Technologies for Transient Voltage Control During Switching of Transmission and Distribution Capacitor Banks

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Abstract - This paper presents a summary of transient overvoltage mitigation techniques for shunt transmission and distribution system capacitor banks. Included in the summary are pre-insertion resistors and inductors, synchronous closing control, fixed reactors, and arresters. Means for evaluation include overvoltage control effectiveness, system and customer considerations, and installation and maintenance factors.

Keywords - shunt capacitor bank, transient overvoltage, pre-insertion resistor, pre-insertion inductor, arresters, synchronous closing control.

I. INTRODUCTION

The application of transmission and distribution system capacitor banks has long been accepted as a necessary step in the design and operation of electric power systems. Design considerations often include traditional factors such as var support, voltage control, power factor, reduced system losses, and released capacity. Control of system transients has always been a factor; however, the transient overvoltages caused by the "normal" energization of these banks has generally not been a significant problem for utility equipment (protected with MOV arresters). Unfortunately, the recent proliferation of sensitive power electronic-based customer equipment has once again made overvoltage mitigation an important issue.

The impact on customer systems has become particularly important as utilities institute higher power factor penalties, thereby encouraging customers to install (power factor correction) capacitors. Coupled with this trend, nontraditional customer loads, such as adjustable-speed drives, are being applied in increasing numbers due to the improved efficiencies and flexibility that can be achieved. This type of load can be very sensitive to the transient voltages produced during utility capacitor switching. The most common methods for controlling these transients include the application of switching control (synchronous closing, preinsertion inductors/resistors), MOV arresters, and series inductances, often referred to as chokes [2]. This paper summarizes the mitigation methods available to the utility capacitor bank designer.

There are a number of important transient related concerns when transmission and distribution voltage level capacitor banks are applied to a power system. The system concerns include insulation withstand level, switchgear capabilities, energy duties of protective devices, and system harmonic considerations. Due to the increased use of power electronic-based low voltage systems, these considerations need to be extended to include sensitive customer facilities. In general, the considerations often evaluated through computer simulation include [5]:

- Overvoltages associated with normal capacitor energizing
- Open line/cable end transient voltages
- Phase-to-phase transients at transformer terminations
- Voltage magnification at lower voltage capacitor banks (including customer systems)
- Arrester duty considerations (restrike events)
- Analysis of current-limiting reactor requirements
- System frequency response and harmonic injection
- Impact on sensitive customer power electronic loads
- Analysis of ferroresonance possibilities

The evaluation of the merits for various overvoltage mitigation technologies requires an understanding of these, and often other, considerations.

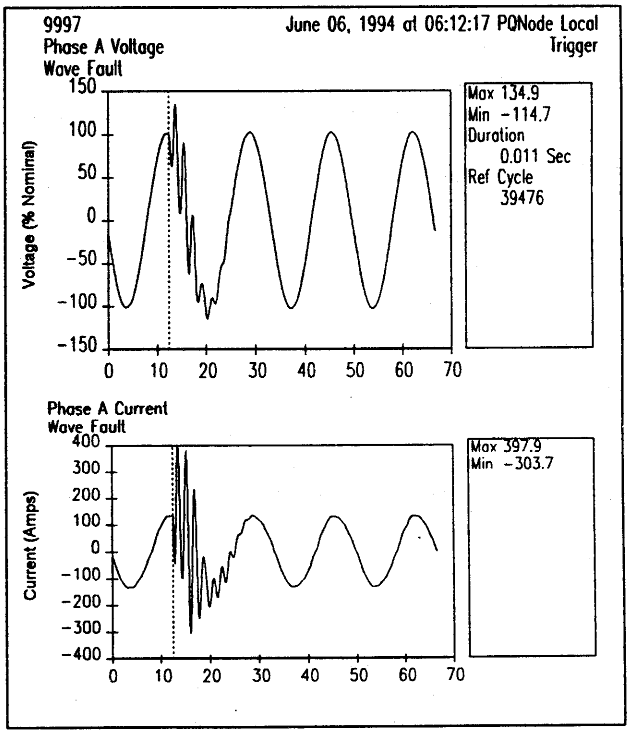

Figure 1 - Typical Distribution Feeder Capacitor Closing Transient Voltage and Current Waveforms

