Surge Protection Techniques in Low-Voltage AC Power Systems

François D. Martzloff
General Electric Company
Schenectady NY

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Significance
Part 6: Tutorials, textbooks and reviews

A tutorial review paper describing the origins of surge voltages and the standardization efforts to characterize these surges.

The principles of operation are described for "crowbar devices" (now generally described under the standardized name of "voltage switching devices") and for "voltage clamping devices: (now generally described under the standardized name of "voltage limiting devices"). Failure modes are aslo discussed.

Briefly mentions one of the early experiments to investigate the coordination between a voltage-switching arrester and a downstream varistor that gained growing recognition in the eighties and nineties. That subject is addressed by several subsequent papers in Part 8 of the SPD Anthology.

SURGE PROTECTION TECHNIQUES IN LOW-VOLTAGE AC POWER SYSTEMS

F.D. Martzloff

Corporate Research and Development
General Electric Company

ABSTRACT

Designers involved in the ac power side of telecommunications equipment have been justifiably concerned with surge protection because field experience is rich in case histories of failures attributable to transient overvoltages. Insufficient knowledge of the exact nature of these overvoltages, however, has made their task difficult in the past. After several years of data collection by a number of organizations, a more definitive understanding of the surge environment is emerging. The next few years' publications from the IEEE, the IEC, NEMA, and other interested groups will document that understanding. This paper presents an overview of the results of data collection and environment descriptions from the point of view of telecommunications power supply problems, as well as a review of applicable techniques and devices.

INTRODUCTION

From the early days of the introduction of semiconductors, voltage surges have been blamed for device failures and system malfunctions. Silicon semiconductors are, indeed, sensitive to overvoltages, more so than their predecessors, such as the obsolete copper oxide or selenium rectifiers. From an early period of frustration and poor knowledge of the actual environment, progress has been made both in the area of defining the environment and of providing new surge protective devices and techniques to deal effectively with the problem.

Recent progress in the technology of transient voltage suppressors has opened new opportunities to improve the level of protection of semiconductors exposed to power system transients. In the past, direct exposure to outdoor system surges required surge arresters with high energy capability to survive the discharge currents associated with direct or indirect lightning effects, at the cost of voltage-clamping levels that were too high to protect sensitive semiconductors. The approach at that time was a coordinated combination of arresters and low-voltage suppressors, an approach that is still valid in many cases. It is now possible, however, to apply a single suppressor, with sufficient capability to withstand outdoor surges while clamping at a level low enough to protect power semiconductors such as power supply rectifiers. Examples of coordinated protection as well as the application of high power surge suppression devices, with experimental verification of performance, will be given in the paper.

THE ORIGIN OF SURGE VOLTAGES

Two major causes of surge voltages 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 destructive and for which economical protection may be difficult to obtain). System switching transients can involve a substantial part of the power system, as in the case of power-factor-correction capacitor switching operations, disturbances that follow the restoration of power after an outage, or load shedding. However, these disturbances do not generally involve substantial overvoltages (more than two or three per unit), but they may be very difficult to suppress because the energies are high. Local load switching, especially if it involves restrikes in the switchgear devices, will produce higher voltages than the power system switching, but generally at lower energy levels. Considering the higher impedances of the local systems, the threat to sensitive electronics is quite real: the few conspicuous case histories of failures blemish the record of a large number of successful applications.

Lightning-Induced Surges

The phenomenon of lightning has been the subject of intensive study by many workers. The behavior of lightning is now fairly predictable in general terms, but the exact knowledge of specific incidents is not predictable. Protection against lightning effects includes two categories: 1. *direct effects* concerned with the energy, heating, flash, and ignition of the lightning current, and 2. *indirect effects* concerned with induced overvoltages in nearby electrical and electronic systems.

