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

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***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.

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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

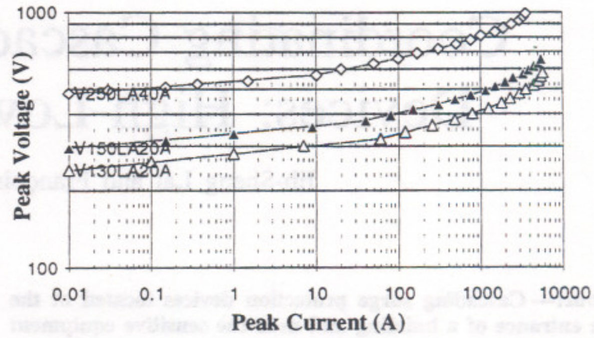

Fig. 1. MOV characteristics obtained from modeling results.

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 $\pm$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 $\times$ 1.1 = 143 and 150 $\times$ 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.

[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.

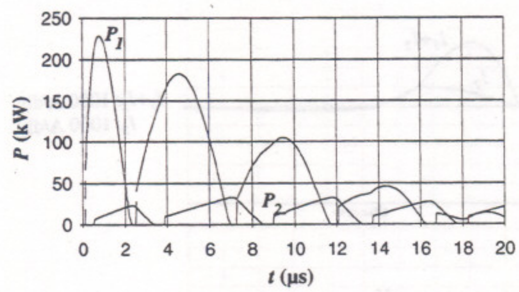

Fig. 10. Simulated Ring Wave instantaneous power for the 250–130 V cascaded devices 10-m that are apart.

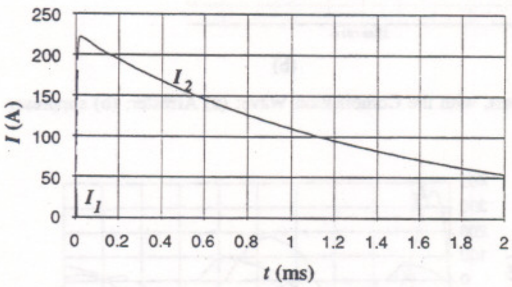

Fig. 11. Simulated Long Wave current responses for the 250–130 V cascaded devices that are 10-m apart.

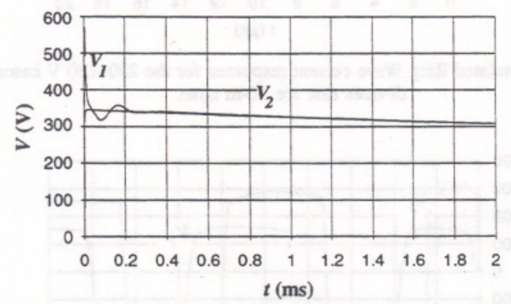

Fig. 12. Simulated Long Wave voltage responses for the 250–130 V cascaded devices that are 10-m apart.

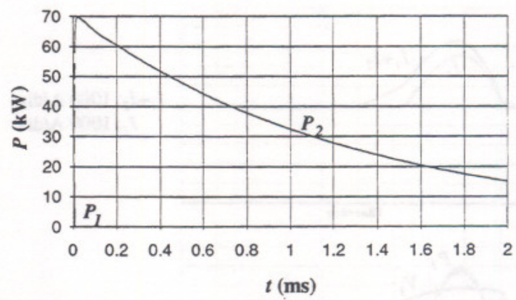

Fig. 13. Simulated Long Wave power responses for the 250–130 V cascaded devices that are 10-m apart.

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*

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.

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.

