Transient Overvoltage Protection Coordination in the Undefined Real World Environment

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Significance
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This paper presents an overview or the origin of transient overvoltages and of current (1979)IEEE and IEC activities to identify and categorize transients. A brief review of available techniques and devices follows, and the major part of the paper describes the principles of coordinated protection with specific experimental examples and results reconciling the unknown with the realities of equipment design.

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Transient Overvoltage Protection Coordination in the Undefined Real World Environment

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TRANSIENT OVERVOLTAGE PROTECTION COORDINATION IN THE UNDEFINED REAL WORLD ENVIRONMENT

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ABSTRACT

Transient overvoltages are no longer an unknown threat to the successful application of power conversion equipment, and protective techniques and devices are available. The appropriate selection of these, however, remains a difficult task because the exact nature of transients in the real world is at best only statistically defined. Therefore, the choice involves technical and economic decisions based on calculated risks rather than deterministic optimization. In addition to this, protection in a complex system is required at more than one point of the circuits. Indiscriminate or uncoordinated application of devices at these several points may be wasteful or ineffective.

This paper presents an overview of the origin of transient overvoltages and of current IEEE and IEC activities to identify and categorize transients. A brief review of available techniques and devices follows, and the major part of the paper describes the principles of coordinated protection with 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 the unavoidable uncertainty as to what a specific power system can impress on a specific piece of power conversion equipment.

A Working Group of IEEE has prepared a Guide describing the nature of transient overvoltages *(surges)* in ac power circuits rated up to 600 V.[1] 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, a subcommittee of the IEC has developed a report concerning Insulation Coordination[2] and has recommended the use of 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 were 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 the 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 could lead to wasteful or ineffective resource allocation as 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 onto this situation, this paper will briefly review some of the origins of transient overvoltages, with reference to IEEE and IEC documents recently completed but not yet published that will 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, as these are generally quite destructive, and protection against these 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 substantial 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 the 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 a very adverse shadow over a large number of successful applications.

VOLTAGE LEVELS

Two different approaches have been proposed to define the voltage levels in ac power systems. At this time, the divergences have not yet been reconciled, as each proposal has its merits and justification. As proposed by the Working Group already mentioned, the IEEE approach involves reciting a rate of occurrence as a function of voltage levels as well as of exposure. The IEC approach indicates only a maximum level for each location category. These two proposals will be quoted in the following paragraphs.

The IEEE Working Group Proposal

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.

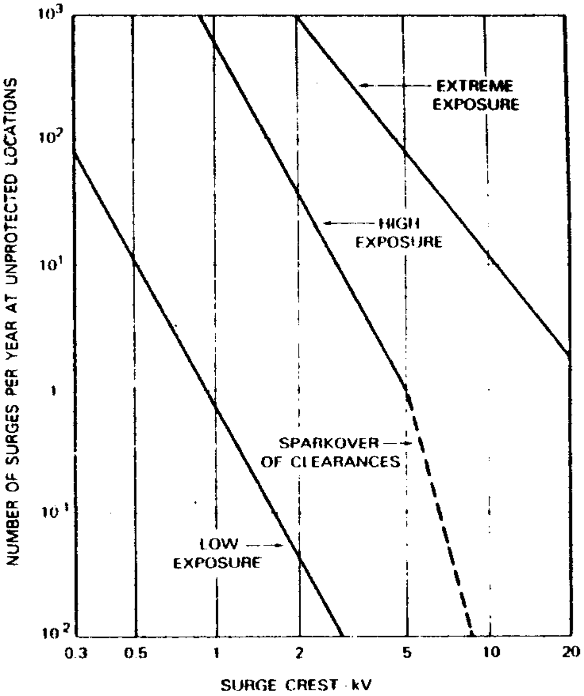


Figure 1. Rate of Surge Occurrence Versus Voltage Level in Unprotected Circuits

The two lower lines of Figure 1 have been drawn at the same slope, since the data base shows reasonable agreement among several sources on that slope. 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.

