Coordination of Surge Protectors In Low-Voltage AC Power Circuits

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Significance:
Part 4 – Propagation and coupling of surges
Part 8 – Coordination of cascaded SPDs

This paper presents a summary of two earlier and detailed proprietary General Electric reports describing experiments conducted in Schenectady NY and in Pittsfield MA, respectively by Martzloff and Crouch. (These have now been declassified by General Electric and are included in this Anthology – see Coordination 1976 and Propagation 1978.) The prime purpose of that paper at the time was to report in a non-classified platform experimental results that could be useful for the development of IEEE Std 587 (later known as IEEE Std C62.41).

In the first experiment, a simple test circuit of two branch circuits originating at a typical service entrance paper was subjected to relatively high-energy unidirectional impulses, with various combinations of surge-protective devices installed at the service panel and/or at the end of the branch circuits. That 1976 experiment was the beginning of recognition of the "cascade coordination" issue that became the subject of intense interest in the 80's and 90's (see the listing of contribution by many authors in Part 1, Section 8).

In the second experiment, the coupling and subsequent propagation of surges was investigated in a more complex circuit that included a distribution transformer, service drop, entrance panel, and several branch circuits. The surge was injected in the ***grounding system, not into the phase conductors***. This experiment thus brought new evidence that ring waves can be stimulated by unidirectional surges. Nevertheless, the threat was considered at that time as a surge impinging onto the service entrance from the utility, not resulting from a direct flash to the building grounding system. On that latter subject, see Dispersion and Role of SPDs.

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COORDINATION OF SURGE PROTECTORS IN LOW-VOLTAGE AC POWER CIRCUITS

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Abstract - Surge protectors can be installed in low-voltage ac power systems to limit overvoltages imposed on sensitive loads. Available devices offer a range of voltage-clamping levels and energy-handling capability, with the usual economic trade-off limitations. Coordination is possible between low-clamping-voltage devices having limited energy capability and high-clamping-voltage devices having high energy capability. The paper gives two examples of coordination, as well as additional experimental results on surge propagation.

1. INTRODUCTION

Surge voltages occurring in low-voltage ac power circuits have two origins: external surges, produced by power system switching operation or by lightning, and internal surges, produced by switching of loads within the local system. Typical voltage levels of these surges are sufficient to cause the failure of sensitive electronic appliances or devices, and high surges can cause the failure of rugged electromechanical devices (clocks, motors, and heaters) [1,2].

For many years secondary surge arresters from a number of manufacturers have been available. These arresters are effective in protecting nonelectronic devices against the high-voltage surges associated with lightning or power system switching. However, the voltage allowed by an arrester is still too high for sensitive electronic devices. Furthermore, installation requires an electrician to connect the device on hot terminals.

The advent of the metal oxide varistor packaged as a convenient plugin device or incorporated into the appliances makes possible a voltage clamping which is more effective than that of the conventional secondary arrester. However, the energy-handling capability of such packages is lower than that of an arrester, so that large currents associated with lightning strikes cannot be handled by these packages.

The availability of these two different types of suppressors now makes it possible to obtain a coordinated protection of all the appliances in a home or all the equipment in an industrial environment. Improper coordination, however, could force the lower voltage device to assume all the current, leaving the high-energy protector uninvolved; this situation could then cause premature failure of the low-voltage suppressor. This paper discusses the elements of a coordinated protective system based on experimentation.

II. SECONDARY ARRESTERS AND LOW-VOLTAGE SUPPRESSORS

Typical secondary arresters for 120 V service consist of an air gap in series with a varistor made of silicon carbide. The device is generally packaged with two arresters in the same housing; the physical arrangement is designed for installation on the outside of a distribution panel, through a knockout hole of the panel enclosure or at the entrance to the building.

Limitations on the gap design imposed for the purpose of reliable operation and clearing after a high current discharge (10 kA, 8 x 20) do not allow the sparkover of the gap to be less than about 2000 V. This sparkover and the time required to achieve it allow injection of a potentially damaging surge into the "protected" power system downstream from the arrester.* While this 2000 V level provides better protection than the protective characteristics indicated in ANSI standards [3], lower voltage clamping is desirable for the protection of sensitive electronics.

