

A New Concept in Arrester Design

R.C. Sakshaug, J.S. Kresge, and S.A. Miske
General Electric Company

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Significance:

Part 7 Annex: Mitigation Techniques

This paper was approved for presentation at the 1976 PES Summer Meeting to announce the availability of zinc oxide varistor material for high-voltage arresters. It is significant that this announcement occurred in 1976, four years after the 1972 trade-press announcement of the low-voltage version of zinc oxide varistors under the trade name of GE-MOV (see [MOV Announce](#) and [Superalpha](#) in this Part 7), and this only after undertaking the research described in this seminal paper.

While technically outside of the scope of the Anthology which is focused on low-voltage SPDs, this seminal paper is included as an Annex to the public-domain SPD Anthology to provide perspective on the extent of the research to which the new material was subjected before launching a commercial product.

A NEW CONCEPT IN STATION ARRESTER DESIGN

E. C. Sakshaug J. S. Kresge

General Electric Company
Pittsfield, Massachusetts

S. A. Miske, Jr.

General Electric Company
Schenectady, New York

ABSTRACT

In 1968 Matsushita Electric Industrial Co. of Osaka, Japan announced a new improved non-linear resistance material based on zinc oxide. The original devices were small low voltage units applicable for use in the electronics industry. In 1970 work was performed by the General Electric Co., and is continuing, using its own funds and technical resources, to develop larger devices for use as a substitute for silicon carbide valve blocks in surge arresters. Development has now progressed to the point where this material, with non-linearity characteristics far superior to silicon carbide, can be used to manufacture station type arresters which do not employ series gaps. The purpose of this paper is to outline some of the characteristics made possible by the new material which is becoming increasingly important to the electrical industry.

INTRODUCTION

It has always been understood that the optimum arrester characteristic would be one in which the arrester would: 1) enter into conduction at some voltage above arrester rating, 2) hold that voltage with little change for the duration of the overvoltage surge, and 3) substantially cease conduction at very nearly the same voltage at which conduction started. Such an arrester would conduct only that current required to reduce the surge voltage to the arrester protective level. Any arrester holding a lower level of voltage during all or part of the conduction period must conduct more current and absorb more energy.

Each major development in the evolution of arrester technology has been a step toward the optimum arrester characteristic. The first arresters were simple spark gaps capable of supporting essentially no voltage during conduction, and as a result, the arresters were generally incapable of clearing power frequency follow current after sparkover. An improvement was made by adding series resistors. A very substantial improvement was obtained by the development of non-linear resistors to allow the arrester to support as much voltage as possible during the flow of power frequency follow current while maintaining reasonably low protective levels. The most recent improvement has been the development of current limiting gaps. Current limiting gaps used in series with non linear resistors made it feasible to further reduce protective levels for surge currents while maintaining a more constant voltage during the flow of arrester current. Fig. 1 illustrates the maximum voltages produced across a current limiting gap arrester at various current levels. It will be noted that, by design, the voltage produced by the current limiting gap is the amount required to obtain a total arrester voltage as near as possible to a constant value equal to the switching surge sparkover of the arrester. Because the arrester voltage is kept as high as it can be without exceeding switching surge protective level, the magnitude and in many cases the duration of current drawn by the arrester is minimized.¹ As a result, the energy that must be dissipated is reduced. Another method for visualizing the situation is to note that in Fig. 1 at a current of even 500 amperes the resistance of an arrester rated 258 kV, for instance, is:

$$\frac{13,000 \text{ volts}}{500 \text{ amps}} \times \frac{258 \text{ kV}}{6 \text{ kV}} = 1118 \text{ ohms}$$

For a surge impedance of 350 ohms, the arrester resistance exceeds the source impedance of the surge. It is well known that maximum power is transferred to a load when the load and source resistance are equal and decreases as the load resistance becomes higher than the source resistance.

The development of current limiting gap arresters was in considerable measure responsible for a number of improvements in arrester performance including:

1. Reduction in lightning discharge voltages made possible by reducing valve element resistance;
2. Reductions in arrester size because of the reduction in energy absorbed for a given surge level and because of energy sharing between gaps and valve elements;
3. A reduction in protective levels on HV and EHV systems in particular because of the overvoltage reseal capability of current-limiting gap arresters.

Current limiting gap arresters have been widely applied with an excellent service record; however, they do possess certain inherent limitations most of which are related to the fact that the arrester voltage is not at the level shown by Fig. 1 during the whole arrester operation. Instead, the arrester voltage falls to the valve element voltage immediately after sparkover, and does not rise to the level shown in Fig. 1 in less than a few hundred microseconds after sparkover.² Until gap voltage is developed, the arrester current is given by:

$$I_{\text{arrester}} = \frac{E_{\text{surge}} - V_{\text{valve element}}}{\text{Surge Impedance}}$$

When the circuit in which the arrester is operating has low surge impedance (multiple lines, capacitor banks, or cable circuits), the initial arrester current can become very high. It is possible in some cases of very low surge impedance for the initial current to be so high that it does not move away from the point of initial arc strike into the normal arc-clearing region of the gap units. As a result the arrester may fail to clear, or the erosion of the electrodes may be sufficiently severe to cause a change in arrester sparkover.³ A similar problem may arise during operation of current limiting fuses because of the ability of such fuses to switch high fault currents very rapidly into arresters of low rating compared to fuse rating.³

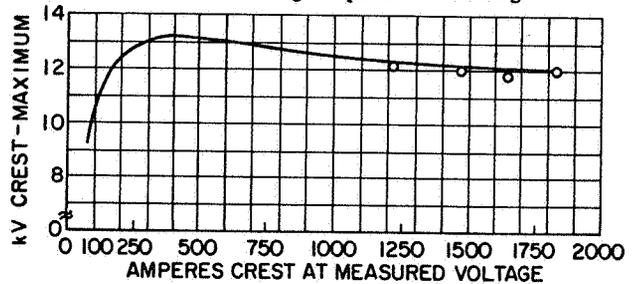


Fig. 1. Maximum voltage vs. current for a 6 kV section of a modern current limiting arrester design.

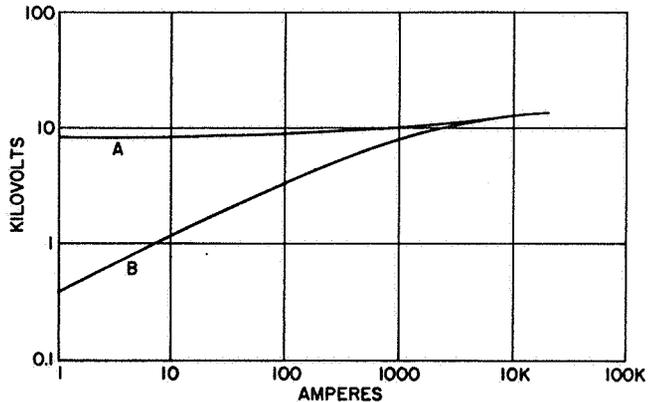


Fig. 2 Volt-ampere characteristic of 6 kV valve elements. A = zinc oxide B = silicon carbide

F 76 393-9. A paper recommended and approved by the IEEE Surge Protective Devices Committee of the IEEE Power Engineering Society for presentation at the IEEE PES Summer Meeting, Portland, OR, July 18-23, 1976. Manuscript submitted March 1, 1976; made available for printing May 4, 1976.

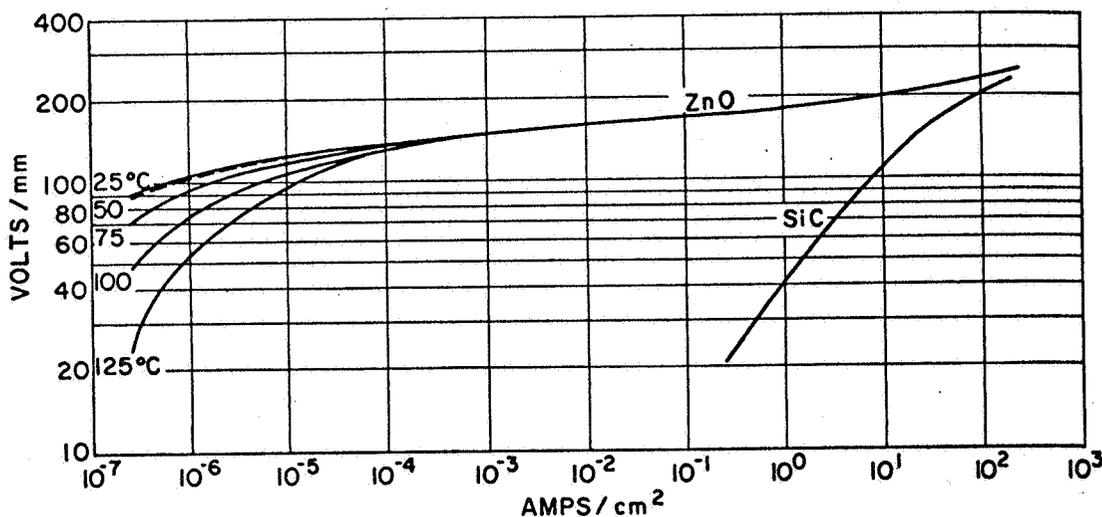


Fig. 3 Normalized volt-ampere characteristic of zinc oxide and silicon carbide valve elements.

