NISTIR 6714-8

Surge Protection in Low-Voltage AC Power Circuits - An Anthology
Part 8 - Coordination of Cascaded Surge-Protective Devices

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U.S. Department of Commerce

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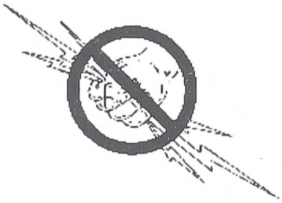

FOREWORD

The papers included in this part of the Anthology provide basic and tutorial information on the coordination of the so-called "Cascaded SPDs" in the context of low-voltage AC power circuits. As presented in this part of the anthology, the subject was approached by a combination of experiments and theoretical considerations. Interest in the subject arose in the early seventies, following the introduction of metal-oxide varistors (MOV).

With the concept of "whole house protection" that emerged in the nineties, a new set of experiments and numerical simulations focused on issues raised by industry's choice of offering very low limiting voltages for plug-in SPDs that made coordination more difficult. Concurrently, more attention was given to the rare but possible scenario of a direct lightning flash to a building, raising the threat level to new heights for SPDs installed at the service entrance.

Industry interest in the matter grew, and resulted in many publications, as shown by the papers contributed by the researchers cited in Annex A. For obvious copyright limitations, those papers from other researchers cannot be reprinted here. The pre-1985 papers in this Part 8 were copyrighted by the IEEE, or were proprietary to General Electric; both graciously gave permission for reprinting in this anthology. The post-1985 papers, written thanks to the support from EPRI PEAC and resources from the National Institute of Standards and Technology, are in the public domain.

Part I of this anthology, Annotated Bibliography, was initially compiled by the author as a contribution to the IEEE SPD Trilogy of the Surge-Protective Devices Committee (a set of three standards on the surge environment). This initial compilation is now complemented with additional relevant papers and reports written by the author. Undertaking a listing of "relevant papers" entails the risk of offending researchers whose papers might have been overlooked in the compilation, which should be seen as a limitation of the compilation effort for the Trilogy, not a deliberate rejection. Given the large number of papers in the complete collection, the breakdown into seven topic categories makes the volume more manageable. Because some of the papers cover more than one topic, for the convenience of readers, they will be found repeated in successive parts as the compilation progresses. In addition to this printed format (available from the U.S. Superintendent of Documents), this Part 8 is also available on the Web, thus opening the door for suggestions of additional entries for additions and periodic updates of the listing that might be suggested by users (Contact point: f.martzloff@ieee.org). The Web version includes an html file of the collection of the anthology papers for each part, which is searchable for any word, with built-in links allowing on-line downloading of the original paper itself in pdf format. The Website URL for the complete Anthology is: http://www.eeel.nist.gov/8l1/spd-anthology/

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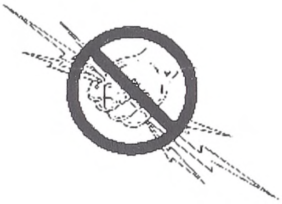
November 2002



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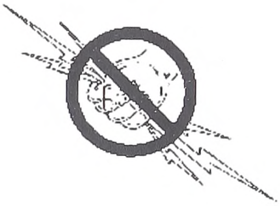

Surge Voltage Suppression in Residential Power Circuits

François Martzloff
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Reprint, with permission, of declassified General Electric Technical Information Series Report 76CRD092

Significance:
Part 4 – Propagation and coupling of surges
Part 7 – Mitigation techniques
Part 8 – Coordination of cascaded SPDs

Laboratory tests on the effect of distance for coordination between a surge-protective device (SPD) at the service entrance and an SPD at the end of a branch circuit.

The service entrance SPD, 1960-1970 vintage, consisted of a silicon carbide disc with a series gap.
The branch circuit SPD consisted of a simple MOV disc incorporated in a modified plug-and-receptacle combination, probably the first attempt at packaging an MOV for residential surge protection.

Tests were performed with a simple generator capable of delivering up to 8 kV peak open-circuit voltage of 2/60 µs waveform and 2 kA peak short-circuit current of 30/50 µs waveform. These values – dating back to pre-IEEE 587 consensus waveforms – were at the time deemed to represent a severe surge associated with a lightning flash to the power system, outside of the residence.

One objective of the tests was to determine the values of surge current and distance between SPDs that produced the transition from no sparkover of the service entrance SPD (maximum stress on the MOV) to sparkover, thus limiting the stress on the MOV. This was one of the first illustrations of what became a series of experimental and theoretical studies of the "cascade coordination" concept.

GENERAL ELECTRIC

General Electric Company
Corporate Research and Development
Schenectady, New York

TECHNICAL INFORMATION SERIES

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SUMMARY Tests performed on a representative residential wiring system with a Home Lightning Protector (HLP) and a Voltage Spike Protector (VSP) installed on the service box and an outlet, respectively, indicate good coordination between the characteristics of the two devices. For surge of relatively small amplitude, the VSP performs all of the voltage clamping functions. As the energy (current) of the surge increases, a point is reached where the HLP spark-over voltage is reached, and this device takes over the function of diverting the surge energy while the VSP keeps the voltage clamped at low levels. The current for which this transfer takes place depends on the distance between the two devices. For practical situations, enough distance (wiring length) will exist to limit the duty imposed on the VSP to acceptable levels, giving the HLP an opportunity to divert high energy surges.

KEY WORDS

transients, spikes, lightning, arrestors, varistors, GE-MOV

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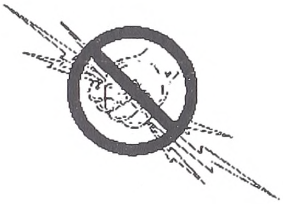

SURGE VOLTAGE SUPPRESSION IN RESIDENTIAL POWER CIRCUITS

- F.D. Martzloff -

I. INTRODUCTION

Surge voltages occurring in residential power circuits have two origins: external surges, produced by power system switching operation or by lightning, and internal surges produced by switching of appliances in the home. The voltage levels of these surges are sufficient to cause failure of sensitive electronic appliances, and some of the higher surges can even fail the more rugged electromechanical devices (clocks, motors and heaters)[1,2].

For many years, the General Electric Company has offered a secondary surge arrester under the name of "Home Lightning Protector" (HLP), which is very effective in protecting non-electronic devices against high energy, high voltage surges associated with lightning or power system switching. However, the protective level of this arrester, consistent with the limitations imposed by the design of such a device, is still too high for sensitive electronic devices. Furthermore, its installation requires a competent electrician.

A new suppressor has been developed and introduced by the Wiring Device Department under the name "Voltage Spike Protector" (VSP); this device incorporates a GE-MOV® varistor in a plug-in device allowing purchase and easy installation by the user. The protective level of this device is substantially lower (that is, better protection is provided) than the HLP, so that protection of sensitive electronic appliances is now possible. However, the energy handling capability of this suppressor is lower than that of the HLP, so that large currents associated with lightning strikes cannot be handled by the device.

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. Installation of the HLP at the service entrance will deal with the larger surges, while the VSP installed at a wall receptacle will protect the more sensitive devices. For the lower surges, the VSP will clamp the voltage to a low level. For the higher surges, the VSP will first attempt to absorb all the surge current, but the voltage developed across the varistor plus the voltage drop in the wiring between the receptacle where the VSP is installed and the service box where the HLP is installed will reach the sparkover voltage of the HLP. The HLP then takes over, diverting the high current surge from the VSP, so that no excessive energy is applied to the latter.

This report describes how this coordination takes place, based on simulated surges in a representative wiring system. The levels of voltage and current in these tests show when the HLP and VSP respectively assume all of the protective function, and where the transfer takes place, depending on the distance between the VSP in an outlet and the service box where the HLP is installed.

II. THE HOME LIGHTNING PROTECTOR

The Home Lightning Protector (HLP), is produced by the Distribution Transformer Business Department. It is a surge arrester of the valve and series gap type (Fig. 1). Earlier designs involved lead oxide pellets, with the oxide pellet acting as a nonlinear resistor and the multiple contact points between the pellets as a multiple gap. A more recent design uses a Thyrite® disc in series with a low voltage gap.

This UL-listed arrester is rated for lightning surge duty, and is described in the GE Handbook as having a sparkover of 2 kV crest under a 10 kV/μs impulse with discharge voltages of 1, 1.2 and 1.4 kV respectively at 1500, 5000 and 10,000 A for a 10 x 20 μs current wave (see Appendix I).

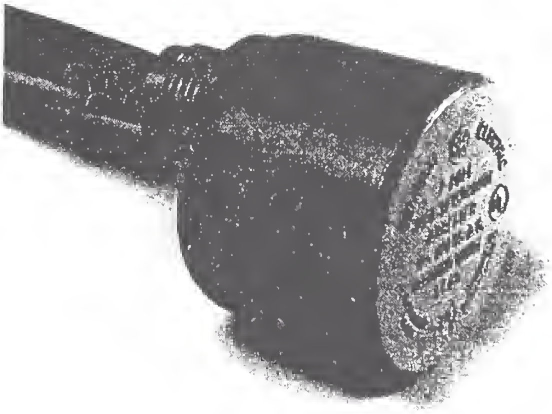

Figure 1. Home Lightning Protector

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Manuscript received May 3, 1976.

As any gap-type arrester will, the HLP has a volt-time characteristic exhibiting some increase in the sparkover voltage as the rate of rise of the impinging surge increases. Typical sparkover voltages for the sample tested under the particular waveform used here were in the order of 2000 V or less. This represents an effective clamping to protect electromechanical appliances, heaters, etc. However, sensitive electronic appliances may well have failure levels below 2000 V. This is recognized in the box label which describes the HLP as a protector for "home and farm non-electronic equipment, wiring appliances and water heaters".

Thus, while the HLP offers reliable protection for non-electronic appliances and a respectable energy handling capability, a device with a lower voltage clamping characteristic is required to protect sensitive electronics. This need is now met through the Voltage Spike Protector, described in the next section.

III. THE VOLTAGE SPIKE PROTECTOR

The heart of this device is a GE-MOV® varistor, connected line-to-line in a combination plug-socket (Fig. 2). This package, developed and produced by the Wiring Devices Department, makes it convenient for the user to install the protector at any outlet in the house, and the socket end allows the user to plug the protected appliance directly into the protector. In fact, protection is afforded to devices in all other wall outlets (to a varying degree, depending on the branch circuit configuration) and it is not mandatory to plug the appliance into the suppressor (it is a shunt, not a series device). One of the reasons for the socket end is just a convenience, so as not to lose the use of a receptacle or require a cube tap.

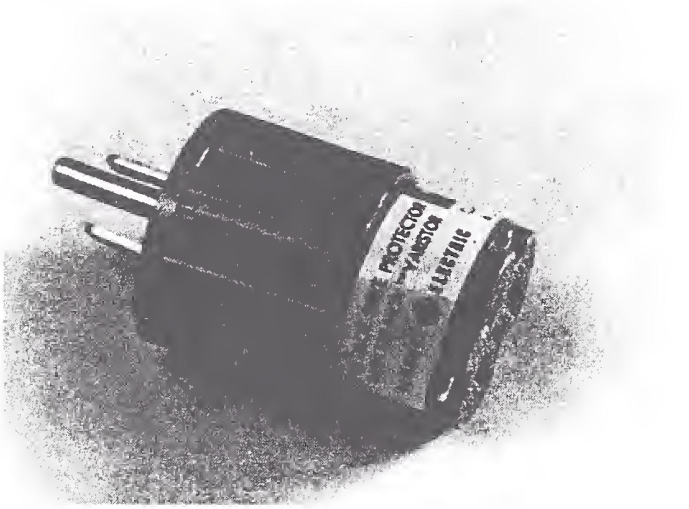


Figure 2. Voltage Spike Protector

In addition to the varistor, a non-resettable, one-shot thermal protection is inserted in series with the varistor, as insurance against thermal runaway of the varistor in case of excessive environmental conditions.

The protective characteristics of the varistor are such that a 15 A surge, typical of large internally-generated surges, will limit the voltage across the suppressor to 500 V, as opposed to values exceeding 2000 V which have been recorded during monitoring of houses known to contain a switching device producing such surges[1]. For large current values such as those associated with "lightning remnants", i.e. surge entering the house when a lightning stroke occurs near the house (but not a direct stroke), one can expect currents in the order of 1000 to 2000 A. These would produce a voltage of 800 to 1000 V across the varistor. However, as we will see, the presence of an HLP device at the service box, ahead of the varistor, will limit the current flowing toward the varistor to a lower value, by diverting the current through the HLP because of the additional drop in the wire which raises the voltage across the HLP to its sparkover voltage.

IV. TEST CIRCUIT

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

All surge currents were applied between the line conductor (black) at the end of the service drop and the reference ground. These impulses were obtained from a 5 μF capacitor, charged at a suitable voltage, and discharged into the wiring system by an ignitron switch. Figure 4 shows the connections and parameters of the surge generator circuit. The resultant open-circuit voltage waveform, a unidirectional wave of 1 μs rise time x 50 μs to 1/2 value time, corresponds to the standard test wave in utility systems. It is a much more severe test than the recommended TCL waveshape[2,4] and as such provides very conservative results. Figure 5 shows typical open-circuit voltage and short-circuit current waveforms. Voltages were recorded by a Tektronix 7633 storage oscilloscope through a P6015 attenuator probe (1000:1); currents by a Tektronix 7633 oscilloscope through a current probe P6042 with a CT-5 1000:1 current transformer. Thus, the calibrations displayed on the oscillogram are to be multiplied by 1000 for the voltage,

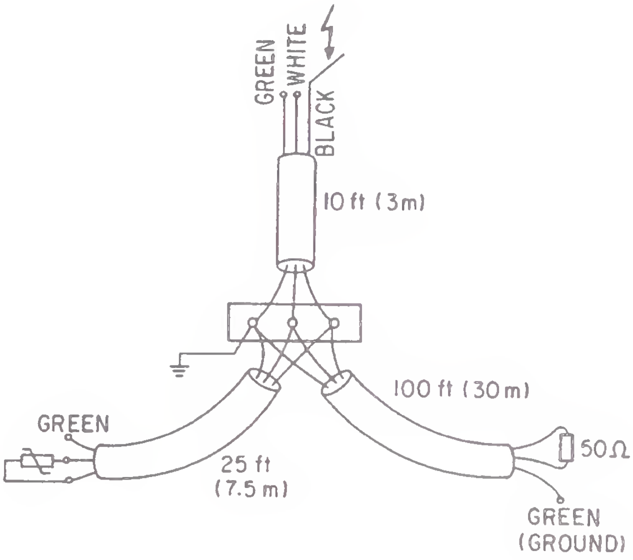


Figure 3. Test Circuit

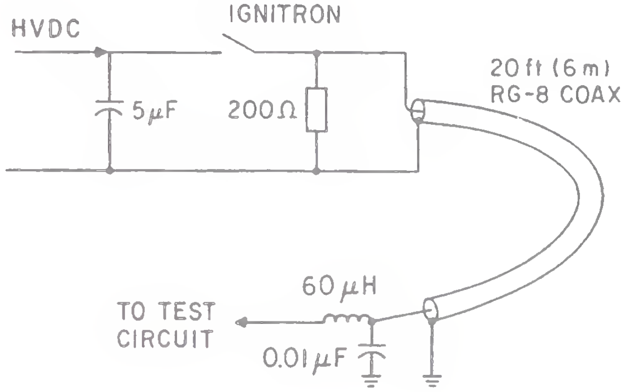


Figure 4. Pulse Generator Circuit

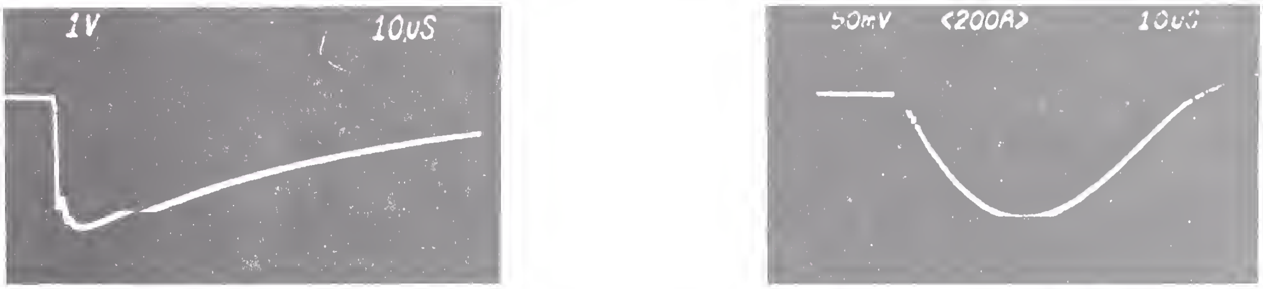
while the current traces show the 50 mV setting corresponding to the rated output of the current probe, with the ampere per division shown corresponding to the current transformer ratio and current probe input setting for a direct reading. Sweep rate is also shown on the oscillograms, at 10 μs/div. for all the tests.

V. TEST RESULTS

Several test conditions were investigated, with the varistor at the end of the short line or at the end of the long line. The HLP and VSP responses were established by connecting them one at a time, in addition to establishing the open-circuit voltage and short-circuit current for each condition. The results will be discussed with reference to specific sets of oscillograms showing voltages and currents in various parts of the circuit, each time for the same setting of the surge generator.

1. HLP AND VSP RESPONSE

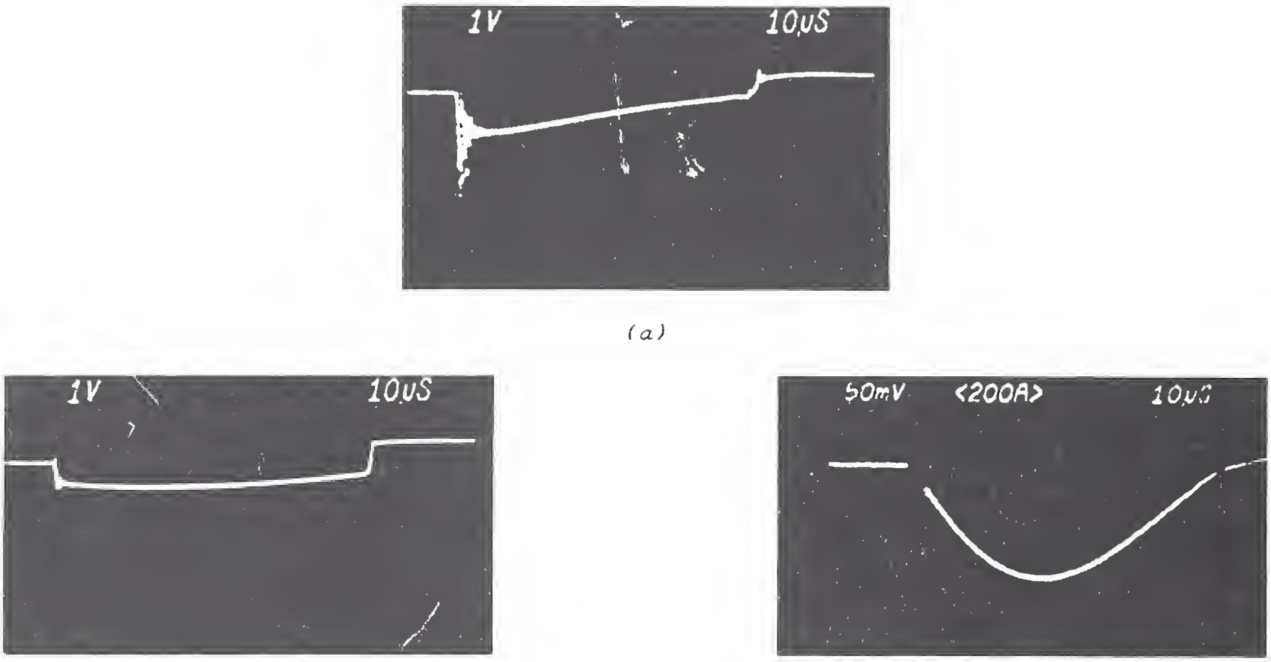
Figure 5a shows a 3000 V open-circuit voltage surge at the service box, with neither suppressor connected. Figure 5b shows the corresponding 600 A short-circuit current for a jumper connected at the service box. Figure 6a shows the voltage across the HLP when subjected to the surge defined by Figures 5a and 5b. Note that the sparkover voltage reaches 2200 V with several oscillations before the voltage settles down to the impulse discharge voltage at about 1000 V at its start.



(a) *(b)*

Figure 5

Open Circuit Voltage and Short-Circuit Current (without any protector)



(a)

(b)

(c)

Figure 6

Response of HLP & VSP

Figures 6b and 6c show respectively the voltage and current across the varistor. Note that the maximum voltage is 600 V, for a 550 A current on the varistor. (The current in the varistor is lower than the available short-circuit current because of the reduced available voltage since the varistor holds off 600.

2. PROPAGATION OF SURGES

Figure 7 shows several oscillograms indicating how the surge propagates in the wiring in the absence of any suppressor, and how the installation of one VSP device at an outlet is reflected elsewhere in the system. Figures 7a and 7b show respectively the open-circuit voltage and short-circuit current at the service box. At the open-ended 25 ft. (7.5 m) line, the voltage is substantially the same as at the box (Fig. 7c). However, at the end of the 100 ft. (30 m) line with a 50 Ω termination, a significant decrease of the slope is noticeable, while the crest remains practically unchanged (Fig. 7d).

In Figures 7e-g, a VSP varistor has been added at the end of the 25 ft (7.5 m) line. Voltage and current at the varistor are shown in Figures 7e and 7f, with a maximum voltage of 500 V for a 200 A surge. Meanwhile, the voltage at the box is limited to 750 V, an appreciable reduction from the 1500 V that would exist without the remote VSP under this surge condition (Fig. 7g).

3. TRANSFER OF SURGES

With the voltage limiting at the box provided by the installation of a VSP, even at a remote outlet (Fig. 7g), an HLP connected at the service box cannot reach its sparkover voltage until substantial surge currents are involved. For a short distance between the service box and the VSP, a larger current will be required 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 25 ft. (7.5 m), the threshold condition where sparkover of the HLP just occurs is depicted in Figure 8. In Figures 8a and 8b, 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 and a short-circuit current of 1.9 kA, hence a calculated source impedance of 4.2 Ω.* This low value of the source impedance (compared

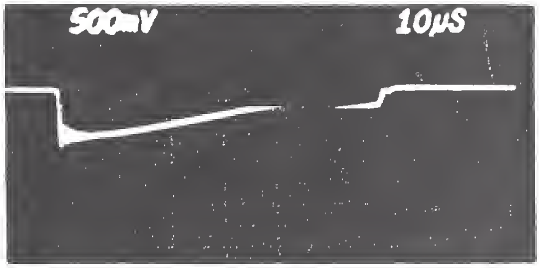
---

* This is only a crude approximation since the current waveform does not match the voltage waveform. Therefore, the circuit impedance is not a pure resistance or characteristic impedance.

(a) open-circuit voltage - at box   *(b) short-circuit current*

(c) open-circuit voltage - 25 ft. (7.5m)   *(d) open-circuit voltage - 100 ft. (100m)*

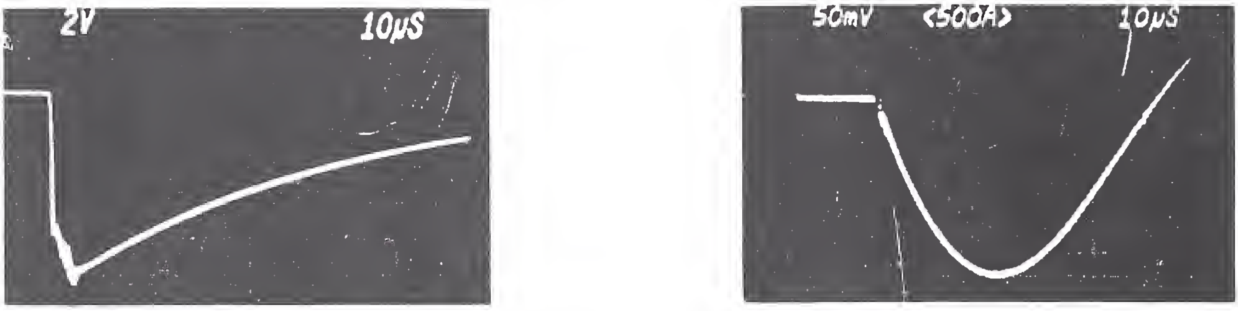
(e) voltage at VSP - 25 ft. (7.5m)   *(f) current in VSP - 25 ft. (7.5m)*



(g) voltage at box with VSP @ 25 ft. (7.5m)

Figure 7
Propagation of Surges

to proposed values[2,3]) provides a very conservative evaluation of the system performance. For the same setting as Figures 8a and 8b, the oscillograms of Figures 8c and 8d show the case where the HLP has sparked over, as indicated by its voltage (8c) and current (8d) traces. In Figures 8e and 8f, the traces show the voltage (8e) and current (8f) in the VSP for a case where the HLP did not spark over (due to 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 VSP would be exposed, for a distance of 25 ft. (7.5m), and in reality is already likely to be an actual lightning stroke on the power system, rather than just a "lightning remnant" associated with a remote or indirect stroke. Figure 8f indicates a crest current of 1200 A in the varistor, which just exceeds the published surge rating of the varistor, however, as an isolated occurrence, this current level has been found acceptable during laboratory tests. As stated above, this level of current would be reached only for direct strokes, and for a VSP connected fairly close to the service box. In a case where there would be no HLP installed at the box, but only the VSP installed at an outlet, the voltage rise in the wiring and the meter coils would most likely result in a flashover of the system, which would then divert the excessive energy away from the VSP, just as the HLP did in the test. Of course, this diversion may take place in an undesirable manner, which is precisely what the HLP is supposed to eliminate when installed. On the other hand, the sale literature for the VSP also specifically excludes direct lightning strokes from the protective ability of the VSP.

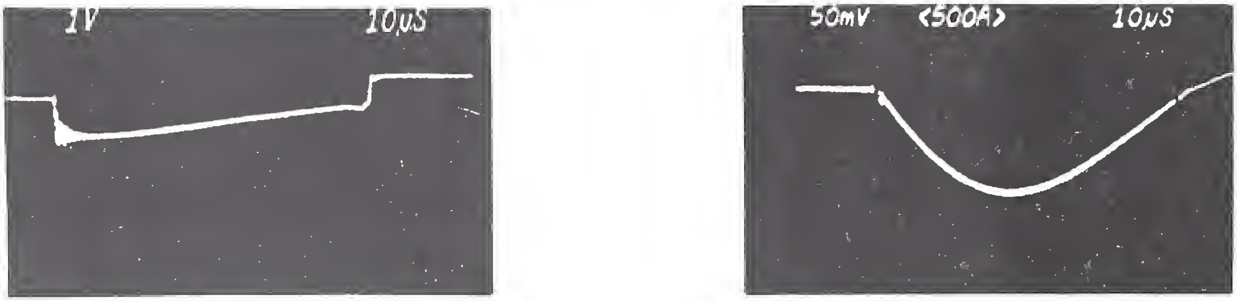


(a) *open-circuit voltage*

(b) *short-circuit current*

(c) *voltage at HLP when HLP does sparkover - VSP at 25 ft. (7.5m)*

(d) *current in HLP after sparkover - VSP at 25 ft. (7.5m)*



(e) *voltage at VSP when HLP does not sparkover - VSP at 25 ft. (7.5m)*

(f) *current in VSP when HLP does not sparkover - VSP at 25 ft. (7.5m)*

Figure 8

Transfer of Surge Conduction

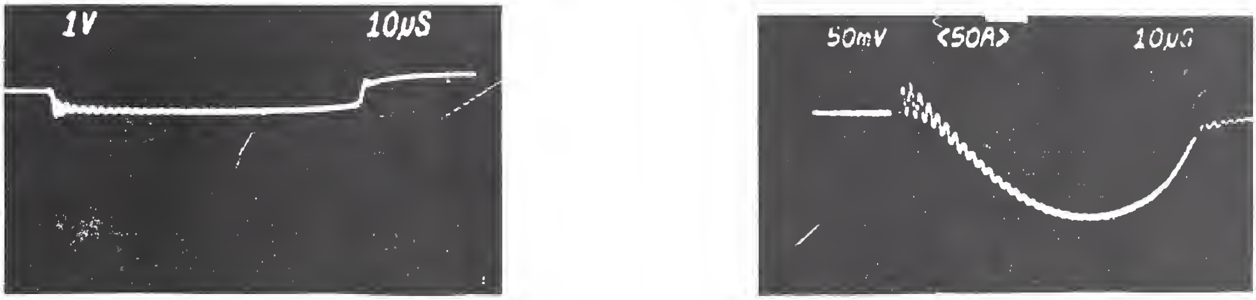
For greater distances between the VSP and the service box, the surge transfer will occur at lower current. For instance, with 100 ft. (30m), the oscillograms of Figure 9 document the transfer of the surge to the HLP at much lower current levels. Open-circuit voltage and short-circuit current are indicated in Figures 9a and 9b as previously. With the VSP at 25 ft., only the VSP carries the surge as indicated in Figures 9c and 9d. However, with the VSP removed 100 ft. (30m) away from the HLP, the latter takes over for this lower available current (700 A) and relieves most of the surge from the VSP, as indicated in Figures 9e through 9h. The current flowing in the VSP is now only 125 A (Fig. 9f) with 500 A flowing in the HLP (Fig. 9h). The corresponding voltage at the VSP and HLP are shown in Figures 9e and 9g.

(a) open-circuit voltage

(b) short-circuit current

(c) VSP at 25 ft. (7.5m) - Voltage of VSP

(d) VSP at 25 ft. (7.5m) - Current in VSP



(e) VSP at 100 ft. (30m) - Voltage of VSP

(f) VSP at 100 ft. (30m) - Current in VSP

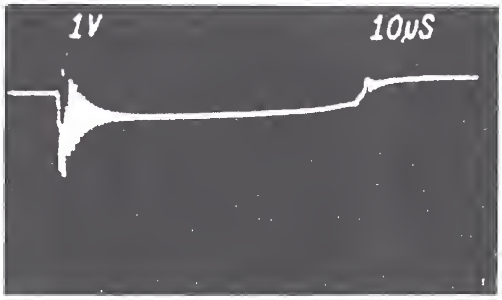
(g) VSP at 100 ft. (30m) - Voltage of HLP

(h) VSP at 100 ft. (30m) - Current in HLP

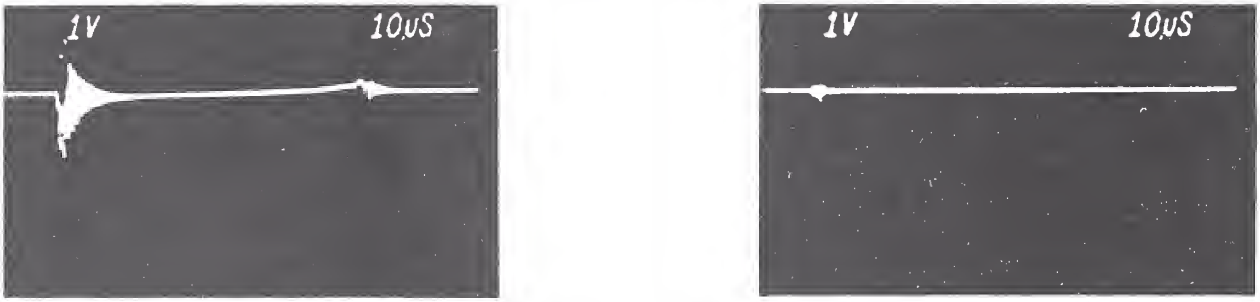
Figure 9

Transfer of Surges

Further information is presented in Figure 10, with oscillograms recorded at the same generator setting as in Figure 9. Figure 10c shows the voltage at the end of the 100 ft. (30m) line, between the line wire and the ground wire (not the ground reference, but the ground carried with the wire); likewise, Figure 10b shows the voltage at the same point between the neutral wire and the ground wire, both oscillograms recorded with the HLP at the service box and the VSP at that line end. These voltages should be compared to the line-to-line (more precisely, line-to-neutral) voltage of only 500 V recorded for the same surge condition in Figure 9e. To check that these voltages were not spurious recording, the oscillogram of Figure 10c was recorded with the probe tip connected to its ground connection, and both of these connected to the ground wire at the 100 ft. line end. The noise background there is insignificant compared to the recordings of Figures 10a and 10b.



(a) Voltage between line (black) to ground (green) VSP connected between black and white. HLP at service box.



(b) Voltage between neutral (white) to ground (green) VSP connected between black and white. HLP at service box

(c) Noise background check

Figure 10

Voltages between Conductors and Ground at End of 100 ft. (30m) Line

VI. CONCLUSIONS

The tests on simulated high energy surges indicate that a transfer occurs from the VSP to the HLP at some current level depending on the distance between the two devices.

Even for a short length of wire, the VSP is relieved from the surge by sparkover of the HLP before excessive energy can be deposited in the varistor of the VSP. At lower current levels where the voltage in the system is clamped by the VSP and thus prevents sparkover of the HLP, the VSP absorbs all of the surge energy.

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

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APPENDIX I

Home Lightning Protector Specifications

HOME LIGHTNING PROTECTOR D-12 **5937**
Page 1
Sept. 2, 1975
Effective Aug. 8, 1975

Home Lightning Protector

Listed by Underwriters' Laboratories (UL)

DESCRIPTION

The Home Lightning Protector is designed to prevent lightning surges (entering through the wiring) from damaging electrical wiring and appliances. The Protector is a sturdy, weatherproof, service-proven device that immediately drains lightning surges harmlessly to ground. Installed at either the weatherhead or service-entrance box, the Protector discharges a surge in a fraction of a second. It will perform this protective function over and over again, without any maintenance required, possessing the same long-life valve-type characteristics obtainable in higher-voltage distribution arresters.

The Protector is a two-pole, three-wire device designed primarily for single-phase 120/240-volt three-wire grounded neutral service. It can also be applied to protect three-phase circuits where the line-to-ground 60 Hertz voltage does not exceed 175 volts. Connection diagrams are included on the inside of each carton.

WHERE TO USE

Farmers—whose livelihood depends on milking machines, incubators, coolers, submersible pumps, and other electrical equipment.

Suburbanites—with considerable dependency on (and investment in) electrical appliances of all sorts.

Rural Homeowners—often far from fire-fighting equipment, and repair facilities.

Everyone—with electrical equipment exposed to the destructive lightning surges that can enter through directly-connected overhead secondary power lines.

*FEATURES

The General Electric Home Lightning Protector
—can prevent costly appliance repair
—can help provide uninterrupted electrical service
—1-year unit replacement guarantee

LISTED
UL
LIGHTNING PROTECTIVE DEVICE

PRICES AND DATA

Distribution Transformer-P(032)

Circuit Rating Volts	Protector Max Permissible line-to-ground Voltage Rms	Protector Model No.	List Price Each, GO-75E	Net Wt Each In Oz.	Std Package
120/240 Ground Neutral	175	9L15DCB002	★$14.95	6	24 Units

PERFORMANCE CHARACTERISTICS *

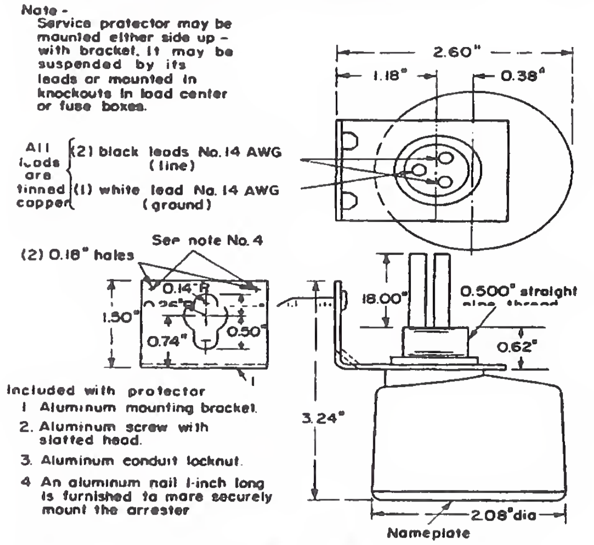
Protector Rating (Volts Rms)	Impulse Sparkover Voltage 10Kv/μsec Kv crest	IR Discharge Voltage Kv Crest (10 x 20 Microsecond Current Wave)		
		At 1500 Amp	At 5000 Amp	At 10,000 Amp
0–175	2	1.0	1.2	1.4

* Average values.