Metal oxide varistors suitable for 120 V line applications can clamp surge voltages at less than 1000 V, typically at 500 to 600 V for surge currents of less than 1000 A. These varistors provide excellent protection for electronic systems. The economics of device size, however, limits the wide use of large varistors, especially since smaller varistors can do an acceptable job if they are not exposed to excessive currents. Proper coordination among the devices used is required to obtain a reliable protection system.

III. PROTECTION COORDINATION

While the installation of surge protective devices functions effectively for high-voltage utility systems coordinated by centralized engineering, the current trend toward regulatory installation in low-voltage systems, because they are seldom centrally engineered and coordinated, can result in damaged equipment and system failure. The successful application of protective devices to a low-voltage system demands a perspective of the total system, as well as a knowledge of individual device characteristics. Where such knowledge and coordination are lacking, a low-voltage suppressor installed in conjunction with an arrester can prevent the voltage at the terminals of an arrester from reaching its sparkover level. As a result, all of the surge current may be forced into the suppressor, which may not have been intended to withstand extreme conditions.

Proper coordination in an arrester/suppressor system requires some impedance between the two devices. This impedance is generally provided by the wiring: at the beginning of the surge, the rapidly changing current produces an inductive voltage drop in this wiring, in addition to the drop caused by the resistance of the wiring. Thus, the voltage at the terminals of the arrester during the current rise of the surge is equal to the clamping voltage of the suppressor, plus the voltage drop in the line (tests reported below indicate that this voltage drop is indeed appreciable). This voltage addition can then raise the terminal voltage of the arrester sufficiently to reach sparkover. In this way the arrester will divert most of the surge current at the entrance, rather than permitting it to flow in the suppressor.

The application of a suppressor alone is likely to occur because electronic appliance manufacturers increasingly provide suppressors incorporated into their products. With no arrester at the service entrance, the wiring clearances can become a voltage-limiting device, thus establishing a clearance/suppressor system. The suppressor would again tend to assume all of the surge current flow. The voltage drop in the line, in a manner similar to that of the arrester/suppressor system, would raise the voltage at upstream points to levels that may spark over the clearances of wiring devices, providing unplanned relief for the suppressor. When sparkover of the clearances occurs, there are three possible results:

a. A power-follow current occurs, with destructive effects on the components.
b. A power-follow current occurs, but overcurrent protection (breaker or fuse) limits the damage. The system can be restored to operation after a mere nuisance interruption.
c. No power-follow current takes place; the overvoltage protective function of the system can be considered as accomplished.

The concept of protecting solid insulation by allowing clearances to spark over first is actively promoted by the Low Voltage Insulation Coordination Subcommittee of the International Electrotechnical Commission [4]. Further discussion of it is outside the scope of the present paper; nevertheless, the concept is worth attention because cost reductions and system reliability could be obtained through its proper application.

Two examples of protection coordination will now be discussed in detail. These examples represent two scenarios on surge injection; they are based on experiments involving an arrester and suppressors in simulated lightning surge conditions. In the first scenario the surge is assumed to be injected between one of the phase wires and the center conductor (ground) of the service entrance. In a second scenario the surge current is assumed to be injected directly into the ground system of a service entrance only. Both experiments show the benefits and importance of proper coordination. In both tests the arrester was a gap-silicon carbide combination (Fig. 1) and the suppressor, a metal oxide varistor in a plugin package (Fig. 2).

IV. SURGE APPLIED BETWEEN PHASE AND GROUND

Test Circuits

The test circuit (Fig. 3) consisted of a terminal board from which two lines, one 7.5 m (25 ft) long and the other 30 m (100 ft) long were strung in the test area. A short, 3 m (10 ft), line simulated the service drop. All of these lines were made of three-conductor, nonmetallic, #12 AWG sheath wire. The neutral and ground wires of the three lines were connected together at the terminal board and from there to the reference ground of the test circuit.

*In this paper the high-energy suppressor, typically installed at the service entrance, will be called *arrester*. The low-energy, low-voltage suppressor, typically installed at an outlet or incorporated into an appliance or connected load, will be called *suppressor*.