It has long been recognized that it would be advantageous to be able to design an arrester without the use of series gaps because:

1. Gaps are subject to change in sparkover if an arrester is not adequately sealed;
2. Overvoltage applications may be limited by the probability of sparkover resulting from surface contamination;
3. The number of parts used in gaps is large compared to the number of parts used in the whole arrester, and the probability of misassembly or part failure usually increases with the number of parts used.

Curve A of Fig. 2 is a voltage-current plot of the new zinc oxide based valve element material. The new valve element has a characteristic so non-linear that the voltage is nearly constant for a wide range of currents. As a result, an arrester designed using these valve elements, and without series gaps, more closely approximates an ideal constant voltage device than is possible using the most modern current limiting gaps in series with silicon carbide valve disks having voltage-current characteristics as illustrated in Curve B of Fig. 2. The new arrester draws very little current until a voltage approaching the protective level is reached, and then only that current is drawn which is necessary to limit the overvoltage to the protective level. As a result, the arrester absorbs the minimum amount of energy required to provide protection at a given voltage level.

Curve A of Fig. 2 has been replotted (on a normalized basis) in Fig. 3 with an extension to much lower currents than for Fig. 2 and with the voltage scale expanded for improved resolution. From Fig. 3 it can be seen that for a change in current over a total range of 5 decades from 10^{-3} to 10^2 amps/cm² the voltage increase is only 56%. With such a high degree of non-linearity it is entirely feasible to use these elements without series gaps in an arrester having a discharge voltage at 10 kA equal to that for present designs. For such an arrester the current at operating voltage is only about 1 milliampere which is the same order as the grading current of existing designs. In fact, the watts loss at operating voltage for such a design is only about 0.15 watts per kV of rating or two-thirds of that for an existing design.

VALVE ELEMENT CHARACTERISTICS

The valve element consists primarily of zinc oxide, but it contains small amounts of other selected metal oxide additives, which serve to produce the desired highly non-linear resistive characteristic of the material. The finely crushed zinc oxide and additives are prepared as a thoroughly mixed flowable powder which can be pressed into disks of the desired size. When the pressed disks are sintered at a high temperature a dense polycrystalline ceramic material results. The basic structure of the sintered body is a matrix of highly conducting zinc oxide grains surrounded and separated by highly resistive intergranular layers consisting primarily of the metal oxide additives. Under sufficient electrical stress the intergranular layers start to conduct, with the conduction characteristic being highly non-linear as illustrated in Fig. 3. The specific characteristics shown in Fig. 3 significant to arrester applications are as follows:

1. The non-linearity of the voltage-current characteristic is exceptional, a change in voltage of only a factor of 1.56 being required to change the current

five orders of magnitude.

2. At all except low current densities (less than 10^{-3} a/cm²) there is a negligible temperature coefficient, and as a result the protective characteristics are unaffected by a change in temperature of the arrester. Such is not the case for the presently used silicon carbide valve elements which exhibit a negative temperature coefficient of about 0.24%/C°. The zinc oxide valve element also exhibits a negative temperature coefficient at low current densities, but this has no influence on protective levels; however it does have an influence on the thermal design of the arrester for normal system voltage conditions.

3. At very high current densities (greater than 10 a/cm²) the volt-ampere curve begins to turn up significantly with the turn-up attributable to the resistivity of the zinc oxide grains. A voltage turn-up at high current density is characteristic of silicon carbide valve elements as well. At the highest current densities encountered in arresters, the turn-up of zinc oxide elements is much less than in silicon carbide elements.

4. Not shown in Fig. 3 but of great significance is the fact that after a zinc oxide valve element is subjected to very high discharge currents the protective characteristics remain essentially unchanged. This is in contrast to silicon carbide valve elements used in conventional arresters which may exhibit increased protective levels after being subjected to impulse current discharges.

PROTECTIVE LEVEL CONSIDERATIONS

If 10 kA is assumed as the current to be used for insulation coordination in a given application, and if the 10 kA discharge voltage is 1.6 x arrester rating, the minimum BIL that may be protected with a margin of 20% is 1.92 times arrester rating. The usual assumption is that the switching surge insulation withstand is 0.83 times BIL; therefore, the switching surge withstand is $0.83 \times 1.92 = 1.59$ x arrester rating. Employing the minimum accepted margin of 15% for switching surge protection, the switching surge protective level should be $1.59/1.15 = 1.39$ times rating. With the new zinc oxide valve elements it is readily possible to provide arresters with a switching surge protective level of 1.39 times rating and a 10 kA discharge voltage of 1.6 x rating. With these protective characteristics a 258 kV arrester on a 345 kV system could even protect 750 kV BIL equipment with a margin of 28% on impulse and 23% on switching surges.

ARRESTER TESTS

Protective Characteristics

1. Sparkover

Because series gaps are not used, the arrester does not have a sparkover characteristic; rather, the valve elements enter into conduction smoothly in accordance with Curve A of Fig. 2 as the voltage is increased above operating level.

2. Discharge Voltage

The Curve of Fig. 2 indicates a discharge voltage at 10,000 amperes of 1.6 x crest arrester rating which is approximately the level normally given for current limiting gap arresters. Because of the higher exponent of the zinc oxide curve, discharge voltages at higher currents tend to be less than discharge voltages of silicon carbide valve element arresters.

Because the arrester does not have a sparkover characteristic, an investigation was made to determine the arrester voltage level on fast front current impulses in order to illustrate the short time characteristics of the arrester. The results of tests made using 10,000 ampere waves cresting in 0.12 μ sec, 1.3 μ sec and 10 μ sec are given in Fig. 4 together with the results of identical tests on conventional silicon carbide arrester valve elements. A curve showing the ratio of front-of-wave sparkover to sparkover at 10 μ sec (which is approximately the same magnitude as the 10 kA discharge voltage on an 8 x 20 μ sec wave for a conventional arrester) is included for reference. The silicon carbide valve element voltage on a wave cresting in 0.12 μ sec is 1.6 times the voltage measured on a wave cresting in 10 μ sec. This is in accordance with previous observations that silicon carbide valve element voltage increases by 8 to 10% each time the time-to-crest is halved for the same current magnitude. It is interesting to note that the ratio of industry⁴ maximum front-of-wave sparkover (occurring at about 0.6 μ sec) to 10,000 ampere 8 x 20 μ sec discharge voltage for arresters rated 258 kV is about 1.25. The curve of Fig. 4, however, indicates that the discharge voltage on a 0.6 microsecond current wave is 1.36 times higher than the discharge voltage on an 8 x 20 μ sec wave. Apparently, the discharge voltage of an arrester of conventional design on a fast front current wave may be at least as high as the front-of-wave sparkover. On the other hand, the zinc oxide valve element voltage on a wave cresting in 0.12 μ sec is 1.28 times the voltage measured on a wave cresting in 10 μ sec and the voltage for a current wave cresting in 0.6 microsecond is only 1.16 times the voltage for a wave cresting in 10 μ sec. Therefore, for wave fronts as short as 0.12 μ sec the voltage across an arrester made using zinc oxide valve elements will be less than either the front-of-wave sparkover or discharge voltage on similar waves for conventional arresters.

2.1 Stability of Discharge Voltage Characteristics

Stability of zinc oxide disks on high current impulses has been measured. The application of two 4 x 8 μ sec, 65 kA impulses results in a change (slight decrease) in discharge voltage of less than 2% at 100 amperes and less than 3% at 10 kA, with repetitive application of 10 kA impulse waves causing no detectable change in the discharge voltage. Silicon carbide valve elements generally show much greater change. In fact, an increase of 10% in 10 kA discharge voltage is permitted in a standard duty cycle test.³

Discharge voltages in arresters using the new valve elements may be adjusted without much difficulty by arranging gaps in shunt with a small portion of the valve elements. That is, the designer must provide for the required total amount of valve material to assure proper operation at normal operating voltage and during temporary overvoltages above arrester rating. If this results in too high a discharge voltage at the selected coordination current, 10 kA for example, a small portion of the disks can be effectively removed at high current levels by paralleling them with properly coordinated shunt gaps.

