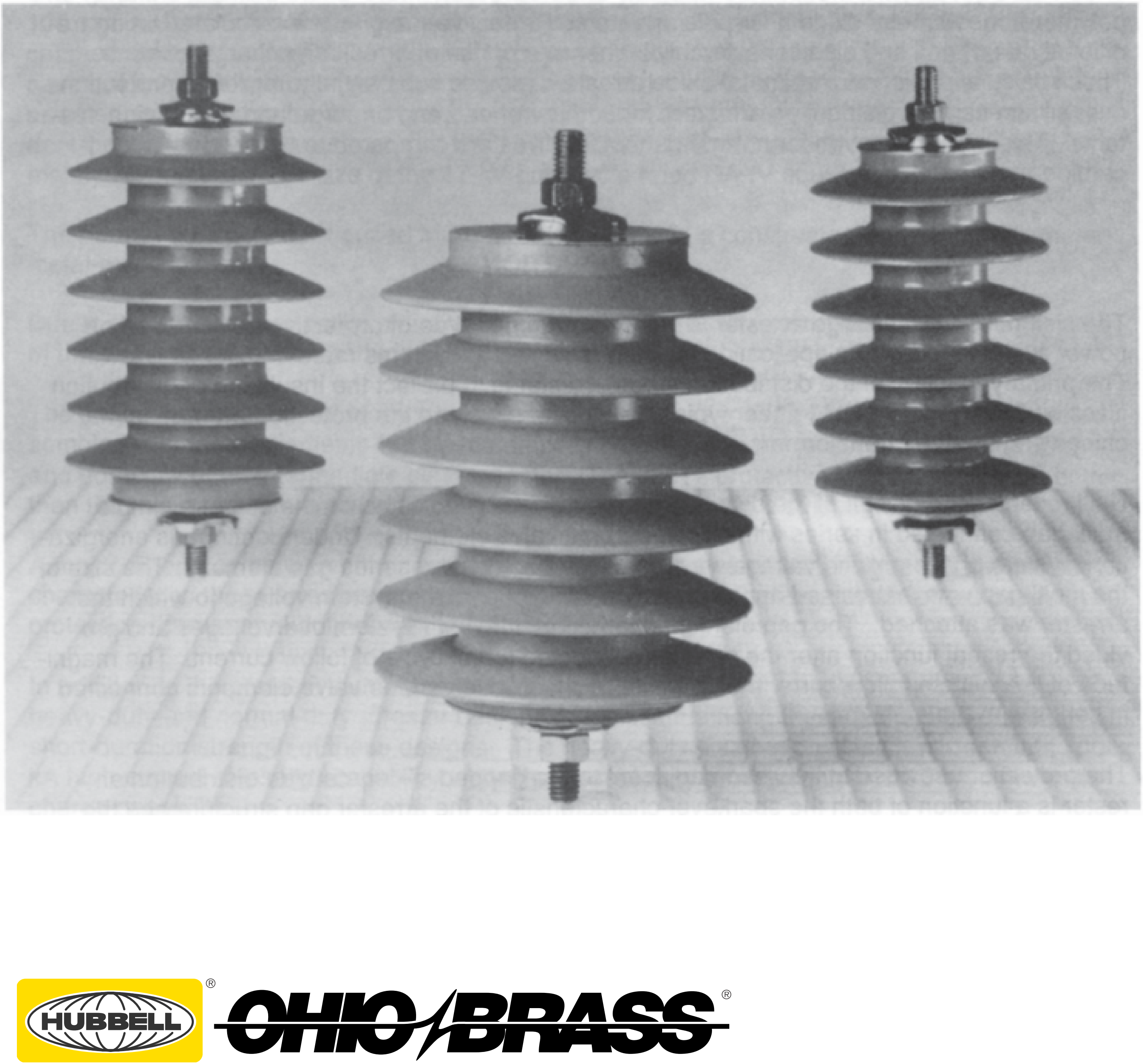
METAL-OXIDE SURGE ARRESTER PROTECTION OF DISTRIBUTION SYSTEMS



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Abstract - Distribution systems traditionally have been protected with silicon-carbide distribution arresters. Even though large protective margins for overhead equipment and adequate margins for underground equipment appears to exist, a significant number of equipment failures do occur.

This paper compares the protection of overhead and underground distribution equipment with silicon-carbide, polymer-housed normal-duty and heavy-duty metal-oxide distribution, and polymer-housed metal-oxide riser-pole arresters. Protective margins are calculated using traditional rate of rise and also considerably higher rate of rise of arrester discharge current. These calculations show that metal-oxide arresters provide substantially improved protection over silicon-carbide distribution arresters for both overhead and underground distribution systems. This holds true even for normal-duty MOV arresters compared to heavy-duty silicon-carbide arresters.

INTRODUCTION

The distribution class surge arrester is the most common type of protective device used on power systems today. Its application typically is limited to systems rated 34.5-kV and lower. The primary function of the distribution surge arrester is to protect the insulation of distribution class oil-filled transformers. Other typical applications include the protection of rotating machines and dry-type transformers.

Until recently, the design of the distribution arrester was predicated on the use of a simple multi-gap connected in series with silicon-carbide valve elements. Under continuous energization, system phase-ground voltage was maintained across the series gap element. The size of the multi-gap was maintained approximately proportional to the system voltage to which the arrester was attached. The gap element sparked over to limit system overvoltages and provided the reseal function after the arrester conducted a half cycle of follow current. The magnitude of the system follow current was limited by the silicon-carbide valve elements connected in series with the multi-gap.

The protection provided to insulation adjacent to the gapped silicon-carbide distribution arrester is a function of both the sparkover characteristic of the arrester gap structure and the discharge voltage characteristic of the silicon-carbide valve elements.

The intent of this paper is to examine the improved protection provided for distribution system insulation by polymer-housed metal-oxide surge arresters. The advantages of the metal-oxide design are discussed. In addition, both overhead and underground applications are examined, and comparisons are made between gapped silicon-carbide and gapless metal-oxide arrester protection.

THE METAL-OXIDE ALTERNATIVE

Three types of Ohio Brass polymer-housed metal-oxide arresters are available for application on distribution systems. They may be used on overhead lines to improve existing protective margins, or on riser-poles adjacent to underground distribution circuits that cannot be adequately protected by conventional silicon-carbide arresters.

One type is a gapless heavy-duty distribution class surge arrester, the DynaVar Type PDV-100, constructed with 40-mm diameter metal-oxide discs. The PDV-100 has lower protective characteristics than the DA-IV heavy-duty gapped silicon-carbide distribution arresters. Because of the excellent energy-absorbing capability of the metal-oxide material, the PDV-100 arrester units are smaller than equivalent sizes of the DA-IV. The size differential is most evident on the large-size units, such as the 22-kV MCOV PDV-100 arrester, which is approximately 75 percent of the size of the 27-kV duty cycle rated DA-IV equivalent.

The normal-duty polymer-housed MOV arrester, PDV-65, is constructed with 32-mm diameter metal-oxide discs.

Due to the superior protective characteristics of the PDV-65 it is compared throughout the rest of the paper to the silicon-carbide DA-IV arrester.

The polymer-housed metal-oxide riser-pole arrester, DynaVar Type PVR, in the study is assembled with larger-diameter 48-mm metal-oxide discs. It has the protective characteristics and durability of an intermediate class arrester. The PVR's protective characteristics are better than those of both conventional silicon-carbide and metal-oxide distribution arresters.

A major difference between the normal-duty and heavy-duty arrester designs are the protective characteristics these arresters possess. The heavy-duty distribution arrester offers better protection than normal-duty distribution arresters.