★*Changed since May 13, 1974 issue.*

(Photo 1219173)

Fig. 1. Home Lightning Protector. Hardware (not shown) is included in carton and detailed below.



Note -
Service protector may be mounted either side up - with bracket. It may be suspended by its leads or mounted in knockouts in load center or fuse boxes.

Included with protector
1 Aluminum mounting bracket.
2. Aluminum screw with slotted head.
3. Aluminum conduit locknut.
4 An aluminum nail 1-inch long is furnished to more securely mount the arrester

Fig. 2. Model No. 9L15BCB002 Home Lightning Protector

NOTE: Minimum order quantity is one (1) standard package containing twenty-four (24) units. Orders will be accepted for shipment from factory stock in lots of one or more standard packages only. Orders for less than standard package quantities should be referred to local distributors.

PUBLICATIONS: (Use latest issue)
Descriptive Bulletin...........GED-4835

Prices and data subject to change without notice

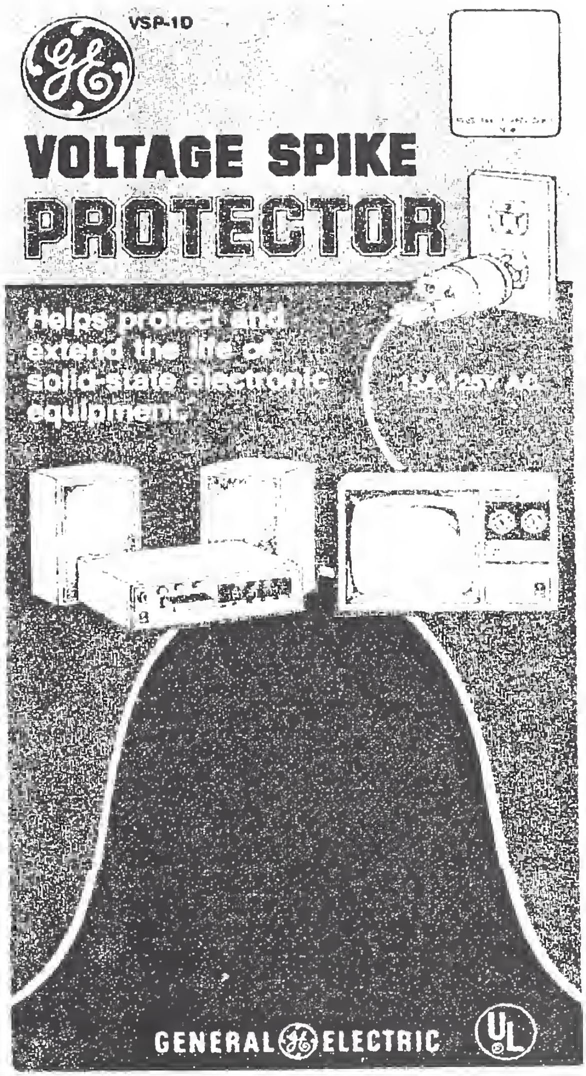
PM 700, 701, 702, 711-714, 721-723, 731-737

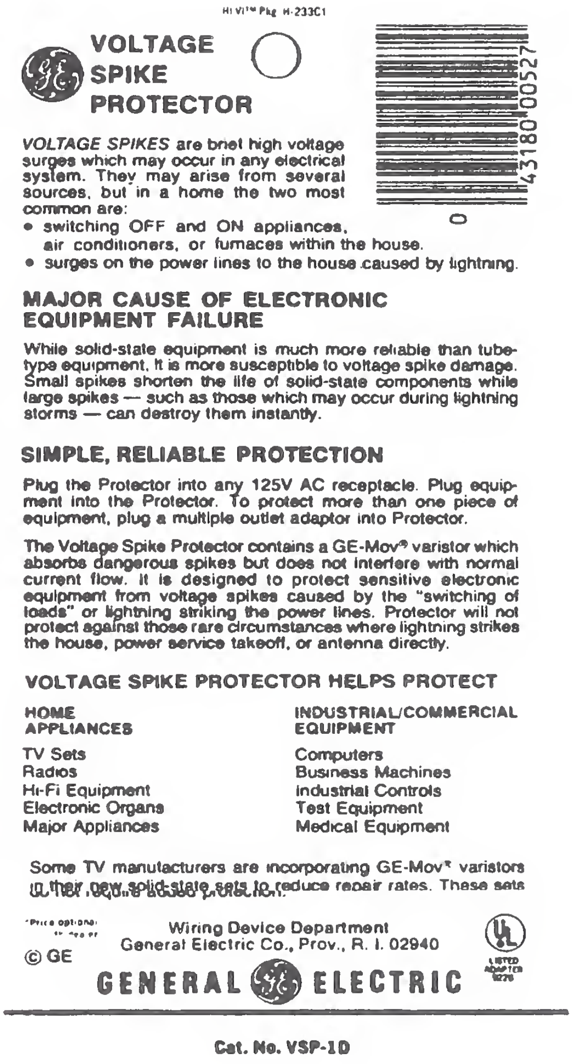
GENERAL ELECTRIC

Home
Protector
Secondary
Arrester

APPENDIX II

Voltage Spike Suppressor Product Information





Hi Vi™ Pkg H-233C1

VOLTAGE SPIKE PROTECTOR

0 43180 00527

VOLTAGE SPIKES are brief high voltage surges which may occur in any electrical system. They may arise from several sources, but in a home the two most common are:

- switching OFF and ON appliances, air conditioners, or furnaces within the house.
- surges on the power lines to the house caused by lightning.

MAJOR CAUSE OF ELECTRONIC EQUIPMENT FAILURE

While solid-state equipment is much more reliable than tube-type equipment, it is more susceptible to voltage spike damage. Small spikes shorten the life of solid-state components while large spikes — such as those which may occur during lightning storms — can destroy them instantly.

SIMPLE, RELIABLE PROTECTION

Plug the Protector into any 125V AC receptacle. Plug equipment into the Protector. To protect more than one piece of equipment, plug a multiple outlet adaptor into Protector.

The Voltage Spike Protector contains a GE-Mov® varistor which absorbs dangerous spikes but does not interfere with normal current flow. It is designed to protect sensitive electronic equipment from voltage spikes caused by the "switching of loads" or lightning striking the power lines. Protector will not protect against those rare circumstances where lightning strikes the house, power service takeoff, or antenna directly.

VOLTAGE SPIKE PROTECTOR HELPS PROTECT

HOME APPLIANCES	**INDUSTRIAL/COMMERCIAL EQUIPMENT**
TV Sets	Computers
Radios	Business Machines
Hi-Fi Equipment	Industrial Controls
Electronic Organs	Test Equipment
Major Appliances	Medical Equipment

Some TV manufacturers are incorporating GE-Mov* varistors in their new solid-state sets to reduce repair rates. These sets [illegible] added protection.

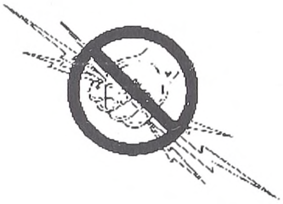
*Price optional [illegible]

Wiring Device Department
General Electric Co., Prov., R. I. 02940

LISTED ADAPTER

GENERAL ELECTRIC

Cat. No. VSP-1D



Coordination of Overvoltage Protection in Low-Voltage Residential Systems

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Canadian Conference on Communications and Power, 78CH1373-0, 1978

Significance
Part 4 – Propagation and coupling of surges
Part 6 – Tutorials

This paper was presented as a summary tutorial aimed at the French-speaking Canadian community to solicit their comments on the development of the IEEE Std 587 Guide. The paper has been translated into English by the author to make the English-speaking community aware of that paper, which served at that time as one output for the release of the extensive test results that were reported in the 35-page GE Memo Report – still proprietary at that time – "Lightning protection in residential AC wiring" (see Part 4 of the anthology).

The tests were performed by injecting a simulated lightning flash current of unidirectional waveshape into the grounding system of a simplified residential wiring system, and observing the coupling and induction of oscillatory surges in the house wiring

Part 8 – Coordination of Cascaded SPDs
Excerpts from the complete test report found in this summary include a discussion of the performance of gapped arresters, as well as MOVs installed at the service entrance, with coordination with an MOV installed at the end of branch circuits.

COORDINATION OF OVERVOLTAGE PROTECTION IN LOW-VOLTAGE RESIDENTIAL SYSTEMS

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General Electric Company
Schenectady, NY

K.E. Crouch
Lightning Technologies, Inc.
Pittsfield, MA

INTRODUCTION

The development of metal-oxide varistors has made possible a substantial improvement in the mitigation of overvoltages in residential, commercial or light industrial power systems. For instance, transient suppressors are now available that can be plugged into a wall receptacle, thus making possible the protection of appliances or electronic devices that might be damaged by overvoltages occurring in power systems [1].

However, due to economic considerations, these suppressors have only a limited capability for absorbing high current surges that may be associated with lightning strikes occurring nearby. Thus, one may ask whether the installation of a suppressor with limited capability might not pose a risk of failure or create a false sense of security.

It is then worthwhile to examine what occurs in a building provided with suppressors having different capability, located at different points of the building. as a function of the surge current intensity imposed by the lightning strike. Furthermore, the combination of several suppressors may allow a coordinated protection for reliable operation, which it would be worthwhile to demonstrate.

CIRCUIT MODEL

Given the complexity of distribution networks and the nonlinear response of the suppressors [2], it would be difficult to compute in detail the behavior of the system subjected to a current surge. Thus, it is more convenient, to the extent that reality can be modelled by a physical model, to make tests directly on the devices actually used in these buildings. Such tests have been performed at the High Voltage Laboratory of the General Electric Company in Pittsfield, MA. We injected, into a physical model, currents corresponding to lightning strikes amplitudes ranging from moderate to extremely high [3].

A model of a typical building was wired with the components used in a residential building: triplen overhead service drop from the distribution transformer, down-conductor to the revenue meter, connection to the service panel provided with circuit breakers, with four branch circuits ranging from 5 to 50 meters and provided with a receptacle at the far end.

Assuming a 100-kA strike on the primary distribution system, an extreme case in the probability of discharges [3], a current division is postulated as shown in Figure 1, resulting from the injection of 30 kA in the (grounded) neutral conductor supplying the building.

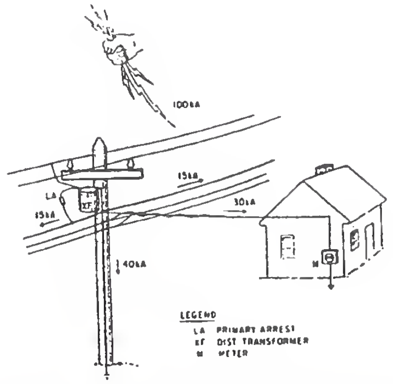

Figure 1. Distribution of the 100-kA current in the ground network near the building

This 30-kA value is predicated by assuming that the lightning current transfers from the primary conductors to the grounding network as a result of the operation of the arrester, or by a flashover from the phase conductor to the ground conductor of the primary circuit, without involving the two conductors of the low-voltage distribution. Only the (grounded) neutral conductor of the service drop is involved, with 70 kA flowing through the grounding connection of the pole involved and toward the two adjacent poles.

Figure 2 shows schematically the path of the 30-kA current injected in the ground conductor to the building, as well as the mechanism for inducing currents and voltages in the circuit model, mostly by electromagnetic coupling into the loop formed by the service drop.

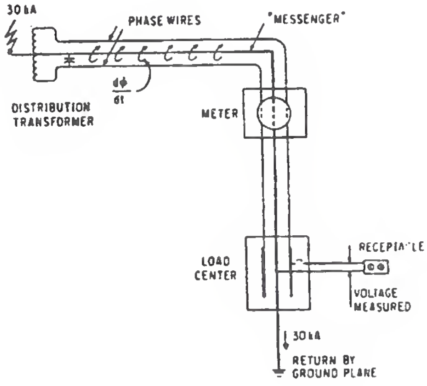

Figure 2. Injection of 30 kA in the ground conductor of the service drop, and resulting voltages

The complete circuit, including the surge generator and the instrumentation, is shown schematically in Figure 3. Of course, the usual precautions were taken in the setup (shielded room for the instrumentation, checks for interference, etc.).

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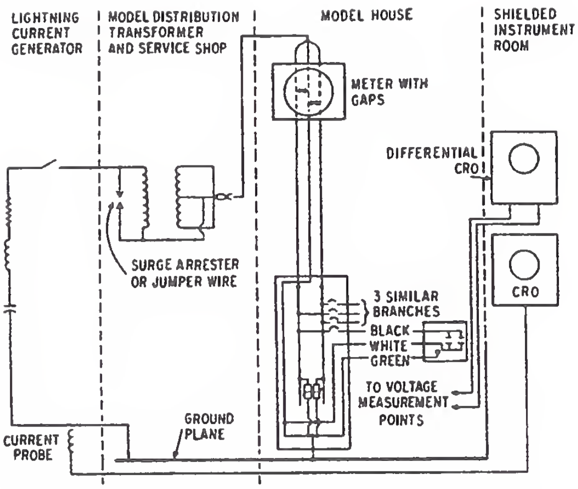


Figure 3. Schematic of the experimental circuit

Figure 4 shows an example of the waveform of the injected current, a 10/25 µs impulse, which is a conservative hypothesis for the current involved. Three different values of the peak current have been used in the tests, 1.5 kA, 10 kA, and 30 kA. The first value, 1.5 kA, is the standard duty test for a secondary arrester, the second, 10 kA, is the standard withstand test, and the last, 30 kA, is a pessimistic level.

Vertical: 500 A/div
Sweep: 5 µs/div

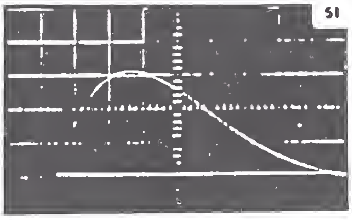


Figure 4. Injected current

TYPES OF SUPPRESSORS

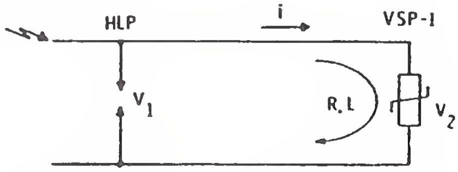
There are two types of commercially available suppressors: a surge arrester that can be installed on the service panel or at the point of anchoring the service drop, and a suppressor which is a plug-in device as previously mentioned.

The surge arrester type, which has been used for many years but only in limited numbers, meets the performance standard for a secondary arrester [4], in particular a rating of 10 kA, 8/20 µs surge. One of the reasons for the lack of market success of this suppressor is undoubtedly the fact that its installation must be contracted out to an electrician because it requires work on the live circuits inside the service panel. Furthermore, this type of arrester has a let-through of about 2000 V, which is excessive for sensitive electronic appliances. Varistor discs with a 32 mm diameter are now available, but only as an industrial component (at this time). These discs have the capability of diverting the 10 kA required by the standard, and thus are excellent candidates for a service-entrance arrester because they can clamp at voltages significantly lower than those of previously available arresters. In the tests that we performed, these discs turned out to be highly promising.

The plug-in type, represented in our test series by GE Model VSP-1, contains a 14-mm diameter varistor, with a rating of 6000 A and capable of absorbing a number of 3 kA surges during its service life.

COORDINATION OF SUPPRESSORS

In an installation where several surge suppressors are connected at different points of the system, the suppressor with the lowest clamping voltage will be called upon to "protect" the suppressor having a higher clamping voltage, by sparking over first or by preventing the second from sparking over. To reverse this situation, it is necessary that the voltage drop in the wiring, produced by the current flowing in the first suppressor and added to the clamping voltage of the latter, exceed the operating voltage of the second. In the case of varistors, which have been designed specially to produce a low clamping voltage, this situation may become critical. Figure 5 illustrates the arrangement where the VSP-1 might prevent the HLP from sparking over if the clamping voltage of the VSP-1 is much lower than the sparkover voltage of the HLP. This situation is another motivation for the tests, to verify that coordination can be maintained between the suppressors in practical applications.



Sparkover of HLP:	$V1 \leq V2 + Ri + Ldi/dt$
All the current in VSP-1:	$V1 > V2 + Ri = Ldi/dt$

Figure 5. Coordination between two suppressors separated by an impedance

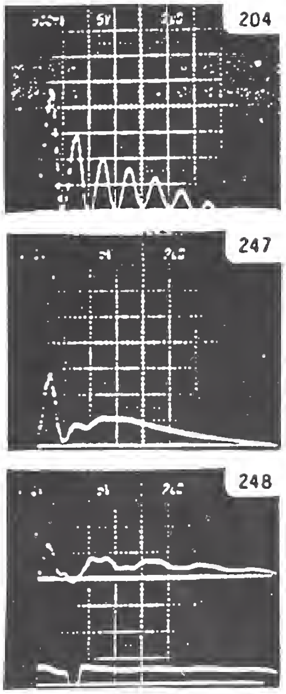
TEST RESULTS

During a first test series conducted at 30 kA, we quickly noted that sparkover occurs at many points in the circuit, making it difficult to obtain reproducible results. It was necessary to reduce the current to 1.5 kA to reach a situation where no sparkover would occur. Even at "only" 10 kA, sparkover still occurred in the unprotected devices (receptacle, service panel). It should be noted that these sparkovers taking place between the conductors (black to white or black to green) result solely from injecting current in the ground conductor of the circuit, not from injecting the surge directly into the phase conductors.

Many oscillograms were recorded, which cannot be reproduced in this paper. Some examples are given in the following figures, to enable comparisons among the various arrangements of the suppressors, showing that an effective protection scheme can be achieved, if only a few precautions are taken.

Effect of the inductance at the end of the line

Oscillograms 204, 247, and 248 (Figure 6) show the attenuation obtained from an impedance at the end of the line, for a 1.5 kA injection, at the end of a 25-m line. Oscillogram 204 shows an open-circuit voltage reaching 2200 V, with oscillations at about 500 kHz decaying in about 20 µs.



Open-circuit
Voltage
500 V/div
2 μs/div

Voltage with
130-Ω load
500 V/div
2 μs/div

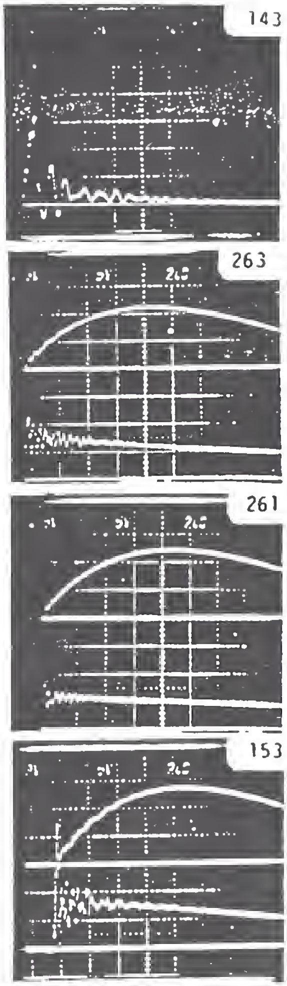
Voltage and current
in the VSP-1 with
130 Ω and VSP-1

Figure 6. Effect of impedance at the end of the line

By connecting a resistive load of 130 Ω at that point, the voltage is reduced down to 1400 V, and the oscillations are replaced by a damped waveform. Adding a varistor (VSP-1) to the 130-Ω resistor produces the clamping shown in oscillogram 248; this oscillogram also shows that only 15 A flow in the varistor. From these oscillograms, the following conclusions may be drawn: an oscillatory voltage at 500 kHz is induced in the line, superimposed to the unidirectional voltage produced by the injection of an unidirectional current. This oscillatory voltage appears to be the result of oscillations occurring in the line, oscillations that can be damped by adding a resistive load at the end of the line. Furthermore, connecting a 130-Ω resistor at the end of the line reduces the voltage at the end of the line from 2200 to 1400 V. One may view this situation as a voltage divider consisting of the source impedance and the impedance at the end of the line. A rough estimation of the "source" impedance, Zs, may be made by neglecting the complex nature of the impedances. The circuit equation may be written as Vr = Vo 130/(130 + Zs), where Vr is the voltage (1400 V) recorded with a resistor in the circuit, and Vo is the open-circuit voltage (2200 V). Solving for Zs yields Zs = 75 Ω. This value, although inaccurate because the equation was not vectorial, is nevertheless a useful result to provide an order of magnitude for the source impedance, the perennial question.

Performance of suppressors at the service entrance

Oscillograms 143, 261, 263, and 153 (Figure 7) show the results obtained by installing various types of suppressors at the service panel, for a 10 kA surge. Without any protection (oscillogram 143), the voltage reaches 7 kV before collapsing to small oscillations. This collapse is actually the result of a breakdown occurring at some other point of the circuit, as demonstrated in other tests. This oscillogram shows that 7 kV peaks may be reached when no protection is provided.



Voltage without
protection
2 kV/div
2 μs/div

Varistor on
the outside
500 A/div
500 V/div
2 μs/div

Varistor on
the inside
500 A/div
500 V/div
2 μs/div

HLP Arrester
400 A/div
500 V/div
2 μs/div

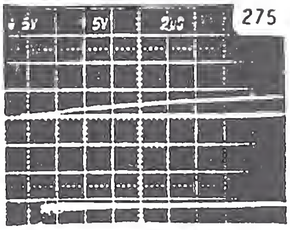
Figure 7. Compared performance of various suppressors at the service panel

By installing a 32-mm disk outside the service panel, an arrangement that requires a total of about 50 cm of wiring, the protective level shown in Oscillogram 263 is obtained, about 800 V, with high-frequency oscillations reaching 1500 V, while about 1100 A flow in the disc. If the disc is connected directly onto the bus bars of the panel, with a maximum connection length of about 15 cm, the protective level is substantially improved: oscillogram 261 shows oscillations of only 900 V and subsequent value of 600 V, with a current of about 1200 A in the disc. In contrast, the HLP arrester (oscillogram 153), which contains a spark gap and silicon carbide varistors, allows the voltage to reach 2400 V before sparking over, then holds a discharge voltage of about 900 V with a peak current of 1300 A. This set of measurements shows how important it is to hold the connections as short as possible. They also show how the new metal-oxide varistors can improve protection, if correctly installed.

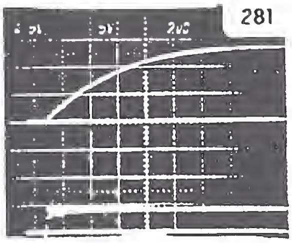
Stress on the suppressors

Considering the limited capability of the VSP-1 device, which is only a 14-mm disc and does not purport to be a lightning arrester, it is interesting to determine the stress that might be imposed by injecting a surge with extreme value.

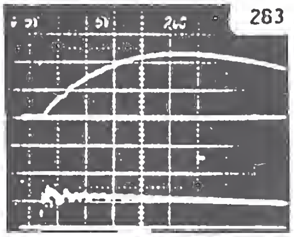
32-mm disc inside
Voltage and current
for VSP-1 at 12 m
500 A/div
500 V/div
2 μs/div



32-mm disc outside
Voltage and current
for VSP-1 at 12 m
200 A/div
500 V/div
2 μs/div



No protection on the panel
Voltage and current
for VSP-1 at 12 m
1000 A/div
500 V/div
2 μs/div



No protection on the panel
Voltage and current
for VSP-1 at 25 m
1000 A/div
500 V/div
2 μs/div

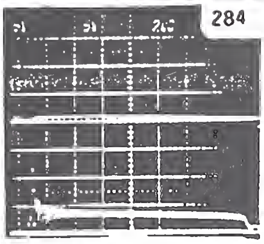


Figure 8. Stresses on the suppressors

Figure 8 shows the results of tests made with an appropriate protection at the service panel (oscillogram 275), with a poor protection at the service panel (281), and without any protection at the service panel (283 and 284).

With a disc connected directly across the bus bars (275), the ideal situation, the current in a VSP-1 located 12 m away from the service panel, resulting from injecting 30 kA, is less than 400 A; the voltage across its terminals, to be applied to the protected load, is less than 500 V. If now the disc is installed outside of the panel (281), a reduction of the effectiveness of the protection, the current in the VSP-1 is slightly increased, with a corresponding increase in the clamping voltage. If no protection is installed at the service panel (283), the VSP-1 would tend to absorb all the current, in this case a 3.3-kA peak with a clamping voltage of 650 V for a VSP-1 installed 12 m away. In contrast, for a VSP-1 installed 25 m away, the voltage drop between the panel and the VSP-1, associated with the line impedance, is such that a breakdown occurs upstream from the receptacle (in this case in a parallel branch circuit), hence the limiting effect shown in oscillogram 284.

Thus, this set of measurements shows that even in the extreme case of injected currents, the current imposed to the VSP-1 remains within acceptable limits for a limited number of surges. Its rating of 6000 A at 8/20 μs allows considering a limit of 4000 A for the product line, with high reliability. Furthermore, this example illustrates the fact that breakdown can occur in a poorly coordinated installation. From the point of view of the safety of the VSP-1, the breakdown shown in oscillogram 284 might be viewed as a safety valve, but from the overall safety point of view, it is not recommended to rely upon a breakdown occurring in the wiring or at the terminals of the wiring devices, because such breakdown may initiate a power fault with significant fire hazard.

CONCLUSIONS

1. It is sufficient to inject, in the ground conductor of the service drop, a surge current corresponding to a moderate lightning stroke to reach hazardous voltages between the phase and neutral conductors within the building.

2. Commercially available protective devices are capable of limiting overvoltages to acceptable limits; even in the case of an injection corresponding to extreme values, several arrangements may be considered:

a) A lightning arrester consisting of a spark gap and silicon carbide varistors can limit the overvoltages to about 2000 V, eliminating the risk of breakdown in the wiring and the attendant fire hazard. This 2000 V limit provides protection for conventional appliances but may be inadequate to protect electronic devices that tend to be more sensitive.

b) A metal-oxide varistor, presently available only as an industrial component package, correctly installed in the service panel (short connections) would be sufficient to limit overvoltages for all the building, even for high amplitude lightning strokes.

b) A varistor with limited capability, the VSP-1, installed at a particular receptacle, will limit overvoltages at that point to values that are acceptable for electronic devices, without being itself exposed to hazardous stress, if its distance from a panel — not equipped with protection — is greater than about 10 meters. For shorter distances, the stress applied to the VSP-1 might exceed the expected reliability, with failure of the varistor. This failure would still provide protection during the surge, but lead to a trip of the panel breaker. Of course, if a protection according to (b) were provided, it would not be necessary to install a VSP-1. If the protection provided at the service panel is less than ideal (HLP), the addition of a VSP-1 at the receptacles that supply sensitive devices would provide protection for these devices, while the HLP would provide diversion of high currents.

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[2] Qu'est-ce .... les varistances ? Paper by "D.M." *EEE Journal.* No. 410, pp 50-55, 28 September 1977.

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Coordination of Surge Protectors in Low-Voltage AC Power Circuits

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First presented at IEEE Summer Meeting, Vancouver, July 1979

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). That contribution was acknowledged by an SPD Committee Paper Award.

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.

This paper received the 1982 Paper Award from the Surge-Protective Devices Committee.

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IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No. 1 Jan./Feb. 1980

COORDINATION OF SURGE PROTECTORS IN LOW-VOLTAGE AC POWER CIRCUITS

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Schenectady, NY 12345

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.

I. 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.

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*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*.

F 79 635-4 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, Vancouver, British Columbia, Canada, July 15-20, 1979. Manuscript submitted February 6, 1979; made available for printing April 3, 1979.

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Fig. 1. Typical arrester for service entrance installation.

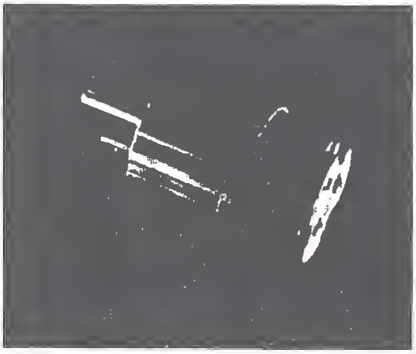


Fig. 2. Typical suppressor for plugin installation.

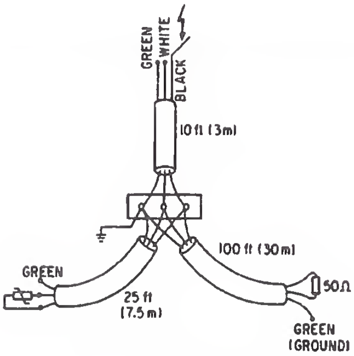


Fig. 3. Test circuit.

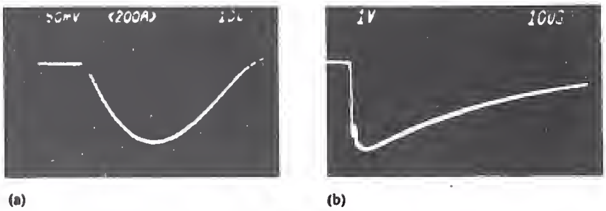


Fig. 4. Open-circuit voltage and short-circuit current (without any protector).

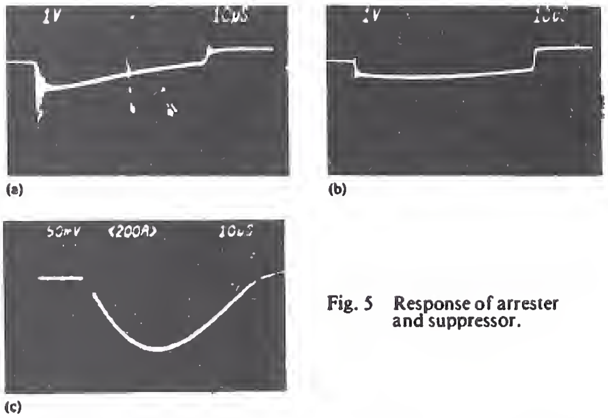


Fig. 5 Response of arrester and suppressor.

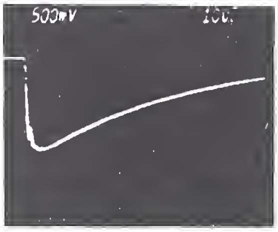
All surge currents were applied between the line conductor (black) at the end of the service drop and the reference ground (green and white). These impulses were obtained from a 5 μF capacitor charged at a suitable voltage and discharged into the wiring system by an ignitron switch. The resultant open-circuit 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

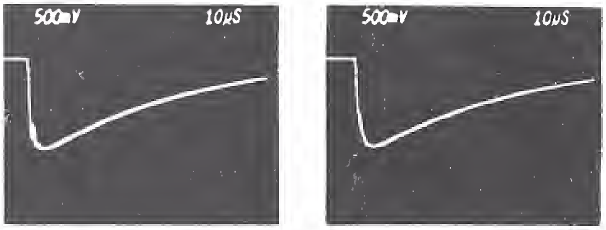
Fig. 5a shows the voltage across the arrester when subjected to the surge defined by Figs. 4a and 4b. Note that the sparkover voltage reaches 2200 V, with several oscillations, before the voltage settles down to the impulse discharge voltage at about 2000 V at its start.

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 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



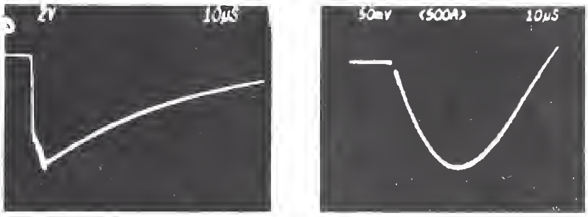
(b) open-circuit voltage-7.5m (25 ft)

(c) open-circuit voltage - 30m (100 ft)

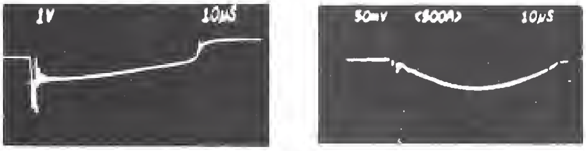
Fig. 6. Propagation of surge.

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.

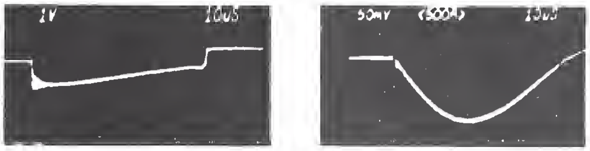
For a distance of 7.5 m (25 ft) the threshold condition for sparkover of the arrester is shown in Fig. 7. In Figs. 7a and 7b the open-circuit voltage and short-circuit current are shown for this threshold setting of the generator. Inspection of the oscillograms shows an open-circuit voltage of 8.1 kV, 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.

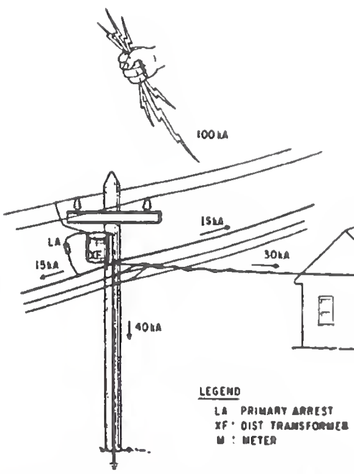


Fig. 8. Division of current assumed for a 100 kA stroke.

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).

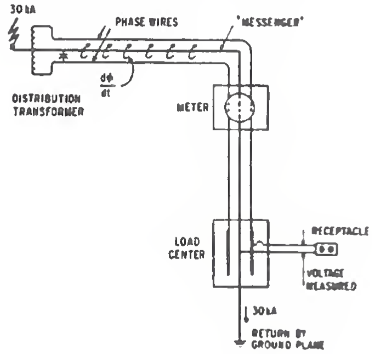


Fig. 9. Voltages induced in the house wiring system.

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.

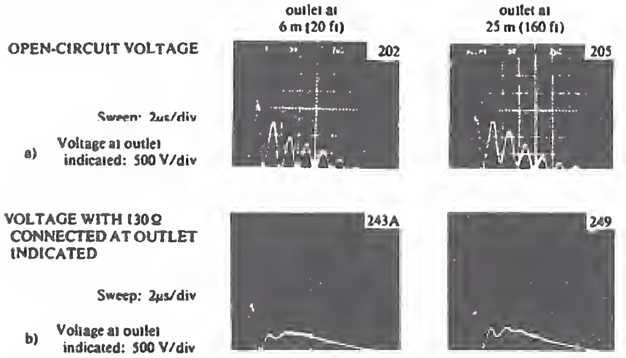


Fig. 10. Open-circuit voltages and effect of terminal impedance. Injected current: 1.5 kA.

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.