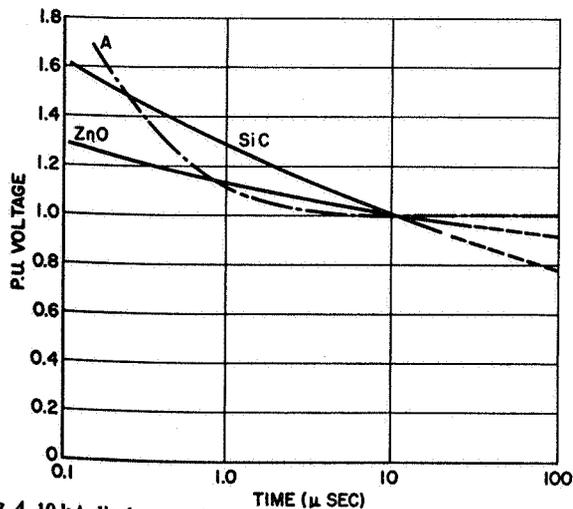


Fig. 4. 10 kA discharge voltage vs. current wave crest time for zinc oxide and silicon carbide valve elements (in per unit of the 10 μ sec values). Curve A is a 264 kV arrester sparkover characteristic in per unit of the 10 kA, 8 x 20 μ sec discharge voltage.

Durability

1. Duty Cycle Tests

One of the most basic tests for arresters developed over the years has been the duty cycle test.⁵ Very generally, this test consists of placing the arrester across a 60 Hz power source at rated voltage of the arrester and subjecting it to high current impulses once per minute for twenty four minutes with the impulses timed to appear at selected points on the 60 Hz wave. The Standard calls for the impulse current to be a 10 kA, 8 x 20 μ sec wave for station class arresters. The basic purpose of the test is to demonstrate durability of the arrester (ability to tolerate the impulse currents combined with the consequent power follow current) and its ability to reseal consistently at rated voltage. It would be expected from study of the curve of Fig. 2 that power frequency follow current through the zinc oxide element should be substantially zero at rated voltage which is $6 \times \sqrt{2} = 8.5$ kV crest. Nevertheless it seemed useful to perform the duty cycle test to demonstrate that there would be no unexpected problems. The oscillograms of Fig. 5 illustrate such tests performed exactly as they would be on a conventional arrester except that a much higher sensitivity than normal is employed for the current trace. Fig. 5(a) shows a typical operation in which the negative polarity impulse was applied at about 30° before crest of the 4th positive half cycle on the oscillogram. Note the lack of a significant follow current on that half cycle although there is undoubtedly a small short duration interaction current caused by the discharge voltage of the arrester forcing current into the inductance of the source.⁶ It should be noted as well that the general shape and magnitude of the arrester current after operation is essentially identical to that before the operation. Fig. 5(b) shows the 20th operation during the duty cycle test. The arrester current trace of this oscillogram shows a DC shift, but this is an instrumentation error caused by the 10 kA impulse shocking the sensitive amplifier used to display these low current levels. In Fig. 5(b) the current after the operation was actually identical to that just prior to the operation. After the 20 operations the arrester current had increased from 4.5 ma zero-to-crest to about 8.5 ma zero-to-crest. Upon cooling back to room temperature the current was almost identical to the original value except for a small deviation caused by a temporary phenomenon to be described in a later section. Such a small increase in arrester current during a duty cycle test is of no consequence since the thermal design of the arrester is capable of dissipating the associated watts loss with no difficulty.

2. Transmission Line Discharge Test

The transmission line discharge test specified in ANSI Standard C62.1-1975 is passed readily by zinc oxide arresters. Current on the final operation is substantially identical to the current on the first operation of the test.

3. Overvoltage Capability

Certain applications demand that an arrester be able to survive several cycles of voltage above rating after being subjected to a relatively high energy switching surge discharge. For example, in picking up a line with an unloaded transformer and its associated arrester at the far end, the arrester may be subjected to a prospective voltage profile of 1.5 or more times rating for one or more half-cycles followed by several cycles of lower voltages still above arrester rating. These overvoltages are caused by reflection of traveling waves on the line as well as by harmonic currents drawn through the line impedance by the transformer. Such overvoltages are generally related to circuit configurations in which the current available to the arrester is limited by the surge impedance of the transmission line. In order to allow the application of arresters in circuits subject to short time overvoltages, most arrester manufacturers now supply information as to specific overvoltage envelopes their arresters will tolerate. For example, station arresters presently manufactured by the authors' company can tolerate overvoltages in per unit of arrester rating equal to 2.0 for one-half cycle followed by 1.3 for 10 cycles or 1.6 for two half-cycles followed by 1.25 for 10 cycles in circuits of surge impedance normally associated with overhead transmission lines.

For conventional arrester the failure mode when overstressed in this kind of operation is generally inability to clear because of gap restriking. Although the new arrester does not have series gaps, it is important to demonstrate that it has adequate energy absorption capability to cope with overvoltage operations.

Fig. 6 is a schematic diagram of one test circuit which has been used to test the capability of prorated arrester sections under overvoltage conditions. In this circuit a generator with source inductance L1 is connected to the test sample, through the resistor R1 representing the surge impedance of the line, by closing the synchronous switch S1. One or two half-cycles later the source voltage is reduced by closing switch S2 to provide a voltage division between L2 and L1. In practice the circuit inductances and switch timing are first adjusted with the sample removed to establish the desired

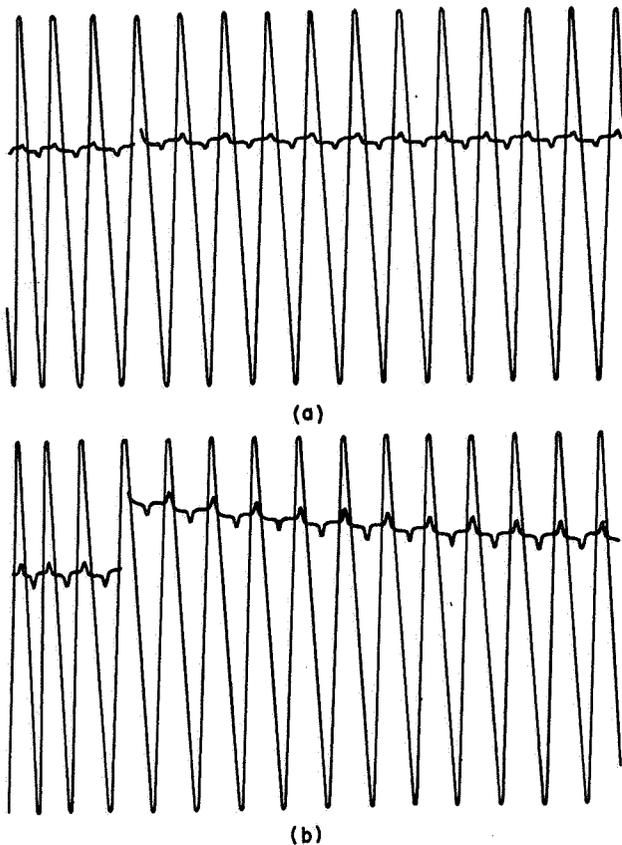


Fig. 5. (a) Typical duty cycle operation at rated voltage with a 10 kA 8 x 20 μ sec impulse. Large deflection trace is arrester voltage. Smaller deflection trace is arrester current (9 ma P-P).

(b) Duty cycle operation after (20) operations at 1 minute intervals. Current increase to 17 ma P-P is due to heating. DC shift in current trace is an instrumentation error.

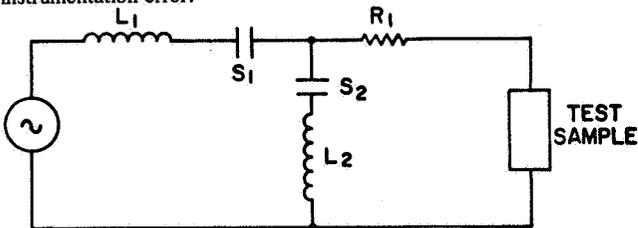


Fig. 6. 60 Hz dual level overvoltage test circuit. L1 = source inductance, L2 = loading inductance S1 & S2 = synchronous switches, S2 closed $\frac{1}{2}$ or 1 cycle after S1 R1 represents surge impedance of transmission line

prospective voltage envelope. The sample is then connected and subjected to the overvoltage test with appropriate monitoring of arrester voltage, current, and energy dissipation. Fig. 7 is an oscillogram of such a test on a prorated model of the new arrester designed to provide a switching surge protective level of 1.39 times rating and a 10 kA discharge voltage of 1.6 times rating. For the results shown in Fig. 7(a) the prospective voltages for successive half-cycles were 2.0, 1.32, 1.35, 1.29, 1.29, --- etc., decaying to 1.19 times rating on the 10th cycle, at which time the voltage was removed. (The reason for the decaying voltage envelope is the transient change in impedance of the rotating machine used as a source.) The arrester drew a current of 760 crest amperes in the first half-cycle with currents of less than 80 crest amperes in the following half-cycles. The total energy absorbed was 5.1 kW sec per kV of rating.

For the test illustrated by the oscillogram of Fig. 7(b) the prospective voltage envelope was 1.61, 1.61, 1.34, 1.31, --- etc., decaying to 1.24 on the 8th cycle. In this case the arrester carried a maximum current of 450 crest amperes and absorbed a total of 5.3 kW sec per kV of rating. The current traces of both oscillograms indicate exactly the currents predicted from the valve element volt-ampere characteristic; therefore, it is clear that the heating from the energy dissipated had no adverse effect on the ability of the elements to limit current as the voltage returned toward normal.