In addition to the protective characteristics there is also a difference in the durability of the heavy-duty and normal-duty arrester designs. Significant among these is the high-current short-duration strength of these designs. The heavy-duty distribution class arrester has a 100-kA high-current discharge capability while the normal-duty arrester only has 65-kA current discharge capability.

METAL-OXIDE ARRESTER APPLICATION

Figure 1 lists several distribution-system voltages and identifies the smallest standard metal-oxide arrester sizes available for application on each system, depending on the grounding effectiveness. Note that for an effectively grounded neutral system, the arrester with a maximum continuous operating voltage (MCOV) greater than or equal to the maximum line-to neutral voltage is the recommended application. For noneffectively grounded systems where high voltages of longer duration can occur on unfaulted phase arresters, larger arrester sizes are required. For this condition, the arrester's overvoltage capability is utilized. The 11 percent overvoltage capability (1.11 times MCOV for 2000 hours) and 23 percent overvoltage capability (1.23 times MCOV for 30 minutes) of the metal-oxide designs allow minimization of arrester protective levels while still maintaining arrester thermal stability during noneffectively grounded system fault conditions.

The above holds true for both the heavy-duty and normal-duty designs.

ADVANTAGES OF METAL-OXIDE ARRESTERS OVER CONVENTIONAL SILICON-CARBIDE DISTRIBUTION CLASS ARRESTERS

The advantages of the polymer-housed metal-oxide varistor (MOV) arrester designs over the conventional silicon-carbide distribution arrester are described below.

Improved Temporary-Overvoltage Capability

When subjected to temporary power-frequency overvoltages, the high-exponent metal-oxide arrester conducts significantly less current than a comparably rated silicon-carbide distribution class arrester. If the silicon-carbide arrester is subjected to an overvoltage condition and simultaneously is forced to spark over, the integrity of the arrester is dependent on the ability of the multi-gap design to successfully interrupt the high power follow currents associated with the overvoltage condition. If the arrester is not able to reseal against the overvoltage condition, failure occurs within a few cycles.

In contrast, at every voltage level, the high-exponent MOV design conducts significantly less current than does the silicon-carbide equivalent. Even though the MOV arrester might begin to heat up due to the increased flow of current through the arrester, in most cases the current levels are low enough that thermal stability is maintained when normal system voltage levels are returned.

Improved Surge-Duty Capability

The high-exponent characteristics of the MOSA design allow the arrester to conduct less than one ampere of follow current after an impulse discharge when energized at equivalent rated voltage. In contrast, the silicon-carbide arrester conducts over 100 amperes of follow current when forced to spark over with rated voltage applied. Therefore, the MOV arrester is not subject to restriking failure that the silicon-carbide arrester may experience at normal operating voltages.

In addition, the MOV arrester has much better multiple-surge-withstand capability than a comparably rated silicon-carbide arrester. The MOV arrester is more suitable than the distribution class silicon-carbide arrester for withstanding the duty associated with high-energy capacitor bank or cable applications.

Improved Contamination Performance

This advantage is most prevalent on higher ratings where the silicon-carbide distribution class arrester is most vulnerable to the influences of contamination, which can cause substantial reduction in sparkover. The gapless MOV arrester is immune to internal problems from external contamination.

Simpler Design with Fewer Parts

An examination of cutaway sections reveals the simpler internal construction of the PDV-100 and PVR designs compared to the DA-IV (Figure 2). The design of the normal-duty polymer is similar except for smaller block and housing diameters.

Resistance to Leaking and Safe Failure Mode

The major cause of arrester failure is moisture ingress. The Ohio Brass polymer-housed arrester makes it nearly impossible for moisture to enter the unit so failures due to leaking are eliminated.

In the extremely unlikely event of an arrester failure due to system conditions the polymer-housed PDV-100 and PVR arresters incorporate fault current withstand capabilities ranging from 20-kA for 10 cycles to 500 amps for 90 cycles for the PVR and 120 cycles for the PDV-1 00 arresters.

The polymer housed PDV-65 arrester has fault current withstand capabilities from 1 0-kA for 10 cycles to 500 amps for 120 cycles.

Improved Protective Characteristics

The remainder of this paper is concerned with the protective characteristics of polymer-housed metal-oxide arresters compared with equivalently sized silicon-carbide arresters. Specific overhead and underground applications are examined, comparing the standard arrester characteristics and examining the advantages of metal-oxide over silicon-carbide designs.

Comparison of Protective Characteristics

Figure 3 compares the standard catalog protective characteristics of the DA-IV silicon-carbide distribution arrester, the PDV-100 heavy duty arrester, the PDV-65 normal-duty arrester, and the PVR riser-pole arrester. In addition to front-of-wave sparkover for the gapped DA-IV design, 0.5-microsecond 10-kA IR also is included in this protective characteristics comparison. Three typical distribution system voltages are examined: 13.2, 24.9 and 34.5-kV.

Notice the normal-duty MOV PDV-65 arrester gives equal or superior protection when compared to the heavy-duty DA-IV unit in nearly all cases.

For insulation-coordination purposes, the arrester front-of-wave characteristic historically is compared with the transformer's chopped-wave strength. Similarly, the BIL protective margin is derived from the transformer BIL strength and the higher of either the 1.2/50 impulse sparkover or the 8/20 discharge voltage, typically for 10- or 20-kA surges. For this study, the 10-kA discharge voltage level is used.

For the 13.2-kV system the 8.4-kV normal-duty PDV-65 arrester front-of-wave and impulse levels are 8 percent and 20 percent lower, respectively than the levels of the 10-kV DA-IV arrester.

The 8.4-kV heavy-duty, PDV-100 arrester's front-of-wave and impulse protective levels are 20 percent and 30 percent lower, respectively, than those of the 10-kV DA-IV arrester. Even better insulation protection is provided by the 8.4-kV PVR arrester with 40 percent lower protective levels than the 10-kV DA-IV arrester. These arrester sizes are equally applicable to 13.8-kV systems.

For the 24.9-kV system, the 15.3-kV MOV normal-duty PDV-65 arrester provides 12 percent lower front-of-wave and 1 percent lower impulse protection than the equivalent 18-kV heavy-duty silicon-carbide DA-IV.

The 15.3-kV MOV PDV-100 arrester provides 22 percent lower front-of-wave and 10 percent lower impulse protection than the equivalently sized 18-kV DA-IV silicon-carbide arrester. The 15.3-kV MOV PVR arrester provides 41 percent lower front 28 percent lower impulse protective levels than the 18-kV DA-IV silicon-carbide arrester.

For the 34.5-kV system, the 22-kV PDV-65 and PDV-100 MOSA and 22-kV PVR riser pole arresters provide protective-level reductions similar to those described for the 24.9-kV system.

OVERHEAD DISTRIBUTION PROTECTION

First, let's examine the application of arresters to overhead distribution systems. Figure 4 lists a comparison of three distribution system voltages, their applicable BIL levels, and the corresponding arresters used on each system. For example, the 24.9-kV system typically is designed for either 125 or 150kV BIL and is protected by 1 8-kV conventionally rated silicon-carbide arresters or by 15.3-kV MCOV metal-oxide arresters.

The important point to note is that, as the system voltage increases, the size of the arrester used on that system increases proportionately. For example, the 24.9-kV system is 1.9 times larger than the 13.2-kV system, and the size of the corresponding arrester increases 1.8 times. However, depending on the specific applications, the BIL levels typically do not increase proportionately as the system voltage increases. Therefore, as the system voltage increases, the protective margins offered by the surge arresters typically decrease.