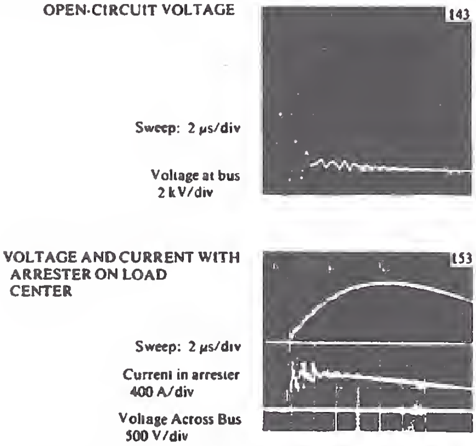
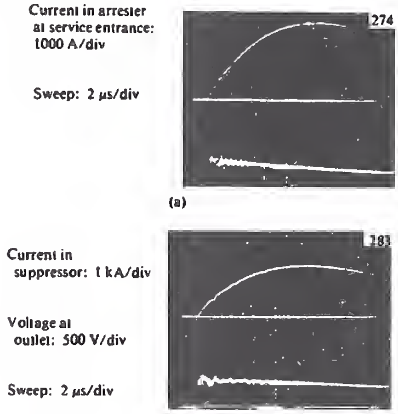


Fig. 11. Protection provided by arrester at service entrance. Injected current: 10 kA.

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.



(b) No Flashover

(c) Wiring Flashover

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

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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.

The Coordination of Transient Protection for Solid-State Power Conversion Equipment

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Significance
Part 6 – Tutorials
Part 8 – Coordination of Cascaded SPDs

This paper was presented as a tutorial aimed at a semiconductor-oriented audience, giving an overview of the origin of transient overvoltages and of IEEE and IEC documents under consideration in the early eighties, identifying and categorizing transients. A brief review of available techniques and devices follows, with a description of the principles of coordinated protection, specific experimental examples, and results reconciling the unknown with the realities of equipment design.

The themes emphasized that effective protection of sensitive electronic equipment is possible through a systematic approach where the capability of the equipment is compared to the characteristics of the environment, a basic tenet of the electromagnetic compatibility documents. As more field experience is gained in applying these documents to equipment design, the feedback loop can be closed to ultimately increase the reliability of new equipment at acceptable costs, while present problems may also be alleviated based on these new findings in the area of transient overvoltages.

THE COORDINATION OF TRANSIENT PROTECTION FOR SOLID-STATE POWER CONVERSION EQUIPMENT

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ABSTRACT

Transient overvoltages are no longer an unknown threat to the successful application of power conversion equipment, thanks to the availability of protective techniques and devices. This paper presents an overview of the origin of transient overvoltages and of recent IEEE and IEC documents identifying and categorizing transients. A brief review of available techniques and devices follows, with a description of the principles of coordinated protection, specific experimental examples, and results reconciling the unknown with the realities of equipment design.

INTRODUCTION

Since the introduction of semiconductors, transient overvoltages have been blamed for device failures and system malfunctions. Semiconductors are, indeed, sensitive to overvoltages. However, data have been collected for several years on the occurrence of overvoltages, to the point where the problem is now mostly a matter of economics and no longer one of lack of knowledge on what the environment of power systems can inflict to poorly protected semiconductor circuits. This statement may represent a slight oversimplification of the general problem because the environment is still defined in statistical terms, with unavoidable uncertainty as to what a specific power system can impress on a specific piece of power conversion equipment.

The IEEE has published a Guide (1) describing the nature of transient overvoltages (*surges*) in low-voltage ac power circuits. This Guide provides information on the rate of occurrence, on the waveshape, and on the energy associated with the surges, as a function of the location within the power system. In addition, the IEC has issued a report concerning insulation coordination (2), identifying four categories of installations, with a matrix of power system voltages and overvoltages specified for *controlled situations*. Other groups have also proposed test specifications, some of which are now enshrined in standards that may be applied where they are really not applicable, but have been applied because no other information was available at the time.

At this time, the environment seems to be defined with sufficient detail. However, there is still a lack of guidance on how to proceed for specific instances, and circuit designers may feel that they are left without adequate information to make informed decisions on the selection of component characteristics in the field of overvoltage withstand or protection. This situation has been recognized, and various groups concerned with the problem are attempting to close the gap by preparing application guides which will provide more specific guidance than a mere description of the environment, although that description in itself is already a considerable step forward.

One of the difficulties in designing a protection scheme in the industrial world of power conversion equipment is the absence of an overall system coordinator, in contrast to the world of electric utilities, for instance, which are generally under the single responsibility of a centralized engineering organization. The user of power conversion equipment is likely to purchase the material from a supplier independently of other users of the same power system, and coordination of overvoltage protection is generally not feasible under these conditions. Worse yet, an uncoordinated application of surge suppressors can lead to wasteful or ineffective resource allocation, since independent users would each attempt to provide protection in adjacent systems or independent designers would provide protective devices in adjacent subsystems.

To shed more light on this situation, this paper will briefly review some of the origins of transient overvoltages, with reference to recently published IEEE and IEC documents, which provide guidance on the environment. Techniques and protective devices will then be discussed, and examples of coordinated approaches presented.

THE ORIGIN OF TRANSIENT OVERVOLTAGES

Two major causes of transient overvoltages have long been recognized: system switching transients, and transients triggered or excited by lightning discharges (in contrast to direct lightning discharges to the power systems, which are generally quite destructive, and against which total protection may not be economical in the average application). System switching transients can involve a substantial part of the power system, as in the case of power factor correction capacitor switching operations, disturbances following restoration of power after an outage, and load shedding. However, these do not generally involve large overvoltages (more than two or three per unit), but may be very difficult to suppress since the energies are considerable. Local load switching, especially if it involves restrikes in switchgear devices, will produce higher voltages than the power system switching, but generally at lower energy levels. Considering, however, the higher impedances of the local systems, the threat to sensitive electronics is quite real, and only a few conspicuous case histories of failures can cast an adverse shadow over a large number of successful applications.

VOLTAGE LEVELS

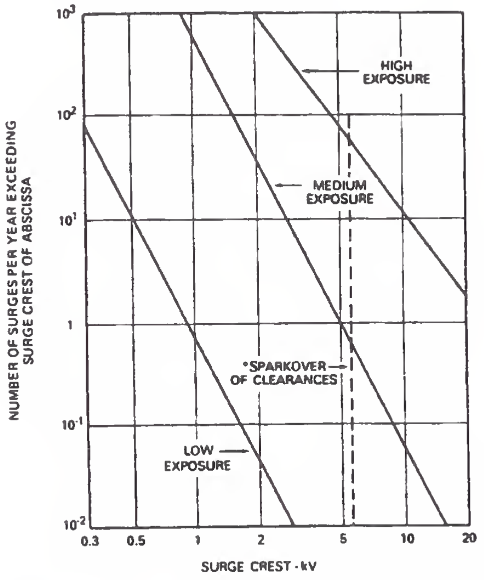
Two different approaches have been proposed to define voltage levels in ac power systems. At this time, the divergences have not yet been reconciled, as each proposal has its merits and justification. The IEEE approach involves reciting a rate of occurrence as a function of voltage levels, as well as of exposure in systems that do not necessarily use protective devices. The IEC approach indicates only a maximum level for each location category, but no higher values are expected because this approach implies the application of protective devices. These two proposals will be quoted in the following paragraphs.

The IEEE Guide (IEEE Std 587-1980)

Data collected from a number of sources led to plotting a set of lines representing a rate of occurrence as a function of voltage for three types of exposures in unprotected circuits (Figure 1). These exposure levels are defined in general terms as follows:

- *Low Exposure* — Systems in geographical areas known for low lightning activity, with little load switching activity.
- *Medium Exposure* — Systems in geographical areas known for high lightning activity, with frequent and severe switching transients.
- *High Exposure* — Rare but real systems supplied by long overhead lines and subject to reflections at line ends, where the characteristics of the installation correspond to high sparkover levels of the clearances.

It is essential to recognize that a surge voltage observed in a power system can be either the driving voltage or the voltage limited by the sparkover of some clearance in the system. Hence, the term *unprotected circuit* must be understood to be a circuit in which no low-voltage protective device has been installed, but in which clearance sparkover will eventually limit the maximum voltage. The distribution of surge levels, therefore, is influenced by the surge-producing mechanisms as well as by the sparkover level of clearances in the system.



***In some locations, sparkover of clearances may limit the overvoltages**

Figure 1. Rate of surge occurrence versus voltage level in unprotected circuits from IEEE Std 587

The voltage and current amplitudes presented in the Guide attempt to provide for the vast majority of lightning strikes but should not be considered as "worst case," since this concept cannot be determined realistically. One should think in terms of the statistical distribution of strikes, accepting a reasonable upper limit for most cases. Where the consequences of a failure are not catastrophic but merely represent an annoying economic loss, it is appropriate to make a tradeoff of the cost of protection against the likelihood of a failure caused by a high but rare surge.

The IEC Approach (IEC Report 664, 1980)

In a report dealing with clearance requirements for insulation coordination purposes, the IEC Subcommittee SC/28A recommends a set of impulse voltages to be considered as representative of the maximum occurrences at different points of a power system, and at levels dependent upon the system voltage (Table I). The report is not primarily concerned with a description of the environment, but more with insulation coordination of devices installed in these systems. This approach rests entirely on the establishment of controlled levels in a descending staircase, as the wiring systems progress within the building away from the service entrance.

The fundamental assumption made in establishing the levels of Table I is that a decreasing staircase of overvoltages will evolve from the outside to the deep inside of a building (system), either as the result of attenuation caused by the impedance network, or by the installation of overvoltage limiters at the interfaces.

If the descending staircase of voltages is provided by a surge protective device at each interface, it must be recognized that the successive devices will interact; the situation is not one of one-way propagation of the surges. Indeed, a protective device installed, say, at the III/II interface might be so close (electrically) to the device at interface IV/III that it could prevent the latter from operating; in other words, the III/II device might face the surge duty normally expected to be handled by the IV/III device. Thus, a vital aspect in the selection of interface devices is that of ensuring proper coordination.

Table I

PREFERRED SERIES OF VALUES OF IMPULSE WITHSTAND VOLTAGES FOR RATED VOLTAGES BASED ON A CONTROLLED VOLTAGE SITUATION

Voltages line-to-earth derived from rated system voltages, up to: (V rms and dc)	Preferred series of impulse withstand voltages in installation categories			
	I	II	III	IV
50	330	550	800	1500
100	500	800	1500	2500
150	800	1500	2500	4000
300	1500	2500	4000	6000
600	2500	4000	6000	8000
1000	4000	6000	8000	12000

In both the IEEE standard and the IEC report, the assumption has been made that the surge is impinging the power system through the service entrance and is occurring between phase and earth. Experience has shown that a frequent cause of distress is the voltage differences existing between conductors reputed to be at ground potential; in fact, one of them is elevated above the other by the flow of surge current. This situation, not addressed in either document, needs to be recognized and dealt with on an individual, case-by-case basis, lest a false sense of security be created by restricting the protection to the power service entrance.

WAVESHAPE OF THE TRANSIENT OVERVOLTAGES

Observations in different locations (3-6) have established that the most frequent type of transient overvoltage in ac power systems is a decaying oscillation, with frequencies between 5 and 500 kHz. This finding is in contrast to earlier attempts to apply the unidirectional double exponential voltage wave, generally described as 1.2/50, although the unidirectional voltage wave has a long history of successful application in the field of dielectric withstand tests and is representative of the surges propagating in transmission systems exposed to lightning. The IEEE Guide recommends two waveshapes, one for the indoor environment, and one for the outdoor and near-outdoor environment (Figure 2). Not only is a voltage impulse defined, but the discharge current, or short-circuit current of a test generator used to simulate these transients, is also defined in the IEEE document.

The oscillatory waveshape simulates those transients affecting devices that are sensitive to dv/dt and to voltage reversals during conduction (7). The unidirectional voltage and current waveshapes, based on long-established ANSI standards for secondary valve arresters, simulate the transients where energy content is the significant parameter.

ENERGY AND SOURCE IMPEDANCE

The energy involved in the interaction of a power system with a surge source and a surge suppressor will divide between the source and the suppressor in accordance with the characteristics of the two impedances. In a gap-type suppressor, the low impedance of the arc after sparkover forces most of the energy to be dissipated elsewhere, e.g., in the power system series impedance or in a resistor added in series with the gap for limiting the power-follow current. In an energy-absorber suppressor, by its very nature, a substantial share of the surge energy is dissipated in the suppressor, but its clamping action does not involve the power-follow energy resulting from the short-circuit action of a gap. It is, therefore, essential to the effective use of suppression devices that a realistic assumption be made about the source impedance of the surge whose effects are to be duplicated.

Unfortunately, not enough data have been collected on what this assumption should be for the source impedance of the transient. Standards or recommendations either ignore the issue, such as MIL STD-1399 or the IEC Report 664 in its present published form,* or they sometimes indicate values applicable to limited cases, such as the SWC test for electronic equipment operating in high-voltage substations (8). The IEEE Guide attempts to relate impedance with three categories of locations, A, B, and C. For most industrial environments, Categories A or B will apply; Category C is intended for outdoor situations (Table II).

MATCHING THE ENVIRONMENT WITH THE EQUIPMENT

On the basis of the various documents mentioned in the preceding paragraphs, an equipment designer or user can take a systematic approach to matching the transient overvoltage capability of the equipment with the environment in which this equipment is to be installed. This design may involve tests to determine the withstand levels (9), some measurements and/or analysis to determine the degree of hostility of the environment, and a review of available protective devices. The latter will be discussed in the following paragraphs.

Transient Suppressors

Two methods and types of devices are available to suppress transients: blocking the transient through some low-pass filter, or diverting it to ground through some nonlinear device. This nonlinearity may be either a frequency nonlinearity (high-pass filter) or a voltage nonlinearity

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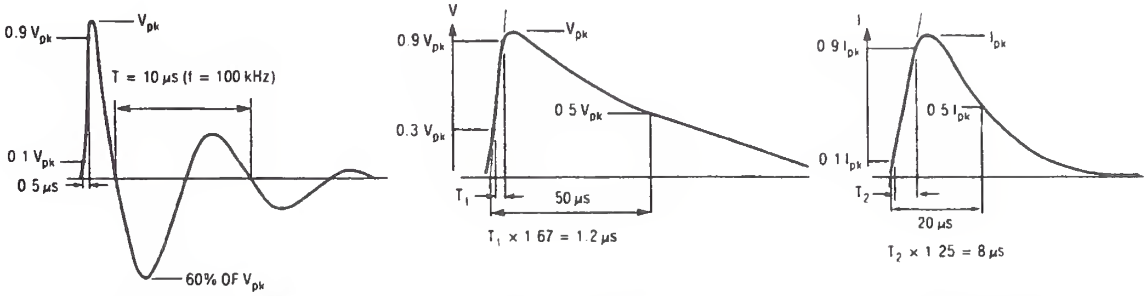
* Continuing studies by the IEC SC/28A Working Group are now addressing this issue, and additional publications are anticipated.



Open-Circuit Voltage, Current Defined by Table II

Open Circuit Voltage

Discharge Current

Indoor Environment

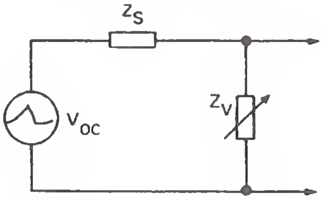
Outdoor and Near-Outdoor Environment

Figure 2. Transient overvoltages and discharge currents in IEEE Std. 587-1980

(clamping action or crowbar action). In this paper, a majority of the discussion will center on the latter type, since voltage clamping devices or crowbar devices are the most frequently used (10).

Voltage-clamping devices have a variable impedance, depending on the current flowing through the device or the voltage across its terminals. These components show a non-linear characteristic, i.e., Ohm's law $E=RI$, can be applied but the equation has a variable R. Impedance variation is monotonic and does not contain discontinuities, in contrast to the crowbar device which shows a turn-on action. As far as volt-ampere characteristics of these components are concerned, they are time-dependent to a certain degree. However, unlike sparkover of a gap or triggering of a thyristor, time delay is not involved here.

When a voltage-clamping device is installed, the circuit remains unaffected by the device before and after the transient for any steady-state voltage below clamping level. Increased current drawn through the device as the voltage attempts to rise results in voltage clamping action. Increased voltage drop (IZ) in the source impedance due to higher current results in the apparent *clamping* of the voltage. It should be emphasized that the device depends on the source impedance, Z, to produce the clamping. A voltage divider action is at work where one sees the ratio of the divider not constant, but changing (Figure 3). The ratio is low, however, if the source impedance is very low. The suppressor cannot work at all with a limit zero source impedance. In contrast, a crowbar-type device effectively short-circuits the transient to ground. Once established, however, this short circuit will continue until the current (the surge current as well as any power-follow current supplied by the power system) is brought to a low level.



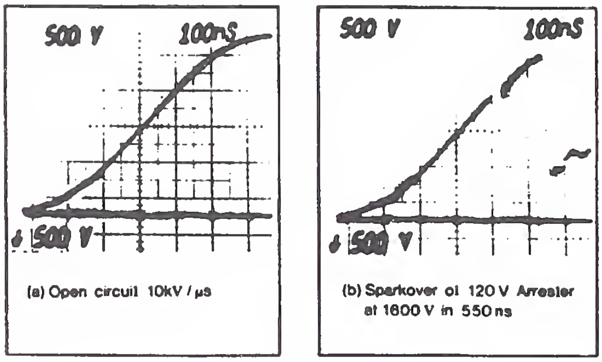
$$V_R = \left(\frac{Z_V}{Z_V + Z_S}\right) V_{OC}$$

Figure 3. Voltage clamping action of a suppressor

The crowbar device will often reduce the line voltage below its steady-state value, but a voltage clamping device will not. Substantial currents can be carried by the crowbar suppressor without dissipating a considerable amount of energy within the suppressor, since the voltage (arc or forward-drop) during the discharge is held very low. This characteristic constitutes the major advantage of these suppressors. However, limitations in volt-time response, power-follow, and noise generation are the price paid for this advantage. As voltage increases across a spark-gap, significant conduction cannot take place until transition to the arc mode has taken place by avalanche breakdown of the gas between the electrodes. The load is left unprotected during the initial rise due to this delay time (typically in microseconds). Considerable variation exists in the sparkover voltage achieved in successive operations, since the process is statistical in nature. For some devices, this sparkover voltage can also be substantially higher after a long period of rest than after successive discharges. From the physical nature of the process, it is difficult to produce consistent sparkover voltage for low voltage ratings. This difficulty is increased by the effect of manufacturing tolerances on very small gap distances. This difficulty can be alleviated by filling the tube with a gas having lower breakdown voltage than air. However, if the enclosure seal is lost and the gas is replaced by air, this substitution creates a reliability problem because the sparkover of the gap is then substantially higher.

Another limitation occurs when a power current from the steady-state voltage source follows the surge discharge (*follow-current* or *power-follow*). In ac circuits, this power-follow current may or may not be cleared at a natural current zero. In dc power circuits, clearing is even more uncertain. Additional means must, therefore, be provided to open the power circuit if the crowbar device is not designed to provide self-clearing action within specified limits of surge energy, system voltage, and power-follow current.

A third limitation is associated with the sharpness of the sparkover, which produces fast current rises in the circuits and, thus, objectionable noise. A classic example of this kind of disturbance is found in oscillograms recording the sparkover of a gap where the trace exhibits an anomaly *before* the sparkover (Figure 4). This anomaly is due to the delay introduced in the oscilloscope circuits to provide an advanced trigger of the sweep. What the trace shows is the event delayed by a few nanoseconds, so that in real time, the gap sparkover occurs while the trace is still writing the pre-sparkover rise. Another, more objectionable effect of this fast current change can be found in some hybrid protective systems. Figure 5 shows the circuit of such a device, as



(a) Open circuit 10kV / µs

(b) Sparkover of 120 V Arrester at 1600 V in 550 ns

Figure 4. Interference to oscilloscope circuits caused by gap sparkover

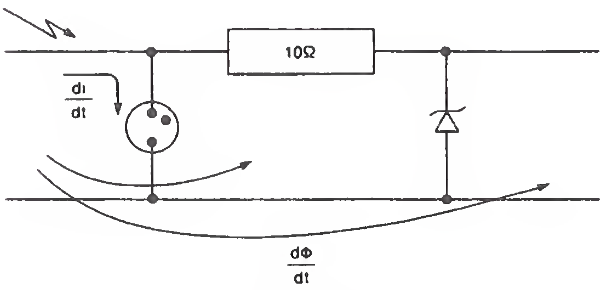


Figure 5. Hybrid protector with gap

found in the commerce. The gap does a very nice job of discharging the impinging high-energy surges, but the magnetic field associated with the high *di/dt* induces a voltage in the loop adjacent to the secondary suppressor, adding what can be a substantial spike to the expected secondary clamping voltage. Consequently, most electronic circuits are better protected with voltage clamping suppressors than with crowbars, but sometimes the energy deposited in a voltage clamping device by a high current surge can be excessive; a combination of the two devices can provide effective protection at optimum cost. However, this combined protection must be properly coordinated to obtain the full advantage of the scheme. The following paragraphs will discuss some of the basic principles of coordination and provide some examples of applications.

PROTECTION COORDINATION

One of the first concepts to be adopted when considering a coordinated scheme is that *current*, not voltage, is the independent variable involved. The physics of overvoltage generation involve either lightning or load switching. Both are current sources, and it is only the voltage drop associated with the surge current flow in the system impedance which appears as a transient overvoltage. Perhaps a long history of testing insulation with voltage impulses has reinforced the erroneous concept that voltage is the given parameter. Thus, *overvoltage protection* is really the art of offering low impedance to the *flow of surge currents* rather than attempting to block this flow through a high series impedance. In combined approaches, a series impedance is sometimes added in the circuit, but only after a low impedance diverting path has first been established.

When the diverting path is a crowbar-type device, little energy is dissipated in the crowbar, as noted earlier. In a voltage clamping device, more energy is deposited in the device, so that the energy handling capability of a candidate suppressor is an important parameter to consider when designing a protection scheme. With nonlinear devices, an error made in the assumed value of the current surge produces little error on the voltage developed across the suppressor and thus applied to the protected circuit (11), but the error is directly reflected in the amount of energy which the suppressor has to absorb. At worst, when surge currents in excess of the suppressor capability are imposed by the environment, because of an error made in the assumption or because nature tends to support Murphy's law or because of human error in the use of the device, the circuit in need of protection can generally be protected at the price of failure in the short-circuit mode of the protective device. However, if substantial power-frequency currents can be supplied by the power system, the fail-short protective device generally terminates as fail-open when the power system fault in the failed device is not cleared by a series overcurrent protective device (fuse or breaker). Note that in this discussion, the term "fail-safe" has carefully been avoided since it can mean opposite failure modes to different users. To some, fail-safe means that the protected *hardware* must never be exposed to an overvoltage, so that failure of the protective device must be in the fail-short mode, even if it puts the system out of operation. To other users, fail-safe means that the *function* must be maintained, even if the hardware is left temporarily unprotected, so that failure of the protective device must be in the open-circuit mode.

EXAMPLES OF COORDINATED SURGE PROTECTION

Retrofit of a Control Circuit Protection

In this case history, a field failure problem was caused by lack of awareness (on the part of the circuit designer) of the degree of hostility in the environment where the circuit was to be installed. A varistor had been provided to protect the control circuit components on the printed circuit board, but its capability was exceeded by the surge currents occurring in a Category B location (Table II). To the defense of the circuit designer, however, it must be stated that the data of Table II were not available to him at the time.

Since a number of devices were in service, complete redesign was not possible, and a retrofit — at an acceptable cost — had to be developed. Fortunately, the power consumption of this control circuit was limited so that it was

Table II

RECOMMENDED VALUES FROM IEEE STD 587

Surge Voltages and Currents Deemed to Represent the Indoor Environment and Recommended for Use in Designing Protective Systems

Location Category	Comparable to IEC No 664 Category	Impulse		Type of Specimen or Load Circuit	Energy (joules) Deposited in a Suppressor* with Clamping Voltage of	
		Waveform	Medium Exposure Amplitude		500V (120 V System)	1000V (240 V System)
A Long branch Circuits and outlets	II	0.5 μs-100 kHz	6 kV	High impedance†	—	—
			200 A	Low impedance‡, §	0.8	1.6
B Major feeders, short branch circuits, and load center	III	1.2 × 50 μs	6 kV	High impedance†	—	—
		8 × 20 μs	3 kA	Low impedance‡	40	80
		0.5 μs-100 kHz	6 kV	High impedance†	—	—
			500 A	Low impedance‡, §	2	4

*Other suppressors having different clamping voltages would receive different energy levels.

†For high-impedance test specimens or load circuits, the voltage shown represents the surge voltage. In making simulation tests, use that value for the open-circuit voltage of the test generator.

‡For low-impedance test specimens or load circuits, the current shown represents the discharge current of the surge (not the short-circuit current of the power system). In making simulation tests, use that current for the short-circuit current of the test generator.

§The maximum amplitude (200 or 500 A) is specified, but the exact waveform will be influenced by the load characteristics.

possible to insert some series impedance in the line, ahead of the low-capacity varistor, while a higher capacity varistor was added at the line entrance to the circuit (Figure 6). Laboratory proof-test of the retrofit demonstrated the capability of the combined scheme to withstand 6 kA crest current surges (Figure 7A) and a 200% margin from the proposed Category B requirement, as well as reproduction of the field failure pattern (Figure 7B). The latter is an important aspect of any field problem retrofit. By simulating in the laboratory the assumed surges occurring in the field (Table II), verification of the failure mechanism is the first step toward an effective cure. Figure 7C illustrates the effect of improper installation of the suppressor, with eight inches of leads instead of a direct connection across the input terminals of the circuit.

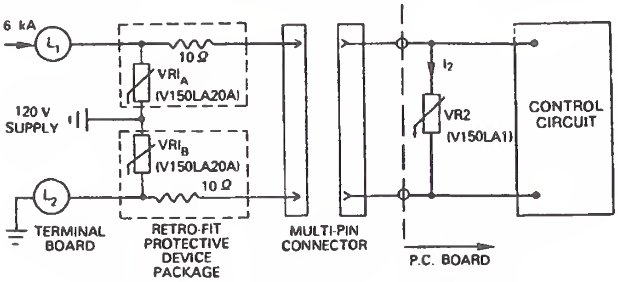
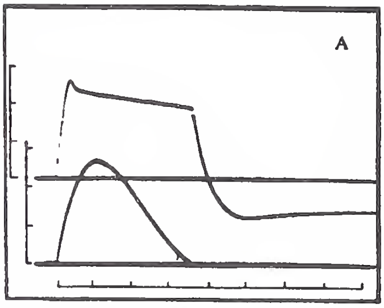


Figure 6. Retrofit protection of control circuit

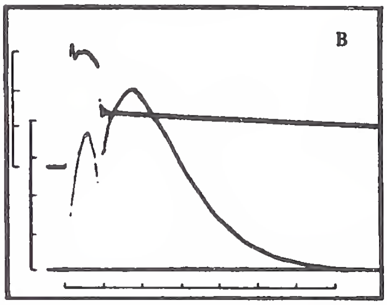
Coordination Between a Secondary Surge Arrester and a Varistor

In this example, the objective was to provide overvoltage protection with a maximum of 1000 V applied to the protected circuit, but to withstand current surges on the service entrance of magnitudes associated with lightning, as defined in ANSI C62.1 and C62.2 standards for secondary arresters. The only arresters available at the time which could withstand a 10 kA crest 8/20 μs impulse had a protective (clamping) level of approximately 2200 V (12). Some distance was available between the service entrance and the location of the protected circuit, so that impedance was in fact inserted in series between the arrester and the protected circuit where a varistor with lower clamping voltage would be installed. The object was to determine the current level at which the arrester would spark over for a given length of wire between the two protective devices, relieving the varistor from the excessive energy that it would absorb if the arrester would not spark over.

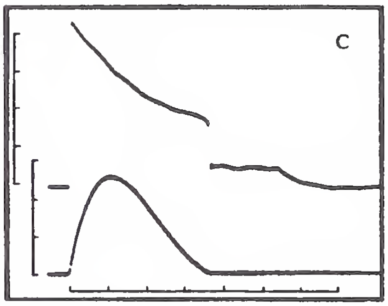
A circuit was set up in the laboratory (13), with 8 m (24 ft) of #12 (2.05 mm) two-wire cable between the arrester and the varistor. The current, approximately 8/20 μs impulse, was raised until the arrester would spark-over about half of the time in successive tests at the same level, thus establishing the transfer of conduction from the varistor to the arrester. Figure 8A shows the discharge current level required from the generator at which this transfer occurs. Figure 8B shows the voltage at the varistor when the arrester does not spark over. Figure 8C shows the voltage at the arrester when it sparks over; this voltage would propagate inside all of the building if there were no suppressor added. However, if a varistor is added at eight meters, the voltage of Figure 8C is attenuated to that shown in Figure 8D, at the terminals of the varistor.



Upper trace: Voltage across V150LA1 varistor on PC board, 200 V/div.
Lower trace: Applied surge current, 2000 A/div.
Sweep speed: 10 μs/div.



Additional surge protection removed: V150L.A1 varistor on PC board is the only protection.
Upper trace: Voltage across V150LA1 varistor
Lower trace: Varistor current 200 A/div. Sparkover occurs at about 700 A: 60 Hz power-follow destroys the PC board.
Sweep speed: 10 μs/div.



Same as A, but with varistor mounted on eight-inch leads from terminal board.

Figure 7. Laboratory demonstration of retrofit effectiveness

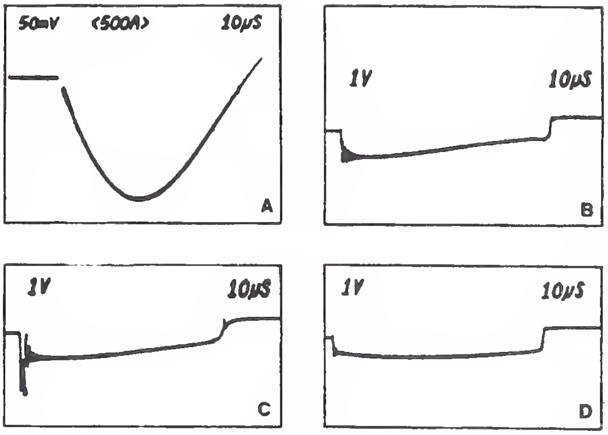


Figure 8. Transfer of conduction in a coordinated scheme of protection

Matching Suppressor Capability to the Environment

It is a recognized fact that varistors exhibit, as do many other components, an aging characteristic, so that a finite life can be predicted. Most manufacturers provide information on this aspect of application, and IEEE standards identify this parameter as one of the significant evaluation tests (14). Carroll has shown (15) how statistical information presented in IEEE Std 587 can be combined with Pulse Lifetime Ratings published by manufacturers (16) to arrive at a rational selection of device ratings, with a specific life goal, in a cost-effective manner.

However, these ratings are generally expressed as a number of pulses of constant value, e.g., the rated life of a given varistor may be 1 pulse of 6 kA at 8/20, 10 pulses at 2 kA, 1000 pulses at 500 A, and so forth. But since the surges encountered in real life have a range of values at a slope of probability versus magnitude described by Figure 1, one must consider the effect of this array of pulses with different values rather than the constant pulses implied by the manufacturer's pulse lifetime rating.

The method described by Carroll in the referenced paper provides a computation that can be applied in general terms, but repeating it here would be too lengthy. Rather, we will take two examples of application and develop a table showing how the Pulse Lifetime Ratings can be combined with the data from IEEE Std 587 to make a reasonable estimation of the rated life consumption. The computations shown in the tables have been made with four digits for the sake of allowing a check of the arithmetic, but the base data are far from four significant digits in their accuracy, and the numbers are read from curves with rather coarse logarithmic scales. However, these examples do illustrate the method and the results that can be expected.

The first task is to convert the voltage surge *density* probability of Figure 1 into a histogram of surge currents. A family of surge voltage cells can be defined from the Figure 1 line, with the density read at the center of the cell. The number of occurrences for any cell is then the value of the ordinate of the line, minus the number of total occurrences of all cells to the right of the cell of interest. In the computations of Table III, this conversion is shown in the first three columns, indicating the voltage level at the cell center, the number per year, and the number of occurrences per year.

From the description of the Category B in IEEE Std 587, one can deduce an implied source impedance of 6 kV/3 kA for a surge or 8/20 μs, or 2 Ω as the *most severe* in Category B. The current that will flow in a varistor connected at this Category B location is then the surge voltage, minus the varistor clamping voltage, divided by the 2 Ω source impedance of the surge. The varistor clamping voltage can be determined if the current is known, so an iteration would be required to obtain the clamping voltage. However, one can assume a clamping voltage, and later check the validity of the assumption against the resulting current obtained. The fourth column of Table III shows this

Table III

LIFE CONSUMPTION – 14 mm, 130 V RMS VARISTOR, CATEGORY B, LOW EXPOSURE

Voltage surge level V	Number per year above level	Total occurrences per year at level	Assumed clamping voltage of varistor V	Available driving voltage	Surge current @ 2 Ω A	Rated number of pulses for this surge current	Percent life consumed per year
3000	0.01	0.01	500	2500	1250	7	0.14
2500	0.02	0.01	480	2020	1010	10	0.10
1700	0.10	0.08	450	1250	625	70	0.11
1300	0.20	0.10	420	880	440	500	0.02
900	1	0.80	400	500	250	2000	0.04
700	2	1	380	320	160	10 000	0.01
500	10	8	370	230	115	80 000	0.01

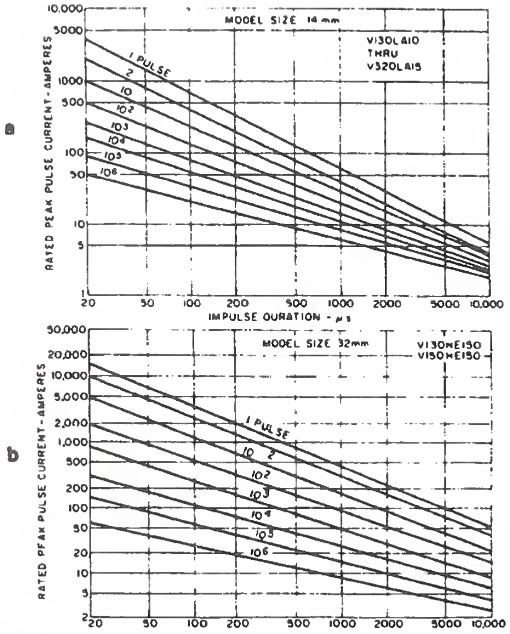
Cumulative life consumption per year	0.43
Time to reach rated life, years	232

assumed and subsequently checked value of the clamping voltage, hence the value of the available driving voltage in the next column, and the resulting surge current value, assumed to be an 8/20 μs waveshape.

Turning then to the published Pulse Lifetime Ratings, one can read the rated number of pulses corresponding to the surge current for each cell. Table III is computed with the ratings for a 14 mm varistor (Figure 9a); Table IV is computed for a 32 mm varistor (Figure 9b). Note that this "rated life" is defined as the condition reached when the varistor nominal voltage has changed by 10%; this is not the *end* of life for the varistor, but only an indication of some permanent change beginning to take place. The varistor has still retained its voltage clamping capability at this point.

For each level of surge current, the number of pulses is read on the family of curves of Figures 9a or 9b, along the vertical axis, since these are 8/20 μs impulses. The number of pulses with constant amplitude is shown in the next-to-last column of Table III. We can now define, for each level, the percentage of life consumed for one year of exposure at that level. For instance, at the 2500 V level of Table III, there will be 0.01 surges of 1010 A per year, with 10 allowed by the ratings. Therefore, in percent, the life consumption is (0.01/yr × 100)/10, or 0.10%. Likewise, taking the 900 V level, the consumption is (0.8/yr × 100)/2000 = 0.04%. The total of these life consumptions at all cell levels is then 0.43% of the rated life in one year, yielding an estimated 232 years for this 14 mm varistor to reach its rated life in the Low-Exposure Category B environment.

