TRANSIENT OVERVOLTAGE PROTECTION SEMINAR

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Significance
Part 6: Tutorials, textbooks, and reviews

A record of three seminars organized in support of the introduction of the GE-MOV varistors in Europe. Text and slide presentation.

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TRANSIENT OVERVOLTAGE PROTECTION SEMINAR

The Origin of Surge voltages
Fundamental Protection Techniques
Surge Testing
Transient Suppressors
Applications of Transient Protection

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FOREWORD

Designers and users of electronic 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, made their task difficult in the past. Also a wide choice of protective techniques and devices is available, but direct comparisons among them are often difficult because techniques vary from one organization to another, and device specifications published by suppliers are not always consistent. However, much progress has been made in recent years to solve this problem. The seminar topics, summarized in the five following written sections, present a brief overview of the current knowledge.

The section on origins of surge voltages covers the two physical phenomena that produce overvoltages: lightning discharges (not necessarily directly to a power system) and switching surges. The second considers fundamental protection techniques that are standard preventive measures: (1) allowing the harmless conduction of surge current to ground, (2) blocking the path between the sources of transients and sensitive devices, and (3) protection against direct effects. The third presents test methods and includes the rationale for testing, safety considerations, and a demonstration of equipment. The fourth addresses the wide choice of available surge protective devices, and the final section gives examples of single device applications as well as coordinated protection schemes.

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THE ORIGIN OF TRANSIENT OVERVOLTAGES

INTRODUCTION

Transient overvoltages no longer pose an unknown threat to the successful application of electronic equipment, for protective techniques and devices are available. The appropriate selection of these, however, remains a critical task because the exact nature of transients in the real world is at best only statistically defined, so that the choice involves technical and economic decisions based on calculated risks rather than certainties. Nevertheless, information has been collected and reviewed by various groups concerned with the problems of transient protection. This work will result eventually in guideline descriptions of the transient environment and proposed standard tests. Such guides and standard tests will simplify the task of ensuring protection.

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 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 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 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.

We will first review the basics of lightning phenomena, then briefly discuss the mechanisms involved in switching transients, and conclude with an overview of standards and guides on the characteristics of representative transients.

LIGHTNING PHENOMENA

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. Although we are examining the direct effects to appreciate the phenomena involved, we are ultimately concerned in this discussion with the indirect effects.

Because there is no conclusive evidence that lightning can be prevented, one must design a facility taking appropriate measures to make lightning strikes harmless. Designers should be familiar with two lightning phenomena: the "cone of protection" and "striking distance," as well as with current theories on the formation of lightning. The descriptions that follow are based on the work of Anderson and Hagenguth (1), Cianos and Pierce (2), and Golde (3).

Generation of the Lightning Flash

The energy that produces lightning is provided by warm air rising into a developing cloud. Several theories vary in detail, but all are based on the observed evidence that the cloud, except for the top, is negatively charged, with a small body of positive charge near the front base of the cloud. Figure 1 shows a typical cloud distribution of charges. The solid lines represent the direction of the air movement in the cloud, with the cloud moving from right to left. As the cloud passes over a point on the ground, an electrical charge is attracted under the cloud on the ground.

However, the first significant event in the formation of a lightning flash occurs at the cloud. A column of ionized air, moving slowly by steps of 30 to 50 meters forms at the cloud. This column is called the ***pilot streamer***. Second, the discontinuous or haphazard ionization and filling of the column with charged particles results in a discharge called a ***step-leader***. The step-leader does not move in a straight line toward the ground but, rather, seeks out the path with least electrical resistance, producing the familiar zig-zag pattern of the final stroke. Branching shows the several paths that may be formed in this process of searching a weak path. Near the ground the last step is completed either by continuation of the process or by meeting a leader of positive charges originating from the ground.

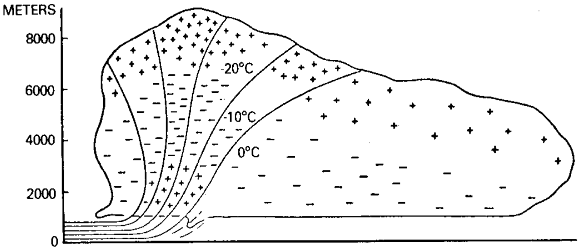


Figure 1. Generalized diagram showing distribution of air currents and electrical charge distribution in a typical cumulonimbus

With the path completed, a positive charge flows upward from the ground into the negative channel left in the wake of the step-leader, neutralizing the charge in this channel. This flow, carrying a current at peaks of 1000 to 100,000 A with rise times in the order of one microsecond, is what constitutes the lightning stroke.

When a very tall object is present, a step-leader can actually originate from it and travel upward to meet the downward moving leader. Subsequent charges will move in the ionized channel left by the first discharge.

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 (4), showing number of storm days per year, is still the most widely used description of the occurrence distribution. Contrary to some popular beliefs, the density of lightning flashes *on the average* is independent of terrain. However, ground objects (trees, buildings, and hills) will produce a bias in the local distribution of this average.

This distribution at the ground level is determined by the final stages of the step-leader coming from the cloud and depends to some extent on what it finds on the ground. Thus, the ***actual point of termination*** can be somewhat controlled, while the probability of a ***given area's receiving*** a lightning stroke cannot. This is where the concept of the striking distance, as explained by Golde (5), becomes useful.

Striking Distance

As the step-leader approaches the ground in the haphazard path described above, the point is reached where one more strike in the discontinuous process will close the path. The distance between the tip of the leader and the object about to be struck (or about to emit the meeting leader) is called ***striking distance.*** The length of this distance is affected by the field established by the leader, which in turn is determined by the amount of charge existing in the ionized channel coming from the cloud. With a large charge in the channel (eventually producing a high discharge current), the field is more intense, so that breakdown can occur for longer distances, while a shorter distance is necessary to produce breakdown for the weaker fields established by smaller charges.

For instance, an average lightning current of 25 kA would correspond to a striking distance of 40 m. Thus, for an average 25 kA stroke, details of the terrain do not affect the point of termination of the stroke beyond this distance, but within this distance will there be a race, or a competition, as to which point will receive the flash, or invite it by sending a meeting streamer. Conversely, very low amplitude flashes have an even shorter striking distance, which means that they will seem to ignore "attractive" points of termination. Amplitudes, together with striking distance, explain some of the puzzling exceptions to the generally assumed effect of tall structures, rods, etc.

Cone of Protection

From the days of Benjamin Franklin (6), the concept of a cone of protection has been used to provide an effective protection of objects within the cone. Briefly, this concept states that objects contained within a cone of 1:1 or 1:2 ratio of height to radius will not receive the lightning stroke but that the object at the apex of the cone will. In the elementary concept, only one object projecting above a ground plane is being considered; in most practical situations involving buildings, multiple cones should be considered.

A classical "cone of protection" rule for the building shown in Figure 2 would assure that the lightning mast shown provides dependable protection for the building against an approaching step-leader. However, if we consider the short striking distance shown by the circles of low discharge in Figure 2(a), we can see that the advancing leader will have ignored the lightning mast and traveled the shortest distance to Point D, to the corner of the building within the "cone of protection" rather than to ground. The path drawn here also exhibits the tell-tale sharp inflection of the last step mentioned above and often photographed.

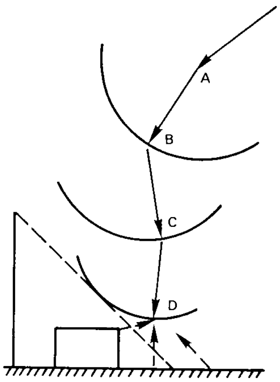


Figure 2(a). Termination of stroke with short striking distance

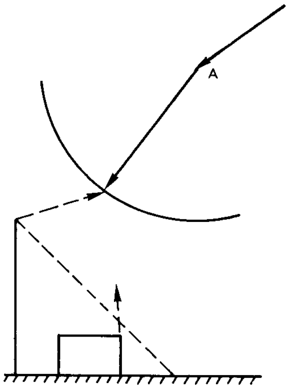


Figure 2(b). Termination of stroke with long striking distance

Although both strokes pass through Point A, the step-leader drawn in Figure 2 (b) for the case of a stroke of higher intensity, and thus a longer striking distance, will terminate at the lightning mast. This course represents the classical cone-of-protection situation; it implies that the step-leader will find within its striking distance an intended point of termination and strike that point, rather than an object that chances to be close enough and shaped in a manner to initiate a streamer to meet the step-leader.

Thus, the designer of a building or outdoor facility can provide predictible and innocuous lightning termination points rather than permit the destructive injection of lightning currents into the power or communication system. (Such measures will be briefly addressed in another section of the seminar.) Nevertheless, indirect effects of this flow of lightning current will inescapably occur: induced voltages caused by the rapid changes of magnetic flux in circuit loops, changes in ground potential as a function of time and space, and/or excitation of oscillations in the power or communication systems. From the point of view of protecting electronic circuits, the indirect lightning effects are therefore more important because they are less avoidable than the direct effects and likely to involve a greater part of a given system, as compared to the massive but localized damage which may be caused by a direct lightning strike to a circuit. In later discussions of transient-producing mechanisms, the indirect effects will generally be the only effects considered.

SWITCHING TRANSIENTS

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

Simple switching transients (7) 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 when 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. Without a surge protective device the current is available to charge the circuit capacitances at whatever voltage is required to store the inductive energy from the current into capacitive energy.

Abnormal Switching Transients

Several mechanisms are encountered in practical power circuits. These mechanisms can produce transient 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.

Current chopping is the name given to the rapid current reduction, prior to the natural current zero of the power system, which fuses or circuit breakers can force when clearing a circuit. When there is inductance in the circuit, this rapid current change can produce high overvoltages – some 10 times the normal circuit voltage. A classical example is an unloaded transformer where the magnetizing inductance is high and the energy stored in the magnetic core can charge only the winding capacitance.

Capacitor switching can be troublesome if the switch restrikes after current interruption: the capacitor voltage remains nearly constant at maximum system voltage, since the interruption occurred at zero current, which is 90° apart from the voltage zero, while the system voltage follows the normal sine wave (Figure 3). At 180 degrees after interruption, the switch has to support twice the system voltage, a stress it might not be able to support with its contacts incompletely separated. A restrike can occur under these circumstances. In such a case the capacitance of the circuit will tend to drive the voltage not toward the system voltage but beyond it, theoretically up to twice the difference. Such an overshoot means a possible voltage of three times the system voltage. While this high frequency oscillation takes place, the switch may clear at a high-frequency current zero, only to restrike again later with an even greater difference of voltage and escalating to an even higher overshoot. The outcome will be either a breakdown in one of the components or, if the switch eventually recovers enough dielectric withstand in its opening gap, no further restrikes. But severe overvoltages will have been impressed on the system.

A similar scenario can unfold when an ungrounded power system experiences an arcing ground fault. The switching action is then not the result of a deliberate parting of contacts but the intermittent connection produced by the arc.

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 behaviour of a circuit element. Lightning-induced transients 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.

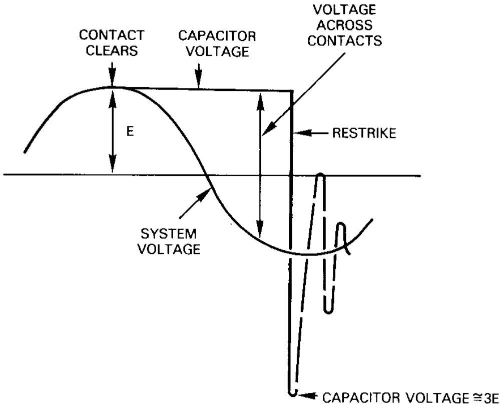


Figure 3. Restrike Mechanism on Capacitor Switching

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. Three such attempts will be discussed in some detail at the end of this section.

TRANSIENT OVERVOLTAGES IN COMMUNICATION CIRCUITS

Communication circuits share with power circuits their exposure to lightning effects, but differ from power circuits in that they do not have the power switching effects just discussed. On the other hand, they are exposed to another source of overvoltages — the injection of power-frequency current into the circuits. This injection can be the result of accidental contact between fallen power wires on overhead communication wires or cables, or even a malicious injection of power-frequency voltage into terminals of communication equipment. This injection can last until a power circuit breaker interrupts the fault it senses on the power system, or it can be enduring, in which case the communication circuit protective devices must provide an acceptable failure mode to maintain the safety and integrity of the communication plant — with interruption of the service until the fault condition is removed.

EXISTING AND PROPOSED STANDARDS ON TRANSIENT OVERVOLTAGES

Several Standards or Guides have been issued or proposed, in Europe by VDE, IEC, CECC, Pro-Electron, CCITT, in the USA by IEEE, NEMA, UL, REA, 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 (8). The document is now being reviewed by the IEEE Standards Board for eventual publication as a standard. 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 (9). For some time now, a document prepared by a Relaying Committee of IEEE under the title "Surge Withstand Capability" (10) has been available. These three documents are now to be reviewed in the pages that follow. Greater emphasis will be placed on the last because it describes the transient environment; the other two 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 transient 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.

The IEC SC/28A Report on Clearances

The Insulation Coordination Committee of IEC, 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 1,2/50 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 further 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 Rate 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 4). 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.

The two lower lines of Figure 4 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

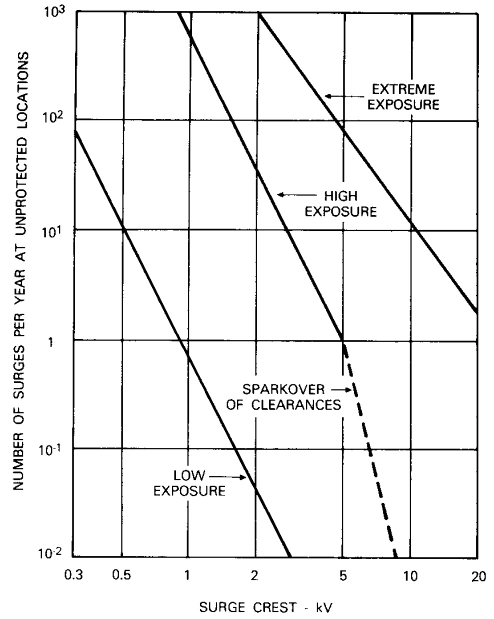


Figure 4. Rate of Surge Occurrence Versus Voltage Level

strikes but none should be considered "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.

Waveshape of The Surges

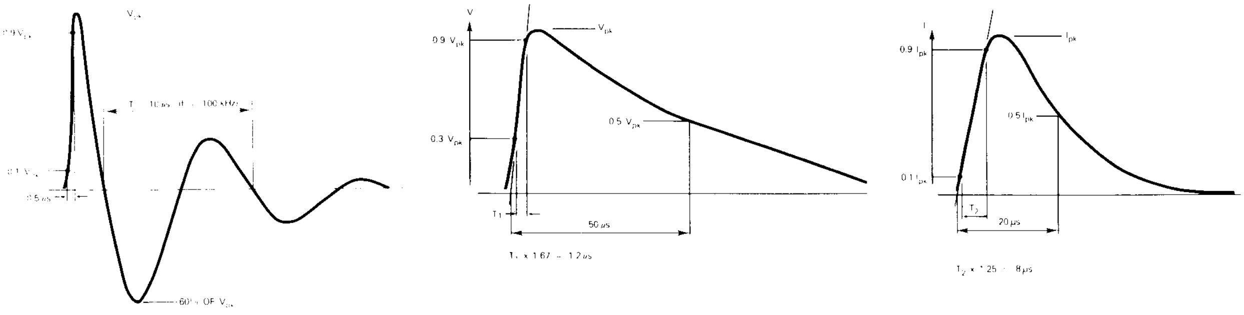
Many independent observations (11,12,13) have established that the most frequent type of transient overvoltage in ac power systems is a decaying oscillation, with frequencies between 5 and 500 kHz. This finding is in contrast to earlier attempts to apply the unidirectional double exponential voltage 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 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 5).