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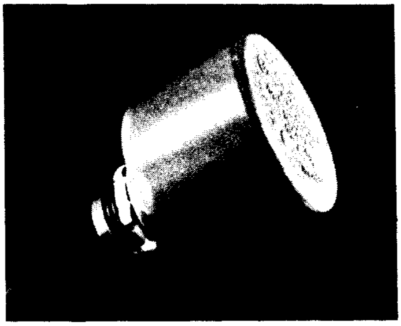


Fig. 1. Typical arrester for service entrance installation.

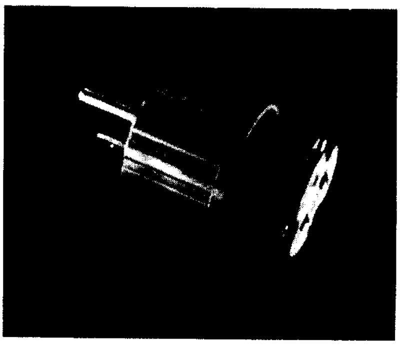


Fig. 2. Typical suppressor for plugin installation.

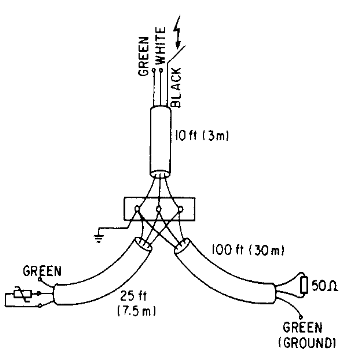


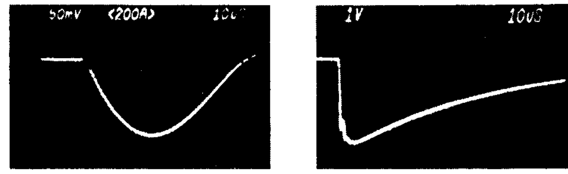
Fig. 3. Test circuit.

All surge currents were applied between the line conductor (black) at the end of the service drop and the reference ground (green and white). These impulses were obtained from a 5 μF capacitor charged at a suitable voltage and discharged into the wiring system by an ignitron switch. The resultant open-circuit voltage waveform, a unidirectional wave of 1 μs rise time x 50 μs to one/half value time, corresponds to the standard test wave in utility systems. Fig. 4 shows typical open-circuit voltage and short-circuit current waveforms. Voltages were recorded by a storage oscilloscope through an attenuator probe (1000:1); currents, through a current probe and a current transformer. Thus, the calibrations displayed on the oscillogram are to be multiplied by 1000 for the voltage. The current traces show the 50 mV setting corresponding to the rated output of the current probe, with the amperes per division shown in parentheses corresponding to the current transformer ratio and current probe input setting for a direct reading. The sweep rate is also shown on the oscillograms, at 10 μs/div. for all the tests.

Test Results

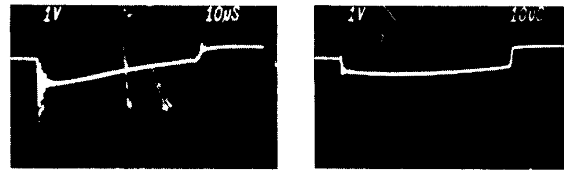
Fig. 5a shows the voltage across the arrester when subjected to the surge defined by Figs. 4a and 4b. Note that the sparkover voltage reaches 2200 V, with several oscillations, before the voltage settles down to the impulse discharge voltage at about 2000 V at its start.

Figs. 5b and 5c show, respectively, the voltage and current across the varistor in the suppressor. Note that the maximum voltage is 600 V for a 550 A

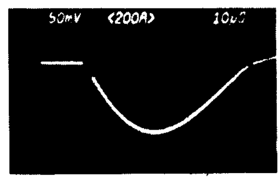


(a) (b)

Fig. 4. Open-circuit voltage and short-circuit current (without any protector).



(a) (b)

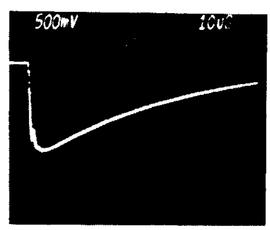


(c)

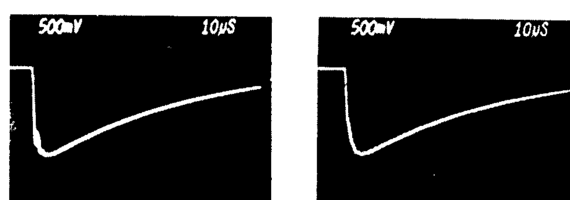
Fig. 5 Response of arrester and suppressor.

current on the varistor. (The current in the suppressor is lower than the available short-circuit current as a result of the reduced driving voltage, because the varistor holds off 600 V.

