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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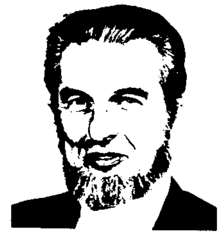

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Abstract - *Cascading two or more surge-protective devices located respectively at the service entrance of a building and near the sensitive equipment is intended to ensure that each device shares the surge stress in an manner commensurate with its 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.

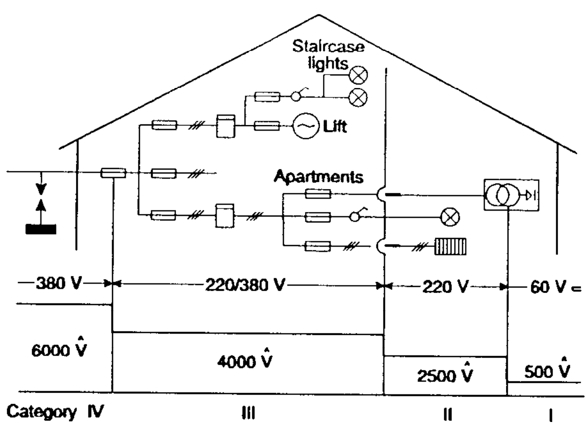

Figure 1
Installation Categories according to IEC Pub 664-1980 [3]

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).

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

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.

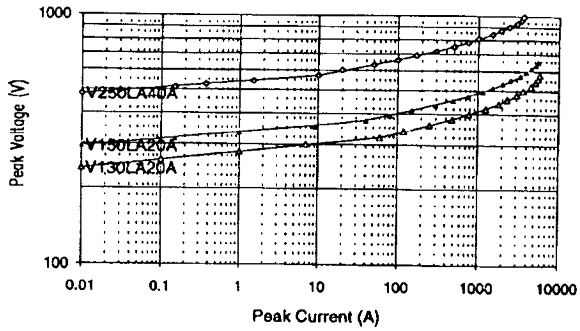

Figure 2
MOV characteristics obtained from modeling results

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.

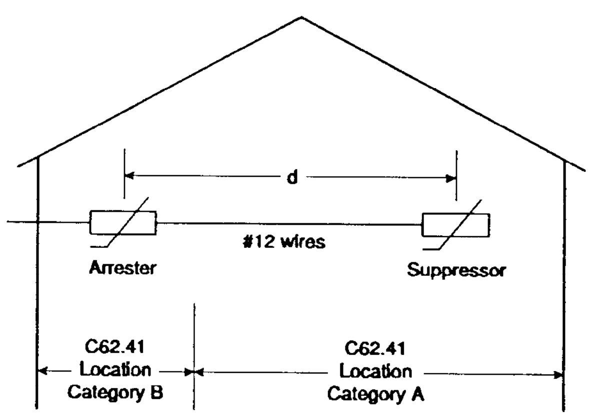

Figure 3
Configuration of a two-stage cascade

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.

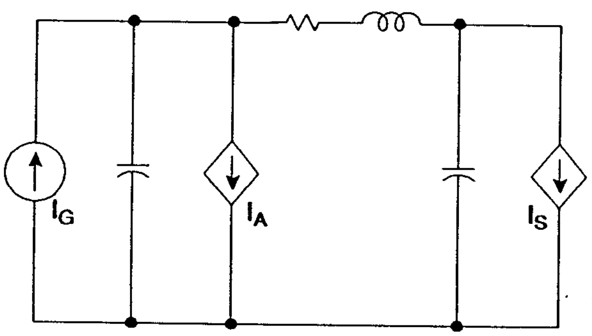

Figure 4
Circuit model for a two-stage cascade

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.

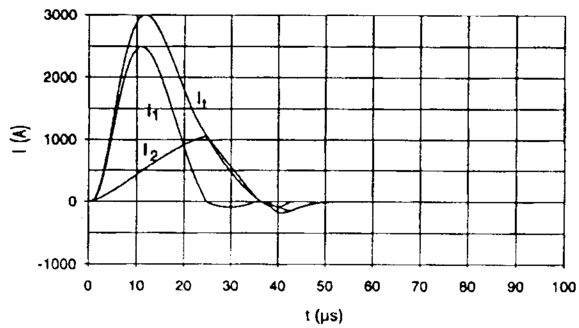

Figure 5
Simulated current responses for 250 V - 130 V cascade, 10 m separation, 8/20 μs applied surge

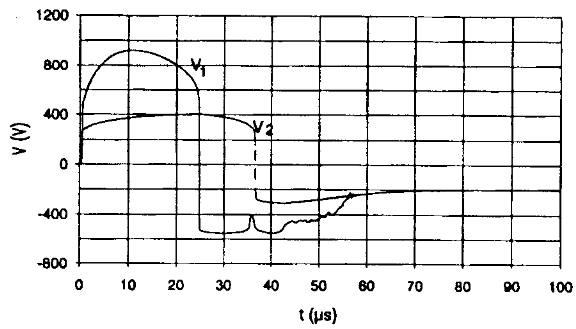

Figure 6
Simulated voltage responses for 250 V - 130 V cascade, 10 m separation, 8/20 μs applied surge