One of the major factors to consider in determining the probability of lightning damage, and thus the need for strong protection, is the number of lightning flashes to earth in a given area for a given time. Such statistics are not generally available; instead the number of "thunderstorm days" is quoted. However, the term "thunderstorm days" includes cloud-to-cloud discharges and does not include the duration and intensity of each storm. Thus it does not represent an accurate parameter. Progress is being made to improve statistics, but new statistics are not yet available; therefore, the "isokeraunic level" map (1), showing the number of storm days per year, is still the most widely used description of the occurrence distribution (2).

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Switching Surges

A transient is created whenever a sudden change occurs in a power circuit, especially during power switching – either closing or opening a circuit. It is important to recognize the difference between the intended switching – that is, the mechanical action of the switch – and the actual happening in the circuit. During the closing sequence of a switch the contacts may bounce, producing openings of the circuit with reclosing by restrikes and reopening by clearing at the high-frequency current zero. Likewise, during an opening sequence of a switch, restrikes can cause electrical closing(s) of the circuit.

Simple switching transients (3) include circuit closing transients, transients initiated by clearing a short-circuit, and transients produced when the two circuits on either side of the switch being opened oscillate at different frequencies. In circuits having inductance and capacitance (all physical circuits have at least some in the form of stray capacitance and inductance) with little damping, these simple switching transients are inherently limited to twice the peak amplitude of the steady-state sinusoidal voltage. Another limit to remember in analyzing transients associated with current interruption (circuit opening) is that the circuit inductance tends to maintain the current constant. At most, then, a surge protective device provided to divert the current will be exposed to that initial current.

Several mechanisms generating abnormal switching transients are encountered in practical power circuits. These mechanisms can produce overvoltages far in excess of the theoretical twice-normal limit mentioned above. Two such mechanisms occur frequently: current chopping and restrikes, the latter being especially troublesome when capacitor switching is involved.

These switching overvoltages, high as they may be, are somewhat predictable and can be estimated with reasonable accuracy from the circuit parameters, once the mechanism involved has been identified. There is still some uncertainty as to where and when they occur because the worst offenders result from some abnormal behavior of a circuit element. Lightning-induced overvoltages are even less predictable because there is a wide range of coupling possibilities. Moreover, one user, assuming that his system will not be the target of a direct hit, may take a casual view of protection while another, fearing his system will experience a "worst case," may demand the utmost protection.

In response to these concerns, various committees and working groups have attempted to describe ranges of transient occurrences or maximum values occurring in power circuits. These transients include both surge voltages and surge currents, although the primary emphasis is generally given to surge voltages.

EXISTING AND PROPOSED STANDARDS ON TRANSIENT OVERVOLTAGES

Several Standards or Guides have been issued or proposed – in Europe by VDE, IEC, CECC, Pro-Electron, and CCITT; in the USA by IEEE, NEMA, UL, REA, FCC, and the Military – specifying a surge withstand capability for specific equipment or devices and specific conditions of transients in power or communication systems. Some of these specifications represent early attempts to recognize and deal with the problem in spite of insufficient data. As a growing number of organizations address the problem and as exchanges of information take place, improvements are being made in the approach. A Working Group of the Surge Protective Device Committee of IEEE has completed a document describing the environment in low-voltage ac power circuits (4). The document is now being reviewed by the IEEE Standards Board for eventual publication as a standard. For some time now, a document prepared by a Relaying Committee of IEEE under the title "Surge Withstand Capability" has been available (5). The FCC has also published regulations concerning equipment interfacing the communications and power systems (6). The Low Voltage Insulation Coordination Subcommittee, SC/28A, of IEC has also completed a report, to be published in 1979, listing the maximum values of transient overvoltages to be expected in power systems, under controlled conditions and for specified system characteristics (7). These documents will be reviewed in the pages that follow. Greatest emphasis, however, will be placed on the IEEE document because it describes the transient environment; the others assume an environment for the purpose of specifying tests.

