# Shunt Capacitor Overvoltages and a Reduction Technique

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*Abstract* — **Switching of shunt capacitor banks results in transients at the switched capacitor bank location and at other locations in the power system. Pre-insertion inductors are often applied to reduce overvoltages and inrush currents associated with switching shunt capacitor banks. This presentation gives an overview of the most common capacitor-switching transients and discusses simple techniques for determining the effectiveness of pre-insertion inductors in reducing these transients. Results of field measurements involving the application of low- and high-resistance pre-insertion inductors are also presented.**

*Keywords* — **shunt capacitors, capacitor switching, switching transients, pre-insertion inductors.**

## I. INTRODUCTION

The switching of shunt capacitor banks at utility substations and on distribution feeders creates voltage and current transients in the power system which may be damaging to power system equipment. Transient overvoltages due to the energizing of capacitor banks are the most common source of overvoltages on many power systems①. The high incidence of capacitor-switching induced overvoltages is a result of a marked increase in the number of shunt capacitor banks used on transmission and distribution systems as well as the frequent switching thereof (in most instances at least one close-open operation per day).

## II. OVERVIEW OF SHUNT CAPACITOR SWITCHING TRANSIENTS

The overvoltage transients created during shunt capacitor bank switching include: oscillatory transient overvoltages at the switched capacitor location and at other capacitor locations due to a phenomenon called "voltage magnification," overvoltages at radially-fed transformers or open-ended lines due to traveling wave phenomena, and fast transients coupled through transformers. Current transients include primarily the high magnitude, high-frequency inrush currents during back-to-back capacitor switching (i.e., when energizing a capacitor bank with one or more already energized banks connected to the same bus).

When the capacitor-bank switching device is closed to energize the capacitor bank, the voltage of the switched capacitor bank bus suddenly collapses to the level of the voltage on the capacitor bank which, with the capacitors discharged, is generally zero. The bus voltage then attempts to return to its normal power-frequency value, but overshoots this value and oscillates about the normal power-frequency wave until the oscillations are damped out. This oscillation typically lasts on the order of one cycle of the power frequency. See Figure 1.

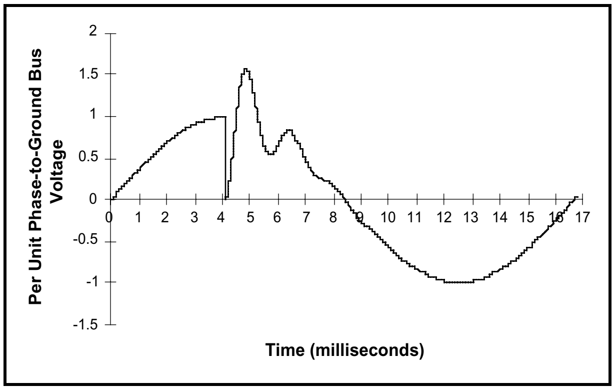

**Figure 1. Typical overvoltage transient at the switched capacitor bank bus when energizing a shunt capacitor bank.**

If the bank is energized at peak voltage, a peak overvoltage of typically 1.5 to 1.8 per unit of peak phase-to-ground voltage results. The initial collapse of the bus voltage is very rapid — usually on the order of a few microseconds — whereas the oscillatory recovery of the bus voltage has a typical frequency of 300 to 800 Hz. This frequency is determined by the source inductance and the capacitance of the bank.

The oscillatory transient overvoltage at the switched capacitor bank bus can excite other near-resonant portions of the power system, creating a magnified oscillatory overvoltage at the sites of other capacitor banks, e.g., other substation shunt capacitor banks, pole-mounted distribution capacitor banks, and power-factor correction capacitors at large industrial installations. These overvoltages can cause nuisance tripping, and possibly failure of sensitive electronic equipment. Voltage-source-inverter type pulse-width-modulated adjustable-frequency drives (VSI PWM AFDs) are especially susceptible to overvoltage tripping and are most likely to be affected by capacitor-switching transient overvoltages②.

