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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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

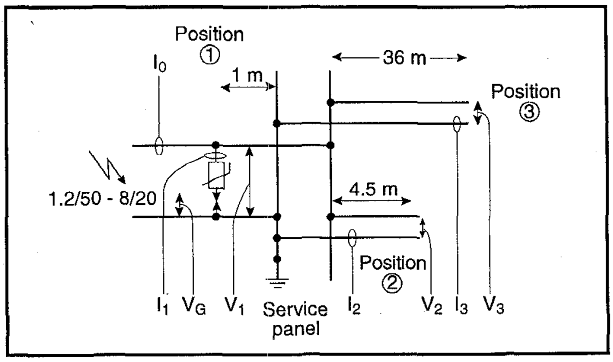
This gapped arrester will use a varistor with a limiting voltage lower than that of the downstream SPDs (in all the following text, "varistor" is to be understood as short-hand for metal-oxide varistor). The gap in series prevents steady-state application of the line voltage which the varistor cannot 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)

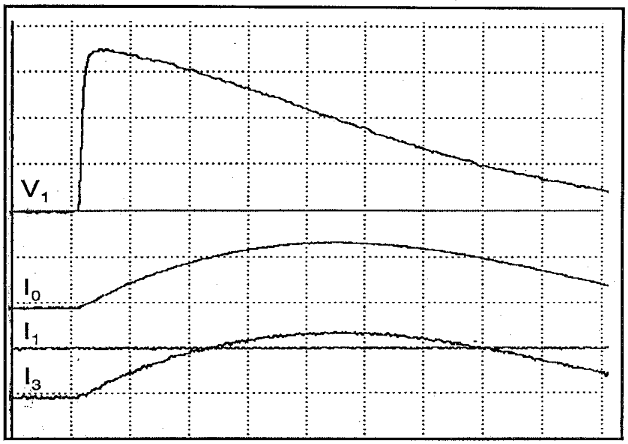
In our replica, the power wiring uses the conventional non-metallic jacket, 2-conductor plus equipment grounding conductor (2 mm dia., AWG #12). The gapped arrester, suitable for a 120/240-V system voltage, consisted of a varistor in series with a gas tube. The downstream SPD was a typical varistor used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

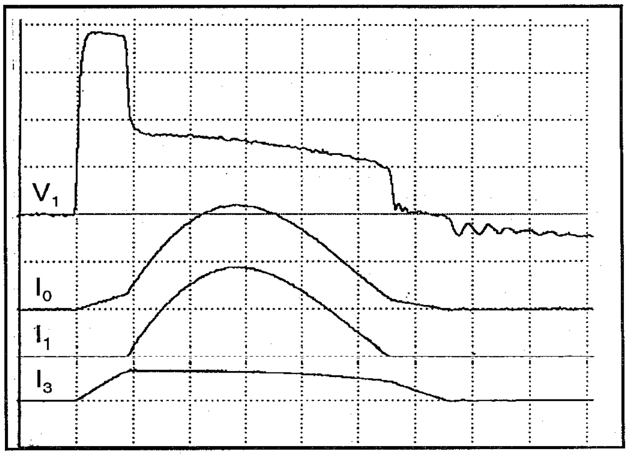


From top to bottom traces (5 μs/div sweep):
V_1 - 200 V/div: 700 V peak
I_0 - 100 A/div: 140 A peak
I_1 - 100 A/div: No current in arrester
I_3 - 100 A/div: 140 A peak (= I_0)

