Overvoltage Protection of Shunt-Capacitor Banks Using MOV Arresters

– By –

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OVERVOLTAGE PROTECTION OF SHUNT-CAPACITOR BANKS USING MOV ARRESTERS

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ABSTRACT

This paper evaluates using metal-oxide-varistor (MOV) surge arresters to protect shunt-capacitor banks from overvoltages. Protection requirements and surge arrester duties are analyzed for both lightning transients and switching-surge overvoltages, using both digital and transient network analyzer (TNA) simulations. Simple analytical expressions are developed for evaluating arrester duty as a function of capacitor bank size. Guidelines and limitations for applying arresters at grounded- and ungrounded-wye capacitor banks are developed based on overvoltage characteristics and arrester capabilities.

INTRODUCTION

The use of shunt-capacitor banks for voltage control and power-factor improvement has increased at both the transmission and the distribution voltage levels. The critical need for reliability in these installations makes careful evaluation of overvoltages - steady-state, harmonic, lightning-surge, and switching-surge - on the capacitor banks themselves and the rest of the system essential.

Steady-state and harmonic overvoltages cannot be effectively limited by surge arresters; these conditions must be controlled via system design and monitoring schemes. Lightning- and switching-surge overvoltages can be limited by surge arresters; however, silicon-carbide (SiC) arresters at capacitor banks can be subjected to excessive duty during transient conditions. The possibility of excessive SiC arrester duty has resulted in many capacitor installations without arrester protection. MOV arresters have higher withstand capability than SiC arresters and can be applied at many capacitor banks where the duty is excessive for SiC arresters. This paper defines the application requirements for MOV arresters at capacitor banks.

REQUIREMENTS FOR PROTECTION FROM LIGHTNING SURGES

Lightning surges are often defined in terms of peak kA and initial rate-of-rise but, when evaluating the resultant voltage on a capacitor or the energy dissipated by an arrester, the charge (Q) of the stroke is more significant. A number of measurements of lightning stroke parameters have been made.[1] Table I summarizes the charge and duration of the negative first strokes observed by Berger[2]. Berger observed values as high as 52 coulombs for negative first strokes and up to 60 coulombs for negative flashes (which include the following strokes). He also observed charges in excess of 400 coulombs for positive strokes, but these rarely strike transmission and distribution lines.

TABLE I
Lightning Parameters Measured for Negative First Strokes

	Cases Exceeding Tabulated Value			
Lightning Parameter	95%	50%	5%	Max
Charge (coulombs)	1.1	5.2	24	52
Time to Half Value (usec)	30	75	200	230

Strokes terminating on a phase conductor very near a capacitor bank may exhibit the high charge values summarized in Table 1. Capacitor banks that are effectively shielded will only see lightning surges that strike the line at a remote location (Figure 1). For these surges voltage levels no higher than the critical flashover (CFO) level of the line insulation can travel down the line toward the capacitor bank, limiting the magnitude of the current surge to

$$I = \frac{CFO}{Z} \qquad (1)$$

Where

Z = Surge impedance of the line.

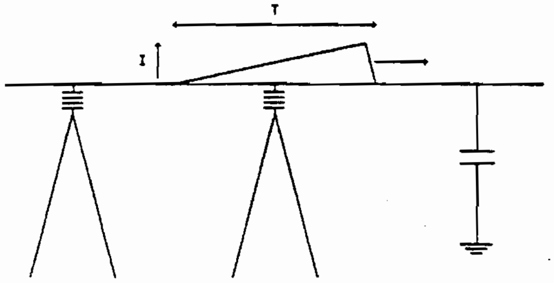

Fig. 1. Surge current due to remote lightning stroke.

From the times shown in Table 1, a value of T = 400 usec is fairly long and conservative for evaluating the charge in the surge in Figure 1. For a 12-kV system with wood poles, CF0 = 500 kV, and Z = 500 ohms:

$$I = \frac{CFO}{Z} = \frac{500\ kV}{500} = 1\ kA;$$

$$Q = IT/2 = (1 \times 10^3)(400 \times 10^{-6}/2) = 0.2\ coulomb.$$

For a 500-kV system with CFO = 2500 kV and Z = 300 ohms:

$$I = \frac{2500 kV}{300} = 8.33\ kA$$

$$Q = (8.33 \times 10^3)(400 \times 10^{-6}/2) = 1.7\ coulombs.$$

It is evident that a close-in lightning surge may have a charge approaching 50 coulombs while a remote stroke will likely deliver less than 2 coulombs.

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Surge Arrester Energy Dissipation Capability

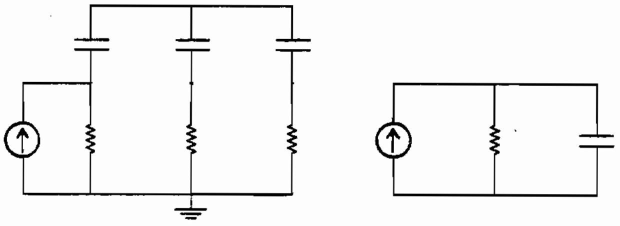
Table II shows typical arrester energy rating values. Since current waveshape influences energy capability, these values may vary significantly.

TABLE II
Typical Arrester Energy Ratings

Arrester Class	Block Material	Energy Rating (kJ/kV of Rating)
Distribution	SiC	1
Intermediate	SiC	2
Station	SiC	3
Distribution	MOV	3
Station	MOV	7
Station w/double column	MOV	13

Arrester-Energy Dissipation Requirements

Distribution and transmission system capacitor banks are usually connected ungrounded wye or grounded wye. For a direct lightning stroke, the equivalent circuits are shown in Figure 2. (Equivalent resistances represent the line surge impedances; equivalent station inductances and capacitances and interphase surge impedances are neglected).


Ungrounded Wye

Grounded Wye

Fig. 2. Equivalent circuits for direct lightning strokes.

A capacitor bank arrester is likely to see fewer operations as a result of lightning than an arrester protecting a distribution transformer because a capacitor bank reduces the transient voltage caused by a lightning surge. An ungrounded-wye capacitor bank, in effect, ties the three phases together, reducing the equivalent surge impedance and the transient voltage caused by the surge current. A grounded-wye bank provides a low-surge impedance path, slowing the surge considerably and reducing the magnitude of the overvoltage.

The energy (E) dissipated in an arrester as a result of a lightning stroke, as a function of arrester voltage (V) and current (I), is expressed as

$$E = \int VI\,dt \qquad (2)$$

The voltage across the arrester is fairly constant during the most significant part of the surge. As an approximation, $V = V_{10}$ where V_{10} is the 10-kA discharge voltage of the arrester,

$$E = V_{10}\int I\,dt = V_{10}Q \qquad (3)$$

The required arrester energy rating for a given stroke charge is shown in Table III, assuming the arrester must discharge the entire stroke current.

Table III
Arrester Energy Requirements

Lightning Stroke Charge Q (coulombs)	Arrester ratio of V_{10}/V_{rating}*	Required Arrester Energy Rating (kJ/kV of Rating)
50	2 to 4	100 to 200
4	2 to 4	8 to 16
1	2 to 4	2 to 4
0.5	2 to 4	1 to 2

*In general, V_{10} is 2 to 4 times the voltage rating of the arrester.

Tables II and III show that an arrester surge current with a charge in excess of 4 coulombs will exceed the energy-dissipation capability of a single-column arrester; therefore, most direct strokes will exceed the capability of even an MOV surge arrester while most indirect strokes will not cause arrester failure.[3, 4]

Figure 3 illustrates the differences in protecting distribution transformers and grounded-wye capacitor banks using SiC and MOV arresters. A 1-coulomb lightning surge with a 10-kA peak was simulated on a 12-kV system using 9-kV arresters. The arrester duty in Case 2 is less severe than in Case 1 because the capacitor bank stores part of the energy that is eventually dissipated in the power system rather than in the arrester. In Case 3, the total energy is only approximately 10 percent higher than in Case 2, but the current peak is more than three times as high. The MOV arrester in Case 4 shows approximately 10 percent less energy dissipated than the SiC arrester in Case 2. An MOV arrester generally has higher energy-dissipation capability than a SiC arrester.