Fig. 6 shows several oscillograms indicating how the surge propagates in the wiring in the absence of any suppressor. Fig. 6a shows the open-circuit voltage at the service box. At the open-ended 7.5 m (25 ft) line, the voltage is substantially the same as at the box (Fig. 6b). However, at the end of the 30 m (100 ft) line with a 50 Ω termination, a significant decrease of the slope is noticeable, while the crest remains practically unchanged (Fig. 6c).



(a) open-circuit voltage-at box

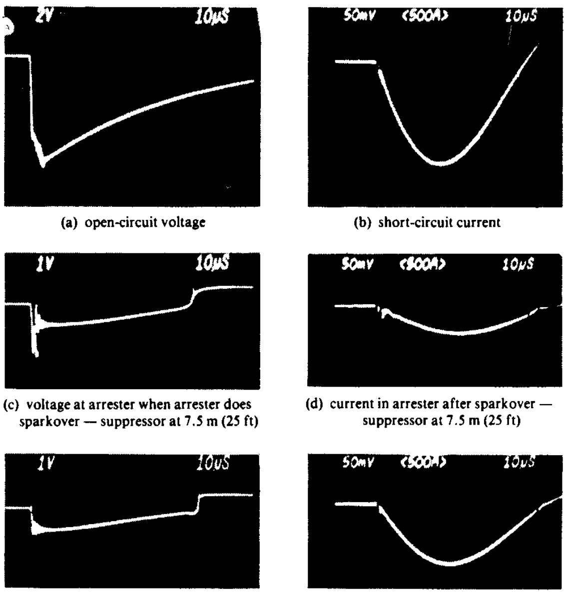


(b) open-circuit voltage-7.5m (25 ft) (c) open-circuit voltage - 30m (100 ft)

Fig. 6. Propagation of surge.

With voltage limiting at the box provided by the installation of a suppressor, even at a remote outlet, an arrester connected at the service box would not reach its sparkover voltage until substantial surge currents were involved. A larger current was required for a short distance between the service box and the suppressor than for a greater distance. The value of the current required to reach sparkover as a function of the distance is therefore of interest.

For a distance of 7.5 m (25 ft) the threshold condition for sparkover of the arrester is shown in Fig. 7. In Figs. 7a and 7b the open-circuit voltage and short-circuit current are shown for this threshold setting of the generator. Inspection of the oscillograms shows an open-circuit voltage of 8.1 kV, with a calculated equivalent source impedance of 4.2 Ω. This low value of the source impedance, compared to proposed values [5], provides a conservative evaluation of the system performance. For the same setting as Figs. 7a and 7b, the oscillograms of Figs. 7c and 7d show the case in which the arrester has sparked over, as indicated by its voltage (7c) and current (7d) traces. In Figs. 7e and 7f, the traces show the voltage (7e) and current (7f) in the suppressor for a case in which the arrester did not spark over (as a result of the scatter of sparkover or a slight difference in the output of the surge generator). This case represents the most severe duty to which the suppressor would be exposed, for a distance of 7.5 m (25 ft).



(a) open-circuit voltage

(b) short-circuit current

(c) voltage at arrester when arrester does sparkover — suppressor at 7.5 m (25 ft)

(d) current in arrester after sparkover — suppressor at 7.5 m (25 ft)

(e) voltage at suppressor when arrestor does not sparkover — suppressor at 7.5 m (25 ft)

(f) current in suppressor when arrester does not sparkover — suppressor at 7.5 m (25 ft)

Fig. 7. Transfer of surge conduction.

From these tests it is apparent that the 1200 A flowing in the line to the suppressor (7f) and establishing 1000 V at the varistor terminals (7e) causes an additional 1000 V drop in the line. The resulting 2000 V appearing at the arrester terminals may cause sparkover of the arrester (7c).