Before looking at specific examples, we should point out that the minimum acceptable protective margin on distribution chopped-wave and BIL insulation strength is typically 20 percent. In the analysis that follows, calculated protective margins for overhead lines of 100 percent are quite common. In spite of many nominal protective margins exceeding 100 percent, an estimated 100,000 transformers fail each year due to insulation failure at an estimated cost to the industry of $35 million.

The question arises, "Why are so many transformers failing?"

Figure 5 lists some factors that can influence the effective protective margin that exists on an overhead distribution transformer.

First, studies have shown that the BIL of a transformer can be lowered by aging and loading effects. A 20 percent reduction in the BIL strength is quite possible, reducing the effective BIL protective margin.

Second, an area of concern is the expected rate of rise of a lightning discharge. The calculated margin for BIL assumes an 8/20 lightning discharge. Lightning studies indicate that stroke currents significantly faster than the assumed 8/20 waveshape are very probable. In fact, one study reveals that over half of the recorded strokes had rates of rise approximately three times faster than expected. In addition, 15 percent of the recorded strokes had recorded times to crest of one microsecond or less (7, 8).

Third, a factor affecting protective margins is the lead length voltage drop, L di/dt. The rule of thumb is to assume a lead voltage of 1.6-kV per foot of lead length, which is added to the arrester discharge voltage. This assumes a lead inductance of 0.4 microhenries per foot and a linear rate of rise for the current wave of 4-kA per microsecond. Although this is conservative for a standard 1 0-kA 8/20 wave, higher lead voltages could result for faster current rates of rise and higher current magnitudes (1, 5).

Figure 6 illustrates one advantage of the metal-oxide arrester over a conventional silicon-carbide design. When subjected to faster-than-normal rates of rise of current, the metal-oxide design exhibits a slower rate of discharge voltage turnup. For these curves, the 8/20 discharge voltage levels for both a metal-oxide and a silicon-carbide disc have been normalized at the 10-kA, 8/20 discharge current level. For a three-times-faster rate of rise of current, the silicon-carbide discharge voltage level increases approximately 20 percent while the metal-oxide voltage level increases only 10 percent. This effect is used in the upcoming examination of protective margins for 13.2, 24.9, and 34.5-kV systems.

Figures 7 through 11 have been developed to allow an examination of calculated protective margins and how these margins are affected by faster rates of current rise, BIL reduction due to aging and overloading, and variations in arrester protective characteristics as a function of the rate of rise of the current discharges. Note that in all the calculations the effect of lead length voltage drop, L di/dt, has been neglected. As mentioned before, lead drop can be significant, particularly if faster rate-of-rise discharges are considered.

Figure 7 examines the protective margin variations for a 13.2-kV overhead distribution system with 95-kV BIL and 110-kV chopped-wave insulation levels. The first two conditions show protective margins afforded by a 10-kV silicon-carbide DA-IV arrester.

Condition 1 assumes full insulation strength and standard voltage and current rates of rise. This yields excellent chopped-wave and BIL protective margins of 124 percent and 111 percent, respectively.

Condition 2 assumes both a 20 percent BIL reduction and a three-times-faster rate of rise. Chopped-wave and BIL margins are reduced to 96 percent and 69 percent, respectively, without any consideration for lead length voltage drop.

Conditions 3 and 4 examine an 8.4-kV MCOV heavy-duty PDV-100 MOV arrester application and correspond to Conditions 1 and 2, respectively, for the 10-kV DA-IV silicon-carbide arrester.

The full insulation and standard rate of rise in Condition 3 yield margins around 200 percent. The three-times-faster rate of current rise in Condition 4 results in a 10 percent increase in the 10-kA discharge voltage level of the metal-oxide distribution arrester, compared to 15 to 20 percent increase for the silicon-carbide design. For Condition 4, which also includes a 20 percent BIL reduction, the chopped-wave and BIL margins are 172 percent and 114 percent respectively.

Conditions 5 and 6 relate to the normal-duty PDV-65 MOV arrester. They show the PDV-65 MOV arrester gives superior protection under the same circumstances applied to the heavy-duty DA-IV arrester. The margins for the PDV-65 MOV are 141 and 90 respectively under the most severe conditions shown.

Conditions 7 and 8 of Figure 7 examine the protection afforded by the 8.4-kV MCOV PVR metal-oxide riser pole arrester under conditions similar to those described for the 8.4-kV MCOV PDV-100 heavy-duty MOV arrester. Under standard conditions, the 8.4-kV PVR arrester provides 286 percent margin for chopped-wave and 258 percent for BIL. Assuming the three-times-faster rate of rise and 20 percent BIL reduction, the 8.4-kV PVR arrester still provides 246 percent and 158 per-wave and BIL margins, respectively.

For the 13.2-kV system, the 10-kV DA-IV, the 8.4-kV PDV-65 and the PDV-100 metal-oxide arresters provide more than adequate protective margins, even when the effects of insulation aging and faster rates of rise are included. However, for higher-voltage distribution systems, the effects of aging and faster rates of rise can produce much lower protective margins. The improved short-time characteristics of the metal-oxide arresters can be utilized to maintain adequate margins. Also, lead length effects will influence protective margins.

Figure 8 examines protective margin variations for a 24.9-kV overhead distribution system with 125-kV BIL and 145-kV chopped-wave insulation strength. Comparison of Condition 1 (full BIL insulation and standard rate of rise) with Condition 2 (20 percent BIL reduction and three times-faster rate of rise) reveals that the 18-kV rated, DA-IV arrester's protective margin is reduced to a marginal condition, neglecting line lead drop.

In comparison, the 15.3-kV MCOV PDV-100 distribution arrester provides 93 percent chopped-wave and 52 percent BIL margins under the above worst-case conditions. Even the PDV-65 arrester gives 73 percent chopped-wave and 36 percent BIL margins under the worst case conditions. As expected, even better protection is provided by the 15.3-kV MCOV PVR arrester.

Figure 9 examines the protective margin variations for a 34.5-kV overhead distribution system with 200-kV BIL and 230-kV chopped-wave insulation levels. The first two conditions are similar to those discussed for Figures 7 and 8. This time, protection is provided by a 27-kV DA-IV silicon-carbide arrester. Note that the BIL protective margin is reduced from 108 percent to 39 percent as a result of a 20 percent reduction in BIL strength and the effects of a three-times-faster rate of rise.

The improved protective characteristics of the 22-kV MCOV PDV-65, PDV-100 and PVR arresters show greater protective margins under the worst case conditions.

Figure 10 examines the 34.5-kV system with lower insulation levels of 150-kV for BIL and 175-kV for chopped wave. For the same 27-kV silicon-carbide DA-IV arrester, the BIL protective margin is reduced from 56 percent to 4 percent as a result of insulation aging and faster rate-of-rise effects.

Advantage can be taken of the 22-kV MCOV PDV-100 and PVR arresters short-time characteristics. For these arresters the BIL protective margin decreases from 67 percent to 21 percent and 108 percent to 50 percent, respectively. The PDV-65 MOV arrester BIL protective margins in this case reduces from 52 percent to 10 percent. For this insulation level, adequate protection can be furnished by PDV-100 and PVR metal-oxide designs.

Figure 11 shows the 34.5-kV system with even lower insulation levels of 1 25-kV for BIL and 1 45-kV for chopped-wave. The BIL protective margin when using a heavy-duty DA-IV arrester for standard conditions is only 30 percent. Including the effects of either the reduced insulation due to aging or faster rates of voltage rise causes the BIL margin to reduce below the minimum 20 percent level. Even the 22-kV PDV-100 arrester provides only a one percent protective margin under the worst scenario.