Similar computations for a 32 mm varistor in a Category B, Medium Exposure, are shown in Table IV. In the case of this "Medium Exposure," we note the high frequency of occurrences below 3000 V, reflecting the "frequent and severe switching transients" cited in the IEEE definition of Medium Exposure. Thus, a still very conservative estimate would be that as many as half of the occurrences would be due to lightning, with the attendent 8/20 μs high energy surges, while the other half would be switching transients, having a lower energy content than the 8/20 μs surges accounted in this computation, being oscillatory as typified by the 0.5 μs — 100 kHz wave. This translates to 13 surges of 760 A, 35 surges of 525 A, and 250 surges of 285 A, still a high number of lightning surges and therefore certainly conservative. Using this conservative estimate of half of the low-magnitude surges and all of the high-magnitude surges being 8/20 μs lightning-related surges, the computation of Table IV yields 21 years to reach rated life for the 32 mm varistor. In this case, where the rated life is reached earlier, it should be pointed out that the results are strongly influenced by the assumption made for the source impedance. Using the IEEE 587 implied value of



NOTE:
End of lifetime is defined as a degradation failure which occurs when the device exhibits a shift in the varistor voltage at one (1) milliampere in excess of ± 10% of the initial value. This type of failure is normally a result of a decreasing V_1 value, but does not prevent the device from continuing to function. However, the varistor will no longer meet the original specifications.

Figure 9. Pulse lifetime ratings

Table IV

LIFE CONSUMPTION — 32 mm, 150 V RMS VARISTOR, CATEGORY B, MEDIUM EXPOSURE

Voltage surge level V	Number per year above level	Total occurrences per year at level	Occurrences due to lightning	Clamping voltage of varistor V	Available driving voltage V	Surge current @ 2 Ω A	Rated number of pulses for this surge current	Percent life consumed
10000	0.08	0.08	0.08	580	9420	4710	15	0.54
6000	0.2	0.12	0.12	550	5450	2725	50	0.24
5000	1	0.8	0.80	520	4480	2240	90	0.89
3000	4	3	3	500	2500	1250	400	0.75
2000	30	26	13	480	1520	760	2000	0.65
1500	100	70	35	450	1050	525	4000	0.88
1000	600	500	250	430	570	285	30000	0.84

Cumulative life consumption per year	4.79
Time to reach rated life, years	21

2 Ω leads to these conservative results. For example, the FCC test for communication equipment interfacing with power lines (17) implies a 2.5 Ω source impedance. Current studies for complementary data to the IEC Report 664 make the assumption of a surge originating on the primary of a distribution transformer, with a 63 Ω source impedance, yielding currents of less than 1 kA available at the service entrance interface. Thus, there is still room for more precise definitions of the source impedance, but we should recognize that any attempt to make broad generalizations will always encounter the contradiction of some special cases.

CONCLUSION

Effective protection of sensitive electronic equipment is possible through a systematic approach where the capability of the equipment is compared to the characteristics of the environment. The combined efforts of several organizations have produced a set of data which provide the circuit designer with reasonable information, albeit not fine specifications, on the assumptions to be made in assessing the hostility of the environment. With the publication of the IEEE Guide, and of application guides in the near future, we can expect better knowledge of the power system environment. As more field experience is gained in applying these documents to equipment design, the feedback loop can be closed to ultimately increase the reliability of new equipment at acceptable costs, while present problems may also be alleviated based on these new findings in the area of transient overvoltages.

ACKNOWLEDGMENTS

The data base for the Guide quoted in the paper as well as the writing of that Guide was provided by the members of the IEEE Working Group on Surge Characterization in Low-Voltage AC Power Circuits. Robert Mierendorf emphasized the significance of clearance sparkover; and Peter Richman's critique of the concepts relating to source impedance proved very effective; and, Eric Carroll's cross examination of the IEEE Std 587 led to the concept of relating varistor pulse lifetime data to the distribution of expected surge currents.

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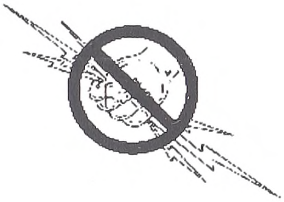

Cascading Surge-Protective Devices: Coordination versus the IEC 664 Staircase

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Significance
Part 8 – Coordination of cascaded SPDs

The early nineties were marked by the emergence of concerns about the coordination of cascaded SPD in the midst of “common wisdom” that ***voltage surges*** impinging upon the service entrance of a building would inherently become less severe as they propagate and divide among the branch circuit of the installation. That perception was reinforced by the publication in 1980 of an IEC Standard on insulation coordination that figured prominently a “staircase” of descending surge voltage levels. As a result of that perception, proposals were made to provide a service entrance SPD with a limiting voltage higher than the limiting voltage of the SPDs installed at the point-of-use receptacles.

Numerical simulations and measurements on actual SPDs demonstrated the pitfalls of that perception. For an effective coordination to occur – service entrance SPD diverting the bulk of the surge current and point-of-use SPD mitigation as needed – the service entrance SPD cannot have a substantially higher limiting voltage than the point-of-use SPD, lest the latter take on the bulk of the energy. The inductance of the wiring between the service entrance can add some voltage drop between the two devices, so that an acceptable degree of coordination can still be achieved if the two device have equal limiting voltages.

The redeeming effect of the wiring inductance is of course dependent upon the waveform of the impinging ***current surge***, as well as the length of the branch circuit. The relationships of these parameters are explored in the computations and experiments reported in the paper.

Cascading Surge-Protective Devices: Coordination versus the IEC 664 Staircase
Montage en cascade de parafoudres: Coordination ou gradins IEC 664 ?

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Abstract - *Cascading two or more surge-protective devices located respectively at the service entrance of a building and near the sensitive equipment is intended to ensure that each device shares the surge stress in an manner commensurate with its rating, to achieve reliable protection of equipment against surges impinging from the utility supply as well as internally generated surges. However, depending upon the relative clamping voltages of the two devices, their separation distance, and the waveform of the impinging surge, coordination may or may not be effective. The paper reports computations confirmed by measurements of the energy deposited in the devices for combinations of these three parameters.*

Sommaire - *Le montage en cascade de plusieurs parafoudres, respectivement à l'arrivée du secteur et au voisinage du matériel à protéger est envisagé dans le but d'assurer que chaque dispositif prenne une part de la contrainte totale associée au transitoire qui corresponde bien à la valeur nominale de chacun. Cette disposition permet d'assurer la fiabilité de la protection contre les transitoires d'origine extérieure aussi bien que ceux produits par le matériel adjacent. Cette communication donne les résultats de calculs, confirmés par des mesures, pour un ensemble de niveaux d'écrêtage relatifs, de distances séparant les dispositifs, et de la forme d'onde postulée pour le transitoire.*

Introduction

Recent progress in the availability of surge-protective devices, combined with increased awareness of the need to protect sensitive equipment against surges, has prompted the application of a multi-step cascade protection scheme. In this scheme, a high-energy surge-protective device is installed at the service entrance of a building to divert the major part of the surge energy. Then, surge-protective devices with lower energy-handling capability and lower clamping voltage than that of the service entrance, are installed downstream near or at the equipment and complete the protection.

To make the distinction between these two devices, we will call the service entrance device 'arrester' and the downstream device 'suppressor'. Such a scheme is described as 'coordinated' if, indeed, the device with high energy handling capability receives the largest part of the total energy involved in the surge event.

This scenario was initially based on the technology of secondary surge arresters prevailing in the 1970s and early 1980s, as well as on the consensus concerning the waveform and current levels of representative lightning surges impinging on a building service entrance. With the emergence of new types of arresters for service entrance duty and the recognition of waveforms with greater duration than the classic 8/20 μs impulse, a new situation arises that may invalidate the expectations on the cascade coordination scenario.

Service entrance arresters were generally based on the combination of a gap with a nonlinear varistor element, the classic surge arrester design before the advent of metal-oxide varistors (MOV) that made gapless arresters possible. With a gap plus varistor element, the service entrance arrester could easily be designed with a 175-V Maximum Continuous Operating Voltage (MCOV) in a 120-V (rms) system. The downstream suppressors were selected with a low level, driven by the perception that sensitive equipment requires a low protective level [1]. The scheme can work if there is a series impedance (mostly inductance) between the arrester and the suppressor, because the inductive drop in the series impedance, added to the clamping voltage of the suppressor, becomes high enough to sparkover the arrester gap. Thereafter, the lower discharge voltage of the arrester (made possible by the gap) ensures that the major part of the surge energy is diverted by the arrester, relieving the suppressor from the heavy duty [2].

This concept was in complete harmony with the 'Installation Category' concept of IEC Pub 664-1980 [3] which featured a descending staircase of voltages, starting with the 'uncontrolled situation' at the building service entrance, with several lower levels within the building (Figure 1). The lower levels would be achieved, according to IEC 664, by means of the natural attenuation caused by the multiple branch circuits, or by a deliberate interface - a surge-protective device.

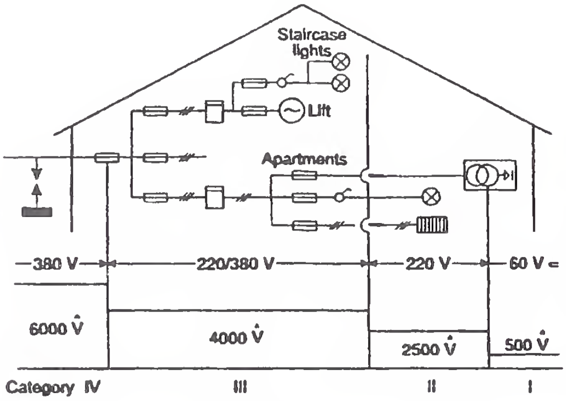


Figure 1
Installation Categories according to
IEC Pub 664-1980 [3]

On the other hand, the ANSI/IEEE C62.41-1980 Guide [4] (updated as a Recommended Practice in 1991) defined a set of 'Location Categories' within a building. According to that concept, constant voltage levels are maintained downstream of the service entrance, but the current levels decrease. That concept was based on recognition that the wiring inductance would decrease the available surge current at locations deeper into the building - for the 8/20 μs current waveform then universally postulated to be representative. Thus, the stage was set for a mind-set of decreasing surge energy as the wiring progresses through the building, away from the service entrance.

The new situation

With the emergence of MOV-based, gapless arresters, a new situation has been created. The Maximum Continuous Operating Voltage of the arrester will determine its clamping level. Some utilities wish to ensure survival of the arrester under the condition of a lost neutral, that is, twice the normal voltage for a single-phase, three-wire service connection. For three-phase systems in which devices are connected between phases and ground (protective earth), the usual practice is to rate these devices for the line-to-line voltage in order to provide for the case of one corner of the delta being at ground, or the case of undefined voltage between neutral and ground.

This survival wish is a motivation for selecting an arrester clamping voltage corresponding to 1.7 to 2 times the single-phase voltage. Meanwhile, if single-phase equipment, typical of home electronic systems ('domotique' in French) are perceived to be sensitive, there will be a tendency to protect them with the lowest possible clamping voltage.

This situation sets the stage for a 'High-Low' combination where the arrester clamping voltage is higher than that of the suppressor [5]. During the ascending portion of a relatively steep surge such as the 8/20 μs, the inductive drop may still be sufficient to develop enough voltage across the terminals of the arrester and force it to absorb much of the impinging energy. However, during the tail of the surge, the situation is reversed; the inductive drop is now negative and thus the suppressor with lower voltage, not the arrester, will divert the current.

For the new waveforms proposed in C62.41-1991 [6], this situation occurs for the 10/1000 μs where the tail contains most of the energy, and the relief provided by the arrester might not last past the front part of the surge. An alternate means has been proposed - 'Low-High' where the arrester clamping voltage is lower than that of the suppressor [7],[8]. Thus, a disagreement has emerged among the recommen-dations for coordinated cascade schemes: the 1970-1980 perception and Ref [5] suggesting a 'High-Low' and the new 'Low-High' suggestion of Refs [7] and [8].

This paper reports the results of modeling the situation created by the emergence of gapless arresters and longer waveforms, with the necessary experimental validation. These results cover a range of parameters to define the limits of a valid cascade coordination, and will serve as input to the surge protective device application guides now under development by providing a reconciliation of the apparent disagreement, which is actually rooted in different premises on the coordination parameters.

MOV Circuit Modeling

The current-voltage (I-V) characteristic of a MOV has long been represented by a power law, i. e., $I = k V^{\alpha}$ [9]. This equation is only applicable in a certain voltage (current) range in which the I-V characteristic presents a linear relationship in a log-log plot. For the high-current region of the characteristic, the current increment rate starts dropping. This change appears on the I-V plot as a voltage upturn in the high-current region. A modified I-V characteristic is proposed here as expressed in (1).

$$I = k V^{\alpha} e^{-(V - V_o)[\lambda - \zeta (V - V_o)]} \qquad (1)$$

The coefficients in (1) can be obtained from a curve fitting technique by minimum-error-norm [10] using a MOV data book [9] or experimental results. The parameter k and exponent α can be obtained from fitting the data in the linear log-log region. The exponential term is added to cover the voltages higher than a threshold voltage Vo where the upturn begins and can be obtained from fitting the I-V characteristics in the higher current (voltage) region. Using (1), the MOV circuit model can then be simply represented by a voltage-dependent current source.

Model parameters in (1) can be obtained from the MOV data book and verified by experiments. The exponent α in this model is a function of the MOV voltage rating. The threshold voltage Vo and coefficients λ and ζ are functions of the voltage rating and the size. Table 1 lists the curve fitting data for the equivalent circuit parameters of three MOVs typical of what might be considered for a 120-V power system: 130 V for 'low', 150 V for 'medium', and 250 V for 'high'. For European systems with a 220-V single-phase voltage, similar ratings would be 250 V for a 'low', 320 V for a 'medium', and 420 V for a 'high'. Note that the numerical values of the parameters are unit-dependent, and are given in Table 1 for units in volts and amperes.

Table 1
Curve fitting results for three 20-mm dia MOVs

Rating	k	α	λ	ζ	Vo(V)
130 V	$4.0 \cdot 10^{-74}$	30	0.051	$8 \cdot 10^{-6}$	320
150 V	$3.9 \cdot 10^{-89}$	35	0.053	$4 \cdot 10^{-6}$	370
250 V	$5.7 \cdot 10^{-110}$	40	0.04	$4 \cdot 10^{-6}$	570

In Figure 2, the marked points are the data directly read from curves in the MOV data book, while the three lines are a plot of the computed I-V characteristic according to (1), using the parameters listed in Table 1. Note the remarkable fit achieved by this model over the range of interest.

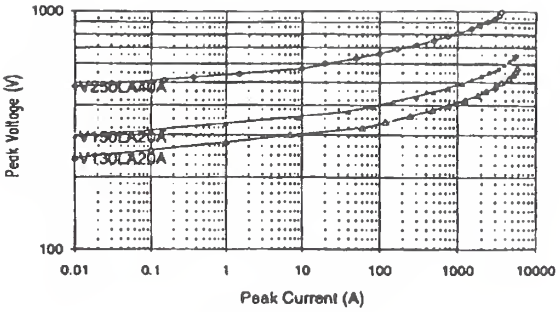


Figure 2
MOV characteristics obtained from modeling results

There is a tolerance of ± 10% on the actual values within a given varistor rating. Figure 2 shows the maximum clamping voltage levels; a device at the low end of the tolerance band would have a characteristic 20% lower than the data book characteristics. In fact, the two closely rated cascaded devices (130 V and 150 V) could in some extreme cases become inverted in the sequence, 'Low-High' becoming in reality 'High-Low', as 130 × 1.1 = 143 and 150 × 0.9 = 135.

Furthermore, results (presented below) show that for the 250-150 combination, the difference is so large that a low-end 250 (225 V) combined with a high-end 150 (165 V) would not make an appreciable difference in the energy sharing. Thus, the simulation computations were performed for all three devices at their nominal values, with appropriate modification of the parameters in the model equation.

Simulation of Cascaded Devices in a Low-Voltage System

Figure 3 shows a typical two-stage cascade surge protection. The arrester and the varistor are separated by a distance *d* determined by the specific installation.

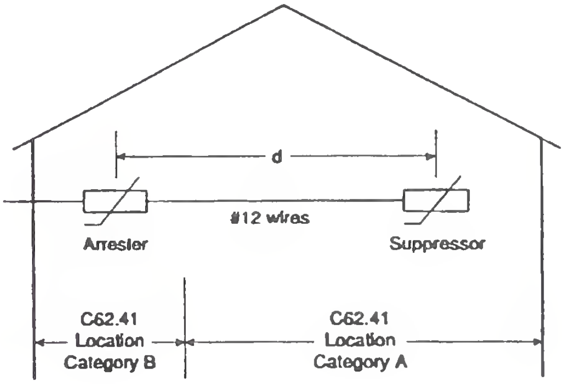


Figure 3
Configuration of a two-stage cascade

Four different d values, 5 m, 10 m, 20 m, and 40 m were used in the simulation, with a #12 AWG (1.83-mm dia.) wire, representative of U.S. practice for 20 A branch circuits. At the frequencies involved in the surges considered, inductance is the dominant parameter and the wire diameter plays only a minor role [11], so that the resistance of the wire could be neglected. However, given the flexibility of the model, it was included.

The complete simulation model, shown in Figure 4, consists of a surge source I_G, two voltage-dependent current sources I_A and I_S, and a line impedance between the two current sources. For three device voltage levels, there is a total of nine possible cascade combinations as shown in Table 2.

Table 2
Nine cascade combinations for three devices

Arrester	Suppressor
250 V	250 V 150 V 130 V
150 V	250 V 150 V 130 V
130 V	250 V 150 V 130 V

Two standard waves from Ref [6] were chosen: the 1.2/50 μs - 8/20 μs Combination Wave, and the 10/1000 μs Impulse Wave. For four distances, two waveforms, and nine cascade combinations, a total of 72 cases are reported here. The case of the 100 kHz Ring Wave was also simulated and tested [12], but is not reported here because the low energy stress involved in that waveform will not deposit substantial energy in the suppressor or the arrester.

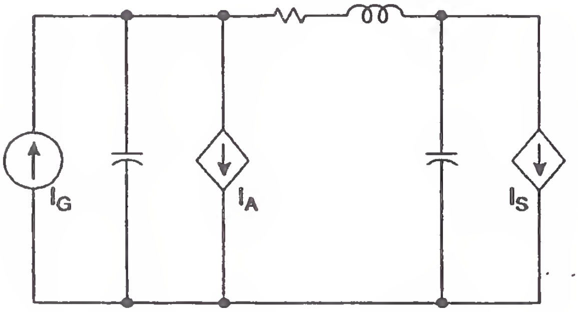


Figure 4
Circuit model for a two-stage cascade

Simulation and Experimental Results - 8/20 Wave

As one example of the combinations that were simulated, consider a cascade with 250 V and 130 V devices separated by 10 m. The simulation results of the currents flowing in the two devices are shown in Figure 5, where I_t is the total current injected into the cascade by the surge source of the model, I_1 is the arrester current, and I_2 is the suppressor current. Figure 6 shows the corresponding device clamping voltages, V_1 and V_2 across the arrester and suppressor respectively. Figure 7 shows instantaneous powers P_1 and P_2, respectively for the arrester and the suppressor. By integrating the instantaneous power, the energy deposited in the arrester and the suppressor were calculated as 29.7 J and 8.6 J respectively.

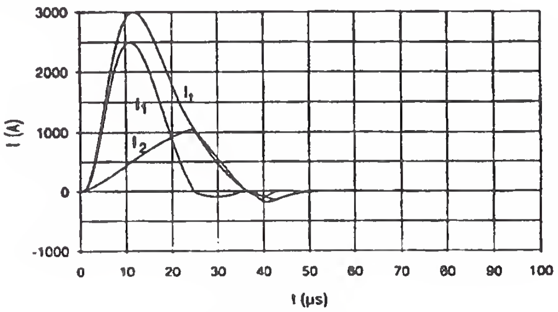


Figure 5
Simulated current responses for 250 V - 130 V cascade, 10 m separation, 8/20 μs applied surge

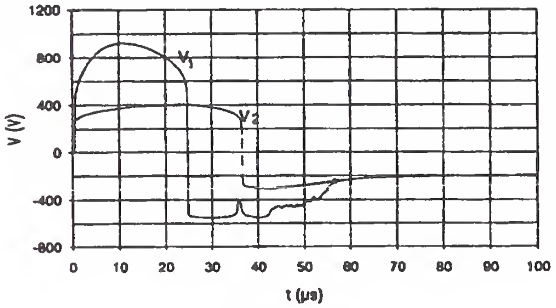


Figure 6
Simulated voltage responses for 250 V - 130 V cascade, 10 m separation, 8/20 μs applied surge

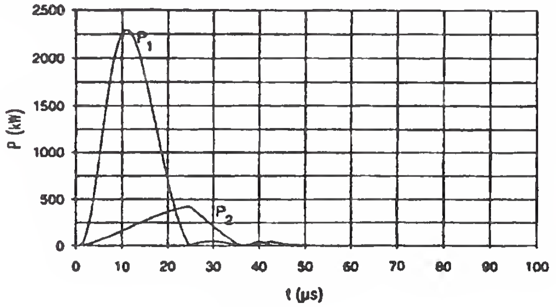


Figure 7
Simulated dissipated power for 250 V - 130 V cascade, 10 m separation, 8/20 μs surge

Table 3 lists the computed results for the 8/20 Wave simulation, as energy deposition in the arrester (A) and suppressor (S) for all the combinations of different High (250 V), Medium (150 V), and Low (150 V) devices as arrester and suppressor.

Table 3
Energy deposition in the cascaded devices with a 3-kA 8/20 Wave as the surge source.

Rating of Device (V)		Energy deposited in each device (joules) as a function of separating distance (meters)							
		5 m		10 m		20 m		40 m	
A	S	A	S	A	S	A	S	A	S
150	250	75.9	27.3	83.5	19.9	89.5	14.4	91.7	9.69
	150	22.2	12.0	29.9	8.52	35.9	5.40	39.8	3.30
	130	21.3	11.9	29.7	8.60	35.3	5.20	40.1	3.30
150	250	24.3	.005	24.3	.006	24.3	.007	24.3	.008
	150	21.2	4.65	23.1	3.06	24.1	1.93	25.5	.880
	130	19.9	5.16	22.2	3.05	24.1	1.86	25.0	1.08
130	250	22.9	.003	22.9	.003	22.9	.004	22.9	.004
	150	20.2	1.71	20.8	1.18	21.3	.760	21.1	.440
	130	18.6	2.92	19.4	1.71	20.3	1.03	20.9	.700

Figure 8 shows in graphic form the results of Table 3, where the lines represent the energy deposited in the suppressor as percentage of the total surge energy, as a function of relative clamping voltages and separation distance. With the scale used in the figure (geometric distance), the curves are approximately straight lines over the range. For the High-Low condition, the energy deposition in the suppressor decreases rapidly when the separation distance increases. This result explains how the High-Low configuration can achieve a good coordination with the 8/20 Wave, provided that there be sufficient distance between the two devices, as stated in Ref [5].

When the distance between two devices is reduced, the energy deposition tends to increase in the suppressor and decrease in the arrester. This decrease occurs because the line inductance does not provide enough voltage drop (*L di/dt*), and the low clamping voltage of the suppressor reduces the voltage across the arrester, and thus reduces the energy deposition level. The total energy deposition in the two devices also varies with the distance for the High-Low configuration. In Table 3, the total energy deposition for the 250-250 combination is near constant at 103 J for different distances. However, for 250-150 and 250-130 combinations, the total energy deposition decreases when the distance is reduced, because the suppressor tends to lower the voltage across the arrester. This situation can be explained by the fact that the impinging surge is defined as a current source, so that offering it diversion through a device with higher clamping voltage results in higher energy deposition.

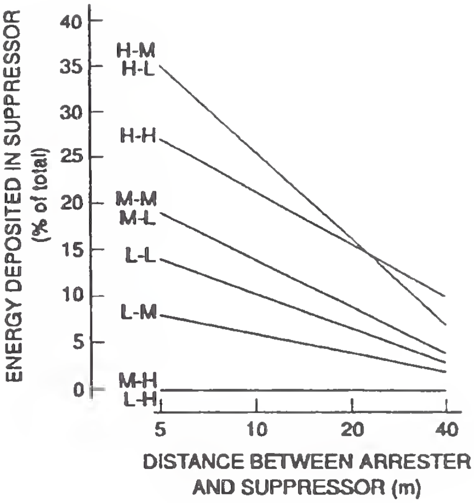
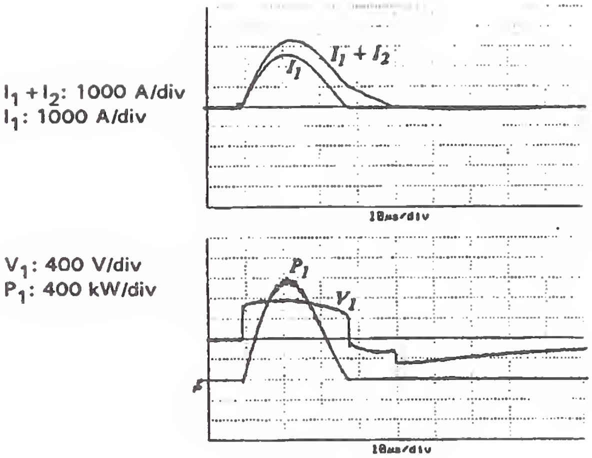


Figure 8
Relative energy deposited by an 8/20 μs Wave in the suppressor for arrester-suppressor combinations of 250 V (H), 150 V (M), or 130 V (L) ratings, as a function of separation distance

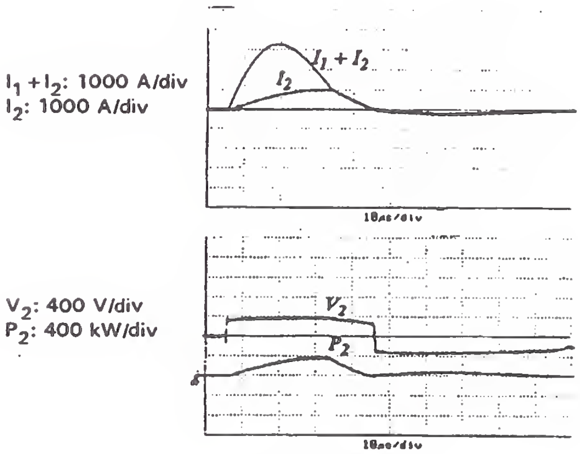
For Low-High configurations such as 150-250 and 130-250 cases, the higher voltage suppressor receives almost zero energy. The use of the suppressor is near redundant in this case, except for its application to mitigate internally generated surges. With closely rated devices (130-150), the 150-V voltage suppressor also receives much less energy than the 130-V arrester.

Now turning to measurements, the same cascade configuration, 250 V - 130 V with 10-m separation (Figure 3), was injected with a surge produced by a Combination Wave generator. The surge generator delivers an approximation of the standard waveform; consequently, the waveforms obtained from the experiment are not exactly the same as the simulated waveforms. However, the power distribution between the two devices shows good agreement between the simulation and the experiment.

Figure 9 shows the experimental results obtained with a cascade of two devices, 250 V and 130 V, with 10 m of separation. Oscillograms were recorded for the current, voltage and power in the two devices, where the subscript 1 corresponds to the arrester and the subscript 2 to the suppressor. The goal was to produce a 3 kA impinging surge ($I_1 + I_2$), but a slightly higher current (3.3 kA instead of 3 kA in the simulation) was produced, typical of the sensitivity of nonlinear circuits to minute changes in the applied voltage. The energy deposited in each device was computed by integration of the power (performed by the oscilloscope): 33.8 J in the arrester and 11.1 J in the suppressor. To compare simulation and measurement, prorating the simulation results (from Figure 7) to 3.3 kA would yield 32.7 J and 9.5 J respectively, a satisfactory agreement.



(a) Arrester



(b) Suppressor

Figure 9
Experimental results for the 250 V-130 V, 10-m apart cascade condition.

Simulation and Experiments Results - 10/1000 Wave

Compared to the 8/20 Wave, the 10/1000 Wave has a slower and longer drooping tail that contains most of the surge energy. During the long tail period, the inductive voltage drop between the arrester and the suppressor is low, and the voltage appearing across the arrester is reduced by the effect of the suppressor even with long distances between the two devices. Thus, the High-Low configuration cannot be coordinated as the high-voltage arrester will not absorb any impinging energy, but the suppressor does. Figures 10, 11 and 12 show the computed current, voltage, and power for the arrester and for the suppressor under a High-Low (250-130) simulation for a 200-A peak surge current. The high-voltage arrester clamps the voltage during the impulse rising period and draws a small amount of the current pulse, I_1, which is almost invisible in the computer-generated plot of Figure 10. The power dissipated in the arrester, P_1, is also a small pulse that appears at the rising period as shown in Figure 12. The low-voltage suppressor absorbs all the impinging energy in this High-Low configuration, defeating the intended coordination.

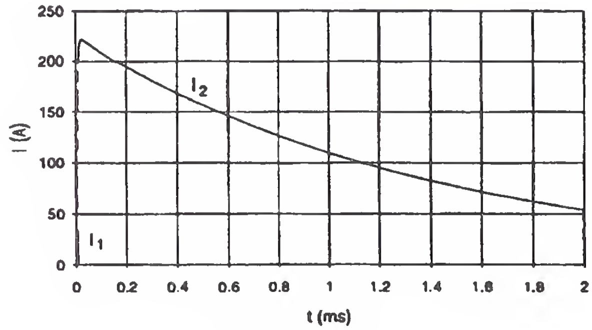


Figure 10
Simulated current responses for 250 V - 130 V cascade, 10 m separation, 10/1000 μs surge

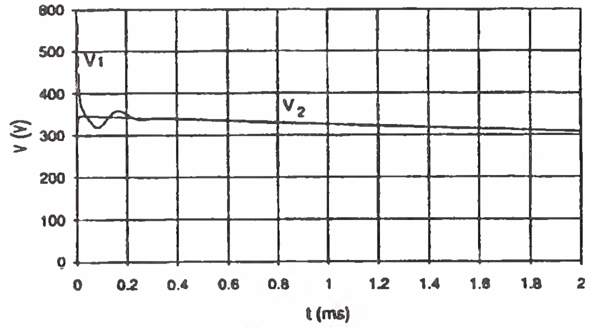


Figure 11
Simulated voltage responses for 250 V - 130 V cascade, 10 m separation, 10/1000 μs surge

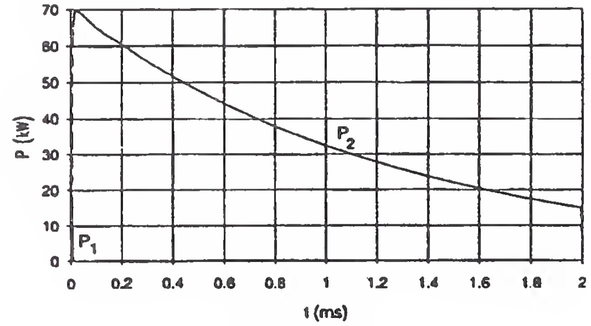


Figure 12
Simulated dissipated power for 250 V - 130 V cascade, 10 m separation, 10/1000 μs surge

Table 4 lists the simulated energy deposition in the cascaded devices for different High-Low and Low-High combinations and for different distances. Figure 13 presents in graphic form the results of Table 4, with lines showing the energy deposited in the suppressor as percentage of the total surge energy, as a function of relative clamping voltages and separation distance.

Table 4
Energy deposition in the cascaded devices with a 220-A, 10/1000 Wave as the surge source.

Rating of Device (V)		Energy deposited in each device (joules) as a function of separating distance (meters)							
		5 m		10 m		20 m		40 m	
A	S	A	S	A	S	A	S	A	S
250	250	73.7	72.7	74.1	72.3	75.1	71.4	73.3	70.1
	150	.031	92.2	.028	92.0	.690	91.7	1.77	91.0
	130	.011	79.3	.125	79.2	.518	78.9	1.42	78.4
150	250	92.2	.001	92.2	.002	92.2	.002	92.2	.003
	150	44.0	42.8	44.7	42.2	45.0	40.9	42.3	39.1
	130	7.92	70.7	8.86	69.8	10.7	68.0	14.3	64.6
130	250	79.2	.001	79.2	.001	79.2	.001	79.2	.001
	150	67.0	11.1	71.7	6.82	71.9	6.67	72.2	6.36
	130	38.0	36.7	38.7	36.1	40.0	34.8	42.3	32.6

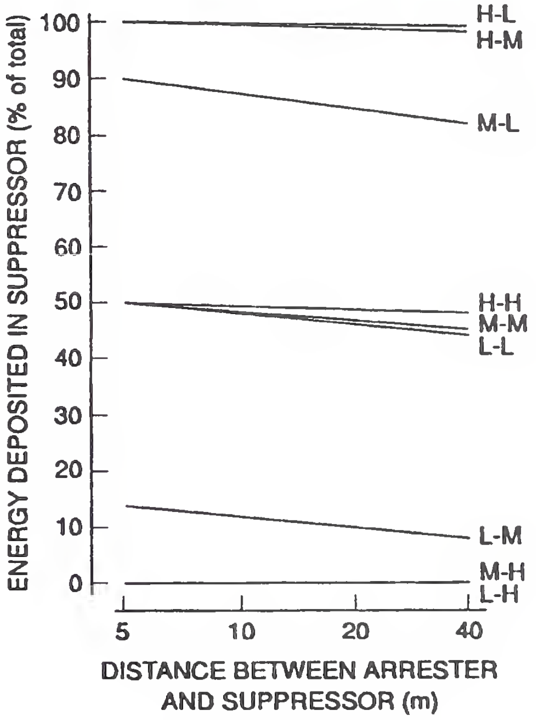


Figure 13
Relative energy deposited by a 10/1000 μs Wave in the suppressor for arrester-suppressor combinations of 250 V (H), 150 V (M), or 130 V (L) ratings, as a function of separation distance

It can be seen from Table 4 that the low-voltage device always absorbs higher energy than the high-voltage device. This situation exists because the voltage across the high-voltage device is clamped to the same level as that of the low-voltage device, and thus the energy is diverted to the device having the lower clamping voltage of the pair.

Unlike the case of the 8/20 Wave, coordination for the 10/1000 Wave can only be achieved by Low-High, Medium-High, or Low-Medium. Equally rated devices (250-250, 150-150, and 130-130) result in 50 % of the surge energy being deposited in the suppressor, not a very good coordination. Note that with two devices of equal nominal value, but random tolerance levels, it is possible that the relative tolerances might in fact produce a situation which would not achieve good coordination: for instance, an effective 150-130 combination can result from tolerance shifts in an intended 150-150 or 130-130 pair. This shift would impose a 70-J duty to the suppressor and only 7 J to the arrester, in the case of 5-m separation.

The experimental response to a 10/1000 Wave, for a Low-Medium configuration is shown in Figure 14 where I_1 and I_2 are the currents flowing in the 130-V arrester and the 150-V suppressor respectively. This figure shows an example of good coordination by Low-Medium, where most of the surge energy is absorbed by the low-voltage arrester, and little surge current propagates into the building - one of the goals of the two-step coordinated approach. The arrester voltage V_1 is almost the same as the suppressor voltage V_2 with a slight difference at the beginning of the surge.