The IEEE Surge Withstand Capability Test

One of the earliest published documents to address new problems facing electronic equipment exposed to power system transients was prepared by an IEEE committee dealing with the exposure of power system relaying equipment to the harsh environment of high-voltage substations. This document, which describes a transient generated by the arcing that takes place when air-break disconnect switches are opened or closed in the power system, presents significant innovations in surge protection. The voltage waveshape specified is an oscillatory waveshape, not the historical unidirectional waveshape; a source impedance, a characteristic undefined in many other documents, is defined; and the concept that all lines to the device under test must be subject to the test is spelled out.

Because this useful document was released at a time when little other guidance was available, users attempted to apply the document's recommendations to situations where the environment of a high-voltage substation did not exist. Thus, an important consideration in the writing and publishing of documents dealing with transients is a clear definition of the scope and limitations of application.

Federal Communications Commission Requirements

The Federal Communications Commission (FCC) has issued regulations describing tests to be applied to equipment interfacing the power distribution system and the communication system. The intent of these tests is protection of the equipment itself as well as protection of the communications plant from surges originating on the ac power side of the equipment. This concern is especially motivated by the recent proliferation of terminal equipment being installed by telephone service subscribers.

The most exacting test specified by these regulations is the application on the ac side of equipment to be connected to the telephone system of a 1 x 10 µs impulse superimposed to the 60 Hz line voltage. The crest of this voltage impulse is 2.5 kV, and the short-circuit capability of the impulse source must be no less than 1 kA. This requirement of a substantial short-circuit capability reflects the perceptions of contributors to the regulation-making process that such surge currents may occur *in the real world*, or it may express a wish to produce *in the laboratory* a detectable burn-in of the fault following sparkover during the application of the surge. Records on the background of this regulation available to the author are not specific on which of the two concerns was primary in the specification of such a high short-circuit capability.

The IEC SC/28A Report on Clearances

The Insulation Coordination Committee of the International Electrotechnical Commission, following a comprehensive study of breakdown characteristics in air gaps, included in its report a table indicating the voltages that equipment must be capable of withstanding in various system voltages and installation categories (Table I).

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:	Preferred Series of Impulse Withstand Voltages in Installation Categories			
(V rms and dc)	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	12 000

The table specifies that it is applicable to a "controlled voltage situation," which phrase implies that some surge-limiting device will have been provided – presumably a typical surge arrester with characteristics matching the system voltage in each case. The waveshape specified for these voltages is the 1.2 x 50 µs wave, a specification consistent with the insulation background of the equipment. No source impedance is indicated, but four "installation categories" are specified, each with decreasing voltage magnitude as the installation is farther removed from the outdoor environment. Thus, this document addresses primarily the concerns of insulation coordination, and the specification it implies for the environment is more the result of efforts toward coordinating levels than efforts to describe the environment and the occurrence of transients. The latter approach has been that of the IEEE Working Group on Surge Voltages in Low-Voltage ac Power Circuits, which we shall now review in some detail.