The oscillatory waveshape simulates those transients affecting devices that are sensitive to dv/dt and to voltage reversals during conduction, 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 protective device will divide between the source and the protective device in accordance with the characteristics of the two impedances. In a gap-type protective device, 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 protective device, 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 surge protective 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 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



Open-Circuit Voltage,
Current Defined by Table II

Open Circuit Voltage

Discharge Current

Indoor Environment

Outdoor and Near-Outdoor Environment

Figure 5. Proposed IEEE 587.1 Transient Overvoltages and Discharge Currents

IEEE 587.1 document attempts to relate impedance to categories of locations but unavoidably remains 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 surge protective device performance and simulated lightning tests. The two levels of discharge currents for the 0.5 µs - 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 4 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.

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 6), will outline the method for assessing the need for transient protection and selecting the appropriate device or system. Parallel work in other IEEE working groups preparing test specification standards (14) 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.

CONCLUSIONS

The two major causes of transient overvoltages, lightning surges and switching surges, have been identified with greater precision in low-voltage ac circuits as well as in communication systems.

While standardizing the *definition* of the environment will not change the environment itself, the emergence of realistic standards will enable designers to increase the reliability of their products. Likewise, users will be able to protect their equipment more effectively.

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	1.2/50 µs	6 kV	High Impedance(1)	--	--
		8/20 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.

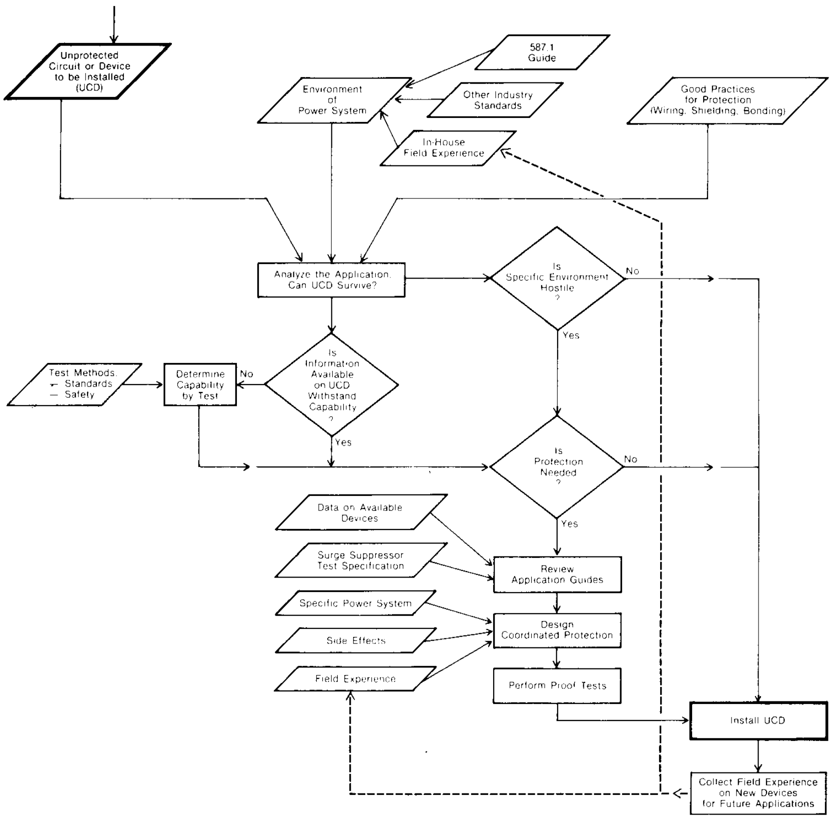


Figure 6. Coordination of Protection Schemes

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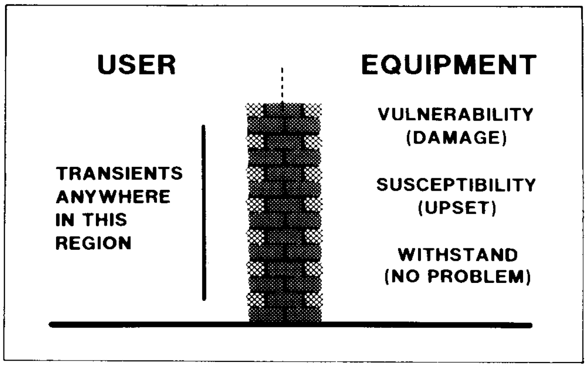
12. F.D. Martzloff and G.J. Hahn, "Surge Voltage in Residential and Industrial Power Circuits," IEEE PAS 89, 6, 1049-1056 (July/August 1970).
13. R. Hasler and R. Lagadec, "Digital Measurement of Fast Transients on Power Supply Lines," Proc. 3rd Symposium and Technical Exhibition on Electro-Magnetic Compatibility, Rotterdam, Holland, 445–448 (May 1979).
14. Test Specifications for Gas Tube Surge Protective Devices, IEEE Standard 465.1-1977.

TRANSIENT OVERVOLTAGE PROTECTION

- THE ORIGIN OF SURGE VOLTAGES
- FUNDAMENTAL PROTECTIONS TECHNIQUES
- TEST METHODS
- PROTECTIVE DEVICES
- APPLICATIONS



THE ORIGIN OF SURGE VOLTAGES

LIGHTNING PHENOMENA
- STRIKING DISTANCE
- CONE OF PROTECTION

SWITCHING TRANSIENTS
- SIMPLE
- ABNORMAL

COMMUNICATION CIRCUITS

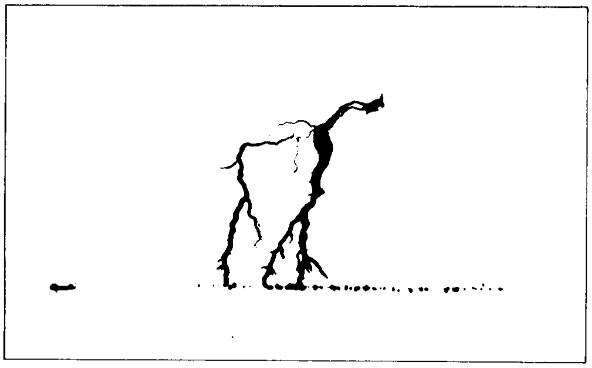
STANDARDS
- SWC-IEEE
- SC28A-IEC
- GUIDE 587-IEEE

