Do Capacitor Switching Transients Still Cause Problems?

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We have been evaluating problems related to capacitor switching transients for many years. Capacitor banks have been used on distribution systems to correct power factor and control the feeder voltage profile since the first overhead distribution systems. Transients caused by switching these capacitor banks didn't cause many problems because both the power system equipment and customer equipment (lighting, heating, motors, etc.) were relatively immune to the transient voltages.

In the late 1970's and early 1980's, the difficulty of obtaining right-of-way for new transmission lines forced electric utilities to try and get as much capacity out of the existing transmission systems as possible. One popular strategy was to apply transmission capacitor banks to support the voltage during heavy power transfer conditions. These transmission capacitor banks caused a number of problems, such as magnified transients at lower voltage capacitors and high phase-to-phase voltages at transmission transformers. These concerns were studied extensively and described in an IEEE paper in 1986 [1]. Problems with switchgear resulted in restriking, which caused even higher transients and arrester failures. The requirements for arresters to protect capacitor banks were described in a 1984 IEEE paper [2].

Two developments occurred in the 1980's that increased the concern for capacitor switching at the customer level:

1. Energy conservation initiatives and power factor penalties increased the application of capacitor banks within customer facilities. These capacitor banks did not result in excessive transients themselves but they often magnified the transients from capacitor banks being switched on transmission and distribution systems. Problems were common in plants with capacitors and power electronics, such as dc drives, usually manifesting themselves as SCR failures in the drives or low voltage capacitor failures.
2. The advent of PWM inverters for adjustable-speed motor drives created a whole new concern for capacitor switching. Capacitor switching transients caused an overvoltage in the dc link of the drive which caused the drive to trip. This problem became widespread wherever ac PWM-type drives were being applied.

These problems were characterized through EPRI case studies with utilities like Pacific Gas & Electric. The problems were described in a Power Quality Conference (Philadelphia, 1990) paper by Tom Grebe and the paper was reproduced in Power Quality Magazine in May/June, 1991 [3]. More complete descriptions of the problems and solutions were outlined in companion IEEE papers in 1991 and 1992 [4,5]. Finally, manufacturers started to implement the simple solution of selling their drives with inductive chokes on the front end (or in the dc link) and many utilities started to use switching controls for their larger capacitor banks, especially for transmission applications.

Believe it or not, with all of this work to characterize capacitor switching transients and available solutions, we are still doing studies to evaluate equipment failures and nuisance tripping associated with capacitor switching events. Why are customers still having problems? Obviously, not enough engineers have read the papers and understand the concerns when they are applying power factor correction equipment or specifying adjustable speed drives. Therefore, I thought it would be worthwhile to quickly review the basic phenomena and outline some simple rules for avoiding problems.

The Capacitor Energizing Transient

When a capacitor bank is energized, there is an instantaneous short circuit at the capacitor location because the voltage across a capacitor cannot change instantaneously. If there is no reactor in series with the capacitor, the bus voltage at the capacitor location is brought to zero. After this step wave change in the voltage, there is an oscillation between the capacitor bank and the system inductance as the voltage tries to get back to its normal value. In the initial oscillation, the transient voltage magnitude can approach two times the normal peak voltage (2 per unit). Usually, damping in the system causes the transient voltage to be less than 1.6 per unit.

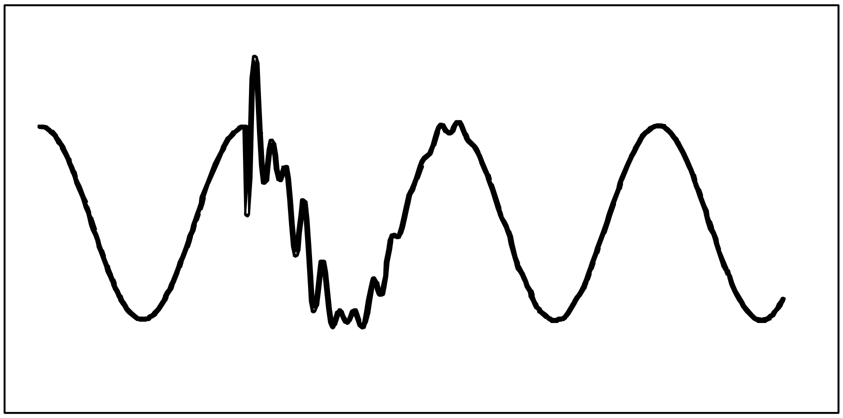

Figure 1. Example capacitor energizing transient.