For a case in which there is no arrester installed at the box but only the suppressor installed at an outlet, the voltage rise in the wiring and the meter coils will most likely result in a flashover of the system, which would then divert the excessive energy away from the suppressor, just as the arrester did in the test. Of course, this diversion may be destructive, a result that the arrester, when installed, is precisely designed to prevent.

For greater distances between the suppressor and the arrester, the transfer of the surge will occur at lower currents. For instance, with the suppressor installed at the end of the 30 m (100 ft) line, only 700 A were required in the suppressor to reach sparkover of the arrester.

Discussion

The tests on simulated high-energy surges indicate that a transfer occurs from the suppressor to the arrester at a current level which depends on the distance between the two devices. Even for a short length of wire, the suppressor is relieved from the surge by sparkover of the arrester before excessive energy can be deposited in the varistor of the suppressor. At lower current levels, where the voltage in the system is clamped by the suppressor and thus prevents sparkover of the arrester, the suppressor absorbs all of the surge energy.

In all instances, the voltage level at the suppressor is held low enough to protect all electronic appliances having a reasonable tolerance level (600 V in most cases, 1000 V in some cases). Furthermore, the installation of only one suppressor in the house provides substantial protection for other outlets, although optimum protection requires the use of a suppressor at the most sensitive appliance, with additional suppressors for other sensitive appliances.

V. SURGE INJECTED INTO GROUND SYSTEM

Assumptions

For this experiment it was postulated that a lightning stroke attaching to the primary side of an overhead distribution system would produce a branching of the current flow into the ground after sparkover of the pole-mounted utility's surge arrester (which was presumed connected at the pole-mounted distribution transformer). Fig. 8 shows the assumed circuit and the division of current flow.

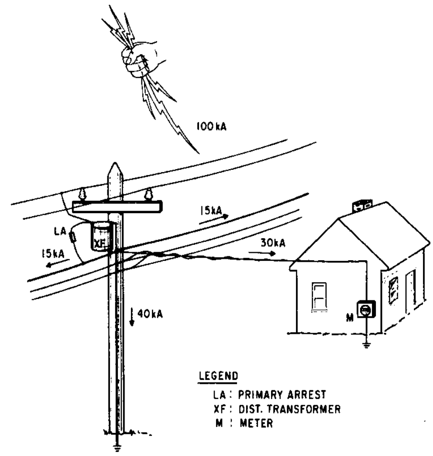


Fig. 8. Division of current assumed for a 100 kA stroke.

In their study of lightning environments, Cianos and Pierce [6] indicate that only 5% of all ground strokes exceed a peak current of 100 kA. The frequency of the strokes is dependent upon the geographic location (isokeraunic levels) [7], as well as upon local configurations. The probable occurrence of a stroke involving the utility pole near a house with no adjacent tall trees or buildings is 1 per 400 years for most of the U.S. For a 5% probability, the likelihood can be reduced 20 times; in areas of high lightning activity, this likelihood can be reduced 10 times. A stroke exceeding 100 kA at one location, therefore, can be expected to occur only once in 10,000 years (but there are millions of poles in the U.S.).

From these assessments, the maximum current to be injected for the house model under discussion was selected to be 30 kA. From this maximum of 30 kA injected into the ground wire of the house service drop, two more values were used during the test series: 10 kA, corresponding to the requirement for the ANSI high-current, short-duration test; and 1.5 kA, corresponding to the requirement for the ANSI duty-cycle test — both specified by ANSI Standard C 62.1 for secondary valve arresters [3]. All had waveshapes of 8 x 20 μs.

Another reason for selecting this low level (1.5 kA) was that no sparkover occurs in the wiring at this level. For the 10 and 30 kA levels, multiple flashovers occur at variable times and locations, making exact duplication of tests impossible. By limiting current to below sparkover levels, repeatability of the results was ensured, allowing comparisons among several alternate circuit configurations.

The generation of transient voltages in the house is attributed to electromagnetic coupling. The lightning current in the messenger establishes a field that couples into the loop formed by the two phase wires encircling the messenger. In addition, there is some capacitive coupling between the wires (Fig. 9).

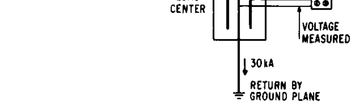


Fig. 9. Voltages induced in the house wiring system.

Test Circuit

The test circuit consisted of a high-current impulse generator, a distribution transformer with a service drop, a simulated simplified house wiring system, and the necessary shielded instrumentation.

