

SELECTING A CAPACITOR-SWITCHING
OVERVOLTAGE CONTROL METHOD EFFECTIVE
IN PREVENTING NUISANCE TRIPPING OF
ADJUSTABLE-SPEED DRIVES

George V. Fantozzi
Director - Power Systems Services
S&C Electric Company
Chicago, Illinois

Presented at the
EEI ES&E Committee Meeting
Clearwater Beach, Florida
April 4, 1995

Selecting A Capacitor-Switching Overvoltage Control Method Effective In Preventing Nuisance Tripping of Adjustable-Speed Drives

It has long been known that switching a shunt capacitor bank at a utility substation can result in voltage and current transients which can create problems at the substation and elsewhere in the power system. It is widely recognized that the following transient phenomena can occur when energizing a capacitor bank:

- High-magnitude and high-frequency inrush currents, especially in the case of back-to-back bank switching;
- Overvoltages at the switched capacitor-bank bus;
- Fast transient overvoltages coupled through transformers; and
- Overvoltages at radially fed transformers and at open-ended lines.

Also, when de-energizing a capacitor bank, reignitions and restrikes \dot{A} can occur in the switching device. Such restrikes can cause substantial overvoltages at the switched capacitor-bank bus, which can result in damage to the switching device, the capacitor bank, and other power system equipment.

To ameliorate transient phenomena during bank energization, three methods of transient overvoltage control have traditionally been used:

- Circuit-Stitchers with pre-insertion inductors. See Figure 1A. Inductors are inserted into the capacitor-energizing circuit for 7 to 12 cycles of the power frequency during closing of the high-speed disconnect blade. Insertion is effected through sliding contact between the blade and the inductor on each pole of the switch; no additional switches are required. Two types of preinsertion inductors are presently available commercially: damped preinsertion inductors, with low inherent resistance, and highly damped pre-insertion inductor, with high inherent resistance.
- Circuit breakers with preinsertion resistors. See Figure 1B. Resistors are typically inserted into the capacitor-energizing circuit for 10 to 15 milliseconds prior to the closing of the main contacts, through the closing of an additional set of contacts. Synchronization between the resistor and main contacts is required and is usually achieved by connecting the resistor contact rod directly to the main contact control rod.
- Controlled closing devices. See Figure 1C. These devices are typically high-speed vacuum switches or SF₆ circuit breakers with sophisticated electronic controls. The individual poles of the switch or breaker are usually controlled to close near voltage zero to minimize voltage and inrush current transients.

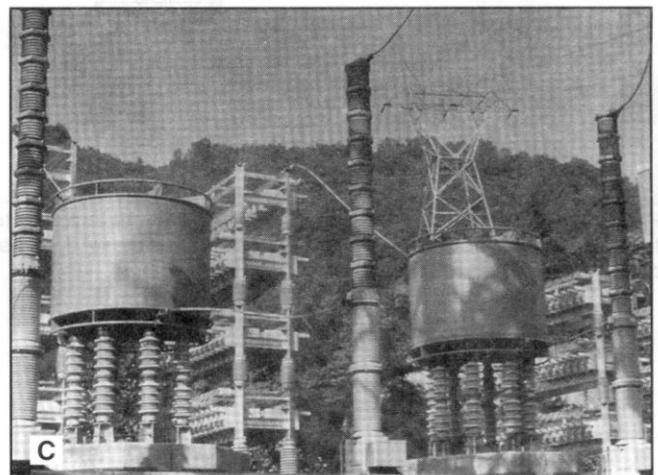
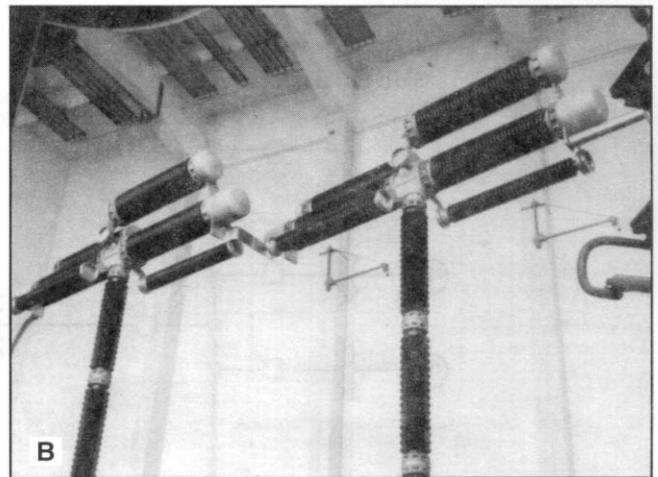
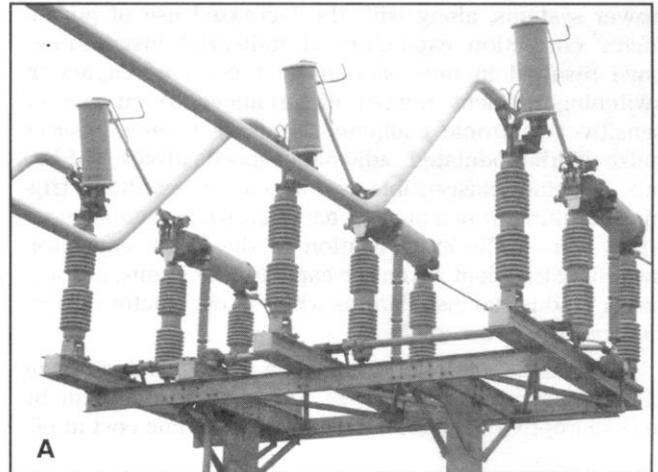


Figure 1. (A) Damped pre-insertion inductors mounted on a Circuit-Switcher. (B) SF₆ circuit breaker with pre-insertion resistors.(C) Vacuum switch with controlled closing.

① Reignitions and restrikes can occur in the switching device during current interruption if the device cannot withstand the transient recovery voltage associated with de-energizing the capacitor bank. A reignition is defined as a re-establishment of current flow within a quarter cycle of initial current interruption. A restrike is defined as a re-establishment of current flow a quarter cycle or later after initial current interruption.