Both the initial step change and the oscillation can be important parts of the capacitor switching transient. The initial step change is important because of the high rate-of-rise. This transient can couple across transformers into end user facilities by the capacitance ratio of step down transformers, resulting in higher magnitude transients at the end user facilities. Usually, the energy levels in this coupled transient are quite low and conventional surge suppression equipment within the end use facility can prevent problems. The oscillation after the initial step change can be more troublesome. The transient magnitude associated with this oscillation is not severe for the transmission or distribution systems. Equipment and devices on these systems are designed to handle transient voltage magnitudes well in excess of 2.0 per unit. Surge arresters on these systems are designed to protect at around 2.0 per unit and will not be stressed significantly by these transients. However, the transient oscillations occurring within end user facilities can be a problem, depending on the types of equipment within the facilities. The lower voltage system concerns fall into two important categories:

1. **Magnification concerns**. This is a problem when lower voltage capacitors cause magnification of the energizing transient. The lower voltage capacitors could be on the utility distribution system (magnifying the transient for a transmission capacitor bank) or within end user facilities (magnifying the transient for a transmission or distribution capacitor bank).
2. **Nuisance tripping of sensitive loads**. Even if the transient is not magnified by lower voltage capacitors, some sensitive loads may be affected by the capacitor switching transient. There is enough energy in many of these transients to cause nuisance tripping of adjustable speed drives or other loads with electronic power supplies.

Magnification of Capacitor Energizing Transients

Magnification of the capacitor energizing transient occurs when the series combination of a step down transformer and a lower voltage capacitor bank causes the energizing transient frequency to be magnified at the lower voltage capacitor. Figure 2 illustrates a circuit where this can be a concern. The magnified transient occurs at the customer capacitor bank (C2).

Figure 2. Example circuit for magnification of capacitor energizing transients.

Magnification is a concern when the switched capacitor on the utility system is significantly larger (kvar) than the capacitor bank in the customer facility. The magnification can be caused by switched capacitors on the distribution system or on the transmission system. Figure 3 gives some example waveforms illustrating magnification at an industrial manufacturing plant from a study performed with Connectiv. This transient caused problems with drives and robotics.

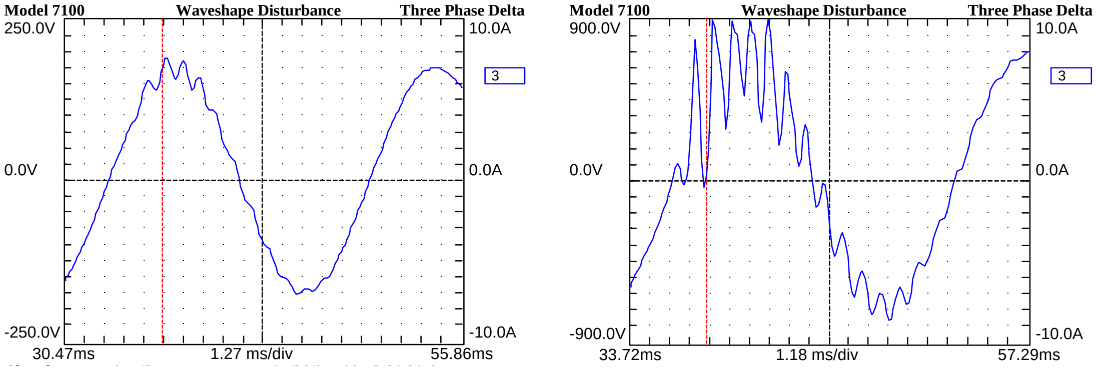

Figure 3. Waveforms illustrating magnification of capacitor energizing transient caused by 480 volt power factor correction capacitors. The first waveform is at a 12 kV bus supplying an industrial plant and the second waveform is at a 480 volt bus with power factor correction. The transient is caused by switching a larger 138 kV capacitor bank on the transmission system.