The IEEE Working Group Proposal

Voltages and Rates of Occurrence

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

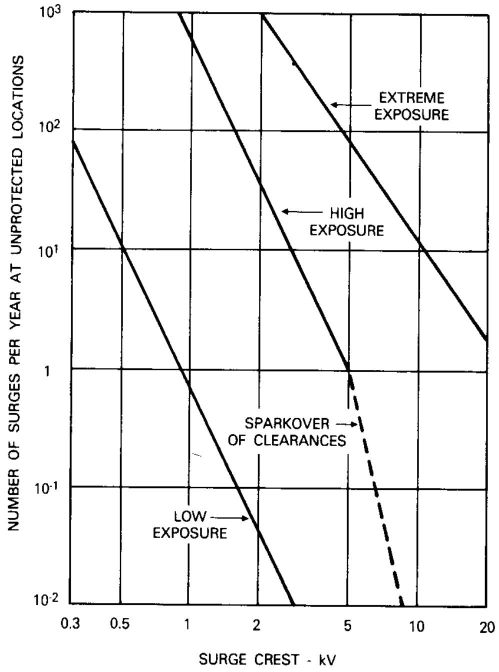
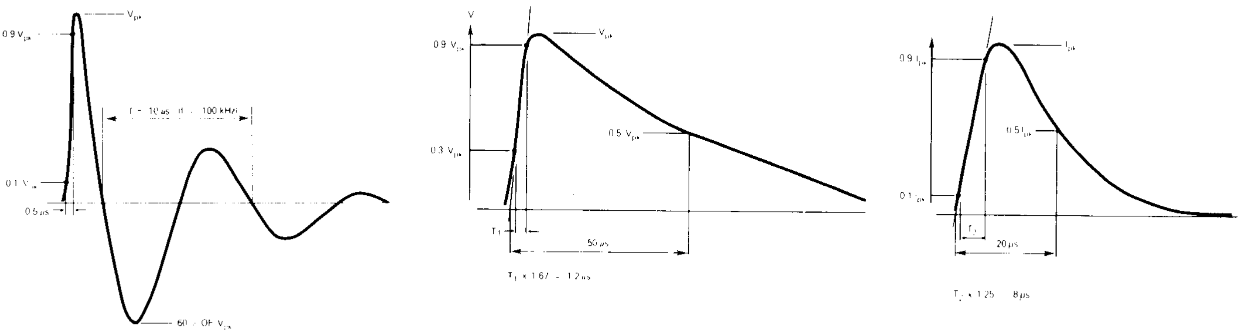


Figure 1. Rate of Surge Occurrence Versus Voltage Level

Both the low-exposure and high-exposure lines are truncated at about 6 kV because that level is the typical wiring device sparkover. The extreme-exposure line, by definition, is not limited by this sparkover. Because it represents an extreme case, the extreme-exposure line needs to be recognized, but it should not be applied indiscriminately to all systems. Such application would penalize the vast majority of installations, where the exposure is lower.

Waveshape of the Surges

Many independent observations (8, 9, 10) have established that the most frequent type of surge voltages 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 x 50. Indeed, 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 power transmission systems exposed to lightning. In order to combine the merits of both waveshape definitions and to specify them where they are applicable, the Working Group proposal specifies an oscillatory waveshape inside buildings and a unidirectional waveshape outside buildings, and both at the interface (Figure 2).



Open-Circuit Voltage,
Current Defined by
Table II

Open Circuit Voltage

Discharge Current

Indoor Environment

Outdoor and Near-Outdoor Environment

Figure 2. Proposed IEEE 587.1 Transient Overvoltages and Discharge Currents

Table II

SURGE VOLTAGES AND CURRENTS DEEMED TO REPRESENT THE INDOOR ENVIRONMENT AND RECOMMENDED FOR USE IN DESIGNING PROTECTIVE SYSTEMS

Location Category	Comparable to IEC SC28A Category	Impulse Waveform	Impulse High Exposure Amplitude	Type of Specimen or Load Circuit	Energy (joules) Deposited in a Suppressor with Clamping Voltage of 500V	Energy (joules) Deposited in a Suppressor with Clamping Voltage of 1000V
A. Long Branch Circuits and Outlets	II	0.5 µs - 100 kHz	6 kV 200 A	High Impedance$^{(1)}$ Low Impedance$^{(2)}$	-- 0.8	-- 1.6
B. Major Feeders, Short Branch Circuits, and Load Center	III	1.2 x 50 µs 8 x 20 µs	6 kV 3 kA	High Impedance$^{(1)}$ Low Impedance$^{(2)}$	-- 40	-- 80
		0.5 µs - 100 kHz	6 kV 500 A	High Impedance$^{(1)}$ Low Impedance$^{(2)}$	-- 2	-- 4

Notes: (1) 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.

(2) 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.

Energy and Source Impedance

The energy involved in the interaction of a power system with a surge source and a surge protective device will divide between the source and the protective device in accordance with the characteristics of the two impedances.