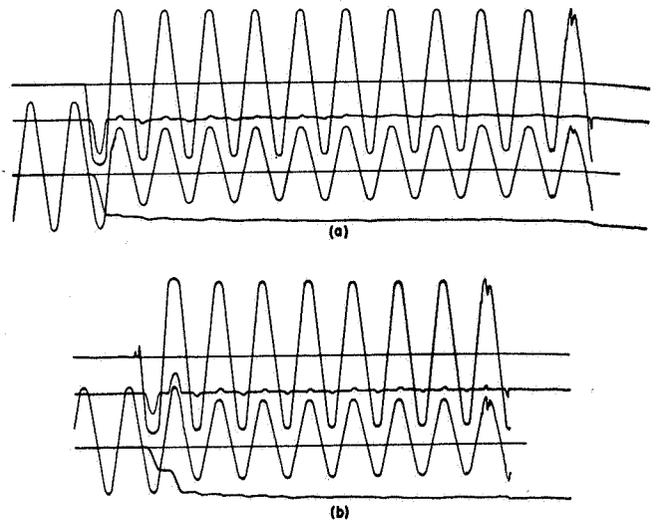


Fig. 7. Arrester operation in 60 Hz overvoltage circuit of Fig. 6. Traces, top to bottom, are arrester voltage, arrester current, source voltage ahead of surge impedance, arrester energy.

(a) Prospective voltages of 2.0, 1.32, 1.29, 1.26, etc. times rating. Max arrester current is 760 crest amps. Total energy is 5.1 kW Sec/kV of rating.

(b) Prospective voltage of 1.61, 1.61, 1.34, 1.31, etc. times rating. Max arrester current is 450 crest amps. Total energy is 5.3 kW Sec/kV of rating.

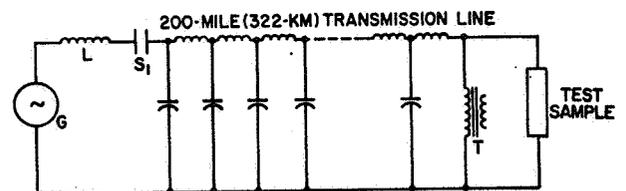


Fig. 8. Test circuit used to generate overvoltages by switching a transformer terminated transmission line.

G = Source Voltage
S1 = Synchronous Switch

L = Source Inductance
T = Unloaded Transformer

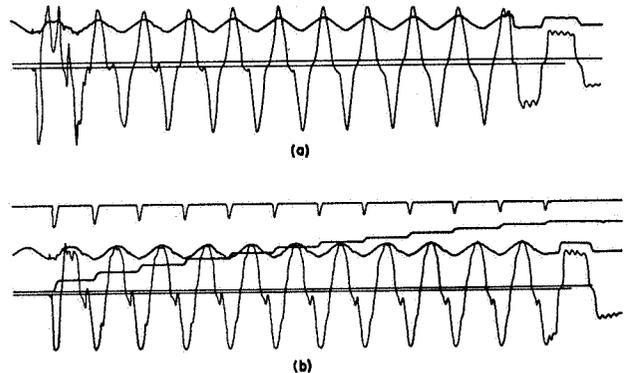


Fig. 9. Arrester operation on overvoltage circuit of Fig. 8. Traces, top to bottom, are arrester current, source voltage, arrester energy, arrester (or line end) voltage.

(a) No arrester connected, showing neg. half cycle prospective voltages at the arrester location of 1.59, 1.61, 1.23, 1.33, 1.40, 1.40, 1.37, etc. times arrester rating.

(b) Arrester connected, showing max. arrester current of 460 crest amps, total absorbed energy of 4.7 kW sec/kV of rating.

The test circuit of Fig. 6 is felt to be excessively severe because the applied voltage is a 60 Hz sinusoid whereas typical overvoltage phenomena with which the authors are familiar are always characterized by a significant harmonic content. The highly peaked nature of these more typical waveforms causes the arrester current for each half-cycle to be of much shorter duration than it would for a sinusoidal 60 Hz voltage and consequently the absorbed energy is significantly less. For this reason the test circuit of Fig. 8 was developed to allow testing of arrester samples under conditions very similar to those actually encountered in service. In this circuit an unloaded transformer terminated transmission line is suddenly energized from a 60 Hz source which is a condition leading to severe system overvoltages. With the test sample removed, the circuit parameters including source voltage, source inductance, switch closing angle, and transformer saturation characteristics can be adjusted to give the desired prospective voltage envelope.

The oscillograms of Fig. 9 illustrate tests with this circuit on a prorated section of an arrester designed to provide a switching surge protective level of 1.35 times arrester rating. The upper oscillogram shows that the prospective negative crest voltages are 1.59, 1.61, 1.23, 1.33, 1.40, 1.40, 1.40, 1.37, 1.34, 1.32, 1.30 times rating with the arrester disconnected. The lower oscillogram, with the arrester connected, shows a maximum arrester current of 460 crest amperes with a total absorbed energy of 4.7 kW sec per kV of rating. It is worth emphasizing that the absorbed energy for Fig. 9 is less than for Fig. 7(b) in spite of the fact that the protective level is lower, the prospective voltages are higher and, consequently, the currents are also significantly higher. As already indicated this is because the overvoltages are peaked rather than sinusoidal and it is believed that this is a far more accurate representation of the practical condition.

Temporary overvoltages sustained for many cycles may result from certain system conditions including line and transformer energization, resonance effects, or load rejection. In such cases the ability of an arrester to tolerate a sustained but moderate overvoltage is of interest.⁷ Fig. 10 is an oscillogram showing the new arrester designed for a switching surge protective level of 1.39 times rating subjected to a 60 Hz voltage of 120% of rating for 60 cycles. The upper trace shows an arrester current which settled down to about 14 amperes zero-to-peak after the first few cycles with no evidence of any distress at the end of the test. The total absorbed energy was only 3.1 kW sec per kV of rating. It will be noted on the oscillogram that within about three cycles after the voltage was applied the current had fallen to approximately one-third of the initial level. The phenomenon of an initial current in excess of the steady state value upon the sudden application of a 60 Hz voltage is a characteristic of the zinc oxide valve elements. It has been observed on all zinc oxide disks, but it is of no real consequence since it is significant only at relatively low currents. In the protective region of several hundreds of amperes, the effect nearly disappears as shown by the oscillogram of Fig. 11. In this test, a voltage was suddenly applied which forced a first half cycle current of 880 amperes and after 2-1/2 cycles the current was 850 amperes which is a reduction of only 3-1/2% from the initial level.

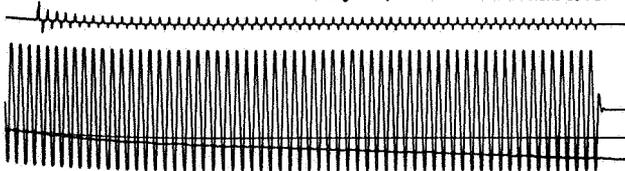


Fig. 10. Arrester operation for 60 cycles at 120% of rated voltage. Top trace is arrester current showing 27 amps P-P after first few cycles. Center trace is arrester voltage. Lower trace is arrester energy (final value is 3.1 kW Sec/kV of rating).

4. Capacitor Discharge Application

It has long been recognized by manufacturers and users of arresters that one of the more difficult applications for arresters is in locations adjacent to large capacitor banks. The basic reason for this is that as the capacitor is charged by the overvoltage source the conventional arrester draws no current until it sparks over. At the instant of sparkover the bank is effectively a zero impedance source charged to arrester sparkover and the arrester impedance is simply that afforded by the valve blocks at a voltage equal to the sparkover voltage. At this voltage the valve blocks will limit the current to no less than about 10 kA which must then be the initial discharge current into the arrester. Depending on whether or not the prospective overvoltage is greater than arrester sparkover, an additional current may be available to the arrester from the energy stored in the circuit inductance.² At this level of current the arcs will stick at the starting points in the gaps and they will not move away from the starting points until the current has dropped to around 1500 amperes or less. If the total charge transferred while the arcs are at the points of close electrode spacing is much more than one coulomb, severe electrode damage may result and restriking of the gap may occur.