A Newly Recognized Capacitor-Switching-Related Problem - Voltage Magnification

The increased application of shunt capacitor banks in power systems, along with the increased use of power-factor correction capacitors at industrial installations, have resulted in more and more reports of capacitor-switching-transient related disturbances to customers' sensitive electronic equipment. Voltage source inverter pulse-width-modulated adjustable-speed drives (ASDs) are especially susceptible to nuisance overvoltage tripping resulting from a phenomenon known as *voltage magnification* - the magnification of the initial capacitor-switching transient at remote capacitor locations, particularly at industrial installations where power-factor correction capacitors are applied.

Such ASDs are often applied in critical industrial or commercial processes, where nuisance tripping can be very disruptive with potentially high downtime cost impli-

cations. Since utility capacitors are typically switched often during peak load periods, the likelihood of nuisance ASD tripping is thereby increased, thus heightening the risk of substantial production losses.

What Causes Voltage Magnification?

The use of shunt capacitor banks elsewhere in the power system, including power-factor correction capacitors at industrial installations, creates the possibility that portions of the power system will be in near-resonance with the transient frequency generated at the switched capacitor bank. See Figure 2. If the natural frequency of oscillation of the series L-C circuit - formed by the inductance of step-down transformers, lines and cables between the switched capacitor bank bus and the remote capacitor location and the capacitance of the remote capacitors - is within a hundred hertz or so of the transient frequency generated at the switched capacitor bank during switching, the possibility of voltage magnification occurring is

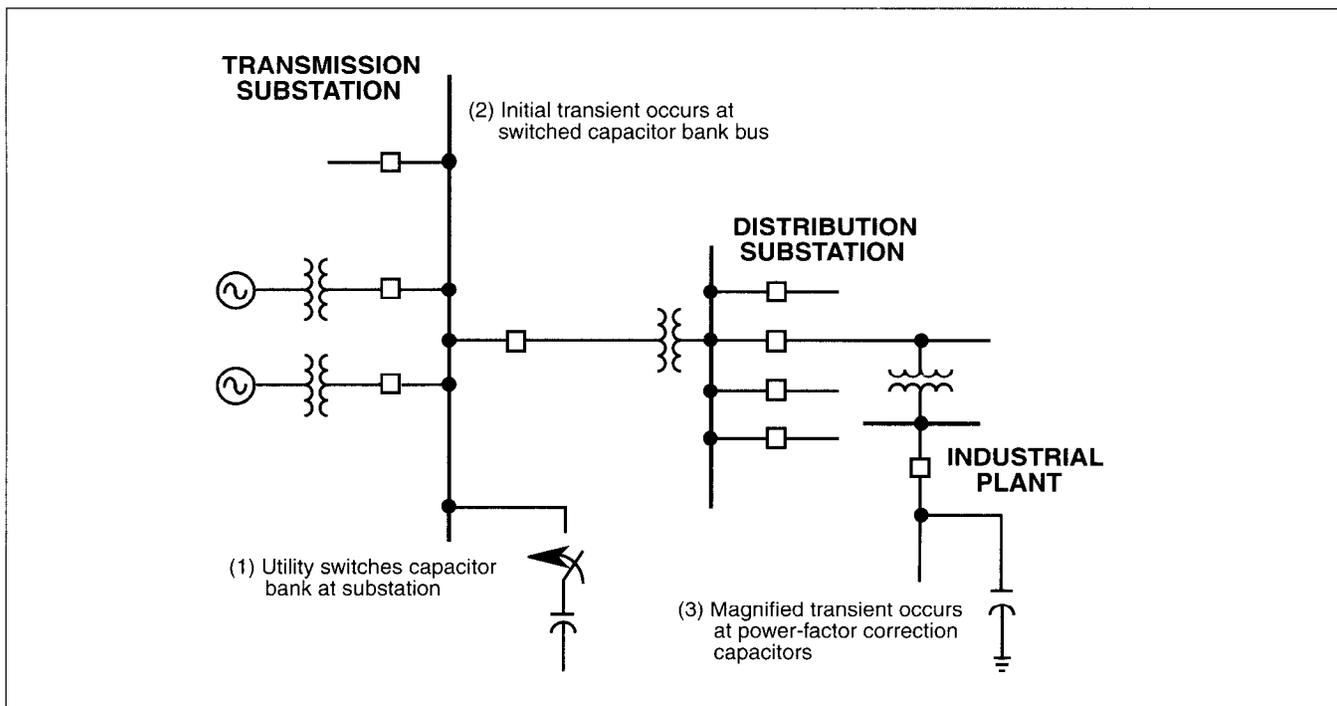


Figure 2. One-line diagram of a typical power system. Switching of the substation capacitor bank excites the L-C circuit formed by the inductance of step-down transformers, lines, and cables, and the capacitance of power-factor correction capacitors at the industrial plant.

quite high. Voltage magnification occurs when the "remote" LC circuit is excited by the initial capacitor-switching transient and then continues to oscillate at its own natural frequency, while also following the oscillation of the initial transient. See Figure 3. The magnitude of the magnified overvoltage transient at the remote capacitor location can be as high as 3.2 per unit^② when energizing a shunt capacitor bank without any form of transient overvoltage control.

The natural frequency of oscillation of the transient at the switched capacitor bank bus is determined by the percent voltage regulation, defined as percent *differential capacitance voltage* in switchgear standards. Most capacitor banks are sized to create a regulation of 0.6% to 4%, giving rise to frequencies in the range of 300 to 800 hertz. In the case of power-factor correction capacitors applied at industrial installations, the natural frequency of oscillation at the utilization-voltage bus ranges from 400 to

800 hertz for typical low-voltage power-factor correction capacitors rated 60 to 1000 kvar and step-down distribution transformers rated 500 to 3750 kVA. Based on the close matching of these frequencies, it is apparent that voltage magnification can potentially occur in a large number of power systems.

How Voltage Magnification Affects ASDS

A typical PWM ASD is shown in Figure 4. It basically consists of a three-phase AC input to a bridge rectifier, a DC link comprised of a large DC bus capacitor, and an inverter section that converts the DC link voltage to a variable AC voltage. A magnified capacitor switching transient can cause the DC bus capacitor to charge up to a higher-than-normal voltage level. If this voltage level equals the overvoltage trip setting of the ASD, protective circuitry will trip-off the drive, in order to protect overvoltage-sensitive components in the inverter section.