An ungrounded-wye capacitor bank was also simulated. For a 1-coulomb, 10-kA lightning stroke, the capacitor bank has very little effect on the arrester duty and the waveforms are similar to those in Case 1. The general observations made for distribution system capacitor banks in Figure 3 also apply to transmission system banks.

REQUIREMENTS FOR PROTECTION FROM SWITCHING SURGES

Transient overvoltages at capacitor banks resulting from different types of switching operations are

- Capacitor energizing transients.
- Capacitor deenergizing transients.
- Magnification of transient overvoltages associated with energizing a remote capacitor, cable, or transmission line.
- Dynamic overvoltages associated with energizing a transformer and capacitor together.

Capacitor Energizing Transients

Energizing an isolated, grounded-wye capacitor bank from a predominantly inductive source (Figure 4) can result in a transient overvoltage approaching 2.0 pu with a characteristic frequency (f) of

$$f = \frac{1}{2\pi\sqrt{L_S C}} \qquad (4)$$

Where
L_S = system source inductance.
C = capacitor bank capacitance.

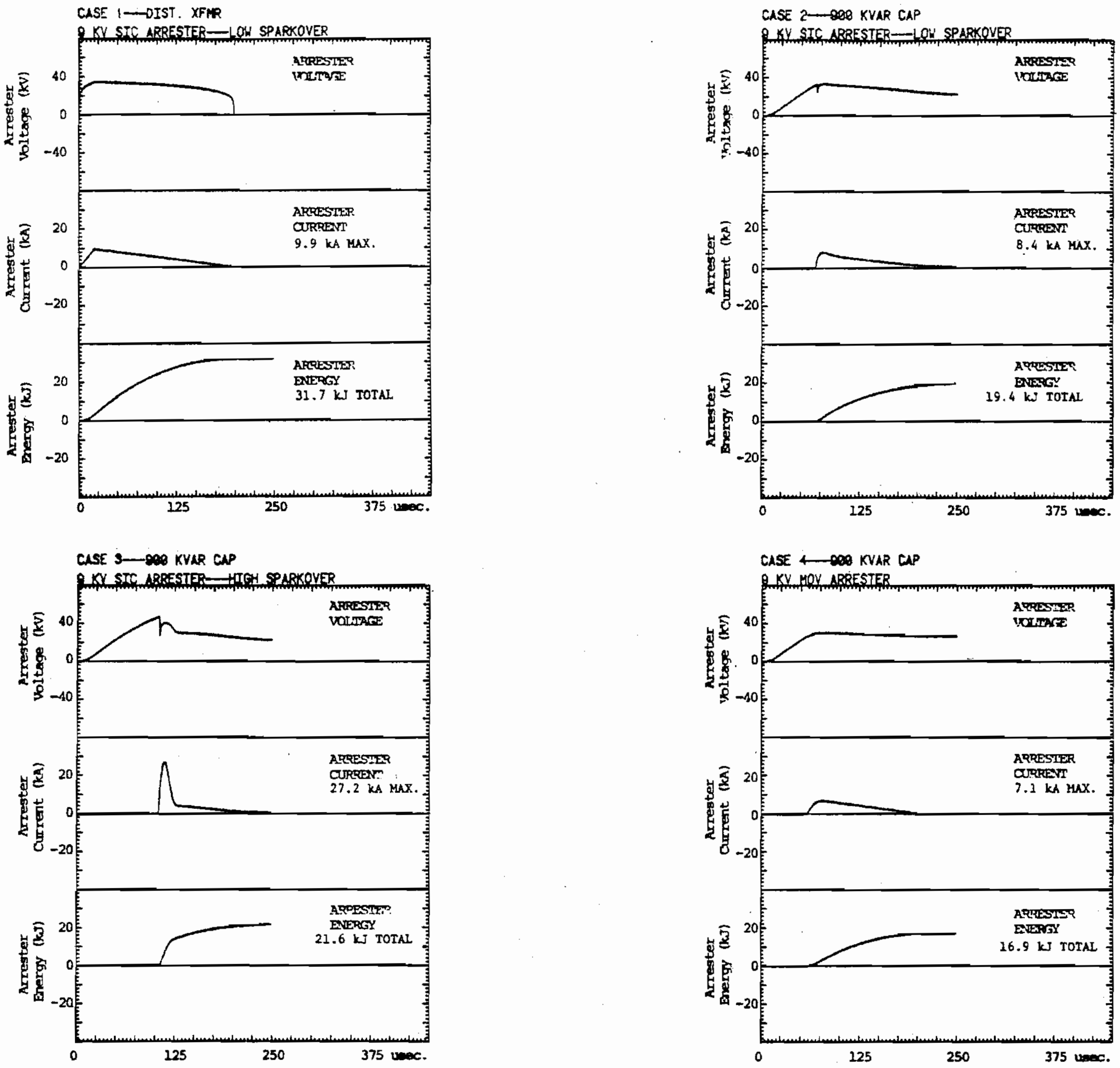


Fig. 3. Arrester duty for 1-coulomb lightning surge.

Energizing an ungrounded-wye capacitor bank can result in slightly higher transient overvoltages because of unequal pole closing. In general, the transient overvoltages associated with normal closing are similar to those for grounded-wye banks. The normal energizing voltage surge does not exceed the arrester switching-surge protection level for most SiC arresters nor does it result in a significant energy duty for MOV arresters.

Significantly higher transient overvoltages can occur at both the capacitor bank and remote locations because of prestrikes in the energizing switch. [5, 6] This occurs when a switch is able to clear the current at one of the high-frequency current zeroes associated with energizing a capacitor bank. This can result in transient overvoltages with very fast rise times at remote locations on open-ended or transformer terminated lines. Prestrike overvoltages can be limited by closing resistors in the switching device and/or surge arresters at the capacitor bank and remote locations.

A mechanical malfunction in a switch can cause a latching failure on closing, resulting in a temporary electrical contact (similar to a prestrike) followed by subsequent switch restrikes as the switch opens. This may result in an excessive trapped dc voltage on that

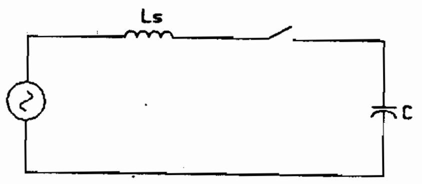


Fig. 4A. Equivalent circuit.

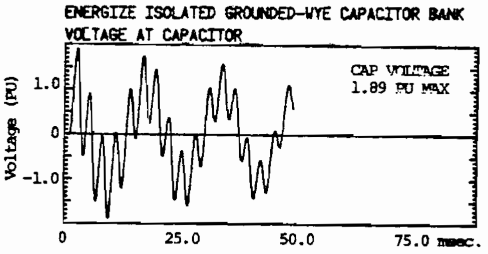


Fig. 4B. Energizing transient voltage.

phase of a grounded-wye bank. On an ungrounded-wye bank, even the other two energized phases would exhibit some trapped dc voltage.

Capacitor Deenergizing Transients

Grounded-Wye Capacitor Banks. In normal grounded-wye capacitor-bank deenergizing, the capacitor current is at peak system voltage, leaving a 1.0-pu trapped charge in the bank. This trapped charge results in an offset in the switch recovery voltage that reaches a peak of 2.0 pu one-half cycle after opening. Significant transient overvoltages can occur if the switch restrikes during clearing. In a worst-case single restrike on a grounded-wye capacitor bank, the restrike occurs when twice the normal system peak voltage appears across the switch contacts (Figure 5). The transient overvoltage in such a case can approach 3.0 pu.