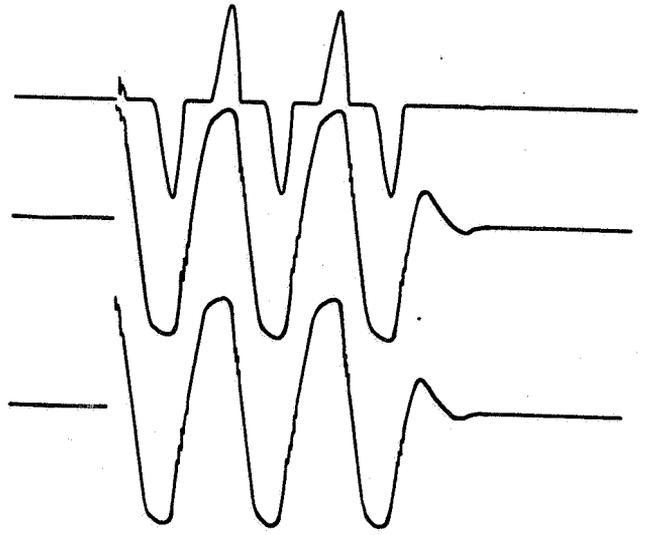


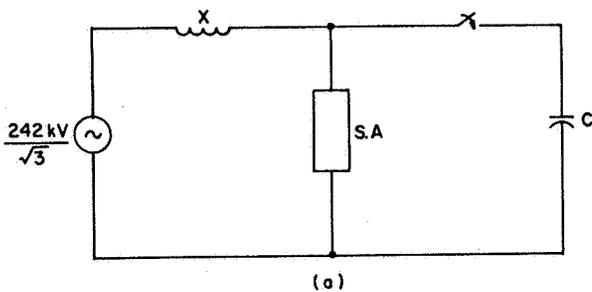
Fig. 11. Operation on a 60 Hz overvoltage set to force a current of about 900 amps. Top trace is arrester current (880 crest amps 1st half cycle, 850 crest amps on 5th half cycle). Lower two traces are arrester voltage.

The new zinc oxide arrester starts to conduct as soon as the voltage approaches the protective level and only enough current is drawn to hold the voltage to that level. The new arrester can be expected to pass much lower peak currents, absorb less energy and pass a lower coulomb charge than a comparable conventional arrester. The advantages of the new arrester in this application are clearly illustrated in Fig. 12 which shows the results of a digital computer solution for an idealized case. The circuit shown in Fig. 12(a) represents a 135 MVAR capacitor bank being switched from a 230 kV system having an available current of 15,000 amperes and protected by an arrester (A) rated 180 kV on the source side of the operating switch. The prospective voltage, had the arrester not conducted, is shown by the dashed lines on the oscillograms. The oscillogram of Fig. 12(b) illustrates a switch operation with a conventional arrester and with a sparkover of 382 kV, or 1.5 times rating, represented. The peak current drawn by the arrester was 12,400 amperes. The charge transfer through the arrester up to the time that the current dropped to 1500 amperes was about 1.1 coulombs, which is a significant duty. In contrast, as shown in Fig. 12(c) a representation of an arrester made without using series gaps, but using zinc oxide valve elements carried a current of only 1800 amperes while limiting the voltage to less than 1.39 times arrester rating. The energy absorbed by the arrester was only about 0.7 kW sec per kV of rating.

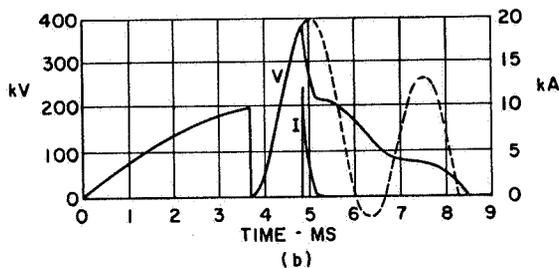
Clearly then in this application, the new arrester can provide superior protection while being subjected to far less duty than the conventional arrester. The reason is made clear by a study of the voltage oscillograms of Fig. 12. Although the zinc oxide arrester limits the voltage to a lower level than the conventional arrester, the voltage remains at nearly a constant level throughout the operation and the arrester extracts no more energy from the circuit than required to perform its protective task. On the other hand, the voltage across the conventional arrester falls to a lower level after sparkover. As a result, the conventional arrester absorbs much more energy and passes more coulombs than the zinc oxide arrester.

The ability of arresters of the new design to function properly in locations adjacent to capacitor banks was demonstrated by experience on a 12,470 volt system in the midwest. In 1973 a request was received from the utility to help them find a way to avoid failures of arresters (not manufactured by the authors' company) being caused by restriking of circuit breakers used to switch capacitors at frequent intervals. Arresters containing zinc oxide valve elements and with no series gaps were installed at two locations on the system, the locations being adjacent to switched capacitor banks of approximately 5.4 and 6.3 MVAR respectively.

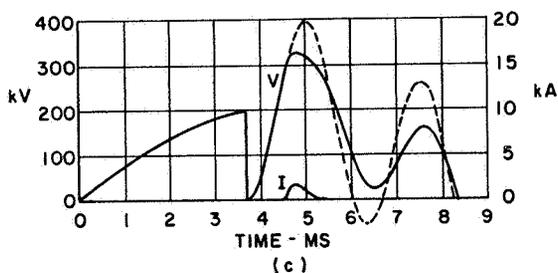
Discharge counters were installed with the new arresters and records kept of the counts recorded through the new arresters as well as on adjacent conventional arresters. The discharge counters on the adjacent conventional arresters virtually ceased to operate and those on the (6) new arresters recorded a total of 1063 counts over a 30 month period. In addition, none of the new arresters have been damaged by the discharge currents from the large capacitor banks. It must also be pointed out that the arresters supplied were of a very preliminary design and the present design incorporates significant improvements such as improved electrical strength and stability of the disks and an improved heat transfer design.



(a)



(b)



(c)

Fig. 12. Comparison of conventional and zinc oxide arresters adjacent to a capacitor bank.

- (a) Circuit representation
- (b) Conventional 180 kV arrester
- (c) Zinc oxide 180 kV arrester

STABILITY UNDER CONTINUOUS AC STRESS

A characteristic of the zinc oxide valve element is a tendency for the low current end of the volt-ampere characteristic to drift very slowly when the device is subjected to continuous AC voltage stress as illustrated in Fig. 13. The low current drift is in a direction which causes an increase in the watts loss under normal operating conditions, and this drift coupled with the positive temperature coefficient of watts loss of the disk makes it imperative that tests be made to demonstrate that the disks will exhibit long term stability at the designed operating stress and temperature. A considerable number of life tests have been made to prove disk stability. The tests were made at elevated temperatures and several AC voltage stress levels with periodic measurements of watts loss during the tests.

The following test information was obtained.

a) For a given test voltage and temperature the normalized watts loss plotted on a logarithmic scale increases linearly with the square root of time after some initial elapsed time, usually several hundred hours, during which a slight decrease in watts loss is often obtained. This relationship is illustrated in Fig. 14. The linear relationship has been confirmed out to 6000 hours (at the time of this writing) at elevated temperatures of up to 115°C and the tests are continuing. The 6000 hour test time at 115°C is equivalent to about 5 million hours at an expected maximum weighted average temperature of 45°C.

b) Tests at various temperatures and several stress levels confirm that the rate of increase in watts loss vs temperature follows the well-known Arrhenius relationship for thermally activated phenomena. That is, the logarithm of the time required for a specific change in a given characteristic is a linear function of the reciprocal of the absolute temperature (K°). This relationship has been widely used in most types of life testing of thermally dependent electrical materials. This is illustrated in the plot of Fig. 15 showing the time required for a doubling of the watts loss vs reciprocal temperature at the operating stress level for a 72% arrester application.

Studies have shown that the maximum weighted average temperature for an arrester operating in a hot climate with long exposure to direct sunlight as experienced in locations such as Phoenix, Arizona would be approximately 45°C (115°F). This weighted average was obtained by determining the expected temperature-time profile for the porcelain housing for a typical day in each of the four seasons of the year. These data were then operated on in accordance with the slope of the Arrhenius curve of Fig. 15 to obtain the overall weighted or effective temperature for a severe application. Fig. 15 shows that approximately 200 years will be required for the watts loss of a 72% arrester to double from the original value. The watts loss for the zinc oxide arrester will be approximately 0.15 watts per kV of rating at 25°C. This is only two-thirds of the loss for an existing conventional design.

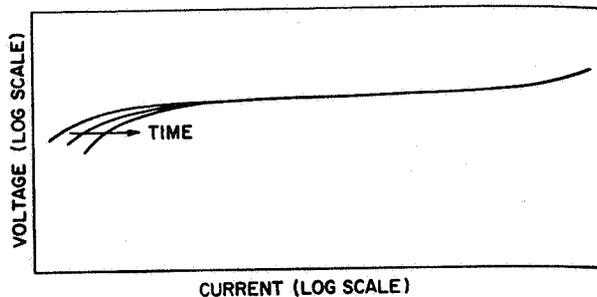


Fig. 13. Illustration of drift in volt-ampere characteristic with time while under a continuous AC voltage stress.