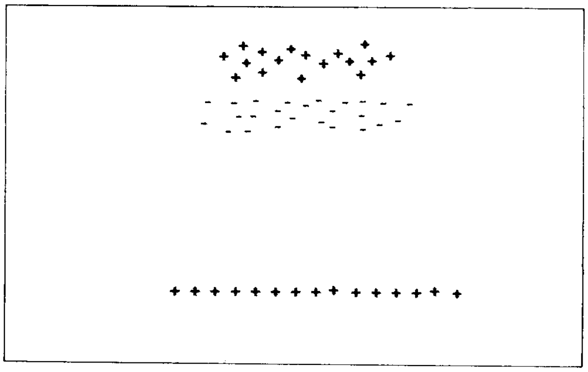
SWITCHING TRANSIENTS

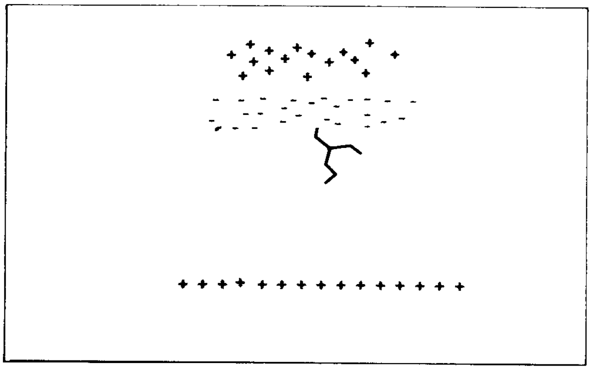
- POWER SYSTEM
- LOCAL SWITCHING

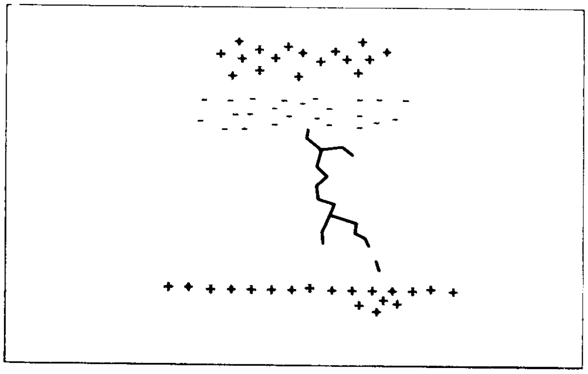
LIGHTNING TRANSIENTS

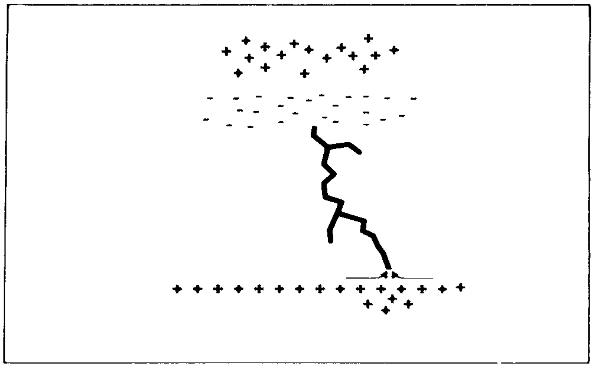
- DIRECT EFFECTS
- INDIRECT EFFECTS

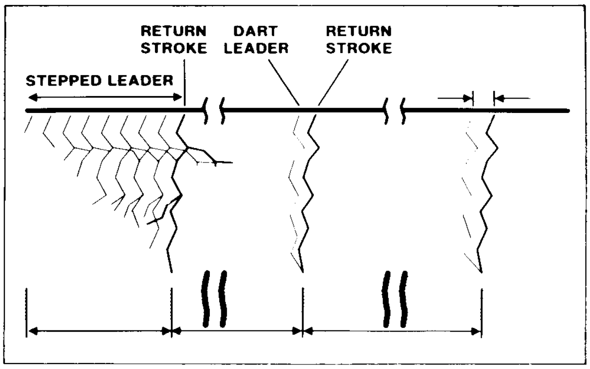


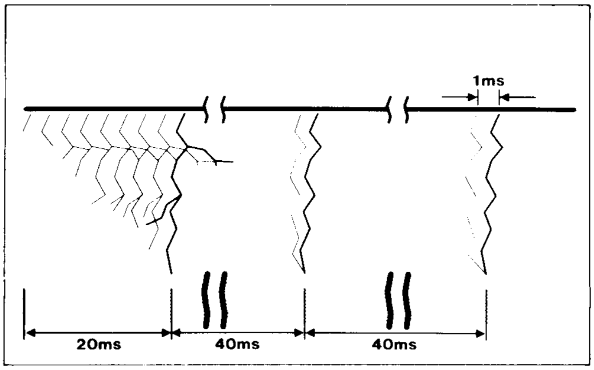


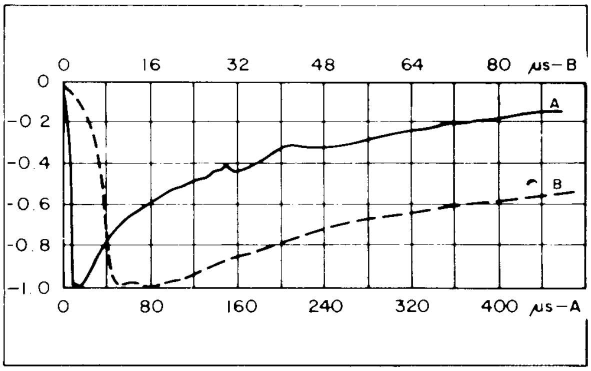


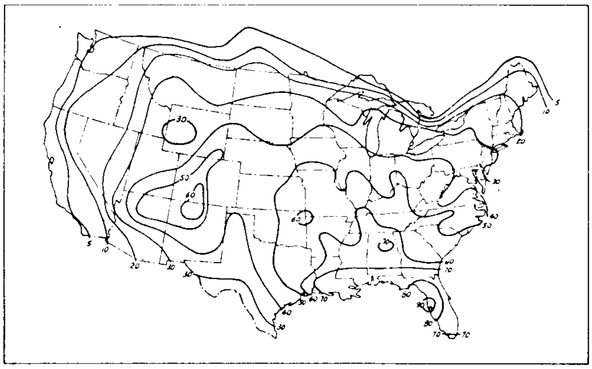


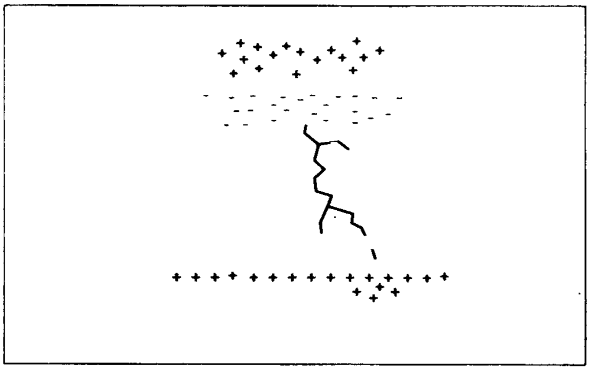


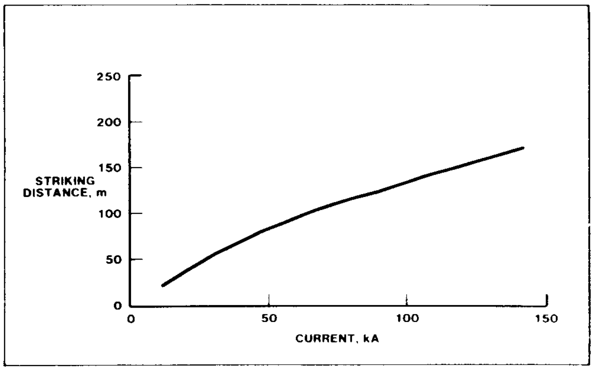

RETURN STROKE
DART LEADER
RETURN STROKE
STEPPED LEADER

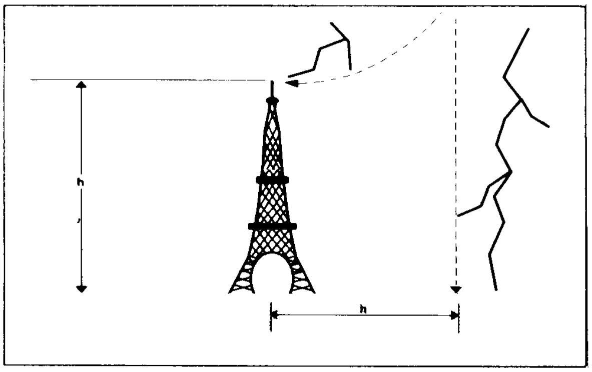

1ms
20ms
40ms
40ms

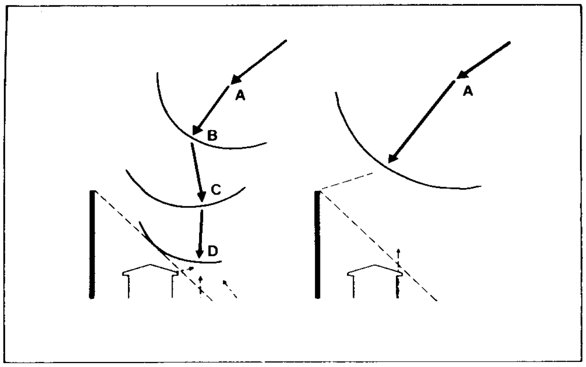

0
16
32
48
64
80
µs–B
0
-0.2
-0.4
-0.6
-0.8
-1.0
A
B
0
80
160
240
320
400
µs–A





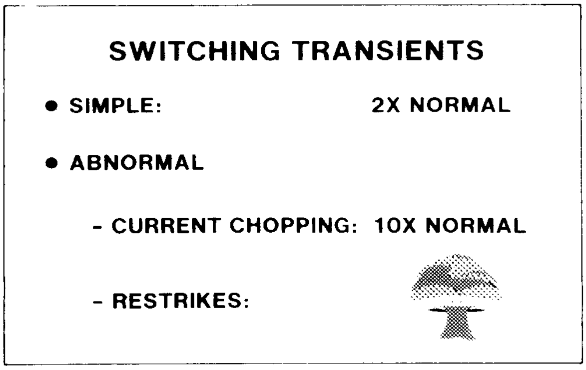

250
200
150
STRIKING DISTANCE, m
100
50
0
0
50
100
150
CURRENT, kA


h
h



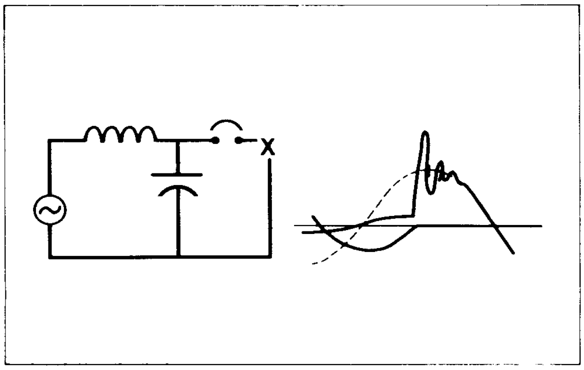
SWITCHING TRANSIENTS

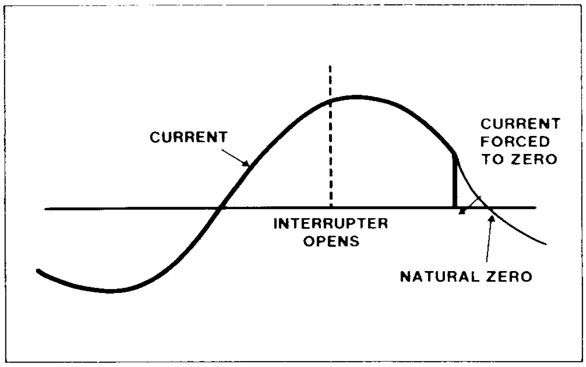
- SIMPLE
- ABNORMAL
  - CURRENT CHOPPING
  - RESTRIKES

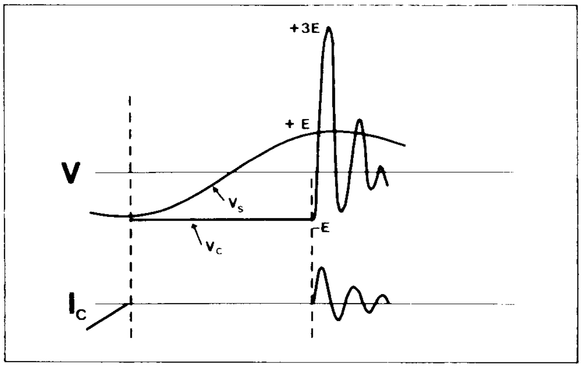


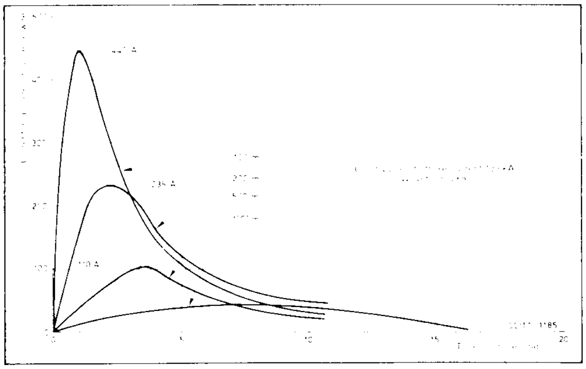
SWITCHING TRANSIENTS

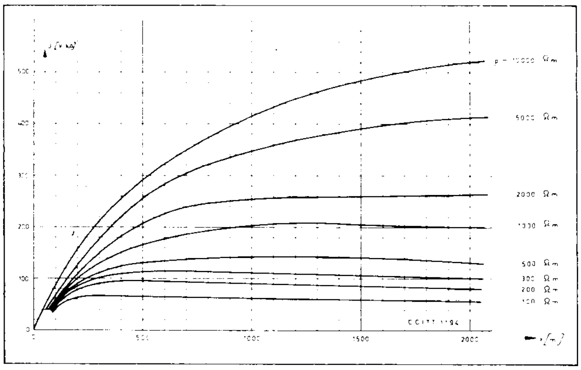
• SIMPLE:	2X NORMAL
• ABNORMAL	
- CURRENT CHOPPING:	10X NORMAL
- RESTRIKES:	

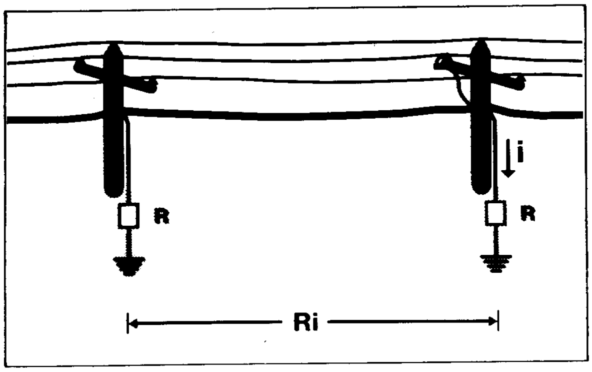


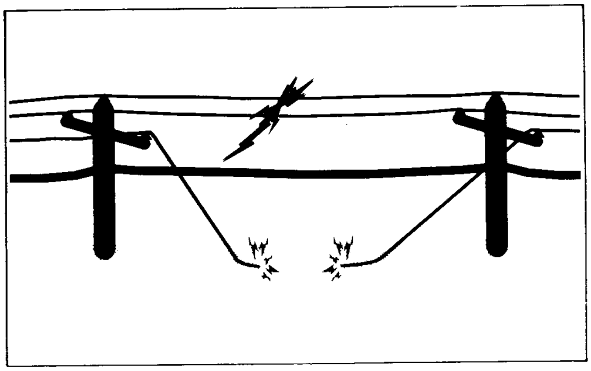




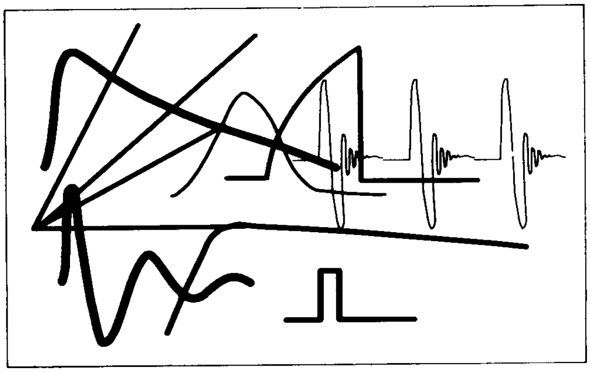


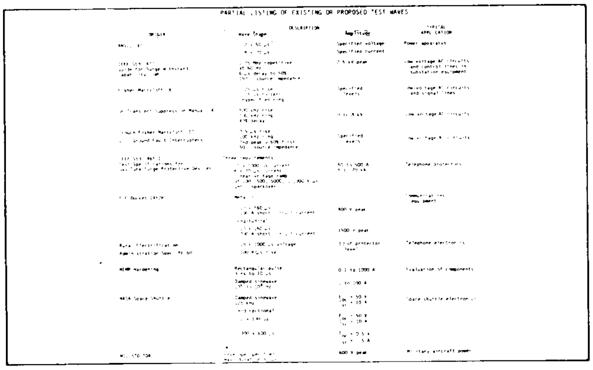






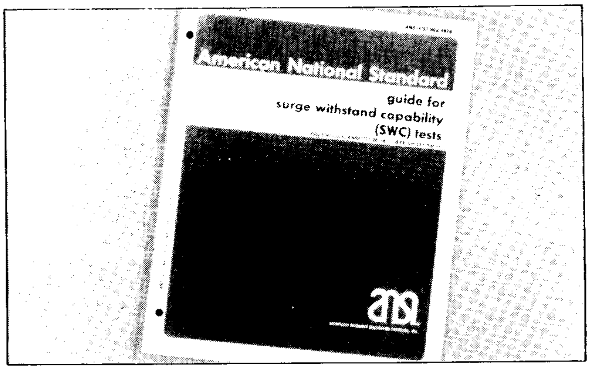
STANDARDS ON
TRANSIENT OVERVOLTAGES



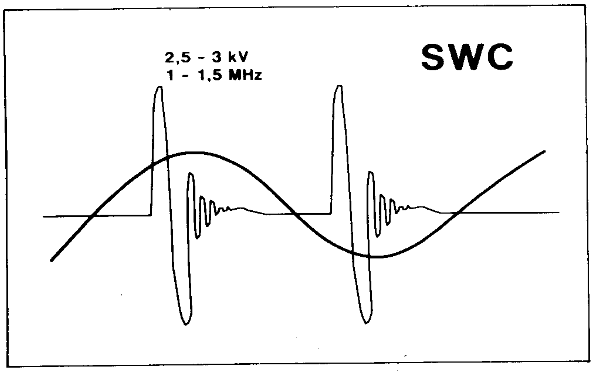


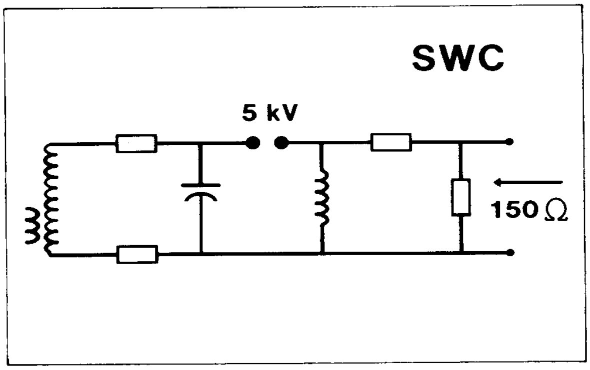
PARTIAL LISTING OF EXISTING OR PROPOSED TEST WAVES

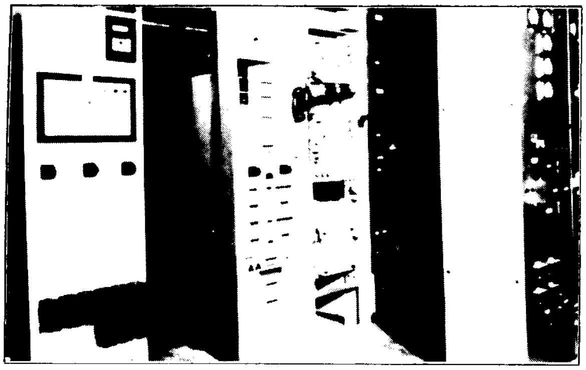
ORIGIN | DESCRIPTION: Wave Shape | Amplitude | TYPICAL APPLICATION

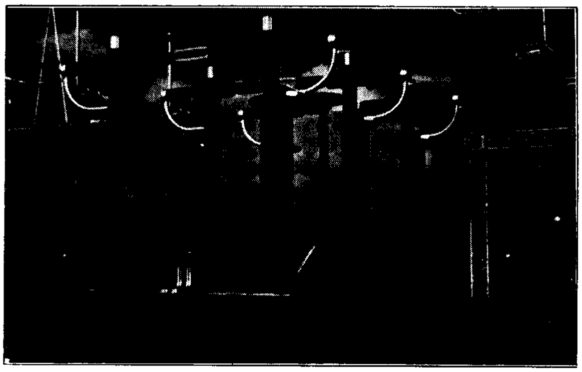


American National Standard
guide for
surge withstand capability
(SWC) tests

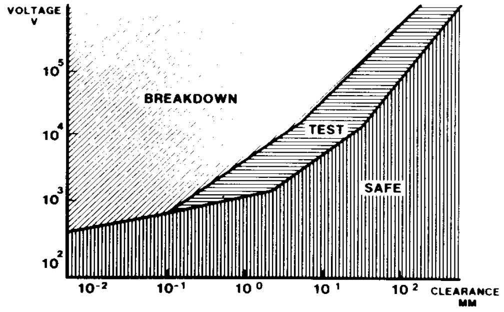






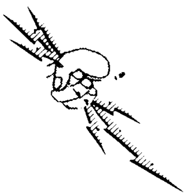


IEC SC/28A



IMPULSE WITHSTAND INSTALLATION CATEGORY

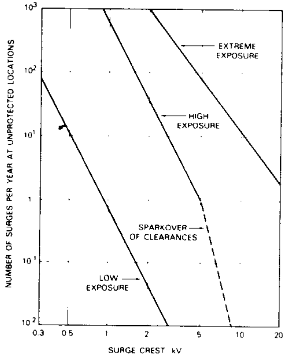
SYSTEM VOLTAGE	I	II	III	IV
50	330	550	800	1500
100	500	800	1500	2500
150	800	1500	2500	4000
300	1500	2500	4000	6000
600	2500	4000	6000	8000
1000	4000	6000	8000	12000

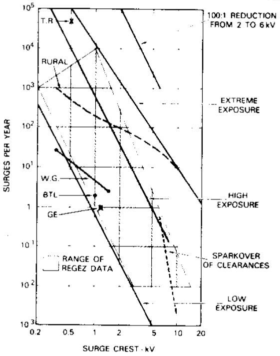


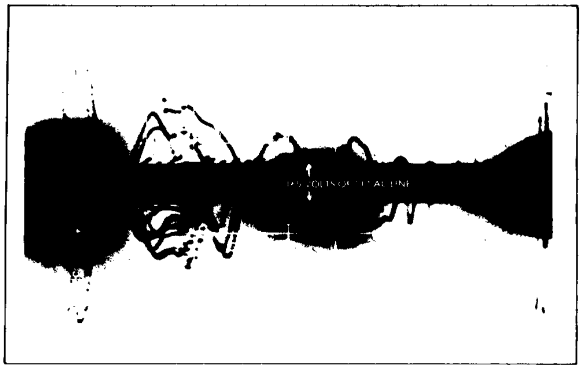
GUIDELINE ON SURGE VOLTAGES IN AC POWER CIRCUITS

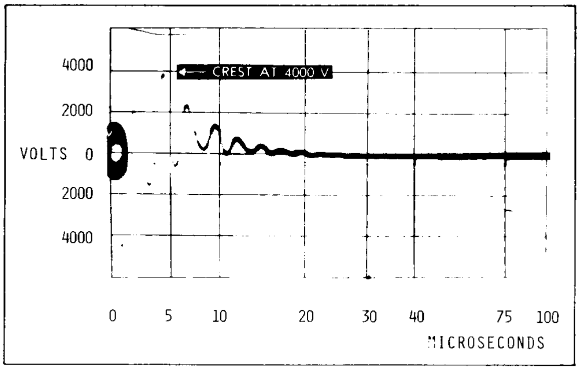
GUIDELINE

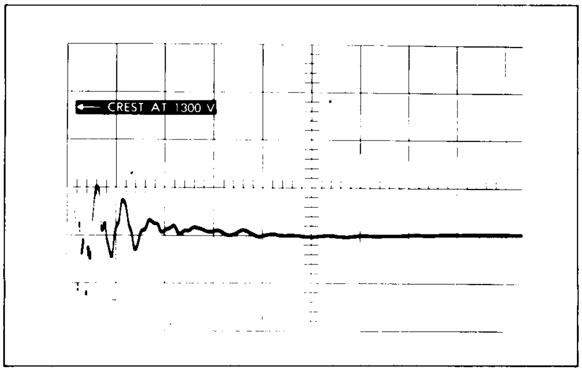
- SCOPE
- ORIGIN OF SURGES
- RATE OF OCCURENCE AND LEVELS
- WAVESHAPE
- ENERGY AND SOURCE IMPEDANCE
- SUPPORTING DATA