While it is desirable to select a switching device that will minimize the possibility of a restrike, it is recommended that the overvoltage protection scheme be designed to withstand this contingency. Arresters applied to limit the overvoltage at a capacitor bank must be capable of withstanding the energy duty associated with the restrike transient.

To calculate arrester energy duty conservatively, a lossless inductive source and an MOV arrester with ideal chracteristics (Figure 6) is assumed. Assuming that the voltage source, V_s, is constant during the transient, the arrester current will be triangular, with the characteristics shown in Figure 7. Equations (Figure 8) for both the arrester current and energy are derived for this circuit in terms of the capacitor value, the source inductance, the system voltage, and the arrester protective level.

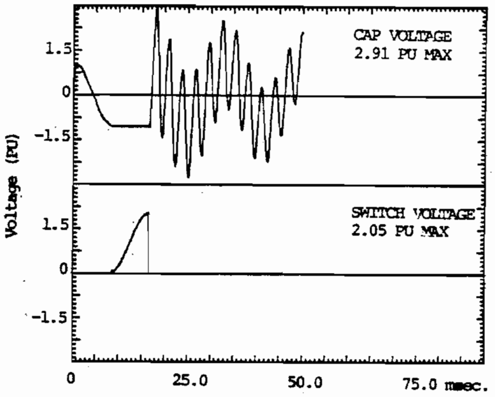


Fig. 5. Restrike on a grounded-wye capacitor bank.

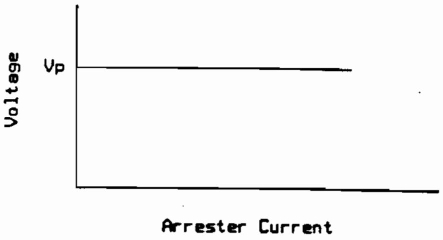


Fig. 6. Ideal MOV characteristics.

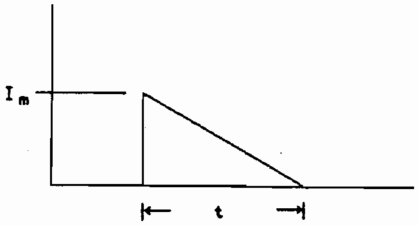
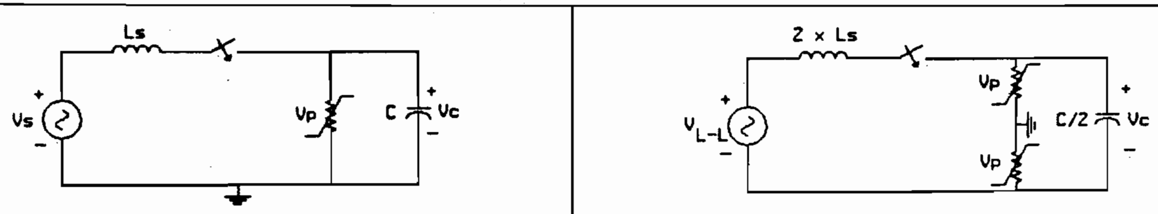


Fig. 7. Assumed current waveshape for restrike transient.



Restrike On
Grounded Wye Capacitor:

$$I_m = [(V_s-V_c)^2-(V_p-V_s)^2]^{1/2} / \sqrt{L_s/C} \quad \text{amps}$$

$$t = \frac{L_s I_m}{V_p-V_s} \quad \text{sec}$$

$$\text{Energy} = 1/2\ I_m\ t\ V_p = 1/2\ \frac{L_s I_m^2}{(V_p-V_s)}\ V_p \quad \text{Joules}$$

For First Restrike:

V_s = peak line-to-neutral voltage
V_p = arrester protective level
V_c = $-V_s$

For Worst Subsequent Restrike:

Same as for First Restrike Except $V_c = -V_p$

Two Phase Restrike On
Ungrounded Wye Capacitor:

$$I_m = [(V_{L-L}-V_c)^2-(2V_p-V_{L-L})^2]^{1/2} / (2\sqrt{L_s/C}) \quad \text{amps}$$

$$t = \frac{2L_s I_m}{(2V_p-V_{L-L})} \quad \text{sec}$$

$$\text{Energy} = 1/2\ I_m\ t\ V_p = \frac{L_s I_m^2}{(2V_p-V_{L-L})}\ V_p \quad \text{Joules}$$

For First Restrike:

V_{L-L} = peak line-to-line voltage
V_p = arrester protective level
V_c = -2.37 x peak line-to-neutral voltage

For Worst Subsequent Restrike:

Same as for First Restrike Except $V_c = -2V_p$

Fig. 8. Analysis of arreser duty for restrike transient.

The equations in Figure 8 can be used to make a conservative analysis of the duty that the arrester must withstand for a switch restrike. For capacitor switching transients, the arrester kJ/kV rating may be reduced to one-third to one-half of the standard published value. (This information is available from arrester manufacturers.) In Figure 9, the maximum arrester duty for the first restrike is plotted as a function of the arrester protection level. For a SiC arrester, the duty is usually more severe because of the partial capacitor discharge which occurs when the arrester sparks over. The current magnitude in this case is an especially important concern. [8]

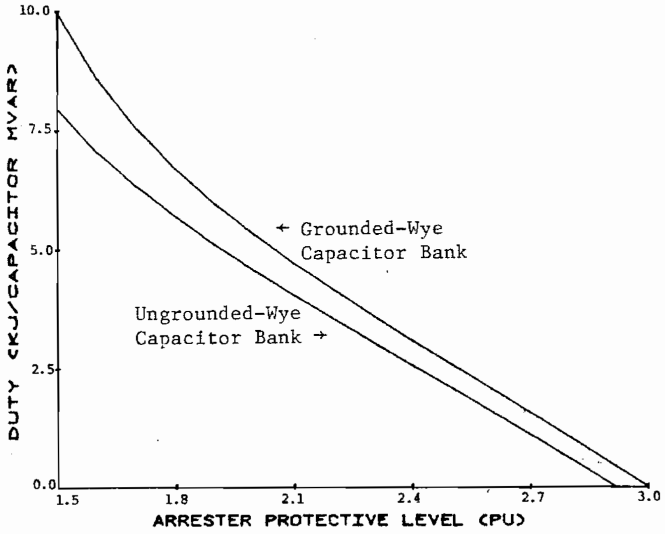


Fig. 9. MOV arrester duty for capacitor switch restrike.

If the conservative analysis indicates that the arrester duty is excessive for a restrike, then the actual circuit—including damping—must be analyzed in more detail. Reduction of the overvoltage can occur due to transmission lines or cables in the source, the X/R ratio of the system source, and/or nearby capacitor banks. Figure 10 compares an MOV arrester operation with that of an SiC arrester for a worst-case restrike transient in a circuit with a source X/R ratio of 10. If the arrester duty—including the effect of damping—is still excessive, multiple-column arresters may be required.

Ungrounded-Wye Capacitor Banks. Ungrounded-wye capacitor banks subject the capacitor-switching device to even higher recovery voltages than the 2.0 pu for grounded-wye banks: [9]

- 2.5 pu on the first phase to open when the other two phases open on the next current zero;
- 3.0 pu on the first phase to open when the other two phases delay opening;
- 4.1 pu on the first phase to open when one of the other two phases delays opening.

If a restrike occurs on the first phase to open at 2.5 pu, a recovery voltage of 6.4 pu can occur on one of the other two phases because of the voltage that builds up across the neutral capacitance. This high recovery voltage on another phase can cause a second restrike, resulting in a two-phase restrike (Figure 11). When a restrike occurs, trapped voltages on the capacitor can be escalated, resulting in even higher switch recovery voltages, thus increasing the possibility of additional restrikes.

