Northeast Power Systems, Inc.

Capacitor Bank Switching Transients

Introduction

Shunt capacitor bank switching transients are often a concern for utility and industrial engineers that are planning to apply capacitors at the distribution voltage level (4.16 kV through 34.5 kV). Their primary area of concern is typically with how the capacitor switching transients will affect power quality for nearby industrial and commercial loads.

This tech-note provides practical background information on capacitor bank switching transients as well as the transient analysis capabilities of NEPSI's consulting engineering group. In addition, information is provided on how the capacitor bank switching transients can be reduced or nearly eliminated.

Background

Capacitor banks applied within distribution substations typically consists of one to four banks of switched capacitors as shown in Figure 1 (which shows a three step switched bank). The switched banks are designed to come on and off automatically based on power factor, vars, and/or voltage. Due to load variations, a number of switching operations will occur daily. Each switching event is followed by a low-frequency decaying ring wave transient that can result in power quality problems for nearby industrial and commercial loads.

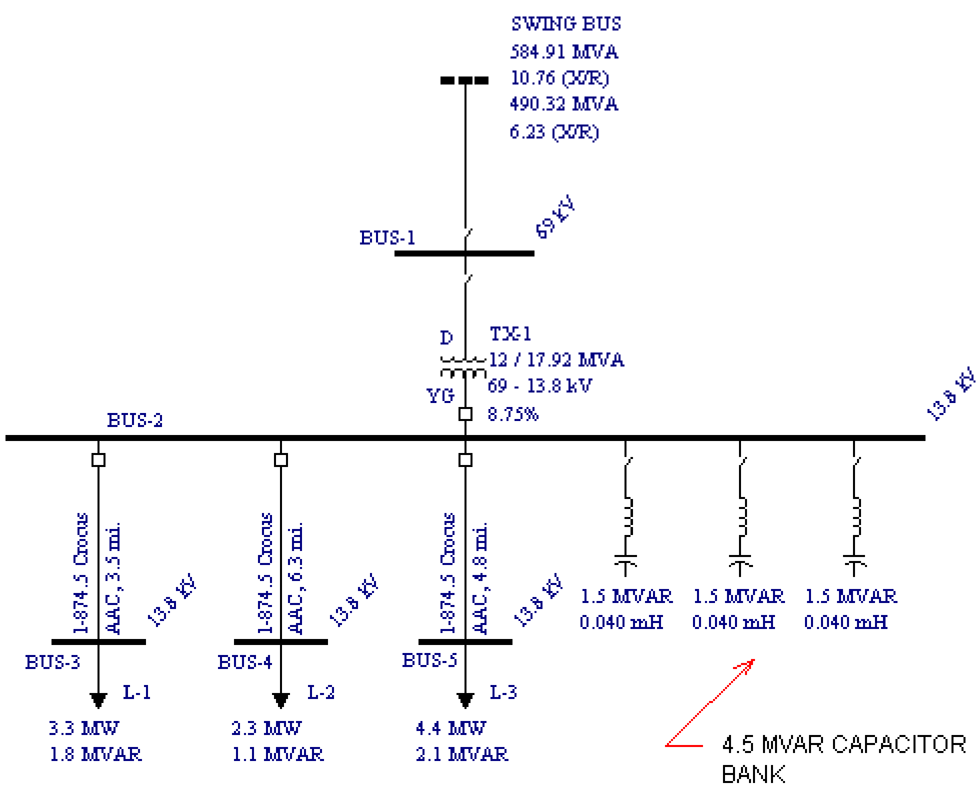

Figure 1 – Typical Utility Substation Showing a 4.5 MVAR Capacitor Bank And Adjacent Distribution Loads

Sample System

To help illustrate capacitor-switching transients, the system shown in Figure 1 was modeled and simulated with a transient analysis program. The figure shows a typical distribution substation with three primary distribution circuits as well as a three step 4500 kvar automatic capacitor bank. The capacitor bank is equipped with 0.040 mH transient inrush reactors to limit the frequency and magnitude of the transient currents associated with back-to-back capacitor bank switching. (*Note: As will be explained later in this document, the inrush reactors have an insignificant impact on improving power quality from switching transients seen by the system. The inrush reactors are installed to prevent premature vacuum switch failure from back-to-back capacitor bank switching transients*).