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. This distinction between actual driving voltage and voltage limited by sparkover is particularly important at the interface between outdoor equipment and indoor equipment. Outdoor equipment has generally higher clearances, hence higher sparkover levels: 10 kV may be typical, but 20 kV is possible. In contrast, most indoor wiring devices used in 120-240 V systems have sparkover levels of about 6 kV; this 6 kV level, therefore, can be selected as a typical cutoff for the occurrence of surges in indoor power systems.

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.

The IEC-SC28A Proposal

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 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.

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

WAVESHAPE OF THE TRANSIENT OVERVOLTAGES

Many independent observations [3,4,5] 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 x 50 or 1,2/50. 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 transmission systems exposed to lightning. Still, this is the waveshape selected by the IEC-SC28/A for low-voltage systems. Other groups have promoted an oscillation, such as that specified in the SWC tests. [6] The IEEE Working Group is recommending 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] while 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, for instance in a resistor added in series with the gap for limiting the power-follow current. In an energy-absorber suppressor, by its very

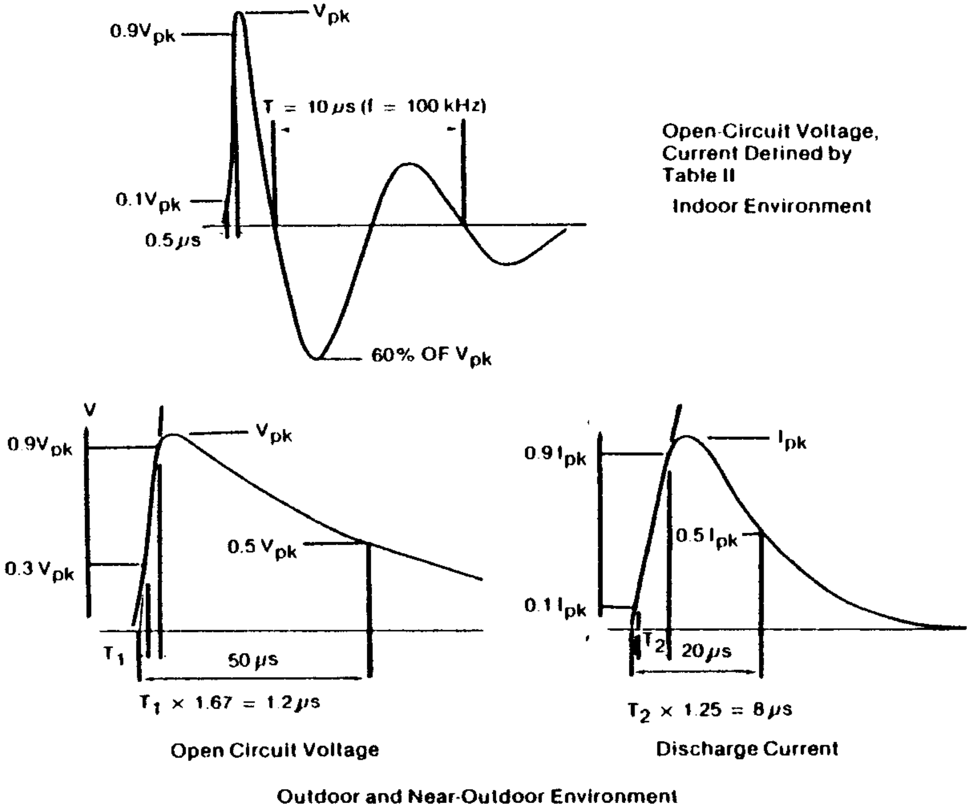


Figure 2. Proposed IEEE 587.1 Transient Overvoltages and Discharge Currents

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 SC/28A Report, or sometimes indicate values applicable to limited cases, such as the SWC test for high-voltage substation equipment. The IEEE 587.1 document is attempting to relate impedance with categories of locations, but unavoidably has to remain somewhat vague on their definitions (Table II).

The 6 kV open-circuit voltage derives from two facts: the limiting action of wiring device sparkover and the unattenuated propagation of voltages in unloaded systems. The 3 kA discharge current in Category B derives from experimental results: field experience in suppressor performance and simulated lightning tests. The two levels of discharge currents for the 0.5μs - 100 kHz wave derive from the increasing impedance expected in moving from Category B to Category A.