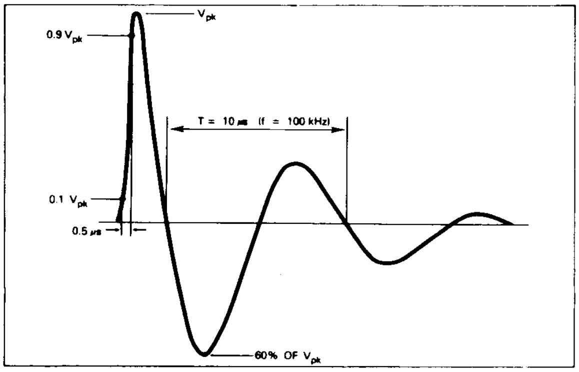


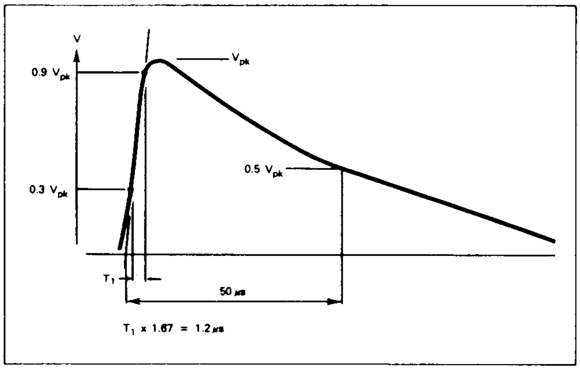


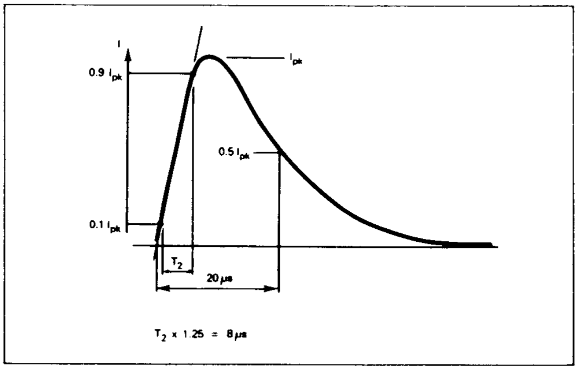


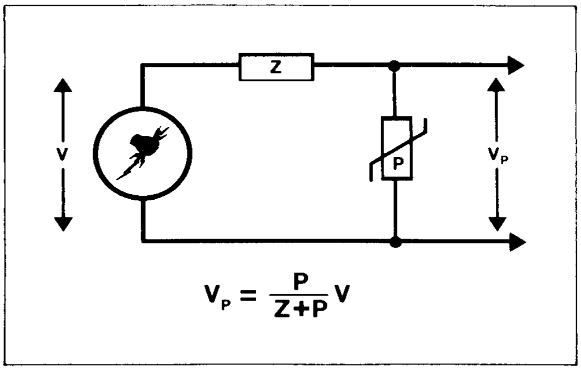

4000
2000
VOLTS 0
2000
4000
CREST AT 4000 V
0
5
10
20
30
40
75
100
MICROSECONDS

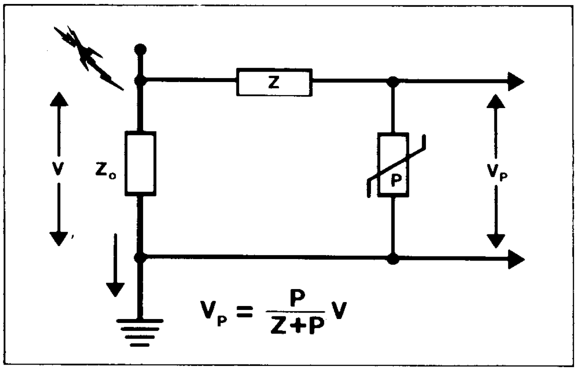

CREST AT 1300 V

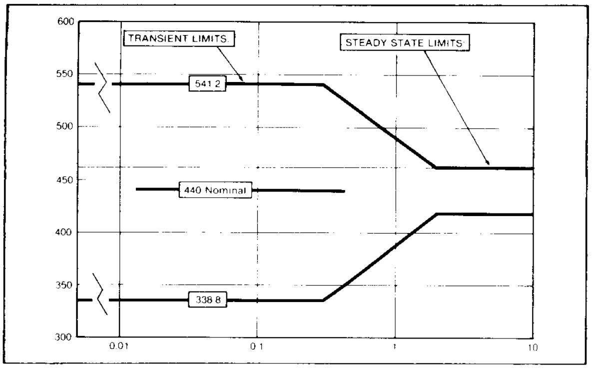

V_{pk}
$0.9\ V_{pk}$
$T = 10\ \mu s\ (f = 100\ kHz)$
$0.1\ V_{pk}$
$0.5\ \mu s$
60% OF V_{pk}

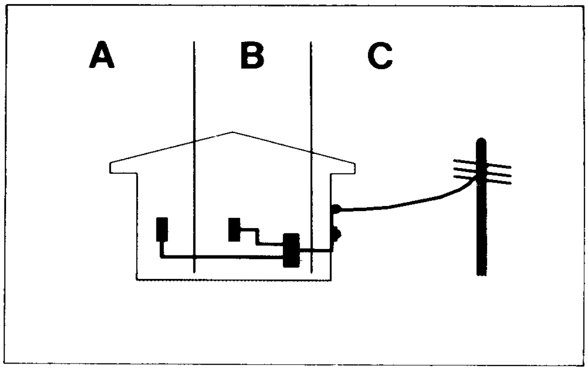

V
$0.9\ V_{pk}$
V_{pk}
$0.5\ V_{pk}$
$0.3\ V_{pk}$
T_1
$50\ \mu s$
$T_1 \times 1.67 = 1.2\ \mu s$

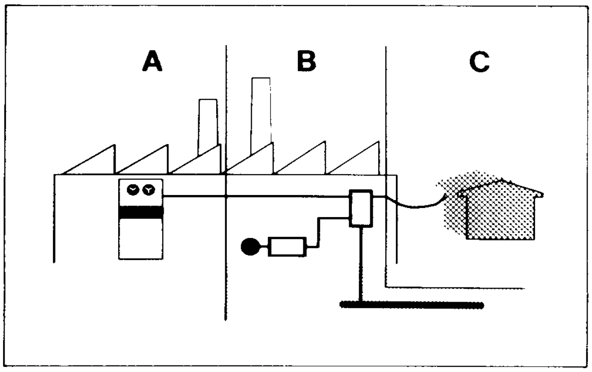

I
$0.9\ I_{pk}$
I_{pk}
$0.5\ I_{pk}$
$0.1\ I_{pk}$
T_2
$20\ \mu s$
$T_2 \times 1.25 = 8\ \mu s$


Z
V
P
V_P
$V_P = \frac{P}{Z+P} V$


Z
V
Z_o
P
V_P
$V_P = \frac{P}{Z+P} V$







Ⓐ LONG BRANCH CIRCUITS

HIGH IMPEDANCE - 6 kV

- OPEN-CIRCUIT 0.5μs - 100 kHz
- NO SUPPRESSOR

LOW IMPEDANCE - 200 A

- SHORT-CIRCUIT 0.5μs - 100 kHz
- SUPPRESSOR

Ⓑ SERVICE ENTRANCE SHORT BRANCH CIRCUITS

HIGH IMPEDANCE	6 kV	6 kV
• OPEN-CIRCUIT	1.2x50	0.5μs - 100 kHz
• NO SUPPRESSOR		
LOW IMPEDANCE	3 kA	500 A
• SHORT-CIRCUIT	8x20	0.5μs - 100 kHz
• SUPPRESSOR		

Ⓒ OUTSIDE

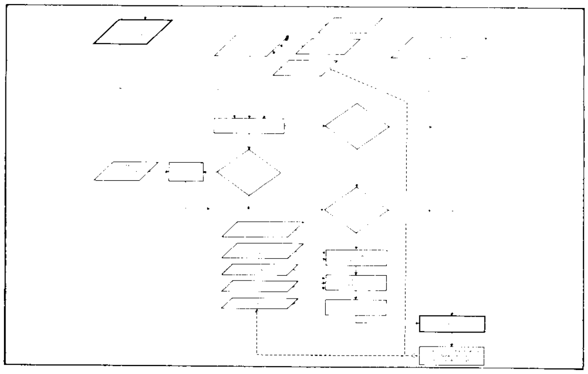
HIGH IMPEDANCE - 10 - 20 kV

- OPEN-CIRCUIT 1.2x50
- NO SUPPRESSOR

LOW IMPEDANCE - 10 kA

- SHORT-CIRCUIT 8x20
- SUPPRESSOR

CATEGORY	ENERGY (J)	
	500V	1000V
A	0.8	1.6
B	2 40	4 80
C	150+	300+



FUNDAMENTAL PROTECTION TECHNIQUES

INTRODUCTION

Protection of a power system, of a communication system, or of an electronic black box against the threats of the surge environment can be accomplished in different ways. There is no single truth or magic cure insuring immunity and success, but, rather, there are a number of valid approaches that can be combined as necessary to achieve the goal. The competent protection engineer can contribute his knowledge and perception to the choice of approaches against a threat which is imprecise and unpredictable, keeping in mind the balance between the technical goal of maximum protection and the economic goal of realistic protection at an acceptable cost. However, just as in the case of accident insurance, the cost of the premium appears high before the accident, not after.

A discussion of fundamental protection techniques that is limited in time and scope has the risk of becoming an inventory of a bag of tricks; yet, there are some fundamental principles and fundamental techniques that can be useful in obtaining transient immunity, especially at the design stages of an electronic system or circuit. All too often, the need for protection becomes apparent at a late stage, when it is much more difficult to apply fundamental techniques.

Our primary goals in this section, then, will be to alert the system and circuit engineer to various aspects of protection and to present some basic concepts of approach.

BASIC TECHNIQUES

Protection techniques can be classified into several categories according to the purpose and the system level at which the engineer is working. For the system as a whole protection is primarily a preventive effort. One must consider the physical exposure to transients - in particular, the indirect effects of lightning resulting from building design, location, physical spread, and coupling to other disturbance sources - as well as such inherent susceptibility characteristics as frequency response and nominal voltage. A data processing system built with low-voltage signals, high-impedance circuits, and installed over a wide geographical area, such as a railroad switching yard or a chemical plant spread over thousands of meters, would, of course, present serious problems.

For the system components, the electronic black boxes, the environment is often beyond the control of the designer or user, and protection becomes a curative effort - learning to live and survive in an environment which is imposed. Quite often this effort is motivated by field failures and retrofit is needed. The techniques involved here tend to be the application of protective devices to circuits rather than the elimination of surges at their origin.

Another distinction can be made in classifying protective techniques. Granted that surges will be unavoidable, one can attempt to block them, divert them, or strive to withstand them; the latter, however, is generally difficult to achieve alone.

SHIELDING, BONDING, AND GROUNDING

Shielding, bonding, and grounding are three interrelated methods for protecting a circuit from external transients. Shielding consists in enclosing the circuit wiring in a conductive enclosure, which in theory cancels out any electromagnetic field inside the enclosure; actually, it is more an attenuation than a cancellation. Bonding is the practice of providing low-impedance connections between adjacent metal parts, such as the panels of a shield, cabinets in an electronic rack, or rebars in a concrete structure. Grounding is the practice of providing a low impedance to "earth," through various methods of driving conductors into the soil. Each of these techniques has its limitations, and each can sometimes be overemphasized. One of Dr. Golde's favorite remarks is that he could retire on a small percentage of the cost of the useless copper buried in the ground to provide "better grounding." We shall now examine each of these techniques, pointing out some of their limitations and some of the controversies concerning them.

Shielding

Shielding conductors by wrapping them in a "grounded" sheath or shielding an electronic circuit by enclosing it in a "grounded" conductive box is a defensive measure that occurs very naturally to the system designer or the laboratory experimenter anticipating a hostile electromagnetic environment. Difficulties arise, however, when the concept of "grounded" is examined in detail and when the goals of shielding for noise immunity conflict with the goals of shielding for lightning surge immunity.

A shield can be the size of a matchbox or an airplane fuselage; it can cover a few inches of wire or kilometers of buried or overhead cables. "Grounding" these diverse shields is not an easy thing to do because the impedance to earth of the grounding connection must be acknowledged. The situation is made even more controversial because of the conflict between the often-proclaimed design rule "ground cable shields at one end only," a rule justified by noise immunity performance, and the harsh reality of current flow and Ohm's law when lightning strikes.

The difficulty may be caused by a perception on the part of the noise prevention designers that the shield serves as an electrostatic shield in which longitudinal currents should not flow. Sometimes the shield is used as a return path for the circuit, in which case shield currents can cause voltage drops added to the signal. But the fact is that, when surge currents flow near the circuits, they will unavoidably inject magnetic flux variations into the circuits, hence induced voltages. By deliberately allowing part of these surge currents to flow in the shields, one obtains a cancellation of the magnetic flux.

This conflict is actually very simple to resolve if recognized in time: provide an outer shield, grounded at both ends (and at any possible intermediate points); inside this shield the electronic designer is then free to enforce his single-point grounding rules. The only drawback to this approach is the hardware cost of "double shields." However, in many installations there is a metallic conduit through which the cables are pulled; with simple attention to maintaining the continuity of this conduit path, through all the joints and junction boxes, a very effective outer shield is obtained at negligible additional cost. That additional cost, then, is the insurance premium, which is well worth accepting.

Bonding

We already mentioned one aspect of bonding in describing the continuity of the outer shield. Another instance of bonding occurs where the shield of an incoming cable is connected to the box of the circuit or to the building ground. The principle is simple: the shield can be viewed as an extension of the box, and thus bonding of the shield to the box should be continuous over 360 degrees. In practice, unless special connectors are used, this is difficult to achieve, for often a shielded cable is terminated at a connection board with the shield peeled back and turned into a pigtail, which in turn is connected to the "ground" terminal of the connection board. One can imagine the many possible variations of current flow, with the shield current now flowing in the pigtail and the creation of the corresponding electromagnetic radiation at the point of cable entry.