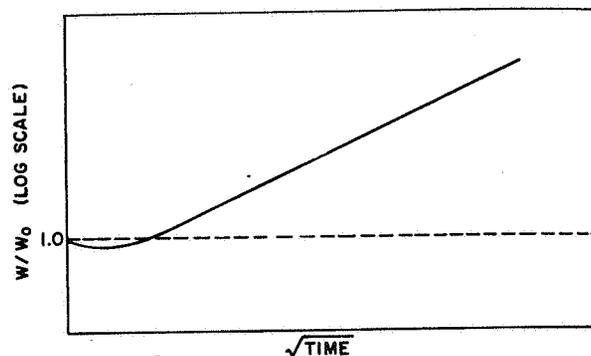


Fig. 14. Illustration of watts loss vs. time for a continuous AC voltage stress at elevated temperature.

EFFECT OF IMPULSE DISCHARGES AND HIGH ENERGY SURGES

When the zinc oxide disks are subjected to short duration impulse (lightning) discharges or to high energy long duration (switching surge) discharges the low current end of the volt-ampere characteristic curve is shifted to the right causing a temporary increase in watts loss much as illustrated for a long term stress in Fig. 13. For example, the watts loss roughly doubles as a result of 20 applications of 10 kA, 10 x 20 μ sec waves. The watts loss is increased by approximately a factor of 1.5 by the application of twenty 1000 ampere, 2 millisecond switching surge discharges.

In all cases, however, the effect is temporary. Since station type arresters are rarely subjected to more than a few discharges of significant magnitude per-year, such discharges will not affect the operating condition of the arrester.

SURGE ENERGY CAPABILITY

For any single event the disks designed for arresters rated 312 kV and lower are capable of absorbing 9 kW sec./kV of rating. For example, a single 1000 ampere discharge of about 4 millisecond duration is permissible. Any greater energy absorption in a single operation may result in disk cracking from thermal shock. After absorbing up to 9 kW sec./kV of rating in a single operation, an interval of 1 to 2 minutes is sufficient to permit equalization of temperature throughout the disk, after which additional energy absorption is permissible up to the limit imposed by transient thermal stability. Some perspective on energy absorption capability may be gained by noting that the stored energy in the line used to perform the standard transmission line discharge test⁵ for 345 kV system arresters is less than 4.5 kW sec./kV of

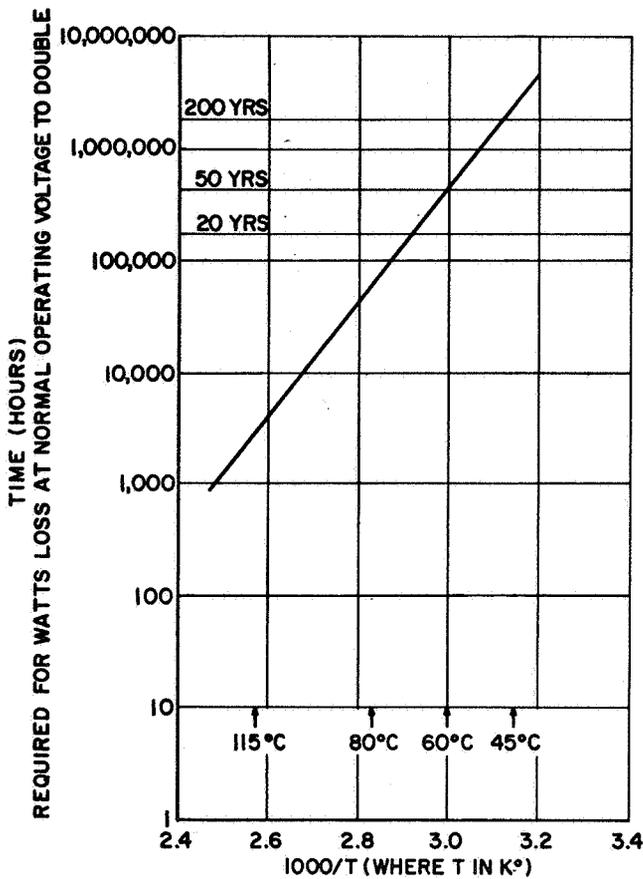


Fig. 15. Arrhenius plot of zinc oxide valve element life vs. reciprocal temperature with a 60 Hz operating voltage.

arrester rating, and the energy actually discharged by a 72% zinc oxide arrester is less than 3 kW sec./kV of rating.

Zinc oxide valve elements exhibit a positive temperature coefficient of watts loss as shown by Curve 1 of Fig. 16. Such a relationship between watts loss and disk temperature makes it necessary that the design incorporate an adequate heat transfer mechanism to insure that the watts loss at operating voltage will not be driven beyond the dissipation capability. To insure stability following high energy discharges, the arrester has been designed with the relatively massive porcelain housing serving as a heat sink for the disks, resulting in a heat transfer capability in accordance with Curve 2 of Fig. 16. Curve 2 of Fig. 16 was determined for a porcelain temperature of 60°C which is the short-time maximum temperature anticipated in a location such as Phoenix, Arizona. Curve 1 gives the watts loss versus disk temperature for normal operation. Curve 3 is Curve 1 with doubled watts loss at each temperature to represent a possible loss condition that could be attained after a large number of years of operation at elevated temperature and soon after being subjected to severe discharges. The continuous operating point for a new arrester with a characteristic in accordance with Curve 1, and with a porcelain temperature of 60°C, is at the lower crossover point of Curves 1 and 2 (0.28 watts per kV of rating and 63°C). When the arrester discharges surge energy, the disk temperature will rise by approximately 7.6°C per kW sec./kV of rating. As shown by Fig. 16, instability would theoretically occur if the disk temperature was raised to the upper crossover point of Curve 1 and 2 (when the watts generated in the disk equals the heat transfer capability of the design). This point is 135°C above the operating point (lower crossover of Curves 1 and 2) so surges of a total energy equal to $135/7.6 = 17.7$ kW sec./kV of rating can be tolerated. This is over three times the energy absorbed from operation in the overly severe test circuit of Fig. 6, nearly four times the energy absorbed from operation in the more realistic circuit of Fig. 8, and approximately 3 times the total energy absorbed in a 24 operation standard duty cycle test. Furthermore, 17.7 kW sec./kV is approximately twice the maximum discharge energy that can be absorbed in a

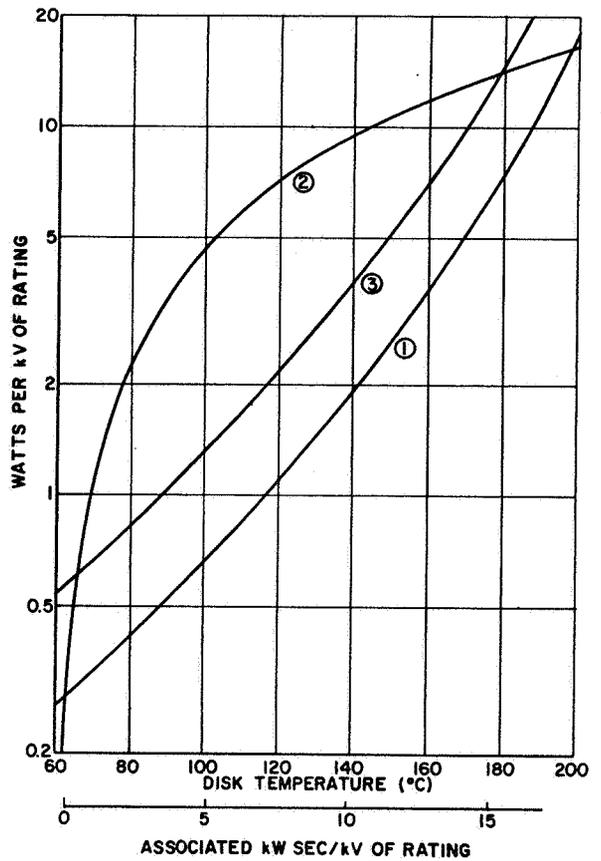


Fig. 16. Watts loss and dissipation characteristic curves.

1. Watts loss vs. temp. at operating voltage (72% arrester application).
2. Thermal dissipation capability of the arrester.
3. Possible watts loss vs. temp. after many years of service.

single operation without causing thermal shock failure of the disks. Even in the extreme case of operation based on Curve 3 of Fig. 16, the allowable energy absorption is 14.8 kW sec./kV of rating which is well above the capability of the conventional arresters.

From the above, it can be concluded that the new arrester will give excellent performance even under the most severe switching overvoltage situations.

CONTAMINATION PERFORMANCE

A major problem which has confronted arrester users over the years is the possibility of arrester damage and even failure when the arresters are applied in severely contaminated environments. With conventional arresters the problem is basically the possibility the sparkover may be depressed to operating voltage levels at least for short periods of time. The power follow current, normally associated with each operation can very quickly cause overheating of the arrester and possible failure through loss of clearing capability.