Unfortunately, not enough data have been collected on what value should be assumed for the source impedance of the surge. Standards and recommendations, such as MIL STD-1399 or the IEC SC/28A Report, either ignore the issue or indicate values applicable to limited cases, such as the SWC test for high-voltage substation equipment. The IEEE 587.1 document attempts to relate impedance to categories of locations but unavoidably remains vague on their definitions (Table II).

Having defined the environment for low-voltage ac power circuits, the Working Group is now preparing an Application Guide, where a step-by-step approach, perhaps in the form of a flow chart (Figure 3), will outline the method for assessing the need for surge protection and selecting the appropriate device or system. Parallel work in other IEEE working groups preparing test specification standards (11) for surge protective devices will be helpful in this selection process. Other groups in the U.S., as well as the international bodies of IEC and CCITT, are now working toward further refinements and the reconciliation of different approaches.

SURGE PROTECTIVE DEVICES

Various devices have been developed for protecting electrical and electronic equipment against surge voltages. They are often called "transient suppressors" although, for accuracy, they should be called "transient limiters," "clamps," or "diverters" because they cannot really suppress transients; rather they limit surge voltages to acceptable levels or make them harmless by diverting the surge current to ground.

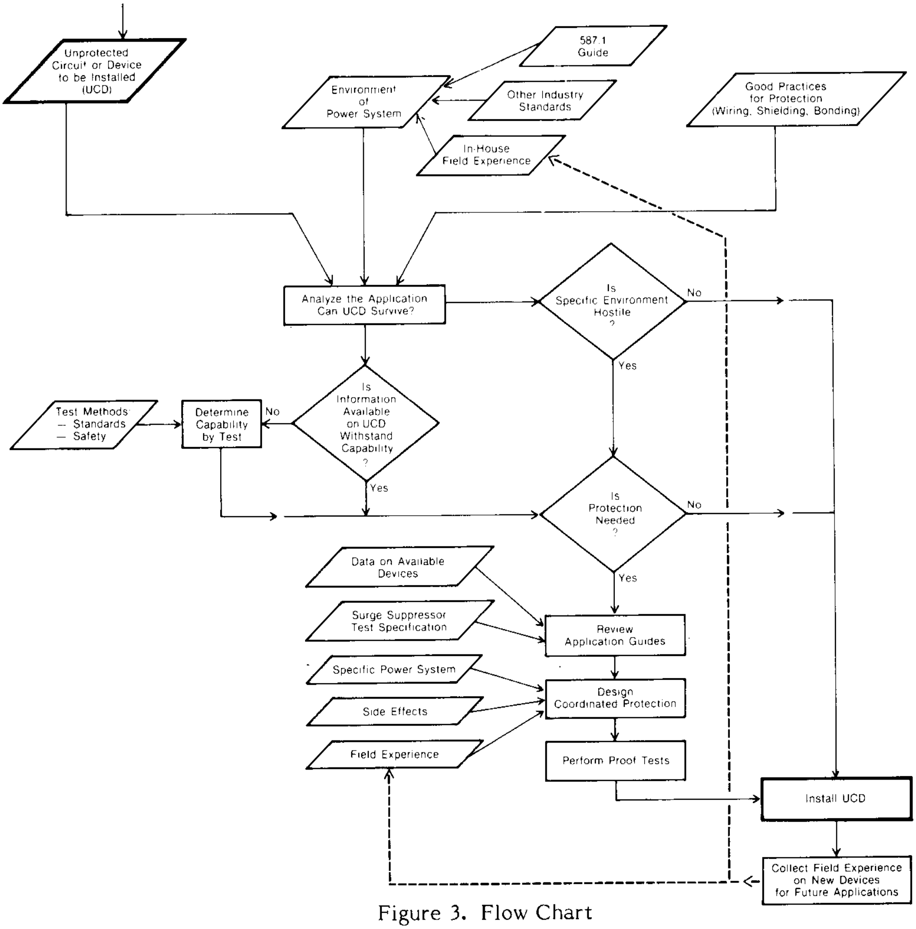


Figure 3. Flow Chart

There are two categories of surge protective devices: those that block the surge voltages, preventing their propagation toward sensitive circuits, and those that divert surge currents, limiting residual voltages. Since some of the surges originate from a current source, the blocking of a surge voltage may not always be possible; the diverting of the surge current is more likely to find general application. A combination of diverting and blocking can be a very effective approach: a first device diverts the surge current toward ground, a second device – impedance or resistance – offers a restricted path to the surge propagation but an acceptable path to the signal or power, and a third device clamps the residual transient overvoltage. Thus, we are primarily interested in the diverting devices. These diverting devices can be of two kinds: voltage-clamping devices and short-circuiting devices (crowbar). Both involve some nonlinearity, either frequency nonlinearity (as in filters) or, more usually, voltage nonlinearity. This voltage nonlinearity is the result of two different mechanisms – a continuous change in the device conductivity as current increases or an abrupt switching as voltage increases.

Crowbar Devices