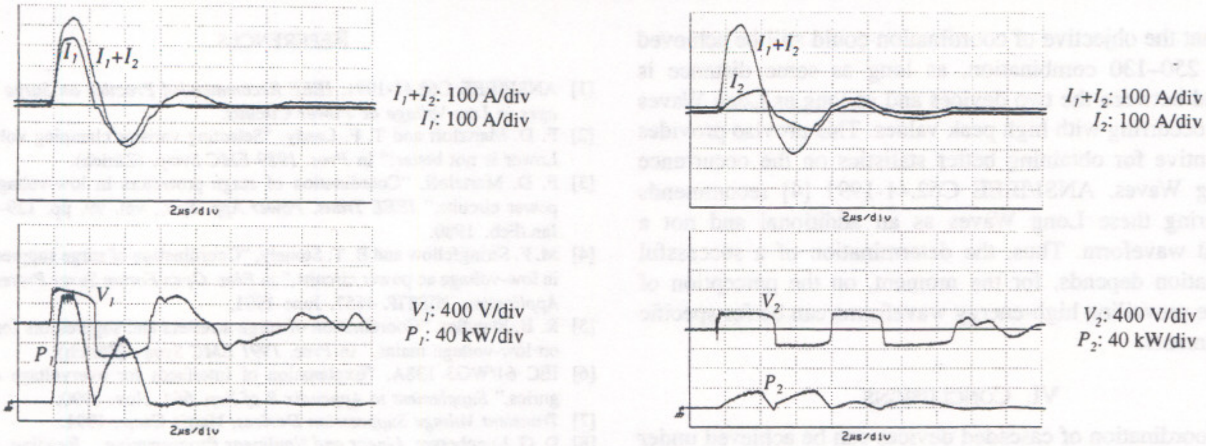

Fig. 14. Experimental results for the 250–130 V cascade, with devices that are 10-m apart, with the Ring Wave: (a) Arrester; (b) suppresor.

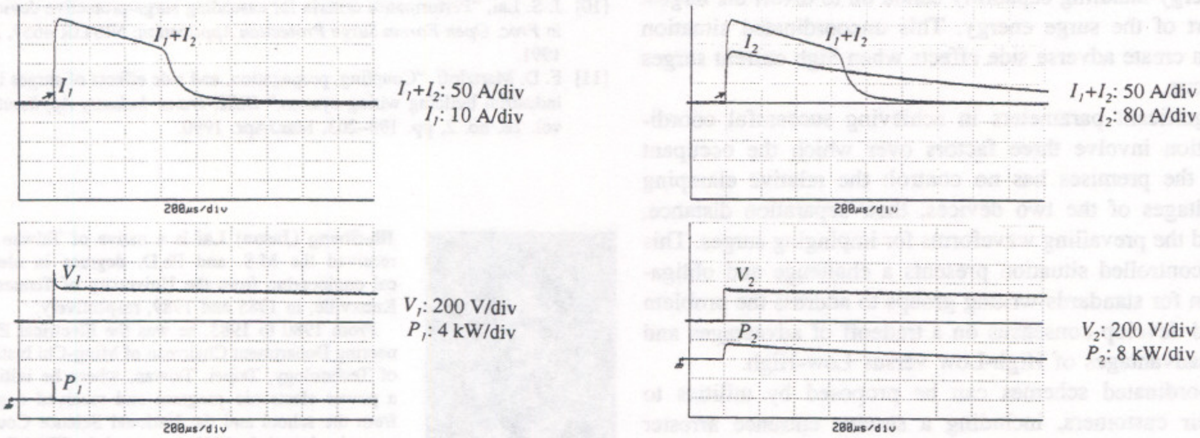

Fig. 15. Experimental results for the 250–130 V cascade, with devices that are 10-m apart, with the Long Wave: (a) Arrester; (b) suppresor.

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.

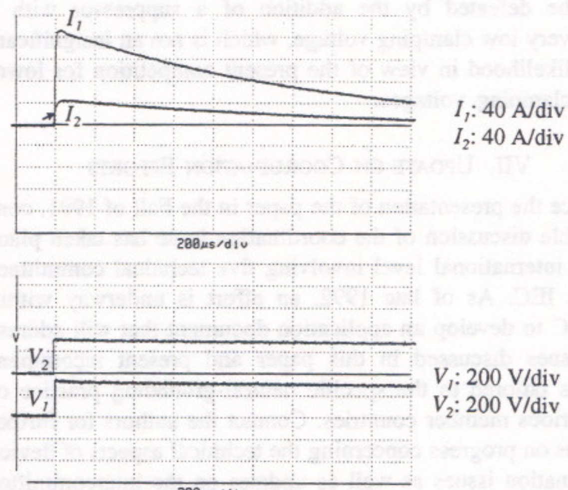

Fig. 16. Experimental results for the 130–150 V cascade, with devices that are 10-m apart, with the Long Wave.

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 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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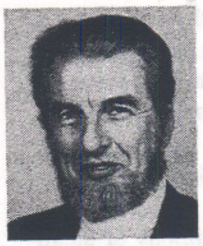

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