The ANSI Standard contamination test¹ can be passed very easily by the new design. Because the standard test produced practically no effect, more demanding tests were performed. The arrester was contaminated using multiple coatings, with drying between applications, of a 400 ohm-cm slurry as specified in the ANSI Standard except that Cabosil was substituted for Bentonite in order to obtain a more tenacious coating. Wetting was accomplished in a polyethylene tent using steam pots. Voltage was removed from the arrester for approximately 30 minutes after application of the fog in order to wet the arrester thoroughly. When operating voltage was applied, leakage current pulses exceeding 100 milliamperes were measured, and occasional

external flashovers occurred. At a level of fog wetting selected to produce maximum leakage current pulses of 50 to 100 milliamperes, the arrester was energized for several hours. Temperature measurements on the internal parts showed a low level of heating well within tolerable limits. Contamination-test performance of the new design compared with test experience of existing designs, which have performed very satisfactorily in service, indicates that the new design has outstanding capability to withstand the effects of very severe external contamination.

CONCLUSIONS

1. The development of zinc oxide based non-linear resistors has progressed to the point where large high energy disks are now available permitting the manufacture of all ratings of station type surge arresters without series gaps and with protective characteristics superior to present designs.
2. The new arrester offers some very significant advantages:
 - a) Improved reliability due to simplicity of the design;
 - b) Superior protective characteristics.
 - c) Minimum energy absorption commensurate with the protective levels provided;
 - d) Superior performance compared to present arresters on low impedance circuits (e.g. cable and capacitor applications);
 - e) Gentle operation — protected equipment is not subjected to sparkover transients;
 - f) Superior energy absorption capability compared to presently available arresters.
3. Extensive tests have demonstrated a performance which is entirely satisfactory.

ACKNOWLEDGEMENT

The authors wish to gratefully acknowledge the following individuals who contributed significantly to the success of this work: Herbert Fishman, Howard Ellis, and Dr. Lionel Levinson, all of the General Electric Company.

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Discussion

Bernard F. Wirtz, (Cleveland Electric Illuminating Co., Cleveland, OH): The authors' new arrester without gaps is very suitable for installation inside of an SF₆ gas insulated substation. Eliminated is the concern that a leak would allow SF₆ gas to enter the gap chamber and change the protective characteristics of the arrester. Are the authors in a position to comment on this new arrester in GIS installations?

In the section dealing with "Stability on Continuous AC Stress", the authors demonstrate the arrester's capability in a "Phoenix" weighted average ambient temperature of 45 degrees C. Would the authors comment on the suitability of the new arrester, if installed in metalclad switchgear, where the air inside of the cable exit compartment is allowed to reach 55 degrees C while the equipment is carrying rated continuous current and the outside or room ambient temperature is 40 degrees C? (See ANSI C37.020-4.4.5(1).) Under emergency conditions, when

currents may exceed the rated values, the temperature inside of the enclosure will be higher, perhaps by 5 or more degrees C.

Similarly, the total temperatures of conductors and of the current carrying parts of circuit breakers and disconnecting switches, etc., are allowed to reach 105 degrees C at rated conditions and often 125 degrees C under emergency conditions. Can the arrester accommodate these temperatures at its connection terminal, or are other measures required?

In capacitor bank applications, the new arrester's unique features of turning on smoothly before the voltage approaches the sparkover level of contemporary arresters and of its ability to control restrike voltages without absorbing excessive energy are welcome as we continue to load up our 37 kV substation buses with 160 MVAR's of capacitors. We use arrester counters to monitor all arresters and to run down any restrike problems on the capacitor switches operated daily. Could the authors indicate at what minimum level of arrester voltage and current the counter will register a count with their new arrester?

On all station type arresters we have required pressure relief devices. The authors do not mention pressure relief devices. How do the authors handle this protective requirement?

Orin W. Queen (Dayton Power and Light Company, Dayton, OH): This paper presents the development and testing of a new surge arrester which is the first significant improvement in a number of years. It overcomes the main disadvantage of the current limiting gap arrester by improving performance on low impedance circuits. The volt-time characteristic is so good in the 0.1 to 1.0 microsecond area that the need for front-of-wave impulse testing of transformers might be eliminated. The high overvoltage capability of the new arrester will make it possible to use a lower voltage rating in some application which will give both better protection and a lower cost. Shipping damage and damage due to vibrations when mounted on transformers have been a problem in the past. What has been done to the new arrester to eliminate these problems? What tests are recommended on the new arrester to determine that it is satisfactory for continuing service? Leaking seals are still a surge arrester problem. What is the affect of moisture on the new valve element? The elimination of gaps should improve the radio and TV interference problems. Were any tests made to confirm this performance? The Author's Company has developed a new arrester which should be of considerable value to the Electrical Utility Industry. I congratulate the Authors on a very informative and complete paper.

Manuscript received August 9, 1976.

J. C. Osterhout and A. Sweetana (Westinghouse Electric Corporation, Bloomington, Indiana): The authors are to be commended for their early publication of data on a zinc oxide based surge arrester, particularly of the station class.

The protective level of 1.6 times arrester rating at 10,000 amperes as indicated, is approximately the same as presently available state of the art arresters. To maintain the protective level at higher currents, the authors require paralleling of a small portion of the disks "with properly coordinated shunt gaps". It is clear from this requirement that the non-linear exponent of the zinc oxide disk is not high enough at this stage of development to permit a truly gapless arrester. Our calculations indicate that the authors have achieved a non-linear exponent of approximately 26. Depending on protective level to be achieved, an exponent of approximately 50 is required for a truly gapless arrester. It would appear that the suggested interim hybrid device may have limited practical use particularly if an economic premium is to be paid.

The Westinghouse Electric Corporation has also utilized its own funds and technical resources for several years and recently joined in a cooperative effort with the utility industry, through EPRI, to leapfrog this hybrid stage; setting as an objective a true gapless device with a protective level of 1.5 P.U. of maximum line to ground voltage (approximately 1.2 P.U. of arrester rating based on an 80% arrester) at 26,000 amperes.

Will the authors please comment on the following questions:

1. In regard to the effect of impulse discharges and high energy surges — The authors state the volt ampere characteristic is shifted due to high current impulses, "in all cases, however, the effect is temporary". The Japanese literature for example, "Gapless Lightning Arresters for Power Systems" written by Syuniti Hieda, Misao Kabayasi et al, UDC 621.316.9; Meiden Review, Series No. 46 1975 No. 2, state that a thermal treatment of 150°C for 3 hours is needed to restore the change to within 3%, beyond which it cannot be corrected. Thermal treatment is also indicated in, "High Voltage ZNR Surge Absorber" by Matsuoka, Eda et al, in *National Technical Report*, Vol. 21, No. 1, Feb. 1975, pp. 109-122. Have the authors encountered this phenomena in the

Manuscript received August 12, 1976.

Manuscript received July 19, 1976

course of their development? Have they examined the effect at higher current levels, say 20,000 amperes? Does temporary mean seconds? hours?

2. Since no photographs or dimensions were given, can the authors indicate a relative or comparative size and weight of the zinc oxide based hybrid arrester with a conventional modern arrester.

3. Can the authors give an indication of the actual number of poles in service and time in service on 230 kV or higher voltage systems?

4. It is not clear what the apparent exponent of the discs or total hybrid device is to currents higher than 10,000 amps. ANSI C62.1-1975 requires measurement of discharge voltage through 20 kA, and it is common industry practice to publish protective characteristics through 40 kA for station class arresters. Can the authors achieve present arrester level of protection at 20, 40, 65 kA with the shunt gap approach, yet leave enough discs in the circuit for power current interruption at maximum system voltage?

D. J. Melvold (Department of Water and Power, Los Angeles): The authors are to be commended for developing what appears to be an arrester with characteristics closely resembling the long sought "ideal" arrester. This arrester appears to make the controversy over the correct lightning current level to use for station insulation coordination a rather moot point.

Our interest, however, extends beyond the use of the arrester on ac systems to which the authors have directed their discussion. Have the authors extended their investigation to the application of this arrester to dc systems? If so, could they elaborate to some extent on their studies to date? Offhand, it would appear from the more horizontal volt-ampere characteristic, that the potential for considerable reduction in margins is possible in dc installations along with better coordination with such devices as thyristor valves. With regard to the latter, the more "gentle operation" — i.e. no ΔV as occurs subsequent to sparkover in conventional arresters — would be desirable, e.g., across the smoothing reactor.

In addition, with regard to dc applications, it is noted that under the section on Stability Under Continuous AC Stress, the authors specifically state "ac". What if the stress were essentially a dc voltage?

Would the authors comment on the possibility of using this arrester instead of a resistor in a circuit breaker for overvoltage suppression or using a zinc-oxide resistor within either ac or dc circuit breakers?

Lastly, what is the comparative size and weight of this arrester in relation to a conventional arrester of the same rating?

Manuscript received August 16, 1976.

U. Burger, H. P. Klein, and B. Knecht (BBC Brown, Boveri and Co., Ltd., Baden, Switzerland): The report shows that the new nonlinear resistance material based on zinc oxide is able to perform as a high voltage arrester. The main advantages of these nonlinear resistors are the simplicity of their mechanical assembly (a sintered body is the only active part) and their favourable characteristic which allows no follow current and minimizes the energy absorbed by the arrester.