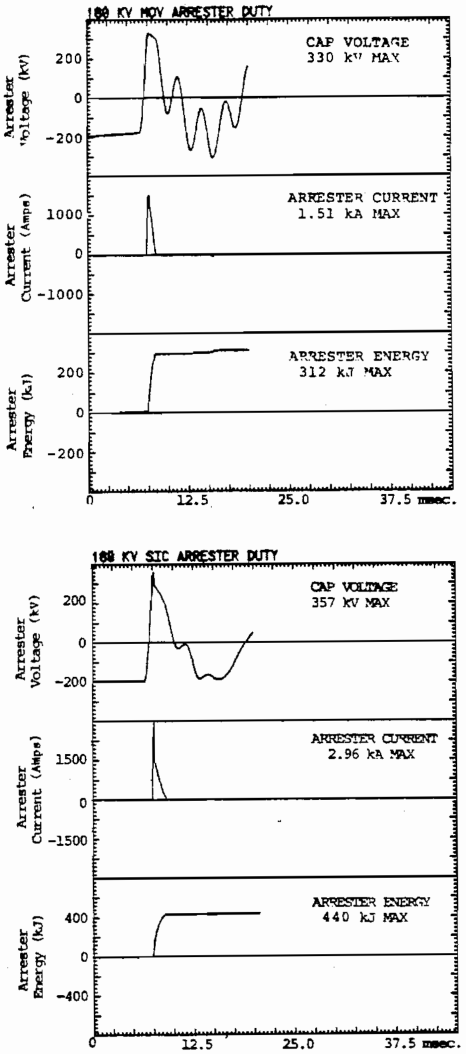


Fig. 10. Switch restrike: 50-Mvar, 230-kV capacitor bank.

The transient voltages on a capacitor bank and the recovery voltages across the switch can be reduced during a restrike by installing arresters on the capacitor side of the switching device (Figure 11). The two-phase restrike can be used as a conservative analysis of the possible arrester duty in such an application (Figure 12). Equations for arrester duty are summarized in Figure 8.

Connecting arresters line-to-ground (L-G) on an ungrounded-wye capacitor bank does not necessarily limit the voltages trapped on the capacitors. Figure 13 shows a single restrike where the trapped capacitor voltage reaches 2.65 pu and the bus voltage is only 2.12 pu. For multiple restrikes, even higher voltages are possible.

Arresters connected from phase-to-neutral on a capacitor bank limit the trapped voltage on the capacitors to lower levels than L-G connected arresters and reduce the switch recovery voltage, thus minimizing the possibility of multiple restrikes. This connection does not limit the high-frequency neutral-to-ground component of the switch transient recovery voltage (TRV); a fourth arrester from neutral to ground can be added if necessary.

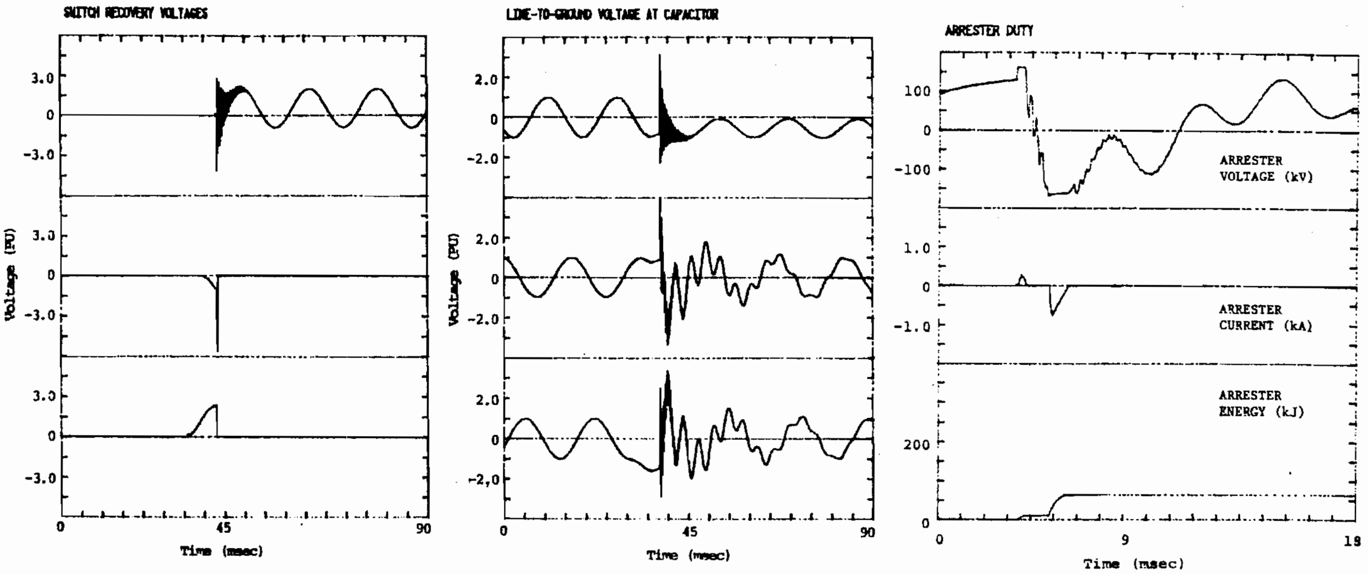


Fig. 11. Two-phase restrike: ungrounded-wye capacitor bank.

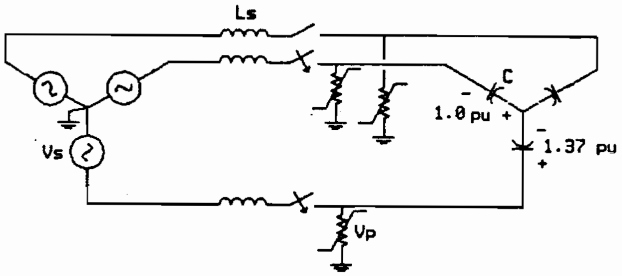


Fig. 12A. Circuit for analyzing two-phase restrike.

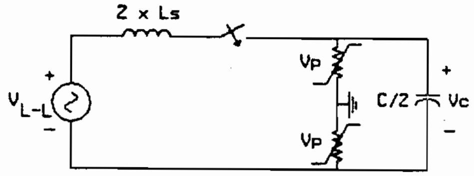


Fig. 12B. Equivalent circuit for analyzing two-phase restrike.

Capacitor Banks at the Same Bus. With two or more capacitor banks at the same bus, the high-frequency inrush due to the parallel capacitor banks can cause transient and trapped voltages on the banks that are significantly greater than the voltages at the main bus where arresters would often be installed. In such cases, arresters may be required at each bank.

If a restrike occurs on Capacitor Bank C2 (Figure 14) while Bank C1 is in service, the transient is composed of

- An inrush component with a frequency determined by the two capacitor banks and the series reactances between them;

- An oscillation at a frequency determined by the two capacitor banks and the source inductance, L_s.

The high-frequency component due to the two capacitor banks and the inductances between the banks results in a transient that is significantly higher at the banks than at the main bus (Figure 14). To reduce the transient at the banks to arrester protection levels, the arresters must be placed as close to the capacitor bank terminals as possible.

