THD is greater than 5%, a more detailed investigation of harmonic levels in the facility is warranted.

12. Compute the Harmonic Number of parallel resonance as shown. Even if calculated THD is acceptable, it is probably not wise to allow a capacitor addition to tune the system parallel resonance to one of the characteristic harmonics (5, 7, 11, 13, ...)

The system tuning can be determined from the simple formula at the bottom of the worksheet. Like the THD calculation, it assumes that the source reactance is dominated by the service entrance transformer. It also assumes that the kV rating of the capacitor is equal to the transformer nominal secondary kV.

Methods for Complex Systems

Once a circuit increases in size beyond the simple circuit just described, manual calculation of harmonics becomes unmanageable. Ideally, one would use the powerful harmonic analysis programs that have been developed for this purpose to simulate all the harmonic sources in detail and calculate the frequency response of the system. However, this requires a great deal of study effort that is not justifiable on smaller-sized facilities.

A simpler technique was developed for this project. Although it still requires a computer, it doesn't require the sophisticated modeling expertise needed for precise simulations. We're interested simply in estimating whether resonance will develop to such a degree that the system will have to be corrected after the capacitors are installed .

The technique is based on the fact that resonance, if it exists, is easily detectable in the capacitor currents. The currents during resonance will generally be a single frequency riding on top of the fundamental current.

Often, the harmonic current is higher than the fundamental. Figure 23.2 shows such a case.

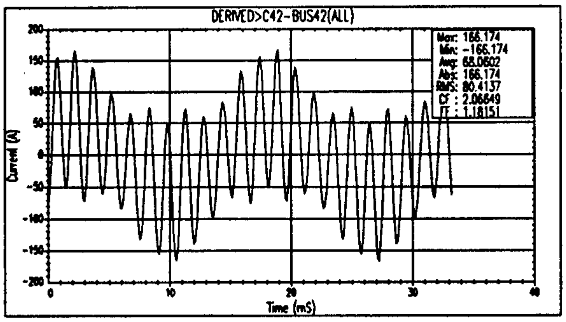


Figure 23.2. Current in capacitor subjected to harmonic resonance.

The method is also predicated on the fact that the system impedance at the main bus is predominantly inductive. This is particularly true for many industrial facilities that are fed directly from a transformer as we have pointed out previously. Therefore, if a good measurement of the main bus voltage distortion can be made with the nonlinear loads operating (preferably without capacitors), we can construct a Thevenin equivalent of the utility system at each frequency using the measured voltage distortion and the short circuit impedance to the bus. Applying this to a model of the plant cables, transformers and capacitors, we can compute a reasonable estimate of the capacitor currents without having to model the nonlinear loads in detail. This is illustrated in Figure 23.3.

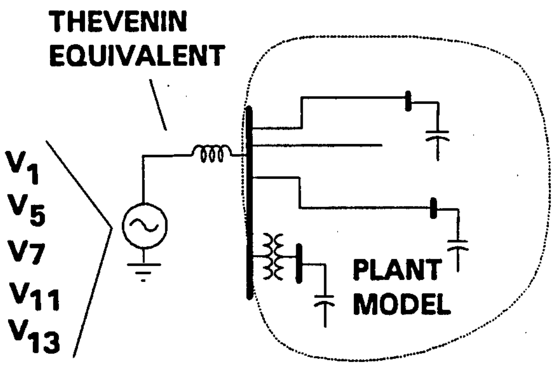


Figure 23.3. Thevenin equivalent utility source model for estimating capacitor harmonic currents without explicit modeling of nonlinear loads.

Then we simply look for capacitors in which the rms current is much higher than normal. Currents above 135% generally indicate trouble and may result in capacitor fuse blowing. Regardless, it is a certain sign of harmonic resonance and corrective action should be taken. There is no black and white cutoff value for an rms value that presents a problem. Some systems seem to function quite well with high values of harmonic currents in the capacitors while others don't. The following are suggested guidelines for judging predicted rms current values:

From	To	Evaluation
100%	120%	OK
120%	135%	Caution
135%	higher	Too high

This concept can be carried over into measurements as well. When capacitors are installed, each phase current should be measured with a current probe capable of reporting the true rms of distorted currents. Normally, the currents will be within a few percent of normal. A large deviation is indicative of resonance and indicates potential problems for the capacitor installation.

If the voltage distortion is not known and cannot be estimated, a conservative approach is to design for a high typical main bus distortion value. For example, you might assume that the harmonic voltage components are as follows:

Harmonic	% Voltage
1st	100
5th	2
7th	1
11th	1
13th	1

In some cases, these values may lead to a decision to install filters when there is no need. However, if the capacitor currents are OK with this excitation, chances are good that the installation will be successful because there are few installations in which the utility bus distortion exceeds these values. Exceptions are generally where the utility system is relatively weak. To eliminate doubt, measurements should be made.