Solutions to the magnification problem can be implemented either at the switched capacitor bank or by modifying the configuration of the low voltage power factor correction. At the switched capacitor, some type of switching control would have to be implemented. This could by a synchronous closing control that closes the breaker contacts close to the zero crossings of the voltage waveform or it could be a preinsertion impedance that is closed in prior to closing the main breaker contacts (to damp out the transient).

At the low voltage level, the problem can be solved by configuring the low voltage power factor correction as tuned banks, rather than just shunt capacitor banks. The series reactor in the tuned bank configuration detunes the resonant circuit and prevents magnification. This solution has the added benefit of controlling harmonic distortion levels within the end user facility as well.

Nuisance Tripping of Sensitive Loads

Even if there is no problem with magnified transient voltages that could cause arrester failures or equipment failures within end user facilities, there still may be equipment that is very sensitive to the normal capacitor energizing transients. Adjustable speed drives (ASDs) are the most common example of equipment that may trip for very low magnitude capacitor energizing transients. The sensitivity is caused by the dc link capacitor bank within the drive (voltage source type inverters) and the sensitive settings in the controls for the dc link overvoltage.

A capacitor switching transient can cause a transient current into the drive which charges up the dc link capacitor (Figure 4). A typical setting for the dc overvoltage trip level is about 760 volts. This translates to less than 1.2 times the normal peak line-to-line voltage at the input to the drive. In other words, a capacitor switching transient with a magnitude less than 1.2 per unit could cause the drive to trip. Other types of power electronic equipment with dc link capacitors can also be sensitive.

This problem is solved easily for most transient conditions with a choke inductance at the input to the drive (see Figure 4). The choke blocks the transient current which charges up the dc link capacitor. After many years of these problems, most manufacturers offer the chokes as either standard equipment or an option for their drives. Even though most manufacturers understand this problem, we still run into cases where PWM type drives do not include input chokes or chokes in the dc link.

Figure 4. Effect of an input line choke on the dc link overvoltage during a capacitor energizing transient. (Note: voltage is in volts across the dc capacitor and the time is in msec)

Preventing Capacitor Energizing Transient Problems

With an understanding of these basic concerns, it should be possible to prevent most capacitor switching problems at the design stage. Some basic design guidelines for both the utility and the customer can be used to avoid almost all problems. These guidelines were developed for EPRI and BPA as part of some general recommendations for utility/customer power quality contracts.

For the Utility

1. The electric utility should consider closing control (synchronous closing, pre-insertion resistors or reactors) for banks which are to be energized in proximity to industrial end users who have large numbers of adjustable speed drives or that use low voltage power factor correction.

2. The electric utility should inform their major industrial end users regarding the location and switching arrangements (probable operating times, closing means, etc.) of large capacitor banks.
3. The electric utility should inform the industrial end users that adjustable speed drives should be fitted with line reactors or other means to provide the device immunity from capacitor switching transients.
4. The electric utility should encourage industrial end users to install their site power factor correction as a tuned harmonic filter to avoid magnification of capacitor switching transients.

For the Customer

1. It is the end-user's responsibility to protect equipment from the effects of typical disturbances on the supply network.
2. Capacitor switching transients on the distribution system can be in the range 1.5-1.8 per unit peak with an oscillation frequency in the range 300-1000 Hz. These transients can occur on a daily basis. End user equipment should not be affected by these transients.
3. The equipment manufacturer should be consulted if there are power factor correction capacitors on the same bus. Concerns for both harmonic resonances and magnification of capacitor switching transients should be evaluated.
4. The equipment should be installed with sufficient line reactance (on the ac side, or on the dc bus) to provide immunity from capacitor switching transients. A 3% input choke is usually sufficient for this purpose as long as there are no low voltage power factor correction capacitors that could magnify the transient.
5. The electric utility should be contacted before power factor correction capacitors are installed, to determine if the utility has any large capacitors banks nearby. The end user should understand that it is possible for its power factor correction capacitors to magnify the existing overvoltage transient caused by a larger bank on the utility system. It may be prudent for the end user to install power factor correction with harmonic detuning to prevent this magnification phenomena.

Eventually, we will get it right. However, it looks like we may be headed for an interesting period where the responsibility for control of capacitor switching transients may be a question. The incentive to solve these problems on the distribution system becomes questionable when customers may be purchasing their power from some third party supplier.