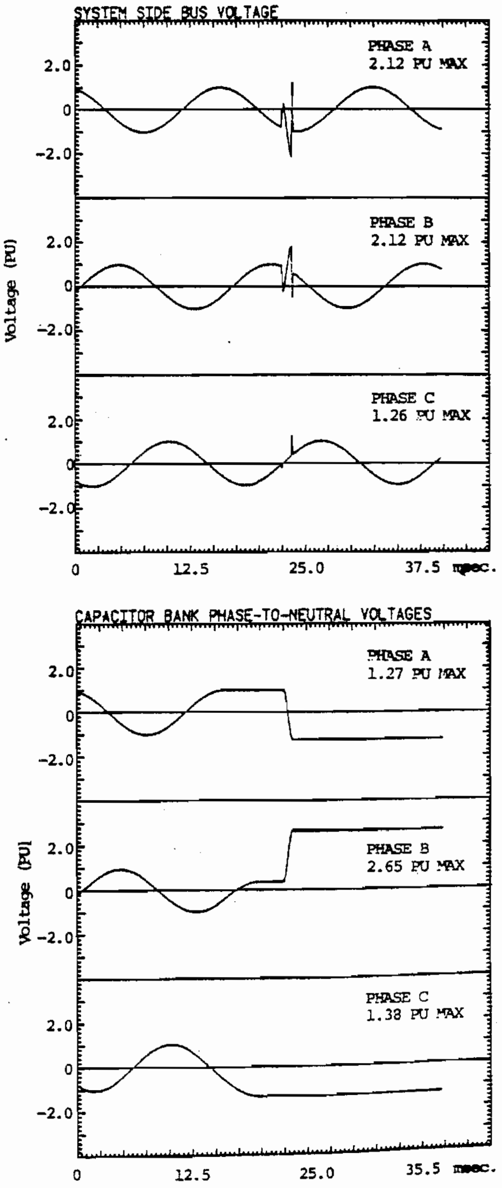


Fig. 13. Restrike on Phase A; Phase B delays opening

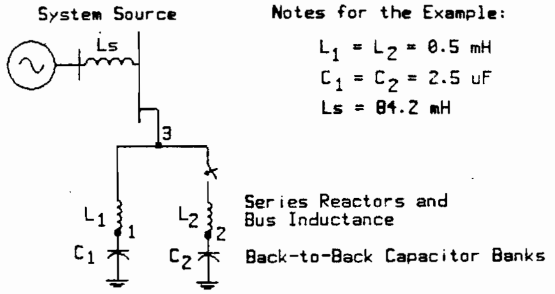


Fig. 14A. Equivalent circuit for back-to-back switching.

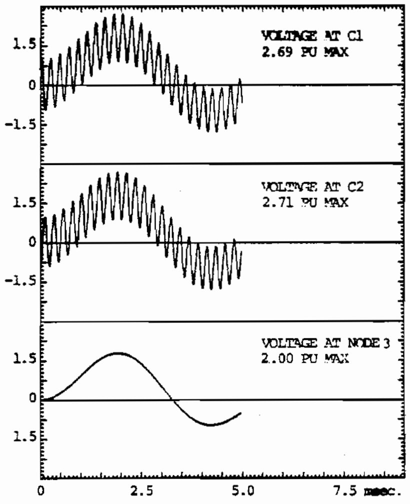


Fig. 14B. Waveforms: Back-to-back capacitor restrike.

Magnification of Transient Overvoltages

The worst transient overvoltages at a capacitor bank are not necessarily caused by switching the bank itself. Severe overvoltages can occur due to magnification of the voltage surge caused by switching a remote capacitor bank, cable, or transmission line; e.g., when a capacitor is switched on a high voltage system and magnification of the voltage surge occurs on an inductively coupled low-voltage system (Figure 15). The highest voltage magnification occurs when [10]

1. The natural frequencies of the two coupled inductive-capacitive circuits are equal; i.e.,

$$L_1C_1 = L_2C_2$$

and

2. The capacitive Mvar of the switched capacitor is significantly greater than the capacitive Mvar of the remote capacitor; i.e.,

$$(\text{Mvar } C_1) \geq 25(\text{Mvar } C_2)$$

Voltage magnification must be considered when evaluating the potential duty on arresters protecting a remote capacitor bank (Figure 15). If the arrester duty is a concern, the transient overvoltages can be reduced substantially by using closing resistors in the switching device for the higher-voltage capacitor bank, cable, or transmission line.

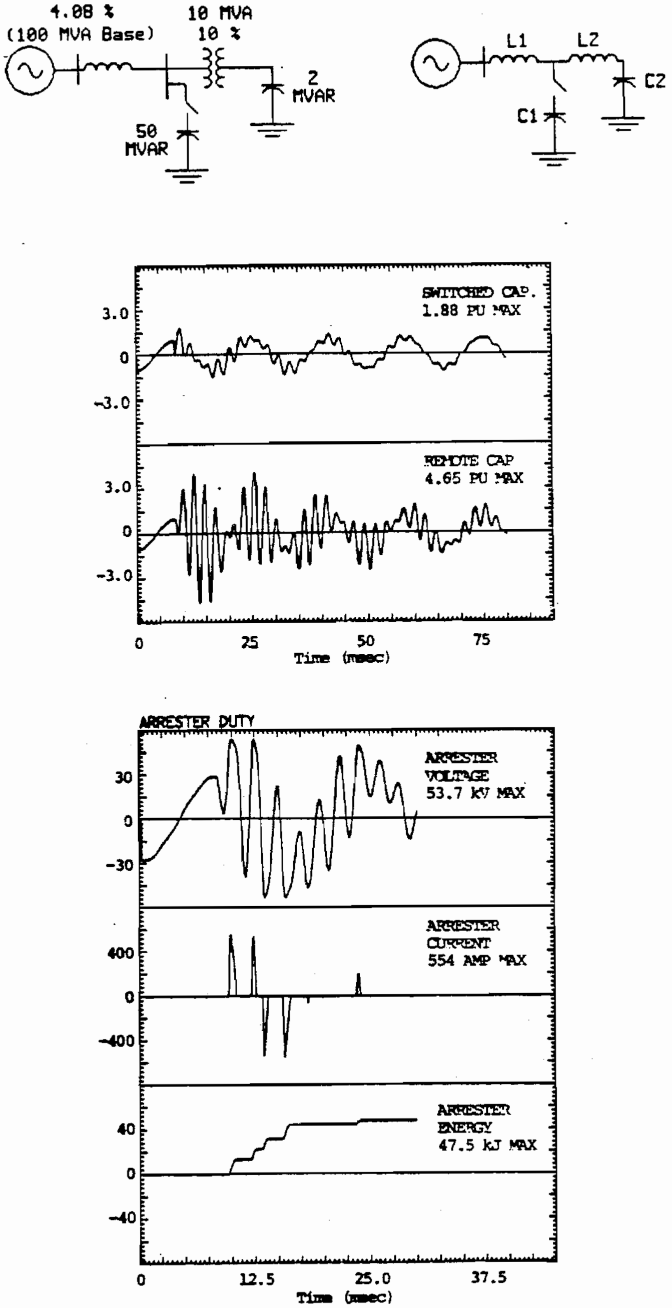


Fig. 15. Voltage magnification: Capacitor switching surge.

Dynamic Overvoltages

Energizing a transformer and a capacitor bank together (Figure 16) can cause exessive dynnamic overvoltages that affect the transformer, the capacitors, the fuses, and the arresters. If the capacitor causes a resonance near one of the harmonics in the transformer inrush current, significant overvoltages lasting for many cycles--even seconds--can occur at the harmonic frequency (Figure 16).

Because arresters cannot effectively protect against steady-state or dynamic overvoltages, switching transformers and capacitor banks together is not recommended unless detailed studies show that the resulting overvoltages will not be excessive.

