POWER QUALITY AND POWER FACTOR CORRECTION

INTRODUCTION

Since most loads in modern electrical distribution systems are inductive, there is an ongoing interest in improving power factor. The low power factor of inductive loads robs a system of capacity and can adversely affect voltage level. As such, power factor correction through the application of capacitors is widely practiced at all system voltages. As utilities increase penalties they charge customers for low power factor, system performance will not be the only consideration. The installation of power factor correction capacitors improves system performance and saves money.

A number of manufacturers have catalogs and design manuals to assist in the application of their products. These publications provide guidance in the selection and placement of capacitors and discuss general provisions that will affect the overall performance of the installation.

Although the methodology for applying capacitors is relatively straight forward, there are a number of influencing factors that must be considered. To ensure that the capacitor installation does not create more problems than it solves, consideration must be given to non-linear loads, utility interaction and system configuration.

PQ PROBLEMS RELATED TO POWER FACTOR CORRECTION

It is ironic to think that as steps are being taken to improve the operating efficiency at a facility, those very steps may be adversely affecting the facility in other ways. This is sometimes the case when power factor correction capacitors are installed at a facility. As an example, general application of capacitors on motors, when applied without regard to the connected system, can result in the inadvertent tuning of a system to a dominant harmonic. (The implications of this are discussed further below).

Although "harmonic problems" are attributed to many power system problems, it is sometimes overly used. There are other ramifications associated with the use of power factor correction capacitors such as voltage rise and switching transients. Each of these power quality concepts will be discussed in turn.

HARMONIC RESONANCE

A common problem that occurs when power factor correction capacitors are installed on a system is harmonic resonance. When this occurs, the power system at a facility is tuned to a specific frequency due to a combination of the system inductance and the added capacitance. The system "resonates" at this frequency, if there are loads at or near the installation that produce that harmonic.

When this occurs, the normal flow of harmonic currents, from load to utility source, is altered. When the currents can flow normally, they combine with other load currents across the system. If the bulk of those loads are linear, there will not be a significant percentage of distorted current. However, when the flow is altered by the installation of capacitors, distortion levels may rise, causing problems within a plant, at nearby utility customers or at system substations or currents may flow where they are not desired.

When parallel resonant conditions exist, shunt capacitor banks appear to the harmonic source as being in parallel with the system source reactance (or short circuit reactance). When harmonic currents, from the harmonic source, flow through this high impedance circuit, high harmonic voltages develop. The high harmonic voltages can result in an overvoltage condition on the capacitors themselves and/or high voltage distortion.

Overvoltage conditions can exceed the voltage rating of the capacitor and result in capacitor failure. High voltage distortion can result in the mis-operation or failure of equipment.

When series resonant conditions occur, the capacitor appears to be in series with line impedance, as seen from the harmonic source. This presents a low impedance path to the flow of harmonic currents. Currents, then, will flow on the system in ways that were unintended. This can result in interference on communications circuits that may be nearby, excessive voltage distortion at the capacitors or conductor heating.

If the capacitors are placed at the end of long feeders, harmonic voltage distortion can occur at the capacitor bank since the bank acts as a ‘sink’ for harmonic currents originating elsewhere on the system. If the capacitors are placed on the secondaries of service transformers, the capacitor/transformer combination can appear like a series tuned filter.

Since this combination behaves like a sharply tuned filter, its resonance at a significant harmonic would result in a very low impedance path. This would result in a high voltage distortion on the secondary while the primary distortion would remain within the limits of IEEE 519.

Capacitors can fail with as little as 10% of fifth harmonic content and this can take place when there are no other noticeable effects on the system. It has been estimated that 30-40% of capacitor installations are not fully functional due to excessive harmonic currents.

In a system that is parallel or series resonant, load has a significant influence on the harmonic distortion. As the load on the system increases, the overall damping factor of the circuit increases and the sharpness of the resonance decreases. When the load decreases, the damping factor decreases and the sharpness of the resonance increases. The sharpness of the resonance determines the impedance that is seen by the harmonic currents. Therefore, harmonic voltage distortion will be worse on lightly loaded systems or when the system load is mostly motors.

Resonant conditions and the influence of load become particularly important when a plant is operating from on-site generators. The steady state positive sequence reactance of a generator is much higher than the utility source impedance mentioned above. As a result, harmonic currents produce higher harmonic voltages and overall voltage distortion. Additionally, generator regulators and control systems are sensitive to distortion on the voltage bus. If the non-linear load on a plant is a significant percentage of the overall generator load, the generator may not stay online. Furthermore, high harmonic currents cause heating in the alternator iron which can lead to premature failure.

SWITCHING TRANSIENTS

As mentioned earlier, capacitors are used at all voltage levels. Utilities install them at various locations on their transmission and distribution systems for voltage and VAR support.