The principle of crowbar devices is quite simple. Upon occurrence of an overvoltage, the device changes from a high-impedance state to a low-impedance state, offering a low-impedance path to divert the surge to ground. This switching can be inherent to the device, as in the case of spark gaps involving the breakdown of a gas or in solid state devices involving a switching action. Some applications have also been made of triggered devices, such as triggered vacuum gaps in high-voltage technology or thyristors in low-voltage circuits, where control circuits sense the rising voltage and turn on the power-rated devices to divert the surge.

The crowbar device, however, has two major limitations. One is the volt-time sensitivity of the breakdown process. As the voltage increases across a spark gap, significant conduction of current - and hence the voltage limitation of a surge – cannot take place until the transition to the arc mode of conduction by avalanche breakdown of the gas between the electrodes occurs. The load is left unprotected during the initial rise because of this delay time.

The most significant limitation to crowbar applications in power systems is the inability of the device to clear the circuit from the power-follow current supplied by the power system after the sparkover of the gap or turn-on of the device. Without some additional device to limit the power-follow current, a crowbar is generally not acceptable in a power system. On the other hand, a crowbar combined with a power frequency current-limiting varistor – the conventional surge arrester – has long been the most widely used protective device in power system.

Voltage-Clamping Devices

Voltage-clamping devices have variable impedance, depending on the current flowing through the device or the voltage across its terminal. These components show a nonlinear characteristic – that is, Ohm's law 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.

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. Nonlinear impedance is the result if this current rise is faster than the voltage increase. The increased voltage drop (IR) 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 to produce the clamping. A voltage divider action is at work, where one sees the ratio of the divider as not constant but changing (Figure 4).

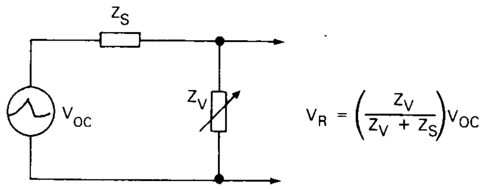


Figure 4. Voltage-Clamping Action of a Suppressor

The principle of voltage clamping can be achieved with any device exhibiting this nonlinear impedance. Two categories of devices, having the same effect but operating on very different physical processes, have found acceptance in the industry: the polycrystalline varistors and the single-junction avalanche diodes. Another technology, the selenium rectifier, has been practically eliminated from the field because of the improved characteristics of modern varistors.

Avalanche Diodes

Avalanche diodes, the Zener diodes, were initially applied as voltage clamps, a natural outgrowth of their application as voltage regulators. Improved construction, specifically aimed at surge absorption, has made these diodes very effective suppressors. Large-diameter junctions and low thermal impedance connections are used to deal with the inherent problem of dissipating the heat of the surge in a very thin single-layer junction.