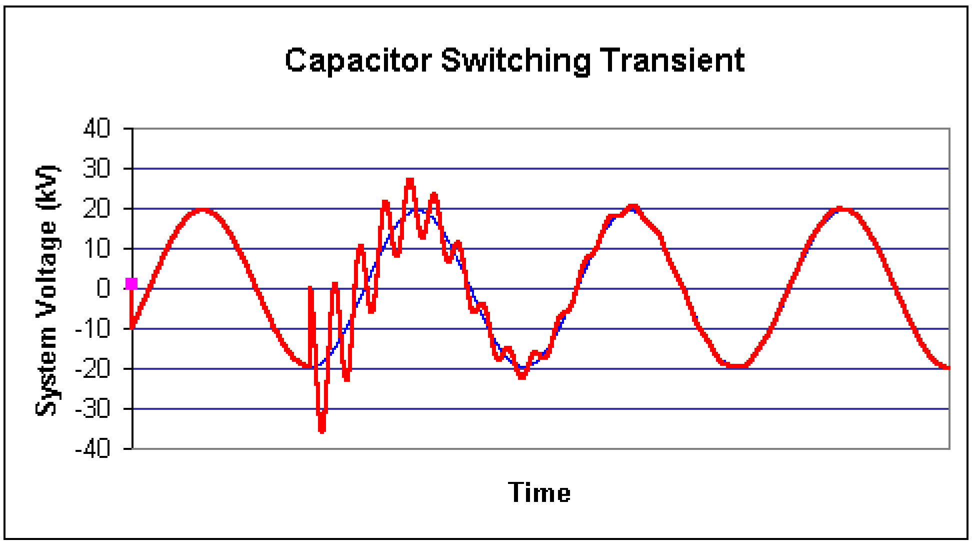

Figure 2 – Capacitor Bank Switching Transient. Bus-2 Phase-to-Phase Voltage Upon Closing of Phase-A and Phase-B Vacuum Contacts.

Figure 2 shows the transient that will occur for the closing of the first 1500 kvar capacitor step of Figure 1, while no other steps are energized. Due to switch variations, and possible pre-strike conditions, phase A and phase B vacuum switches are assumed to close prior to the phase C switch. For an ungrounded bank, the first phase switch to close will result in no current flow or voltage transient. The neutral voltage will then follow the phase voltage, and phase-to-phase voltage will be impressed across the remaining two switches. Upon closure of a second contact, a transient such as the one shown in Figure 2 will occur. The worst case transient will occur when the second switch closes near the peak of the phase-to-phase voltage waveform. Measurements by NEPSI on many capacitor banks at the 15kV level have indicated that switches will begin to conduct near peak voltage due to pre-strike.

The transient of Figure 2 is actually composed of a decaying ring-wave transient (red curve) superimposed on the voltage waveform (blue curve) as shown in figure 3. The duration of the decaying ring-wave transient is dependent on the system X/R ratio at the capacitor bank. High X/R ratios will result in long durations, while low X/R ratios will result in short duration transients.

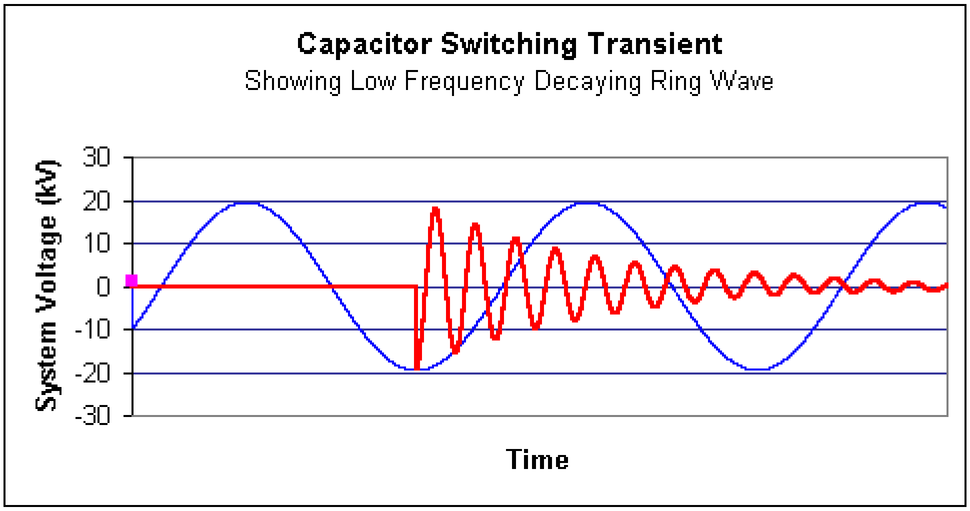

Figure 3 – Low Frequency Decaying Ring Wave Resulting From Capacitor Switching

In examining the transient waveforms shown in figures two, three, and four, the following statements can be made in regard to single capacitor bank switching.