When the utility energizes a discharged capacitor, the bus voltage will momentarily collapse. This occurs because the voltage across a capacitor can not change instantaneously. This is followed by an oscillatory recovery that lasts about ½ of a cycle. The overshoot associated with this oscillation can result in a voltage that has a theoretical peak value of two times the maximum value of the 60Hz sine wave (crest voltage). The same effect can occur when a capacitor is switched off, if re-strike occurs during the switching operation.

Transients of this magnitude and duration are usually not a problem on the utility system but they can produce problems at a user facility. Severe over-voltages can appear on facility capacitors through a phenomenon known as voltage magnification. The voltage at the end-user capacitor can be greater than the voltage at the utility capacitor. This translates to a peak voltage with a theoretical upper value of 400% although this is rarely seen.

The highest transient voltages occur at the low voltage capacitor bank when the characteristic frequency of the switching transient is nearly equal to the resonant frequency of the low voltage system and when the switched capacitor is ten or more times the size 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" transient over-voltages from 205% - 354% of rated peak kV (depending on the number of times a year the over-voltage occurs).

Generally speaking, the voltage magnification will not result in capacitor damage. The problem that usually occurs is the failure or mis-operation of sensitive loads in the facility where the low voltage capacitors are installed.

VOLTAGE RISE

At many facilities, fixed capacitors are used to reduce cost. Fixed capacitors are those that are permanently connected to the load bus and are not switched on and off as the load changes. When the load on the facility is low, the voltage may increase due to the capacitor being sized for the higher load.

The limit on steady state voltage is generally taken to be 110% of the rated voltage. If the voltage is allowed to rise above this point, transformers will saturate and overheat, mis-operation of equipment may occur and equipment life will be reduced. If the prevailing bus voltage happens to be high, due to conditions on the distribution system feeding the facility, the voltage rise would be added to this already higher voltage. Therefore, system voltage should be checked when considering voltage rise.

FACILITY SURVEY/NEW CAPACITOR INSTALLATIONS

Capacitor installations are usually straightforward, however, a number of steps can be taken to ensure that the maximum benefit is derived and there will be no problems when the capacitors are installed. For example, a comprehensive facility survey and cost analysis will indicate whether the benefit from the installation justifies the cost.

Many times, when a decision has been made to install power factor correction capacitors, the cost analysis has been limited to an examination of the utility bills and an estimation of the likely savings. In most cases this is probably sufficient. However, when there are power quality issues to consider, this type of analysis may not reveal all of the costs.

The presence of non-linear loads, utility capacitors and mis-operating equipment might indicate that power quality problems exist and could be made worse by adding capacitors to a system. The true final cost may also include extended monitoring, an engineering study, relocation of existing capacitors, filter design and installation, switching equipment and/or follow-up measurements and re-work.

To determine what elements may be required, it is best to begin with a facility survey to identify non-linear loads, the size of the service entrance transformer, other plant data and utility information. This information, taken together, is usually sufficient. In some cases, additional information is required which may involve extended monitoring and/or verification of the system one-line diagram. The cost analysis would take into consideration the additional requirements and indicate what the true costs will be.

After data has been collected on the facility, a quick assessment can be made to determine what level of effort may be required to complete an installation. For a simple installation, where there are no non-linear loads, the process may be as simple as sizing the capacitor and having it installed.

IS AN ENGINEERING STUDY REQUIRED?

The following checklist identifies situations where an engineering study is probably required. This checklist can be used if:

- capacitors are being added for the first time
- capacitors are currently installed and additional capacitors are being added
- capacitors are currently installed and problems are being encountered.

	Are capacitors being added to a system where 20% of the connected load is harmonic sources?
	Have there been unexplained operations of fuses or other protective devices?
	Are measured RMS capacitor currents 135% (or greater) of rated current?
	Have there been any failures of capacitors currently installed at the facility?
	Have there been any instances of swelling or unusual noises on capacitors currently installed at the facility?
	Have there been unexplained failures or mis-operations of sensitive equipment?
	Have there been an unusual number of motor failures or unexplained motor failures?
	Has the utility imposed harmonic limits?
	Is a plant expansion currently being planned that might include additional harmonic sources?
	Is there on-site generation that will provide power to a significant number of harmonic sources?

MITIGATION TECHNIQUES

DETUNING

De-tuning a system refers to techniques that are used to change the resonance point of a system and move it away from significant harmonics. As mentioned earlier, when shunt power factor correction capacitors are added to a system, the parallel combination of these capacitors and the system source impedance can tune the system to resonate at a particular harmonic frequency. This high impedance path is the source of harmonic voltages when harmonic load current flows through the system.

One technique used to de-tune a system is to add a reactor to the system. Harmful resonance conditions are generally between the shunt capacitors and the source impedance. The reactor is added between the source and the capacitor bank. An effective way to do this to add the reactor in series with the capacitor bank to move the system resonance point without tuning the capacitor to create a filter..