Location Category C is likely to be exposed to substantially higher voltages than Location Category B because the limiting effect of sparkover is not available.

The *extreme exposure* rates of Figure 1 could apply, with voltage in excess of 10 kV and discharge currents of 10 kA, or more. Installing unprotected load equipment in Location Category C is not recommended; the installation of secondary arresters, however, can provide the necessary protection.

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

MATCHING THE ENVIRONMENT WITH THE EQUIPMENT

On the basis of the various documents described in the preceding paragraphs, an equipment designer or a user can take a systematic approach at matching the capability or requirement for withstand of the equipment with the environment in which this equipment is to be installed. Figure 3 shows a flow chart concept of this systematic approach. This may involve tests to determine the withstand levels,[8] 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 briefly surveyed 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 (clamping action or crowbar action). We will be mostly discussing the second type in this paper, since voltage clamping devices or crowbar devices are the most frequently used.[9]

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, i.e., 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. As far as volt-ampere characteristics of these components is 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. Nonlinear impedance is the result if this current rise is faster than the voltage increase. 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

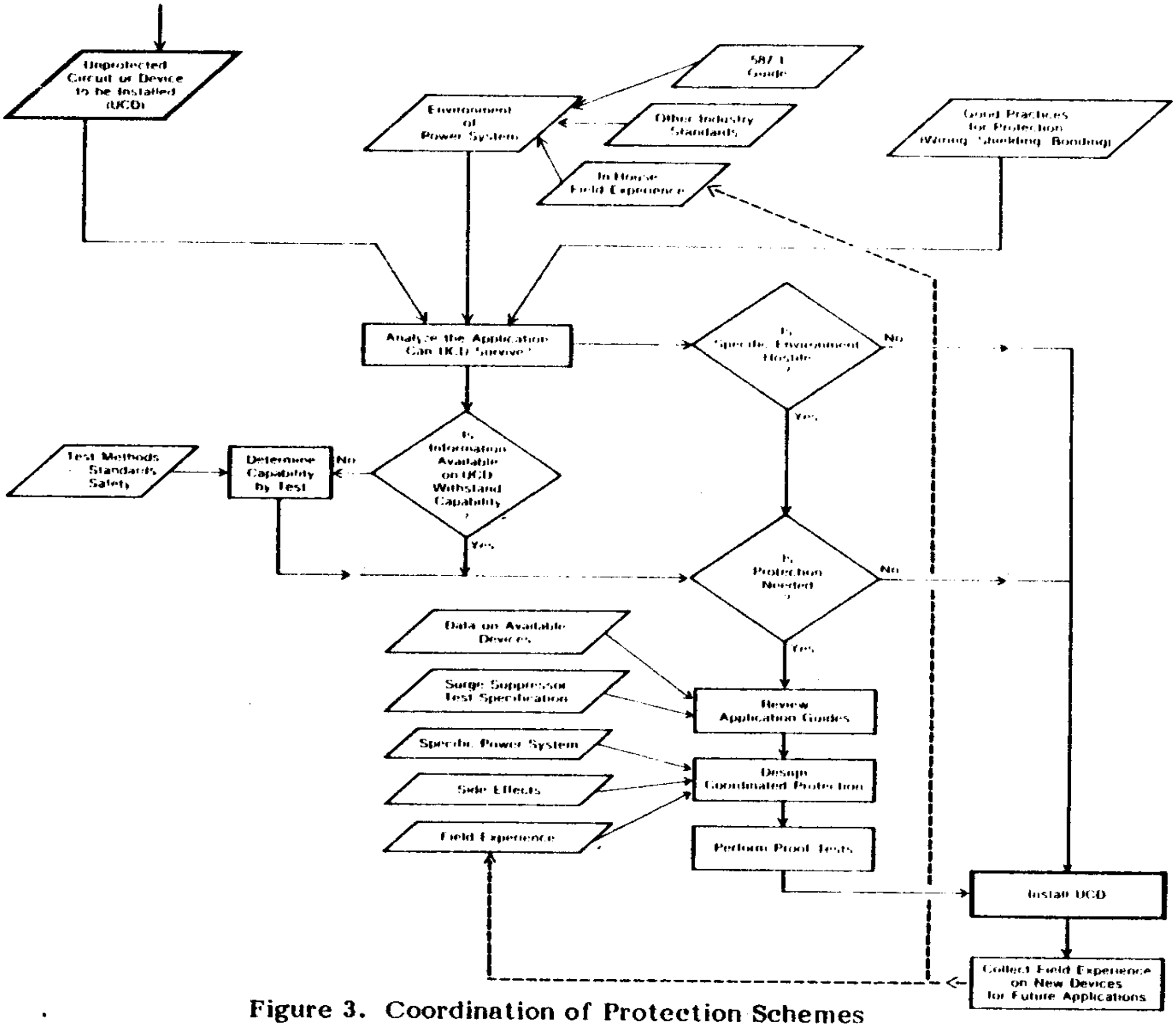
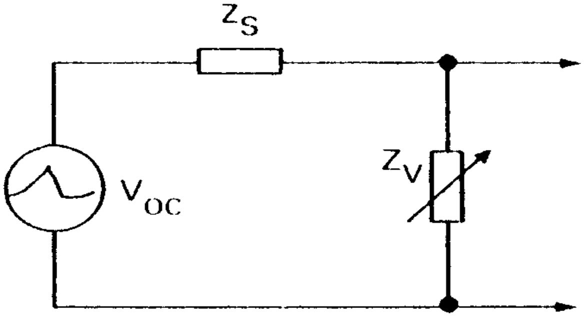