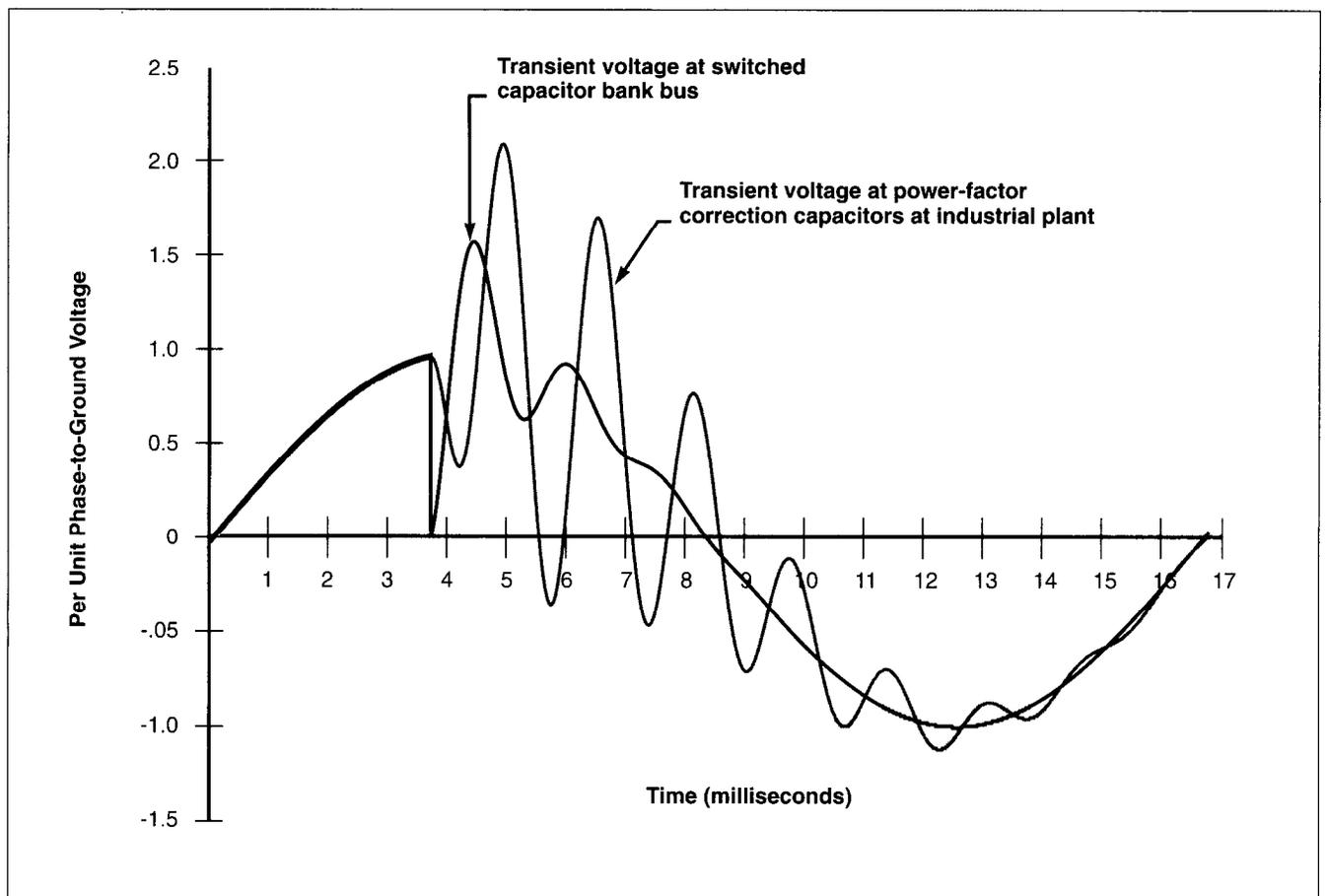


Figure 3. Voltage magnification occurring at power-factor correction capacitors at industrial plant, during energization of shunt capacitor bank at the utility substation.

②One per unit voltage is based on the peak of the nominal system phase-to-ground voltage, i.e., $\sqrt{\frac{2}{3}} \times$ rated system phase-to-phase voltage.

The vulnerability of a particular ASD to transient overvoltages is dependent upon the size of the DC bus capacitor, the presence of a DC bus choke or an AC line choke, and the overvoltage trip setting. Both the AC line choke and DC bus choke enhance transient overvoltage ride-through capability by limiting the rate-of-rise of transient inrush current to the DC bus capacitor, thus delaying the charging of the capacitor while some of the transient energy is removed by the load. The three-phase AC line choke is generally used where transient overvoltages are of concern. Since the power transistors used in the inverter section of 460-V ASDs are normally rated for 1000 V to 1200 V and can be damaged from switching at elevated voltages, the overvoltage trip level is typically set in the range of 760 V to 820 V (1.17 P.U. to 1.26 P.U.), with 780 V (1.2 P.U.) being most common.³

Switching a capacitor bank at the utility substation can result in overvoltages in the range of 1.2 P.U. to 1.6 P.U. phase-to-phase at the substation if no overvoltage control is furnished. With voltage magnification, capacitor-switching induced overvoltages far in excess of 1.2 P.U. phase-to-phase are typical at the utilization-voltage bus. If the ASD is not equipped with either an AC line or DC bus choke, the phase-to-phase overvoltage at the utilization-voltage bus will be transferred directly to the DC bus of the ASD. Thus, with voltage magnification, nuisance overvoltage tripping of ASDs can occur quite frequently if these devices are not equipped with chokes; nuisance overvoltage tripping is also likely even if the ASDs are equipped with chokes.

There are currently no industry standards or guidelines covering transient overvoltages or other power quality considerations for ASDs.⁴

Evaluating Methods for Controlling Transient Overvoltages Due to Voltage Magnification

S&C recently completed a comparative evaluation of commercially available methods for controlling transient overvoltages during capacitor bank energization in 138-kV systems, to determine their effectiveness in preventing nuisance tripping of ASDs. This evaluation considered Circuit-Switchers with new highly damped 40-millihenry 81-ohm pre-insertion inductors (a recently introduced Enhanced-Duty Preinsertion Inductor option for Circuit-Switchers); circuit breakers with 150-ohm pre-insertion resistors; and controlled closing devices with nominal closing time after voltage zero of 300 microseconds and standard deviation, due to drift and temperature changes, of 400 microseconds. As a reference, the performance of a capacitor-switching device without any transient overvoltage control method was also evaluated.