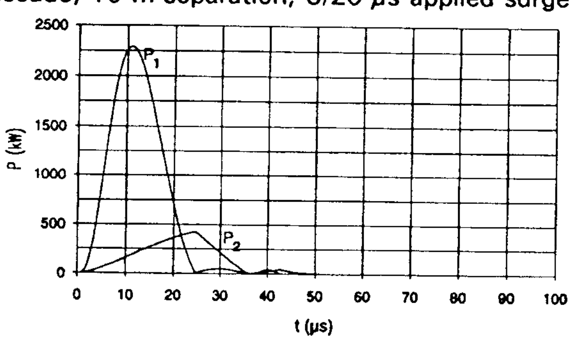

Figure 7
Simulated dissipated power for 250 V - 130 V cascade, 10 m separation, 8/20 μs surge

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
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	39.8	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.

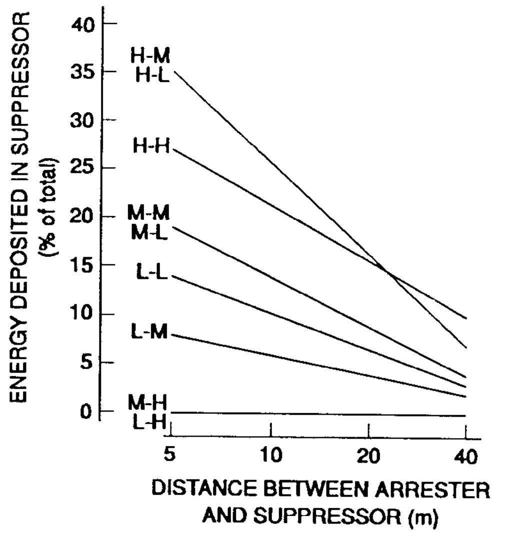

Figure 8
Relative energy deposited by an 8/20 μs Wave in the suppressor for arrester-suppressor combinations of 250 V (H), 150 V (M), or 130 V (L) ratings, as a function of separation distance

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.

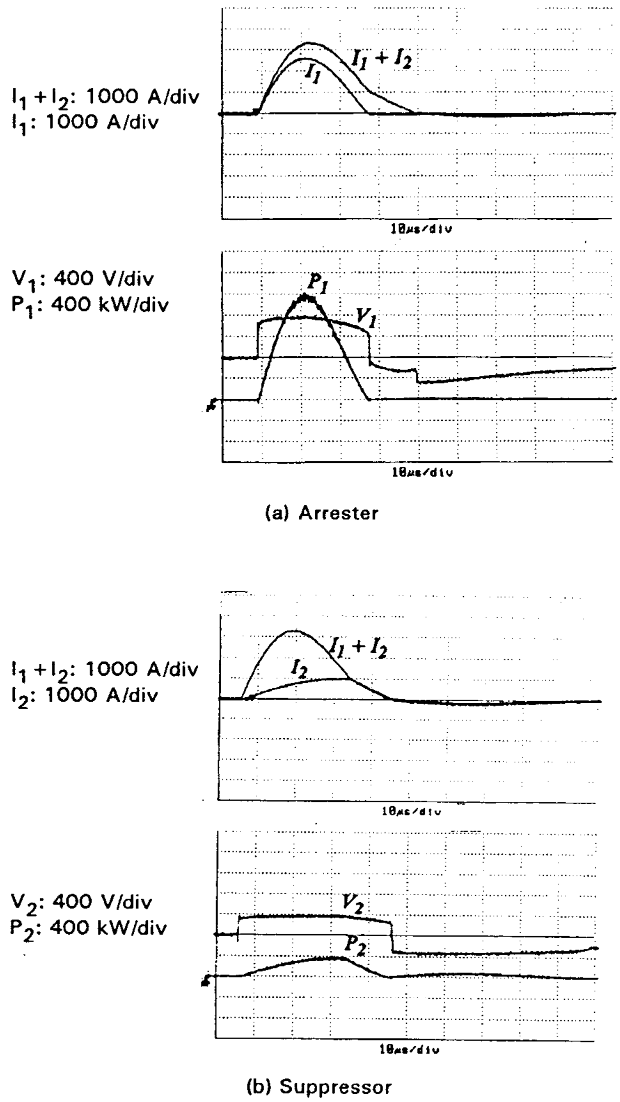

Figure 9
Experimental results for the 250 V-130 V, 10-m apart cascade condition.

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.