24. Overcurrent Protection

Conductors which connect a capacitor to the system must have an ampacity of at least 135% of rated capacitor current. This is based on a +15% error in capacitor nameplate kVAr, capacitor voltage equal to 110% of nominal, and a 10% increase in rms current due to harmonics. If the capacitor is connected between a motor and motor starter, the ampacity of the capacitor conductors must be at least 1/3 of the ampacity of the motor conductors. The effect of the capacitor must be ignored when sizing motor conductors.

Capacitors must be provided with dedicated switching device *and* an overcurrent protective device. One exception is made: a motor starter can serve these functions if it is provided with overload protection. If so done, the National Electric Code requires that the motor overload devices be adjusted to reflect the reduction in motor line current achieved with the capacitor.

The switching device must open all ungrounded conductors simultaneously. The device must be able to withstand a downline fault, as well as 135% of rated capacitor current continuously. (Some types of devices require a higher continuous rating, so manufacturer guidance should be obtained.) De-energizing capacitors must be permitted as a normal operating procedure.

The primary function of the overcurrent protective device is to interrupt system short-circuit current. The overcurrent trip level must be as low as possible, but no lower than 135% of rated capacitor current. The overcurrent device may also be required to prevent capacitor rupture due to an internal fault. This is not a concern in many modern low voltage capacitor designs due to one or more of the following reasons: internal arcing is unlikely, arcing will not result in gas generation, or integral rupture protection is provided (e.g. fuses, pressure-operated capacitor disconnects).

The overcurrent trip level of capacitor breakers are normally set to 135% of rated current, but fuses must be rated at 150 - 250% in order to withstand energizing transients. As noted in Chapter 20., this may not protect against harmonic-induced overloads if the capacitor is rated at nominal bus voltage.

Banks of capacitors may be protected individually or as a group. Group fusing is more economical, particularly when integrated with the required capacitor switching device. However, individual fusing - offered as an option by most capacitor manufacturers - is attractive because it offers optimum protection and eliminates the possibility of an incorrect fuse application.

Capacitor application at greater than 600 V imposes additional restrictions:

- There are specific requirements with regards to reducing the probability of capacitor rupture.

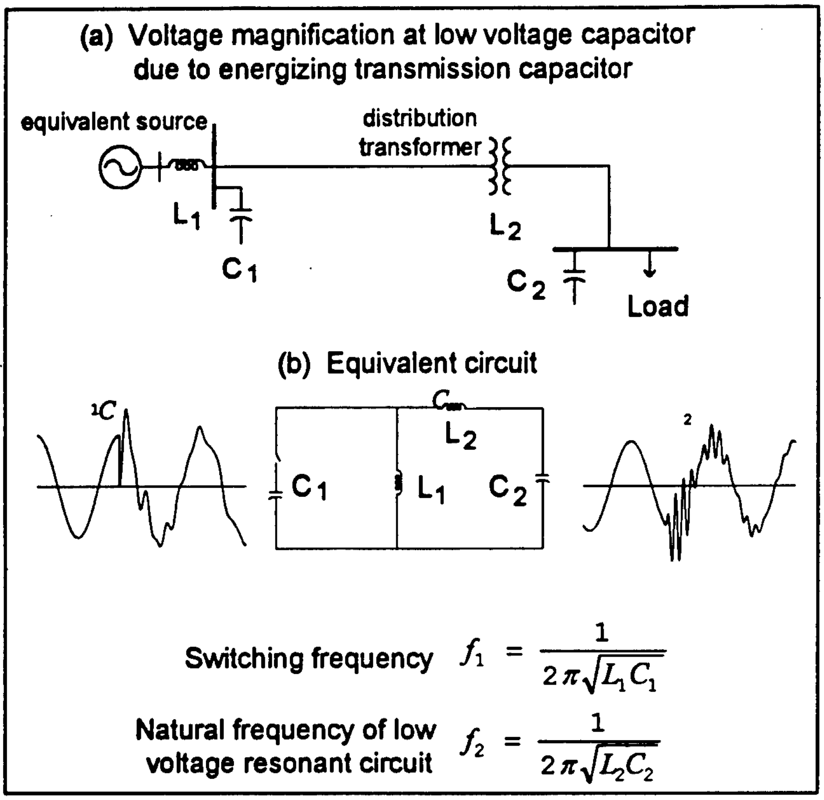
- Vacuum circuit breakers may be required for repetitive switching at voltages beyond 5 kV. Vacuum breakers used for capacitor switching must be derated in accordance with ANSI/IEEE C37.012-1979. Special precautions may be necessary to protect equipment in the event of a restrike (arc reignition) during breaker opening.