The sudden collapse of the switched capacitor bank bus voltage when the shunt capacitor bank is energized transmits fast traveling waves along each line connected to the bus. These fast traveling waves can be doubled at radially-fed transformers and open-ended lines, and can be reflected many times between the substation bus and these locations before being finally damped out by line losses. If the length of line is such that the traveling wave arrival at the radially-fed transformer or open-ended line is coincident with the peak of the oscillatory transient at this location, high-magnitude overvoltages can result.

Delta-connected transformers can be subjected to phase-to-phase overvoltages of up to 5.7 per unit of peak phase-to-ground voltage as a result of this traveling wave phenomenon, and can cause severe stress on the end windings of the transformer, resulting in insulation breakdown.

## III. USING PRE-INSERTION INDUCTORS FOR TRANSIENT REDUCTION

Several devices are commercially available to reduce or eliminate the effects of capacitor-switching transients. These devices include high-resistance or low-resistance pre-insertion inductors used with circuit switchers, controlled closing circuit breakers or vacuum interrupters, and circuit breakers with pre-insertion resistors. A comparative evaluation of the effectiveness of these devices in preventing nuisance tripping of AFDs due to voltage magnification is presented in ③.

Pre-insertion inductors furnish an impedance, which is frequency dependent, in series with the bank capacitance during the initial energization of the capacitor bank. This impedance reduces the collapse in bus voltage by the amount of voltage developed across the inductor during the inrush of current into the bank. Since the impedance of the pre-insertion inductor is frequency-dependent, its value appears to be quite large during initial inrush current into the bank when the frequency is quite high. Thereafter, the effective impedance of the pre-insertion inductor is reduced when the steady state, 60 Hz, current value of the bank is attained. The pre-insertion inductor — like any other pre-insertion impedance — gives rise to a second transient when the inductor is bypassed (after the 60-Hz current is attained). This transient, referred to as the bypass transient, is generally much smaller than the initial transient, unless the bank is quite large.

The pre-insertion inductor is comprised of a number of close-coupled layers of stainless-steel or aluminum wire wound, along with resin-impregnated filament-fiberglass roving, to form a hollow glass-reinforced tube. The outer roving is finished with a coat of silicone-alkyd paint for all-weather durability. If wound with stainless-steel wire, the pre-insertion inductor has a high inherent resistance, while a low inherent resistance is obtained if aluminum wire is used. The use of stainless-steel wire results in the improved damping performance afforded by high-resistance pre-insertion inductors.

The pre-insertion inductor is typically applied with a circuit switcher having a high-speed disconnect blade, which inserts the pre-insertion inductor for 7 to 12 cycles (depending on system voltage) during closing, to energize the bank. See Figure 2.

The effectiveness of pre-insertion inductors in reducing the capacitor-switching transient overvoltage can be assessed by considering the two portions of the capacitor switching transient voltage: the rapid collapse in bus voltage and the oscillatory transient.

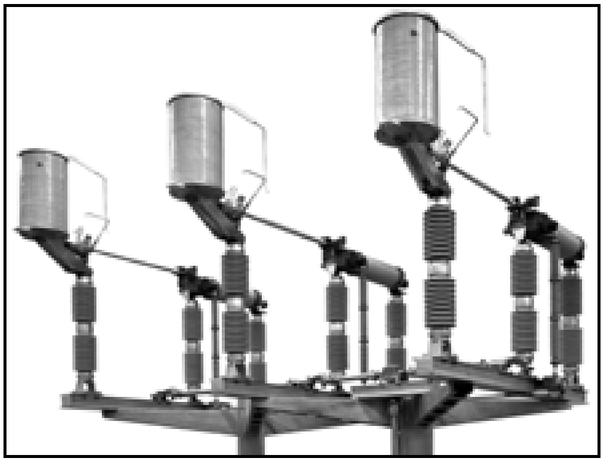

**Figure 2. High-resistance pre-insertion inductors mounted on a 138-kV Mark V Circuit-Switcher.**

### A. Reduction in bus voltage collapse

When the pre-insertion inductor is applied for transient reduction, the inductance thereof appears in series with the equivalent inductance of the source impedance during initial energization. The pre-insertion inductor and source inductance appear like a potential divider, with the pre-insertion inductor acting to reduce the initial bus voltage collapse. In reducing the bus voltage collapse, the oscillatory transient is correspondingly reduced, and the excitation voltage for remote LC circuits is also reduced. For a substation with available 3-phase short-circuit capacity of *MVAsc*, the percent bus voltage collapse, %$\Delta V$, can be determined by the following equation:

$$\%\Delta V = \frac{100 \times L_s}{L_s + L_{PII}} = \frac{100}{1 + \left(\frac{\omega L_{PII}\, MVA_{sc}}{1000 V_{ll}^2}\right)} \tag{1}$$

where $L_s$ is the equivalent source inductance (in mH), $L_{PII}$ is the inductance of the pre-insertion inductor (in mH), $\omega$ is the radian frequency of the system (approximately 377 radians per second for a 60-Hz system) and $V_{ll}$ is the rated system voltage (in kV). It is clear from equation (1) that the effectiveness of the pre-insertion inductor in reducing the amount of bus voltage collapse during initial energization is increased as the three-phase short-circuit capacity at the switched capacitor bank bus is increased for a given rated system voltage. Figure 3 depicts what the percent bus voltage collapse would be for a 138-kV system where a pre-insertion inductor with inductance value of 40 mH would typically be recommended. The range of three-phase short-circuit capacities depicted corresponds to three-phase available fault currents ranging from 2 kA to 40 kA at 138 kV.

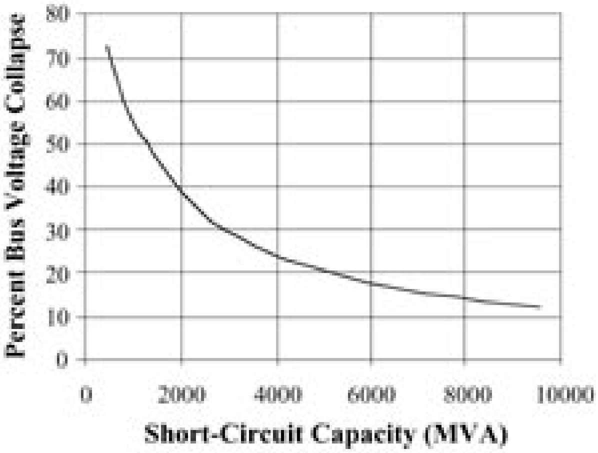

**Figure 3. Percent bus voltage collapse when using a 40 mH pre-insertion inductor for capacitor switching transient reduction in a 138-kV system.**

Since the percent bus voltage collapse that would occur when using a controlled closing device with a maximum deviation in closing of 1 millisecond after voltage zero would be approximately 37 percent, this amount of bus voltage collapse can be used as a performance guideline in assessing the feasibility of pre-insertion inductors for overvoltage transient mitigation. Pre-insertion inductors can still be effective even if a larger bus voltage collapse occurs, but high resistance may than be required for increased damping.

### B. Reduction in oscillatory transient voltage

As explained before, following the initial collapse in bus voltage, the bus voltage recovers to its normal power-frequency value in an oscillatory fashion. If a high-resistance pre-insertion inductor is utilized, the oscillatory transient will be reduced by the damping action of the high resistance of the inductor windings. This damping is in addition to the damping afforded by system loads and losses. The pre-insertion inductor also lowers the frequency of the oscillatory transient, significantly reducing the chance that the capacitor-switching transient may be in near-resonance with other LC circuits. The amount of damping that can be provided by high-resistance pre-insertion inductors is limited by the amount of voltage that would be developed across the inductor once the steady-state bank current is attained; this voltage gives rise to a second transient when the pre-insertion inductor is bypassed (i.e., switched out of the circuit by the closing of the high-speed disconnect blade). The percent maximum bypass voltage, $\%\Delta V_{bp}$ , for a given pre-insertion inductor with total impedance $Z_{PII}$, and steady-state RMS bank current, $I_b$ (in kA), for a bank applied at rated system voltage, $V_{ll}$ (in kV), is equal to:

$$\%\Delta V_{bp} = \frac{100 Z_{PII} I_b}{V_{ll} / \sqrt{3}} \quad (2)$$

Note that the effect of the pre-insertion inductor on the magnitude of the RMS bank current during the insertion period is neglected in equation (2). This equation suggests that, as the bank size increases at a given rated system voltage, the percent maximum bypass voltage will increase correspondingly. It should be noted that the peak bypass voltage occurs at an instant on the phase-to-ground voltage waveform determined by the net impedance of the pre-insertion inductor in series with capacitance of the capacitor bank. Without the pre-insertion inductor, the bank current leads the bus phase-to-ground voltage by 90 degrees; with the pre-insertion inductor in the circuit, the phase angle is reduced somewhat. For example, for a 75 MVAR, 138-kV capacitor bank using a 40 mH-81 ohm (high-resistance) pre-insertion inductor, the phase angle is reduced to about 71 degrees. Thus, when peak bank current occurs, the bus phase-to-ground voltage is at 19 degrees after voltage zero, or at about 33% of peak voltage. Consequently, the peak overvoltage at the substation will not be much over the nominal peak voltage, and at remote capacitor locations will be determined by the extent of phase shifts introduced by delta-wye-connected transformers. Since the bypass transient appears to be the same as an uncontrolled transient, the objective should be to limit the percent bypass voltage to less than 37 percent (refer to discussion in section III.A). Figure 4 depicts what the percent bypass voltage would be for various capacitor bank sizes in a 138-kV system when using a 40 mH – 81 ohm high-resistance pre-insertion inductor.

In general, if the percent bus voltage collapse during initial energization when using a low-resistance pre-insertion inductor is less than the percent bypass voltage when using a high-resistance pre-insertion inductor, a low-resistance pre-insertion inductor may be more effective. The complete range of standard pre-insertion inductors currently commercially available is summarized in Tables 1A and 1B on page 4.

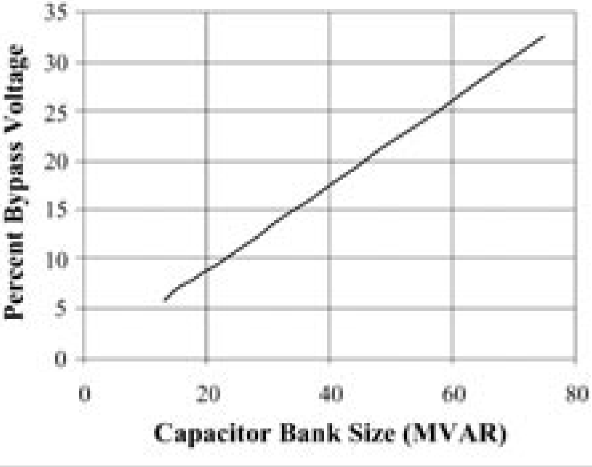

**Figure 4. Percent maximum bypass voltage when using a 40 mH – 81 ohm pre-insertion inductor for switching various sizes of 138-kV capacitor banks.**

TABLE 1A—Range of commercially available high-resistance pre-insertion inductors

| System Voltage Rating, kV, Nominal | Capacitor Bank Size, Mvar | Inductor Description |
|---|---|---|
| 34.5 | 3 to 11 | 18 mH – 39 ohm |
| | 12 to 22 | 10.6 mH – 17 ohm |
| 46 | 4 to 18 | 18 mH – 39 ohm |
| | 19 to 36 | 10.6 mH – 17 ohm |
| 69 | 5 to 20 | 40 mH – 81 ohm |
| | 21 to 42 | 18 mH – 39 ohm |
| 115 | 10 to 60 | 40 mH – 81 ohm |
| 138 | 13 to 75 | 40 mH – 81 ohm |