Figure 3. Coordination of Protection Schemes

clamping. A voltage divider action is at work where one sees the ratio of the divider not constant, but changing. The ratio is low, however, if the source impedance is very low. The suppressor cannot work at all with a limit zero source impedance (Figure 4). In contrast, a crowbar type device effectively short-circuits the transient to ground; but once established, 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.

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 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 constitues the major advantage of these suppressors. However, limitations in volt-time response and power-follow 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. This sparkover voltage can, in addition, be substantially higher



$$V_R = \left(\frac{Z_V}{Z_V + Z_S}\right)V_{OC}$$

Figure 4. Voltage Clamping Action of a Suppressor

after a long period of rest than after successive discharges, for some devices. 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 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*). This power-follow current may or may not be cleared at a natural current zero, in ac circuits. In dc 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. 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 an 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 independant 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. 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 combined approaches, a series impedance is sometimes added in the circuit, but only after a low impedance diverting path has first been established.

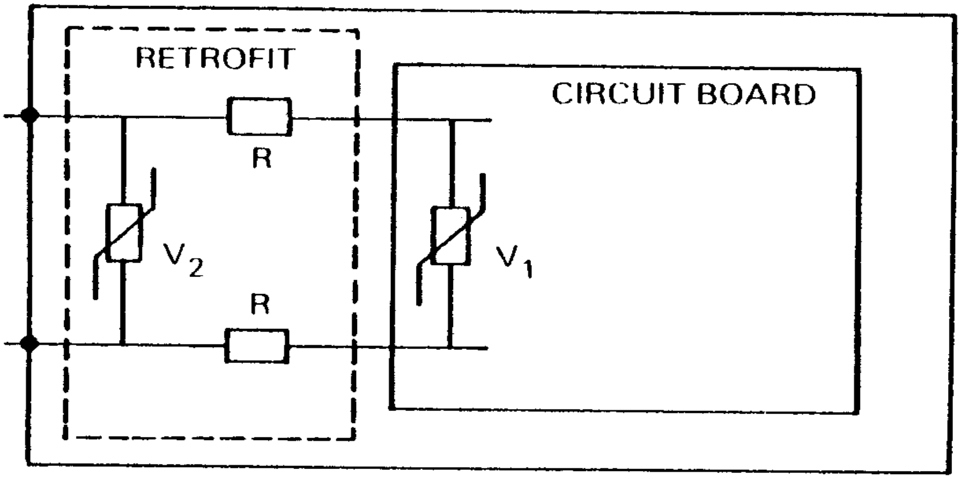
When the diverting path is a crowbar type device, little energy is dissipated in the crowbar, as noted earlier. In a voltage clamping device, more energy is deposited in the device, so that energy handling capability of a candidate suppressor is an important parameter to consider when designing a protection 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,[10] 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, 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). 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 (the first question asked in the flow chart of Figure 3). 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.