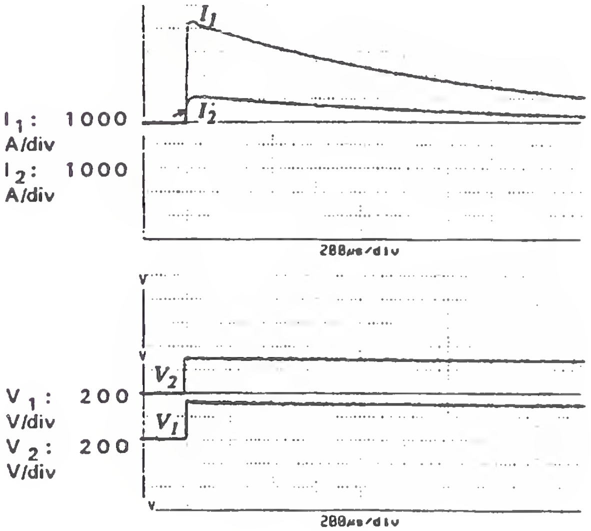


Figure 14
Experimental results for a 130 V - 150 V, 10-m apart cascaded condition with 10/1000 Wave.

Discussion

The benefit from a coordinated approach is to allow a single device at the service entrance to perform the high-energy duty, while several smaller devices within the premises can perform local suppression. This arrangement avoids the flow of large surge currents in the branch circuits of the installation, a situation known to produce undesirable side effects [13].

On the other hand, the situation exists where millions of small suppressors have been installed within equipment or as plug-in devices, with only sporadic and anecdotal reports of problems. Thus, it is evidently possible to obtain protection with suppressors alone, while a coordinated scheme would provide additional benefits and eliminate side-effects.

Some utilities wish to provide a service-entrance arrester capable of withstanding the 240-V overvoltage that can occur on the 120-V branches when the neutral is lost. This desire will force the coordination scheme into a High-Low situation because of the uncontrolled installation of low clamping voltage suppressors by the occupant of the premises. The results of the simulation and experimental measurements show that the objective of coordination could still be achieved with a 250-130 combination, as long as some distance is provided between the two devices, and as long as long waves such as the 10/1000 μs are not occurring with high peak values. This proviso provides an incentive for obtaining better statistics on the occurrence of long waves. ANSI/IEEE C62.41-1991 [4] recommends considering these long waves as an additional, not a standard waveform. Thus, the determination of a successful coordination depends for the moment on the perception of what the prevailing high-energy waveforms can be for specific environments.

Conclusions

1. Coordination of cascaded devices can be achieved under various combinations of parameters, but some combinations will result in having a suppressor with low energy-handling capability called upon to divert the largest part of the surge energy. This uncoordinated situation can create adverse side effects when high current surges occur.

2. Significant parameters in achieving successful coordination involve three factors, over which the occupant of the premises has no control: the relative clamping voltages of the two devices, their separation distance, and the prevailing waveforms for impinging surges. This uncontrolled situation presents a challenge and obligation for standards-writing groups to address the problem and develop consensus on a trade-off of advantages and disadvantages of High-Low versus Low-High.

3. Coordinated schemes can be proposed by utilities to their customers, including a service entrance arrester and one or more plug-in devices to be installed for the dedicated protection of sensitive appliances. However, even such an engineered, coordinated arrangement could be defeated by the addition of a suppressor with a very low clamping voltage, not an insignificant likelihood in view of the present competition for lower clamping voltages.

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Cascading Surge-Protective Devices: Options for Effective Implementations

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Significance
Part 8 – Coordination of cascaded SPDs

The early nineties were marked by the emergence of concerns about the coordination of cascaded SPD as the concept of "Whole-house protection" was gaining popularity. However, it appeared that the selection of service entrance SPDs and point-of-use plug-in SPDs was not an integrated process, hence some possibility that the expected coordination might not be achieved. On the other hand, if a well-designed combination could be implemented by a single authority responsible for the selection of the two devices, then the competing requirements for these to devices might be accommodated.

The service entrance SPD is generally selected from the point of view of the utility, and therefore tends to be a rugged device with relatively high limiting voltage because of the desire to have a conservative maximum continuous operating voltage (MCOV). On the other hand, the point-of-use SPDs, for those purchased independenly from the service entrance SPD, are generally designed to offer the lowest possible limiting voltage. This relationship makes coordination difficult. If the two devices are selected with the same limiting voltage (and thus comparable MCOVs), then the inductance separating the two devices can have a chance to decouple the two devices sufficiently to achieve a satisfactory coordination. The inductance of the wiring between the service entrance can add some voltage drop between the two devices, so that an acceptable degree of coordination can still be achieved if the two device have equal limiting voltages. The redeeming effect of the wiring inductance is of course dependent upon the waveform of the impinging ***current surge***, as well as the length of the branch circuit.

In this paper, the relationships of these parameters are explored by numerical simulations. Cross-validation of simulation and measurements in actual circuits for typical applied surges was demonstrated in earlier papers so it was not repeated here.

CASCADING SURGE-PROTECTIVE DEVICES: OPTIONS FOR EFFECTIVE IMPLEMENTATIONS

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Abstract — The basic and critical parameters for a successful coordination of cascaded surge-protective devices include the relative voltage clamping of the two devices, their electrical separation through wiring inductance, and the actual waveform of the impinging surge. The authors examine in detail the implications of the situation resulting from the present uncoordinated application of devices with low clamping voltage at the end of branch circuits and devices with higher clamping voltage at the service entrance. As an alternative, several options are offered for discussion, that might result in effective, reliable implementation of the cascaded protection concept.

INTRODUCTION

Coordinating cascading surge-protective devices is a concept whereby two devices are connected at two different points of a power system, with some physical, but mostly electrical, separation (inductance) between the two points. The upstream device is designed to divert the bulk of an impinging surge, while the downstream device, close to the equipment to be protected, is intended as a final clamping stage, including surges generated within the facility.

Successful coordination is achieved when the heavy-duty upstream device does indeed divert the bulk of the surge, rather than letting the downstream device attempt to divert an excessive amount of the surge current. To distinguish between the two surge-protective devices (abbreviated as 'SPD'), the heavy-duty, upstream device will be referred to as 'arrester', while the lighter duty, downstream device will be referred to as 'suppressor'. The basic and critical parameters for successful coordination of the arrester-suppressor cascade include the relative voltage clamping of the two devices, their electrical separation through wiring inductance, and the actual waveform of the impinging surge.

The prime objective of a cascade arrangement is to maximize the benefit of surge protection with a minimum expenditure of hardware. Another benefit of a cascade is the diversion of large surge currents at the service entrance, so that they do not flow in the building, thereby avoiding side effects (Martzloff, 1990).*

The idea of a two-step protection has been explored by many authors over the last two decades, as can be seen in the bibliography included in this paper. Starting with different premises, and with changing opportunities as the technology evolved, these authors have reached conclusions that are sometimes convergent, and sometimes divergent, giving the appearance of contradictions.

In two previous papers (Lai & Martzloff, 1991; Martzloff & Lai, 1991), we have examined the simple case of a two-wire, single-phase circuit where each of the two SPDs is connected between the high-side of the line and the low-side (neutral or grounding conductor), showing by numerical examples the effect of three significant parameters: relative clamping voltage, separation, and impinging waveform. When these three parameters are all taken into consideration, many of those earlier divergent conclusions no longer appear contradictory. Rather, they become for each case a limited view of a consistent set that changes over the complete matrix of the possible ranges for the three parameters.

The two-wire circuit is a simplification applicable to the U.S. practice for residential service, which is generally single-phase, with a mid-point neutral bonded to the local ground at the entrance to the building. In some countries, a notable difference exists in the practice of grounding: the neutral is grounded at the distribution transformer but is not grounded at the service entrance as well. Instead, the installation includes a distinct 'protective-earth' conductor that is bonded to the local earth ('ground' in U.S. English), not to the neutral. In contrast, U.S. practice is to bond to local ground, at the service panel, both the neutral and the 'equipment grounding conductor' that serves the same protective function as the 'protective earth' in European practice.

This difference in the utility grounding practice has implications on the implementation of a cascade in the European context, where a service entrance arrester is more likely to be connected between the incoming lines and protective earth, while end-of-circuit suppressors are more likely to be connected between line and neutral. This arrangement is more complex than the simple two-wire cascade corresponding to the U.S. practice, and we propose a model that takes into consideration this more complex circuit. In the unbonded neutral connection scheme, there is a greater separation between the two cascaded devices and thereby the likelihood of successful coordination can be expected to increase.

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* *Citations are presented as (Author, Date) rather than as numbered items, and are listed alphabetically in the appended bibliography. The bibliography also includes items not cited in this paper, as an indication of the increasing level of interest in this subject.*

† Technology Administration, U.S. Department of Commerce

It is one thing to design an approach based on optimum coordination where all the parameters are under the control of the designer. Such an opportunity existed in utility systems implemented under centralized engineering. It is an altogether different challenge to attempt, after the fact, coordinating the operation of surge-protective devices connected to the power system by diverse and uncoordinated (and uninformed) users. For example, excessively low clamping voltages may be a threat to long-term reliability of varistors (Martzloff & Leedy, 1987; Davidson, 1991).

Our effort in promoting a coordinated approach may come too late for the de facto situation of having millions of suppressors in service with a relatively low clamping voltage. This situation will impose an upper limit to the clamping voltage of a candidate retrofitted arrester. Therefore, close attention must be paid to the selection of the relative clamping voltage of the two devices, in view of the conflicting requirements for performance under surge conditions — a successful cascade — and reliable withstand for temporary power-frequency overvoltages. Nevertheless, coordination might still be achieved through understanding the possible tradeoffs; in the future, users could avoid the pitfalls of poor coordination or the disappointment of implementing protection schemes that cannot provide the hoped-for results.

Finally, we propose for discussion among utilities and manufacturers a different approach to the selection of the service entrance arrester: a one-shot expendable device that would protect the installation against rare, but catastrophic sustained temporary overvoltages at power frequency.

THE RELATIVE VOLTAGE PARAMETER

Figures 1 and 2, from (Martzloff & Lai, 1991), illustrate the impact of the relative voltages on the energy sharing between the two devices. In these two figures, a plot is shown of the percentage of the total energy dissipated in the suppressor, as a function of the distance separating the two devices, for various combinations of clamping voltages, and for two postulated waveforms. In the plots, H, M, and L correspond respectively to a high, medium, and low voltage rating, in the context of a 120-V rms circuit application.

As long as the only postulated impinging waveform remained the classical 8/20-μs current surge (Figure 1), good coordination could be expected, even with an arrester clamping at a voltage somewhat higher than the clamping voltage of the suppressor. That philosophy was espoused in the development of several insulation coordination documents of the International Electrotechnical Commission (IEC) in the last decade (Crouch & Martzloff, 1978; Martzloff, 1980; IEC 28A[USA/Las Vegas]09, 1983 and its later modifications).

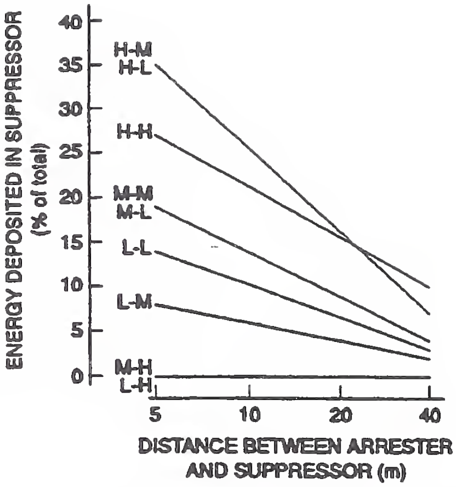


Figure 1
Relative energy deposited by a 3-kA, 8/20-μs wave in the suppressor for arrester-suppressor combinations of 250 V (H), 150 V (M), or 130 V (L) ratings, as a function of separation distance

However, if, in accordance with new descriptions of the surge environment, we apply a surge with longer waveform, such as the 10/1000 μs of ANSI/IEEE C62.41-1991, or the German 10/350 μs (Hasse et al., 1989), then coordination cannot be obtained if the arrester has a higher clamping voltage than that of the suppressor (Figure 2).

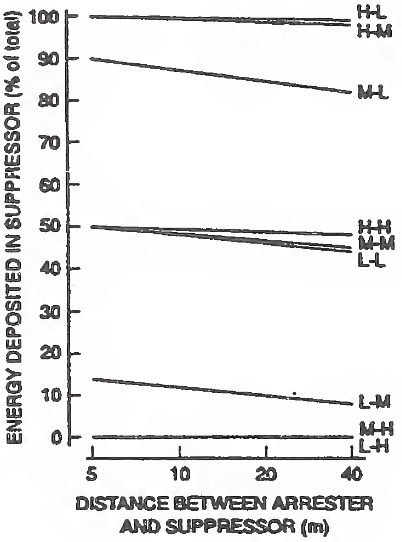


Figure 2
Relative energy deposited by a 220-A, 10/1000-μs wave in the suppressor for arrester-suppressor combinations of 250 V (H), 150 V (M), or 130 V (L) ratings, as a function of separation distance

A partial remedy might be expected in a scenario where the arrester and the suppressor would be specified with the same nominal (rms) voltage. The arrester would have, by definition, a larger cross-section than the suppressor, in order to fulfill its mission of prime dissipator of energy. The larger cross-section results in a lower current density, lowering the clamping voltage compared with that developed for the same current into the suppressor experiencing a higher current density. Thus, we could expect some relief of the 50%-50% division of energy shown in Figure 2 for two devices of equal voltage rating.

To quantify this expectation, we have modeled a 40-mm diameter varistor rated 150 V rms, and used the model defined in our 1991 paper for a 20-mm diameter varistor. Figure 3 shows the I-V characteristics for the two devices. Starting with the same voltage at 1 mA (equal by definition of the nominal voltage), the 40-mm varistor indeed provides a slightly lower clamping voltage than the 20-mm varistor, for currents above 1 mA. Conversely, for the same voltage (parallel connection), the plots show that in the 200-A range (the value selected for the 10/1000-μs wave in the 1991 tests), there is a 200/300 ratio in the currents flowing in the two devices. In the 3-kA range (the value shown in ANSI/IEEE C62.41 for the 8/20-μs wave), the 2000/3000 ratio is practically the same.

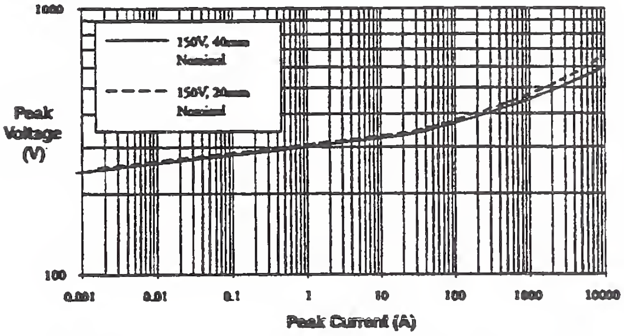


Figure 3

Curve-fitting for the nominal I-V characteristics of 150-V rated varistors, with diameters of 20 and 40 mm

This unequal sharing of the current for two parallel-connected devices with vertically offset characteristics is generally viewed as an obstacle to satisfactory operation, when the objective is to increase the energy handling capability of the two devices connected at the same point. In the present case, however, the objective is opposite: a very unequal sharing is sought to effect coordination between the two devices.

Figure 4 shows a cascade using the 40-mm varistor as service entrance arrester and the 20-mm varistor as surge suppressor. The figure also shows the concepts of location categories (A and B) defined in ANSI/IEEE C62.41-1991.

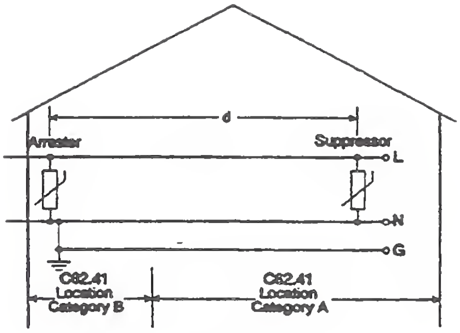


Figure 4

Configuration of a two-stage cascade, with both devices connected between line and neutral conductors

The arrester and the varistor are separated by a distance d, justifying the transition from Category B at the service entrance to Category A at the receptacle.

In the numerical examples and computer-generated plots illustrated below, we selected only one value, 10 meters, for the distance separating the arrester and the suppressor. In our referenced 1991 papers, we gave examples of distances ranging from 5 to 40 meters, as well as plots from measurements of the surge currents in an actual circuit. The correspondence between the modeling results and the experimental measurements was demonstrated in these papers. Therefore, for the similar combination of devices discussed here, we can use the same numerical model (with appropriate modification of the device parameters), and thus limit ourselves to modeling — precisely the point of having developed a valid model.

Figure 5 shows the computed current division between arrester (I_1) and suppressor (I_2) for a 3-kA, 8/20-μs wave impinging upon a cascade of two varistors, 40 mm for the arrester and 20 mm for the suppressor, each rated 150 V. Figure 6 shows the division for the same cascade with a 220-A, 10/1000-μs impinging wave.

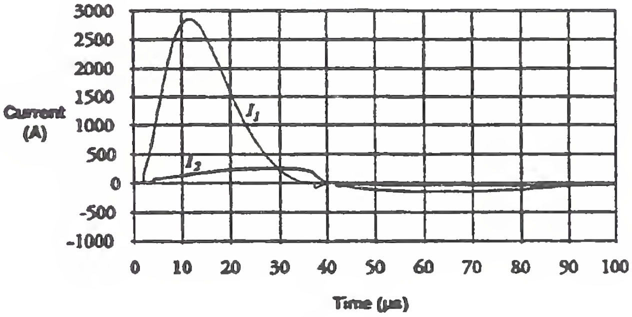


Figure 5

Division of the current between arrester (I_1) and suppressor (I_2) for a 150-V, 40-mm/20-mm cascade, 10-m separation, with a 3-kA, 8/20-μs impinging surge

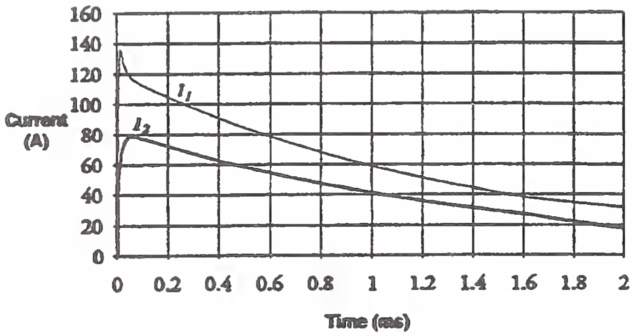


Figure 6
Division of the current between arrester (I_1) and suppressor (I_2) for a 150-V, 40-mm/20-mm cascade, 10 m separation, 220-A, 10/1000-μs impinging surge

Inspection of these two figures also provides qualitative insight on the behavior of the circuit. For the 8/20-μs wave, the inductance of the 10-m length of wire retards the rise of current in the suppressor during the first part of the surge, but tends to maintain the current in the suppressor even after the arrester current has decayed to zero. For the 10/1000-μs wave, the wiring contributes a significant difference in the currents only during the rapidly-changing period — the front of the wave — with the difference in the tail solely attributable to the difference in cross-section between the arrester and the suppressor.

Because of the quasi-constant voltage across the varistor during the surge event, the same behavior appears in the power plots of Figures 7 and 8 which show the power dissipated in each device, respectively for the 8/20-μs surge and the 10/1000-μs surge. The corresponding energy was obtained by integrating the two power curves. The results are shown in Table 1, which also includes the results for the original 20-mm/20-mm cascade.

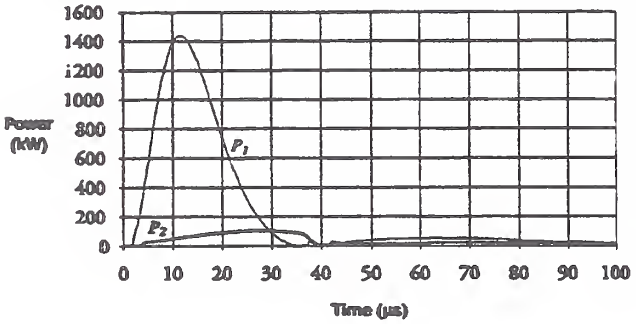


Figure 7
Division of the power between arrester (P_1) and suppressor (P_2) for a 150-V, 40-mm/20-mm cascade, 10 m separation, 3-kA, 8/20-μs impinging surge

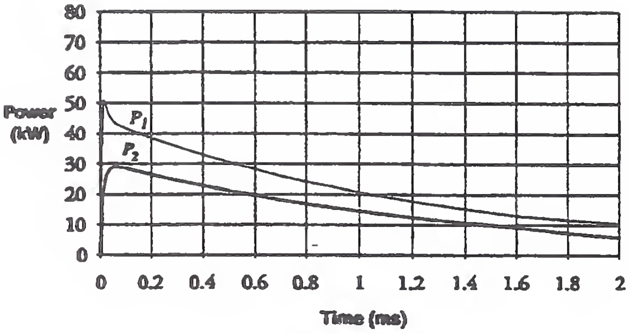


Figure 8
Division of the power between arrester (P_1) and suppressor (P_2) for a 150-V, 40-mm/20-mm cascade, 10 m separation, with a 220-A, 10/1000-μs impinging surge

Table 1
Distribution of deposited energy in arrester and suppressor, 20-mm/20-mm and 40-mm/20-mm cascades, 10 m separation, 8/20-μs and 10/1000-μs impinging surges

Waveform	Devices	Arrester (joules)	Suppressor (joules)	Suppressor (% of total)
8/20 μs 3 kA	20-20	23	3	12
	40-20	23	3	12
10/1000 μs 220 A	20-20	45	42	48
	40-20	46	31	40

Predictably, the 8/20-μs waveform produces a good coordination, for a 20-mm/20-mm cascade as well as for a 40-mm/20-mm cascade. In fact, the only difference between the two is a fraction of joule, which is not shown in the table where the values have been rounded off.

When postulating a 10/1000-μs waveform, the 40-mm arrester indeed diverts slightly more current than the 20-mm suppressor, as shown in Figure 6. However, when the energy levels are compared (see Table 1), the improvement obtained by changing from 20-mm/20-mm to 40-mm/20-mm cascades is only a small reduction in percentage of the total, down to 40% from the 48% of the original 20-mm/20-mm cascade.

The small 8% advantage of the 40-mm/20-mm cascade is likely to be lost when the statistics of possible tolerances for the two devices are considered. Figure 9 shows the effects of combining the relative tolerance deviations from nominal values, the same nominal values that were used in computing the advantage of the 40-mm/20-mm cascade over the 20-mm/20-mm cascade.

	Arrester High	Arrester Low
Suppressor High	8%	Increased
Suppressor Low	Decreased	8%

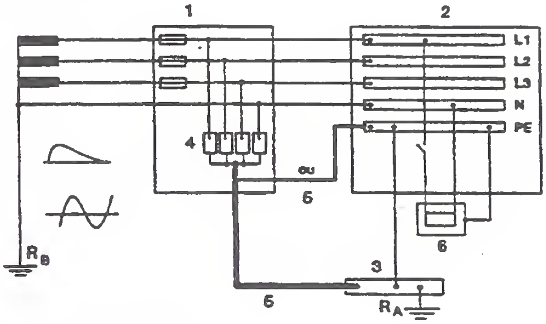
Figure 9
Advantage of 40-mm/20-mm cascade over 20-mm/20-mm cascade

For any cascade where the tolerances move in the same direction (50% of the cases), the advantage remains at 8%. For combinations where the tolerances make the arrester lower than the suppressor (25% of the cases), the advantage is improved. For combinations where the arrester is higher than the suppressor (25% of the cases), the advantage is decreased and may be completely wiped out. Thus, the hoped-for improvement from the lower current density might not be very substantial.

EFFECT OF GROUNDING PRACTICES

In polyphase systems, or even single-phase systems, the bonding between neutral and earth (ground) may be at some distance from the arrester — at the limit, one might consider a system with ungrounded neutral or no neutral. In such cases, the arresters are likely to be connected line-to-ground. Yet, the majority of suppressors are likely to be connected line-to neutral — the two conductors feeding the power port of the sensitive load in need of surge protection. Indeed, some countries or some suppliers object to any other mode of connection for surge-protective devices installed at receptacles or incorporated in connected equipment. Thus, the simple case treated in our 1991 papers, with the two devices (arrester and suppressor) diverting the surge to the same neutral conductor, may be more complicated — perhaps with the welcome effect of a greater separation of the two devices.

Figure 10, from (Roulet, 1992) shows a typical connection diagram for a three-phase system with a protective earth distinct from the neutral. This configuration could be modeled for the complete circuit; however, as an illustrative example and for comparison with the case of Figure 4, we have simplified the circuit as shown in Figure 11. The two varistors have the same voltage rating (150 V). Of course, in a European context of a 230/400-V three-phase system, the modeling should be done with varistors of appropriate ratings, say, 320 V. The generic conclusions reached for the example of the typical single-phase 240/120-V in use in the U.S. can be extended to the 230/400-V situation. We interpreted the configuration of Figure 10 and postulated for the coupling of the impinging surge as a common mode scenario, that is, a surge coupled by earth currents or by inductive coupling into the loop formed by all four conductors and earth.



Source: (Roulet, 1992)
LEGEND

RB:	Earth ground at the distribution transformer
1:	Service entrance panel
2:	Sub-panel with feeders for branch circuits
3:	Local earth electrode (PE)
4:	Arresters connected to local earth (PE)
5:	Connection of arresters to PE
6:	Single-phase equipment that may contain an SPD

Figure 10
Typical three-phase installation with protective earth separate from the system neutral

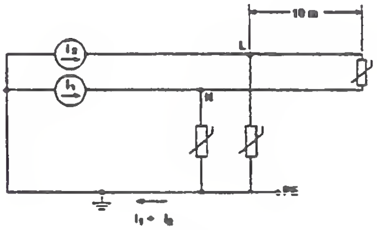


Figure 11
Simplified single-phase model derived from the three-phase system of Figure 10

Inspection of this circuit model reveals that separation between the two devices of the original cascade is no longer the simple length of two-conductor wire. The impinging surge, postulated to be common mode, must be revisited for such a power system configuration. If the two induced surge currents were exactly equal (the ideal common mode) and the two arresters were identical, the voltages produced at points L and N by the surge current flowing in each of the arresters would be equal. Thus, there would be no stress imposed upon the suppressor connected line-to-neutral at the end of the branch circuit.

For a voltage to appear between L and N, we must postulate unbalanced currents in the conductors L and N and a tolerance combination difference between the two arresters. Using this simplified model, we then computed the currents, powers, and energy depositions in a cascade consisting of two 40-mm varistors for the arresters, and a 20-mm varistor for the suppressor, both rated 150 V. We postulated a tolerance of +10% for the line arrester and a tolerance of -10% for the neutral arrester. For the current imbalance, we postulated respectively 3 kA and 1 kA for the case of an 8/20-μs impinging surge, and respectively 200 A and 100 A for a 10/1000-μs surge.

Figure 12 and Figure 13 show respectively the current distributions among the three devices for these two impinging surge waveforms. Even with the wide range of postulated differences between the arresters, the current in the suppressor is negligible.

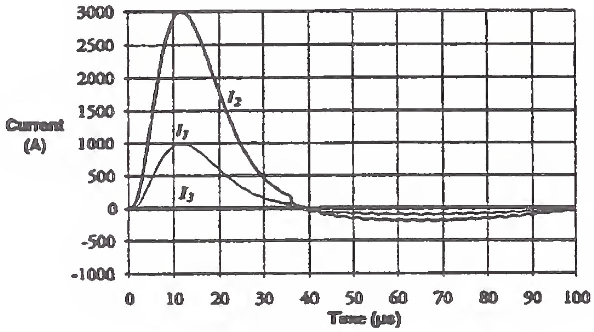


Figure 12
Division of the current among arresters (neutral, I_1), (line, I_2) and suppressor (I_3) for a 150-V cascade, 10-m separation, 1-kA/3-kA, 8/20-μs surge, and tolerances of +10% and -10% on the arresters

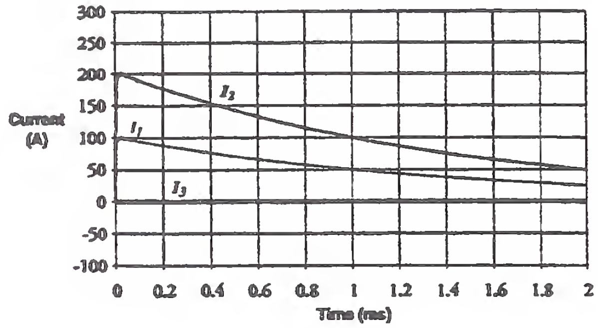


Figure 13
Division of the current among arresters (neutral, I_1), (line, I_2) and suppressor (I_3) for a 150-V cascade, 10-m separation, 100-A/200-A, 10/1000-μs surge, and tolerances of +10% and -10% on the arresters

Intuitive analysis of highly nonlinear varistor circuits can lead to severe errors. However, in this case, the results of the accurate numerical computations can be readily understood by recognizing that the difference in voltages at points N and L is only 20% of the arrester clamping voltages, too little to cause a significant current in the suppressor.

Thus, a marked difference in the cascade behavior occurs, depending upon the neutral earthing practice of the utility and the corresponding postulated scenario for coupling the impinging surge. It is important to note that we have presented only two possible configurations among the many that may be encountered for different countries. Therefore, correct application of surge-protective devices will be achieved only through a good understanding of the context — the grounding practices — of a particular application. Such an understanding will require coordination of the application information now being developed in several Technical Committees or Subcommittees of the International Electrotechnical Commission (IEC), specifically SC28A (Insulation Coordination), SC37A (Low-Voltage Surge-Protective Devices), 64 (Installation Wiring), SC77B (High-Frequency Disturbances), and 81 (Lightning Protection).

SERVICE ENTRANCE ARRESTER OPTIONS

Among electric utilities, different philosophies and different standards are encountered on what is deemed to be an acceptable temporary overvoltage level. For instance, in the U.S., ANSI Std C84.1-1989 only cites a moderate allowance for temporary overvoltages (+6% for 'Range B') but acknowledges the possibility for greater overvoltages to occur, in which case "prompt corrective action shall be taken." The French utility* considers that temporary (over 5 seconds) overvoltages of 1.5 times the nominal system voltage must be accepted as a realistic, unavoidable level in their distribution systems. Some utilities may even wish to have a service entrance arrester survive the condition of a loose neutral connection in a three-wire, neutral bonded to center-tap system, where overvoltages on the lightly-loaded side can reach values up to almost twice the nominal system voltage.

The occurrence of a temporary (seconds) overvoltage of 1.5 per-unit, or more, is likely to cause massive failure of consumer-type equipment in a residence, raising the issue of liability of the utility for this failure, in view of the European trends in legislating that 'electricity is a product' and that suppliers thereof are liable in the case of a defective product.

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* Communication by J.P. Meyer at *UTE Workshop on Surge Arresters*, Paris, March 20, 1992.

An effective solution to this problem might be to design the service entrance arrester in such a manner that its relatively low maximum continuous operating voltage (made necessary by the millions of low-rated suppressors) will cause it to fail — *in an acceptable short-circuit mode* — and thereby protect the equipment within the residence. Service would be interrupted and a replacement of the one-shot, expendable arrester would be required, but the consequential liability of massive appliance failures would be avoided. This option seems to merit careful examination by the electric utilities, the arrester manufacturers, and the standards- or code-writing bodies.

THE DILEMMA OF SPD VOLTAGE RATINGS

The foregoing results, added to those presented in the many papers cited in the bibliography, forebode quite a challenging task of coordinating a cascade downstream of the service entrance. This challenge is made even more difficult by including the concerns about the 'Low-Side Surges' that have led to the recommendation of service-entrance arresters with ac rms ratings higher than the classic 175 V (Dugan & Smith, 1986; Dugan, Kershaw & Smith, 1989; Marz & Mendis, 1992).

Caught between the inescapable, too-late-to-be-changed situation of the 130-V varistors embedded in appliances and the recommendation of 175 V or more for arresters at the service entrance, the coordination schemes proposed by different authors appear elusive: equal voltages (Huse, Martzloff), lower voltage for the entrance (Hasse et al., Standler, Hostfet et al.), or slightly higher arrester voltage (Stringfellow). Perhaps, the 1970s-vintage protection schemes, with a gap-type arrester (Martzloff, 1980), rekindled as a result of the new coordination issues (Hasse et al., 1989), might be another solution. From the diverse interests and expertise of the five IEC committees mentioned above, a solution might emerge, although it is not obvious at this time.

CONCLUSIONS

1. The reality of having many millions of 130-V rated varistors installed on 120-V systems, and 250-V rated varistors installed on 230-V systems makes the ideal scenario of a well-coordinated cascade difficult or perhaps unattainable in the near future.

2. As a compromise, a cascade with equal voltage ratings for the arrester and the suppressor can offer successful coordination, if the impinging surges are presumed to be relatively short.

3. The coordination of a simple cascade of an arrester and a suppressor of equal voltage rating, both connected line-to-neutral, is slightly improved by the larger cross-section of the arrester. However, an unfavorable combination of tolerances for the two devices can wipe out the improvement.

4. The neutral grounding practice of the utility has a profound effect on the cascade behavior, and must be thoroughly understood for successful application of cascaded surge protection. Clearly, additional studies are required in this area.

5. The waveform of the impinging surge has also a large effect on the outcome. If more data were available on the frequency of occurrence of 'long surges', some of the uncertainty surrounding the success of a cascade would be lifted.

6. The idea of an expendable, one-shot arrester at the service entrance could offer a solution out of the dilemma and should be further investigated.

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François D. Martzloff is a native of France. After undergraduate studies there, he obtained an M.S., E.E. at Georgia Tech in 1952 and, twenty years later, an M.S., I.A. at Union College. After 32 years in the private sector (Southern States Equipment, 1953-1956, and GE, 1956-1985), he joined the National Bureau of Standards, now National Institute of Standards and Technology. His early professional experience included the design of high-voltage fuses and high-voltage bushings. He changed to semiconductor technology, but his high-voltage experience led him to the study of transients, which he has steadily pursued for the last 30 years.

As an IEEE Fellow, he has contributed a number of papers and led the development of several standards on surge characterization and surge testing. He has been granted 13 patents, mostly on surge protection. In the IEC, he is serving as Convenor of two working groups and chairs Subcommittee 77B (High-frequency Disturbances) of TC77 on Electromagnetic Compatibility (EMC).

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* *The authors and the concerned IEC Working Groups would welcome contributions of additions to this bibliography.*

Coordinating Cascaded Surge Protection Devices: High-Low versus Low-High

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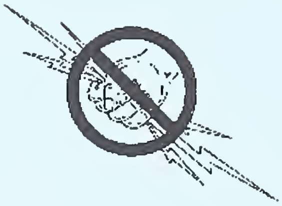
Significance:
Part 8 – Coordination of cascaded SPDs

For a “cascade” of two MOV-based SPDs, the combined numerical modeling and the laboratory measurements cross-validate to provide information on the relationship of impinging waveform and amplitude, distance between the two SPDs, and relative values of the SPD limiting voltage.

Results show that separate selection of the service entrance SPD and point-of-use SPD can produce an ineffective coordination, with the point-of-use SPD “protecting” the service entrance SPD and in so doing, take on the dissipation of a disproportionate part of the impinging surge energy.

This situation make the case for giving careful attention to the selection of device parameters, such as providing the two devices from an authoritative source from which a well-engineered approach should be expected.