However, the 22-kV PVR arrester has a 74 percent BIL margin for standard conditions. The effects of aging and faster rates of rise still show this arrester to have an adequate BIL margin of 25 percent.

UNDERGROUND DISTRIBUTION PROTECTION

Another important arrester application is protection of underground distribution circuits and the equipment connected to these circuits. Cable circuits traditionally are protected with arresters at the riser-pole to prevent lightning surges from damaging the cable terminator, the cable, or the connected equipment. Either silicon-carbide or metal-oxide arresters of proper voltage rating easily protect the terminator and the cable insulation but introduce a traveling-wave voltage in the cable. The traveling-wave traverses the cable at a velocity of about 500 feet per microsecond, and it reflects positively if the far end of the cable presents a high impedance, such as a transformer or an open switch. If arrester protection is not applied at the open point, the positive reflection produces a nearly doubled voltage that can endanger the cable and connected equipment (Figure 12).

For a gapless metal-oxide arrester, the traveling wave magnitude is a function of the arrester's discharge voltage characteristics. The arrester's values for 0.5-microsecond 1 0-kA discharge voltage and 8/20 10-kA discharge voltage are doubled when calculating the protective margins with protection at the riser pole only.

With a gapped silicon-carbide arrester at the riser pole, the arrester's values for front-of-wave sparkover and 8/20 10-kA discharge voltage are doubled when calculating protective margins.

Some insulation protective methods for underground distribution circuit protection are summarized in Figure 13. For 13.2 and 1 3.8-kV underground systems, a single arrester located at the riser pole normally provides adequate protective margin to cable-connected equipment (2). For higher-voltage systems, protection only at the riser pole may not be adequate.

The addition of an overhead shield wire extending half a mile from the riser pole location substantially reduces the probability of direct lightning strokes on the phase conductors near the riser pole. This reduces the expected discharge-current magnitudes in the riser-pole arrester. In addition, the rate of rise of voltage surges at the riser pole is reduced because of the elimination of close-in strokes. Discharge currents can be limited to 5-kA by proper shielding of the overhead conductor adjacent to the riser pole.

For higher-voltage distribution circuits, an arrester only at the riser pole may not provide adequate protection for connected underground equipment of normally used BIL (3). Therefore, adequate protection can be obtained only by providing additional arrester protection in the underground circuit. This can be avoided only if there is no reflection point, such as on a system using closed-loop protection where both ends of the loop are protected by arresters and the loop is never broken.

A common protection method for high-voltage distribution systems is to locate one arrester at the riser pole and another arrester at the reflection point, which could be the end transformer or an open tie point. With this method, the maximum voltage developed in the underground cable is a combination of the characteristics of both arresters, and it is higher than the maximum voltage at either end of the cable.

The best protection method for cable-connected equipment is to locate one arrester at the riser pole and another arrester at each piece of equipment. This alternative normally is not necessary unless each equipment location becomes an open reflection point in the underground circuit.

We will explore the protective margins available for different types of arresters used only at the riser pole, and for 34.5-kV systems with arresters at the riser pole and at the reflection point in the cable circuit. With silicon-carbide arresters at the reflection point, the voltage must rise to sparkover for the arrester to operate. Therefore, this becomes the maximum voltage at the reflection point. The traveling-wave voltage produced by the riser-pole arrester and the surge impedance of the cable limit the discharge current in the arrester at the reflection point to values less than 5-kA unless the cable is very short. Therefore, for a silicon-carbide arrester the discharge voltage is less than the sparkover. For a metal-oxide arrester, however, the elimination of the gap makes the protection dependent only on the discharge voltage.

Figure 14 shows the discharge voltage as a function of time to voltage crest for discharge currents from 1.5-kA through 40-kA for a typical 40-mm diameter metal-oxide distribution arrester disc. This is a more detailed presentation of the phenomenon shown in Figure 6. The discharge voltages for the various currents shown at a time of about 6 microseconds to voltage crest would be the values published for discharge voltage for an 8/20 current wave. The equivalent front-of-wave protective level normally published is the value for a 10-kA wave fast enough to produce a discharge voltage cresting in 0.5 microseconds. Since the arrester at the reflection point carries discharge current less than 5-kA, for calculating the margin of protection for the equipment at the open end of the cable reasonable discharge voltages would be those at 5-kA for 34.5-kV systems and at 3-kA or less for 24.9 and 13.2-kV systems.

Figures 15 through 17 contain analyses of protective margins obtainable with silicon-carbide distribution arresters, metal-oxide riser-pole arresters, and metal-oxide distribution arresters for 13.2-kV (or 13.8-kV) systems with 95-kV BIL, 24.9-kV systems with 125-kV BIL, and 34.5-kV systems with 150-kV BIL. In each case, the traditional calculation is done comparing front-of-wave sparkover or 0.5-microsecond discharge voltage with chopped-wave withstand and standard rate of voltage rise using 10-kA IR and no arrester lead drop with BIL, assuming doubling at the reflection point. The second analysis in each case assumes a 4-foot lead with a voltage drop of 1.6-kV per foot, as suggested in the ANSI application guide (1). This lead drop may be slightly high for 10-kA waves with standard rate of rise. The third analysis assumes a three-times-faster rate of rise, as discussed previously for overhead protection, and again a 4-foot lead. In this case, a lead drop of 3.2-kV per foot is used because of the steeper rate of rise of current (5).

The arrester lead drop often is neglected in overhead protection calculations because margins are high. It is dangerous, however, to neglect this effect when protecting cable-connected equipment because the margins are much tighter. The analyses show that lead length effects can be very important and that efforts should be made to keep line and ground leads in series with the arrester as short as possible.

Figure 15 shows that the adequate margin calculated for a standard DA-IV silicon-carbide distribution arrester, while assuming standard rate of rise and no lead length, disappears when a steeper rate of rise and some lead are assumed. The PVR arrester has comfortable margins in essentially all cases. Since the recommendation of a 20 percent margin in the normal calculation is made partly because of contingencies such as lead length and high rate of rise, the full margin probably is not needed for the assumed lead length and steep rise, because some attenuation of the traveling wave in the cable occurs.

Figure 16 shows that for a 24.9-kV system, the DA-IV arrester does not provide adequate margins for protecting 125-kV BIL cable-connected equipment. Similarly, the PDV-65 and PDV-100 arresters with 15.3-kV MCOV give very small protective margins (or negative margins in the case of the PDV-65 arrester), even if no lead length and standard rate of rise are assumed. The PVR arrester with 15.3-kV MCOV shows adequate margins if lead length is kept very short.

Figure 17 examines the protection of cable-connected equipment with an arrester at the riser pole and also at the open tie point or end transformer. Adequate protection cannot be obtained with an arrester only at the riser pole for 150-kV BIL.

With an arrester at the riser pole and at the open tie, the voltage at the open-tie transformer is the protective level of the arrester at that point. In the case of the silicon-carbide arrester, the protective level is the front-of-wave sparkover because the discharge current is low enough that the discharge voltage is less than sparkover unless the cable is very short. The voltage at intermediate points in the cable is the discharge voltage of the riser-pole arrester plus the reflected wave, equal to one-half the sparkover of the open-tie arrester. This analysis shows that with the silicon-carbide distribution arrester, adequate protection is not easily obtained even with arresters at both ends of the cable, particularly if significant lead length and higher rate of rise of current through the riser-pole arrester are assumed.