II. THE CAPACITOR ENERGIZING TRANSIENT

A. Overview

Energizing a shunt capacitor bank from a predominantly inductive source results in an oscillatory transient which can approach twice the normal peak system voltage. The characteristic frequency (f_s) of this transient is given by:

$$f_s = \frac{1}{2\pi\sqrt{L_s C}} \quad (1)$$

and the peak inrush current (I_{pk}) is determined from:

$$I_{pk} = \frac{V_{pk}}{\sqrt{\left(L_s/C\right)}} \quad (2)$$

where: L_s = source inductance (H)
C = capacitance of bank (F)
V_{pk} = peak line-to-ground bus voltage (V)

For a shunt capacitor bank on a substation high voltage bus, transmission line capacitance and other capacitor banks cause the energizing transient to have more than one natural frequency. However, for the first order approximation, the equation above (1) can still be used to determine the dominant frequency.

The energizing transient is important because it is one of the most frequent system switching operations. It can produce high phase-to-phase overvoltages on a terminating transformer, excite circuit resonances resulting in transient voltage magnification in secondary voltage networks, or cause problems with sensitive electronic equipment in customer facilities.

For a practical capacitor bank energization without trapped charge, system losses, loads, and transmission system capacitance cause the transient magnitude to be much less than the theoretical 2.0 pu (peak phase-to-ground voltage). Typical levels range from 1.2 to 1.7 pu. Figure 1 illustrates an example (measured) distribution system capacitor energizing transient.

Transient frequencies due to utility capacitor switching usually fall in the range 300-1000 Hz. Transient overvoltages which result are usually not of concern to the utility, since peak magnitudes are just below the level of which utility surge protection, such as arresters, begins to operate. Because of the relatively low frequency, these transients will pass through stepdown transformers to customer loads.

Power quality symptoms related to utility capacitor switching include: customer equipment damage or failure (due to excessive overvoltage), adjustable-speed drive or other process equipment shutdown (due to dc bus overvoltage), TVSS failure, and computer network problems (UPS cycling).

B. Voltage Magnification

Voltage magnification occurs when the transient oscillation, initiated by the energization of a utility (transmission or distribution) capacitor bank, excites a series resonance formed by the low voltage system. The result is a higher overvoltage at the lower voltage bus. Previous analysis [4] has indicated that the worst magnified transient occurs when the following conditions are met:

- The size of the switched capacitor bank is significantly larger (>10) than the lower voltage (often customer power factor correction) bank (i.e. 3 MVAr versus 200 kVAr = 15).

- The energizing frequency (f_s) is close to the series resonant frequency formed by the stepdown transformer and the power factor correction capacitor bank (f_2).

- There is relatively little damping (resistive) provided by the low voltage load (typical industrial plant configuration - primarily motor load).

Computer simulations and in-plant measurements have indicated that magnified transients between 2.0 and 4.0 per-unit are possible over a wide range of low voltage capacitor sizes. Typically, the transient overvoltages will simply damage low-energy protective devices (MOVs) or cause a nuisance trip of a power electronic device. However, the author is aware of several cases when complete failure of customer equipment (single process device) occurred.

C. Nuisance Tripping of Adjustable-Speed Drives

Nuisance tripping refers to the undesired shutdown of an adjustable-speed drive (or other power electronic process device) due to the transient overvoltage on the device's dc bus. Very often, this overvoltage is caused by distribution capacitor bank energization. Considering the fact that many distribution banks are time clock controlled, it is easy to see how this event can occur on a regular basis, thereby causing numerous process interruptions for a plant.

The nuisance tripping event consists of an overvoltage trip due to a dc bus overvoltage on voltage-source inverter drives (pulse-width modulated - PWM) [3]. Typically, for the protection of the dc capacitor and invertor components, the dc bus voltage is monitored and the drive tripped when it exceeds a preset level. This level is typically around 760 volts (for 480 volt applications), which is only 117% of the nominal dc voltage.

The potential for nuisance tripping is primarily dependent on the switched capacitor bank size, overvoltage controls for the switched bank, the dc bus capacitor size, and the inductance between the two capacitors. It is important to note that nuisance tripping can occur even if the customer does not have power factor correction capacitors.