- On closing of the second contact (for an ungrounded bank), the line-to-line system voltage will be pulled to near zero volts. This is most easily seen in figure four. This will be referred to as a voltage depression.
- Immediately following the voltage depression, the system voltage will attempt to recover, but will over-shoot the normal system voltage by an amount that is nearly equal to the voltage dip. Theoretically, two per-unit over-voltages can occur due to capacitor switching.
- The frequency of the capacitor transient is equal to the system's natural frequency. Therefore, large capacitor banks will result in lower frequency decaying ring wave transients, while small banks will result in higher frequency ring wave transients.
- The duration of the ring-wave transient is dependent upon the system X/R ratio at the capacitor bank. Systems with higher X/R ratios result in longer duration transients. Transients associated with substation capacitor banks can last as long as long at 30 to 40 cycles.

Power Quality Concerns

There are three power quality concerns associated with single capacitor bank switching transients. These concerns are most easily seen in figure 4, and are as follows:

1. The initial voltage depression results in a loss of voltage of magnitude "D" and duration "T1".
2. The recovering system voltage will result in an initial transient over-voltage of magnitude "S" and Duration "T2".
3. Multiple zero-crossings. For the transient in figure 4, a total of three zero crossings occur before the natural system voltage zero crossing.

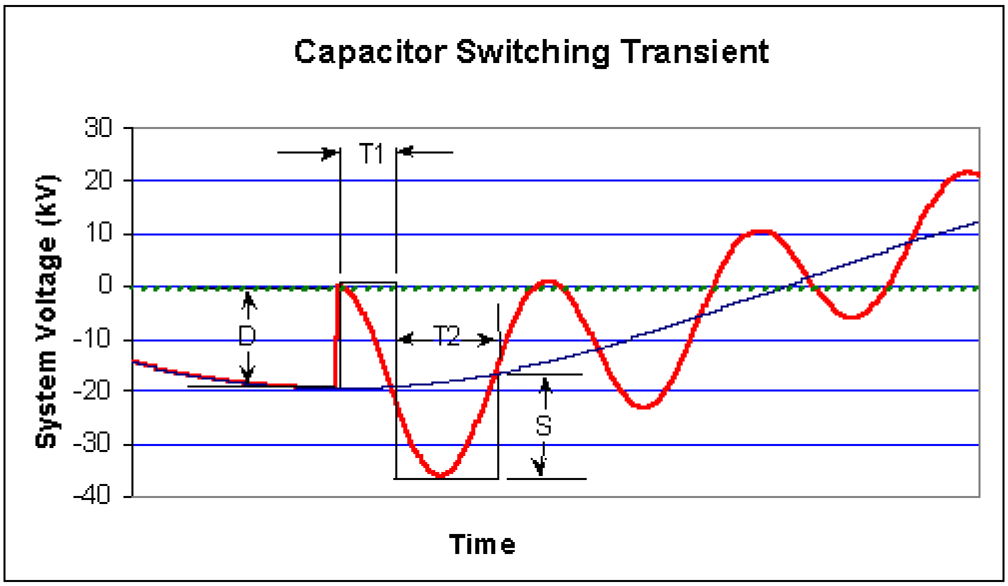

Figure 4 – Height, Depth, and Time of Voltage Dip and Spike Shown On Transient Waveform

Power quality concerns listed as one and two above are most easily evaluated with the ITI (CBEMA) Curve shown in figure 5. This curve describes an AC input voltage envelope which typically can be tolerated (no interruption in function) by most Information Technology Equipment (ITE) and forms a basis for evaluating system transients. The curve and its application are for both steady-stage and transitory conditions and are applicable to 120-volt nominal system voltages obtained from 120V, 208Y/120V, and 120/240V 60 Hertz systems. Since the transient voltages associated with capacitor switching will reflect through a transformer (by the turns ratio for frequencies up to 3 kHz), the curves applicability for medium voltage switching transients and their effects on low voltage equipment is valid.