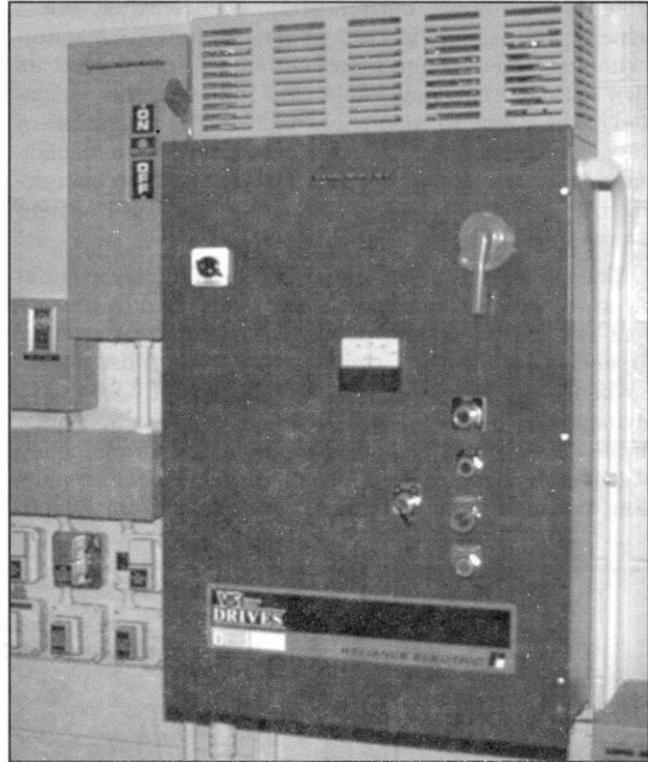


Figure 4. Typical PWM ASD.

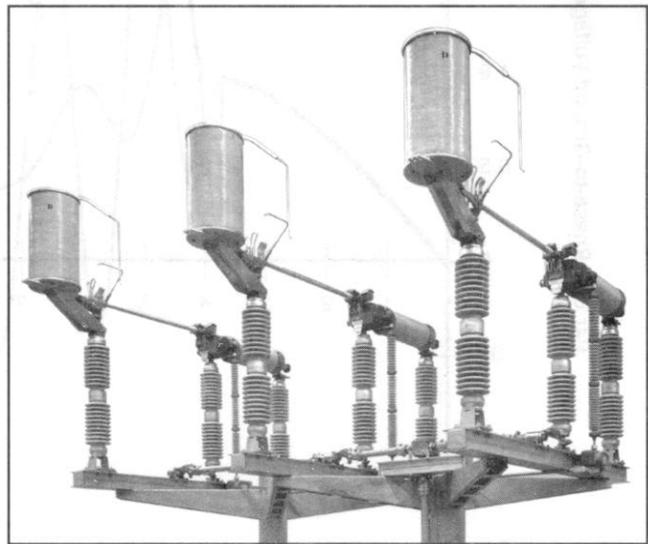


Figure 5. 138-kV Circuit-Switcher with new highly damped pre-insertion inductors.

³ One per unit DC bus voltage is equal to 1.35 times rated phase-to-phase input voltage to the ASD (648 V for a 460-V ASD at a utilization voltage of 480 V).

⁴ The 5-kHz ring-wave test recommended in IEEE Standard C62.41 is primarily intended for surge protection devices and does not address the transient response characteristics of ASDs. Also, the curve for voltage-sag and transient-overvoltage ride-through for data processing equipment developed by the Computer Business Equipment Manufacturers Association (CBEMA) does not address the performance requirements of ASDs. Efforts are presently underway to develop industry-wide recommendations and guidelines with regard to ASD power quality considerations by the IEEE P1346 Working Group and by the Electric Power Research Institute (EPRI).

The highly damped pre-insertion inductors shown in Figure 5 have a high inherent resistance which effectively damps the oscillatory recovery of the switching transient during capacitor bank energization, thereby substantially reducing the magnitude of the transient at remote capacitor locations. Each inductor is comprised of three or more close-coupled layers of stainless-steel conductor wound, along with resin-impregnated filament-fiberglass roving, to form a hollow glass-reinforced tube. An integral counter-wound stainless-steel damping winding is also provided to limit the voltage across the inductor during closing. A layer of roving separates the layers of conductor and still other layers of roving are utilized for added mechanical strength and stability. The outer roving is finished with a coat of silicone-alkyd paint for all-weather durability.

Simulation Study

To simulate the DC bus transient voltage response of small-horsepower ASDs, an equivalent circuit of a typical power system was developed, containing the essential power system parameters affecting the voltage magnification phenomenon. See Figure 6. ASDs with and without 3% AC line chokes were connected at the utilization-voltage bus.

Since the parameters affecting the magnitude of the capacitor-switching-induced overvoltage at the customer's utilization-voltage bus can vary over a wide range in a given utility distribution system, the selection of equivalent circuit parameters was made on a statistical basis using known utility system data. For each of the equivalent circuit parameters shown in Figure 6, a representative statistical distribution of values was derived, representing 200 typical utility systems. The performance of each transient overvoltage control method was then evaluated, for each of the 200 statistically selected utility systems, by simulating the transient voltage response on the DC bus of the ASDs during statistically distributed pole-closing sequences characteristic of each switching device. Since shunt capacitor banks are typically switched about 250 times a year, 250 switching operations were simulated per system for each device - resulting in a total of 50,000 simulations per switching device.