Another method that can be used is to change the size of the capacitor bank being considered. This is often one of the least expensive options. If the capacitor can be sized to move the resonance point without impacting other operational aspects (over/under correction, voltage rise, etc.) there would be no requirements for other mitigation.

De-tuning can also be accomplished by moving capacitors to a point in the system with a different short-circuit impedance. This can also be considered if the installation of a capacitor causes telephone interference problems. In many cases, the capacitor can not be moved far enough in a plant to make a difference, however, the technique should not be dismissed outright.

If capacitors are currently installed and problems related to harmonic current sources have been encountered, it may be cost effective to remove the capacitors. In this case, a comprehensive cost-benefit analysis must be performed.

FILTERING

In some situations it may be necessary to install filters to minimize the harmonic currents that are flowing on a system. Generally, filters provide a low impedance path to shunt the harmonic currents rather than them flowing back through the distribution system. Filters also change the system frequency response, most often, but not always for the better.

Adding a filter creates a sharp parallel resonance point at a frequency below the filer’s tuned frequency. Filters are tuned slightly below the harmonic in case there is a change to the system or there is a component failure, either of which might move the resonance point into the filter. Filters typically cost about three times what a simple capacitor installation might cost.

Filters are usually applied close to the component in a system where there is significant generation of harmonic currents. These filters are typically tuned to the fifth harmonic, for three phase loads, and the third harmonic for single-phase loads. These frequencies represent the lowest harmonic usually encountered on these systems and the first filter in a system should be tuned to the lowest frequency.

Filter application is not as simple as simple capacitor application. Analysis that may range in scope from a survey to long term monitoring and computer modeling may be required.

Filter capacitors are usually wired in a delta configuration on 480-volt systems. As a result, they are largely ineffective when it becomes necessary to control third-harmonic currents. If triplen harmonics are determined to be a problem, other configurations can be used.

Filters should be placed on a bus where the available fault current is expected to remain constant. Although the notch frequency of the filter will not change, the system resonance point might move.

Finally, filters must be designed with the capacity of the bus in mind. The filter can not be sized solely on the load that is producing the harmonic.

GROUPING OF LOADS

In installations where there are several harmonic current sources, it may be possible to electrically group the loads. As an example, this technique is used when the sources are 6-pulse motor drives. Groups of 6-pulse drives can be fed from transformers with different winding configurations. If the loads are balanced, the fifth and seventh harmonics tend to cancel with the net profile being closer to that of a 12-pulse drive.

In a configuration such as this, the lowest harmonic would be the eleventh or thirteenth. This not only moves the predominant harmonic away from typical resonance points but it results in higher frequency harmonics. High frequency harmonics do not have enough energy to damage a system, as would a low order harmonic.

In addition to grouping loads for transformer feeds, the grouping also allows some cancellation that naturally occurs from the statistically random nature of loads and the corresponding harmonic spectrums. Although this cancellation is not of the magnitude discussed above, it is noteworthy.

EQUIPMENT CHANGES

If it is determined that power factor correction capacitors may affect power quality at a facility, one solution may be to make some equipment changes. This may mean replacing some equipment with newer technology equipment or adding enhancements to that equipment.

If adjustable speed drives were installed without isolation transformers or line-side reactors, consideration can be given to adding the appropriate equipment to the installation. Transformers and line reactors can provide solutions to a number of problems.

Line reactors are a cost-effective way to eliminate nuisance tripping of drives due to the transient over-voltages that result from utility capacitor switching. In addition, line reactors prolong the current pulse that is typical of the rectifiers on the input of these drives. This results in a different, and much improved, harmonic current spectrum. Determining the correct reactor size, for transient voltage isolation, requires a detailed transient simulation that takes into account utility capacitor size and transformer rating.

Standard isolation transformers can provide the same sort of transient isolation but size and cost considerations may preclude this option. Specialized transformers that provide harmonic mitigation may also be used. Any equipment added should be installed close to the drive and electrical connections should be kept as short as possible.

If grouping of 6-pulse adjustable speed drives is not practicable, consideration may be given to replacing an older technology drive with a newer one or with a 12-pulse unit.

UTILITY SUPPORT

If voltage transients resulting from utility switching are having an effective on power quality at a facility, consideration can be given to discussing mitigation techniques with the utility. There are a number of techniques that the utility can use to minimize these effects.

The most common control techniques are pre-insertion devices and controlled closing. When pre-insertion is used, a resistive/reactive element is inserted into the circuit briefly to damp the first peak of the transient. When reactors are used, they are helpful in limiting the higher frequency components.

Controlled closing involves using a control system to ensure that the capacitor switching mechanism closes when the voltage on the capacitor closely matches the system voltage when the contacts mate. This avoids the step voltage that causes the circuit to oscillate.

Finally, it may be possible to schedule the switching at a time that will have the least impact on the facility. The timing may be coordinated with the switching of facility capacitors or the start up of a process. This may involve switching on capacitors before they are needed but this should not have adverse effect, particularly if a thorough analysis has been completed.