The service drop connection between the distribution transformer and the meter socket was made with three 13 in.- (45 ft-) long AWG #6 wires, twisted at a pitch of about 5 turns/m (1.5 turns/ft). This service drop was folded in a loose "S" shape at about 0.5 m (1.5 ft) above the ground plane serving as the return path for the lightning current, in order to reduce the loop inductance seen by the generator. This configuration does not influence the coupling between the messenger and the wires wrapped around it, coupling which has been identified as the voltage-inducing mechanism.

The simulated house wiring started at the meter socket and continued to a load center over a distance of 3 m (10 ft). From this load center four "branch circuits" connected to the load center breakers were established, each terminating at a wall receptacle. Individual lengths of the branch circuits were 6, 12, 24, and 48 m (20, 40, 80, and 160 ft).

Test Results

Many tests were performed to investigate the effects of various combinations. A selection was made from several hundred recorded oscillograms to illustrate these effects. The results are presented in the form of oscillograms with corresponding commentary, generally providing a comparison of voltages and currents with or without protectors installed.

The first striking result noted was that the injection of a unidirectional impulse into the ground system produces oscillatory voltages between the phase and ground wires. Inspection of the no-load oscillogram (Fig. 10a) reveals two interesting phenomena. First, the frequency of the major voltage oscillation is constant for all branch circuit lengths (period = 2 μs). Thus, we can conclude that this frequency is not affected by the line length and that other circuit parameters, rather, are responsible for inducing this 500 kHz oscillation from a 8 x 20 μs current wave. Second, the minor oscillations visible during the first loop in each oscillogram are spaced apart at a distance that increases with line length. One can conjecture that these may be caused by reflections.

Loading the line termination with a 130 Ω resistor (Fig. 10b) eliminates the later oscillations and reduces the first peak to about 60% of the value without load. From this reduction, a Thevenin's calculation of circuit parameters, if applicable in an oversimplified form, would show that 130 Ω is 60% of the total loop impedance, while the source impedance* is 40% of the total loop impedance. Hence, one can conclude that the equivalent source impedance is in the order of four-sixths of 130, or about 85 Ω, in this scenario.

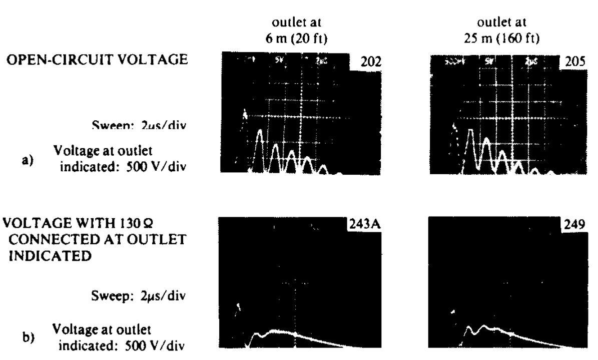


Fig. 10. Open-circuit voltages and effect of terminal impedance. Injected current: 1.5 kA.

With no protectors at the load center nor at any outlets, the wiring flashes over at 10 kA injected current, but not before crests in the range of 8 kV have been reached (Fig. 11a). With an arrester installed at the load center, voltages are limited to 2.2 kV, with about 1 kA current discharge in the arrester (Fig. 11b). While eliminating the hazard of a wiring flashover or the failure of a typical electromechanical device, this 2.2 kV protective level may still be excessive for sensitive electronics.

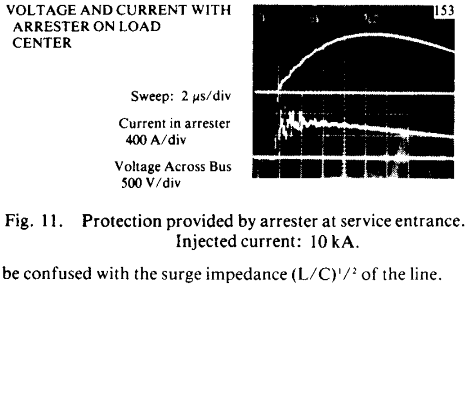


Fig. 11. Protection provided by arrester at service entrance. Injected current: 10 kA.

*Not to be confused with the surge impedance $(L/C)^{1/2}$ of the line.