Because a number of devices were in service, complete redesign was not possible, but a retrofit – at an acceptable cost – had to be developed. Fortunately, the power consumption of this control circuit was limited so that it was 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 5). Laboratory proof-test of the retrofit demonstrated the capability of the combined



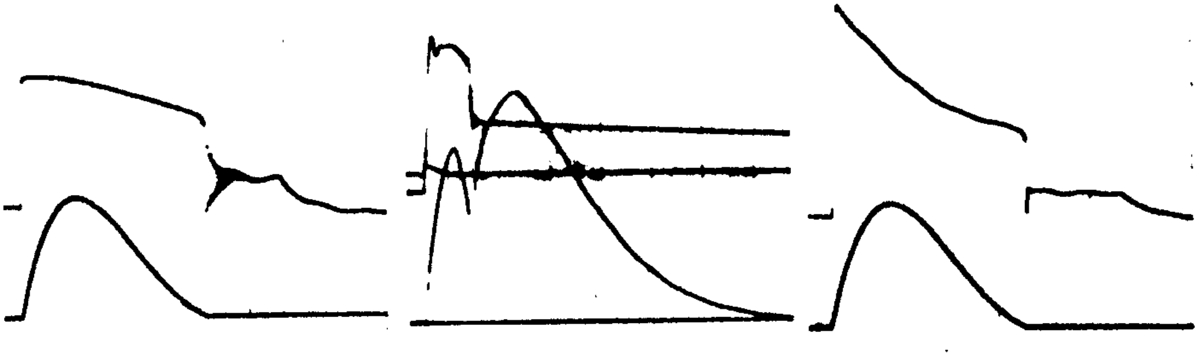
V1 : V150LA1 varistor

V2 : V150LA20A varistor

R : 10 Ω 1W carbon resistor

Figure 5. Retrofit Protection of Control Circuit

scheme to withstand 6 kA crest current surges (Figure 6A), a 200 % margin from the proposed Category B requirement, as well as reproduction of the field failure pattern (Figure 6B). 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 6C illustrates the effect of improper installation of the suppressor, with 8 inches of leads instead of a direct connection across the input terminals of the circuit.



A. Upper trace: Voltage across V150LA1 varistor on PC board, 200 V/div.
Lower trace: Surge current, 2000 A/div.
Sweep speed: 40 μs/div.

B. Additional surge protection removed: V150LA1 varistor on PC board is the only protection.
Upper trace: Voltage across V150LA1 varistor
Lower trace: Surge current 200 A/div.
Sparkover occurs at about 700 A: 60 Hz power follow destroys the PC board.
Sweep speed: 40 μs/div.

C. Same as Figure 6A, but with varistor mounted on eight-inch leads from terminal board.

Figure 6. Laboratory Demonstration of Retrofit Effectiveness

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 C62.1/2 Standards for secondary arresters. The only arresters available at the time which could withstand a 10 kA crest 8x20 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 object 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 would not spark over.

A circuit was set up in the laboratory, with 8 meters (24 ft) of #12 two-wire cable between the arrester and the varistor. The current, approximately 8x20 impulse, was raised until the arrester would sparkover 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 7A shows the discharge current level required from the generator at which this transfer occurs. Figure 7B shows the voltage at the varistor when the arrester does not spark over. Figure 7C shows the voltage at the arrester when it sparks over; this voltage would propagate inside all of the building if there was no suppressor added. However, if a varistor is added at 8 meters, the voltage of Figure 7C is attenuated to that shown in Figure 7D, at the terminals of the varistor.

