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

François Martzloff
Corporate Research and Development
General Electric Company
Schenectady, New York, USA
f.martzloff@ieee.org

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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

F.D. Martzloff

Corporate Research and Development
General Electric Company
Schenectady, New York, USA

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.

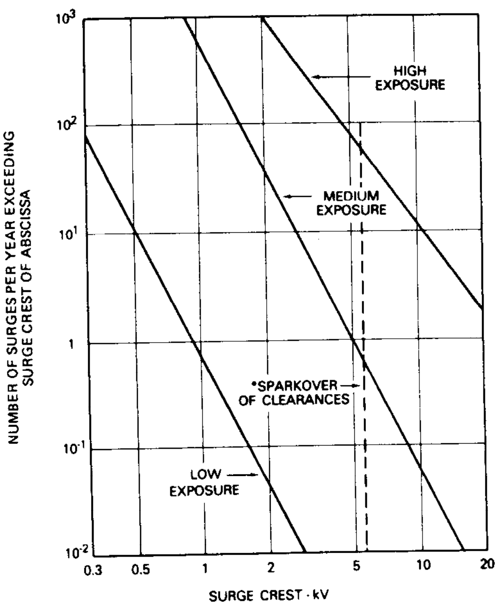
The IEEE Guide (IEEE Std 587-1980)

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.

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.



*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 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).

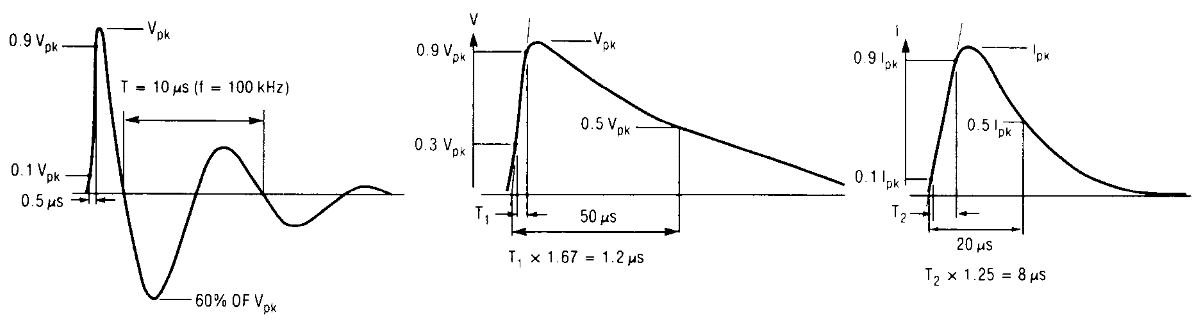
MATCHING THE ENVIRONMENT WITH THE EQUIPMENT

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

* 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.

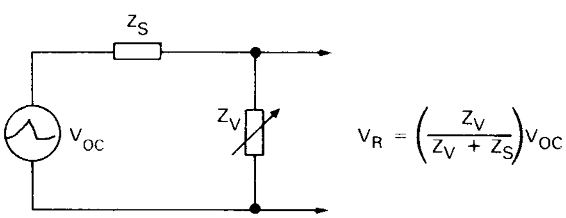


Figure 3. Voltage clamping action of a suppressor

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

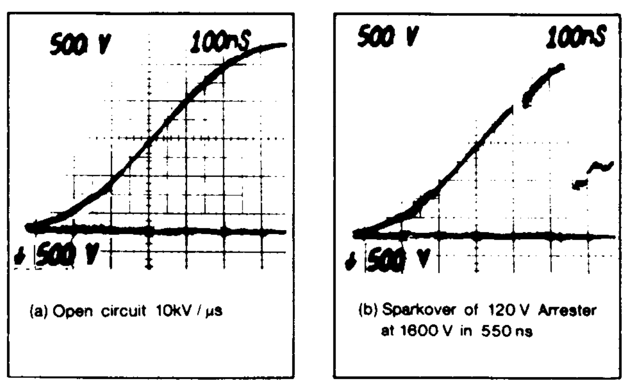


Figure 4. Interference to oscilloscope circuits caused by gap sparkover

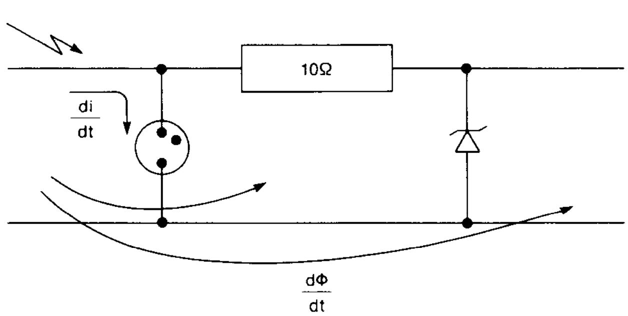


Figure 5. Hybrid protector with gap

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: Waveform	Impulse: Medium Exposure Amplitude	Type of Specimen or Load Circuit	Energy (joules) Deposited in a Suppressor* with Clamping Voltage of 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.