25. Capacitor Switching Transients

Capacitor voltage cannot change instantaneously. Thus, when the utility energizes a discharged capacitor, the bus voltage will momentarily collapse. It then undergoes an oscillatory recovery, usually lasting less than ½ cycle. Theoretically, the overshoot associated with the oscillation can cause peak voltage to reach twice the 60 Hz crest voltage. However, system losses, loads, and transmission system capacitance reduce worst-case peak voltages to 120 - 150% of the nominal crest.

The characteristic frequency of the switching transient, f_1, is shown in Figure 25.1, where C_1 is the switched capacitance, and L_1 is the equivalent source inductance seen at the capacitor bus. f_1 is typically in the 300 - 1000 Hz range.

Transients of this magnitude and duration are no problem on the utility system, but they can produce severe overvoltages at end user low voltage capacitors through a phenomenon known as *voltage magnification*. That is, the overvoltage at the end user capacitor can be greater than that at the utility capacitor. Peak voltage at the end user capacitor can reach 400% of nominal crest in theory, but peaks above 220% are rare.



$$f_1 = \frac{1}{2\pi\sqrt{L_1C_1}}$$

$$f_2 = \frac{1}{2\pi\sqrt{L_2C_2}}$$

Figure 25.1. Voltage magnification due to capacitor switching.

The highest transient voltages occur at the low voltage capacitor bank when the frequencies f_1 and f_2 are nearly equal, and the switched capacitor size is 10 or more times that of the low voltage capacitor.

The *IEEE Standard for Shunt Power Capacitors*, ANSI/IEEE Std. 18-1992, specifies that capacitors "may reasonably be expected to withstand" overvoltages of the following magnitudes and frequencies:

Events per year	Max voltage, % rated peak kV
4	354%
40	283%
400	240%
4000	205%

Table 25.1. Permissible capacitor overvoltages.

Therefore, the problem with voltage magnification is *not* capacitor damage, but rather failure or nuisance tripping of sensitive loads such as ASDs. The most obvious solution to the magnification problem is to select capacitor sizes that detune the circuit (that is, maximize the difference between f_1 and f_2). However, given the restraints of desired power factor, no load voltage rise, etc., capacitor size usually cannot be altered sufficiently. Effective detuning *can* be accomplished by converting capacitors to harmonic filters. Filter reactors also help to isolate bus voltage from the transient voltage at the capacitor.

Frequently, the most practical option is to insert a line reactor in series with the ASD. This prevents the high frequency transients from reaching the ASD.

Another option is to apply surge arresters at the load capacitors. One problem with this approach is that the arrester protective level (about 180% of nominal peak voltage) may not be low enough to protect the sensitive loads. Another problem is arrester duty. For transients, an oscillation of less than 1000 Hz is very slow, which means that a capacitor switching overvoltage will force an arrester into conduction for a relatively long period of time. It must have a high energy duty to survive.

The transient overvoltage can be controlled by synchronizing the closing of the capacitor switch with a natural zero crossing of the system voltage. This is expensive, because only vacuum breakers can provide the required speed. Another option is to use a switch with pre-insertion resistors or pre-insertion reactors, which are placed in series with the capacitor as it is energized, and are shorted out after about ½ cycle.

Appendix

CheckList for Initial Plant Survey for Power Factor Correction

- ☐ Get copies of several monthly bills, if available. If not, request maximum demand, power factor, typical energy usage and power factor penalty.
- ☐ Get demand interval load data from utility or plant, if available. Not all sites will have this data, but it is very useful in understanding how the plant load fluctuates.
- ☐ Identify motor load:
  What percentage of the load that is motor load?
  What portion of the motors are constant running and which are cycled on and off?
- ☐ Identify potential harmonic-producing loads:
  Are there any Adjustable Speed Drives? If so, how much of the load?
  Are there any other harmonic-producing devices? (e.g., arc furnaces, induction furnaces, welders, significant amounts of fluorescent or sodium-vapor lighting, etc.)
  How much distortion is in the bus voltage?
- ☐ Obtain copies of any previous harmonic measurements or spot-check main bus voltage and selected currents with portable instrument.
- ☐ *Any existing capacitors?* If so, *any problems with existing capacitors?* (could point to harmonics or switching problems)
- ☐ Make a sketch of the one-line diagram of the plant, noting all transformers, main feeders, existing capacitor banks and significant motor control centers and other control centers.
- ☐ Obtain all transformer % impedances and kVA and kV ratings. These should be readily visible on the transformer nameplates. Cable and wire sizes can wait for a detailed monitoring effort. We are looking for heavily loaded transformers that would suggest that power factor correction would be very beneficial in reducing losses and releasing capacity, and for impedance data to do quick spot checks of resonance calculations.