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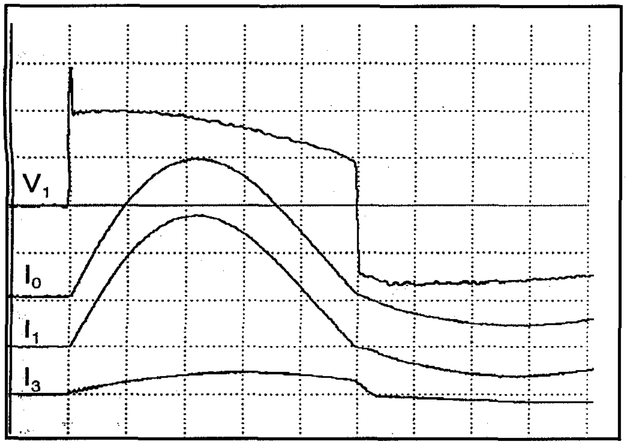
† *The measurements reported in this paper have been made with instrumentation for which the combined uncertainty should not exceed ±5% to ±6%. Given the process of applying the measurement results to the response of surge-protective devices exposed to environments with characteristics that are at best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



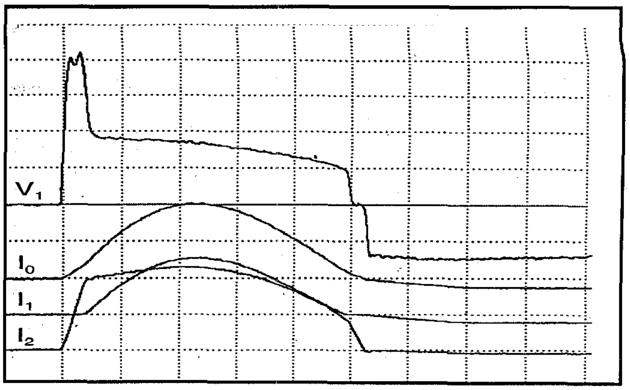
From top to bottom traces (5 µs/div sweep):

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).

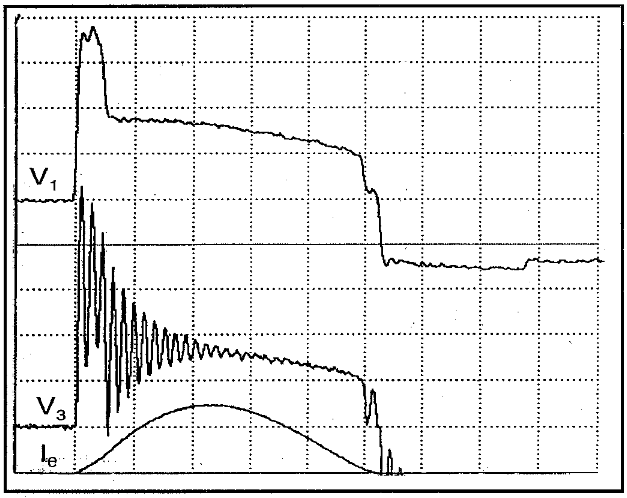
In the scenario of Figure 6, the long branch circuit was left open at Position ③, producing a ringing caused by reflections and undamped oscillations at that end. In this test, the driving voltage V_1 developed at the upstream gapped arrester (Position ①) is only 730 V, but the voltage at the end of 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_0 - 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.

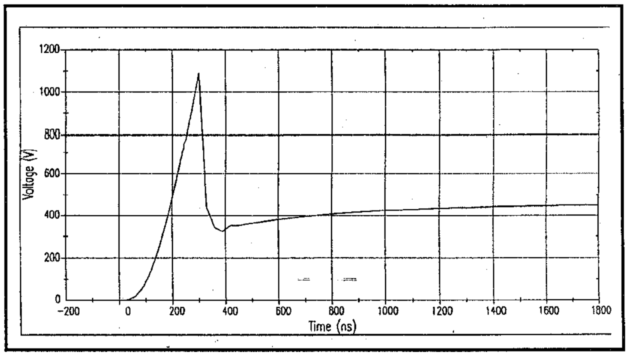
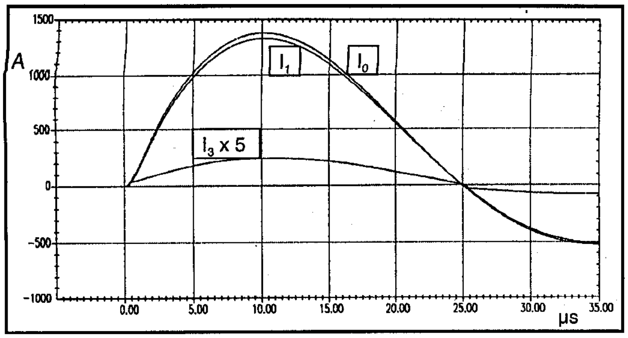