The transients associated with switching 1500 kvar, 3000 kvar, and 4500 kvar are plotted on the CEBEMA curve with colored diamonds. The diamonds at 0% voltage represent the initial voltage dip that occur upon closing of the vacuum contacts, while the diamonds near 200% nominal voltage are for the voltage over-shoot as the system voltage attempts to stabilize. The plot of figure 5 shows that the two power quality concerns are of boarder-line concern. Since the dip and over-voltage do not actually last as long the duration depicted in Figure 4, power quality problems associated with over-voltage and under-voltage are only probable for larger banks.

The CBEMA curve, however, is not suitable for evaluating the power quality effects of multiple zero-crossings on industrial and commercial electrical equipment. Equipment that utilizes the zero-voltage crossing for timing or control is prone to miss-operation. The transformer connection, capacitor bank size, capacitor bank connection (grounded or ungrounded), system impedance, and X/R ratio influence the occurrence of multiple zero crossings. Even small banks will result in multiple zero crossings.

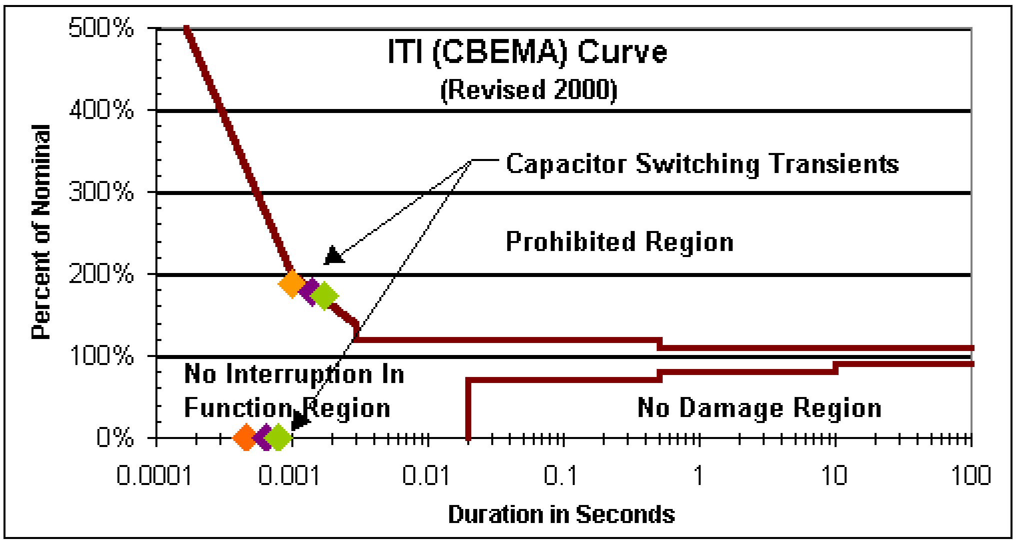

Figure 5 – ITI (CEBEMA) Curve Showing Voltage Dip and Spikes Caused By Various Size Capacitor Banks

Key to Figure 5
Orange = 1500 kvar Switching Transient
Purple =3000 kvar Switching Transient
Green = 4500 kvar Switching Transient

Back-to-Back Capacitor Bank Switching Transients

Multiple Capacitor Bank Switching Transients occur when a capacitor bank is energized in close proximity to capacitor bank that is already energized. Such a switching operation is common in multi-step automatic capacitor banks as shown in figure 1. Upon energization of the uncharged bank, the adjacent charged bank dumps a high frequency high magnitude current into the uncharged bank. This high frequency high magnitude current is limited by the impedance between the capacitor stages (resistance and reactance of bus work, fuses, vacuum switches, etc.). Most banks have to be supplemented with transient inrush reactors to reduce the magnitude of the transients to within the vacuum switch and fuse ratings. The high magnitude current is not seen by the power system as it occurs between the parallel banks.