Adjacent cabinets in a lineup must be bonded together for safety as well as transient and noise immunity. In principle, a flat strap has a lower inductance than a round wire of the same area. This concept may be somewhat overused; actually several strategically located smaller wires provide a much more effective bond than one massive strap either round or flat. The difficulty lies in implementing this alternate view, and overcoming the comforting sight of a large grounding strap at the bottom of the cabinet lineup. Such a strap does no harm and is a good safety practice, but it may not do as much good as advertised.

Grounding

Grounding, which is also referred to as "earthing," has different meanings as well as different roles. The primary definition is the connection of the circuit, shield, or reference to earth. But what is "earth"? System designers, construction crews, inspectors, and technical conference authors are concerned with establishing, measuring, and maintaining a low ground resistance, often determined by dc measurements on rods driven into the ground. Driving rods into the ground does not ensure a low impedance under the transient conditions of high rate of current change associated with lightning discharges. This remark is not intended as a criticism of the efforts going into achieving a low resistance but, rather, to alert the system designer that there is more to it than just low resistance, and that one can overdo the act of burying copper in the ground.

When one deals with a reasonably compact system, be it cabinet-size, room-size, or building-size, it is more effective to view the grounding as a well-bonded connection to the outer shield (if any), building frame, or cabinet enclosure. The resistance (impedance) from that reference to "earth" is not very significant as long as other wires at "ground" potential are not brought to the system. Since there is little chance of dealing with an absolutely isolated system, the question is What should be done with incoming wires? These wires can be isolated from the local ground during normal operation, but one must recognize that, during transient conditions of lightning surge or power system faults, high voltages will appear across these isolated wires and local ground, which in some cases are totally beyond the withstand capability of insulation. That insulation, then, must be protected by suitable devices which in fact do ground the wires for the duration of the transient. This type of grounding is one function of transient suppressors.

Power System Grounding

In the context of grounding it is appropriate to mention the questions raised by proponents of ungrounded and grounded power systems. Indeed, a discussion of grounding practices would not be complete without reference to these questions.

It has been a long-established practice to operate some three-phase power systems without an intentional ground connection of the neutral. The intent is to increase service continuity, in principle allowing the system to continue operating with one ground fault, as opposed to grounded systems, where an outage will be the result of the first ground fault to occur. Examples of such concerns are found in military power systems ("ride through the first shell") and industrial low-voltage systems.

Closer analysis of the consequences of this choice indicates, however, that the overall performance of the ungrounded systems may not necessarily be improved over the safer, more predictable grounded system. An excellent discussion of the advantages and disadvantages can be found in IEEE Standard 142-1972. A detailed description is presented of multiple faults to ground, arcing faults to ground (which can be caused by sparkover after a transient overvoltage and result in massive equipment damage), location of faults, personnel safety, performance with overvoltages, and system costs.

The effects of these concepts on the roles performed by shielding, bonding, and grounding can be summarized in a set of relatively simple design guidelines, which are stated in the Appendix.

Isolation of Subsystems

In the case of systems involving separate buildings, remote sensors, or the interconnection of a power system with a communication system, other requirements may dictate the isolation of the subsystems, creating the illusion that protection against overvoltages has also been accomplished. And yet we have seen that during transient conditions high voltages can occur.

Where moderately high voltages only can occur, effective isolation can be accomplished by the insertion of isolating transformers, or when metallic isolation is not required, by insertion of a filter.

Where the voltages will reach levels exceeding the withstand capability of economically or technically feasible insulation, two possibile solutions exist. The first, already mentioned, is to bond the two systems during the transient by means of a nonlinear surge protective device, which returns to a high level of insulation after the transient has subsided. Another method, and one which is becoming increasingly attractive, is the insertion of a fiber optics link into a control or data system. Complete decoupling of electrical transients and noise can be achieved in this manner.

CONCLUSIONS

A number of fundamental protection techniques are available to limit the penetration of lightning surges into a system. These are best implemented at the early stages of design. They include the provision of points where a lightning stroke can attach and be diverted without harm to earth, shielding of circuits, bonding of enclosures, and grounding of the shields and reference points.

It is a dangerous illusion to believe that lightning effects can be eliminated by the isolation of conductors or subsystems. It is much safer, and quite acceptable if included in the design, to provide bonding during transient conditions by suitable protective devices. The important point to remember is that lightning is a fairly well-defined phenomenon, with known characteristics and effects in general, but its probability of occurrence at a particular location is unknown. For the successful operation of a system, foresight is needed in applying fundamental protection techniques at the beginning.

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APPENDIX

BASIC CONSIDERATIONS ON SURGE CONTROL FOR ELECTRONIC SYSTEMS

(Frank A. Fisher, General Electric Company,
Surge Protection of Electronics, University of Wisconsin, March 1979, Conference Notes)

PROTECTION FROM THE DIRECT EFFECTS OF LIGHTNING

1. Try to divert the stroke away from the system, the farther the better.

2. If the stroke cannot be diverted away completely, it must be carried to ground along a path where it does the least damage. This basically means providing a system of lightning rods and lightning conductors to a low-resistance ground.

3. Reduce the resistance along the current-carrying path as much as feasible. This is particularly true of the ground resistance where the lightning conductor is grounded.

4. In buildings housing electronic equipment, establish a uniform potential ground plane over as much of the building as possible. In new buildings all reinforcing steel in concrete and structural steel members should be bonded together and connected to ground rods. These should be located around the periphery of the building. Bonding should be done at many points. All water pipes and utility conduits should be bonded to this ground system where they enter and at frequent intervals within the building.

5. Insofar as feasible, the building should be arranged to form a grounded metal enclosure (Faraday cage). External magnetic and electric fields will not penetrate into a perfect Faraday cage.

6. Power systems should be protected with commercially available surge arresters.

7. Avoid the use of ground systems for electronic equipment that are isolated from building or power system grounds. This means using a multiple ground system rather than a single-point ground system.

8. Connect the cases of all electronic equipment to the nearest building ground point. This insures that as a minimum the cases will not assume a high potential, under lightning flash conditions, relative to the surrounding structure and so will not present an electrical hazard to people operating the equipment. Ground leads should be as short and direct as possible, possessing a minimum of resistance and (especially) inductance.

9. All wiring between different locations in the [system] should be carried in shielded cables, with shields grounded at both ends.

10. Electronic equipment should be designed to withstand surge voltages. Surges can be carried into such equipment on input and output leads and on power supply leads, and consideration should be given to the use of protective devices on these circuits.

PROTECTION COMPATIBLE WITH NOISE ATTENUATION DESIGN

An approach which has been used successfully to provide lightning protection of communication systems without compromising the systems' steady-state noise performance is shown on [the figure that follows]. The important elements of the system are as follows:

1. Electrical cables carrying signals between sensitive or critical apparatus in separated locations *must* have an overall shield. This shield *must* be continuous and *must* be grounded at each end (A and B) to the *building* ground systems.

2. The individual cables within this bundle should be shielded, but this is not an absolute requirement.

3. The shields on these individual cables should be grounded at each end (C and D), but may, at the circuit designer's discretion, be grounded at only one end (E and F) if such a practice is preferable for the control of steady-state noise. As long as the designer leaves the overall shield alone, he can do whatever he wishes with any internal shields.

4. The electronic equipment to which the cables connect should have the housings (G and H) connected to the building ground system (I).

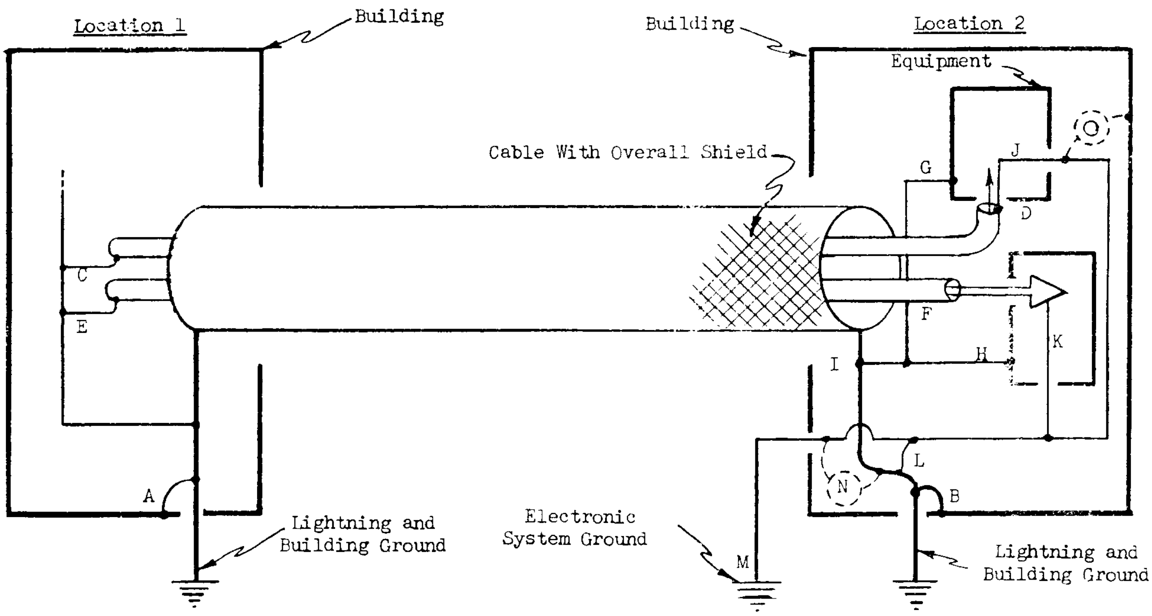
5. A ground bus within the individual pieces of electronic equipment, but isolated from the equipment case, is often desirable. If such ground busses are provided (J and K), it is preferable from the viewpoint of lightning protection that they be connected to the building ground system at the point of entry (L) of the building ground system.

6. If direct connection of the ground systems cannot be tolerated, a separate electronic ground (M) can be provided. A spark gap or other voltage-limiting device (N) should then be provided to limit the surge voltages that can be developed between the two ground systems.

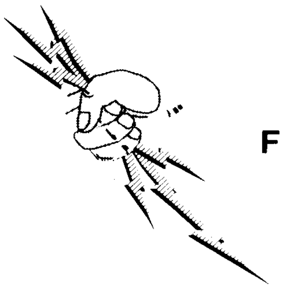
7. If the electronic ground system is very extensive, it may be desirable to provide other voltage-limiting elements (0) between the electronic ground system and the building ground system.

8. Electronic cables are generally carried between locations in cable trays. These trays, though not shown on [the] figure, should be connected to the building ground system at each end. The cable trays should be electrically continuous over their entire length. Cable trays, if used, do not eliminate the need for an overall shield on the cables within the tray.

9. If cables are carried between two locations in electrically continuous metallic conduits, such conduits being connected to the building ground system at each end, the overall shield on the cables may be eliminated, since the conduits take the place of the shield. Cables carried in nonmentallic conduits, however, must have the overall shield.



Lightning Protection Measures Which Provide Minimum Disruption to Steady-State Operation



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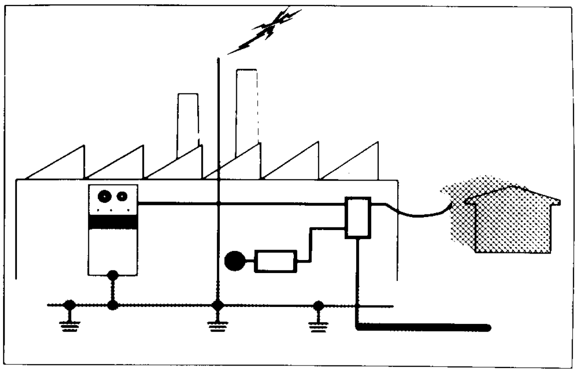
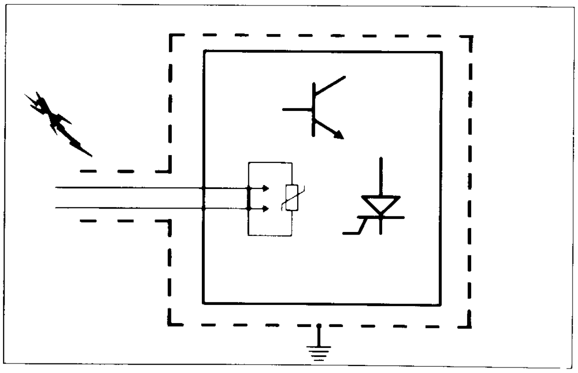
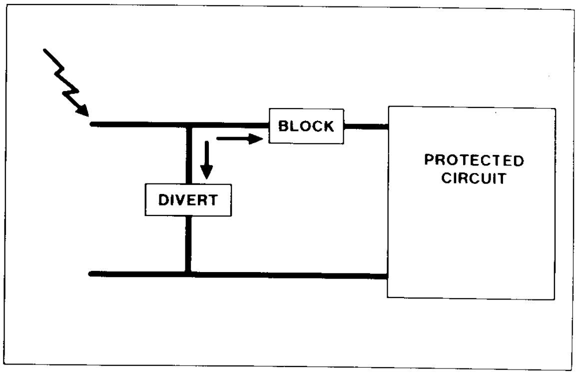
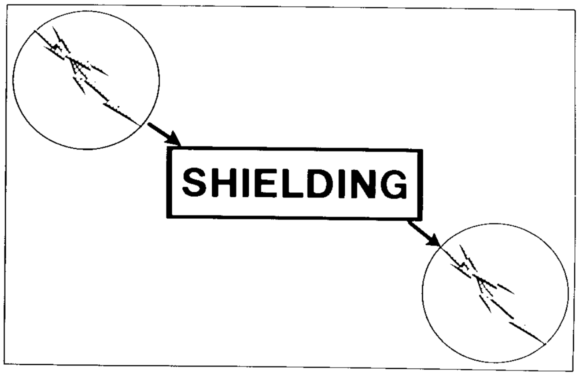






SHIELDING
BONDING
GROUNDING



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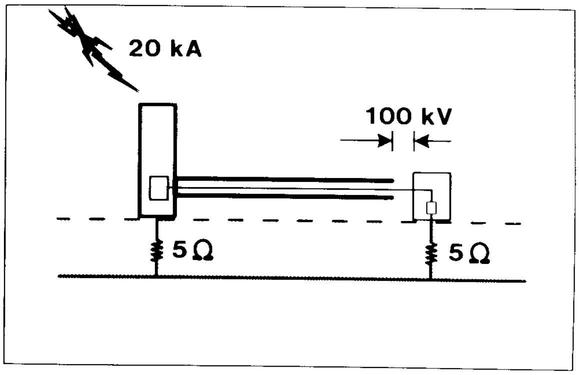