Figure A-1. Initial Plant Survey

Plant Inventory Checklist

- ☐ One-line diagram
- ☐ Transformer Impedances (% Resistance and % Reactance)
- ☐ Transformer Voltage Ratings
- ☐ Transformer kVA Ratings
- ☐ All Transformers Accounted For?
- ☐ Existing Capacitor kvar Ratings
- ☐ Existing Capacitor Voltage Ratings
- ☐ Check for Current in each Phase of Existing Capacitors
- ☐ Capacitor Locations on One-Line Diagram
- ☐ All Capacitors Accounted For?
- ☐ Conductor Wire Sizes
- ☐ Cable Lengths
- ☐ Motor hp or kva Ratings
- ☐ Motor Duties: Percent of Time Operating
- ☐ kW and PF Trend at Service Entrance (Utility Meter)
- ☐ kW and PF Trend in Main Feeds to Motor Control Centers
- ☐ kW and PF Trend in Larger Motors
- ☐ kW and PF Trend in Lighting and Heating Loads
- ☐ Harmonic Distortion in Voltage, all Voltage Levels
- ☐ Harmonic Distortion of Current in Main Feeds
- ☐ Harmonic Distortion of Current in Capacitors
- ☐ Ratings, Harmonic Spectra of Adjustable-Speed Drives
- ☐ Ratings, Spectra of Other Harmonic Sources
- ☐ kvar Ratings, Parameters of Harmonic Filters
- ☐ All Harmonic Sources Accounted For?

Figure A-2. Plant Inventory Checklist.

Cable Impedance Data

The following tables are based on data found in IEEE Std. 141-1993, *IEEE Recommended Practice for Electric Power Distribution for Industrial Plants.* All impedances are given in ohms per 1000 ft.

AWG or kcmil	In magnetic duct: 600 V & 5 kV nonshielded*		In magnetic duct: 5 kV & 15 kV shielded*		In nonmagnetic duct: 600 V & 5 kV nonshielded*		In nonmagnetic duct: 5 kV & 15 kV shielded*	
	R	X	R	X	R	X	R	X
6	0.8470	0.0530			0.8470	0.0420		
4	0.5320	0.0500	0.5320	0.0680	0.5320	0.0400	0.5320	0.0540
2	0.3350	0.0460	0.3350	0.0630	0.3350	0.0370	0.3350	0.0500
1	0.2650	0.0480	0.2650	0.0590	0.2650	0.0350	0.2650	0.0470
1/0	0.2100	0.0430	0.2100	0.0560	0.2100	0.0340	0.2100	0.0450
2/0	0.1670	0.0410	0.1670	0.0550	0.1670	0.0330	0.1670	0.0440
3/0	0.1330	0.0400	0.1320	0.0530	0.1330	0.0370	0.1320	0.0420
4/0	0.1060	0.0390	0.1050	0.0510	0.1050	0.0310	0.1050	0.0410
250	0.0896	0.0384	0.0892	0.0495	0.0894	0.0307	0.0891	0.0396
300	0.0750	0.0375	0.0746	0.0479	0.0746	0.0300	0.0744	0.0383
350	0.0644	0.0369	0.0640	0.0468	0.0640	0.0245	0.0638	0.0374
400	0.0568	0.0364	0.0563	0.0459	0.0563	0.0291	0.0560	0.0367
500	0.0459	0.0355	0.0453	0.0444	0.0453	0.0284	0.0450	0.0355
600	0.0388	0.0359	0.0381	0.0431	0.0381	0.0287	0.0377	0.0345
700	0.0338	0.0350	0.0332	0.0423	0.0330	0.0280	0.0326	0.0338
750	0.0318	0.0341	0.0310	0.0419	0.0309	0.0273	0.0304	0.0335
1000	0.0252	0.0341	0.0243	0.0401	0.0239	0.0273	0.0234	0.0331

* Cross-linked polyethylene insulation, 90 °C

Table #.1. 60 Hz impedance of aluminum cable, three single conductors.