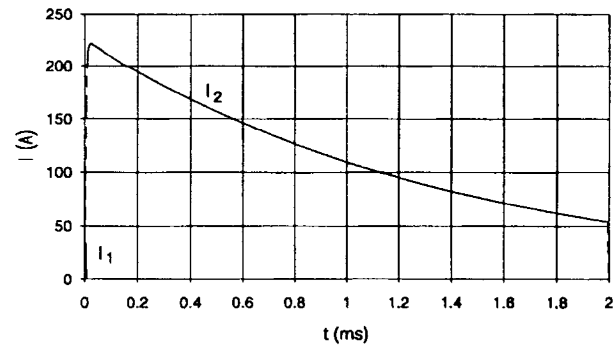

Figure 10
Simulated current responses for 250 V - 130 V cascade, 10 m separation, 10/1000 µs surge

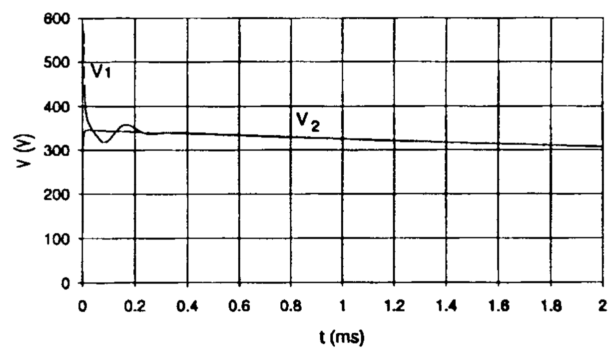

Figure 11
Simulated voltage responses for 250 V - 130 V cascade, 10 m separation, 10/1000 µs surge

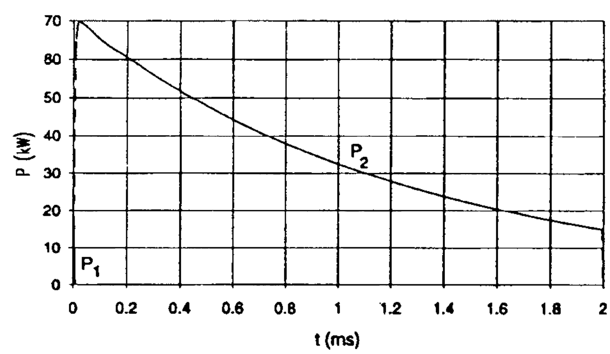

Figure 12
Simulated dissipated power for 250 V - 130 V cascade, 10 m separation, 10/1000 µs surge

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	47.3	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

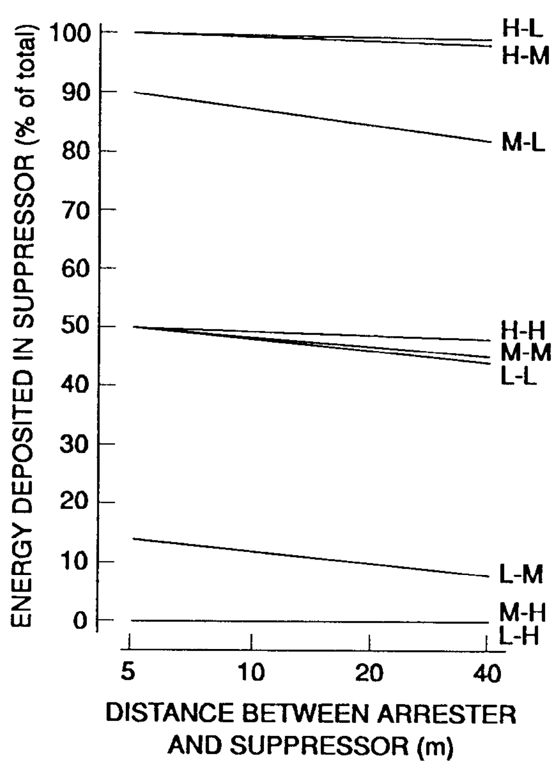

Figure 13
Relative energy deposited by a 10/1000 μs Wave in the suppressor for arrester-suppressor combinations of 250 V (H), 150 V (M), or 130 V (L) ratings, as a function of separation distance

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.

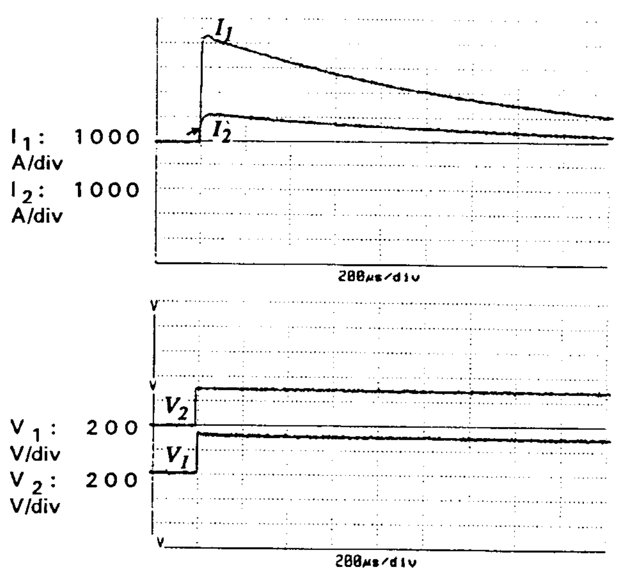

Figure 14
Experimental results for a 130 V - 150 V, 10-m apart cascaded condition with 10/1000 Wave.

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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