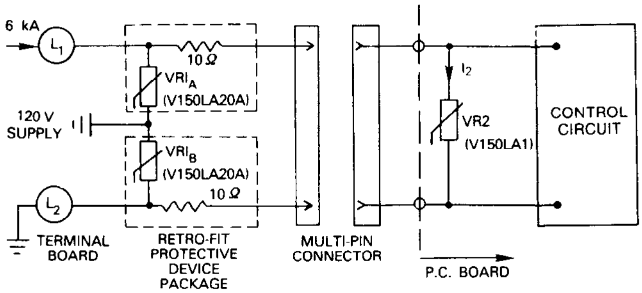
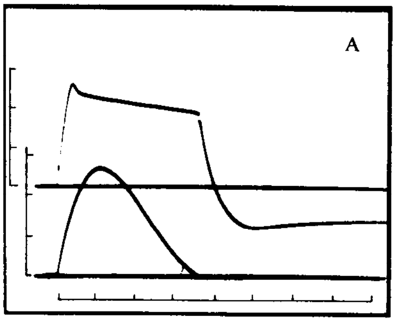


Figure 6. Retrofit protection of control circuit

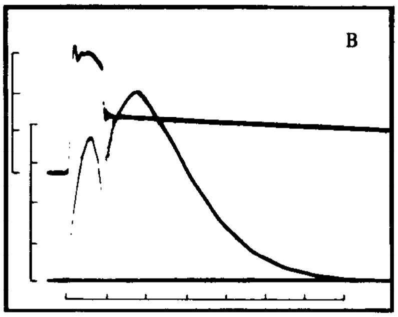
Coordination Between a Secondary Surge Arrester and a Varistor

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.

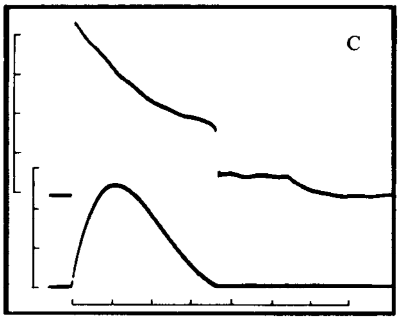
A circuit was set up in the laboratory (13), with 8 m (24 ft) of #12 (2.05 mm) two-wire cable between the arrester and the varistor. The current, approximately 8/20 μs impulse, was raised until the arrester would spark-over about half of the time in successive tests at the same level, thus establishing 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

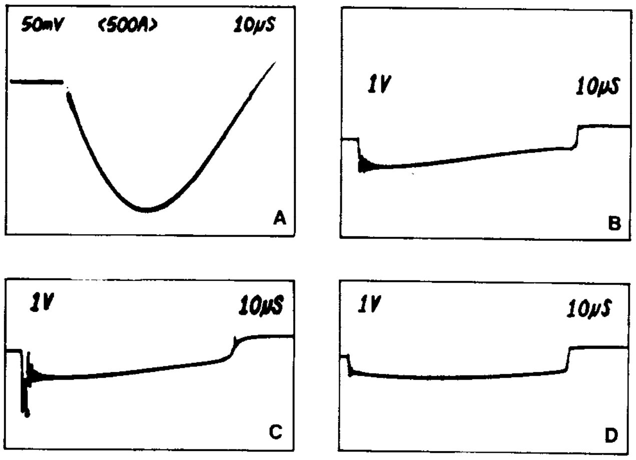


Figure 8. Transfer of conduction in a coordinated scheme of protection

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

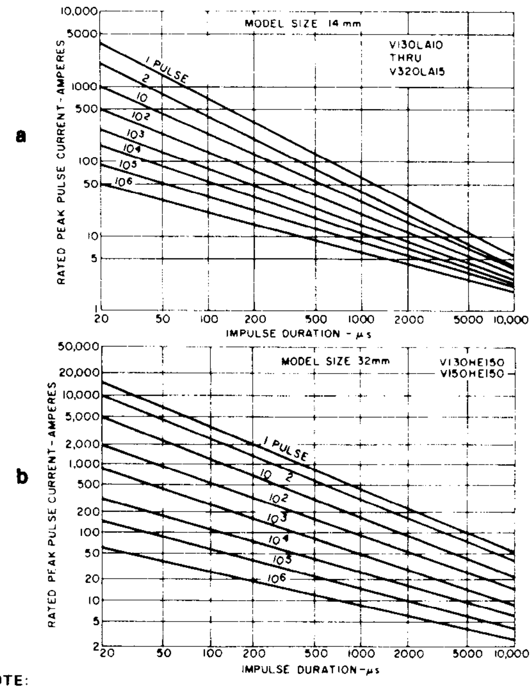
Cumulative life consumption per year 0.43
Time to reach rated life, years 232

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.

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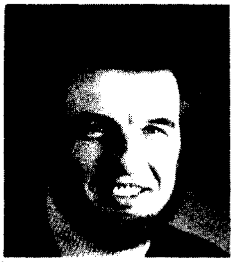

François D. Martzloff (M'56) was born in France, and received his undergraduate degree at the Ecole Spéciale De Mécanique et D'Electricité in 1951; he received the MSEE degree from Georgia Tech in 1952 and the MSIA degree from Union College in 1971.

Since 1956 he has been with the General Electric Company, where he 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 is active on the Surge Protective Devices Committee. He is chairman of the Working Group on Surge Characterization in Low-Voltage Circuits. He is also a member of the Ad Hoc Advisory Subcommittee of the USA Advisory Committee on IEC S/C 28A and ANSI C.62 Subcommittee on Low-Voltage Surge Protective Devices. He has been awarded 10 U.S. patents, primarily in the field of varistors and transient protection.