AWG or kcmil	In magnetic duct: 600 V & 5 kV nonshielded*		In magnetic duct: 5 kV & 15 kV shielded*		In nonmagnetic duct: 600 V & 5 kV nonshielded*		In nonmagnetic duct: 5 kV & 15 kV shielded*	
	R	X	R	X	R	X	R	X
6	0.8470	0.0530			0.8470	0.0420		
4	0.5320	0.0500			0.5320	0.0400		
2	0.3350	0.0460	0.3350	0.0560	0.3350	0.0370	0.3350	0.0450
1	0.2650	0.0480	0.2650	0.0530	0.2650	0.0350	0.2650	0.0420
1/0	0.2100	0.0430	0.2100	0.0500	0.2100	0.0340	0.2100	0.0400
2/0	0.1670	0.0410	0.1670	0.0490	0.1670	0.0330	0.1670	0.0390
3/0	0.1330	0.0400	0.1330	0.0480	0.1330	0.0370	0.1320	0.0380
4/0	0.1060	0.0390	0.1050	0.0450	0.1050	0.0310	0.1050	0.0360
250	0.0896	0.0384	0.0895	0.0436	0.0894	0.0307	0.0893	0.0349
300	0.0750	0.0375	0.0748	0.0424	0.0746	0.0300	0.0745	0.0340
350	0.0644	0.0369	0.0643	0.0418	0.0640	0.0295	0.0640	0.0334
400	0.0568	0.0364	0.0564	0.0411	0.0563	0.0291	0.0561	0.0329
500	0.0459	0.0355	0.0457	0.0399	0.0453	0.0284	0.0452	0.0319
600	0.0388	0.0359	0.0386	0.0390	0.0381	0.0287	0.0380	0.0312
700	0.0338	0.0350	0.0335	0.0381	0.0330	0.0280	0.0328	0.0305
750	0.0318	0.0341	0.0315	0.0379	0.0309	0.0273	0.0307	0.0303
1000	0.0252	0.0341	0.0248	0.0368	0.0239	0.0273	0.0237	0.0294

* Cross-linked polyethylene insulation, 90 °C

Table #.2. 60 Hz impedance of three-conductor aluminum cable.

	In magnetic duct				In nonmagnetic duct			
AWG or kcmil	*600 V & 5 kV nonshielded**		*5 kV & 15 kV shielded***		*600 V & 5 kV nonshielded**		*5 kV & 15 kV shielded***	
	R	X	R	X	R	X	R	X
8	0.8110	0.0754	0.8110	0.0860	0.8110	0.0603	0.8110	0.0688
8 (solid)	0.7860	0.0754	0.7860	0.0860	0.7860	0.0603	0.7860	0.0688
6	0.5100	0.0685	0.5100	0.0796	0.5100	0.0548	0.5100	0.0636
6 (solid)	0.4960	0.0685	0.4960	0.0796	0.4960	0.0548	0.4960	0.0636
4	0.3210	0.0632	0.3210	0.0742	0.3210	0.0506	0.3210	0.0594
4 (solid)	0.3120	0.0632	0.3120	0.0742	0.3120	0.0506	0.3120	0.0594
2	0.2020	0.0585	0.2020	0.0685	0.2020	0.0467	0.2020	0.0547
1	0.1600	0.0570	0.1600	0.0675	0.1600	0.0456	0.1600	0.0540
1/0	0.1280	0.0540	0.1280	0.0635	0.1270	0.0432	0.1280	0.0507
2/0	0.1020	0.0533	0.1030	0.0630	0.1010	0.0426	0.1020	0.0504
3/0	0.0805	0.0519	0.0814	0.0605	0.0766	0.0415	0.0805	0.0484
4/0	0.0640	0.0497	0.0650	0.0583	0.0633	0.0398	0.0640	0.0466
250	0.0552	0.0495	0.0557	0.0570	0.0541	0.0396	0.0547	0.0456
300	0.0464	0.0493	0.0473	0.0564	0.0451	0.0394	0.0460	0.0451
350	0.0378	0.0491	0.0386	0.0562	0.0368	0.0393	0.0375	0.0450
400	0.0356	0.0490	0.0362	0.0548	0.0342	0.0392	0.0348	0.0438
450	0.0322	0.0480	0.0328	0.0538	0.0304	0.0384	0.0312	0.0430
500	0.0294	0.0466	0.0300	0.0526	0.0276	0.0373	0.0284	0.0421
600	0.0257	0.0463	0.0264	0.0516	0.0237	0.0371	0.0246	0.0412
750	0.0216	0.0445	0.0223	0.0497	0.0194	0.0356	0.0203	0.0396

* varnished cambric insulation, 75 °C ** neoprene insulation, 75 °C

Table #.3. 60 Hz impedance of copper cable, three single conductors.