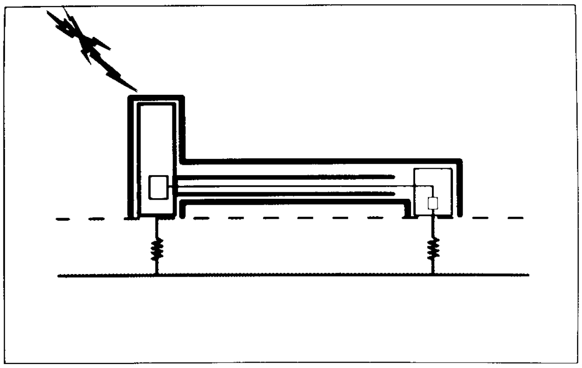

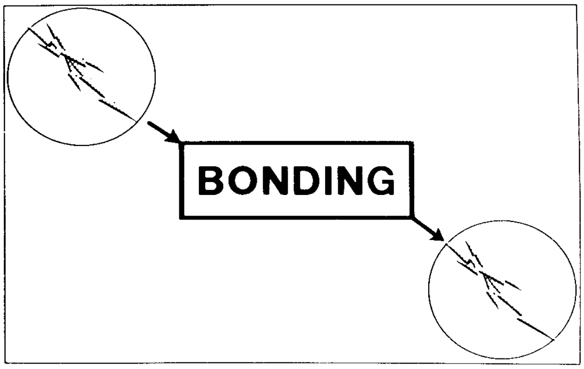
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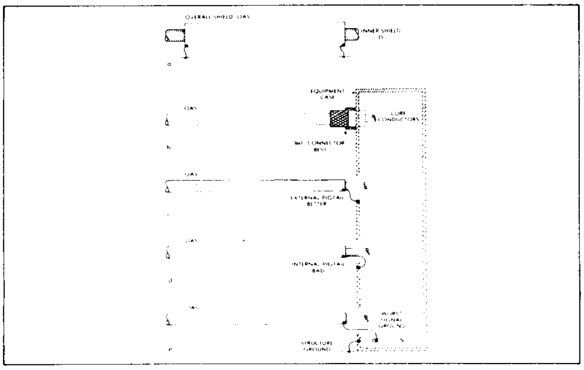
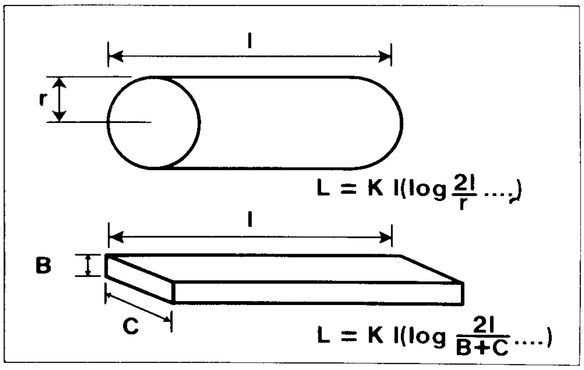

OVERALL SHIELD (OAS)
INNER SHIELD (IS)
a
EQUIPMENT CASE
OAS
CORE CONDUCTORS
360° CONNECTOR BEST
b
OAS
EXTERNAL PIGTAIL BETTER
c
OAS
INTERNAL PIGTAIL BAD
d
OAS
WORST SIGNAL GROUND
STRUCTURE GROUND
e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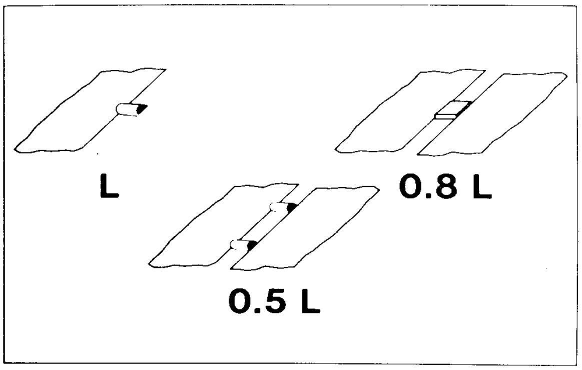
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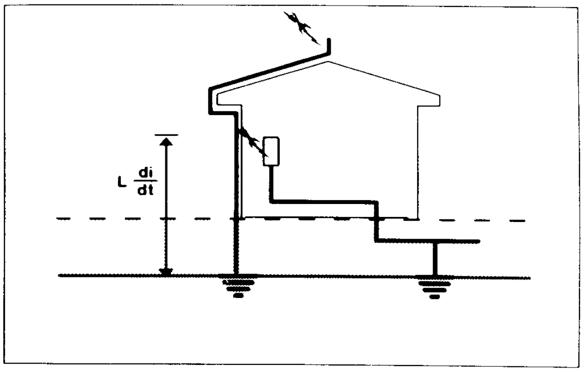
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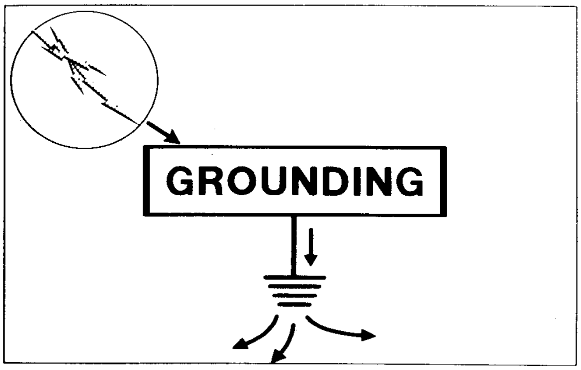
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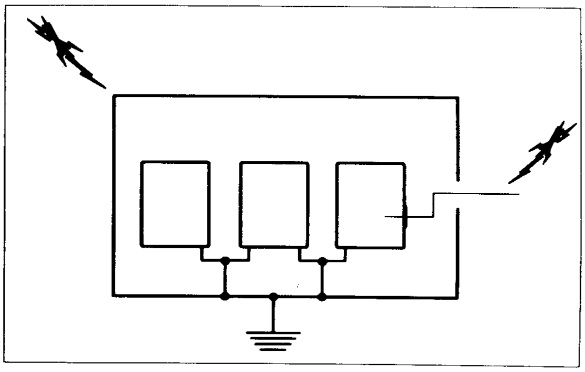

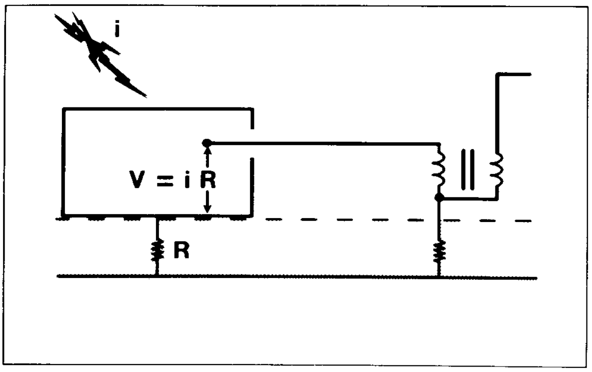

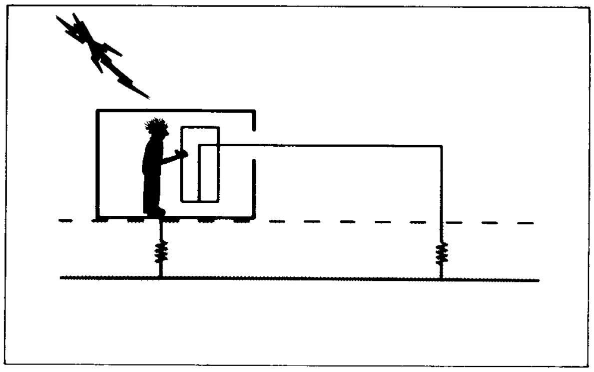

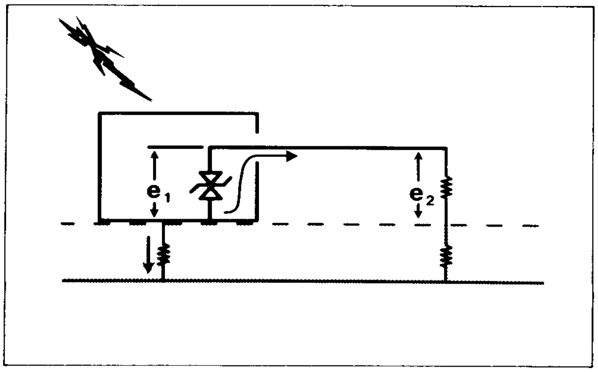

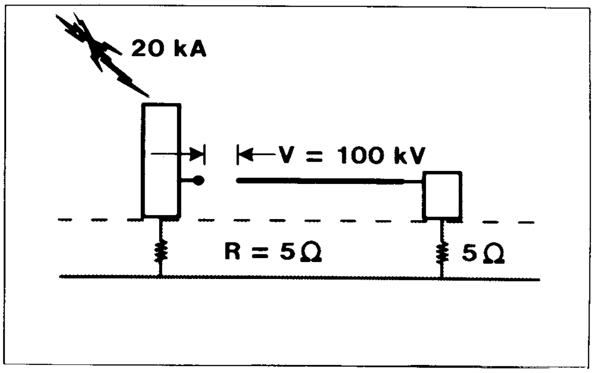

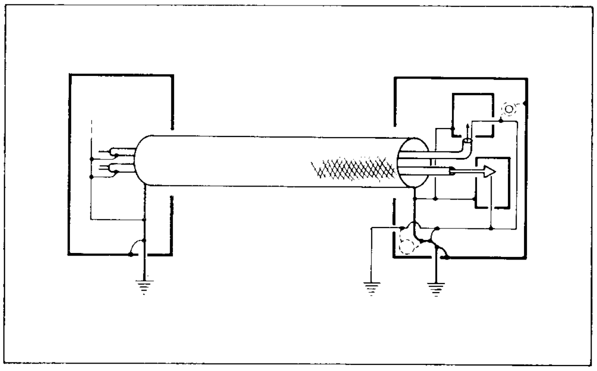

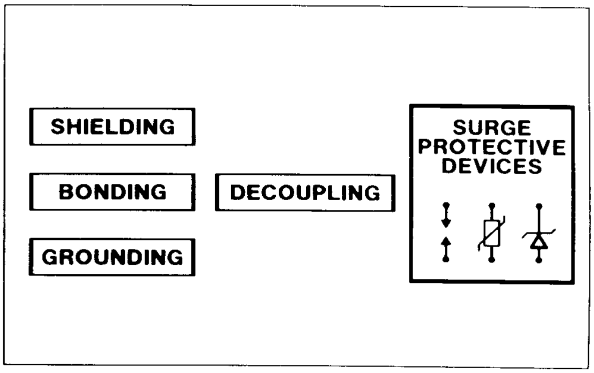
SHIELDING

BONDING

GROUNDING

DECOUPLING

SURGE PROTECTIVE DEVICES

SURGE TESTING

INTRODUCTION

Surge testing is very important in the successful application of surge protection devices for two reasons: (1) subjecting equipment to expected environmental surges makes possible an assessment of protection needs and (2) subjecting protective components to expected environmental surges makes possible an evaluation of component performance. Another aspect of surge testing also needs recognition, although it may be somewhat painful. A large portion of the surge protection engineer's work involves post-mortems, because even a conservative engineer will often push to the limit the optimization of low cost with performance and because a field failure is one way to calibrate the design limits. Confronted with the remains of a field failure (often obscured by the resulting effects of a transient-induced power-follow), the engineer must duplicate in the laboratory the effects of a field overvoltage before he can evaluate the effectiveness of a proposed retrofit or redesign.

Thus, for surge testing the engineer needs transient-generating equipment as well as transient-measuring equipment. The literature is fairly abundant on high-voltage techniques but scant on the transients and the circuits involving low-voltage electronics.

TRANSIENT MEASUREMENTS

Transient measurements in the laboratory are easier to obtain than are transient measurements for monitoring purposes, but precautions are nevertheless necessary – technical precautions to ensure the accuracy of the experiment and safety precautions to ensure the survival of the experimenter.

The fundamental tool for measurements is still the cathode-ray oscilloscope, although digital instruments are being improved in performance and convenience. Great advances over the cumbersome taking of photographs with a nonpersistent oscilloscope display have been made in fast-storage oscilloscopes that speed the examination of test data. Major oscilloscope manufacturers offer a wide choice of instruments, and their catalogues and application information are valuable for selecting the correct instrument. Where fast transients are involved, it is useful to remember that minor secondary oscillations, which may not be of any consequence to the circuit performance, tend to produce a very fast sweep of the electron spot, often making the trace invisible except at the peaks of the secondary oscillation and producing a dotted line trace rather than the clean record expected in principle. It is the clean oscillogram record that is valuable in understanding phenomena and that makes the oscilloscope the best friend (if trustworthy) of the engineer.

This trustworthiness of the oscilloscope can and should be tested by the engineer before he draws hasty conclusions from transient measurements. Here again the literature will provide guidance; in addition there are some simple checks: freedom from background noise and radiation into the oscilloscope preamplifiers, alertness to the pitfalls of the built-in delay line, proper compensation of attenuator probes, and avoidance of ground loops.

When repetitive transient tests are involved, digital instruments are valuable and require less operator training. For large evaluation programs, incoming or outgoing quality control, automated equipment is now available, either as separate monitors or in combination with the surge generators.

TRANSIENT (SURGE) GENERATORS

The basic surge generator is generally a charged capacitor, discharged through a wave-shaping circuit into the test piece. A variant can be a pulse-forming network providing a quasi-constant pulse form, generally of the flat-top variety. In some cases involving a current source, special circuits have been developed to provide constant-current, switchable power supplies.

Since most surge tests are based on some agreed upon standard, there are generally only a limited number of test waveshapes to be produced for a given application. Ideally, the surge generator should be so powerful that undesirable loading by the test piece could not occur. In some cases, however, loading of the circuit by the interaction of the generator source impedance and the test piece impedance is precisely the point of the experiment. Practical limitations also exist on the cost of a large-capacity machine, the difficulty in maintaining fast fronts for high-power impulses, and the safety hazards of large energy storage.

Some test standards include in their specifications the test circuit to be used; in that case the engineer has little choice except to build the circuit or to find a commercial equipment supplier of the gear. Other standards specify only the electrical characteristics of the impulse, leaving the exact test circuit to be determined by the laboratory engineer.

Traditionally, manufacturers of utility equipment have maintained competent staffs of laboratory engineers and technicians to perform the required tests. Such finely honed competence is not always found in the laboratories of electronics manufacturers, in part because the need has not been as obvious as it is in the high-voltage equipment. While it may be highly educational for the electronic engineer to build his own surge generator, the process can be frustrating and dangerous if safety precautions are not rigidly observed because many capacitors are not simply capacitors but have internal inductance, and inductors have stray capacitance. Instead of obtaining test results on his equipment, the busy engineer observes overshooting, ringing, and exploding carbon resistors. Thus, for purely economic reasons, the typical electronics engineer would be better advised to purchase a commercial surge generator, even if it is custom made. These are the reasons that an equipment demonstration has been included in the program.