Coordinating Cascaded Surge Protection Devices: High-Low versus Low-High

Jih-Sheng Lai and François D. Martzloff, *Fellow, IEEE*

***Abstract*— Cascading surge protection devices located at the service entrance of a building and near the sensitive equipment is intended to ensure that each device shares the surge stress in an optimum manner to achieve reliable protection of equipment against surges impinging from the utility supply. However, depending on the relative clamping voltages of the two devices, their separation distance, and the waveform of the impinging surges, the coordination may or may not be effective. The paper provides computations with experimental verification of the energy deposited in the devices for a matrix of combinations of these three parameters. Results show coordination to be effective for some combinations and ineffective for some others, which is a finding that should reconcile contradictory conclusions reported by different authors making different assumptions. From these results, improved coordination can be developed by application standards writers and system designers.**

I. INTRODUCTION

RECENT PROGRESS in the availability of surge-protective devices, combined with increased awareness of the need to protect sensitive equipment against surge voltages, has prompted the application of a multistep cascade protection scheme. In the multistep cascade scheme, a high-energy surge protective device would be installed at the service entrance of a building for the purpose of diverting the major part of the surge energy. Then, surge-protective devices with lower energy-handling capability and lower clamping voltage than that of the service entrance would be installed downstream and complete the job of protecting sensitive equipment at the point of entry of the line cord. To make the distinction between these two devices, we will call the service entrance "arrester" and the downstream device "suppressor," somewhat in keeping with U.S. usage of the transient voltage surge suppressor (TVSS) for devices used on the load side of the mains disconnect. Such a scheme is described as "coordinated" if, indeed, the device with high-energy handling capability receives the largest part of the total energy involved in the surge event.

This scenario was based on the technology of secondary surge arresters prevailing in the 1970's and early 1980's as well as on the consensus concerning the waveform and current levels of representative lightning surges impinging on a building service entrance. This consensus has gradually evolved toward recognition that the surge environment may include waveforms of longer duration than the classical 8/20 μs current surge. ANSI/IEEE C62.41–1991 [1] provides a description of the surge environment. With the emergence of new types of arresters for service entrance duty and the recognition of waveforms with greater duration than the classic 8/20 μs impulse, a new situation arises that may invalidate the expectations of the cascade coordination scenario.

Service entrance arresters were generally based on the combination of a gap with a nonlinear varistor element, which was the classic surge arrester design before the advent of metal-oxide varistors that made gapless arresters possible. With a gap-plus-varistor element, the service entrance arrester could easily be designed for a 175-V maximum continuous operating voltage (MCOV) in a 120-V (rms) system. The downstream suppressors were selected with a low level, driven by the perception that sensitive equipment requires a low protective level [2]. The scheme can work if there is a series impedance (mostly inductance) between the arrester and the suppressor because the inductive drop in the series impedance, added to the clamping voltage of the suppressor, becomes high enough to spark over the arrester gap. Thereafter, the lower discharge voltage of the arrester (made possible by the gap) ensures that the major part of the surge energy is diverted by the arrester, relieving the suppressor from heavy duty [3].

Now, if the arrester is of gapless type, its MCOV will determine its clamping level. Some utilities wish to ensure survival of the arrester under the condition of a lost neutral, that is, twice the normal voltage for a single-phase, three-wire service connection. The "high-low" combination has been proposed, where the arrester clamping voltage is higher than that of the suppressor [4]. During the ascending portion of a relatively steep surge such as the 8/20 μs, the inductive drop may still be sufficient to develop enough voltage across the terminals of the arrester and force it to absorb much of the impinging energy. However, during the tail of the surge, the situation is reversed; the inductive drop is now negative, and thus, the suppressor with lower voltage (not the arrester) will divert the current. For the new waveforms proposed in C62.41–1991 [1], this situation occurs for the 10/1000 μs where the tail contains most of the energy, and the relief provided by the arrester may not last past

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TABLE I
CURVE FITTING RESULTS FOR CIRCUIT MODELING OF THREE MOV'S

MOV number	k	α	λ	ζ	V_0(V)
V130LA20A	4.0×10^{-74}	30	0.051	8×10^{-6}	320
V150LA20A	3.9×10^{-89}	35	0.053	4×10^{-6}	370
V250LA40A	5.7×10^{-110}	40	0.04	4×10^{-6}	570

the front part of the surge. For the low-frequency (5 kHz or less) capacitor-switching ring waves, the inductive drop will be much smaller than that occurring with the 8-μs rise time so that the additional voltage may be negligible, leaving the suppressor in charge from the beginning of the event. An alternate means has been proposed (Low-High) where the arrester clamping voltage is lower than that of the suppressor [5], [6]. Thus, a disagreement has emerged among the recommendations for coordinated cascade schemes: the 1970–1980 perception and [4], suggesting a "High-Low" and the new "Low-High" suggestion of [5] and [6].

This paper reports the results of modeling the situation created by the emergence of gapless arresters and longer waveforms with the necessary experimental validation. These results cover a range of parameters to define the limits of a valid cascade coordination and serve as input to the surge protective device application guides now under development by providing a reconciliation of the apparent disagreement, which is actually rooted in different premises on the coordination parameters.

II. MOV CIRCUIT MODELING

The current-voltage (I-V) characteristic of a metal oxide varistor (MOV) has long been represented by an exponential equation, i.e., $I = kV^{\alpha}$ [7]. This equation is only applicable in a certain voltage (current) range in which the I-V characteristic presents a linear relationship in a log-log plot. When the voltage exceeds this "linear region," the current increment rate starts dropping. A modified I-V characteristic is proposed here as expressed in (1).

$$I = kV^{\alpha}e^{-(V-V_0)(\lambda-\zeta(V-V_0))}. \tag{1}$$

The parameters in (1) can be obtained from a minimum-error-norm curve fitting technique [8] using a manufacturer's data book [7] or experimental results. The parameters k and α can be obtained from fitting the data in the linear log-log region. The exponential term is added to cover the voltages that are higher than a threshold voltage V_o and can be obtained from fitting the I-V characteristics in the higher current (voltage) region. Using (1), the MOV circuit model can be simply represented by a voltage-dependent current source.

Model parameters in (1) can be obtained from the manufacturer's data book and verified by experiments. The parameter is typically a function of the MOV voltage rating. The threshold voltage V_0 and coefficients λ and ζ are functions of the voltage rating and the size. Table I lists curve fitting results for the

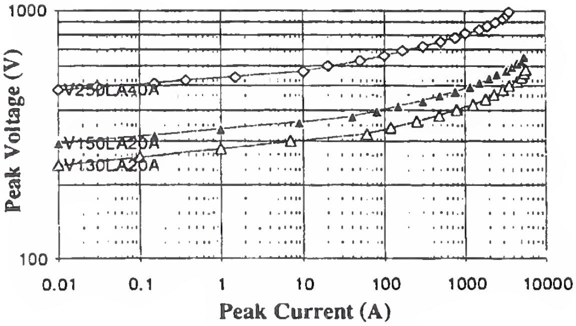

Fig. 1. MOV characteristics obtained from modeling results.

TABLE II
PARAMETERS FOR NOMINAL I-V CHARACTERISTICS OF THREE MOV'S

MOV number	k	α	λ	ζ	V_o(V)
V130LA20A	9.4×10^{-66}	27	0.046	0.8×10^{-6}	285
V150LA20A	4.8×10^{-79}	31.5	0.053	1.6×10^{-6}	340
V250LA40A	1.7×10^{-97}	36	0.044	1.6×10^{-6}	520

equivalent circuit parameters of three MOV's for units of voltage and current in volts and amperes.

The MOV number[1] actually reflects the device voltage rating and the size. For V130LA20A, the continuous operating voltage rating is 130 V(rms). The other two devices are 150 and 250 V(rms), respectively. All three devices have a 20-mm diameter. Fig. 1 shows fitted curves for the three devices.

In Fig. 1, the marked dots were the data directly obtained from the manufacturer's data book, whereas the three solid lines were calculated from (1) using the parameters listed in Table I.

It should be noted that each individual MOV may have slightly different I-V characteristics even with the same model number. In Fig. 1, the data show the maximum clamping voltage levels, which are 10% higher than the nominal voltage level. A typical off-the-shelf device has a tolerance within ±10% of the nominal voltage level, which means a lowest-level device could have an I-V characteristic that is 20% lower than the data book characteristics. In fact, the two closely rated cascading devices (130 and 150 V) could, in some extreme cases, become inverted in the sequence ("Low-High" becoming in reality "High-Low") as 130 × 1.1 = 143 and 150 × 0.9 = 135. Furthermore, the results show that for the 250-150 combination, the difference is so large that a low 250 (225 V) combined with a high 150 (165 V) would not make an appreciable difference in energy sharing. Thus, the simulation computations were performed for all three devices at their nominal values. From the maximum voltage tolerance parameters listed in Table I, the parameters for the nominal (zero tolerance) I-V characteristics were derived, as listed in Table II.

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[1] Certain commercial products are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the Power Electronics Applications Center or the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best for the purpose.

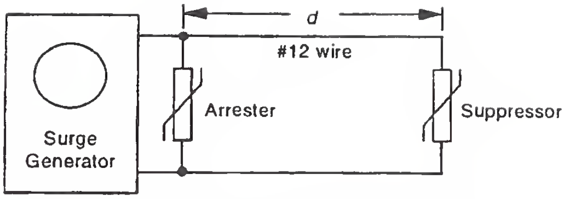


Fig. 2. Two-stage cascade surge protection system.

TABLE III
NINE POSSIBLE CASCADE COMBINATIONS FOR THREE DEVICES

Arrester	Suppressor
250 V	250 V
	150 V
	130 V
150 V	250 V
	150 V
	130 V
130 V	250 V
	150 V
	130 V

III. SIMULATION OF CASCADED SURGE PROTECTION DEVICES IN A LOW-VOLTAGE SYSTEM

In a two-stage cascade surge protection system, the arrester is placed near the surge source (the service entrance for premises wiring), and the suppressor is placed near the load. Fig. 2 shows a typical two-stage cascade surge protection system. The arrester and the varistor are separated by a distance d, which depends on the specific installation. In the following simulation study, four different d values are considered. They are 5, 10, 20, and 40 m. The #12 wire is a typical size for the premises wiring and is used for the following simulation and experiment study. Based on an impedance-meter measurement, the resistance of #12 wire is 0.00104 Ω/m, and the inductance is 1 $\mu\mathrm{H/m}$ (per two parallel wires). For high-frequency waves (the 1.2/50 – 8/20μs Combination Wave and the 0.5μs – 100 kHz Ring Wave), the inductive drop is the more dominant [9]. The complete simulation consists of a surge source, two voltage-dependent current sources, and a line impedance between the two current sources [10].

For the three selected device voltage levels, there is a total of nine possible cascade combinations as shown in Table III. Three standard waves from [1] were chosen to cover different frequency responses. These are 1.2/50 – 8/20μs Combination Wave, 0.5 – 100 kHz Ring Wave, and 10/1000μs impulse wave. For the sake of brevity, these three waveforms will be called "Combo Wave," "Ring Wave," and "Long Wave." For four distances, three voltage waves, and nine cascade combinations, a total of 108 cases were studied in the simulation: about 200 hours of machine time on a 25-MHz personal computer.

A. Simulation Results with the Combination Wave

Because of the back filter effect, a waveform generator might not couple a true standard wave to the test circuit. Fig. 3 shows an oscillation of the standard 8/20μs current wave. Curve A is the standard 8/20μs current, and curve B is the actual coupled wave with a small negative swing. For the standard 8/20μs wave, the current is always positive, and the clamping voltage is always positive. When applying curve B as the surge source, the negative current portion will cause a negative clamping voltage. This has been observed in the experiments. In order to reflect the experimental results, the following simulation will use curve B as the combo wave source.

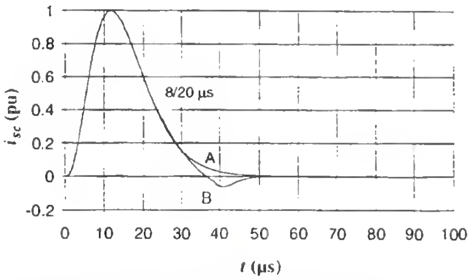


Fig. 3. Standard 8/20 μs short-circuit wave and a possible negative swing caused by the filtering circuit.

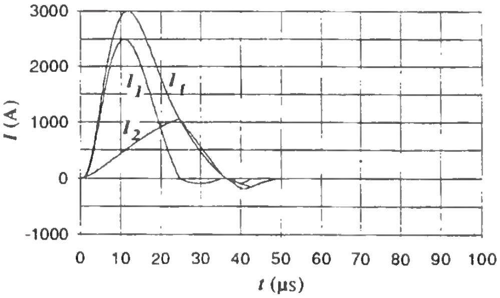


Fig. 4. Simulated Combo Wave current responses for the 250–130V cascaded devices that are 10-m apart.

Consider a 250–130 V cascade of two devices that are 10 m apart. The simulation results of the currents flowing in the two devices are shown in Fig. 4, where I_t is the total current injected into the cascade by the surge source of the model, I_1 is the arrester current, and I_2 is the suppressor current. Fig. 5 shows device clamping voltages with V_1 and V_2 representing arrester and suppressor voltage, respectively. Fig. 6 shows instantaneous powers with P_1 and P_2 representing arrester and suppressor power, respectively. By integrating the instantaneous power, the energy deposition values in the arrester and the suppressor were calculated as 29.7 and 8.6 J, respectively.

Before proceeding with further simulations, the simulation results were verified by an experiment. With the experimental setup of Fig. 2 and 250 and 130 V rated devices in cascade, the experimental results for the arrester and suppressor are shown in Fig. 7. Because the surge generator generates nonstandard waveforms, the waveforms obtained from the experiment are not exactly the same as the simulated waveforms. However, the power distribution between the two devices shows good agreement between simulation and experiment. For the same

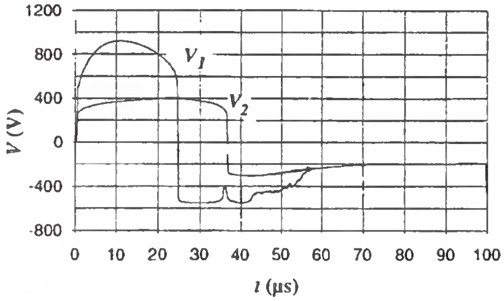


Fig. 5. Simulated Combo Wave voltage responses for the 250–130 V cascaded devices that are 10-m apart.

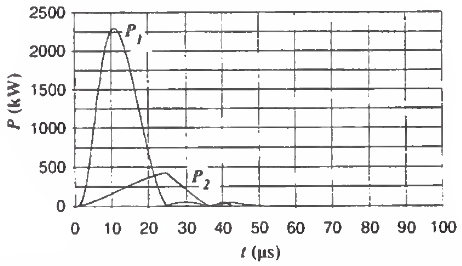


Fig. 6. Simulated Combo Wave power responses for the 250–130V cascaded devices that are 10-m apart.

250–130, 10-m cascaded case but slightly higher peak surge current (3.3 kA instead of 3 kA in simulation), the experimental result shows 33.8 and 11.1 J energy depositions in the arrester and the suppressor, respectively. Prorating the simulation results from Fig. 6 to 3.3 kA would yield 32.7 and 9.5 J, respectively, which is a reasonable agreement.

Table IV lists Combo Wave simulation results of the energy deposition in the arrester (A) and suppressor (S) for all the combinations of different High-Low and Low-High cascade conditions. For the High-Low condition, the energy deposition in the suppressor increases when the distance decreases. This result explains how the High-Low configuration can achieve a good coordination under the Combo Wave, provided that there is sufficient distance between the two devices, as stated in [3].

Consider the High-Low configuration with a 250-V device as the arrester. When the distance between two devices is reduced, the energy deposition tends to increase in the suppressor and decrease in the arrester. This decrease occurs because the line inductance does not provide enough voltage drop ($L\ di/dt$), and the low clamping voltage of the suppressor reduces the voltage across the arrester and thus reduces the energy deposition level. The total energy deposition in the two devices also varies with the distance for the High-Low configuration. In Table IV, the total energy deposition for the 250–250 combination is near constant at 103 J for different distances. However, for the 250–150 and 250–130 combinations, the total energy deposition decreases when the distance is reduced because the suppressor tends to lower the voltage across the arrester.

For Low-High configurations such as the 150–250 and 130–250 cases, the high-voltage suppressor receives almost zero energy. The use of the suppressor is near redundant in this case, except for its application to mitigate internally generated surges. With closely rated devices (130–150), the 150-V voltage suppressor also receives much less energy than the 130-V arrester.

TABLE IV
ENERGY DEPOSITION IN THE CASCADED DEVICES WITH A 3-kA COMBO WAVE AS THE SURGE SOURCE

Clamping voltage of device (V)		Distance separating devices and energy deposited in each device (J)							
		5 m		10 m		20 m		40 m	
A	S	A	S	A	S	A	S	A	S
250	250	75.9	27.3	83.5	19.9	89.5	14.4	91.7	9.69
	150	22.2	12.0	29.9	8.52	35.9	5.40	39.80	3.30
	130	21.3	11.9	29.7	8.6	35.3	5.2	40.1	3.3
150	250	24.3	0.005	24.3	0.006	24.3	0.007	24.3	0.008
	150	21.2	4.65	23.1	3.06	24.4	1.93	25.5	0.88
	130	19.84	5.16	22.16	3.05	24.05	1.86	25.02	1.08
130	250	22.9	0.003	22.9	0.003	22.9	0.004	22.9	0.004
	150	20.2	1.72	20.8	1.18	21.30	0.76	21.1	0.44
	130	18.6	2.92	19.4	1.71	20.3	1.03	20.9	0.70

B. Simulation Results with the 0.5 μs–100 kHz Ring Wave

The energy deposition in the surge protection devices under the Ring Wave surge is considerably less than that of the Combo Wave because of lower current. However, the high-frequency Ring Wave shows similar characteristics to the Combo Wave under the High-Low cascade condition; a voltage drop between the two devices can be established by the line inductance, provided that there is sufficient distance between the two devices. Figs. 8 and 9 show simulation results of current and voltage for the cascaded arrester and suppressor under the High-Low condition. I_1 and V_1 represent the 250-V arrester current and voltage, whereas I_2 and V_2 represent the 130-V suppressor current and voltage, respectively, for a 400-A peak surge current.

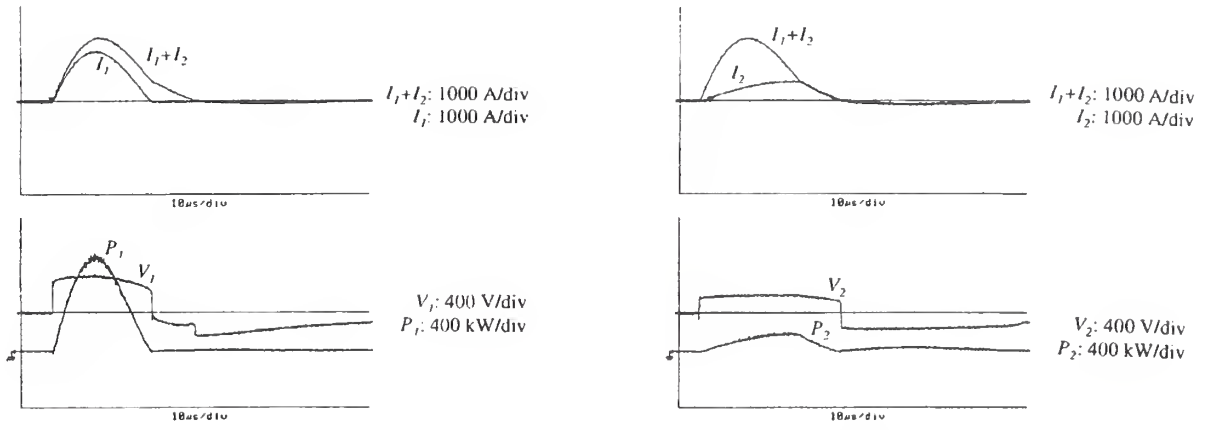
Fig. 10 shows the instantaneous power dissipated in the two cascaded devices. P_1 and P_2 represent the 250-V arrester power and 130-V suppressor power, respectively.

Table V lists the simulated energy deposition in the cascaded devices for different High-Low and Low-High combinations. The energy is the integration of the instantaneous power over the total 20-μs simulation period. Unlike the Combo Wave, the Ring Wave tail still contains a small amount of power, and the total amount of the energy deposition is affected by the integration interval. From Fig. 10, it is apparent that the power contribution to the total (past 20 μs) is becoming negligible.

Similar to the Combo Wave, the High-Low configuration shows good coordination as the high-voltage arrester absorbs higher energy under the high-frequency Ring Wave surge, and the Low-High configuration shows almost zero energy deposition in the high-voltage suppressors.

C. Simulation Results with the 10/1000 μs Long Wave

Compared with the Combo Wave, the Long Wave has a slower and longer drooping tail that contains most of the surge energy. During the long tail period, the inductive voltage drop between the arrester and the suppressor is low due to low Ldi/dt, and the voltage across the arrester is reduced by the



(a) (b)

Fig. 7. Experimental results for the 250–130 V cascade with devices that are 10-m apart, with the Combination Wave: (a) Arrester; (b) suppresor.

TABLE V
ENERGY DEPOSITION IN THE CASCADED DEVICES WITH A 400-A PEAK RING WAVE AS THE SURGE SOURCE

Clamping voltage of device (V)		Distance separating devices and energy deposited in each device (J)							
		5 m		10 m		20 m		40 m	
A	S	A	S	A	S	A	S	A	S
250	250	1.287	0.398	1.405	0.291	1.512	0.158	1.593	0.114
	150	0.996	0.625	1.301	0.317	1.536	0.127	1.613	0.094
	130	0.938	0.501	1.213	0.312	1.425	0.183	1.624	0.083
150	250	1.21	0.002	1.21	0.003	1.21	0.003	1.21	0.004
	150	1.05	0.15	1.11	0.097	1.15	0.059	1.17	0.035
	130	0.945	0.218	1.06	0.127	1.13	0.07	1.17	0.04
130	250	0.99	.0006	0.99	.0005	0.99	.0004	0.99	.0003
	150	0.97	0.020	0.97	0.019	0.97	0.019	0.97	0.017
	130	0.90	0.123	0.96	0.078	0.99	0.049	1.010	0.278

suppressor even with long distance between the two devices. This makes the High-Low configuration not coordinated as the high-voltage arrester will not absorb any impinging energy, but the suppressor does. Figs. 11, 12, and 13 show the simulated Long Wave current, voltage, and power, respectively, for the arrester and the suppressor under a High-Low (250–130) configuration for a 200-A peak surge current.

The high-voltage arrester clamps the voltage during the impulse rising period and draws a small amount of the current pulse I_1, which is almost invisible in the computer-generated plot of Fig. 11. The power absorbed by the arrester P_1 is also a small pulse that appears at the rising period as shown in Fig. 13. The low-voltage suppressor absorbs all the impinging energy in this High-Low configuration, defeating the intended coordination.

Table VI lists the simulated energy deposition in the cascaded devices for different High-Low and Low-High combinations as well as for different distances.

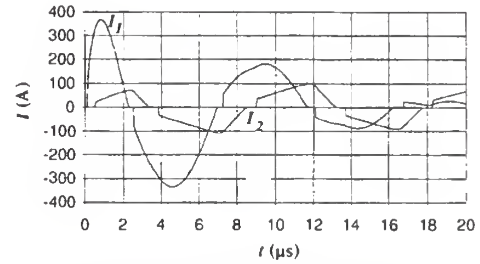


Fig. 8. Simulated Ring Wave current responses for the 250–130 V cascaded devices that are 10-m apart.

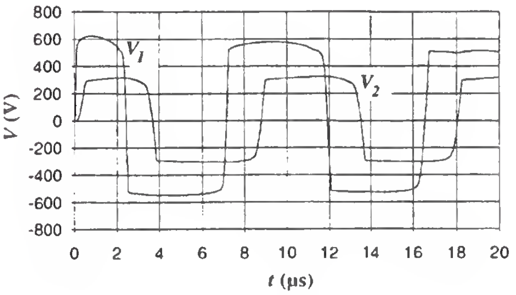


Fig. 9. Simulated Ring Wave voltage responses for the 250–130 V cascaded devices that are 10-m apart.

It can be seen from Table VI that the low-voltage device always absorbs higher energy than the high-voltage device because the voltage across the high-voltage device is clamped to the same level as that of the low-voltage device, and the energy is diverted to the low-energy device. Unlike the Combo Wave and the high-frequency Ring Wave, the coordination for the slow Long Wave can only be achieved by Low-High or equally rated devices (250-250, 150-150, and 130-130). Note that with two devices of equal nominal value, it is possible that the relative tolerance might, in fact, produce a High-Low situation, which would not achieve good coordination; for instance, a 150-130 combination resulting from tolerance shifts imposes a 70-J duty to the suppressor in the case of 5-m separation.

IV. EXPERIMENTAL RESULTS

In order to verify the validity of the simulation, a series of experiments has been conducted using the three waves for different High-Low and Low-High combinations, especially

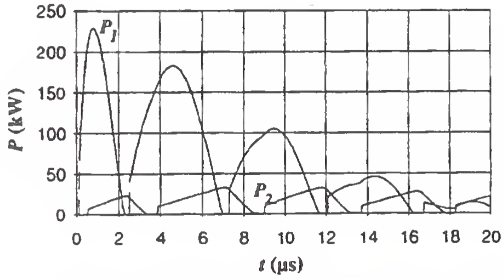


Fig. 10. Simulated Ring Wave instantaneous power for the 250–130 V cascaded devices 10-m that are apart.

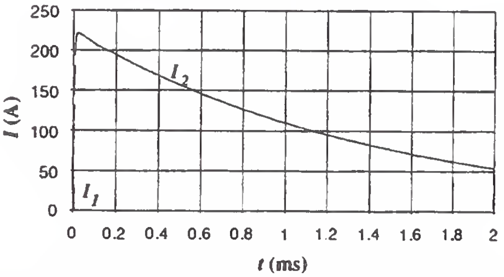


Fig. 11. Simulated Long Wave current responses for the 250–130 V cascaded devices that are 10-m apart.

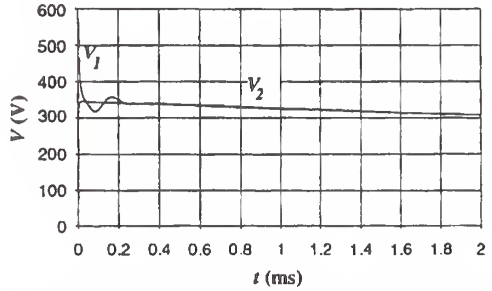


Fig. 12. Simulated Long Wave voltage responses for the 250–130 V cascaded devices that are 10-m apart.

for the Long Wave, which has not been used for cascaded coordination studies in the literature. Table VII lists experimental results (from Figs. 7, 14, and 15) using the three waveforms for 250–130 V cascaded devices that are 10-m apart. Note that peak currents do not occur simultaneously. A * sign shows that the low-voltage suppressor absorbs almost all the energy under the 10/1000 μs Long Wave. The experimental results, in general, agree with the simulation results, especially for the Combo Wave, which has well matched surge sources and a limited surge period (the tail does not extend over the integration period). For the Ring Wave and the long wave, the total integration period and the surge source are not matched between simulation and experiment, and thus, the numbers in Table VII have higher deviation from the simulation results. However, the proportion between the arrester and the suppressor energies agrees well between simulation and experiment, which explains that the simulation can be effectively used for the coordination analysis.

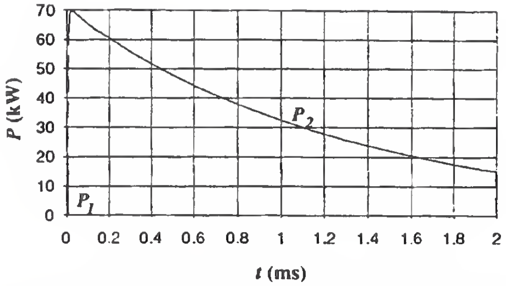


Fig. 13. Simulated Long Wave power responses for the 250–130 V cascaded devices that are 10-m apart.

TABLE VI
ENERGY DEPOSITION IN THE CASCADED DEVICES WITH A 220-A PEAK LONG WAVE SURGE SOURCE

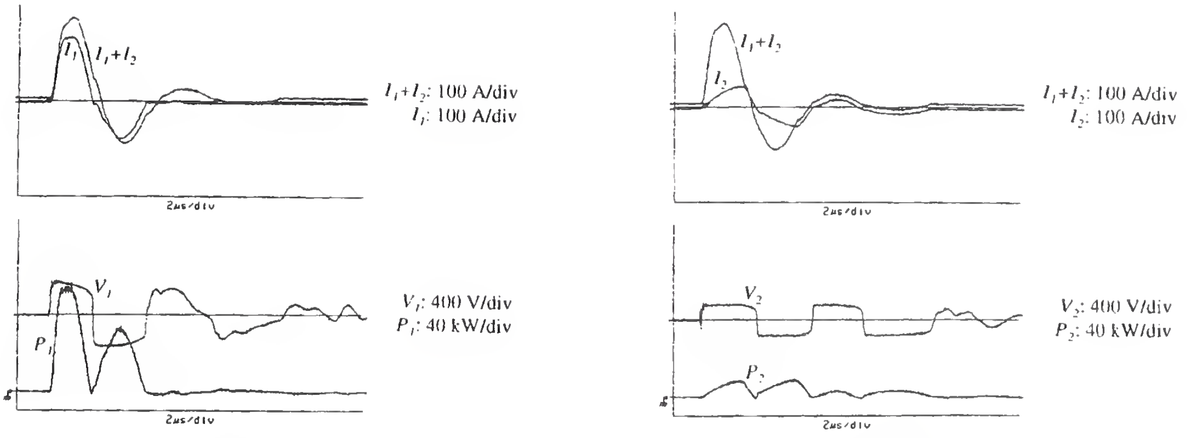
Clamping voltage of device (V)		Distance separating devices and energy deposited in each device (J)							
		5 m		10 m		20 m		40 m	
A	S	A	S	A	S	A	S	A	S
250	250	73.63	72.76	74.10	72.31	75.06	71.38	76.28	70.13
	150	0.031	92.15	0.028	92.03	0.69	91.70	1.77	91.00
	130	0.011	79.23	0.125	79.16	0.518	78.94	1.424	78.42
150	250	92.17	0.001	92.17	0.002	92.17	0.002	92.17	0.003
	150	44.03	42.79	44.69	42.15	45.96	40.91	47.32	39.12
	130	7.92	70.67	8.86	69.76	10.72	67.97	14.28	64.58
130	250	79.20	0.001	79.20	0.001	79.20	0.001	79.20	0.001
	150	66.98	11.12	71.72	6.82	71.87	6.67	72.21	6.36
	130	38.03	36.74	38.70	36.09	39.98	34.84	42.28	32.62

TABLE VII
EXPERIMENTAL RESULTS USING DIFFERENT WAVEFORMS FOR 250–130 V CASCADED DEVICES THAT ARE 10-M APART

Applied Wave	Arrester			Suppressor		
	V_{pk} (V)	I_{pk} (A)	W (J)	V_{pk} (V)	I_{pk} (A)	W(J)
Combo 3 kA pk	790	2600	33.8	400	1000	11.1
Ring 430 A pk	720	340	0.6	350	100	0.2
Long 220 A pk	450	6	0.05	320	220	64.4*

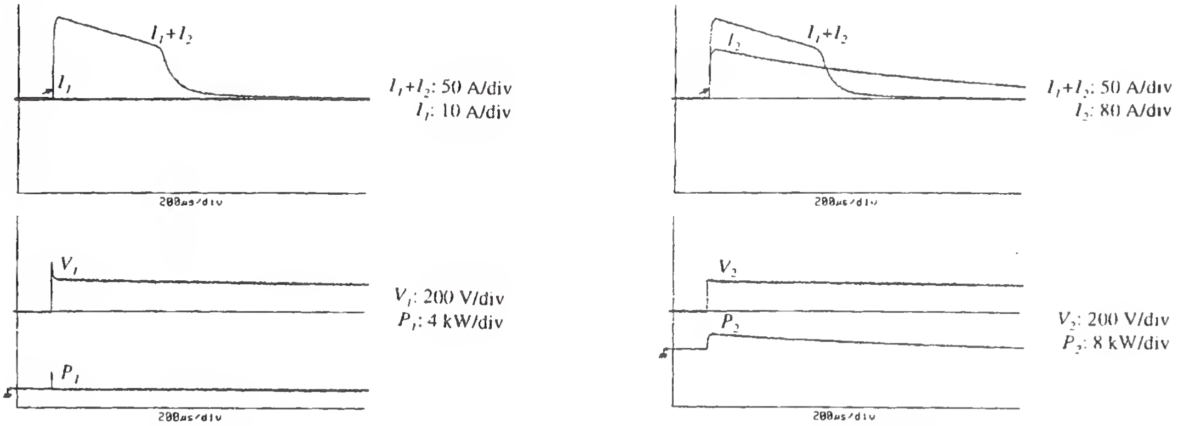
The experimental verification of the Combo Wave for the simulation can be seen from Fig. 7. For the Ring Wave and the Long Wave, experimental current, voltage, and power waves are shown in Figs. 14, 15, and 16, respectively. The Ring Wave coupled from the surge generator is distorted and is attenuated much faster than the standard Ring Wave. The measurement of the coupled Long Wave shows a saturation on the small CT (5000 A peak and 65 A rms rated). However, the current flowing through the surge protection devices were measured by a large CT (20 000 A peak and 325 A rated) and were not saturated.

The experimental Long Wave response for a Low-High configuration is shown in Fig. 16, where I_1 and I_2 are the currents flowing in the 130-V arrester and the 150-V suppressor, respectively. This figure shows an example of good coordination by Low-High, where most of the surge energy is absorbed by the low-voltage arrester. The arrester voltage V_1 is almost the same as the suppressor voltage V_2 with a slight difference at the beginning of the surge.



(a) (b)

Fig. 14. Experimental results for the 250–130 V cascade, with devices that are 10-m apart, with the Ring Wave: (a) Arrester; (b) suppresor.



(a) (b)

Fig. 15. Experimental results for the 250–130 V cascade, with devices that are 10-m apart, with the Long Wave: (a) Arrester; (b) suppresor

V. DISCUSSION

The concept of coordination of surge-protective devices is based on the selection of a first device with high energy-handling capability that is to be located at the service entrance and is expected to divert most of the surge current at that point. The second device, which is installed within the premises, can then have a lower energy-handling capability.

The benefit from this coordinated approach is to allow a single device at the service entrance to perform the high-energy duty, whereas several smaller devices within the premises can perform local suppression. This arrangement avoids the flow of large surge currents in the branch circuits of the installation, which is a situation known to produce undesirable side effects [11].

On the other hand, the situation where millions of small suppressors have been installed within equipment, or as plug-in devices, exists with only sporadic and anecdotal reports of problems. Thus, it is evidently possible to obtain protection with suppressors alone, whereas a coordinated scheme would provide additional benefits and eliminate side effects.