	In magnetic duct				In nonmagnetic duct			
AWG or kcmil	*600 V & 5 kV nonshielded**		*5 kV & 15 kV shielded***		*600 V & 5 kV nonshielded**		*5 kV & 15 kV shielded***	
	R	X	R	X	R	X	R	X
8	0.8110	0.0577	0.8110	0.0658	0.8110	0.0503	0.8110	0.0574
8 (solid)	0.7860	0.0577	0.7860	0.0658	0.7860	0.0503	0.7860	0.0574
6	0.5100	0.0525	0.5100	0.0610	0.5100	0.0457	0.5100	0.0531
6 (solid)	0.4960	0.0525	0.4960	0.0610	0.4960	0.0457	0.4960	0.0531
4	0.3210	0.0483	0.3210	0.0568	0.3210	0.0422	0.3210	0.0495
4 (solid)	0.3120	0.0483	0.3120	0.0508	0.3120	0.0422	0.3120	0.0495
2	0.2020	0.0448	0.2020	0.0524	0.2020	0.0390	0.2020	0.0457
1	0.1600	0.0436	0.1600	0.0516	0.1600	0.0380	0.1600	0.0450
1/0	0.1280	0.0414	0.1280	0.0486	0.1270	0.0360	0.1280	0.0423
2/0	0.1020	0.0407	0.1030	0.0482	0.1010	0.0355	0.1020	0.0420
3/0	0.0805	0.0397	0.0814	0.0463	0.0766	0.0346	0.0805	0.0403
4/0	0.0640	0.0381	0.0650	0.0446	0.0633	0.0332	0.0640	0.0389
250	0.0552	0.0379	0.0557	0.0436	0.0541	0.0330	0.0547	0.0380
300	0.0464	0.0377	0.0473	0.0431	0.0451	0.0329	0.0460	0.0376
350	0.0378	0.0373	0.0386	0.0427	0.0368	0.0328	0.0375	0.0375
400	0.0356	0.0371	0.0362	0.0415	0.0342	0.0327	0.0348	0.0366
450	0.0322	0.0361	0.0328	0.0404	0.0304	0.0320	0.0312	0.0359
500	0.0294	0.0349	0.0300	0.0394	0.0276	0.0311	0.0284	0.0351
600	0.0257	0.0343	0.0264	0.0382	0.0237	0.0309	0.0246	0.0344
750	0.0216	0.0326	0.0223	0.0364	0.0197	0.0297	0.0203	0.0332

* varnished cambric insulation, 75 °C ** neoprene insulation, 75 °C

Table #.4. 60 Hz impedance of three-conductor copper cable.

Glossary of Terms for Power Factor Correction

active power — The in-phase component of volt-amperes in an electric circuit; same as power. Also called real power. See reactive power.

adjustable speed drive (ASD) — An electric drive designed to provide easily operable means for speed adjustment of the motor.

alternating current (ac) — An electric current or voltage that reverses direction of flow periodically, as contrasted to direct current, and has alternately positive and negative values. Most electricity used in the U.S. today is alternating current.

amp, ampere (A) — A unit of measurement of electric current, which is the rate that electrons flow in a wire; one ampere is 6.023 x 10^{23} electrons per second. The measurement is similar to gallons per minute of water in a pipe.

apparent power — The mathematical product of volts and amperes.

background harmonic voltage distortion levels — The harmonic voltage distortion at a site, which is not caused by the site load.

bus — A conductor or group of conductors that serves as a common connection for two or more circuits and is used to interconnect equipment of the same voltage.

capacitance — The property of an arrangement of conductors and dielectrics that stores energy in the form of an electrical charge when potential differences exist between the conductors. See inductance.

capacitor — 1) In a power system, installed to supply reactive power. See reactive power. 2) A device to store an electrical charge (usually made of two or more conductors separated by a non-conductor such as glass, paper, air, oil, or mica) that will not pass direct current and whose impedance for alternating current frequencies is inversely proportional to frequency. 3) In a power system, capacitors consist of metal-foil plates separated by paper or plastic insulation in oil or other suitable insulating fluid and sealed in metal tanks.

characteristic harmonic — One of the predominate frequencies present in a harmonic source. For example, the characteristic harmonics of a six-pulse converter are 5,7,11,13,17,19,..... .

circuit breaker — A switching device capable of making, carrying, and interrupting currents under normal circuit conditions and also making, carrying for a specified time, and interrupting currents under abnormal circuit conditions such as those under faults or short circuits. The medium in which circuit interruption is performed may be designated, as in oil circuit breaker, air-blast circuit breaker, gas or sulfur hexafluoride circuit breaker, or vacuum circuit breaker.

contactor — A device, operated other than by hand, for repeatedly establishing and interrupting a low voltage (600 volts or less) circuit under normal conditions.

converter — A device that changes alternating current to direct current or vice versa, or changes one frequency to another.

crest factor (CF) — The ratio of the peak value of a periodic waveform to the rms value. The crest factor of a sinewave is 1.414. For distorted waveforms the crest factor can vary.