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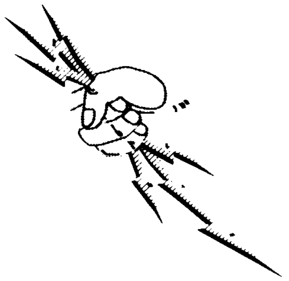
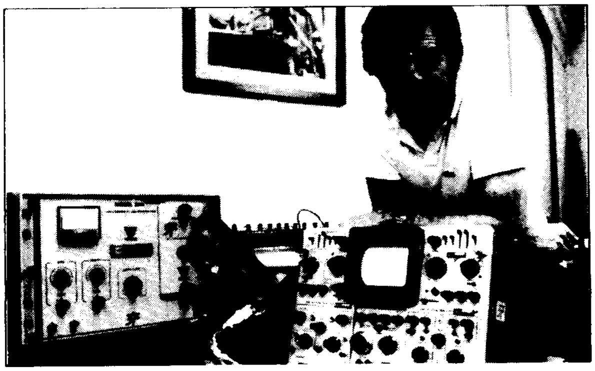
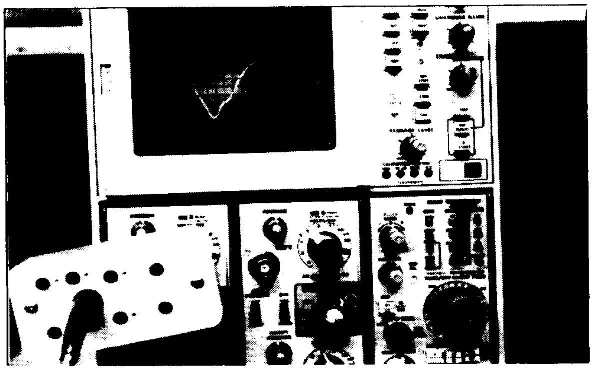


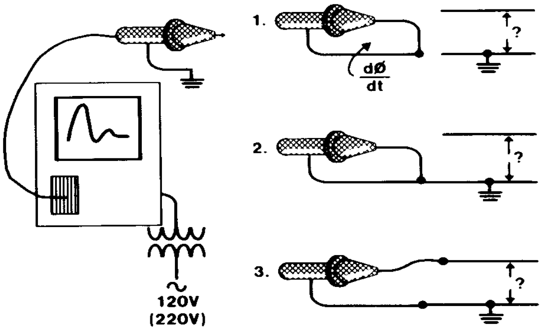
SURGE TESTING

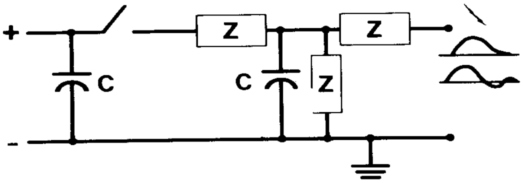
SURGE TESTING

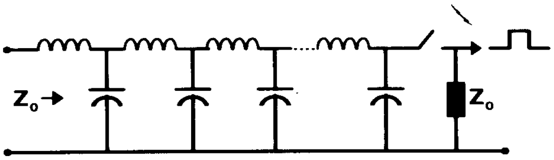
- EVALUATE DEVICE WITHSTAND
- EVALUATE PROTECTIVE DEVICES
- DUPLICATE FIELD FAILURES

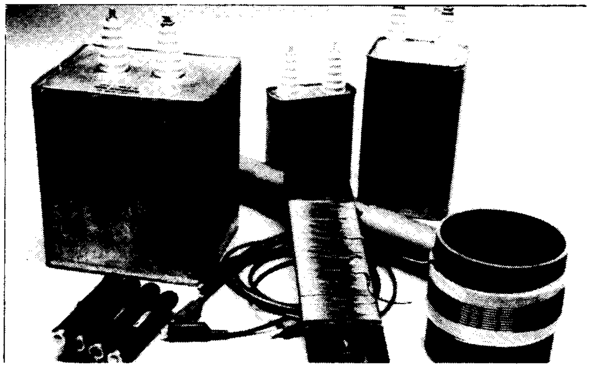


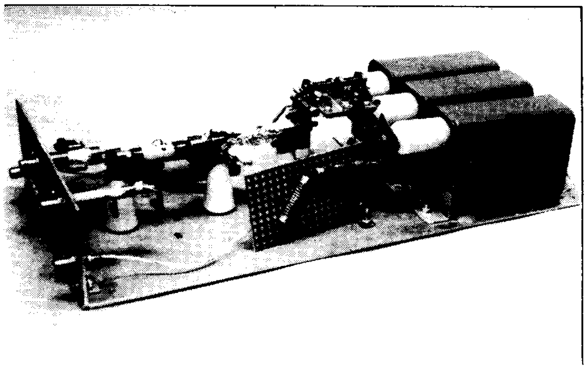


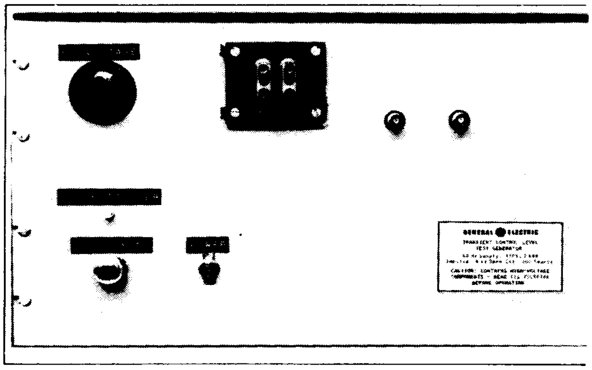











GENERAL ELECTRIC
TRANSIENT CONTROL LEVEL
TEST GENERATOR

TRANSIENT SUPPRESSORS

INTRODUCTION

Various devices have been developed for protecting electrical and electronic equipment against transients. 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 transients to acceptable levels or make them harmless by diverting them to ground.

There are two categories of transient suppressors: those that block transients, preventing their propagation toward sensitive circuits, and those that divert transients, limiting residual voltages. Since some of the transients originate from a current source, the blocking of a transient may not always be possible; the diverting of the transient is more likely to find general application. As we shall see in the section on coordination, a combination of diverting and blocking can be a very effective approach. This approach generally takes the form of a multistage circuit, where a first device diverts the transient toward ground, a second device – impedance or resistance – offers a restricted path to the transient propagation but an acceptable path to the signal or power, and a third device clamps the residual transient. 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.

Because technical and trade literature contains many articles on these devices, we shall limit the discussion of the details and refer the reader to the bibliography at the end of this section. We shall, however, make some comparisons to point out the significant differences in performance.

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 a new breed of 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 major advantage of the crowbar device is that its low impedance allows the flow of substantial surge currents without the development of high energy within the device itself; the energy has to be spent elsewhere in the circuit. This "reflexion" of the impinging surge can also be a disadvantage in some circuits when the transient disturbance associated with the gap firing is being considered. Where there is no problem of power-follow (discussed below), such as in some communication circuits, the spark gap has the advantage of very simple construction with potentially low costs.

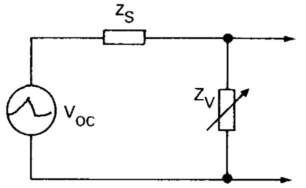
The crowbar device, however, has two major limitations. One is the volt-time sensitivity of the breakdown process. As the voltage increases across a spark gap, significant conduction of current – and hence the voltage limitation of a surge – cannot take place until the transition to the arc mode of conduction by avalanche breakdown of the gas between the electrodes occurs. The load is left unprotected during the initial rise because of this delay time (typically in microseconds). Considerable variation exists in the sparkover voltage achieved in successive operations, since the process is statistical in nature. This sparkover voltage, in addition, can 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, but it can be alleviated by filling the tube with a gas having a 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 circuits, clearing is even more uncertain. Additional means, therefore, must 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. This combination of a gap with a current-limiting, nonlinear varistor has been very successful in the utility industry as a surge arrester or surge diverter. The principles and applications of these devices will be examined in some detail in later paragraphs.

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. As far as their volt-ampere characteristics are concerned, these components are time-dependent to a certain degree. However, unlike the sparkover of a gap or the triggering of a thyristor, time delay is not involved.

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. 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 1). 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.



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

Figure 1. 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.

Varistors

The term ***varistor*** is derived from its function as a variable resistor. It is also called a ***voltage-dependent resistor***, but that description tends to imply that the voltage is the independant parameter in surge protection, a concept which we will contest repeatedly in this Seminar. Two very different devices have been sucessfully developed as varistors: silicon carbide disks have been used for years in the surge arrester industry, and, more recently, metal oxide varistor technology has come of age.

In silicon carbide varistors as well as in metal oxide varistors, the relationship between the current flowing in the device and the voltage appearing across its terminals can be represented approximately by a power function $I = kV^a$, where the higher the value of a, the more effective the clamping. Hence there has been a race between manufacturers and specification writers for higher and higher values of a. We will see, however, that there are practical limits to this race and that, in fact, better performance can be obtained at high current densities by departing somewhat from the large values of the exponent a.

In silicon carbide varistors, the physical process of nonlinear conduction is not completely understood, and the manufacturing of the material has remained an art, successful as it is. It seems that the process takes place at the tips of the grains of silicon carbide, held together by a binder. The story goes that the device action was found accidentally by having a grinding wheel on a disorderly work bench connected to an experimental circuit; for many years silicon carbide varistors indeed looked like grinding wheels, each complete with a hole in the center.

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. For more effective application of these devices, it is worthwhile for this purpose to consider their electrical behavior rather than details of the construction and solid-state physics involved.

ELECTRICAL CHARACTERISTICS OF VARISTORS

Because the prime function of a varistor is to provide the nonlinear effect, other parameters are generally the result of tradeoffs in design and inherent characteristics. The electrical behavior of a varistor can be understood by examination of the equivalent circuit of Figure 2. The major element is the varistor proper, R_V, whose I-V characteristic is assumed to be the perfect power law $I = k V^a$. In parallel with this varistor, there is a capacitor, C, and a leakage resistance, R_P. In series with this three-component group, there is the bulk resistance of the zinc oxide grains, R_S, and the inductance of the leads, L.

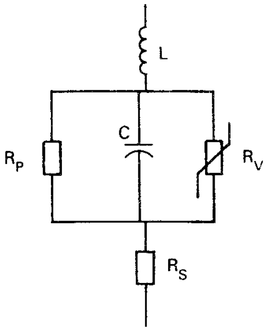


Figure 2. Equivalent Circuit of a Varistor

Under dc conditions (at low current densities because obviously no varistor could stand the high energy deposited by dc currents of high density), only the varistor element and the parallel leakage resistance are significant. Under pulse conditions at high current densities, all but the leakage resistance are significant: the varistor provides low impedance to the flow of current, but eventually the series resistance will produce an upturn in the V-I characteristic; the lead inductance can give rise to spurious overshoot problems if it is not dealt with properly; the capacitance can offer either a welcome additional path with fast transients or an objectionable loading at high frequency, depending on the application.

V-I Characteristic

When this V-I characteristic is plotted on a log-log graph, the curve of Figure 3 is obtained, with three regions as shown, resulting from the dominance of R_P, R_V, R_S as the current in the device goes from nanoamperes to kiloamperes.

This V-I characteristic is then the basic application design tool for selecting a device in order to perform a protective function. For a successful application, however, other factors, which are discussed in detail in the information available from manufacturers, must also be taken into consideration. Some of these factors are the selection of the

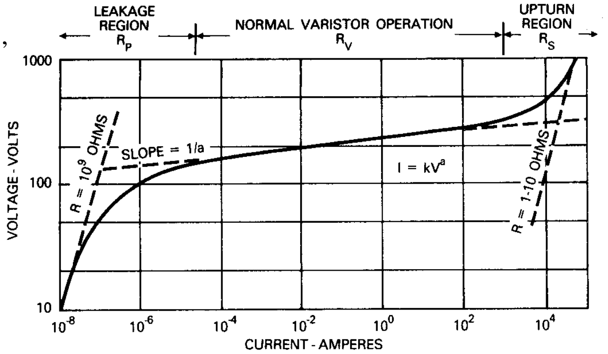


Figure 3. Typical V-I Characteristic

appropriate nominal voltage for the line voltage of the application, the selection of energy-handling capability (including source impedance of the transient, waveshape, and number of occurrences), heat dissipation, and finally, proper installation in the circuit. In fact, enough instances of poor installation practices have been observed, and enough questions have been raised on alleged "overshoot" that a brief discussion of lead effects is in order.

Overshoot: A Lead Effect

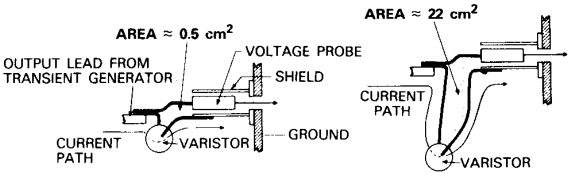
To illustrate the effect of lead length on the overshoot, two measurement arrangements were used. As shown in Figures 4(a) and 4 (b), respectively, 0.5 cm^2 and 22 cm^2 of area were enclosed by the leads of the varistor and of the voltage probe.

The corresponding voltage measurements are shown in the oscillograms of Figures 4 (c) and 4 (d). With a slow current front of 8μs, there is little difference in the voltages occurring with a small or large loop area, even with a peak current of 2.7 kA. With the steep front of 0.5 μs, the peak voltage recorded with the large loop is nearly twice the voltage of the small loop. (Note on Figure 4 (d) that at the current peak, L di/dt = 0, and the two voltage readings are equal; before the peak, L di/dt is positive, and after, it is negative.)

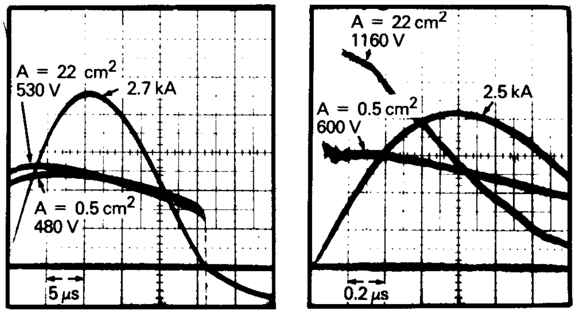
Hence, when one is making measurements as well as when one is designing a circuit for a protection scheme, it is essential to be alert to the effects of lead length (or more accurately of loop area) for connecting the varistors. This warning is especially important when the currents are in excess of a few amperes with rise times of less than 1 μs.

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 by 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 to 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.



(a) Minimal Loop Area (b) Excessive Loop Area



(c) Current Rise of 8 μs (d) Current Rise of 0.5 μs

Figure 4. Effect of Lead Length on Overshoot

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 protective 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).

COMPARISONS OF PROTECTIVE DEVICES

Linear Versus Nonlinear Devices

When a protection scheme is designed for an electronic system operating in the environment which is not completely defined (as discussed in the first part of this Seminar), it is often necessary to make an assumption about the parameters of the transients expected to occur. In particular, if an error is made in assuming the source impedance of the transient, the consequences for a linear protective device and for a nonlinear protective device are dramatically different, as demonstrated by the following comparison.

A SIMPLIFIED COMPARISON BETWEEN PROTECTION WITH LINEAR AND NONLINEAR SUPPRESSOR DEVICES

Assume an open-circuit voltage, V_{OC}, of 3000 V (See Figure 1).

1. If the source impedance is $Z_S = 50\ \Omega$ with a suppressor impedance of $Z_V = 8\ \Omega$, the expected current is

$$I = \frac{3000}{50 + 8} = 52\ \text{A}$$

$$V_R = 8 \times 52$$

$$= 416\ \text{V}$$

The maximum voltage appearing across the terminals of a typical nonlinear V150LA20A varistor at 52 A is 285 V.

Note that:

$$Z_s \times I = 50 \times 52 = 2600\ \text{V}$$

$$V_R \times I = 8 \times 52 = \underline{835\ \text{V}}$$

$$\text{OCV} \simeq 3000\ \text{V}$$

2. If the source impedance is only 5 Ω (a 10:1 error in the assumption), the voltage across the same linear 8 Ω suppressor is:

$$V_R = 3000 \frac{8}{5 + 8}$$

$$= 1850\ \text{V}$$

However, the nonlinear varistor has much lower impedance; again, by iteration from the characteristic curve, try 450 V at 500 A, which is correct for the V150LA20A:

$$Z_s \times I = 5 \times 500 = 2500\ \text{V}$$

$$V_R = \underline{450\ \text{V}}$$

$$V_{oc} \simeq 3000\ \text{V}$$

which justifies the trial selection of 500 A in the circuit.