III. MITIGATION TECHNIQUES

The devices currently available for transient overvoltage control either attempt to minimize the transient overvoltage (or overcurrent) at the point of application, or limit (clip) the overvoltage at local and remote locations. These devices include:

- Pre-insertion resistors (transmission and distribution)
- Pre-insertion inductors (transmission)
- Synchronous closing (transmission and distribution)
- Fixed inductors (transmission and distribution)
- MOV arresters (transmission and distribution)

Previous studies (digital simulation and TNA) have suggested that the effectiveness of these control methods is system dependent, and that detailed analysis is required to select the optimum control scheme. While often justifiable for large transmission applications, analysis of distribution system capacitor applications is rarely completed, and in general, banks are installed without transient overvoltage control. Each of these methods (summarized in Table 1) has various advantages and disadvantages in terms of transient overvoltage reduction, cost, installation requirements, operating/maintenance requirements, and reliability.

A. Pre-insertion Impedance

A pre-insertion impedance (resistor or inductor) provides a means for reducing the transient currents and voltages associated with the energization of a shunt capacitor bank. The impedance is "shorted-out" (bypassed) shortly after the initial transient dissipates, thereby producing a second transient event. The insertion transient typically lasts for less than one cycle of the system frequency.

The performance of pre-insertion impedance is evaluated using both the insertion and bypass transient magnitudes, as well as the capability to dissipate the energy associated with the event, and repeat the event on a regular basis.

Resistors:
Pre-insertion resistors are one of the most effective means for controlling capacitor energizing transients; however, reliability issues have often caused utilities to select other means.

The optimum resistor value for controlling capacitor energizing transients depends primarily on the capacitor size and the source strength. It should be approximately equal to the surge impedance (Z_s) formed by the bank and source:

$$R_{optimum} \approx \sqrt{\left(\frac{L_s}{C}\right)} \qquad (3)$$

Figure 2 illustrates the impact of a 6.4Ω pre-insertion resistor (commercially available) on the energizing transient for a 3.0 MVAr, 12.5kV distribution capacitor bank.

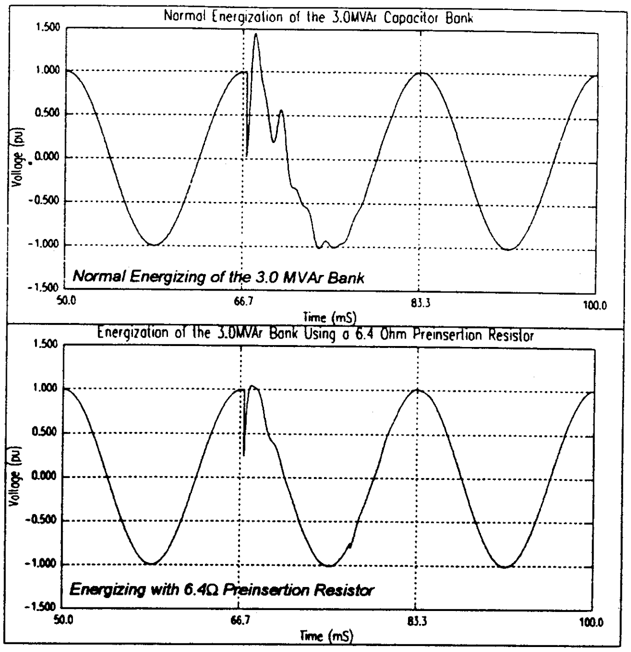

Figure 2 - Simulation of Impact of Closing Resistor on Distribution System Bus Voltage for a 3.0 MVAr Capacitor Bank Energization

Inductors:
Pre-insertion inductors, which are primarily used for overcurrent control for back-to-back applications also provide some level of transient overvoltage reduction. Often applied to circuit switchers, inductors are less sensitive to thermal considerations (resistor failure mode) and are more economical than resistors [7].