current transformer (CT) — A device for transferring electrical energy from one circuit to another by magnetic induction, usually between circuits of different voltages. Consists of a magnetic core on which there are two or more windings. In power systems, most frequently used for changing voltage levels.

damping — A power system characteristic which tends to retard the effects of transient conditions or harmonics.

delta connected — A connection of the windings of a three-phase transformer or three single-phase transformers making up a three-phase bank that are in series to form a closed path. Delta connections may also be used for three-phase shunt reactor banks, shunt capacitor banks, or generator windings.

displacement power factor (DPF) — The ratio of the active power to the apparent power (power factor) between the fundamental (60 Hz) components of the voltage and current, neglecting the influence of harmonics.

distortion power — The harmonic content of apparent power not contributing toward real power.

filter — In an electric system, a device that blocks certain frequencies while allowing other frequencies to pass.

fixed capacitor bank — A capacitor bank that is left in circuit, without any automatic controls.

frequency — The repetition rate of a periodically recurring quantity, commonly stated in hertz (Hz), kilohertz (kHz), or megahertz (Mhz). The standard frequency of alternating-current power in the U.S. is 60 Hz.

frequency response (power systems) — A formula or a graph which depicts the impedance of an electrical network or device versus driving frequency.

fundamental frequency — The lowest frequency component of a periodically recurring, complex (multi-frequency) wave.

fuse — An overcurrent protective device with a circuit-opening fusible part that is heated and severed by the passage of excessive current through it.

harmonic	A sinusoidal wave having a frequency that is an integral multiple of a fundamental frequency. For example, a complex wave whose frequency is twice that of the fundamental frequency is called the second harmonic. .
harmonic distortion	Distortion in the waveshape of voltage or current caused by the presence of harmonics..
harmonic resonance	Conditions where circuit inductive and capacitive reactances negate each other at a particular harmonic frequency.
Hertz (Hz)	The unit of frequency in cycles per second; power systems in the U.S. operate with a frequency of 60Hz.
I	Symbol for current.
I^2R losses	Heating losses due to the flow of current through a resistance in a transformer, motor, or conductor.
imaginary power	See reactive power.
impedance	A characteristic of an electric circuit that determines its hindrance to the flow of electricity. The higher the impedance, the lower the current. The unit of measure is the same as resistance (ohms).
inductance	The property of an electric circuit that causes it to store energy in the form of a magnetic field and because of which a varying current in a circuit induces an electromotive force (voltages) in that circuit or a neighboring circuit. Also see capacitance.
kilo (k)	A prefix indicating 1,000.
kVA	Kilovoltamperes. See apparent power.
kvar	Kilovars. See reactive power.
kW	Kilowatts. See active power.
lagging	An electrical current whose phasing is behind the phasing of a voltage is said to lag.
leading	The phase relationship (advance) between two circuits. An electrical current whose phasing is ahead of the phasing of a voltage, for example, is said to lead.
line to line voltage	The usual voltage reference for three phase power systems.
line to neutral voltage	The usual voltage reference for single phase power systems.
linear load	An electrical load which draws a sinusoidal current from a sinusoidal voltage source.
load	A device that receives electrical power.
losses	The general term applied to energy (kilowatthours) and power (kilowatts) lost when operating an electric system, occurring mainly as energy turns to waste heat in electrical conductors and apparatus.
maximum demand	The greatest demand of a load occurring during a specified time period.
Mega (M)	Prefix meaning 1,000,000.
micro (m)	Prefix meaning 1/1,000,000th.

milli (m)	Prefix meaning 1/1000th.
modeling	Technique of system analysis and design using mathematical or physical idealizations of all or a portion of the system.
MVA	Megavoltamperes. See apparent power.
neutral	The common connection (or average value) between three phases of a power system.
nominal system voltage	The voltage by which the system is designated and to which certain operating characteristics are related, and near the voltage level at which the system operates (generally is about 5 to 10 percent below the maximum system voltage for which system components are designed).
nonlinear load	An electrical device drawing power that does not draw a sinusoidal current wave form.
one line diagram	A diagram which shows, by means of a single phase representation, the structure of electric circuits and components.
overcurrent	Current in excess of the rated capacity of a circuit.
overvoltage	A voltage above the normal rated voltage or above the maximum statutory limits.
parallel	Two circuit elements connected across the same two points.
parallel resonance	Electricity, resonance occurs when the capacitive reactance and inductive reactance of a device are adjusted so that the device either maximizes or minimizes current flow at a specific frequency.
per unit (pu)	Percentage expressed as a ratio to one. For example 70% is 0.7pu. Power system quantities are often expressed in per unit of defined system base values.
phase angle	In a power system, the displacement, in time, of the phase of one quantity (voltage or current) from the phase of the same quantity at a different or reference location.
positive sequence	The component of three phase voltages or currents that are balanced.
power	1) The rate of energy production or transfer. 2) Electrically, power is expressed in watts (the product of applied voltage and resulting in-phase current. Same as active or real power in contrast with reactive or apparent power. Used interchangeably with although technically not a synonym of energy. 3) Power delivered to a load is also termed demand.
power factor	The ratio of power in watts to the apparent power (product of volts times amperes) in voltamperes. The power factor of an alternating-current transmission system is unity when the voltage and current are in phase. There is no power factor with direct-current power. See reactive power.
power factor correction	A method to improve the power factor toward unity.
pulse width modulated (PWM)	A power electronic switching technique where voltage (or current) is switching on and off many times during the fundamental period.