Fig. 12 shows the recordings made during a 30 kA current injection. This extreme condition is capable of producing a 3500 A current in an arrester installed at the service entrance (Fig. 12a). If now we postulate a pessimistic situation where there is no arrester at the service entrance, but only a suppressor at an outlet, there are two possible outcomes. When no wiring sparkover occurs, as discussed in Section III, all the surge is indeed forced upon the suppressor (Fig. 12b). This current may be excessive for some suppressors, but this example is certainly a limited case. The more likely scenario is illustrated in Fig. 12c, where sparkover of the wiring upstream of the suppressor limits the current in the suppressor. In this last scenario, protection is obtained downstream from the suppressor. It is important to note that no additional hazard is created by installing the suppressor: the undesirable sparkover would occur even without the suppressor; in fact, without the suppressor, sparkover would be even more likely to occur.

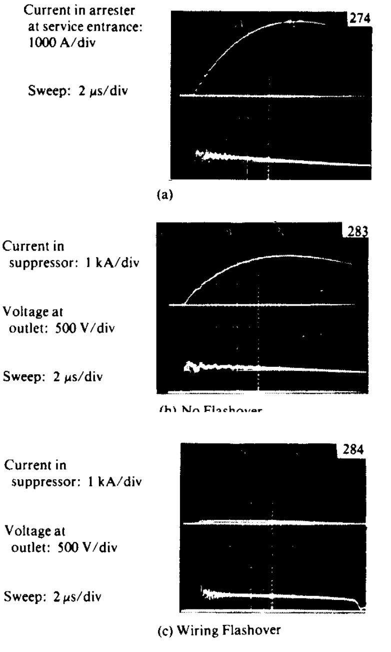


Fig. 12. Duty imposed on single suppressor with 30 kA injection.

VI. CONCLUSIONS

Coordination of surge protectors is feasible with existing devices, even if device characteristics vary. The experiments reported in the paper show three facts from which conclusions can be drawn:

Fact 1. Where a unidirectional current is injected into the ground system only, the response of the system is an oscillating voltage, at 500 kHz for the system described.

Fact 2. The equivalent source impedance, as determined by loading the system, is in the range of 50 to 100 Ω for the particular system investigated.

Fact 3. Without substantial connected loads in the system, the open-circuit surges appearing at the service entrance propagate along the branch circuits with very little attenuation.

Concl. 4. Coordination of surge suppressors requires a finite impedance to separate the two devices, enabling the lower voltage device to perform its voltage-clamping function while the higher voltage device performs the energy-diverting function.

Concl. 5. The concept that surge voltages decrease from the service entrance to the outlets is misleading for a lightly loaded system. Rather, the protection scheme must be based on the propagation of unattenuated voltages.

Concl. 6. Indiscriminate application of surge protectors may, at best, fail to provide the intended protection and, at worst, cause disruptive operation of the suppressors. What is needed is a coordinated approach based on the recognition of the essential factors governing devices and surge propagation.

VII. ACKNOWLEDGMENT

The contribution of K. E. Crouch in obtaining the current injection test results is gratefully acknowledged.

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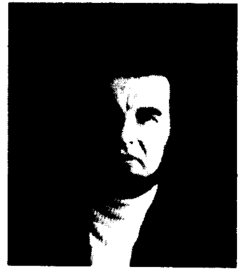

Francois D. Martzloff (M, 1956) was born in France and received his undergraduate degree at the Ecole Spéciale De Mécanique et d'Electricité in 1951; he received the MSEE degree from Georgia Tech in 1952 and the MSIA degree from Union College in 1971.

Since 1956 he has been with the General Electric Company, where he first gained experience in the Transformer and Switchgear Divisions. Upon joining General Electric Corporate Research and Development in 1961, he became involved in power semiconductor circuits and overvoltage protection. He has participated in the introduction and application of metal oxide varistors since 1971.

In IEEE Mr. Martzloff has been active on the Surge Protective Devices Committee and chairman of the Working Group on Surge Voltages in AC Power Circuits Rated 600 V or Less. He is also a member of the Ad Hoc Advisory Subcommittee of the USA Advisory Committee on IEC S/C 28A. He has been awarded 10 U.S. patents, primarily in the field of varistors and transient protection.