B. Synchronous Closing Control

Synchronous closing is independent contact closing of each phase near a voltage zero, as illustrated in Figure 3 (grounded bank). To accomplish closing at or near a voltage zero (avoiding high prestrike voltages), it is necessary to apply a switching device that maintains a dielectric strength sufficient to withstand system voltages until its contacts touch. Although this level of precision is difficult to achieve, closing consistency of ±0.5 milliseconds should be possible. Previous studies have indicated that a closing consistency of ±1.0 millisecond provides overvoltage control comparable to properly sized pre-insertion resistors. The success of a synchronous closing scheme is often determined by the ability to repeat the process under various (system and climate) conditions.

C. Fixed Inductors

Fixed inductors have been used successfully to limit inrush currents during back-to-back switching. Typically the value of these inductors is on the order of several hundred microhenries. In addition, inductors provided for outrush (into a nearby fault) current control may be applied, and are typically 0.5 - 2.0 millihenries. Previous simulations indicate that these fixed reactors do not provide any appreciable transient overvoltage reduction.

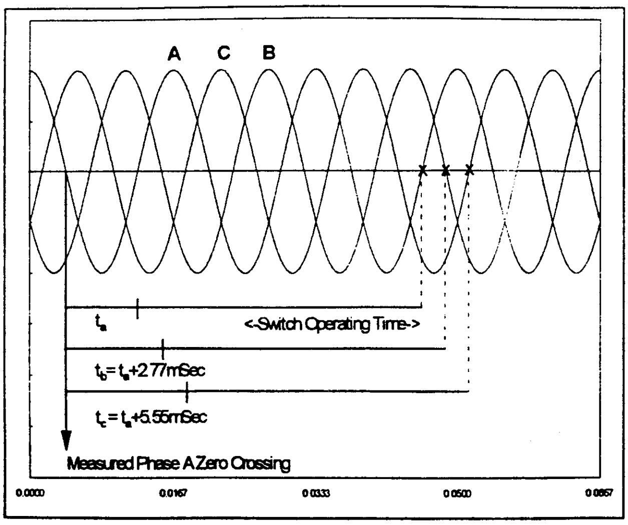

Figure 3 - Capacitor Breaker Closing Sequence for Synchronous Closing on a Grounded Bank

D. MOV Arresters

Metal oxide varistors (MOVs) can limit the transient voltages to the arrester's protective level (maximum switching surge protective level, typically 1.8 - 2.5 pu) at the point of application. The primary concern associated with MOV application is the energy duty during a restrike event. Although a rare occurrence, a switch restrike generally results in the highest arrester duty for arresters located at the switched capacitor. In addition, remote arresters (including low voltage customer applications) may be subjected to severe energy duties if voltage magnification occurs. This condition could be especially troublesome for distribution systems if SiC arresters remain in service.

IV. SYSTEM CONSIDERATIONS

A. Application Experience

Each of the technologies previously described has been utilized in the field with varying degrees of success. The criteria by which these devices are evaluated, however, is changing significantly. For example, design requirements often state that protection of utility equipment (i.e. transformers - phase-to-phase transients) is the primary factor. However, the recent concern for customer systems has prompted a number of utilities to seek a "transient-free" solution. This fact is best illustrated by reviewing the concern for nuisance tripping of adjustable-speed drives. As previously stated, the dc bus overvoltage trip setting for small voltage-source inverter drives may be as low as 117% of nominal. Using this value as the maximum (low voltage) transient during utility capacitor switching means that the mitigation technology will have to be very robust. A recent study indicated that even with an error window of ±1.0 millisecond (using synchronous closing control), the dc bus levels would be within 10% of the drive's trip setting (drive without input choke).

In addition to the overvoltage design limits, there are a number of other factors that have delayed the widespread application of mitigation technologies. One obvious obstacle is cost, however, an equally important reason has been reliability. Several examples include:

- A number of utilities indicate that the cost of the technology has not reached a point where widespread application is feasible, especially at the distribution level where the number of banks "near" sensitive customers is significant. Another factor in the cost is system studies, and custom designs (utilities would prefer to apply one technology and have it work anywhere on the system).
- Pre-insertion resistor failures (thermal) prompted one manufacturer to move to a pre-insertion inductor design. Several studies have indicated that under certain system conditions (i.e. weak source), these inductors provide minimal local overvoltage control and may even cause the remote overvoltages to increase.
- A number of utilities have reported drift (usually climate related) of the synchronous closing control. Even a minor error could be enough to produce low voltage transients sufficient to cause drive tripping. The error is correctable, however, it requires a technician to "zero-in" the controls.
- A number of utilities have reported equipment failure during a capacitor switch restrike event. Although the mitigation scheme does not play a role in the restrike, a lack of arresters (MOVs), due to the existence of the control, would certainly affect the event (perhaps leading to multiple restrikes and subsequent equipment failure).