Similar analyses are shown for the metal-oxide riser-pole and distribution arresters. In this case, the arrester at the open tie also creates a reflected wave that adds to the incoming traveling wave of discharge voltage from the riser-pole arrester. The value of this reflected wave is not easily calculated. The values used in Figure 17 are based on a computer simulation (6). This analysis shows that PDV-100 and PVR metal-oxide arresters can provide adequate margins for equipment connected throughout the cable length with arresters at the riser pole and the open tie, even if substantial lead length and faster rate of current rise through the riser-pole arrester are assumed.

As can be seen from the above examples it is imperative that the line and ground leads of the arrester be kept as short as possible. There are methods in which the line and ground leads can be virtually eliminated from the protective margin calculations. First we need to understand what constitutes line and ground leads.

Figure 18 shows a riser-pole configuration with 12 inches each of line and ground lead. For the line and ground lead to add to the discharge voltage of the arrester it must meet both of the following criteria: the lead must be electrically in parallel with the equipment being protected and it must carry full arrester discharge current. As can be seen in Figure 18 the lightning discharge current path will be through the 12 inch line and ground leads and these are in parallel with the equipment being protected.

Figure 19 shows a configuration to eliminate line lead from the protective margin calculations. In this case the lead from the overhead conductor is attached first to the line terminal of the arrester then to the cable terminator. In this case the lead from the overhead conductor to the arrester is not electrically in parallel with the equipment being protected and so does not add to the discharge voltage the equipment sees. No change has been made in the ground lead in this situation so this 12 inches of ground lead does still add to the discharge voltage of the arrester.

Figure 20 shows an arrangement eliminating both the line and ground leads from the calculations in this case the concentric neutral from the cable is attached directly to the ground lead of the arrester. In this case the discharge voltage which will be seen by the cable termination is only the discharge voltage of the arrester itself.

CONCLUSIONS

The protective margins arresters provide distribution equipment have been examined for standard conditions and also with higher rates of rise, and in some cases with reduced BILs from aging of transformers. This analysis shows that Ohio Brass' polymer housed metal-oxide arresters provide substantially better protection than silicon-carbide distribution arresters for overhead and underground distribution equipment. The advantage is emphasized when higher rates of current rise than the standard 8/20 discharge current wave are assumed.

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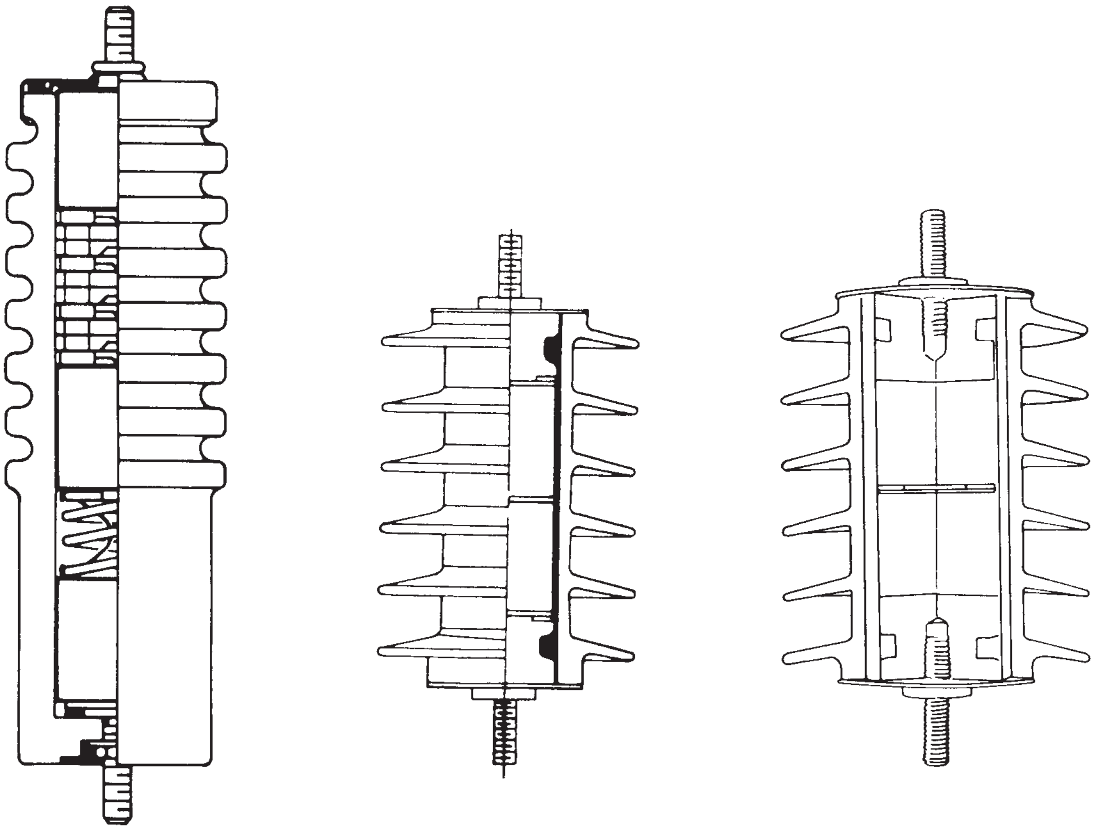
NORMALLY RECOMMENDED DISTRIBUTION AND RISER POLE MCOV FOR VARIOUS DISTRIBUTION SYSTEM VOLTAGES

System L-L Voltage kV		Arrester MCOV–kV	
Nominal	Maximum	Effectively Grounded Neutral Circuits	Impedance Grounded and Ungrounded Circuits
2.4	2.54	—	2.55
4.16	4.40	2.55	5.1
4.8	5.08	—	5.1
6.9	7.26	—	7.65
12.0	12.7	7.65	12.7
12.47	13.2	7.65	—
13.2	13.97	8.4	—
13.8	14.52	8.4	15.3
20.78	22.0	12.7	22.0
22.86	24.2	15.3	22.0
23.0	24.34	—	22.0
24.94	26.4	15.3	—
34.5	36.5	22.0	—

Figure 1



DA-IV
Silicon Carbide

PDV-100
Metal-Oxide
Polymer-Housed

PVR
Metal-Oxide
Polymer-Housed

Figure 2

Protective Characteristics of Silicon-Carbide vs. Metal-Oxide PDV vs. Metal-Oxide PVR Arresters

Grounded Neutral System Voltage	Recommended Arrester	FOW S.O.	0.5 µsec 10-kA IR	1.2×50 S.O.	8×20 µsec 10-kA IR
13.2	DA-IV 10-kV Rating	45	47	45	36
	PDV-100 MOV 8.4-kV MCOV	--	36.5	--	32
	PDV-65 MOV 8.4-kV MCOV	--	41.8	--	36
	PVR MOV 8.4-kV MCOV	--	28.5	--	26.5
24.9	DA-IV 18-kV Rating	55	87	55	67
	PDV-100 MOV 15.3-kV MCOV	--	68	--	60
	PDV-65 MOV 15.3-kV MCOV	--	75.5	--	66
	PVR MOV 15.3-kV MCOV	--	51.4	--	48
34.5	DA-IV 27-kV Rating	79	125	79	96
	PDV-100 MOV 22-kV MCOV	--	102	--	90
	PDV-65 MOV 22-kV MCOV	--	113.2	--	99
	PVR MOV 22-kV MCOV	--	77.1	--	72

Figure 3

System Voltage – Insulation BIL – Arrester Selection for Overhead Distribution System