Recognizing that capacitor banks are switched frequently and that nuisance tripping of ASDs can significantly disrupt industrial customers, it is obvious that the overvoltage trip setting of an ASD should never be reached during any switching operation. Thus, for each of

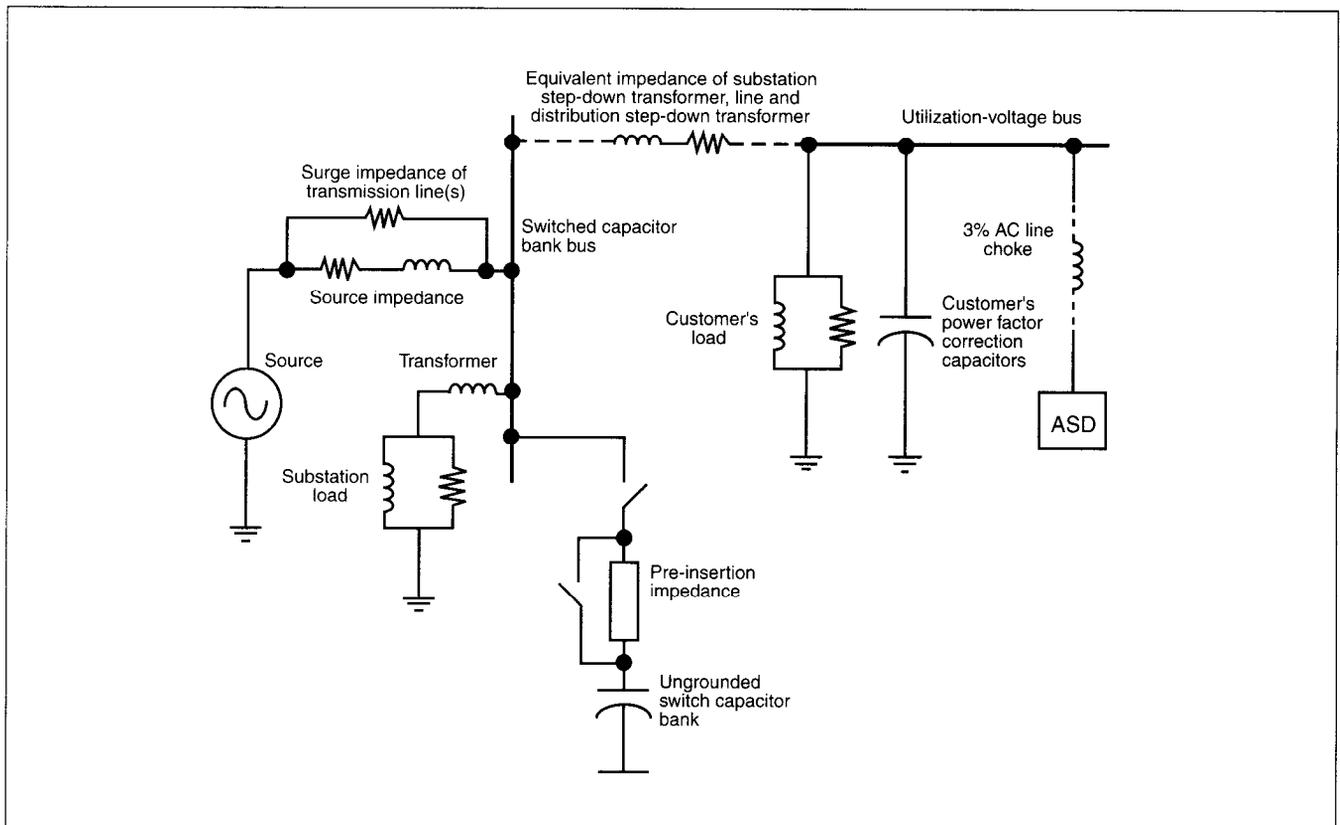


Figure 6. Equivalent circuit model for voltage magnification simulations.

the 200 systems studied, the highest DC bus voltage attained during any switching operation can be considered indicative of the performance of the method of overvoltage control utilized on the system (and of the associated switching device). A method of overvoltage control may be considered effective for a system if the highest simulated DC bus overvoltage does not equal or exceed the specified overvoltage trip setting.

Simulation Results

The simulation results indicate the extent of the ASD overvoltage tripping problem in systems where power-factor correction capacitors are utilized. Figure 7 illustrates the sensitivity of ASDs to nuisance overvoltage tripping when no transient overvoltage control method is applied at the utility substation and the ASDs are not equipped with 3% AC line chokes (or other transient mitigating devices); it shows how ASDs could trip-off in almost all systems, even at a higher overvoltage trip setting of 1.26 per unit. Figure 7 also illustrates how the situation is somewhat improved if a transient overvoltage control method is used at the utility substation; nuisance

tripping is prevented in 22 to 48% of the systems with highly damped 40 mH - 81 ohm pre-insertion inductors, 8 to 25% with pre-insertion resistors, and 3 to 15% with a controlled closing device.

Figure 8 reflects the much-improved situation when transient overvoltage control is utilized at the utility substation and the ASDs are equipped with a 3% AC line choke. The three methods of transient overvoltage control can be seen to be almost equally effective at preventing nuisance tripping of ASDs; they range in effectiveness from about 88% to 100% of the systems studied, over the range of typical ASD overvoltage trip levels. Circuit-Switchers with highly damped pre-insertion inductors limit the ASD DC bus voltage to about 1.23 per unit or less in 100% of the systems studied. Using the values of time deviation in closing after voltage zero discussed earlier in this paper, it can be concluded that the maximum deviation in closing after voltage zero should not exceed about 1 millisecond to ensure that the performance of the controlled closing device remains comparable to that of the pre-insertion inductors and pre-insertion resistors.