These, and most certainly other factors have prompted a number of utilities to evaluate elaborate schemes, and have motivated manufacturers to design new options. The result of one "hybrid" scheme is illustrated in Figure 4. The current and voltage waveforms correspond to the energization of a 367.5MVAr, 500kV capacitor bank equipped with pre-insertion resistors *and* synchronous closing control. Simulation results indicated that optimum performance would be achieved by energizing the pre-insertion (200Ω) contact at a voltage zero and delaying the shorting contact ¼cycle (4.1667mSec). This condition energizes the capacitor at a voltage zero and shorts the resistor at a current zero (voltage zero across resistor). The primary function of the resistor is to provide "backup" in the case of synchronous closing drift [1].

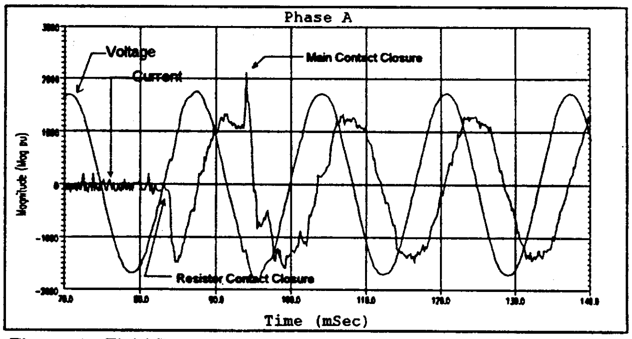

Figure 4 - Field Recording Illustrating Zero Voltage Closing Control

Table 1 - Summary of Overvoltage Mitigation Devices

Mitigation Technique	Local Overvoltages	Remote Overvoltages	Customer-Side PQ Considerations	Estimated Relative Cost	Install & Maintain	Comments
Transmission Level:						
No control	Moderate - High	High - Very High	High - Very High	—	—	Many older banks without protection
Standard pre-insertion inductor	Low - Moderate	Moderate - Very High	Moderate - High	Moderate	Minimal	May not reduce remote xfmr overvoltages
High-loss pre-insertion inductor	Low	Low - Moderate	Low - Moderate	Moderate - High	Moderate	Thermal considerations unknown
Pre-insertion resistor	Low - Moderate	Low - Moderate	Low - Moderate	Moderate	Moderate	Thermal failures
Synchronous closing	Low	Low - Moderate	Low - Moderate	Moderate	*High	*Adaptive control should reduce to moderate
Fixed inductors	Moderate - High	High - Very High	High - Very High	High	Moderate	Provides overcurrent protection
Arresters (MOV & SiC)	Moderate - High	Moderate - High	Moderate - High	Moderate	Minimal	Provides restrike protection
						Generally needed at substation anyway
Distribution Level:						
No control	Moderate - High	Moderate - High	Moderate - High	—	—	Very typical on distribution
Pre-insertion resistor	Low	Low	Low - Moderate	Low - Moderate	Moderate	Common up to 15kV
Synchronous closing	Low	Low - Moderate	Low - Moderate	Moderate - High	High	Adaptive control required
Arresters (MOV & SiC)	Moderate - High	Moderate - High	Moderate - High	Moderate	Minimal	Provides restrike protection

B. Device Enhancements

Several manufacturers have recently introduced new options for mitigation of capacitor energizing transients. These enhancements were driven by some of the same concerns previously mentioned.

First, one manufacturer has developed a synchronous closing control scheme that has the ability to "learn" from previous events [6]. The primary benefits of this capability are the control's ability to compensate for environmental factors and the increased reliability (less frequent maintenance) that can be achieved. For each event, the timing error (time between current flow and voltage zero) is measured and then provided to the "compensation algorithm" for use in determining the subsequent control signal.