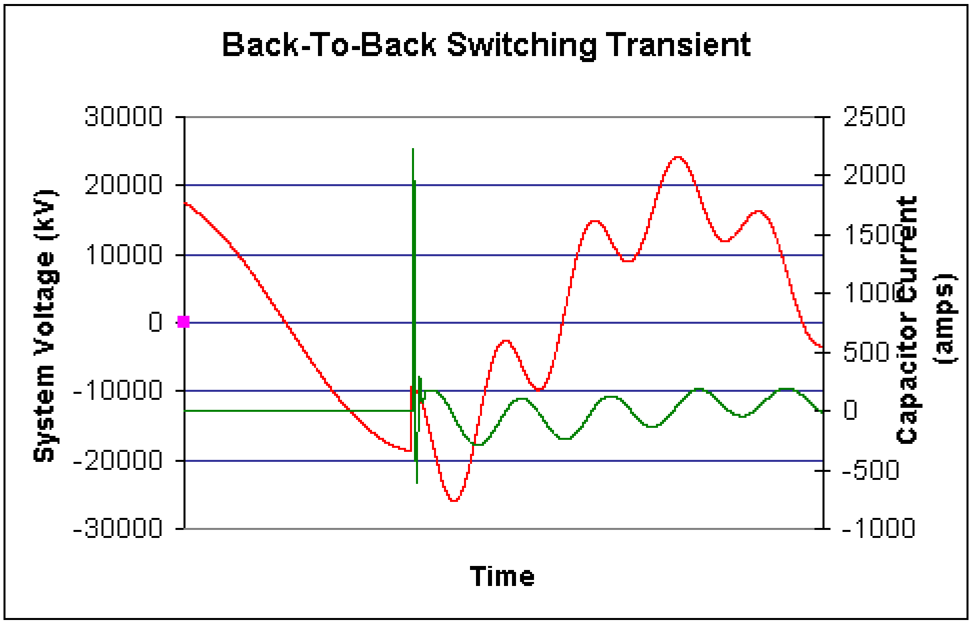

Figure 6 – Voltage (Red) and Current (Green) Waveform Associated With Back-To-Back Capacitor Bank Switching. Current Waveform Is Current Flowing Into Capacitor Bank Being Energized

In observing figure 6, the following should be noted in regards to back-to-back capacitor bank switching:

- The system voltage still experiences a low frequency decaying ring wave transient.
- The voltage depression is not to zero volts, as was the case for single capacitor bank switching transients.
- The system voltage over-shoot is reduced to an amount equal to the voltage depression.
- Multiple zero-crossings are still possible.

Mitigating Transients Associated With Capacitor Bank Switching

In purchasing and specifying capacitor banks and harmonic filter banks, the cost associated with nearby electrical equipment miss-operation or damage should be evaluated against the cost of additional equipment to eliminate switching transients. Capacitor banks and harmonic filter banks in the 2.4kV through 34.5kV voltage range can be equipped with zero voltage closing controls to nearly eliminate switching transients. These controls operate their associated vacuum switches so that contact closure occurs at the zero-voltage crossing point.

Figure 7 shows waveform plots for a capacitor bank switching event involving the energization of a single 13.8kV 1500 kvar ungrounded-wye connected capacitor bank. Phase A contacts close at its own phase-to-ground 0-voltage crossing. At this time, no current flows because the bank is ungrounded. The capacitor bank neutral voltage, however, follows the Phase-A voltage (red and blue curve on top waveform plot). When the phase A voltage or neutral voltage crosses the Phase-C voltage, Phase-C vacuum switch closes. At this time Phase-C and Phase-A vacuum switches begin to conduct current (see bottom set of waveforms). Phase-B vacuum switch will close when the neutral voltage (or Phase-A to Phase-C voltage) and phase voltage equal zero. At this time, all three phases are conducting vars and the capacitor bank has come on with virtually no voltage transient.