The advantage of the avalanche diode, generally a PN silicon junction, is the possibility of achieving low clamping voltage and a nearly flat volt-ampere characteristic over its useful power range. Therefore, these diodes are widely used in low-voltage electronic circuits for the protection of 5 or 15 V logic circuits, for instance. For higher voltages, the heat generation problem associated with single junctions can be overcome by stacking a number of lower voltage junctions, admittedly at some extra cost.

In the same category, we find silicon diodes used in the *forward* direction rather than in the reverse avalanche. A stack of such diodes is required to produce the necessary clamping voltage (0.75 V per diode), but the result is a protective system with large current capability.

Varistors

The term varistor is derived from its function as a variable resistor. The European usage is the term *voltage-dependent resistor*, but the term seems to imply that the voltage is the independent parameter in surge protection, a concept which is misleading. Two very different devices have been successfully developed as varistors: silicon carbide discs have been used for years in the surge arrester industry; more recently, metal oxide varistors (MOV) have come of age, with the result that these new varistors are sometimes referred to as "movistors" (12).

Metal oxide varistors depend on the conduction process occurring at the boundaries between the large grains of oxide (typically zinc oxide) grown in a carefully controlled sintering process. Detailed descriptions of the process can be found in many publications (13, 14, 15, 16, 17).

Metal oxide varistors were initially developed as electronic circuit protection devices. Later large metal oxide varistors were developed and applied to large station surge arrestors (18). No device, however, was available in a rating suitable for power distribution systems. The surge currents occurring in these systems are excessive for electronic-type varistors, a fact demonstrated by field failures resulting from improperly applied varistors. Such failures could have been anticipated had the data included in the proposed IEEE Guide reviewed above been available at the time. In this context, it is worthwhile to examine the implication of failure modes for the surge protective devices.

Failure Modes

An electrical component is subject to failure either because its capability was exceeded by the applied stress or because some latent defect in the component went unnoticed in the quality control processes. While this situation is well recognized for ordinary components, a surge protective device, which is no exception to these limitations, tends to be expected to perform miracles, or at least to fail graciously in a "fail-safe" mode. The term "fail-safe," however, may mean different failure modes to different users and, therefore, should not be used. To some users, 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. It is more accurate and less misleading to describe failure modes as "fail-short" or "fail-open," as the case may be.

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 protective device is an important parameter to consider in the designing of 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 protectice device and thus applied to the protected circuit, but the error is directly reflected in the amount of energy which the protective device has to absorb. At worst, when surge currents in excess of the protective device capability are imposed by the environment, either 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).

PROTECTION COORDINATION

By protection coordination we mean a deliberate selection of two or more protective devices used with the goal of reliable protection at minimum cost. With the present situation of the unregulated and uncoordinated application of protective devices, this may seem an unattainable goal for complete systems. In specific cases, it is fully attainable, as the example that follows will show. One can hope that success will eventually spread the concepts and increase the drive to generalize the approach.

One of the first concepts to be adopted when a coordinated scheme is considered is that current, not voltage, is the independent variable involved. The physics of overvoltage generation involves 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. Furthermore, there is a long history of testing insulation with voltage impulses which 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 low-power systems, a series impedance is sometimes added in the circuit, but only after a low-impedance diverting path has first been established; for high-power systems, that option is generally not available.

Coordination Between an Arrester and a Varistor

This example involves a load circuit for which the maximum transient overvoltage had to be limited to 1000 V (on a 120 V ac line) although lightning surges were expected on the incoming service. The only arresters available at the time which could withstand a 10 kA crest, 8 x 20 µs impulse had a protective (clamping) level of approximately 2200 V. 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 testing objective was to determine at what current level 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 did not spark over.