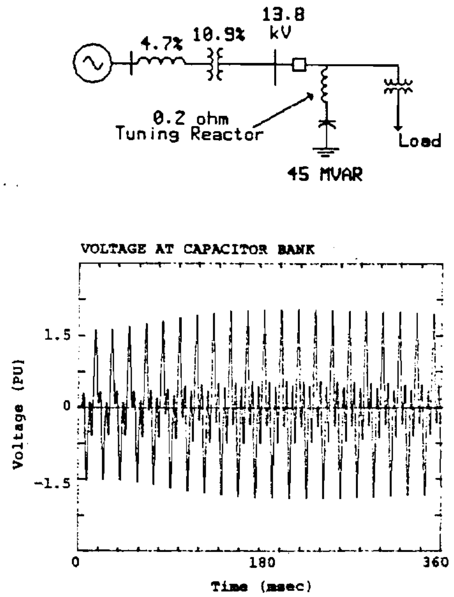


Fig. 16. Dynamic overvoltages.

CONCLUSIONS

Both lightning and switching surges must be evaluated when determining the requirements for overvoltage protection at shunt-capacitor banks. Long-duration overvoltages such as steady-state, harmonic, and dynamic overvoltages cannot be effectively controlled by surge arresters; these overvoltages must be limited by system design and operating procedures.

Protecting Shunt-Capacitor Banks from Lightning Surges

1. Arresters do not provide adequate protection for direct strokes. Good shielding of capacitor banks is required as it is for transformers.
2. For indirect strokes, MOV arresters provide better protection than SiC arresters because MOV arresters have higher energy-dissipation capability and lower discharge currents.
3. The MOV arrester duty resulting from a lightning surge is less severe for an arrester protecting a capacitor bank than it is for an arrester protecting a transformer. This is not true for a SiC arrester because of the capacitor discharge into the arrester when the gap sparks over coupled with the power-follow current.

Protecting Shunt-Capacitor Banks from Switching Surges

1. In general, the highest capacitor switching transients are associated with prestrikes or restrikes in the switching device. Surge arresters can limit both the capacitor transient and switch recovery voltages, but the arrester duty must be evaluated.
2. Worst-case analysis of MOV arrester duty for prestrike or restrike can be made with a fairly simple equivalent circuit and its associated equations.
3. For back-to-back or multiple capacitor banks, transient overvoltages can be significantly higher at the capacitor bank terminals than at the main bus in a switch prestrike or restrike. Surge arresters installed as close as possible to the capacitor bank terminals are required to limit these transient voltages to arrester protection levels.
4. Significant transient overvoltages can occur at capacitor banks due to magnification of the voltage surge associated with switching a remote capacitor bank, cable, or transmission line. The arrester duty must be evaluated if voltage magnification is a potential problem.

When properly sized for energy requirements, MOV arresters connected line-to-ground at a capacitor bank can protect a grounded-wye bank from both lightning and switching surges and an ungrounded-wye capacitor bank from lightning surges. An ungrounded-wye bank is best protected from switching surges by connecting the neutral of the MOV arresters to the neutral of the capacitor bank.

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Discussion

W. Watson, and **A. Narang** (Ontario Hydro, Toronto, ON, Canada): The authors have presented in a very clear and readable manner some of the consideration in the application of MOVs for overvoltage protection of shunt capacitor banks. However in our opinion it is equally as important to justify the need for such protection.

For protection against a lightning strike remote from the installation, the authors present calculated arrester duties for a 1 Coulomb surge on a 12 kV, 900 kVAr capacitor bank. Since one would expect such small capcitor banks to be applied only at small substations or on distribution feeders where effective shielding is not normally provided, the possibility of a close-in lightning strike may not be discounted. However the data provided in Tables I, II and III suggests that arresters could not survive the duty associated with a close-strike. Could the authors comment on this?

At larger substations supplying larger loads, effective shielding is normally provided. In this case, as the authors point out, a remote strike would deliver less than 2 Coulombs to the station. But capacitor banks installed at such larger substations would normally be of higher capacity in order to provide the required power factor improvement, and hence may not need surge protection. Considering as an example a typical 20 MVAr capacitor installation on Ontario Hydro's 13.8 kV system (sized to provide up to 5 percent voltage rise when switched-in), a lightning discharge of up to 3 Coulombs superimposed on 1 pu 60 Hz voltage peak could be absored without exceeding 2 pu voltage on the capacitor bank.

On the topic of switching surges, our experience over many years with large shunt capacitor banks (grounded and ungrounded) has shown that overvoltages due to restrikes are unlikely to exceed 2.5 pu/1/. We would question the need for surge protective devices to limit such surges since power equipment should normally be able to withstand such surges without any degradation in performance. In cases where surge limiting is nevertheless desired, or where restrikes could produce higher transient overvoltages as a result of one of the mechanisms described, metal-oxide arresters of multi-column design have been deemed necessary at the capacitor bank and at remote locations to provide adequate protection. In such instances, at current state of metal-oxide technology, restrike-free breakers have offered a more viable technical and economic alternative.

And finally it must be recognized that even in instances where transient voltage magnitudes are kept in check, the oscillatory nature of the waveshapes generated by capacitor switching can result in undue electrical stress on transformer windings [2,3]. High frequency transients ranging up to a few kilohertz can result at nearby transformer stations upon energizing capacitor banks. Although such waveshapes can also result from other events on the power system, the concern with capacitor banks is the potential increase is frequency of occurrence of such transients.

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Manuscript received February 21, 1984.

R. A. Jones and **K. R. Chakravarthi** (Southern Company Services, Birmingham, AL): The authors are to be congratulated on an informative paper. It summarizes many of the factors to be considered in the application of capacitor banks. Due to the large transients generated by the switching of ungrounded capacitor banks and due to the transient recovery voltages (TRV) imposed on the switching device, most large EHV capacitors in the past have generally been operated with solidly grounded neutrals. But with the advent of better switching devices that are capable of withstanding high TRV stress and metal oxide arresters capable of withstanding severe switching duty, the application of large EHV capacitors with ungrounded neutrals seems to be a viable choice. The ungrounded banks also minimize resonance problems due to certain harmonics. We would like to know if the authors consider the application of an ungrounded capacitor bank, adequately protected by an MOV arrester, as a better alternative to a grounded bank?

In the paper the authors mention the transient overvoltages resulting at remote locations on open-ended or transformer terminated lines due to prestrikes in the engergizing switch of the capacitor bank. These overvoltages can be both phase-to-neutral and phase-to-phase. The application of surge arresters, even if MOV type, may not necessarily reduce the phase-to-phase overvoltages to a level that can be safely withstood by three-phase equipment at the remote end. This is especially true if the three-phase equipment, such as a transformer, is purchased with a reduced BIL due to economic reasons. Closing resistors in the switching device, as suggested by the authors, is an excellent way to alleviate this problem. However, it must be pointed out that the optimum value for these closing resistors may be quite small in EHV circuits with large capacitor banks. This is due to the lower surge impedance of the circuit. The resistors must be properly selected to withstand the thermal duty. In our digital studies we have observed that phase-to-phase surges of considerable magnitude can also result at the location of the capacitor bank. Will the authors please comment on their study experience in this regard?