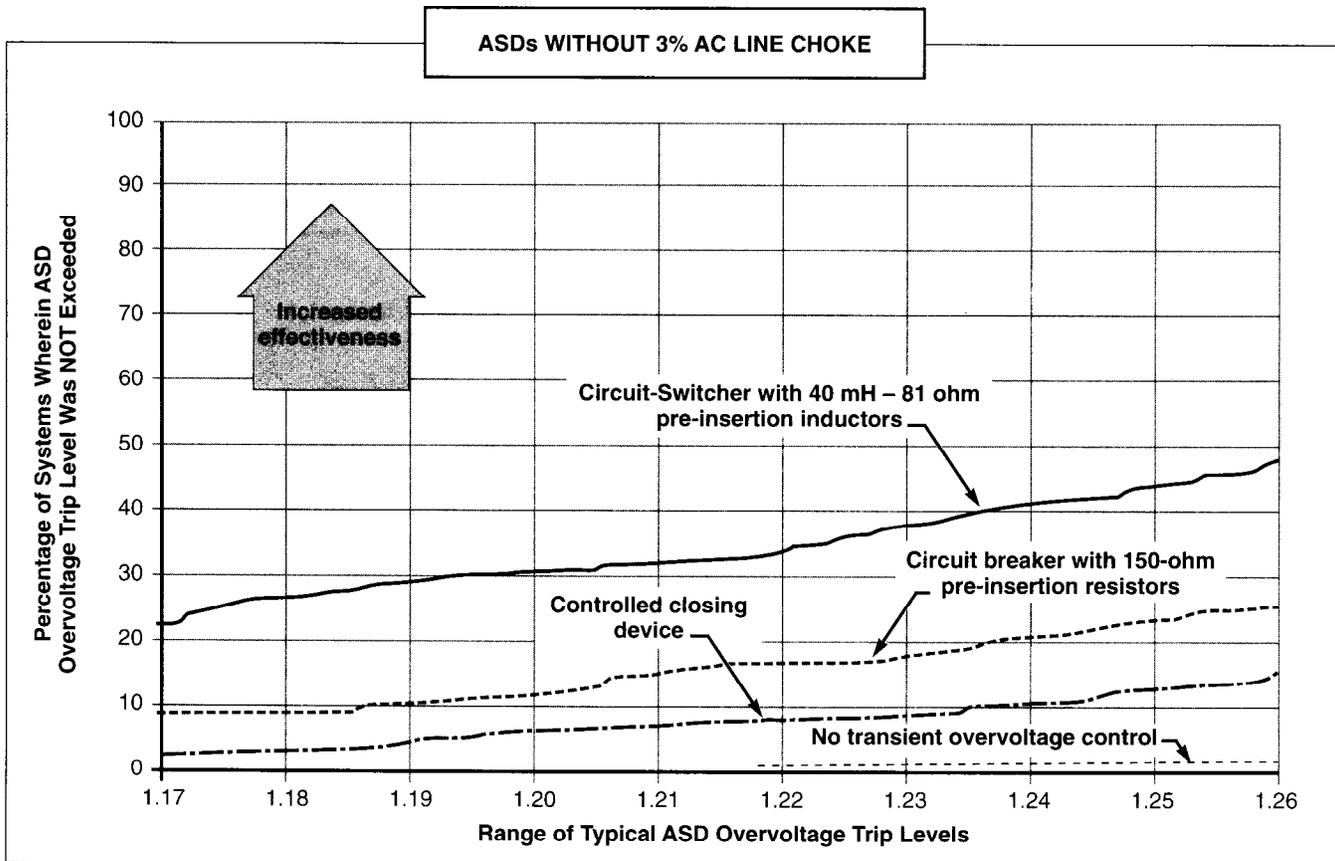


Figure 7. Percentage of systems in which overvoltage trip levels of ASDs were not exceeded for different methods of transient overvoltage control. ASDs are not equipped with a 3% AC line choke.

Figure 8 also shows that if no transient overvoltage control is provided at the utility substation, nuisance tripping is prevented in only about 47% to 68% of the systems. Thus, the addition of a 3% AC line choke to ASDs may not always prevent nuisance tripping if transient overvoltage control is not applied at the utility substation.

Evaluating Switching Devices for Preventing Overvoltages When De-energizing Shunt Capacitor Banks

Although the simulation study results discussed in the preceding section show comparable performance from the transient overvoltage control methods during capacitor bank energization, the overvoltages occurring during de-energization must be considered as well. If a restrike occurs during current interruption, phase-to-ground overvoltages in excess of 3.2 per unit can result at the remote capacitor location under voltage magnification conditions – irrespective of the method of transient overvoltage control used.^⑤

The benefits offered by the various methods of tran-

sient overvoltage control when energizing the capacitor bank are nullified if restrikes occur in the switching device. See Figure 9.

The initial rate of rise of recovery voltage across the terminals of a switching device is very low when interrupting capacitive currents. As a result, it is easy for the switching device to interrupt such currents. Interruption is often achieved with very small contact separation. After interruption with a small contact separation, it is possible that the switching device can restrike during the subsequent rise of the recovery voltage - at power frequency rate - to values as high as 4.1 per unit phase-to-ground voltage in ungrounded capacitor bank applications.

The ability of the switching device to interrupt capacitive currents without restriking is largely determined by its mechanical design as well as the interrupting medium utilized. In order to withstand transient recovery voltages with peak values up to 4.1 per unit, special design techniques must be applied.