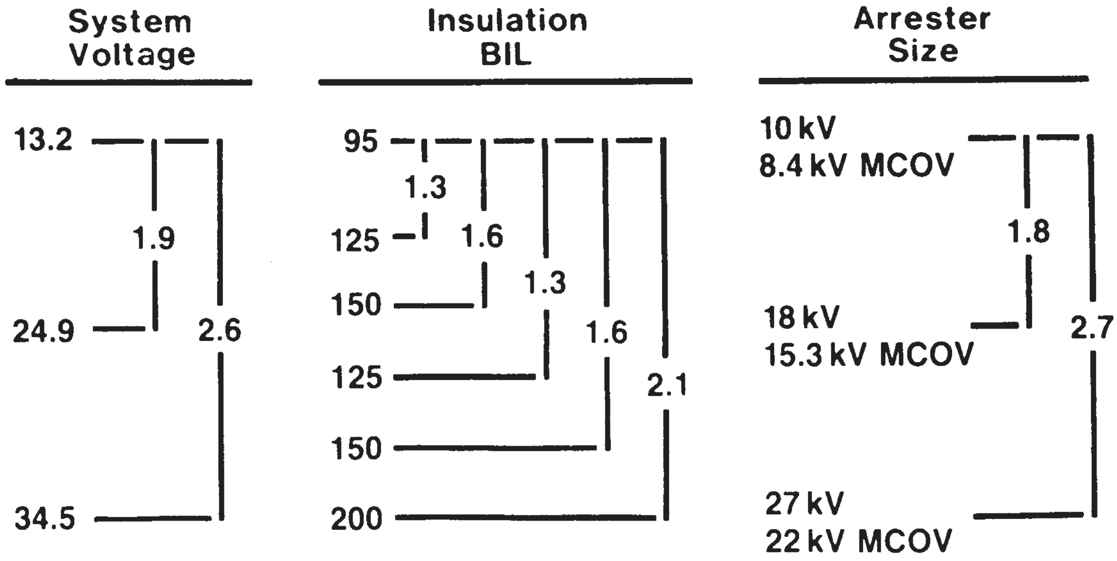


Figure 4

Factors Influencing Insulation Protective Margins for Overhead Distribution Systems

A. Transformer BIL Reduction Caused by Aging and Loading - 20% Reduction Quite Possible

B. Increased Probability of Stroke Currents With Rates of Rise Significantly Faster Than Standard 8 x 20 Microsecond

C. Lead Length $L^{di}/_{dt}$

Figure 5

Discharge Voltage vs. Time to Voltage Crest

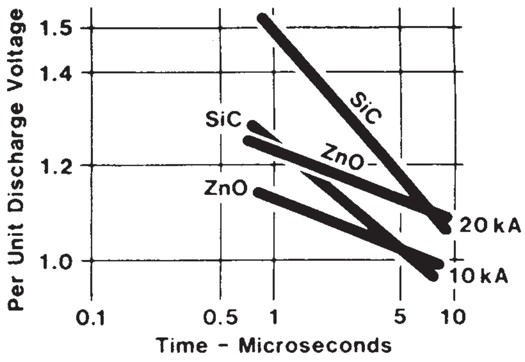


Figure 6

Protective Margin Variations for Insulation on 13.2-kV Overhead Distribution System

Transformer Insulation		Arrester Data					Percent Margin		
CW	BIL	Type	FOW S.O.	FOW	1.2×50 S.O.	8×20 μsec 10-kA IR	CW	BIL	Comments
110	95	DA-IV 10	45	49	45	36	124	111	Std. ROR Full Insulation
110	76	DA-IV 10	52	56	45	43	96	69	3 Times Faster ROR BIL 20% Reduction
110	95	PDV-100 MOV-8.4	--	36.5	--	32	201	197	Std. ROR Full Insulation
110	76	PDV-100 MOV-8.4	--	40.5	--	35.5	172	114	3 Times Faster ROR BIL 20% Reduction
110	95	PDV-65 MOV-8.4	--	41.2	--	36	167	164	Std. ROR Full Insulation
110	76	PDV-65 MOV-8.4	--	45.7	--	40	141	90	3 Times Faster ROR BIL 20% Reduction
110	95	PVR MOV-8.4	--	28.5	--	26.5	286	258	Std. ROR Full Insulation
110	76	PVR MOV-8.4	--	31.8	--	29.5	246	158	3 Times Faster ROR BIL 20% Reduction

Figure 7

Protective Margin Variations for Insulation on 24.9-kV Overhead Distribution System

Transformer Insulation		Arrester Data					Percent Margin		
CW	BIL	Type	FOW S.O.	FOW	1.2×50 S.O.	8×20 μsec 10-kA IR	CW	BIL	Comments
145	125	DA-IV 18	55	87	55	67	73	87	Std. ROR Full Insulation
145	100	DA-IV 18	63	100	55	80	45	25	3 Times Faster ROR BIL 20% Reduction
145	125	PDV-100 MOV-15.3	--	68	--	60	113	108	Std. ROR Full Insulation
145	100	PDV-100 MOV-15.3	--	75	--	66	93	52	3 Times Faster ROR BIL 20% Reduction
145	125	PDV-65 MOV-15.3	--	75.5	--	66	92	89	Std. ROR Full Insulation
145	100	PDV-65 MOV-15.3	--	83.8	--	73.3	73	36	3 Times Faster ROR BIL 20% Reduction
145	125	PVR MOV-15.3	--	51.4	--	48	182	160	Std. ROR Full Insulation
145	100	PVR MOV-15.3	--	57	--	53	154	89	3 Times Faster ROR BIL 20% Reduction

Figure 8

Protective Margin Variations for Insulation on 34.5-kV Overhead Distribution System

Transformer Insulation		Arrester Data					Percent Margin		
CW	BIL	Type	FOW S.O.	FOW	1.2×50 S.O.	8×20 μsec 10-kA IR	CW	BIL	Comments
230	200	DA-IV 27	79	125	79	96	84	108	Std. ROR Full Insulation
230	160	DA-IV 27	91	144	79	115	60	39	3 Times Faster ROR BIL 20% Reduction
230	200	PDV-100 MOV-22	--	102	--	90	125	122	Std. ROR Full Insulation
230	160	PDV-100 MOV-22	--	112.5	--	99	104	62	3 Times Faster ROR BIL 20% Reduction
230	200	PDV-65 MOV-22	--	113.2	--	99	103	102	Std. ROR Full Insulation
230	160	PDV-65 MOV-22	--	125.7	--	109	83	46	3 Times Faster ROR BIL 20% Reduction
230	200	PVR MOV-22	--	77.1	--	72	198	178	Std. ROR Full Insulation
230	160	PVR MOV-22	--	85.6	--	80	169	100	3 Times Faster ROR BIL 20% Reduction

Figure 9

Protective Margin Variations for Insulation on 34.5-kV Overhead Distribution System

Transformer Insulation		Arrester Data					Percent Margin		
CW	BIL	Type	FOW S.O.	FOW	1.2×50 S.O.	8×20 µsec 10-kA IR	CW	BIL	Comments
175	150	DA-IV 27	79	125	79	96	40	56	Std. ROR Full Insulation
175	120	DA-IV 27	91	144	79	115	22	4	3 Times Faster ROR BIL 20% Reduction
175	150	PDV-100 MOV-22	--	102	--	90	72	67	Std. ROR Full Insulation
175	120	PDV-100 MOV-22	--	112.5	--	99	56	21	3 Times Faster ROR BIL 20% Reduction
175	150	PDV-65 MOV-22	--	113.2	--	99	55	52	Std. ROR Full Insulation
175	120	PDV-65 MOV-22	--	125.7	--	109	39	10	3 Times Faster ROR BIL 20% Reduction
175	150	PVR MOV-22	--	77.1	--	72	127	108	Std. ROR Full Insulation
175	120	PVR MOV-22	--	85.6	--	80	104	50	3 Times Faster ROR BIL 20% Reduction