The authors recommend that surge arresters be connected from phase-to-neutral across an ungrounded capacitor bank to reduce the recovery voltages across the switching device and therefore, reduce the probabilities of multiple restrikes. They also state that a fourth arrester may be necessary to limit the neutral-to-ground component of the transient recovery voltage. There is another compelling reason to install an arrester from neutral-to-ground on an ungrounded capacitor bank. That is to protect the potential transformer. It is a common practice on the Southern electric system to install a potential transformer (PT) from neutral-to- ground on an ungrounded bank to provide overvoltage protection for the remainder of the capacitor units if some of the units fail. During the de-energerization of an ungrounded capacitor bank, the neutral of the bank may reach fairly high voltages if a restrike occurs or if mechanical asynchronism causes one pole of the switching device to be delayed in opening.[1]

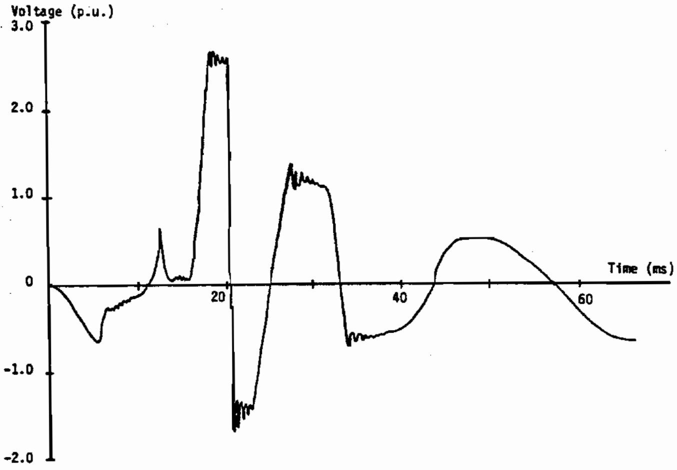

Figure 1-Capacitor bank neutral voltage

Figure-1 is a reproduction of a voltage oscillogram recorded during the de-energization of a 115kV, 36 MVAR capacitor bank at a substation in the Southern electric system. Since this voltage oscillation on the neutral was low frequency in nature, the 69kV non-resistive type PT was being subjected to severe overexcitation, which led to a failure of this PT. This problem can be solved by replacing the non-resistive type PT with a resistive type PT. The resistive type PT would not be as susceptible to overexcitation. However, a metal oxide arrester of a suitable rating connected across the non-resistive type PT can limit the capacitor bank neutral overvoltage and damp out the voltage oscillations. Thus, the PT in the neutral will be protected. A silicon-carbide arrester would probably not be able to withstand the energy discharge which would be imposed on it.

As mentioned previously, the paper recommends that metal oxide arresters be connected phase-to-neutral on an ungrounded capacitor bank to limit trapped charge and therefore, reduce recovery voltages. Do the arresters also serve another purpose? Are they needed to protect the capacitor from overvoltages which may be trapped on it? The industry standard for shunt power capacitors (IEEE Std. 18-1980, Section 8.3.2.3) gives guidance on the peak transient voltages that a capacitor may resonably be expected to withstand. However, when restrikes occur during the de-energization of capacitors, high values of voltage may be trapped on the capacitors. This would not be considered a transient voltage because it would take several minutes for the voltage to decay. It would be more like a DC voltage on the capacitor rather than a transient voltage. Would the authors care to comment on the necessity of surge arresters to protect the capacitor from the effects of overvoltages which may become trapped on it?

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Manuscript received February 23, 1984.

J. P. Skliutas (General Electric Company, Schenectady, NY): It is important to note that system grounding can have a large impact upon arrester duty and should be included in the analysis. This aspect becomes particularly important when considering the case of breaker restrike while clearing a bank with a single phase fault. This case is of great interest due to the fact that single phase faults occur most frequently. Should an unfaulted phase clear first, the highest transient recovery voltage (TRV) is experienced and presents the greatest chance for restrike. The TRV and subsequent arrester duty upon restrike increases as the zero sequence impedance or X_0/X_1 ratio as seen from the bank increases. This is due to higher and higher trapped charge on the unfaulted phases. The following example will bear out this relationship.

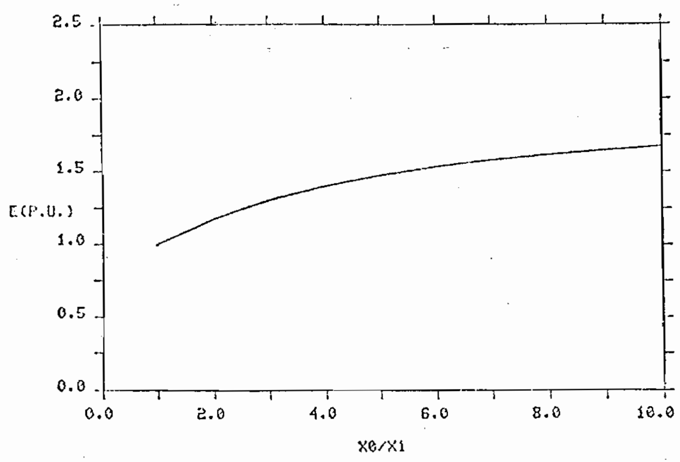

Fig. 1 Relative arrester energy as a function of system grounding.

Figure 1 shows relative arrester energy as a function of system grounding. For this analysis, the system voltage, capacitor bank, positive sequence equivalent inductance and arrester protective level are constant. The capacitor is protected to 1.7 times line-to-ground crest voltage. A single phase restrike on this bank with a perfectly grounded system ($X_0/X_1 = 1$) results in 1.0 per unit energy. Typically EHV systems are effectively grounded ($x_0/x_1 = 3$) and if there is no local transformer with a tertiary winding, the arrester energy can be about 30 percent higher than the base case. In addition, the duration of arrester current increases significantly as system inductance increases.

These items can have significant influence upon arrester design. Typically it leads to a multiple column design to handle either or both the extra energy or longer current conduction.

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J. E. Harder (Westinghouse Electric Corp. Bloomington, IN): The authors are to be commended for their publication of this timely paper discussing the application of metal oxide arresters in connection with shunt capacitor banks. This subject has received considerable discussion in recent months in connection with the application of large capacitor banks at transmission voltage. The following remarks focus principally on the application of metal oxide arresters with these high voltage shunt capacitor banks.

The gapless metal oxide arrester is much superior to the former gap type silicon carbide arrester for application in connection with capacitor banks. As early as 1978 this benefit was being exploited (1). Some of the restrictions required in the application of silicon carbide arresters are not required with the new metal oxide arrester, leaving the way open for some innovations in these applications.

There are some considerations, in addition to those already capably covered by the authors, which may affect this kind of application.

First, most of these large high voltage shunt capacitor banks do not require arrester protection for the capacitors beyond what already exists in the substation. Most of the recent installations are grounded wye banks within shielded substations that have existing arresters at least at the transformers, and often on the bus sections and line entrances. The wave sloping effect of the grounded capacitor will insure that the voltage at the capacitor is very close to the same as the voltage at the arrester. An 80 percent arrester with a protective level of 1.6 per unit on an arrester base will provide a voltage at the capacitor of less than 2 per unit. Based on the application guide in capacitor standards (2), capacitor units should be able to withstand about 3.5 per unit, at least 4 times per year. Where arresters already exist on the bus, additional arresters are not usually required to provide adequate protection for the grounded wye capacitor bank.

For ungrounded wye banks there is an additional consideration of the neutral to good insulation. Where the neutral to ground insulation is the same as the bus insulation, neutral arresters are not required to protect the netural to ground insulation. On many occasions users have applied reduced voltage potential transformers or potential devices at the neutral for use with the unbalanced protection. For many of these applications gaps or arresters have been applied quite satisfactorily to protect this reduced voltage insulation. Certainly the application of metal oxide arresters in this application is very desirable, being somewhat less subject to damage from high capacitor discharge currents than conventional arresters or gaps.

For ungrounded wye banks, phase to neutral arresters are not normally required to insure satisfactory bank performance. There are many ungrounded wye capacitor banks in service at all voltages without phase to neutral arresters with quite excellent service. The normal switching and lightning overvoltages are well within the capability of the capacitors suggested by industry standards.

If a superior protection of the capacitor equipment is desired, then an attractive alternative is to place a metal oxide arrester accross each series group of the capacitor equipment. Such an arrester will protect the capacitor bank not only against system imposed overvoltages, but also against overvoltages which may be generated by occurrences within the bank, i.e., fuse malfunction, fuse normal recovery voltages, partial short circuiting of the capacitor bank, etc. While placing the arresters across each series group may require a few more individual arrester units, it does remove the requirement for a separate support insulator and foundation.