In the case of circuit breakers, interruption of large

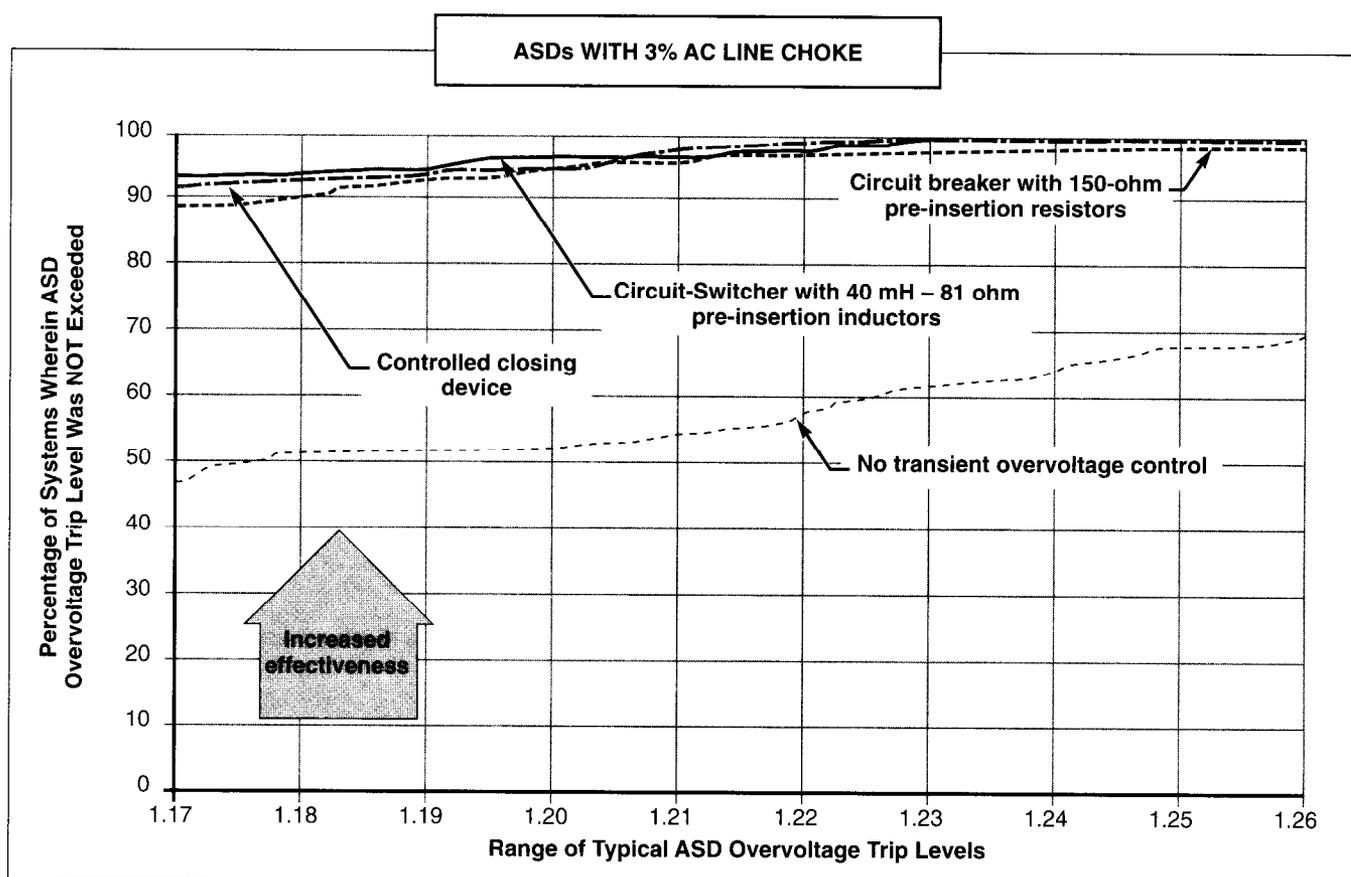


Figure 8. Percentage of systems in which overvoltage trip levels of ASDs were not exceeded for different methods of transient overvoltage control. ASDs are equipped with a 3% AC line choke.

^⑤ Fixed current-limiting reactors, usually applied for inrush current control, will slightly reduce the effects of voltage magnification during restrikes. Switched capacitor bank bus voltage collapse will be slightly reduced due to the voltage drop across the reactor caused by the inrush current, thereby resulting in reduced level of excitation of the remote L-C circuit.

inductive fault currents, with high-frequency transient recovery voltages, results in prolonged arcing times; interruption is thus achieved only at relatively large contact gaps. On the other hand, interruption of relatively small capacitive currents, with power-frequency transient recovery voltages, results in very short arcing times. The latter can result in interruption with very small contact gaps in capacitor-switching applications. Hence, the probability of restriking is increased, since very small contact gaps can be severely stressed by the ensuing transient recovery voltages.

Circuit-Switchers typically have lower interrupting capabilities than circuit breakers, making their design more suitable for capacitor-switching applications. Further, the sophisticated interrupting design techniques utilized in Circuit-Switchers can eliminate restriking, thus negating the possibility of damaging transients during current interruption.

The ability of a vacuum interrupter to interrupt current without restriking is determined by its contact material, contact design, and gap dielectric field strength.⁶ Due to the effects of large inrush currents, the probability of

restriking is increased in back-to-back capacitor bank switching applications. The ability of a specific vacuum switch to interrupt capacitive currents without restriking must therefore be ascertained.

Other Considerations

Switching of capacitor banks is probably the most common cause of transient overvoltages on many systems, second only to lightning in frequency of occurrence on most other systems. As a result, due consideration must be given to all transient phenomena associated with capacitor switching when selecting a method of transient overvoltage control and associated switching device. Reid⁷ describes various transient phenomena associated with capacitor switching. The three methods of control presented in this paper will reduce the initial collapse in the bus voltage either through voltage support by current flow through a pre-insertion impedance, or by closing at a reduced bus voltage level in the case of the controlled closing device. This reduction in the initial collapse in bus voltage (referred to as the fast front) will reduce all effects of phenomena associated with the fast front of the transient, e.g., overvoltages at radially fed transformers or