TABLE 1B—Range of commercially available low-resistance pre-insertion inductors

| System Voltage Rating, kV, Nominal | Capacitor Bank Size, Mvar | Inductor Description |
|---|---|---|
| 34.5 | 3 to 33 | 10 mH – 2.4 ohm |
| 46 | 4 to 36 | 10 mH – 2.4 ohm |
| 69 | 5 to 50 | 10 mH – 2.4 ohm |
| | 5 to 50 | 40 mH – 5.5 ohm |
| 115 | 10 to 65 | 40 mH – 5.5 ohm |
| 138 | 13 to 75 | 40 mH – 5.5 ohm |
| 230 | 17 to 177 | 10 mH – 2.4 ohm (2) |

## IV. FIELD MEASUREMENTS OF TRANSIENT REDUCTION USING PRE-INSERTION INDUCTORS

Since their introduction in 1993, high-resistance pre-insertion inductors have been used throughout the US to address concerns associated with voltage magnification and nuisance tripping of AFDs④. In 1992 Nebraska Public Power District (NPPD) determined that nuisance tripping of AFDs at two facilities served from one of their 115-kV/34.5-kV substations may be due to voltage magnification. They were switching a 34.5-kV, 10.8-MVAR ungrounded-wye-connected capacitor bank in the substation. Both facilities applied 480-V capacitors for power factor correction. Figure 5(a) illustrates the apparent voltage magnification at the first of the two facilities affected. Since only low-resistance pre-insertion inductors were available at the time, NPPD installed a circuit switcher with 10 mH-2.4 ohm low-resistance pre-insertion inductors to reduce the transient overvoltages. The three-phase available fault capacity at the substation is about 457 MVA at 34.5 kV. Thus, the percent voltage collapse expected when using the low-resistance pre-insertion inductors was about 41% [from equation (1)]. The resultant reductions in the transient overvoltages at the two facilities are illustrated in Figures 5(b) and 5(c). Although the peak overvoltage at the second facility was already significantly reduced, there were still occasional reports of nuisance tripping of AFDs at this facility. NPPD resolved to installing the newly introduced high-resistance pre-insertion inductors. For the 34.5-kV, 10.8-MVAR bank involved, the 18 mH-39 ohm high-resistance pre-insertion inductor was recommended (see Table 1A). The increased inductance value of the pre-insertion inductor was expected to reduce the amount of initial bus voltage collapse to only 28% [from equation (1)]. However, the percent maximum bypass transient voltage was expected to be about 36% [from equation (2)], but because the maximum bypass voltage occurs nearer to the phase-to-ground voltage zero at the substation, the peak overvoltage at the remote locations was still expected to be significantly less than that measured with the low-resistance pre-insertion inductors (refer to discussion in section III.B). After installation transient voltage measurements were again made at the second facility. "Worst" case transient phase-to-phase voltage waveforms is illustrated in Figure 5(d). It is clear that the transient in this case occurs during bypass because there appears to be very little damping following the trigger indicator.

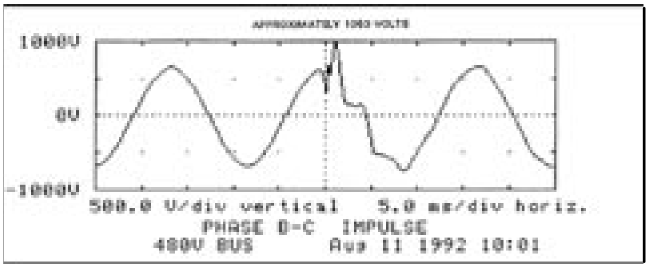

**Figure 5(a). Apparent voltage magnification at facility 1 during switching of 34.5-kV, 10.8-MVAR bank at substation. Peak overvoltage is approximately 1.55 per unit of peak phase-to-phase voltage.**