Figure 10

Protective Margin Variations for Insulation on 34.5-kV Overhead Distribution System

Transformer Insulation		Arrester Data					Percent Margin		
CW	BIL	Type	FOW S.O.	FOW	1.2×50 S.O.	8×20 µsec 10-kA IR	CW	BIL	Comments
145	125	DA-IV 27	79	125	79	96	16	30	Std. ROR Full Insulation
145	100	DA-IV 27	91	144	79	115	0	-13	3 Times Faster ROR BIL 20% Reduction
145	125	PDV-100 MOV-22	--	102	--	90	42	39	Std. ROR Full Insulation
145	100	PDV-100 MOV-22	--	112.5	--	99	29	1	3 Times Faster ROR BIL 20% Reduction
145	125	PDV-65 MOV-22	--	113.2	--	99	28	26	Std. ROR Full Insulation
145	100	PDV-65 MOV-22	--	125.7	--	109	15	-8	3 Times Faster ROR BIL 20% Reduction
145	125	PVR MOV-22	--	77.1	--	72	88	74	Std. ROR Full Insulation
145	100	PVR MOV-22	--	85.6	--	80	69	25	3 Times Faster ROR BIL 20% Reduction

Figure 11

Traveling Wave Characteristic

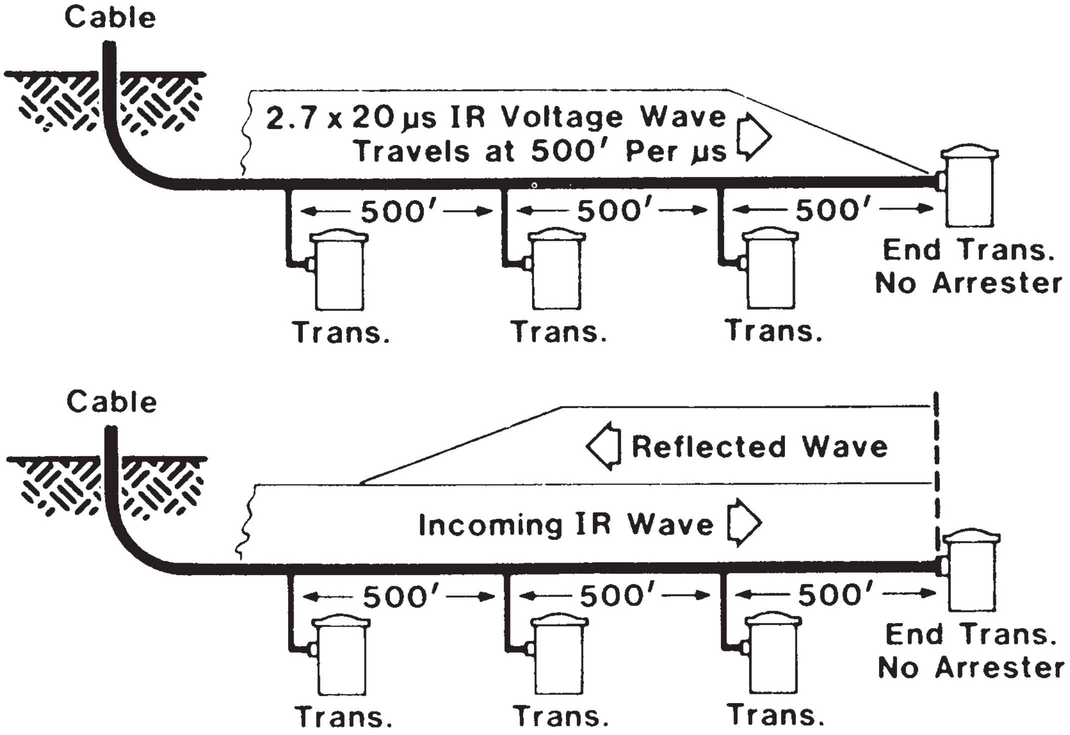


Figure 12

Insulation Protection Schemes for Underground Distribution Systems

A. Single Arrester Located at Riser Pole *Only*

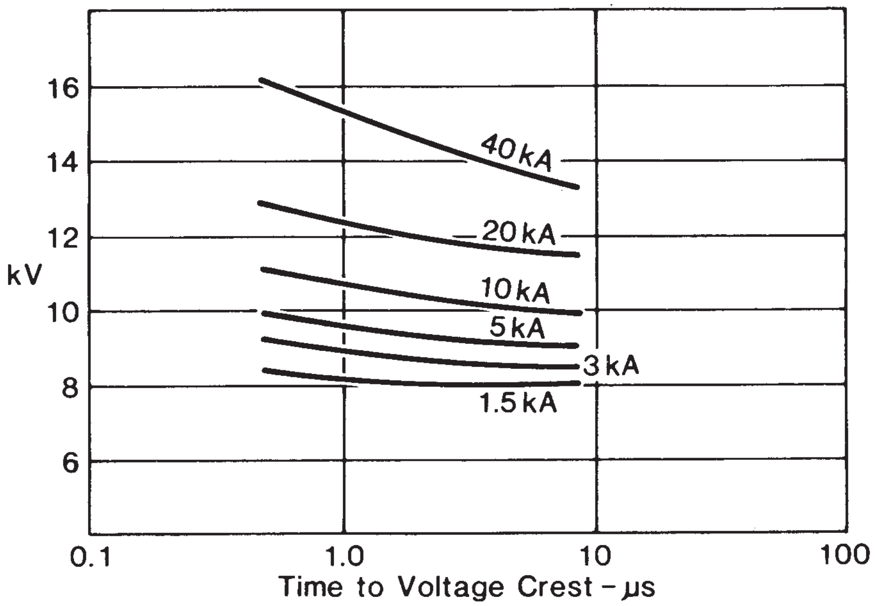
B. Parallel Arresters Located at Riser Pole *Only*

C. Shield Wires on Overhead Lines Adjacent to Riser Pole

D. Riser Pole Arrester *Plus...*

1. Arrester Located at Open Point of Underground Circuit Brought Above Ground at Another Riser Pole - *Closed Loop*
2. Arrester Located at Open Point in Underground Circuit *Only*
3. Arresters Located on *All* Equipment in Underground Circuit

Figure 13


Volt-Ampere Characteristic

40-mm Diameter x 30-mm Long Metal-Oxide Disc

Figure 14

Underground Insulation Protective Margins with Arrester at Riser Pole Only -- 13.2-kV System

Insulation		Arrester and Lead Data			Voltage Doubling		Percent Margin		Type of Protection
CW	BIL	Type	FOW	10-kA IR	(2) FOW	(2) 10-kA IR	CW	BIL	
110	95	DA-IV 10	45	36	90	72	22	32	No Lead Standard ROR
110	95	DA-IV 10	51.4	42.5	102.8	85	7	12	4' Lead Standard ROR
110	95	DA-IV 10	69	56	138	112	-20	-15	4' Lead 3 Times Faster ROR
110	95	PDV-100 MOV-8.4	36.5	32	73	64	51	48	No Lead Standard ROR
110	95	PDV-100 MOV-8.4	42.5	38.5	85	77	29	23	4' Lead Standard ROR
110	95	PDV-100 MOV-8.4	54	48	108	96	2	-1	4' Lead 3 Times Faster ROR
110	95	PDV-65 MOV-8.4	41.2	36	82.4	72	33	32	No Lead Standard ROR
110	95	PDV-65 MOV-8.4	47.6	42.5	95.2	85	16	12	4' Lead Standard ROR
110	95	PDV-65 MOV-8.4	58.5	52.8	117	105.6	-6	-10	4' Lead 3 Times Faster ROR
110	95	PVR MOV-8.4	28.5	26.5	57	53	93	79	No Lead Standard ROR
110	95	PVR MOV-8.4	35	33	70	66	57	44	4' Lead Standard ROR
110	95	PVR MOV-8.4	44	42	88	84	25	13	4' Lead 3 Times Faster ROR