Figure 7 - Model plot of the voltage across arrester, for conditions similar to those of Figure 4. (See also Figure A.2 in the Appendix)



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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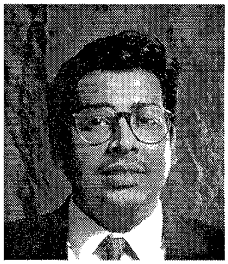

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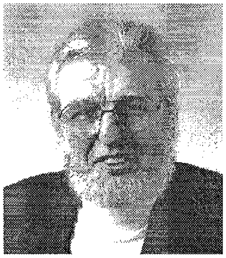

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APPENDIX

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

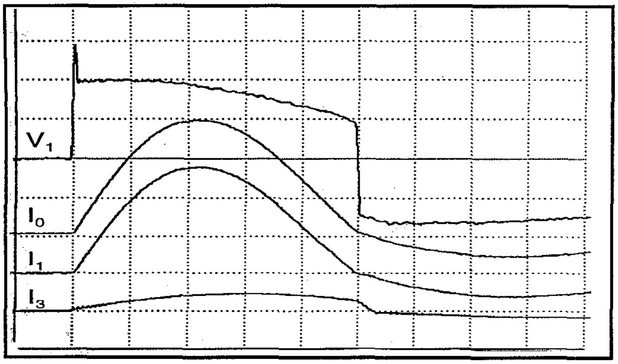
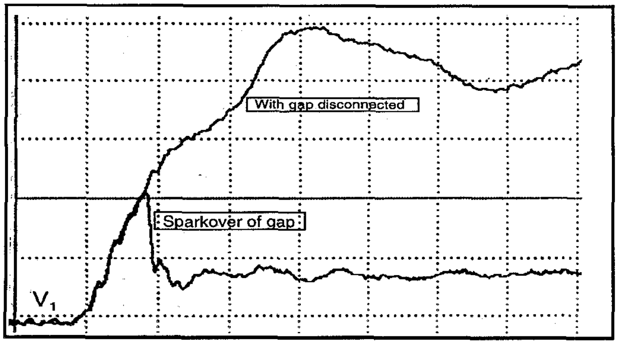


Figure A.1 (Same traces as Figure 4): The peak of trace V_1 is not completely resolved because the sampling rate made necessary by the desire to show a 100 µs window did not provide enough data points around the peak.

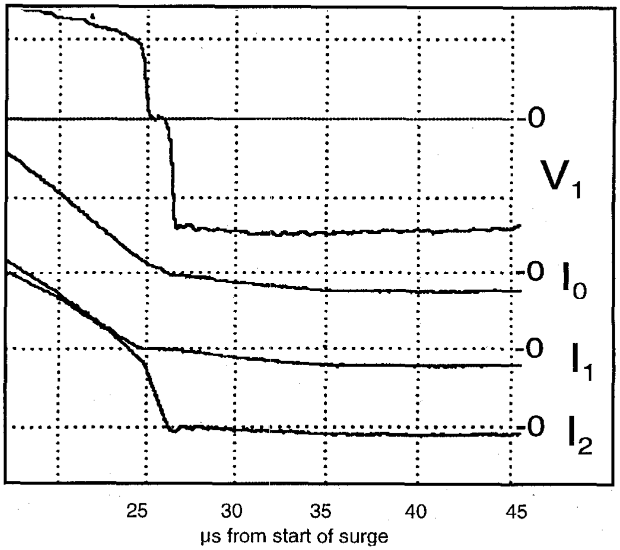


Top trace: Voltage with gap disconnected
Bottom trace: Voltage with gap reconnected
(500 V/div, 200 ns/div)

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