quality factor (Q)	The electrical quality of a coil, capacitor, or circuit. Mathematically, Q is the ratio of reactance to resistance. The higher the Q, the greater the selectivity of the circuit.
reactive power (var)	The out-of-phase component of the total voltamperes in an electric circuit, usually expressed in var (voltamperes reactive). It represents the power involved in the electric fields developed when transmitting alternating-current power (the alternating exchange of stored inductive and capacitive energies in a circuit). See power factor.
reactor	In an electrical system, a device used to introduce inductive reactance into a circuit.
rectifier	A device that converts alternating current into direct current.
rms	The value of an alternating current or voltage that produces the same amount of heat in certain resistance as an equal direct current or voltage is called the effective, or the RMS, value. The RMS value of a periodic quantity is the square root of the average of the squares of the values of the quantity taken throughout the period. If the periodic quantity is a sine wave, its effective RMS value is .707 of peak amplitude.
series connected	Two electrical circuit elements are series connected when the same identical current must flow through both.
series resonance	If the circuit capacitance and inductance are in series, the device exhibits a low impedance at resonance and the current flow through the device is maximized at resonance.
short circuit	An unintentional connection between a point in a circuit and ground, or between two points in a circuit.
short circuit capacity	An abnormal connection between two or more points in a circuit. May be either deliberate (as in a protective grounding) or accidental (as in a system fault).
silicon controlled rectifier (SCR)	A semiconducting electrical switch similar to a diode, but the conduction (turning on) firing angle is controlled. See thyristor.
sinusoidal	The shape of a wave form such as an alternating current or voltage that has alternating positive and negative cycles (sine wave).
six-pulse converter	A three-phase rectifier that utilizes six diodes (or other power electronic) switches to convert ac voltage to dc voltage.
source impedance	The strength of electrical supply, as characterized by the equivalent impedance seen by a short circuit to ground or neutral.
steady state	When the operating condition of a system is consistent.
stiff system	A system with a low source impedance.
surge arrester, suppressor	A device which is used to protect other electrical equipment from overvoltage by discharging or bypassing surge current..
switched capacitor bank	A power factor correction bank which has automatic controls to vary the amount of power factor correction, according to the site power factor or voltage.
synchronous machine	An electric motor with an excitation system which allows it to rotate at synchronous frequency (without slip).

thyristor — A semiconductor switch with "on" and "off" states. May be uni-directional or bi-directional, and may be a triggered three-terminal device (a controlled rectifier), or a two-terminal device (diode).

total harmonic distortion (THD) — The ratio of the rms value of the harmonic content to the rms value of the fundamental. THD is usually expressed as a percent of the fundamental.

transformer — A device for transferring electrical energy from one circuit to another by magnetic induction, usually between circuits of different voltages. Consists of a magnetic core on which there are two or more windings. In power systems, most frequently used for changing voltage levels.

true power factor — See power factor and compare to displacement power factor.

twelve-pulse converter — A three-phase rectifier that utilizes two six-pulse converters connected to cancel the 5th and 7th harmonic components.

volt (V) — The unit of electromotive force, or voltage, that if steadily applied to a circuit having a resistance of one ohm will produce a current of one ampere.

voltage (V) — The driving force that causes a current to flow in an electric circuit. Voltage and volt are often used interchangeably.

voltampere (VA) — The mathematical product of volts and amperes. Same as apparent power.

Watt (W) — 1) The electrical unit of power. 2) The rate of energy transfer when one ampere is passing across one volt. Analogous to horsepower or footpounds per minute of mechanical power (one horsepower is equivalent to approximately 746 watts; one kilowatt equals 1,000 watts; one megawatt equals 1,000,000 watts).

wye or Y connected — A connection of the windings of a three-phase transformer (or three single-phase transformers making up a three-phase bank) such that one end of each winding is connected to a common point.

Z — Symbol for impedance.

zero sequence — The component of unbalance in a three phase system that is in phase on all phases.

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