Figure 15

Underground Insulation Protective Margins with Arrester at Riser Pole Only -- 24.9-kV System

Figure 16

Insulation		Arrester and Lead Data			Voltage Doubling		Percent Margin		Type of Protection
CW	BIL	Type	FOW	10-kA IR	(2) FOW	(2) 10-kA IR	CW	BIL	
145	125	DA-IV 18	87	67	174	134	-17	-7	No Lead Standard ROR
145	125	DA-IV 18	93	73.5	186	147	-22	-15	4' Lead Standard ROR
145	125	DA-IV 18	113	93	226	186	-36	-33	4' Lead 3 Times Faster ROR
145	125	PDV-100 MOV-15.3	68	60	136	120	7	4	No Lead Standard ROR
145	125	PDV-100 MOV-15.3	74.5	66.5	149	133	-3	-6	4' Lead Standard ROR
145	125	PDV-100 MOV-15.3	88	79	176	158	-18	-21	4' Lead 3 Times Faster ROR
145	125	PDV-65 MOV-15.3	75.5	66	151	132	-4	-5	No Lead Standard ROR
145	125	PDV-65 MOV-15.3	91.9	72.4	163.8	144.8	-11	-14	4' Lead Standard ROR
145	125	PDV-65 MOV-15.3	96.6	86.1	192.4	172.2	-25	-27	4' Lead 3 Times Faster ROR
145	125	PVR MOV-15.3	51.4	48	102.8	96	41	30	No Lead Standard ROR
145	125	PVR MOV-15.3	58	54.5	116	109	25	15	4' Lead Standard ROR
145	125	PVR MOV-15.3	69.3	66	138.6	132	5	-5	4' Lead 3 Times Faster ROR

Underground Insulation Protective Margins with Arrester at Riser Pole and at Open Tie -- 34.5-kV System

Figure 17

Insulation BIL	Arrester and Lead Data			Maximum Cable Voltage	Percent Margin BIL	Type of Protection
	Type	FOW	10-kA IR			
150	DA-IV 27		79	96	10	No Lead Standard ROR
150	DA-IV 27		79	102	6	4' Lead Standard ROR
150	DA-IV 27		79	128	-11	4' Lead 3 Times Faster ROR
150	PDV-100 MOV-22		102	90	26	No Lead Standard ROR
150	PDV-100 MOV-22		102	96.5	20	4' Lead Standard ROR
150	PDV-100 MOV-22		102	112	6	4' Lead 3 Times Faster ROR
150	PDV-65 MOV-22		113.2	99	14	No Lead Standard ROR
150	PDV-65 MOV-22		113.2	105.5	8	4' Lead Standard ROR
150	PDV-65 MOV-22		113.2	122.7	-4	4' Lead 3 Times Faster ROR
150	PVR MOV-22		77.1	72	53	No Lead Standard ROR
150	PVR MOV-22		77.1	78.5	44	4' Lead Standard ROR
150	PVR MOV-22		77.1	92.5	27	4' Lead 3 Times Faster ROR

* IR of SiC arrester plus 1/2 sparkover of open-tie arrester.

** IR of PVR arrester plus a reflected wave of 26 kV for Riser Pole, 29 kV for PDV-100 MOV -- and 33 kV for PDV-65 MOV; from computer simulation.

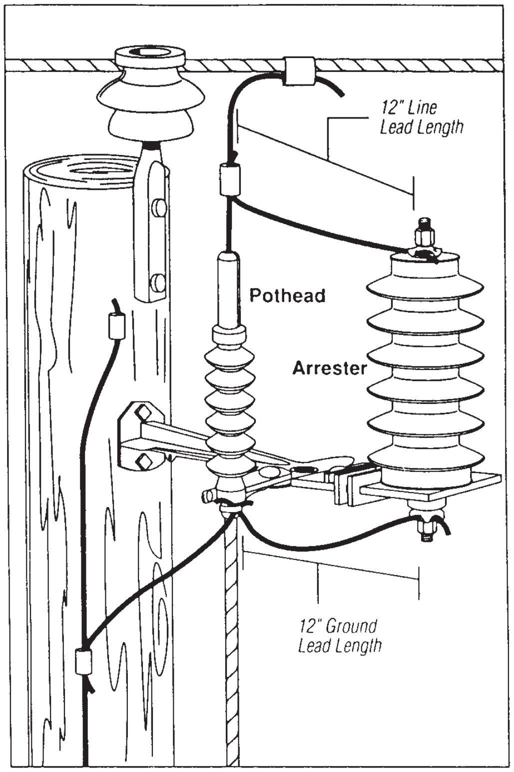


Figure 18

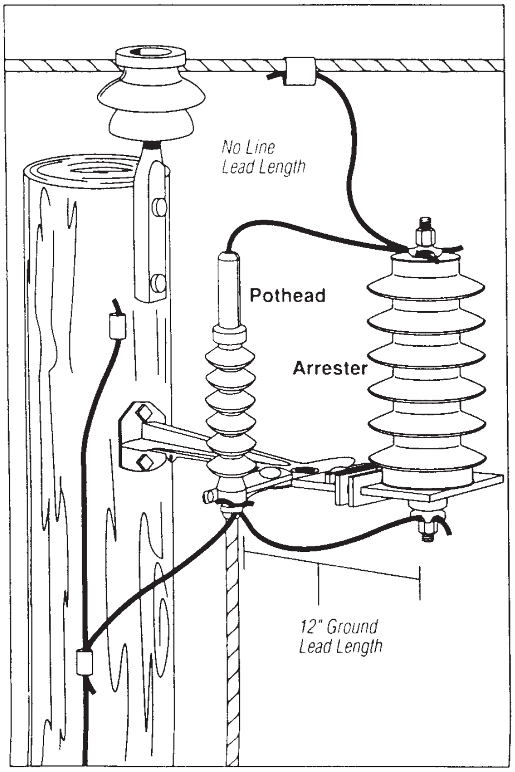


Figure 19

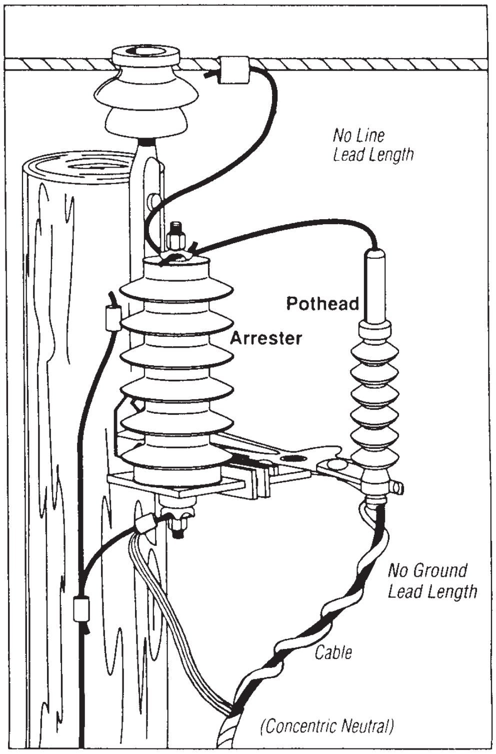


Figure 20

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