A circuit was set up in the laboratory (19), with 8 m of typical two-wire cable between the arrester and the varistor. The current, approximately 8 x 20 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 5A shows the discharge current level required from the generator at which this transfer occurs. Figure 5B shows the voltage at the varistor when the arrester did not spark over. Figure 5C shows the voltage at the arrester when it sparked over, a voltage that would propagate inside all of the building if there were no suppressor added. However, when a varistor is added at 8 m, the voltage of Figure 5C is attenuated to that shown in Figure 5D, at the terminals of the varistor.

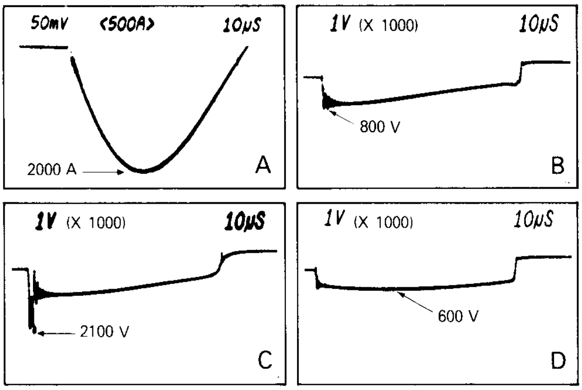


Figure 5. Transfer of Conduction in a Coordinate Scheme

Comparison Between a High-Energy Varistor and an Arrester/Low-Power Varistor

In the case of power circuits where no regulation or centralized engineering authority can madate a coordinated approach, individual protection of each piece of equipment may remain the only safe approach to the manufacturer of equipment installed under this uncontrolled situation. The choice of protection is then a question of economics and calculated risks: provide equipment with low-cost, low-capability protection, or with high-capability protection at a higher cost.

The first choice, low-cost, low-capability protection, will be effective in the vast majority of indoors locations, such as Category A, or even B, described in the proposed IEEE Guide (4); there is, however, a finite probability of failure if the equipment is installed close to the outdoor environment in a high-exposure location. An arrester installed at the service entrance would relieve the low-capability protection from absorbing excess energy. In that case, the situation explored in the experiment reported above would prevail: suitable coordination of the respective protective levels of the two devices and the impedance existing between them.

The second choice, provision of a high-capability protection in each piece of equipment, would obviously provide adequate protection and might be justified where the cost of equipment failure in terms of money, deadtime, or embarrassment outweighs the initial outlay of component investment. It is doubtful, however, that even mass-production could lower the cost of the high-capability device.

In the case of power circuits where a centralized engineering authority is in a position to enforce coordinated protection and practices, the appropriate procedure is evident and much more economical: provide a single high-capability protective device at the service entrance to deal with incoming lightning-induced surges and power system switching surges; if necessary, complement the protection with *coordinated* low-capability protective devices at individual pieces of equipment, to deal with any internal switching transients that may occur. Indeed, coordination of the two protective devices is imperative to prevent the low-capability (and low clamping voltage) device from clamping the incoming surge and thus absorbing all the energy.

Such coordination is now possible, since varistors with surge ratings to 25 kA for single surges and appropriate derating for multiple surges (11) have become available. This rating is higher than the requirements of ANSI Standards for secondary arresters (20, 21) and thus would be suitable for Category C (10 kA) of the proposed IEEE Guide. These high-capability varistors will clamp the voltage at a level sufficiently low – typically 600 V in a 120 V system under a surge of 10 kA, or 1100 V in a 240 V system for the same 10 kA surge (by comparison, conventional arresters have a protective level of 2 to 3 kV). The availability of low clamping voltage devices for both the high-energy service entrance duty and the low-cost individual equipment protection makes an effective coordination easy to achieve.

CONCLUSIONS

After many years of data collection and evaluation, a consensus is now emerging on the definition of the ac power system transient overvoltage environment, including both voltage and current levels.

This definition will enable protection engineeers in centralized organizations, such as those existing in the operating communications companies, to design coordinated schemes of protection, and will enable equipment designers and manufacturers to assess the risks involved in providing various levels of protection for their equipment on the basis of economic and functional criteria.

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