Another advantage of this design is that the adaptive control scheme is paired with a three-phase breaker (eliminating the need for three independent switches). The new breaker operating mechanism makes use of a single energy storage system with three independently controllable drive rods.

The author is aware of two installations using this technology. (115kV, 54.0 & 25.2 MVAr). Early indications indicate proper operation, however, the "test of time" will be the most important factor in evaluating this new technology.

Second, a manufacturer of pre-insertion inductors has recently developed an "enhanced-duty" device. The primary benefit of this enhancement is a value of resistance that is significantly larger (30-40 times) than the existing technology. Simulations performed by the manufacturer indicate that the level of damping provided by the enhanced duty inductor is sufficient to eliminate most cases of nuisance tripping. The added resistance provides additional damping of transients that typically occur at (or near) a voltage peak. The enhanced duty inductor size is approximately four times larger (mH) than the existing unit. The added inductance provides addition overcurrent protection during back-to-back switching and should provide better overvoltage control for phase-to-phase transients (weak system concern). Thermal considerations will be a primary factor in evaluating this technology.

Finally, one manufacturer of vacuum switches and synchronous closing control now offers a pole top option for distribution applications.

It should be noted that none of these options provide overvoltage/overcurrent protection in the event of switch restrike. Typically, overvoltage protection is provided by applying MOV arresters, either at the bus or on the capacitor bank. MOVs on the capacitor side of the switch can protect the bank from excessive overvoltages during multiple restrike events, and may indeed reduce the likelihood of a such an event. If MOVs are applied at the bank, coordination with bus arresters should be considered.

Considering the severity of a restrike event, one manufacturer has used the synchronous closing technology to develop a synchronous opening option. The concept is that initial contact parting is timed, rather than a random event. A signal to open is sent immediately after a current zero, thereby allowing the contacts to part for a full ½ cycle before arc extinction. The dielectric strength should then be sufficient to prevent a restrike from occurring.

C. System Studies

The analysis of high voltage capacitor switching concerns in the utility environment consists primarily of measurements and computer simulations (and/or TNA). In general, studies are completed to evaluate the effectiveness of various overvoltage mitigation options, as well as to develop recommendations regarding overvoltage protection for both utility and customer. Measurements on customer systems provide information regarding power quality levels during utility capacitor switching.

Perhaps the most important factor in the system study is selecting a "reasonable" design goal and then determining the mitigation technology that best meets all of the factors considered, including cost, reliability, and customer power quality issues. In general, system studies for capacitor applications require a model that contains the "local" system. However, the need to evaluate customer low voltage systems may extend the model significantly. In fact, the author is aware of a case where a 230kV capacitor energizing event tripped a 480 volt adjustable-speed drive.

V. CONCLUSIONS

- The recent proliferation of sensitive power electronic-based equipment has caused many utilities to reevaluate their capacitor application criteria. Low voltage problems include voltage magnification and nuisance tripping of adjustable-speed drives.
- Typical capacitor energizing overvoltages range from 1.2 - 1.7 pu and have a principle frequency of between 300 - 1000 Hz.
- Transient mitigation techniques include pre-insertion resistors, pre-insertion inductors, synchronous closing control, and MOV arresters.
- There has been a reduction in the use of pre-insertion resistors due a number of thermal failures.
- The application of zero voltage closing control has proven to be an effective method for controlling overvoltages, when closing errors can be consistently kept between ±1.0 millisecond.
- Pre-insertion inductors may not provide adequate overvoltage protection for some system conditions.
- Fixed inductors (up to several millihenries), commonly used for overcurrent control, do not provide any appreciable overvoltage reduction.
- Most transient control schemes do not provide any benefit during restrike events. Restrike concerns must be evaluated separately.
- Improved overvoltage and power quality control should be possible with several new device enhancements, namely high loss pre-insertion inductors, and adaptive synchronous closing control.
- System studies may be required to properly select an overvoltage control technique, however, widespread acceptance should be possible (especially at distribution level) without costly analysis.

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VII. BIBLIOGRAPHY

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