The comments so far have dealt with the use of metal oxide arresters for the protection of the capacitor against overvoltages. There is also a consideration of the protection of the system against high discharge currents from a capacitor charged to an excessive voltage. Some users have chosen to apply metal oxide arresters with a very low protective level to reduce the vulnerability of other arresters on the bus or other equipment. This application must be made carefully since, for instance, the low sparkover of an existing arrester may cause an excessive current through it because of its relatively low discharge voltage, even when the protective level of the metal oxide arrester is lower than the guaranteed protective level of the gapped silicon carbide arrester.

For protection of the system against damage from an ungrounded capacitor bank, phase to phase arresters will provide for better protection than phase to neutral arresters. While the phase to phase arrester may not protect the capacitor as well (the capacitor usually has ample margin), it will reduce the maximum phase to phase voltage driving a transient current into the system and help limit the maximum phase to phase voltage appearing at transformers, etc.

Summarizing, while the advent of metal oxide arresters *permits* some new innovations in the application, in general these innovations are not required to provide adequate protection for today's capacitors. Today's metal oxide arresters are expected to provide quite adequate protection when applied as they had been for transformer protection, bus protection, and line and protection; without any requirement for special arresters at the capacitor banks. Arresters across each series group for capacitor protection or phase to neutral or phase arresters will likely be the exception rather than the rule. For these exceptional applications, the suggestions made by the authors in the paper are a valuable contribution.

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Manuscript received February 27, 1984.

M. F. McGranaghan and **W. E. Reid:** We appreciate the very worthwhile contributions made by each of the discussers. These contributions enhance the value of the paper significantly. We will try to address the questions raised on a point by point basis.

Messrs. Watson and Narang had a number of comments which dealt with justifying the need for arrester protection at capacitor banks. As indicated in the paper, arrester requirements should be evaluated based on concerns for both lightning and switching transients.

We agree that arresters are not generally required for lightning protection at large substation capacitor banks, connected line-to-ground, where effective shielding is provided. Lightning protection is most important for small capacitors located on distribution feeders. The paper illustrates that the energy storage capability of the capacitor reduces the metal oxide varistor [MOV] arrester duty for a lightning transient. However, even at capacitors and even with the increased energy ratings of MOV arresters, the arresters should not be expected to survive a direct stroke. Reliable protection for direct strokes can only be obtained by shielding.

A number of switching concerns can result in the need for arrester protection at capacitors. These concerns include magnification of transients cause by remote capacitor switching and overvoltages due to prestrikes or restrikes of the switching device. The discussers indicate that overvoltages due to restrikes are unlikely to exceed 2.5 pu. It should be noted that overvoltages of this magnitude may be unacceptable for a couple of reasons:

1) The 2.5 pu overvoltage can cause sparkover and possible damage of existing arresters if they are not designed for the required energy duty.
2) The overvoltage resulting from a restrike is likely to be left on the capcitor as a trapped charge, decaying with a time constant on the order of 40 seconds due to dicharge resistors. Depending on the frequency of occurence, this may cause capacitor damage and possible failure. MOV arresters can generally limit the overvoltage and corresponding trapped charge to approximately 2.0 pu. Also, the arresters must be connected line-to-neutral on an ungrounded capacitor bank to a accomplish this objective.

If a switching device were truly restrike-free, it would not be necessary to design for this case.

The discussers raised another concern for switching capacitor banks which does not really involve the need for protection at the capacitor itself-the possibility of high frequency oscillations at nearby transformers. The concern exists when a transformer terminates one of the lines emanating from the capacitor station. This is a potential problem for two reasons:

1) The frequency of oscillation can be high enough to cause internal resonance conditions in the transformer. The frequency is a function of the line length between the capacitor and the transformer.
2) The oscillations can cause high phase-to-phase overvoltages at the transformer, exceeding the phase-to-phase withstand strength. Line-to-ground arresters at the transformer do not necessarily limit phase-to-phase transients to acceptable levels.

The high frequency transients and the phase-to-phase overvoltages can be limited with circuit breaker closing resistors (low ohmic values are required) or with series reactors at the capacitor bank.

Messrs. Jones and Chakravarthi asked for a general comment regarding the application of grounded capacitors vs. ungrounded capacitors. Obviously, the evaluation of grounded vs. ungrounded capacitor connections will be dependent on the particular application. However, the major differences and concerns for each connection can be summarized to facilitate the evaluation:

1) Circuit Breaker Requirements. The transient recovery voltage associated with deenergizing an ungrounded capacitor is more severe than for a grounded capacitor and can result in increased costs for the switching device.
2) Harmonics. Capacitor banks can result in resonant conditions which magnify harmonic currents generated by transformers or nonlinear loads. An ungrounded connection prevents the magnification and flow of zero sequence harmonic currents but does not affect the positive sequence resonance. The effect of capacitor connection on harmonic resonance is very situation specific.
3) Arrester Energy Duties. The effect of capacitor connection on MOV arrester duties is given in the paper (Figure 9). Arresters at ungrounded banks have somewhat lower energy requirements for a switch restrike.
4) Other Concerns. Ungrounded capacitor banks will not discharge into a single line-to-ground fault. This may be a factor in evaluating capabilities of existing breakers to withstand outrush current.
5) Capacitor Bank Design. The connection may effect the fusing required for the bank as well as the neutral insulation requirement. These effects will vary from application to application.

All of these concerns should be considered in each case to determine the best connection.

The discussers mention that high phase-to-phase transient overvoltages can occur at the capacitor location, as well as at remote transformer (discussed above). The phase-to-phase transients at the capacitor location should be considered in specifying switching devices for the capacitor bank; closing resistors of appropriate size may be the only method of adequately controlling these overvoltages. The phase-to-phase transients should be evaluated with respect to transformer withstand capabilities.

The discussers provided an interesting example of a ferroresonant overvoltage across a neutral PT. An arrester connected neutral-to-ground on an ungrounded capacitor bank serves two purposes-it limits switch transient recovery voltages in the event of a restrike and it protects neutral monitoring equipment for unbalanced protection. A neutral arrester would not necessarily provide adequate protection for the ferroresonant condition which can result if there is a neutral PT and the capacitor switch opens or closes with any significant pole asynchronism.

Mr. Skliutas raised a very important point regarding the worst case energy duty which an arrester located at a capacitor bank must be able to withstand. If the XO/Xl ratio at the capacitor bus is greater than one, the worst case recovery voltage and restrike arrester duty will be associated with clearing a single line-to-ground fault. This is due to the higher 60 Hz voltages on the sound phases during the single line-to-ground fault. Although this case is less likely to occur than normal deenergizing at a switched bank, it still should be considered in sizing the arresters.

Mr. Harder provided a number of valuable comments regarding the need for arrester protection at capacitors. We would agree that phase-to-neutral arresters are not needed to protect ungrounded-wye capacitors during normal switching. However, they do provide better protection in the event of a breaker or switch restrike. Maximum trapped charge left on the capacitor is the limiting concern.

Mr. Harder also mentions that superior protection can be obtained by placing MOV arresters across each series group of the capacitor equipment. The arresters in this configuration must be sized to withstand the 60 Hz overvoltage which will occur when a unit fails, i.e. until the fuse clears. For example, in the case of a two series group grounded wye capacitor bank, a short in one series group will result in 200 percent 60-Hz voltage in the other series group. The capacitor bank should be designed so that this fault is cleared before the arrester fails (this would typically be less than 3 cycles).

Arresters connected phase-to-phase provide better protection against phase-to-phase overvoltages at transformers, as indicated by Mr. Harder. This is a viable method of protecting transformers from overvoltages such as those discussed above—the phase-to-phase transient can be limited to approximately 3.4 pu. Phase-to-phase connected arresters do not provide better capacitor protection. The best capacitor protection is always achieved by connecting the arresters directly across the capactiors being protected.

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