Surge Injected into Ground System

Lightning surge currents flowing in the ground conductors of a power system can induce substantial overvoltages in the phase conductors, without having lightning

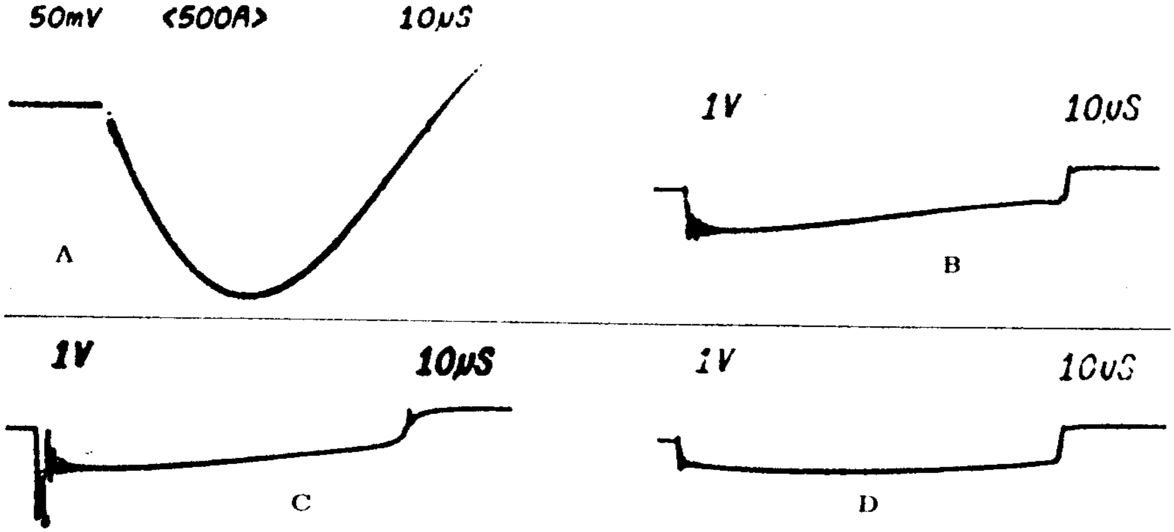


Figure 7. Transfer of Conduction

current directly injected into these phase conductors. A laboratory simulation of this situation was conducted,[11] from which interesting observations were made. First, the injection of a *unidirectional* 8x20 surge current in the ground conductor of the service entrance to a building caused *oscillatory* voltage transients in the phase-to-ground outlets within the simulated building wiring system. Second, the impedance of the equivalent source could be estimated by comparing the open-circuit voltage at the outlet with the lower voltage observed when a known load resistance was connected across the outlet. Third, while applicable only in the simulated condition, some numerical data can be quoted to illustrate the possible consequences of injecting high current into the ground conductors, i.e., if a direct lightning stroke were to occur in the distribution system outside the building. Table III shows some of the values recorded.

Table III
RESULTS OF SURGE INJECTION TESTS

Injected current into ground of service entrance	Observations Inside the 'Building'
1.5 kA	• open-circuit 2200 V crest, 500 kHz at 6 m (20 ft) from entrance • with 130 load, 1400 V crest, fast damping at same point
10 kA	• 8 kV open circuit voltages in wiring produces sparkover of the clearances of the wiring devices
30 kA	• an arrester connected at the service entrance will discharge about 3.5 kA between the phase conductors and ground

From the first observation, one can compute an equivalent source impedance of about 80 Ω for the discharge current of 1.5 kA source, consistent with the orders of magnitude shown in Table II. The clearance sparkover of the second observation is predictable and confirms the comments made earlier in discussing the rate of occurrence of Figure 1. The 30 kA example, which may seem a very high current, corresponds to a lightning discharge of 100 kA, or the 5 % level of crest discharges[12] where 70 kA is assumed to flow directly into the pole ground and overhead ground conductors to adjacent poles of the outdoor distribution system. Thus, for this extreme assumption, an acceptable current level is imposed at the service entrance arrester (for which the ANSI requirement is 10 kA).

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. A Guide and Application Guides will be available in the near future to better define the characteristics 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 cost, while current problems may also be alleviated based on these new findings in the area of transient overvoltages.

ACKNOWLEDGMENTS

The data base for the Guide quoted in the paper as well as the writing of that Guide was provided by the members of the IEEE Working Group on Surge Voltages in AC Power Circuits Rated 600 V or Less. Robert Mierendorf made available the data of Table I and emphasized the significance of clearance sparkover; Peter Richman's critique of the concepts relating to source impedance proved very effective; Paul Speranza suggested the flow chart approach developed in Figure 5.

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