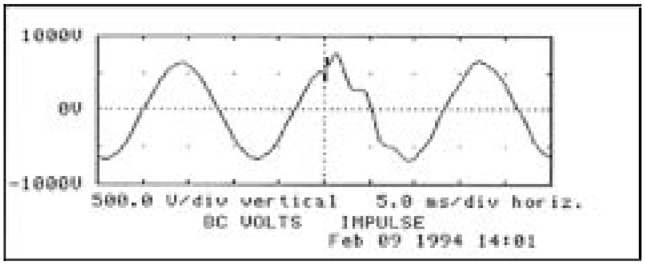

**Figure 5(b). Phase-to-phase voltage at facility 1 during switching of 34.5-kV, 10.8-MVAR bank with 10 mH-2.4 ohm (low-resistance) pre-insertion inductors at substation. Peak overvoltage is approximately 1.12 per unit of peak phase-to-phase voltage.**

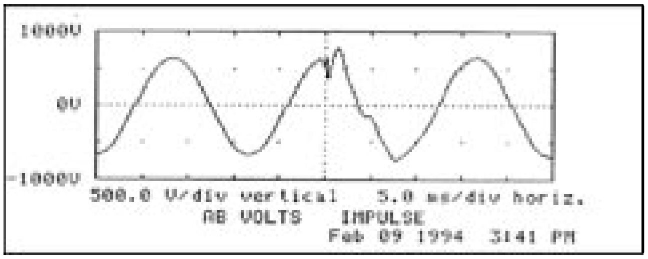

**Figure 5(c). Phase-to-phase voltage at facility 2 during switching of 34.5-kV, 10.8-MVAR bank with 10 mH-2.4 ohm (low-resistance) pre-insertion inductors at substation. Peak overvoltage is approximately 1.18 per unit of peak phase-to-phase voltage.**

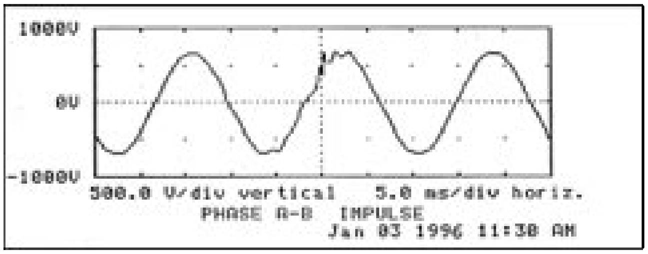

**Figure 5(d). Phase-to-phase voltage at facility 2 during switching of 34.5-kV, 10.8-MVAR bank with 18 mH-39 ohm (high-resistance) pre-insertion inductors at substation. Peak overvoltage is just over 1 per unit of peak phase-to-phase voltage.**

Results obtained at other installations will be dependent upon the available short-circuit capacity at the substation, capacitor bank size, and the size of the pre-insertion inductors recommended for the application.

## V. CONCLUSIONS

Pre-insertion inductors can reduce transients associated with shunt capacitor bank switching significantly. Simple calculations can be used to determine the effectiveness of pre-insertion inductors in reducing these transients. These calculations involve determining the percent bus voltage drop during initial energization and subsequent maximum bypass transient voltage, based upon the three-phase available short-circuit capacity at the substation and the size of the capacitor bank. Results of field measurements involving the application of low- and high-resistance pre-insertion inductors on NPPD's 34.5-kV system illustrated the effectiveness of pre-insertion inductors in reducing shunt capacitor switching transient overvoltages.

## VI. ACKNOWLEDGEMENTS

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## VIII. BIOGRAPHY

**Ernst H. Camm** received his BSc(Eng) degree in Electrical and Electronic Engineering from the University of Cape Town, South Africa in 1984, and his MSEE degree from the Ohio State University in 1992. From 1984 to 1990, he held various positions in Plant and Project Engineering. He is currently a Project Engineer in the Engineering Services Department at S&C Electric Company. He has had extensive involvement in capacitor switching transient analysis at S&C, including analysis in the development of optimally sized pre-insertion inductors for capacitor switching transient mitigation. He is the author of and co-presenter of S&C's "Seminar on Capacitor Switching Transients and Their Impact on Your System" and has co-authored several technical papers on capacitor switching transient mitigation. Ernst is a member of the IEEE's PES and IAS. He serves on the Switching Transients Task Force of the IEEE PES's Modeling and Analysis of System Transients Working Group and on the Shunt Capacitor Application Guide Working Group.