Some utilities wish to provide a service-entrance arrester thta is capable of withstanding the 240-V overvoltage that can occur on the 120-V branches when the neutral is lost. This desire will force the coordination scheme into a High-Low situation because of the uncontrolled installation of low clamping voltage suppressors by the occupant of the premises. The results of the simulation and experimental measurements

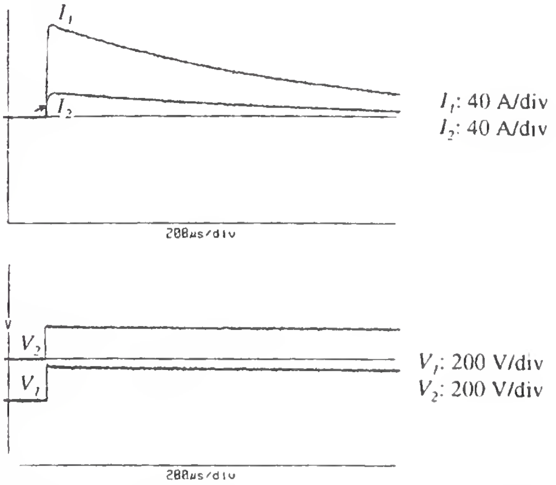


Fig. 16. Experimental results for the 130–150 V cascade, with devices that are 10-m apart, with the Long Wave.

show that the objective of coordination could still be achieved with a 250–130 combination, as long as some distance is provided between the two devices and as long as Long Waves are not occurring with high peak values. This proviso provides an incentive for obtaining better statistics on the occurrence of Long Waves. ANSI/IEEE C62.41-1991 [4] recommends considering these Long Waves as an additional and not a standard waveform. Thus, the determination of a successful coordination depends, for the moment, on the perception of what the prevailing high-energy waveforms can be for specific environments.

VI. CONCLUSIONS

1. Coordination of cascaded devices can be achieved under various combinations of parameters, but some combinations will result in having a suppressor with low energy-handling capability called on to divert the largest part of the surge energy. This uncoordinated situation can create adverse side effects when high current surges occur.
2. Significant parameters in achieving successful coordination involve three factors over which the occupant of the premises has no control: the relative clamping voltages of the two devices, their separation distance, and the prevailing waveforms for impinging surges. This uncontrolled situation presents a challenge and obligation for standards-writing groups to address the problem and develop consensus on a tradeoff of advantages and disadvantages of High-Low versus Low-High.
3. Coordinated schemes can be proposed by utilities to their customers, including a service entrance arrester and one or more plug-in devices to be installed for the dedicated protection of sensitive appliances. However, even such an engineered, coordinated arrangement could be defeated by the addition of a suppressor with a very low clamping voltage, which is not an insignificant likelihood in view of the present competition for lower clamping voltages.

VII. UPDATE ON COORDINATION EFFORTS

Since the presentation of the paper in the Fall of 1991, considerable discussion of the coordination issue has taken place at the international level involving five technical committees of the IEC. As of late 1992, an effort is underway within the IEC to develop an application document that will address the issues discussed in this paper and present recommendations tailored to the specific neutral-grounding practice of the various member countries. Contact the authors for further updates on progress concerning the technical aspects of device coordination issues as well as updates on the intercommittee coordination and liaison.

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Dr. Lai has two patents in high-frequency power conversions for adjustable-speed drives and more than 25 articles published in the fields of control systems, power systems, and power electronics.

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Mr. Martzloff has been granted 13 patents, mostly on surge protection. In the IEEE, he serves as Chair of the Working Group on Surge Characterization. In the IEC, he is serving as Convenor of two working groups and chairs Subcommittee 77B (High-Frequency Phenomena) of TC77 on Electromagnetic Compatibility.

Gapped Arresters Revisited:
A Solution to Cascade Coordination

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Significance
Part 8 – Coordination of cascaded SPDs

The goal of implementing a well-coordinated cascade of SPDs with simple MOVs at both the service entrance of a building and point-of-use (the latter typically by an add-on plug-in SPDs typical of what consumers purchase from electronic stores – the so-called "TVSS") presents a dilemma because the service entrance arresters tend to be designed with conservative MCOV ratings (hence relatively high limiting voltages) while the TVSSs tend to be designed with the lowest possible limiting voltage. Such relationship in the limiting voltages is the contrary of what is necessary to achieve coordination between the rugged service entrance arrester and the limited energy-handling capability of the TVSS.

The situation has been created by the decision, early in the introduction of TVSSs and possibly motivated by the UL requirement to show the limiting voltage (with a misguided notion that a lower limiting voltage ensures better protection). By now, this de facto presence of millions of low limiting voltage for the TVSS makes it practically impossible to achieve coordination if the twp SPDs consist of simple MOVs.

Ironically, upon introduction of MOVs in the mid-seventies, residential-type service entrance arresters that consisted of a series combination of a gap and a silicon carbide varistor were replaced by simple MOV discs, viewed at the time as a significant improvement of the protective level provided by a service entrance arrester – hence the "revisited" aspect of this paper.

A solution to this dilemma might be to design the service entrance as a gapped arrester that can relieve the TVSS from the major part of the energy-dissipation stress, while the de facto TVSS can still provide point-of-use surge protection for the connected loads.

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Gapped Arresters Revisited : A Solution to Cascade Coordination

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Abstract - This paper provides a brief perspective on how the coordination of cascaded surge-protective devices (SPDs) has become an issue. We propose an approach where the 'ancient' technology of gapped arresters may well be the answer to the dilemma of the incompatibility of a service-entrance SPD having relatively high limiting voltage with the proliferation of built-in or plug-in SPDs having relatively low limiting voltage inside the buildings. The solution involves providing a gapped arrester at the service entrance and gapless SPDs inside the building. An example is given of such a combination, with experimental verification of the proposed solution and computer modeling that allows a parametric evaluation of the significant factors in any candidate combination of SPDs.

I. INTRODUCTION

A quarter of a century ago, metal-oxide varistors ("MOVs"), initially developed as electronic components [1], [2], were introduced to power-system applications and were promptly hailed as the revolutionary technology that would make possible the elimination of gaps in surge arresters and surge-protective devices (SPDs) in general [3]. The conventional arresters at that time combined a gap with a silicon carbide (SiC) varistor disc because the I-V characteristic of silicon carbide, for the desired protection level under surge conditions, resulted in excessive standby current under the normal power system conditions.

For the high-voltage surge arresters, this SiC varistor-gap combination had reached great sophistication in the development of gap structures and construction with modular elements. For low-voltage applications, one SiC varistor disc and one gap were sufficient for the arrester function, but only a few of that type were used in residential applications. The gap sparkover characteristics made the device adequate enough for insulation protection but not effective for the protection of the emerging solid-state appliances [4]. Thus, a market was opened for all-MOV arresters to replace SiC-based gapped arresters and, as the cliché goes, the rest is history.

However, this apparently happy state of affairs with the new, improved, MOV-based gapless SPDs is not the end of the story. Arresters developed with electric utility applications in mind were designed by specialists with strong motivation to ensure a reliable, long-life and ultimately cost-effective application of their products. This philosophy included due consideration of the maximum continuous operating voltage (MCOV), where the drive for low protection levels was tempered by the need to survive the variations and extremes of the power system environment. This criterion was well understood by utilities and manufacturers.

In this paper, we propose to show the opportunity to revive — revisit — the approach of a gapped arrester that was all but abandoned, as a possible solution to the dilemma of coordination between an arrester designed with a prudent and conservative MCOV at the service entrance, and the many SPDs proliferating inside the building and having a de facto low limiting voltage. This paper is not a product announcement but is an invitation to both manufacturers and users to recognize the opportunity and develop a viable product based on this revisited approach. We only suggest that an appropriate coordination is possible between an arrester capable of withstanding high temporary overvoltages, according to utility practice, and the small, de facto SPDs inside the building. We leave the actual product design to the ingenuity and skill of SPD manufacturers responding to the need of the utilities.

II. THE RACE FOR LOWEST PROTECTION LEVEL

Those designs are now found throughout utility systems, down to the service entrance of the end-user customers. Meanwhile, the designers of appliances, driven by the economic pressures of mass production, had selected solid-state components with relatively low surge immunity. This fateful design and marketing decision led to the need for adding surge-protective devices at the equipment level (incorporated at the power port of the appliance), or as an interface plug-in device separately purchased and installed by the end-user. There, the motivation became one of offering the lowest conceivable protection level, for instance 330 V for 120-V applications [5]. However, some of the implications of this race for the lowest protection level were not fully recognized [6].

Now, an additional concern is emerging as the idea of the so-called "whole-house surge protection" is gaining popularity. In that scheme, a relatively large SPD is installed at the service entrance and additional, smaller SPDs are installed inside the building to complement the first line of protection provided at the service entrance. The service-entrance arrester would be a simple (gapless) varistor SPD, based on the conservative

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approach of the utilities (sufficient MCOV, hence medium level limiting voltage for the SPD). However the de facto situation *inside* the building is the uncontrolled proliferation of small SPDs with low limiting voltage. Note that given the uncoordinated status of cascaded SPDs, it would be pointless to try and pin down precisely the qualifiers of 'high', 'medium' and 'low' limiting voltage. The point is only to indicate a relative level.

This situation is uncontrolled because the design and surge immunity of appliances has not benefitted from generic standards on surge immunity. The result is that the small SPDs can in fact 'protect' the service entrance arrester and invite the largest part of an impinging surge to pass by the entrance arrester — intended to divert the large surges but by-passed — to be dissipated into the small devices — that might not be suitable for the large surge.

At this point of our discussion, we deliberately use the vague qualifier "large" to refer to the size and energy-handling capability of an SPD and to the stress threat of the impinging surge [7]. An additional concern is that inviting the flow of large surge currents inside the building has adverse side effects from the electromagnetic compatibility (EMC) point of view by shifting the potential of signal reference points associated with the equipment grounding conductors [8].

III. EMERGENCE OF COORDINATION ISSUES

These emerging issues led to the recognition of "Cascade Coordination" as an important objective for the application of SPDs. A coordinated cascade is the parallel connection of two or more SPDs across the line, one upstream and one or more downstream, each with voltage limiting characteristics that ensure sharing of the surge energy in a ratio commensurate with the energy-handling capability of each SPD.

The stage was set nearly two decades ago, with the publication of IEC Report 664 on insulation coordination [9] proposing "Installation Categories" with a descending staircase of voltages from the service entrance to the end of the branch circuits in a building. That concept was valid at the time, based on the availability of conventional arresters using a silicon-carbide varistor in series with a gap. Consequently, equipment manufacturers, including manufacturers of SPDs, became biased toward a philosophy that advocated higher limiting voltage at the service entrance and progressively lower limiting voltages inside the building.

It took some time and several contributions from independent researchers to recognize that this downward staircase cannot be implemented by a cascade of parallel-connected, varistor-type SPDs, even if separated by some distance along the wiring from the service entrance to the end of the branch circuits. This reality was first discussed in several unpublished committee working papers before a rush of published papers brought the realization into the open [10], [11], [12], [13], [14]. It turns out that SPDs included in equipment or added by users have lower limiting voltages than all-varistor SPDs installed at the service entrance and thus unintentionally "protect" the service entrance SPD by attracting the surge current to the device with the lowest limiting voltage.

IV. A POSSIBLE SOLUTION: RETURN TO A GAPPED ARRESTER

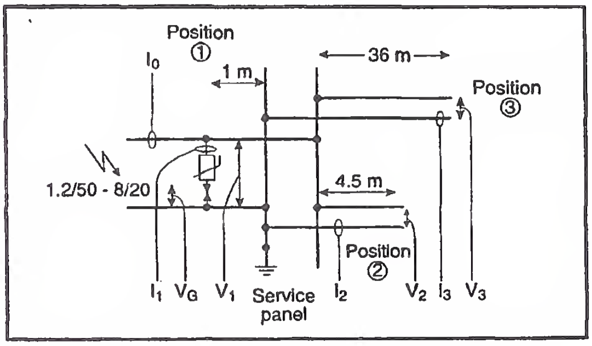
This gapped arrester will use a varistor with a limiting voltage lower than that of the downstream SPDs (in all the following text, "varistor" is to be understood as short-hand for metal-oxide varistor). The gap in series prevents steady-state application of the line voltage which the varistor cannot sustain for more than one half-cycle. An impinging surge will cause the gap to spark over, inserting the low-limiting varistor ahead of the downstream varistors. We have postulated that by appropriate selection and design of the gap, the power-frequency current which will flow in the varistor after the surge will be cleared by the gap at the first natural current zero.

4.1 Criteria for coordination

The basic principle of coordination for a cascade is that the two SPDs — for instance one upstream at the service entrance, and one downstream at the end of a branch circuit or incorporated in the connected equipment — are decoupled from each other by some impedance. With a gapped arrester at the service entrance with a varistor with limiting voltage lower than that of the downstream SPDs can serve as the most attractive SPDs in the cascade and thus divert the surge current away from internal branch circuits after the gap has sparked over. The gap can also serve to provide a higher MCOV and allow the arrester to survive the loss of neutral in a 120/240-V system.

4.2 Experimental verification

To demonstrate that it is possible to obtain a satisfactory coordination, we used our replica of a residential wiring system [8], connecting two of its branch circuits, one 4.5 m long, the other 36 m long (Figure 1). We then installed a gap-varistor combination at the service entrance of the replica and a downstream varistor either at the end of the 4.5-m branch circuit or at the end of the 36-m branch circuit. Figure 1 shows the configuration of the circuit and defines the various current and voltages that will be cited in reporting the results.



I_0 : Current delivered by the generator
I_1 : Current flowing in gapped arrester
I_2 : Current flowing in SPD when at ②
I_3 : Current flowing in SPD when at ③

V_1 : Voltage at arrester
V_2 : Voltage of SPD when at ②
V_2 : Voltage of SPD when at ③
V_G: voltage across gap

Figure 1 - Test circuit for experimental verification of coordination between a gapped arrester installed at the service entrance (Position①) and an SPD installed at the end of branch circuits (Positions ② or ③)

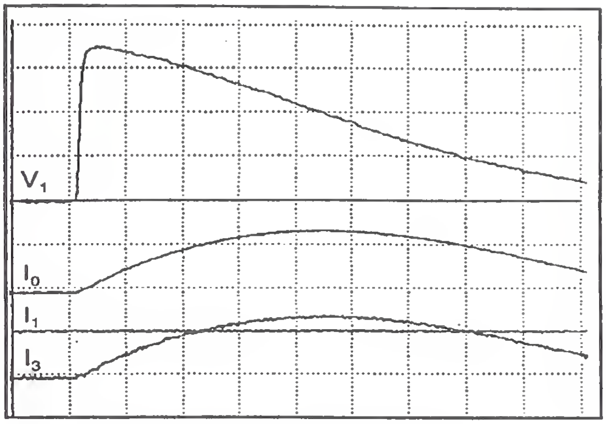
In our replica, the power wiring uses the conventional non-metallic jacket, 2-conductor plus equipment grounding conductor (2 mm dia., AWG #12). The gapped arrester, suitable for a 120/240-V system voltage, consisted of a varistor in series with a gas tube. The downstream SPD was a typical varistor used in plug-in SPDs, rated 130 V rms [15], [16].

The surge, applied at the service entrance of the replica, was produced by a generator capable of delivering a 6 kV, 1.2/50 μs open-circuit voltage or a 5 kA, 8/20 μs short-circuit current, as described in IEEE C62.41-1991 [17]. Suitable † differential voltage probes and current-viewing transformers were used to monitor voltages and currents during a surge event. Tests were conducted in accordance with procedures described in IEEE C62.45-1987 [18]. Instruments used for measurements are listed in the appendix, which also includes, as a contribution toward the updating of C62.45, examples of pitfalls in interpretation of digital oscilloscope recordings.

Aware of the fact that the critical point for coordination is not the maximum surge current that may be encountered in the application, but some intermediate current for which the transition occurs as the gap first sparks over, we sought that transition point for each of the line lengths considered in the experiment. We would expect that in the case of the short decoupling line, it would be more difficult to produce coordination for a given combination of downstream limiting voltage and gap sparkover, as the inductive drop would be smaller than in the case of the longer line. Nevertheless, we made both experiments because the long line, for which coordination is easier, creates other problems, as we will see later.

Figures 2, 3, and 4 show respectively, for the case of the long branch circuit, the transition from no gap sparkover to gap sparkover, occurring first on the tail of the wave, then on the front of the wave as the impinging surge current is raised.

In Figure 2, the 700-V voltage developed across the arrester is insufficient to sparkover the gap, and all the applied current (140 A peak) goes to the downstream varistor. In the experiment where the current I_0 reflects the interaction of the circuit with the generator, the current is reduced by the impedance of the long branch circuit; compared with the larger I_0 (440 A) of Figure 3 after gap sparkover. In the real world where the impinging surge is a current source, there would not be that reduction of the surge current and all of the impinging current, unimpeded, would be forced into the downstream varistor and flow in the branch circuit, an EMC problem [8].



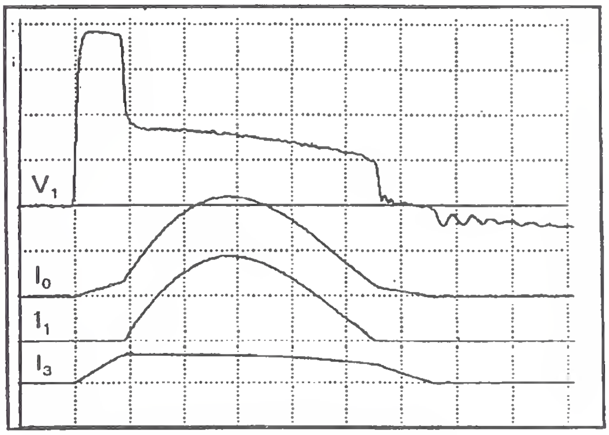
From top to bottom traces (5 μs/div sweep):

V_1 - 200 V/div:	700 V peak
I_0 - 100 A/div:	140 A peak
I_1 - 100 A/div:	No current in arrester
I_3 - 100 A/div:	140 A peak (= I_0)

Figure 2 - Voltage and currents for a surge producing a voltage lower than gap sparkover (long branch circuit)

In Figure 3, the 750-V level developed across the arrester is sufficient to cause sparkover of the gap, but still in the tail of the wave, 4 μs into the surge. This sparkover transfers the impinging current to the upstream arrester, limiting the rise of current into the downstream varistor at 65 A instead of 140 A.

The only stress left on the downstream varistor is to slowly discharge the energy stored in the 36-m branch circuit by the initial rise of current. Note the sudden increase in I_0 at 4 μs as the load impedance presented to the generator changes from 36 m of cable to the short path between generator and upstream arrester.



From top to bottom traces (5 μs/div sweep):

V_1 - 200 V/div:	750 V peak
I_0 - 200 A/div:	440 A peak
I_1 - 200 A/div:	380 A peak
I_3 - 100 A/div:	65 A peak

Figure 3 - Voltage and currents for a surge producing a voltage causing gap sparkover on the tail (long branch circuit)

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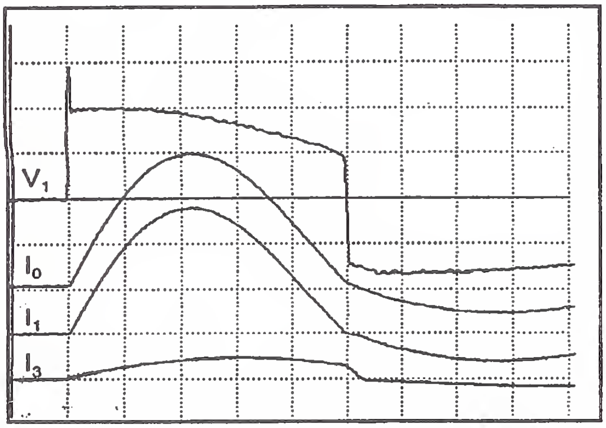
† *The measurements reported in this paper have been made with instrumentation for which the combined uncertainty should not exceed ±5% to ±6%. Given the process of applying the measurement results to the response of surge-protective devices exposed to environments with characteristics that are at best known within an order of magnitude, this level of uncertainty does not affect the practical conclusions.*

Certain commercial instruments are identified in the appendix list of instrumentation in order to adequately describe the test procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that these instruments are necessarily the best for the purpose.

With the current rise shut off in the downstream varistor as the upstream arrester starts conducting, the current in the downstream varistor is then limited to 65 A: a greater surge current results in less current in the downstream varistor after the transition of current levels from no gap sparkover to gap sparkover: *"more begets less!"* [19].

In Figure 4, the larger applied surge (1450 A) results in the gap sparking over on the front of the wave, with very little delay to allow only the beginning of current build-up in the downstream varistor. However, the higher voltage after sparkover (400 V, compared to 350 V in Figure 3) produces further increase in the current I_3, an increase that does not stop until the voltage V_1 falls below 350 V, 15 µs into the surge. This figure was recorded to show the complete event, including the end of the current pulse, and provide a comparison with Figure 2 and Figure 3 at the same sweep rate. As discussed in the Appendix, the sharp spike at the front of the voltage trace must arouse suspicions that the digital oscilloscope might have missed the peak because the need of displaying a 50 µs window means that the resulting sampling rate, reflecting the memory size, is not sufficient to resolve the peak. The value of this figure is then limited to indicating current values and the timing of events, but not the peak of the voltage spike.



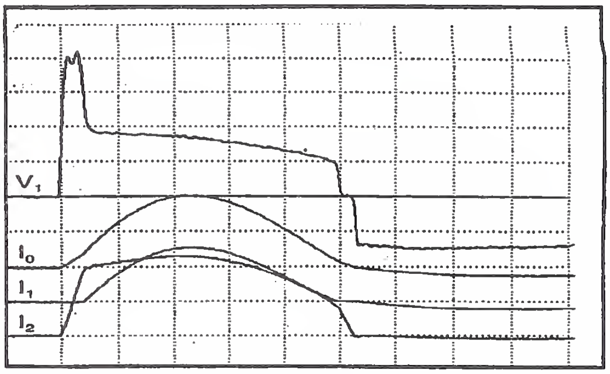
From top to bottom traces (5 µs/div sweep):

V_1 - 200 V/div:	Not resolved - See Appendix
I_0 - 500 A/div:	1450 A peak
I_1 - 500 A/div:	1400 A peak
I_3 - 100 A/div:	50 A peak

Figure 4 - Timing of sparkover and currents for a surge producing sparkover of the gap on the front of the wave (long branch circuit)

Turning now to the case of the SPD connected at the end of the short (4.5 m) branch circuit, Figure 5 shows the transition from no sparkover to sparkover. In this example, the sparkover occurs early in the tail of the wave. Instead of the spike shown in Figure 4, the occurrence of the sparkover in the tail provides sufficient data points to obtain a valid display of the voltage.

In this more difficult coordination scenario (smaller decoupling impedance afforded by the short branch circuit), the build-up of the current I_2 in the downstream varistor is greater than for the case of the long branch circuit.



From top to bottom traces (5 µs/div sweep):

V_1 - 200 V/div:	840 V peak
I_0 - 500 A/div:	1010 A peak
I_1 - 500 A/div:	780 A peak
I_2 - 100 A/div:	230 A peak

Figure 5 - Voltage and currents for a surge causing gap sparkover into the tail (short branch circuit)

In Figure 5, the current I_2 reaches 200 A before the arrester shuts off the fast increase, about 2 µs into the event, leaving the current with only a modest increase to 230 A before it slowly decreases, half-way into the surge event. Thus, the stress caused by the energy deposition into the downstream varistor is greater than for the case of the long branch circuit. Even so, it is still acceptable for the 20-mm diameter varistor typically used for plug-in SPDs [11]. Note also the ringing visible as the voltage V_1 reaches its maximum (840 V), resulting from the oscillation of the open-ended 36-m branch circuit.

The appearance of ringing noted in Figure 5 serves as a warning that the propagation of surges is not a simple matter [20]. To give an example of such complexity, and to give an answer to the frequently asked question "do we need an SPD on each branch circuit, or is one sufficient ?" Figure 6 shows the voltage V_3 at the end of the 36-m branch circuit (Position ③, Figure 1) during a surge scenario similar to that shown in Figure 5 (one only downstream SPD located at Position ②, none in Position ③).

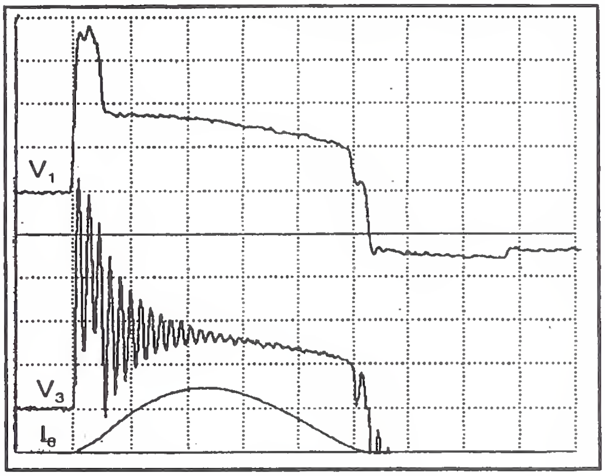
In the scenario of Figure 6, the long branch circuit was left open at Position ③, producing a ringing caused by reflections and undamped oscillations at that end. In this test, the driving voltage V_1 developed at the upstream gapped arrester (Position ①) is only 730 V, but the voltage at the end of the long branch circuit (Position ③) exceeds 1100 V during the ringing. Note that for an actual installation, a load connected at Position ②, where an SPD would be present in this scenario, would not be subjected to this relatively high voltage ringing. At Position ③, a load that would be connected at the end of the long branch circuit assumed to be without SPD, where the ringing occurs, is likely to damp out the ringing.

To validate this expectation, we connected a resistive load at the end of the 36-m branch circuit (Position③), showing that the ringing can be considerably reduced, if not completely eliminated. An unloaded branch circuit, by its very definition, raises no concern for equipment since none is present.

A light load, such as a solid-state control circuit during the off-state of the controlled load, would be the worst case by being at the same time a light load and potentially the most vulnerable type of load.

This situation provides an incentive for the so-called "whole-house protection" where, as mentioned in Section II, a service-entrance arrester as well as plug-in SPDs are provided as a complete package. It is this package approach that will make possible the specification, and actual implementation, of a coordinated gapped arrester and simple varistor plug-in SPDs.

Table 1 shows, for a range of load resistances, how the oscillations (recorded during our tests with a narrow window as discussed in the appendix but not shown here, to limit the length of the paper) are reduced as the load resistance is decreased. The large decrease from 500 Ω to 100 Ω occurs because above 125 Ω, the characteristic impedance of the line [21], a voltage enhancement occurs while below, a voltage reduction occurs.



From top to bottom traces:

V_1 - 200 V/div:	730 V peak
V_3 - 200 V/div:	Peaks not resolved - See Table 1
I_o - 500 A/div:	750 A peak
(5 μs/div sweep)	

Figure 6 - Voltages at the service entrance and at the end of a long open-ended branch circuit for a sparkover occurring in the service entrance arrester

TABLE 1

PEAK OF THE RINGING VOLTAGE AT THE END OF THE 36-m BRANCH CIRCUIT AS A FUNCTION OF THE CONNECTED LOAD.

Load, Ω	open	10 k	5 k	1 k	500	100	50
Peak, V	1170	1170	1150	1020	920	680	650

4.3 Modeling the experiment

A numerical model of the wiring was developed with the EMTP code [22] for the equivalent parameters of the circuit, as measured in our replica of residential wiring [8]. The "Line Constants" subroutine of EMTP was used to generate various models which were subsequently used in the main data file to compute the response of the circuit to various surge waveforms. A time step of 0.01 μs was used for the EMTP simulation [23].

Experimentally recorded waveforms of surge current were digitized. Using the least-squares fitting technique, parameters for the current source were determined. Using the "Freeform FORTRAN" expression capability of the EMTP code, any surge current waveform that can be expressed as a closed form equation can be modeled.

This capability provides a powerful tool for analyzing circuit response to various other surge waveforms now under consideration by standards-writing organizations.

The characteristics of the varistors are represented by a set of I-V points derived from published characteristics [15] and verified by measurements at several current values. In our first approximation, the gap is represented by a switch that closes when the voltage across it reaches 1100 V. In the future, we plan to increase the sophistication of the model by adding an arc voltage to the gap characteristic and the presence of fuses to be provided as the disconnector device required by the SPD standards now being developed.

The equation used for the impinging current is a damped sine wave that allows a close approximation of the current delivered by typical Combination Wave generators into inductive loads [13]. It is known that actual generators tend to produce an "undershoot" when connected to an inductive load, and this case was no exception. However, computational artifacts occur when using a simple damped sine wave because its ***di/dt*** derivative (a cosine) is not zero at time zero. Furthermore, we know that nature does not allow an instantaneous jump of current from zero to a steep rise. By adding a multiplier term $[1-e^{(-t)}]$, these artifacts are eliminated and the waveform has a "gentle toe" [19] which is a better model of reality. This improved equation is then:

$$I = 2121 * \sin(0.126t) * e^{(-t/26.1)} * [1-e^{(-t)}] \qquad (1)$$

with I in amperes and t in microseconds.

Figures 7 and 8 show plots obtained from modeling the same case as that of Figure 4, that is, the application of a surge current such that sparkover of the gap will occur on the front of the wave. Figure 7 shows the voltage V_1, similar to the time-stretched trace of Figure A.2 in the Appendix.

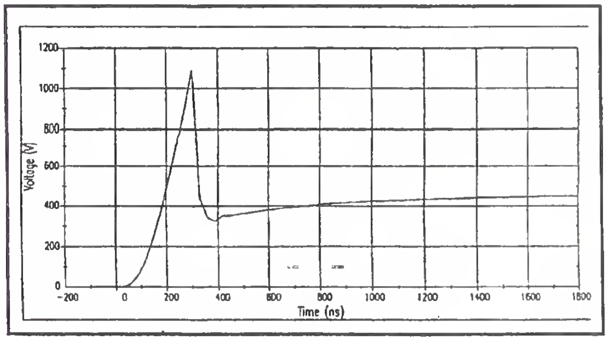
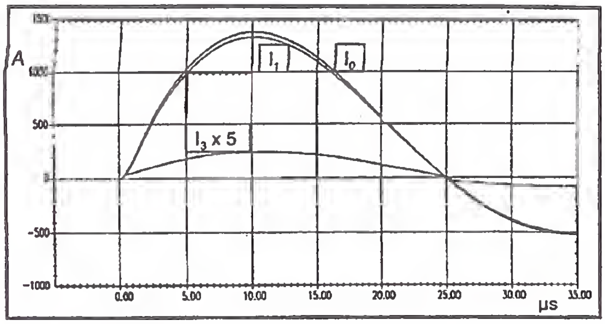


Figure 7 - Model plot of the voltage across arrester, for conditions similar to those of Figure 4. (See also Figure A.2 in the Appendix)



I_0 - 500 A/div; - 1400 A
I_1 - 500 A/div : 1350 A
I_3 - 100 A/div : 50 A (Change of scale by plotting software)

Figure 8 - Model plot of currents, for conditions similar to Figure 4

Figure 8 shows the three current traces, similar to the current traces of Figure 4. The top trace is the applied surge, 1400 A, postulated according to Eq. (1) to match the current involved in the measurement of Figure 4. Practically the same peak values are obtained for the resulting currents, respectively 1300 A for the current in the arrester, I_1, and 50 A for the current in the downstream SPD, I_3. (Note that to present the three traces on the same software-driven plot, the I_3 trace is scaled by a factor of five, to fit the 500 A/div versus 100 A/div of the respective scales of Figure 4).

4.4 *Other important factors*

The objective of this paper, as stated in the introduction, is only to show how the dilemma of cascade coordination might be resolved by recourse to a gapped arrester at the service entrance. We have shown that effective coordination becomes possible by appropriate selection of the limiting voltages of the varistors and of the gap sparkover characteristics. However, there are other factors that will need to be addressed by designers before this approach can be transitioned to viable hardware. We have not attempted at this stage to study in detail all of these factors, but suggest the following list of topics for consideration.

These are familiar to arrester manufacturers and this list is not intended to tutor them, but simply to place the idea in perspective so that no false expectations are raised that an immediate and easy solution is already at hand. We will have accomplished our purpose if the old idea is just given new consideration. Among the topics to be studied, the following are most important:

- Ability of the varistor to reduce the follow current to a level that will allow the gap to clear at the first current zero — as postulated.
- Ability of the varistor to conduct the follow current that the power system can deliver at the point of installation.
- Ability of the gap to withstand the unavoidable power-frequency overvoltages of the power system without going into conduction and yet to have an acceptable sparkover voltage.

V. THE NEW OPPORTUNITY

The results of our experimental measurements, which can be expanded by parametric modeling, show how a happy state of affairs — an effective coordination of cascaded SPDs — could be obtained by gapped arresters at the service entrance. These arresters would combine the best of the two technologies, gas tubes and metal-oxide varistors. This will not happen, however, if the decision is not made to apply such a gapped arrester. That decision must be made by utilities and installers. In contrast, the de facto situation inside the building, imposed by millions of installed appliances, is now hopelessly immovable. Typically, when these appliances include a built-in SPD or, when the end-user purchases and installs an add-on, plug-in SPD, these SPDs are of the type with low limiting voltage [5], resulting in difficult if not impossible coordination.

This very difficult coordination, however, should not be construed as a recipe for disaster. The reality of the present situation is that these low limiting voltage SPDs manage in general to survive even in the absence of a service entrance arrester. As discussed earlier, this is not a desirable situation, hence the proposals for whole-house surge protection. But if the proposed service entrance arrester were designed to use a simple varistor with ratings commensurate with utility practices, it is most likely that the internal SPDs will "protect" the service entrance arrester, which then serves no useful purpose and is a waste of resources. Furthermore, as more electronics and equipment with low logic voltages are installed, the existing practices may lose effectiveness.

Standards or regulations cannot prescribe the particular type of service entrance arrester (furthermore, the provision of a service entrance arrester is required in only a few countries), so the decision is left to the community of utilities, SPD manufacturers and end-users. The manufacturers would probably respond to the need for gapped arresters if informed system designers were to call back from retirement the 'ancient' gapped device and, with appropriate technology update, give the old idea a new lease on life.

VI. CONCLUSIONS

1. The dilemma of coordinating a cascade of surge-protective devices can be solved by providing a gapped arrester at the service entrance, that will coordinate with the de facto situation inside the building.
2. The need for a service-entrance arrester to withstand the scenario of lost neutral can be satisfied by a gapped arrester having sufficient maximum continuous operating voltage capability.
3. Experimental verification of this coordination has been demonstrated for typical branch circuit lengths and limiting voltages applicable to the 120/240-V systems used in residential applications in North America. The same principles can be applied to other power systems with appropriate adaptation of voltage ratings and careful consideration of the local grounding practices.

4. The behavior of a complex system such as the interactions between circuit impedances and the nonlinear characteristics of surge-protective devices can be successfully modeled to allow parametric studies.
5. Other factors need attention, for which good engineering practice applied by surge-protective device manufacturers can provide adequate design.
6. While the idea appears sound, it cannot be implemented by individual end-users. It will take an initiative by a centralized organization, such as the utility serving the district, to persuade manufacturers that a market opportunity exists to which they can contribute.