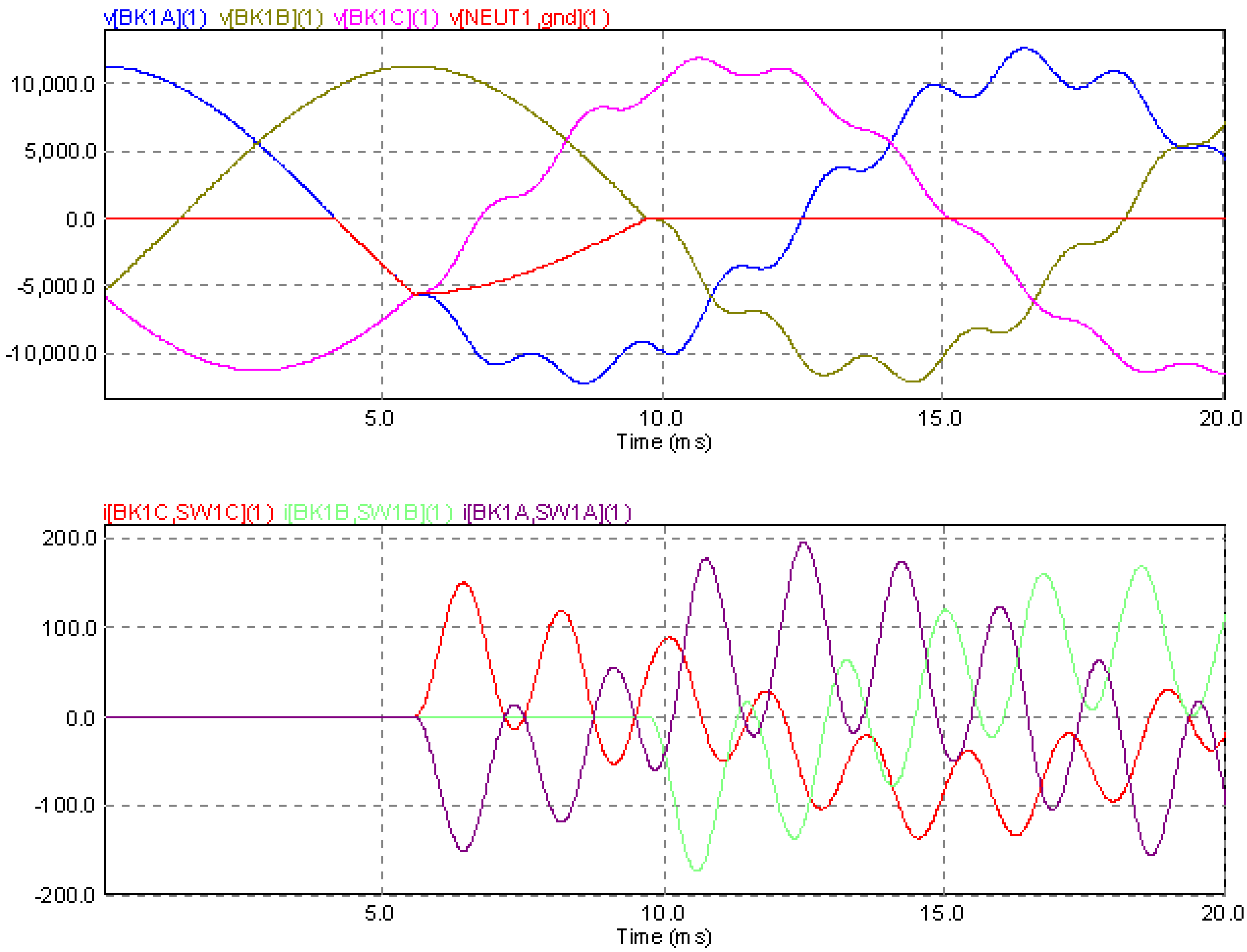

Figure 7 – Simulated Phase-to-Ground Voltage, Capacitor Bank Neutral Voltage and Vacuum Switch Current Associated with Zero-Voltage Closing

Key to Figure 7

[BK1A](1) = Phase A to Ground Voltage at Main Bus
V[BK1B](1) =Phase B to Ground Voltage at Main Bus
V[BK1C](1) = *Phase C to Ground Voltage at Main Bus*

V[NEUT1, gnd](1) = *Capacitor Bank Neutral to Ground Voltage*
I[BK1C,SW1C](1) = *Phase C Vacuum Switch Current*
I[BK1B,SW1B](1) = *Phase B Vacuum Switch Current*
I[BK1A,SW1A](1) = *Phase A Vacuum Switch Current*

In observing Figure 7, the following key points can be made:

- The transient over-voltage associated with the energization of the capacitor bank is negligible.
- The possibility of multiple zero crossings is eliminated.
- High inrush currents are eliminated (increasing vacuum switch life).

Northeast Power Systems, Inc.
66 Carey Road
Queensbury, New York 12804
Phone: 518-792-4776
Fax: 518-792-5767
E-mail: sales@nepsi.com
Website : www.nepsi.com