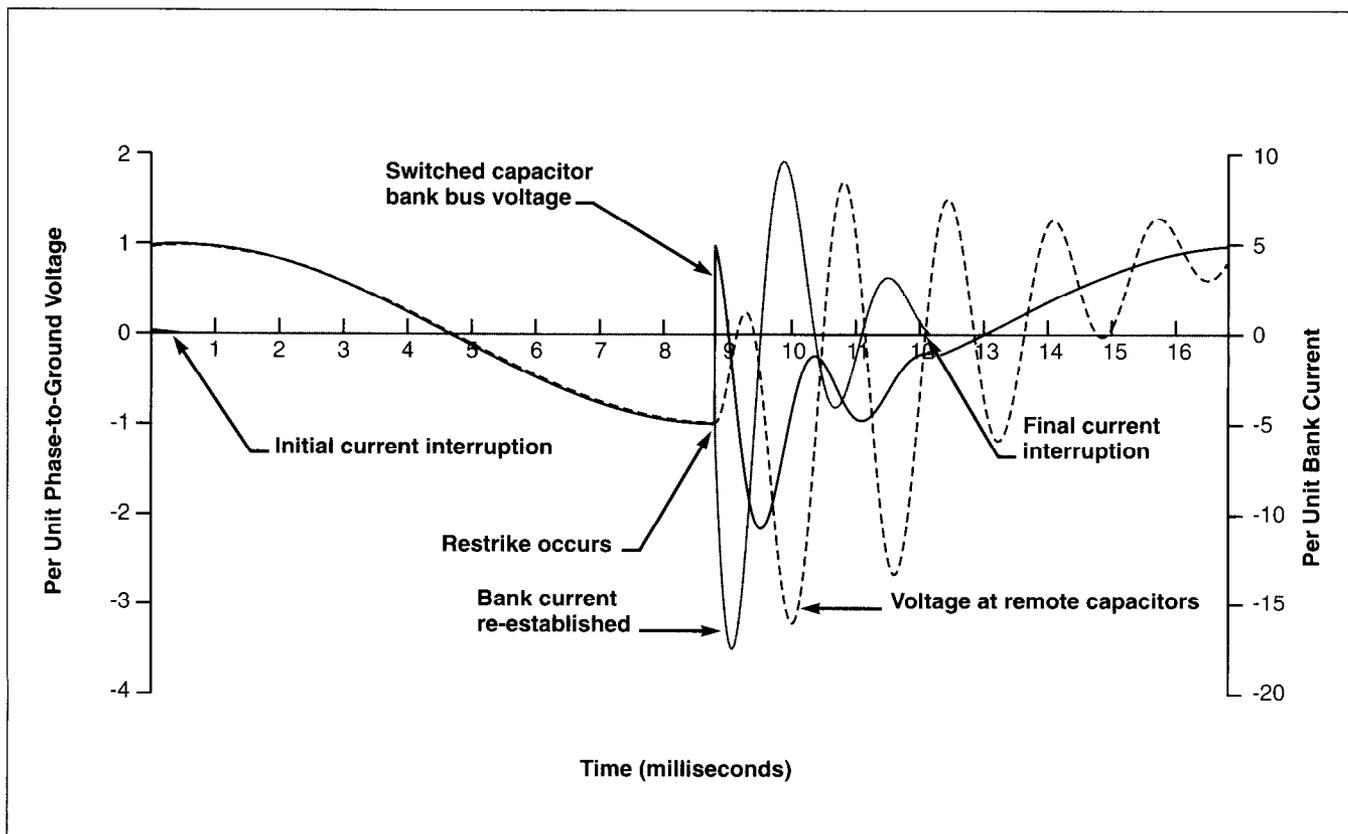


Figure 9. voltage magnification at remote power-factor correction capacitors due to a restrike in the capacitor-switching device during current interruption.

⁶ I. Oshim, et al, "Shunt Capacitor Switching Performance of Vacuum Interrupters," presented at the IEEE/PES 1990 Summer Meeting, Minneapolis, Minnesota, July 15 - 19, 1990.

⁷ W. E. Reid, "Capacitor Application Considerations-Utility/User Interface," presented at the 11th IEEE/PES Transmission and Distribution Conference and Exposition, New Orleans, Louisiana, April 6, 1991.

open-ended lines, and fast transients coupled through transformers. A comparative evaluation of methods for controlling overvoltages at radially fed transformers is presented by O'Leary and Harner.[®] In this regard, the primary difference between the effects of pre-insertion inductors and other control devices is the reduction in the rate-of-change in bus voltage during the fast front, which reduces the stress concentrations across the end turns of transformer windings due to capacitive distribution of voltages across the windings.

The optimum size of the pre-insertion resistor for overvoltage control is selected equal to the characteristic impedance formed by the source inductance and the capacitance of the bank. In reality, the close-and-latch ratings associated with circuit breakers determine the minimum value of resistance due to the energy dissipation requirement in the resistor. Since the selection of resistor size is usually dictated by the resistor sizes which are commercially available, the effectiveness of this method of overvoltage control can be somewhat affected.

Even though the poles of a Circuit-Switcher tend to close when the voltage across it is near peak, the pre-insertion inductor limits the initial collapse in bus voltage during bank energization by means of the voltage developed across it as a result of the flow of inrush current. In addition, the high inherent resistance of the highly damped pre-insertion inductor serves to damp the ensuing oscillatory transient. Insertion is effected through a simple mechanical sliding contact arrangement which provides high reliability and repeatability. In that the pre-insertion inductor is inserted only for a few cycles, it does not require the normal current, short-time current, and full BIL ratings.

Circuit breakers with pre-insertion resistors utilize an additional set of contacts to effect pre-insertion, thus increasing the complexity of the circuit breaker. The impact of this added complexity on the reliability of the device must be assessed. The resistor reduces the initial collapse in bus voltage and also damps the ensuing transient. Like the pre-insertion inductor, the pre-insertion resistor does not require normal current, short-time current, and full BIL ratings.

The closing accuracy of vacuum switches and SF₆ circuit breakers with controlled closing is determined by factors such as drift in timing controls, cold welding, and temperature variation. To ensure high reliability, deviation in closing accuracy should typically not exceed more than 1 millisecond after voltage zero. The need for, and frequency of, timing adjustments to maintain required closing accuracy must also be considered.

Summary

Table I summarizes the most important considerations when selecting a capacitor-switching device with transient overvoltage control.

The effectiveness of any transient overvoltage control method in any particular system can best be determined based on simulation studies for that particular system. This is particularly true in instances where ASDs are not equipped with AC line chokes.

Application Consideration	Comments
Effectiveness in preventing nuisance tripping of ASDs if ASDs are not equipped with 3% AC line choke	System study may be necessary to ensure effectiveness of available control methods
Effectiveness in preventing nuisance tripping of ASDs if ASDs are equipped with 3% AC line choke	Available control methods evaluated are effective in 88 to 100% of systems studied
Ability to interrupt current without restriking	Consult manufacturer
Effectiveness in addressing other capacitor-switching-related transients	For back-to-back switching applications, vacuum switches may require current-limiting reactors in series
Reliability	Consider mechanical and electrical simplicity of switching device and overvoltage control method
Maintenance requirements	Consider need for, and frequency of, adjustments to switching device and overvoltage control method
Cost	Will vary based on voltage class, required interrupting capability, etc.

Table 1. Summary of application considerations when selecting a capacitor-switching device with transient overvoltage control.

Extensive simulation studies performed by S&C indicate that appropriately sized highly damped pre-insertion inductors can be successfully applied at various system voltages ranging from 34.5 to 138 kV, to address nuisance tripping of ASDs due to voltage magnification when the ASDs are equipped with a 3% AC line choke or other equivalent transient mitigating device. The effectiveness of highly damped pre-insertion inductors when ASDs are equipped with a 3% AC line choke has been verified for 200 typical power systems at 34.5 kV, 46 kV, 69 kV, 115 kV, and 138 kV; hence no further system studies are necessary in such instances.

[®] R. P. O'Leary, and R. H. Harrier, "Evaluation of Methods for Controlling the Overvoltages Produced by the Energization of a Shunt Capacitor Bank," International Conference on Large High Voltage Electric Systems, August/September 1988, Paris.