The following comments should however be made:

For a residual voltage at 10,000 A of $1.6 \times$ crest arrester rating the nonlinear resistor has to be used in the flattest part of the current-voltage characteristic i.e. from Fig. 3 between a current density of 10^{-5} A/cm² and 10^2 A/cm²; above and below these values the slope of the *I-V*-curve increases very quickly^{1,2}. This implies a minimum cross-section of the zinc-oxide ceramic of 100 cm². Let us as an example consider a 1 kV arrester (RMS rating), which we want to use in an application where the residual voltage at 10 kA is $1.6 \times$ crest arrester rating = 2263 V. We therefore write for the current-voltage characteristic

$$I = 10^4 (V/2263)^\alpha$$

and from Fig. 3 of the paper we see that $\alpha = 26$ over the current range of interest. For a sinusoidal applied voltage, the watts loss can be calculated as

$$W = 4.56 \cdot 10^{-85} \hat{V}^{27} \text{ Watts.}$$

If the crest applied voltage \hat{V} is equal to the crest arrester rating 1414 V, the watts loss is therefore 5 W.

Thus for any arrester of this type the watts loss with an applied voltage equal to the arrester rating is 5 W/kV of rating at room temperature and presumably more at higher temperatures. If we plot the corresponding point on Fig. 16, we see immediately that it lies well above the thermal dissipation capability curve; therefore such high losses

Manuscript received August 16, 1976.

cannot be dissipated. Thus the arrester can work at this voltage for a very short period of time only, otherwise thermal runaway will set in. Application for a significant period of time of a voltage equal to the arrester rating is only possible if one allows the ratio of residual voltage at 10,000 A to the crest arrester rating to be about 2.2 instead of 1.6.

It should be emphasized that Fig. 15 is only valid for ac applied voltage. From the data sheet for small GE-MOV® for low power applications the deterioration under applied dc voltage is considerably more severe as well as faster. Thus HVDC applications of these new elements of these new elements requires further studies.

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E. C. Sakshaug, J. S. Kresge, and S. A. Miske, Jr.: The authors wish to thank those who have submitted discussions to the paper.

Mr. Wirtz has pointed out some of the potential advantages of the new arrester in gas insulated substations. While we believe that the new arrester will be well suited to this application, we have not yet proven that zinc oxide valve elements will operate in a stable manner in an SF₆ atmosphere. Tests are being made to assess this capability. Metal clad switchgear installations, in common with other installations, must be considered in terms of weighted average temperature rather than maximum. The maximum porcelain temperature in the Phoenix area is expected to be 60°C, and exposure to this temperature or even higher temperatures for short times is not a matter of concern as long as the weighted average temperature does not exceed 45°C for a 72% arrester application. If the weighted average temperature is higher than 45°C, it may be necessary to increase the arrester rating to compensate for the increased temperature if a service lifetime approximating that shown by Figure 15 is expected. Temperature weighting is accomplished by noting that the temperature effect doubles for each 6°C rise in temperature. That is, 5 hours at 50°, 9 hours at 44°C and 10 hours at 38°C yields an average weighted temperature of 44°C for a 24 hour period as compared to an arithmetic average of 42.75°C. The effect of high temperatures of current carrying conductors on the arrester temperature must be considered, and it would probably be desirable to separate the arrester terminal from the high temperature conductors by a few inches of lead length of relatively small diameter wire.

It is not possible to comment on the current sensitivity of counters supplied by other manufacturers, but the counter marketed by the author's company will count for discharges exceeding approximately 500 microcoulombs. This is equivalent to an average current of 50 amperes for 10 microseconds.

The new arrester will be equipped with a pressure relief arrangement similar to that used in conventional designs. Pressure venting will be accomplished by means of pressure sensitive diaphragms with arc gas directing arrangements made to cause external flashover for high failure currents.

Messrs Burger, Klein and Knecht have calculated correctly that the watts loss at rated voltage for a gapless arrester with a characteristic as shown illustrated in Figure 3 is in the range of 5 watts. It is important to note that high voltage arresters, certainly those designed for operation on systems rated 230 kV or higher, do not operate at rated voltage for longer than the several cycles required to clear a line-to-ground fault. Normal operating voltage for a high voltage arrester is approximately 80% of rating, and as stated in the paper, the watts loss at normal operating voltage is approximately 0.15 watts per kV of rating. The arrester will pass the ANSI C62.1 Standard duty cycle which requires that the arrester be held at rated voltage while it is subjected to impulses of 10,000 ampere magnitude with the impulses spaced one minute apart, and this is the definition of arrester voltage rating provided by the ANSI Standard. This method of performing the duty cycle test is, of course, more severe than that given in IEC 99-1 which permits the arrester to be deenergized between impulses. As indicated in the paper, moreover, the residual voltage at high impulse current can be reduced by shunting a small percentage of the valve element with gaps arranged to spark over on high current surges. This permits an increase in the valve element resistance to reduce the steady state heating while maintaining the desired residual voltage characteristics, and allows the ratio of operating voltage to residual voltage to be changed within reasonable limits.

The efforts of Messrs Osterhout and Sweetana to improve the exponent of zinc oxide material beyond its present state of development are commendable. It is our hope as well that valve disks having further improved exponent characteristics will be developed in the future; however, as has been shown in the paper, arresters designed using the zinc oxide disks that have been developed have protective characteristics and reliability superior to existing conventional arresters. It is doubtful

Manuscript received September 22, 1976.

that the utility industry is prepared to accept and take full advantage of arresters having a protective level of 1.2 times rating at 26,000 amperes. On the other hand, the curve of Figure 3 shows that the ratio of protective level to rating may be improved by increasing the disk cross section, and this effect together with the judicious use of shunt gaps could result in an arrester having approximately the protective levels being sought by Messrs. Osterhout and Sweetana.

Thermal treatment of disks to restore a temporary change in low current characteristics is neither necessary nor practical in an arrester designed using the disks described in the paper. There is no shift whatever in protective characteristics because the disk characteristics do not change at high current. The low current shift lasts for a few days and is small, and needs only to be taken into account in the design of the heat transfer system.

The only arresters of this design in service now are those involved in the protection of the capacitor banks referred to in the paper. It is of interest to note that three of the arresters from this installation were returned for inspection after approximately three years of service. Laboratory tests revealed no change in characteristics after over 1000 operations had been recorded even though the valve elements in these arresters were not nearly stable enough to meet our present stability criteria. Field experience can be very revealing if laboratory work is not carefully done, but it is rare that a combination of environmental and system conditions can be found which will stress an arrester sufficiently to demonstrate in a reasonable length of time that the arrester will have a good field service record.

As would be expected from the shapes of the zinc oxide and silicon carbide curves shown in Figure 3, the level of protection of an arrester made using zinc oxide valve elements is better than that obtained using silicon carbide valve elements at currents above 10 kA when the level of the two arresters is the same at 10 kA.

We thank Mr. Queen for his comments, and we agree with the points he has made. Mr. Queen has asked several questions regarding reliability. The new arrester will be much less susceptible to shipping and vibration damage than older designs because of construction simplicity. In addition, the heat transfer arrangement is used to

provide extremely effective shock mounting. The new valve element is not affected by moisture, and although the housings will be sealed, it is very probable that a sealing system is not necessary. Field tests recommended for a demonstration of serviceability are leakage current measurements at operating or rated voltage. Leakage current measurements are very effective for the new arrester because the operating components are being measured whereas a leakage current test on a conventional arrester measures the condition of a grading system in parallel with the operating components. Tests have indeed confirmed that potential radio and TV interference are considerably reduced.

Mr. Melvold's interest in DC applications is appreciated. Stability under operating stress is known to be a function of wave shape, and applications of DC arresters without series gaps will be made only after the completion of adequate stability studies using proper representations of applied voltage wave shapes. The actual wave shapes encountered in practical DC systems are sufficiently complex and varied to require rather extensive studies. We agree that there should be significant advantages gained by the use of zinc oxide arresters in DC applications for the reasons Mr. Melvold has mentioned. It was announced by the author's Company in 1975 that the DC arresters recently supplied for two DC projects utilized zinc oxide valve elements, but included series gaps to isolate the valve elements from operating voltage. Gaps were included in these designs because sufficient knowledge of the effects of the voltage waves to be applied to these arresters had not yet been obtained. The use of zinc oxide valve elements permitted a considerable simplification of the series gaps, an improvement of protective characteristics and a reduction in arrester size compared to the arresters supplied for the West Coast DC Intertie.

It is reasonable to expect that there might be a considerable advantage in using zinc oxide resistors for surge suppression in both DC and AC circuit breakers.

The heights of the new arresters are approximately the same as the heights of conventional arresters because these heights tend to be set by strike and creep requirements. Weights are in the range of 2/3 to 3/4 of the weights of conventional arresters because of the reduction in procedure diameter.