VII. ACKNOWLEDGMENTS

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APPENDIX

Limitation of Digital Oscilloscopes

In discussing Figure 4, mention was made of the limited number of sampling points in digital oscilloscopes, in relation to the time of the display window. For fast-changing phenomena, such as the gap breakdown shown in Figure 4 (reproduced here as Figure A.1), the allocation of sampling points is insufficient to resolve the peak voltage on the trace V_1, that is, the peak can occur between sampling points. It takes a narrower window (faster speed) to record all of the peak waveform, as shown in Figure A.2. A cursory examination of the peak in Figure A.1 might have led the unwary to conclude that the V_1 peak is only 600 V, but Figure A.2 reveals a peak at 1200 V. This example should be a useful reminder to exercise caution in the use of these otherwise sophisticated and very convenient digital oscilloscope.s

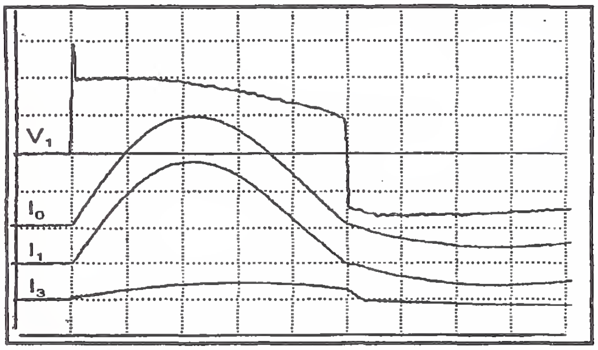
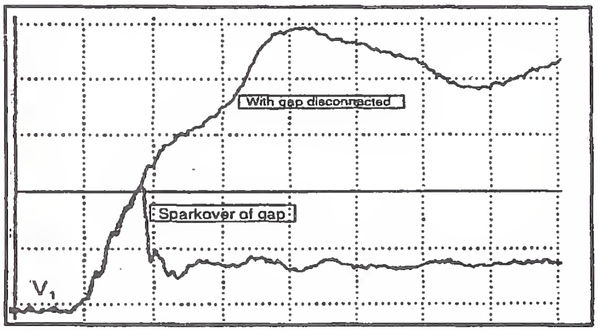


Figure A.1 (Same traces as Figure 4): The peak of trace V_1 is not completely resolved because the sampling rate made necessary by the desire to show a 100 μs window did not provide enough data points around the peak.

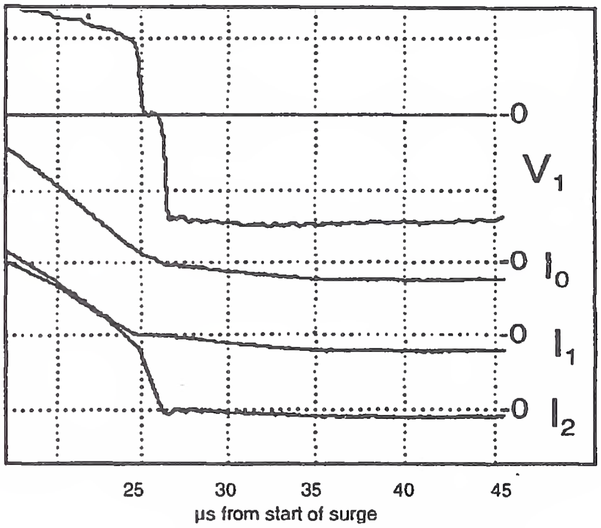


Top trace: Voltage with gap disconnected
Bottom trace: Voltage with gap reconnected
(500 V/div, 200 ns/div)

Figure A.2 - Resolution of the actual peak voltage V_1 shown in the recording of Figure A.1, obtained with more data points

Understanding the Circuit Behavior

Figure A.3 shows a zoomed portion of the oscillogram of Figure 5, with the voltage across the upstream arrester and the three currents I_0 (generator), I_1 (upstream SPD), and I_2 (downstream SPD). The polarity of the voltages and currents, as visible in the oscillogram, have been tabulated for three time ranges, 0 to 25 μs, 25 to 27 μs, and after 27 μs. At time 25 μs, the current delivered by the generator becomes less than the current I_2 required by the inductance of the branch circuit, so that the upstream arrester is starved: a short period of rest in the I_1 trace can be seen on the zoomed picture, while it was hard to detect in Figure 5. The current I_2 then falls more rapidly (this can exacerbate inductive effects in its vicinity) until it reaches zero at 26.5 μs, and only then, the generator current I_0 reverses its polarity, the classic "undershoot."



	Voltage and current polarity		
	0 to 25 μs	25 to 27 μs	27 to 45 μs
V_1 - 200 V/div:	positive	zero	negative
I_0 - 500 A/div:	positive	positive	negative
I_1 - 500 A/div:	positive	zero	negative
I_2 - 100 A/div:	positive	positive	negative

Figure A.3 - Zoom view from Figure 5 showing voltages and currents during the transition at the end of the surge

Instrumentation List

Surge generator:	KeyTek 711 and P7
Differential voltage probe:	KeyTek IL-1PK1001
Current transducers:	Pearson 411
Attenuators:	Tektronix 011-0054-02
Digital signal analyzer:	Tektronix DSA 602A
Preamplifiers:	Tektronix 11A32; 11A33

The Role and Stress of Surge-Protective Devices in Sharing Lightning Current

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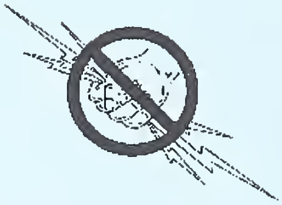
Significance
Part 2 – Development of standards — Reality checks
Part 4 – Propagation and coupling — Numerical simulations

Most simulations performed to investigate the sharing (dispersion) of lightning current for the case of a direct flash to a building have focused on the role and stress of surge-protective devices (SPDs) installed at the service entrance of a building and their involvement in that part of the lightning current that exits the building via the power supply connection to the energy supply.

The numerical simulations performed for this paper, based on a postulated waveform and amplitude suggested by current standards, include downstream SPDs, either incorporated in equipment or provided by the building occupant. The results show that a significant part of the exiting lightning current can involve those downstream SPDs with some likelihood that their surge withstand capability might be exceeded. Such a possibility then raises questions on the validity of the postulated amplitude in the face of the relatively rare occurrence of reported failures.



THE ROLE AND STRESS OF SURGE-PROTECTIVE DEVICES IN SHARING LIGHTNING CURRENT

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Abstract – This paper examines the sharing of lightning current associated with a direct flash to a building. This sharing involves not just those surge-protective devices (SPDs) that might be installed at the service entrance, but also all SPDs involved in the exit path of the lightning current. Such sharing might involve built-in SPDs of some equipment located close to the service entrance, but heretofore not included in numerical simulations performed by many researchers. From the numerical simulations reported in this paper, conclusions are offered that may influence the design and EMC testing of equipment, as well as the risk analysis associated with lightning protection.

I. BACKGROUND AND RATIONALE

This paper offers additional information to the body of knowledge accumulated on how the lightning current of a direct flash, injected into the earthing system of a building, is shared among the many available paths towards intended or opportunistic earthing electrodes.

Recent developments in the International Electrotechnical Commission (IEC) and the Surge-Protective Devices (SPD) Committee of the Institute of Electronics and Electrical Engineers (IEEE) have focused on the role of SPDs connected at the service entrance of a building in the case of a direct lightning flash to the building. This scenario is described in IEC 61312-3 (2000) [9], IEEE PC62.41.1 [12] and PC62.41.2 [13].

Prior to this new focus, most of the considerations on SPD applications were based on the scenario of surges impinging upon the service entrance of a building as they come from sources external to the building. The new (additional) focus addresses the scenario of the earth-seeking lightning current as it is shared among the many possible paths to earth, including the deliberate and opportunistic exit paths of the building earthing system, services other than the power system connection and, mostly, the power supply connection.

Quite independently from these lightning protection considerations, the IEC Subcommittee SC77B had developed a series of documents on the electromagnetic compatibility of equipment, IEC 61000-4-5, Surge withstand capability [8] in particular. These documents were primarily concerned with immunity against typical disturbances, the rare case of a direct lightning flash to a building containing electronic equipment not included.

Increasing recognition of the need to include the scenario of a direct flash to a building – rare as it might be – has motivated the formation of an IEC Joint Task Force TC81/SC77B for the purpose of considering surge stresses on equipment higher than those currently described in the IEC document 61000-4-5 on immunity testing [8].

The purpose of the paper is to examine in detail the sharing of lightning current, not just by the SPDs at the service entrance, but also by all SPDs that might be involved in the exit path of the lightning current. Such sharing might well involve SPDs incorporated in the equipment located close to the service entrance, but not always included in the numerical simulations that have been performed by many researchers (Altmaier et al., 1992) [1]; (Standler, 1992) [23]; (Rakotomalala, 1994) [20]; (Birkl et al., 1996) [3]; (Mansoor and Martzloff, 1998) [15]; (Mata et al., 2002) [19]. In its recent development of a Guide and a Recommended Practice on surges in low-voltage ac power circuits [13] the IEEE has refrained from identifying SPDs as being those that may be connected at the service entrance. Instead, it refers to "SPDs involved in the exit path" without reference to their point of installation.

Given the tendency of equipment manufacturers to include an SPD at the equipment power input port, the issue of "cascade coordination" arises. Several previous papers (Martzloff, 1980) [17]; (Goedde et al., 1990) [5]; (Lai and Martzloff, 1991) [14]; (Standler, 1991) [22]; (Hostfet et al., 1992) [7]; (Hasse et al., 1994) [6] have explored the concept of cascade coordination involving two or more SPDs connected on the same power supply but at some distance from each other.

The legitimate wish of the energy service providers to specify robust SPDs at the service entrance results in SPDs having a relatively high Maximum Continuous Operating Voltage (MCOV). On the other hand, some equipment manufacturers tend to select SPDs with a low MCOV under the misconception that lower is better (Martzloff and Leedy, 1989) [18]. This dichotomy can result in a situation where the low-MCOV SPDs included in equipment might well become involved in the "exit path" and thus become overstressed in the case of a direct flash to the building. This situation is made more complicated by the fact that commercial SPDs packages are assembled from typical distributors' supplies that can have an allowable tolerance band of ±10% on the voltage-limiting rating.

To explore the possibility and implications of a questionable coordination, numerical simulations were performed on a simplified model of a building featuring SPDs installed at the service entrance and SPDs that may be incorporated in equipment connected inside the building near the service entrance.

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II. NUMERICAL SIMULATIONS

II.1 Basic circuit

Figure 1 shows a simplified building power system that includes the key elements of this scenario: the building earthing system and all earthing electrodes, with the corresponding exit paths via the service-entrance SPDs and a built-in SPD provided at the power port of a typical item of electronic equipment. In this example, these SPDs are metal-oxide varistors (MOVs) with typical voltage ratings (150 V at the service entrance and 130 V in the equipment) selected for a 120/240 V residential power system. (The conclusions obtained for this type of power system will also be applicable to 240/400 V systems.)

Numerical analysis of the circuit behavior by EMTP [4] allows inclusion of the SPD characteristics as well as the significant R and L elements of the wiring, with injection of a stroke current of 100 kA 10/350 µs at any selected point – the earthing system in this case. The selection of a 100 kA peak is consistent with the postulate made in many published simulations, but might be questioned on the basis of field experience and lightning detection statistics, as will be discussed later in this paper.

In Figure 1, the neutral is defined as part of a "multiple-grounded neutral" system (TN-C-S), with distributed R and L elements between its earthing electrode connections. The R and L values for the cables used in the numerical simulation, but not shown in the figure to avoid clutter, were selected to emulate the typical wire diameters used in low-voltage power distribution systems and building installations.

Previous studies (Birkl et al., 1996) [3]; (Mansoor and Martzloff, 1998) [15] have validated the intuitive expectation that the tail of the 10/350 µs waveform often postulated for simulations will be shared among the available paths simply according to the relative values of resistance in the paths leading to the earthing electrodes. This fact is apparent in the results of Figure 2, for example at the 350 µs time: when inductive effects have dwindled, the current I_H in the 10-Ω earthing resistance of the building is ten times smaller than the total current exiting the building $[I_N+I_{L1}+I_{L2}]$ toward the power distribution system in which multiple earthing electrodes offer an effective earthing resistance of only 1 Ω. It is also worthy to note that this sharing is controlled by the ***relative*** values of the resistances, so that any earth conductivity differences associated with local conditions will wash out.

The combination of the service-entrance 150-V MOV on Line 2 and the 130-V MOV incorporated at the power port of the equipment constitutes a so-called "cascade". When two such cascaded SPDs are to be coordinated, a decoupling impedance must be provided between the two SPDs so that the voltage drop caused by the current flowing in the decoupling impedance – in this example the impedance of the 2,5 mm^2 diameter wires – and added to the limiting voltage of the 130-V MOV, will cause enough of the current to flow through the 150-V MOV to reduce stress on the 130-V MOV.

The simulation was performed for three values of the impedance (length) of the connection, i.e., 0,1 m, 1 m, and 10 m to assess the effect of this impedance for practical situations. Figure 3 shows the results for these three cases and Table 1 shows the resulting energy deposition in the respective MOVs.

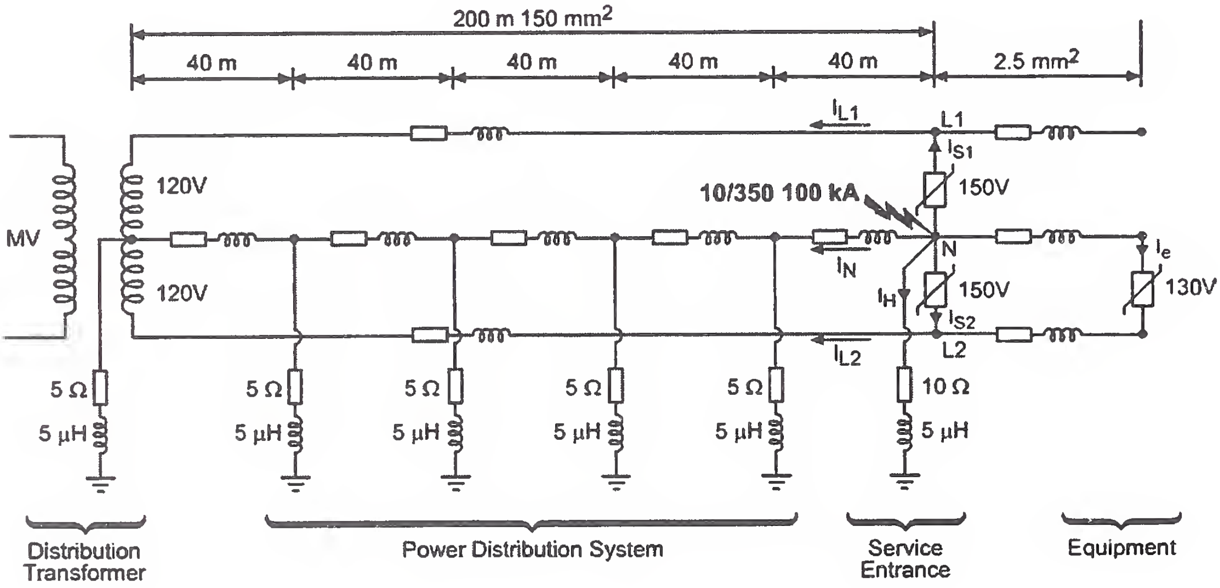
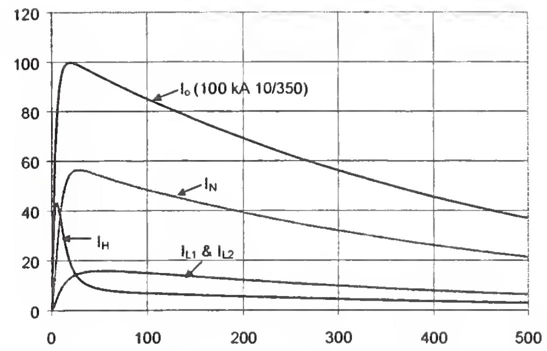


Figure 1 Simplified building schematic with service-entrance SPDs, one built-in equipment SPD, and multiple-grounded power distribution system in case of a direct lightning flash to the earthing system



Legend

I_O: 100 kA, 10/350 μs stroke to the building earthing system
I_N: current exiting via the neutral of the power supply
I_{L1}, I_{L2}: current exiting via the two lines of the power supply
I_H: current into the building earthing electrode(s)

Vertical scale: current in kA – Horizontal scale: time in μs

Figure 2 – Sharing of the lightning current among available paths to earth electrodes

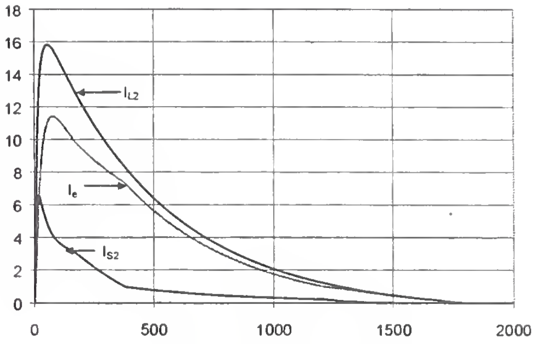
In the traces of Figure 3, the total current in Line 2 (sum of the two currents in the two MOVs) remains essentially unchanged for the three combinations, but the sharing of the current between the two MOVs is significantly affected.

Figure 3a, with only 0,1 m of separation, is not a practical example of connection of equipment that close to the service entrance – except perhaps an electronic residual current device incorporated in the service panel. The two other figures, 3b and 3c, show how the 130-V MOV that took the largest part of the current in the case of Figure 3a, now takes on less as separation length increases. An interesting situation develops as the current flowing in the 10-m line to the 130-V MOV stores energy that will cause a stretching of the current in the 130-V MOV long after the 150-V MOV current has decayed. This is significant because the total energy deposited in the MOVs is the criterion used for coordination, even though the current in the 130-V MOV could be lower than the current in the 150-V MOV. Table 1 shows how this energy sharing changes with the length of the decoupling connection, according to the integration of the varistor currents and voltages obtained from EMTP.

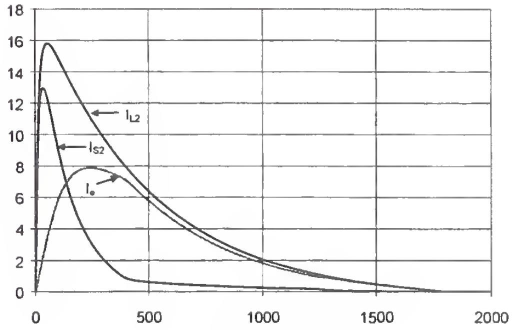
Table 1 – Sharing energy between MOVs for three different connection lengths

SPD	Energy deposition (joules)		
	0,1 m	1 m	10 m
150-V MOV	620	1090	2470
130-V MOV	2560	2030	890

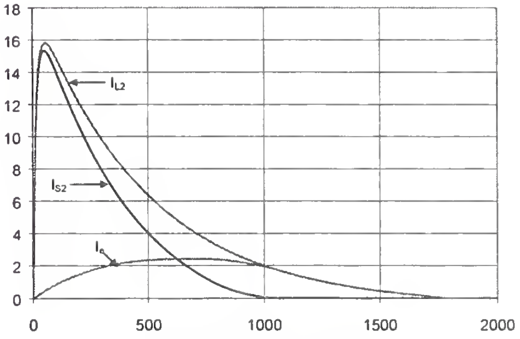
These energy levels might be acceptable for a 150-V MOV sized for service entrance duty, but the 890-joule deposition into the 130-V MOV incorporated in the equipment exceeds common-wisdom ratings for such devices.



a) 0,1 m connection



b) 1 m connection



c) 10 m connection

Legend

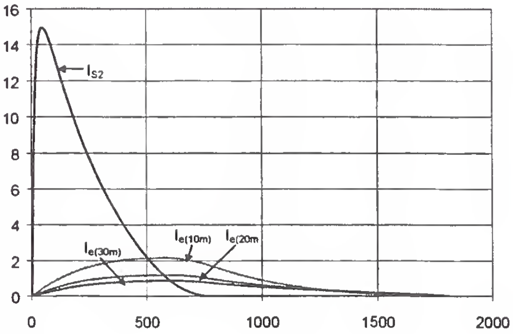
I_{L2}: current exiting via the power supply phase conductor
I_{S2}: current into the service entrance SPD
I_e: current into the equipment SPD

All vertical scales: current in kA
All horizontal scales: time in μs

Figure 3 – Sharing of lightning stroke current

This finding then raises a question on the effectiveness of a cascade for the case of direct flash to the building. In an actual installation, there would be more than one piece of equipment, presumably each with a 130-V built-in MOV at the power port. One might expect that some sharing among these multiple SPDs would reduce the energy stress imposed on these devices.

To explore this situation, an additional simulation was performed for three branch circuits, respectively 10 m, 20 m, and 30 m, each of them supplying equipment incorporating a built-in 130-V MOV. Figure 4 shows the sharing of current among these three MOVs and the 150-V service entrance MOV, and Table 2 shows the energy deposition.



Legend

I_{S2}: current into the service entrance SPD
I_e: currents in the three SPDs at end of 10, 20, and 30 m lines

Vertical scale: current in kA – Horizontal scale: time in µs

Figure 4 – Sharing of current among MOVs

Table 2 – Energy sharing among MOVs

Branch circuit length and energy deposition into three 130-V MOVs			Service entrance 150-V MOV
10 m	20 m	30 m	
620 J	370 J	280 J	1930 J

II.2 Effect of manufacturing tolerances on commercial-grade metal-oxide varistors

The simulations discussed so far were performed by postulating that both the 150-V MOV and the 130-V MOV had their measured voltage limiting at the nominal value as specified by typical manufacturer specifications. Such a postulate is of course difficult to ensure in the reality of commercial-grade devices. For instance, the nominal voltage-limiting value of MOVs rated 130 V rms is 200 V, with lower limit of 184 V and upper limit of 220 V. To check that aspect of the problem, an arbitrary lot of 300 devices rated 130 V rms was purchased from a distributor and the actual measured voltage-limiting value at 1 mA dc was determined in accordance with IEEE Std 62.33-1994 [11]. For this lot, the standard deviation (sigma) was found to be 8 V.

On the basis on these measurements and to give an indication of the significance of tolerance effects, the computations reported for Figure 3c (10 m separation) were repeated, still with a 150 V MOV at the service entrance, but with varistors at ±1 sigma of the 130 V rms rating, that is, 122 V and 138 V rms. The results are shown in Table 3.

Table 3 Energy sharing for three values of the equipment built-in MOV (10 m separation)

Equipment MOV rating (V rms)	Energy deposited (J)	
	Equipment MOV	150-V service entrance MOV
122	915	2320
130	890	2890
138	750	2650

These results illustrate the significance of tolerances in a situation where the difference between the two SPDs of the cascade is not large, because of the de facto situation of low values of MCOV that the industry has unfortunately adopted. Of course, if tolerances were also taken into consideration for the service entrance MOV, the extremes of distributions for both MOV would make an effective coordination between a nominal 150-V MOV and a nominal 130-V MOV even more problematic.

II. 3 Nonlinearity of circuit elements

Most of the reported simulations, as cited above, have been performed with a conservative postulate of a 100 kA 10/350 lightning discharge. The median of the current peaks compiled in the seminal Berger et al. paper [2] is only 20 kA. Occasional reservations have been voiced on the validity of these data collected with technology dating back to the 1970's. A recent (July 2000) actual case history was communicated to the authors by a colleague for two major lightning storms recorded in the area of Tampa in Florida by means of the Lightning Detection System [24], during which over 30 000 flashes were detected in a period of less than 12 hours, with only one at the 150 kA level, and a median of 20 kA, confirming the Berger at al. data.

One could expect that the dispersion of the lightning current that results from the combined action of linear elements (resistance and inductance) with nonlinear components (MOVs) might produce a different sharing of the current as the decoupling element is linear but the SPDs are nonlinear. To explore this hypothesis, the computations for the case of Figure 4 and Table 2 were repeated, for peak currents of 100 kA (the original value of the computation), 50 kA, and 25 kA (about the median of the statistics). Table 4 shows the results of these computations. It is interesting to note that as the applied stroke is decreased 4 to 1 (from 100 to 25), the total energy deposited in the varistors is decreased by a factor of 3200/610 = 5.2. This relative greater decrease is caused by the larger portion of the current exiting via the linear-path neutral, further relief for all the SPDs involved in the exit path.

Table 4 Nonlinear effects on current sharing

10/350 stroke (kA)	Branch circuit length and energy deposited into three 130-V MOVs			Energy into service entrance 150-MOV	Total energy in the MOVs
	10 m	20 m	30 m		
100	620 J	370 J	280 J	1930 J	3200 J
50	329 J	215 J	179 J	700 J	1423 J
25	170 J	120 J	90 J	230 J	610 J

III. DISCUSSION

We have made all these computations based on postulating that the insulation levels are sufficient to prevent a flashover that would drastically affect the continuing energy deposition in the downstream SPDs. We have not included the limits of energy handling of the devices, which of course should be compared with computed deposited energy levels in a practical case.

Another set of readings from the EMTP computations confirmed that the presence of SPDs at the critical points prevents such overvoltages from occurring (as long as the SPDs can carry the resulting currents)

Not surprisingly, the results of the simulation confirm that the sharing of the lightning current occurs in inverse ratio of the resistances leading to the earthing electrodes after the initial phase of the 10/350 μs stroke. Likewise, one can expect that inductances will limit the current flow so that low-inductive paths, such as intended and opportunistic earth electrodes of the building itself, compared to the longer lines of the power supply, will carry a larger share of the total current during the initial phase of the current. This effect is clearly visible on the I_H of Figure 2, for the relatively slow rise time of 10 μs of a first stroke. One may expect that for the subsequent strokes, or the flashes associated with triggered lightning experiments that have shorter rise times (Rakov et al., 2001) [21], this effect will be even more apparent.

An important finding – predictable on a qualitative basis but heretofore not quantified for the case of a direct lightning flash to buildings containing electronic equipment – concerns the cascade coordination of built-in SPDs in the equipment. From the simple examples presented, it appears that a cascade of a robust service-entrance SPD and a built-in SPD sized for limited energy-handling capability, according to the common-wisdom practice, might well be a delusion.

A solution to the difficult coordination could be to replace the all-MOV SPD at the service entrance with a combined series gap-varistor device (Mansoor et al., 1998) [16]. Such a device would also alleviate the concerns about the temporary overvoltage problems associated with MOV-only SPDs. Sparkover of the gap during the initial rise of the lightning current (when the coordination by means of the decoupling inductance occurs) will invite the remainder (continuing rise and tail) of the surge current exiting via SPDs to use the service entrance SPD rather than the simple and less robust built-in MOVs downstream.

Last but not least, the practical question remains open on the need to provide surge protection against worst cases – the combined worst case of a direct flash to the building and the high-level 100 kA stroke, which is only at the 4% probability, according to the Berger et al. data [2] and even lower in the yet-anecdotal case of the Tampa Bay lightning storm [24]. The nonlinearity effect presented in II.3 adds further credibility to the overall need to make reasonable risk assessments of cost-effectiveness before specifying high surge level requirements, both for the service entrance SPDs and for built-in SPDs in connected equipment.

IV. CONCLUSIONS

1. When accepting the postulate that the reference parameter of a direct lightning flash to a building should be a 10/350 μs current with a peak of 100 kA, the numerical simulations performed for a simplified system with one surge- protective device installed at the service entrance, and one or more built-in SPD in downstream equipment indicate that the downstream SPD is very likely to be overstressed and fail, most likely catastrophically.

2. There are several possible explanations for the apparent contradiction between a prediction of downstream equipment failures based on this postulated lightning parameters, and equipment field experience that does not report such frequent failures, although of course anecdotes abound.

- The occurrence of a direct flash to a building can cause such extensive damage that a post-mortem for investigating the specifics of a prevailing ineffective coordination is not performed at that time and the issue is ignored.
- Enough uncontrolled clearance flashovers occur in the installation to provide significant relief for any at-risk SPDs incorporated in downstream equipment.
- In an installation where many built-in or plug-in SPDs are present, the sharing illustrated by Figure 4, combined with a low probability of a 100 kA stroke, might reduce the stress on downstream devices to a value within their capability. In particular, many commercial plug-in SPDs advertise capabilities of hundreds of joules, unlike the 20 joules of a single MOV, which might be provided at the input port of electronic equipment.
- Insufficient field failure data have been obtained, compiled, shared, and published to enable realistic assessment of frequency and severity of occurrences involving an unsuccessful cascade coordination.

3. It is impractical at this point to mandate high energy handling capability for built-in SPDs. Such a move might meet with strong objections from manufacturers whose products have satisfactory field experience, and a risk analysis might show it to be not cost-effective.

4. Economic and political realities related to the type and mission of the installations to be protected should be kept in mind. Clearly, mass-market applications such as cost-conscious consumers, in a framework of regulated or unregulated installations, are different from bottom-line-conscious industrial applications, and even more so in the case of national assets – be they cultural or military.

5. Another approach for manufacturers might be to avoid placing low MCOV varistors at the input port of their equipment. Rather, they should select an SPD with an MCOV and resulting surge-protective level as high as their equipment can inherently stand. This is a "selfish" approach which is mentioned here half-seriously, half-facetiously: there are enough low MCOV SPDs installed by users or included in other equipment in a typical system that those unfortunate low-MCOV devices will take up the stress, leaving unscathed the equipment wisely provided with high MCOV SPDs!

V. REFERENCES

Note: The citations that appear in the text are listed here by alphabetical order of the lead author, not by chronological order of appearance in the text.

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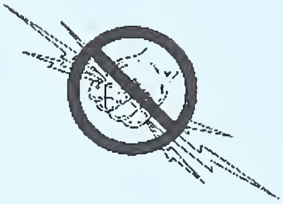
Annex A

Citations Part 8

Coordination of cascaded SPDs



Annex A

Citations Part 8 – Coordination of cascaded SPDs

(Alphabetical order by author, as listed in Part 1)

GOEDDE, G.L., MARZ, M.B., and HENRY, D.C., "Coordinating Lightning Stroke Protection From the Utility System to Load Devices," *Proceedings, Second International Power Quality/ESD Conference*, October 1990.

- Describes secondary surge phenomena and the importance of transformer secondary circuit protection coordination to both utilities and end users.
- An effective MOV protection coordination scheme is described and recommended.
- Multiple grounds at different potentials, especially under lightning surge conditions, prevent distribution transformer primary arresters from protecting secondary circuits.
- 13 references

HASSE, P., ZAHLMANN, P., WIESINGER, J., and ZISCHANK, W., "Principle for an Advanced Coordination of Surge-protective Devices in Low-voltage Systems," *Proceedings, 22nd International Conference on Lightning Protection*, Budapest, 1994.

- Proposes a scheme where the performance of SPDs for any waveform is converted to an equivalent configuration referred to the performance under the Combination Wave.
- 7 references

HOSTFET, O.T., HERVLAND, T., NANSEN, B., and HUSE, J., "Coordination of Surge Protective Devices in Power Supply Systems: Needs for Secondary Protection," *Proceedings, 21th International Conference on Lightning Protection*, Berlin, September 1992.

- On the basis of observed failures on secondary surge protection devices, theoretical and experimental investigations are performed in order to clarify the need for such protection including the sharing of energy stresses in relation to the primary surge protection system.
- The higher energy stresses will generally occur on the device with the lowest limiting voltage. Therefore, the protection level for the secondary protection should be selected higher than for the primary protection.
- 5 references

LAI, J.S., "Performance Criteria for Cascading Surge-Protective Devices," *Proceedings, Open Forum on Surge Protection Application, NISTIR-4654*, August 1991.

- Voltage limiting level of cascaded devices, their separation distance, and surge waveform are used as parameters to compute the energy deposited in the devices.
- Experimental verification shows reasonable agreement between simulation and experiment.
- Contains details of the data base used for the Lai & Martzloff *IEEE Transactions IA-24* 1993 paper [291].
- 10 references

LAI, J.S. and MARTZLOFF, F.D., "Coordinating Cascaded Surge-Protection Devices: High-Low versus Low- High," *IEEE Transactions IA-24,* No.4, July/August 1993. (First publication, *Conference Record, IEEE IAS Annual Meeting*, September 1991.)

- Computations and experiments showing the effect of line length and impinging surge waveform on sharing energy between service entrance arrester and SPD inside building.
- While the 8/20 μs waveform can still result in a contribution from both devices to sharing the energy, the 10/1000 μs waveform does not produce any inductive separation of the devices past the rise time, so that energy is equally shared between devices of equal rating.
- 11 references

MANSOOR, A., MARTZLOFF, F.D., and PHIPPS, K., "Gapped Arresters Revisited: A Solution to Cascade Coordination," *IEEE Transactions PWRD-13*, No.4, December 1998.

- Demonstrates the principle of a coordination scheme compatible with downstream SPDs having lower limiting voltage than the SPD at the service entrance.
- 23 references

MARTZLOFF, F.D., "Surge Voltage Suppression in Residential Power Circuits," *Unclassified GE TIS Report 76CRD092*, 1976.

- Performance of mid-seventies vintage of service entrance SPD and simple MOV plug-in SPD.
- Introduction of the concept of cascade coordination achieved by the inductance of wiring.
- 4 references

MARTZLOFF, F.D., "Coordination of SPDs in Low-Voltage AC Power Circuits," *IEEE Transactions PAS-99*, No. 1, Jan/Feb 1980.
- Coordination between voltage-switching and voltage-limiting SPDs.
- Coupling between equipment grounding conductor and phase wires.
- Where an unidirectional current is injected into the ground system only, the response of the system is an oscillating voltage involving the phase conductors.
- 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.
- 7 references

MARTZLOFF, F.D. and LAI, J.S., "Cascading Surge-Protective Devices: Coordination versus the IEC 664 Staircase," *Proceedings, PQA '91 Conference.*
- Coordination of cascaded devices can be achieved under various combinations of parameters, but some combinations might leave the smaller device subjected to the highest stress.
- Significant parameters in achieving successful coordination involve three factors, over which the occupant of the premises has no control: the relative limiting voltages of the two devices, their separation distance, and the prevailing waveforms for impinging surges.
- 13 references

MARTZLOFF, F.D. and LAI, J.S., "Cascading Surge-Protective Devices: Options for Effective Implementation," *Proceedings, PQA '92 Conference*, September 1992.
- Implications of the situation resulting from the present uncoordinated application of devices with low limiting voltage at the end of branch circuits and devices with higher limiting voltage at the service entrance.
- The reality of having many millions of 130-V rated varistors installed on 120-V systems makes the ideal scenario of a well-coordinated cascade difficult or perhaps unattainable in the near future.
- As a compromise, a cascade with equal voltage ratings for the arrester and the suppressor can offer successful coordination, if the impinging surges are presumed to be relatively short.
- Tolerances on device characteristics might make the compromise ineffective.
  - Bibliography with 32 citations

MARZ, M.B. and MENDIS, S.R., "Protecting Load Devices from the Effects of Low-Side Surges," *Proceedings, IEEE/ICPS Conference*, May 1992.
- Utilities are becoming aware of the low-side surge phenomenon and are applying secondary arresters to protect their distribution transformers. This practice can increase the voltage stress at the customer service entrance.
- If any ground paths exist on the customer side of the service entrance, these surges can penetrate further into the customer's system.
- Damage caused by low-side surges can be avoided if properly coordinated arresters are installed at the transformer secondary, service entrance, and load device.
- 15 references

STANDLER, R.B., "Coordination of Surge Arresters and Suppressors for Use on Low-Voltage Mains," *Proceedings, 9th International Zürich Symposium on Electromagnetic Compatibility*, 1991.
- Results of both a theoretical analysis and laboratory experiments are reported on sharing of current between an arrester at the service entrance and a suppressor at receptacles during surges.
- Shows that it is better to design the arrester with a smaller conduction voltage than the suppressor, in order to obtain better coordination, better electromagnetic compatibility, and lower cost.
- Computations were made with only resistance of wire between cascaded devices, no inductance.
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STRINGFELLOW, M.F. and STONELY, B.T., "Coordination of Surge Suppressors in Low-Voltage AC Power Circuits," *Proceedings, Forum on Surge Protection Application, NISTIR-4657*, August 1991.
- Experiments showing the effect of line length and impinging surge waveform on sharing energy between service entrance arrester and surge suppressor inside building.
- Metal-oxide varistors were applied at three points on the system. These were at the service entrance, at the distribution panel and at the load.
- Removal of protection at either load or distribution panel resulted in unacceptably large oscillatory voltages. Best load protection was achieved with MOVs in all three locations.
- 4 references