3. Results:

Protective Level Achieved	Assumed Source Impedance	
	50 Ω	5 Ω
Linear 8 Ω	416 V	1850 V
Nonlinear Varistor	385 V	450 V

Spark Gap Versus Varistor

The choice between these two devices will be influenced by the inherent characteristics of the application. Where power-follow is a problem, there is little opportunity to apply a simple gap. Where very steep front transients occur, the gap alone may let an excessive voltage go by the "protected" circuit until the voltage is limited by sparkover. Where the capacitance of a varistor is objectionable, the low inherent capacitance of a gap seems attractive. If very high energy levels can be deposited in a varistor, compared to the lower levels inherent with the crowbar action of a gap, a high-capacity surge arrester may be required, with a combination of a lower clamping voltage varistor farther into the circuit (see Applications of Transient Protection).

Avalanche Diode Versus Varistor

The basic performance characteristics of these two devices are similar, and therefore the choice may be dictated by clamping voltage requirements (the avalanche diode is available at lower clamping voltages), by energy-handling capabilities (the avalanche diode is generally lower in capability per unit of cost), and by packaging requirements (the varistor material is more flexible and does not require hermetic packaging).

Conventional Surge Arresters Versus Gapless Arresters

Surge arresters (diverters) have reached a high degree of sophistication over the years by using precision gaps in series with silicon carbide varistors. For high voltage applications the arrester is made of a stack of modules, generally of 3 or 6 kV each. With the use of current-limiting gaps, the clearing of power-follow current in dc application was made possible. A series gap was required in all these arresters using silicon carbide because, for a set discharge voltage and discharge current, the standby current at the power frequency would otherwise be excessive.

With the advent of metal oxide varistors, the high exponent of the V-I characteristic reduced the standby current to a very low level, one that can be tolerated by the varistor under steady-state condition. The series gap can thus be eliminated, producing three considerable improvements: in performance (elimination of abrupt sparkover); in reliability (elimination not only of the gap and all trigger circuitry but also of the parallel voltage-grading varistors); and in contamination withstand (elimination of effects of leakage current on the outer shell).

In low-voltage circuits, where secondary arresters using gaps were heretofore the only devices capable of meeting the ANSI requirement of a 10 kA, 8/20 discharge current, high-energy varistors are now capable of meeting this requirement, without the problems associated with series gaps.

CONCLUSIONS

Surge protective devices are available for protecting low-voltage electronics. Two basic types offer different characteristics: crowbar devices have high-current capability but generally involve power-follow when applied on a power system; voltage clamping devices, either silicon avalanche or varistors, are free from the power-follow problem.

Avalanche diodes offer low clamping voltage, which makes them most suitable for low-voltage, low-power electronics. Metal oxide varistors are now available in a wide range of clamping voltages and energy-handling capacities. Each of these devices has its own best field of application, insuring greater reliability of the circuits in the not-quite-defined electromagnetic environment of power and communication systems.

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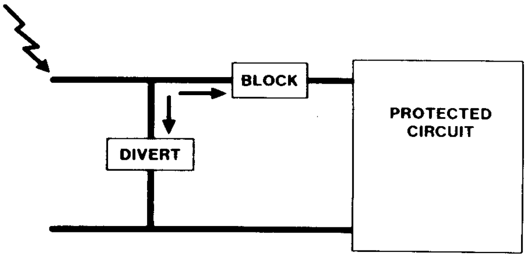
TRANSIENT SUPPRESSORS

- SUPPRESSORS
- LIMITERS
- CLAMPS
- DIVERTERS
- ARRESTERS
- PROTECTORS
- PROTECTIVE DEVICES

GAPS	• CARBON BLOCKS • GAS TUBES • ROD GAPS • ....CLEARANCES !
NON LINEAR RESISTORS	• SILICON CARBIDE • METAL OXIDE VARISTORS
SEMI-CONDUCTORS	• SELENIUM RECTIFIERS • SILICON AVALANCHE DIODES
LINEAR	• RESISTORS • CAPACITORS

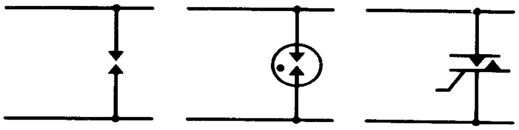


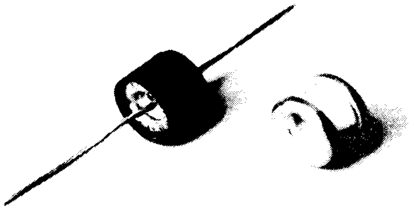
BLOCK

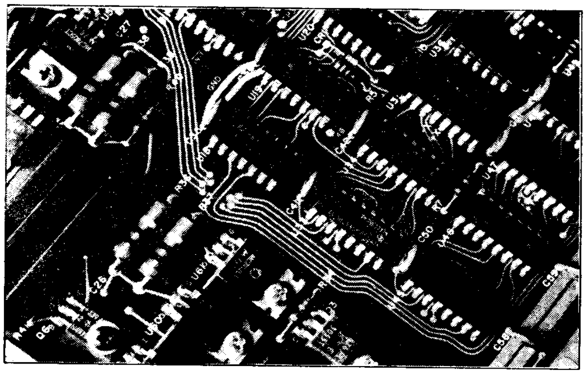
DIVERT

PROTECTED CIRCUIT

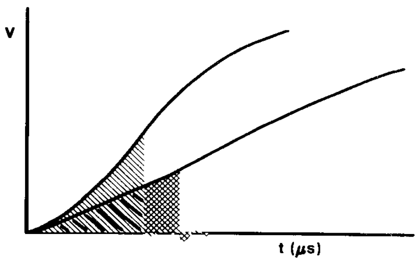
CROWBAR



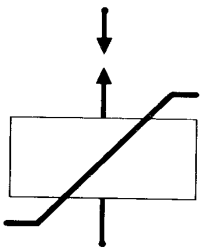


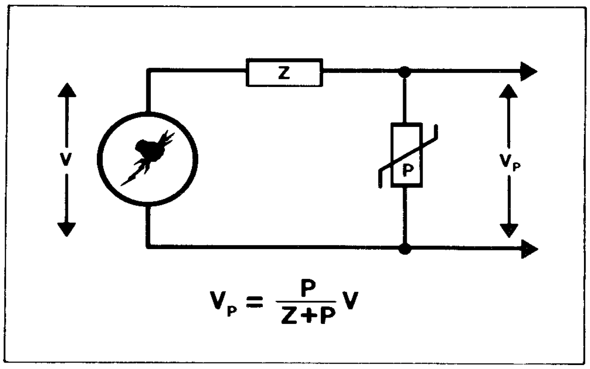


CROWBAR



ARRESTER (DIVERTER)

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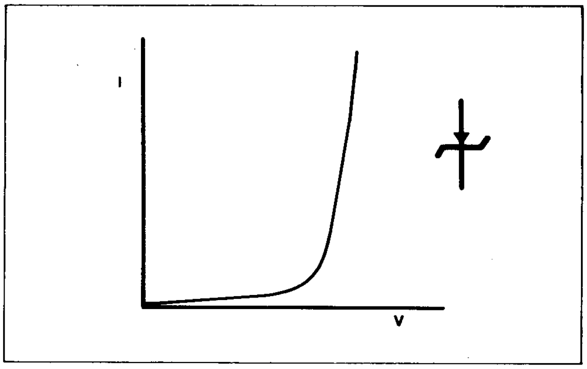
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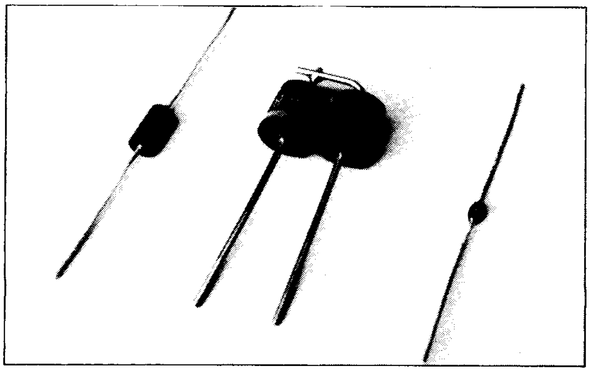
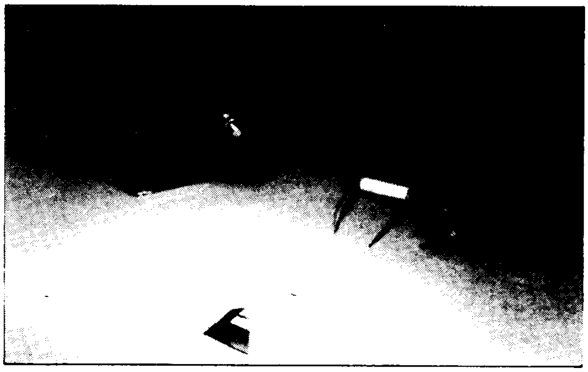
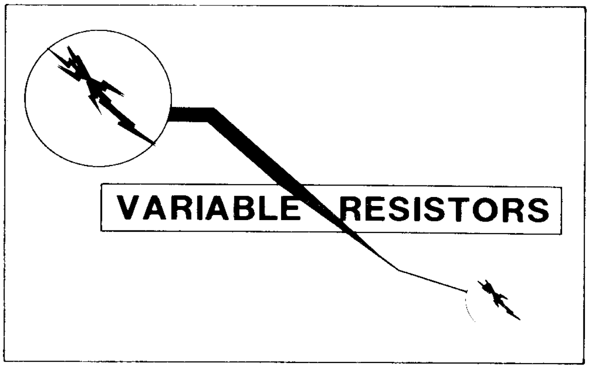
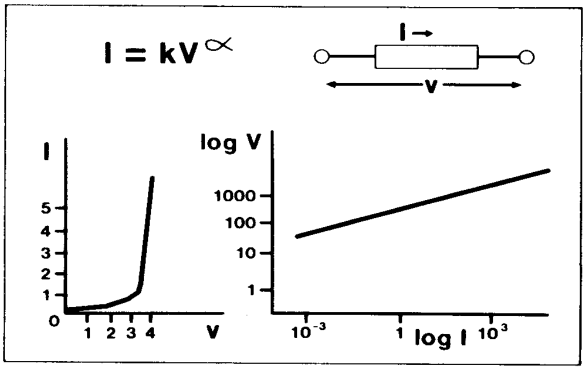





VARIABLE RESISTORS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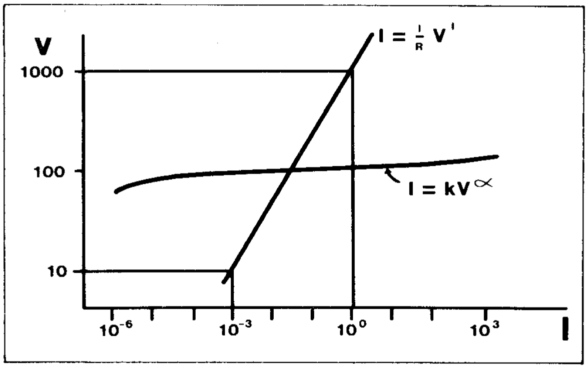
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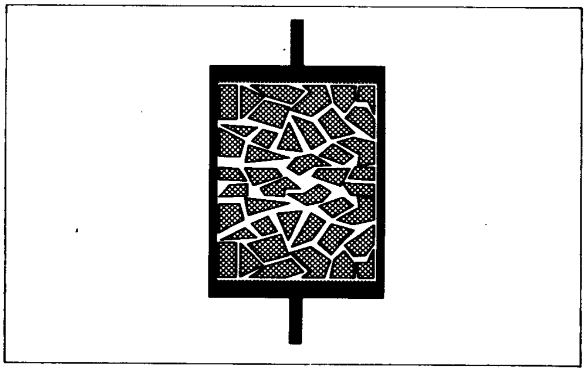

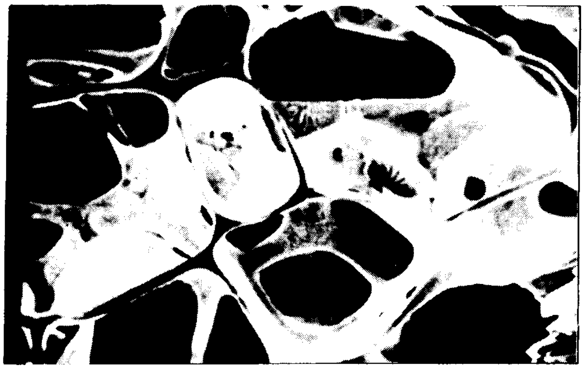

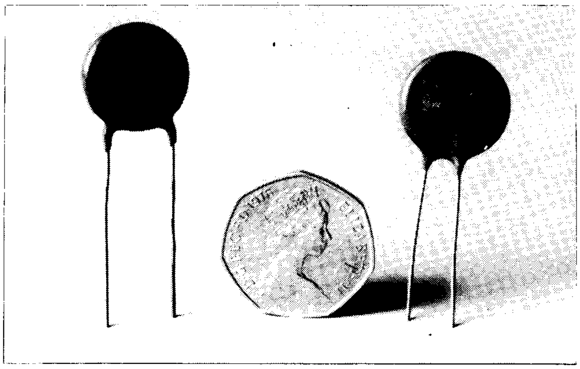

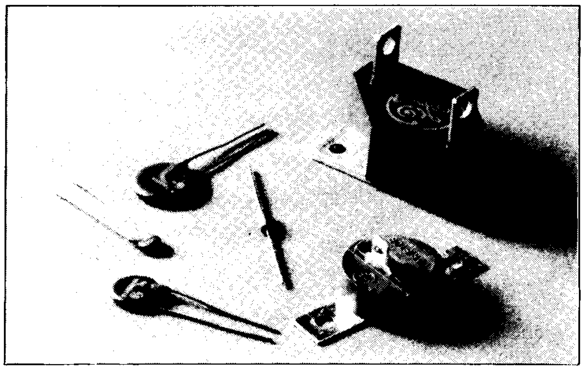

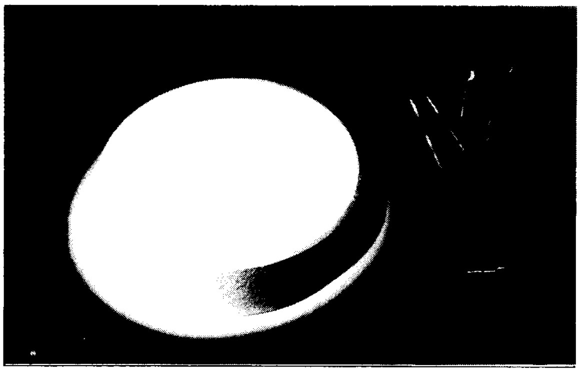

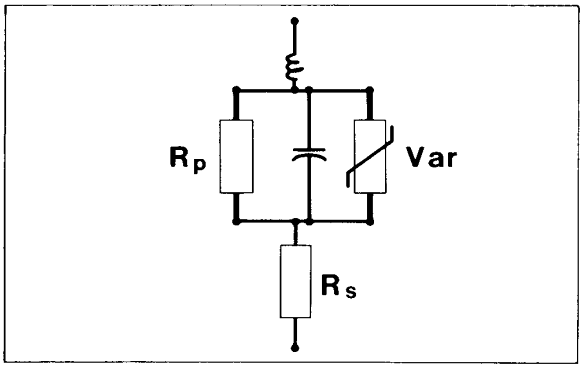
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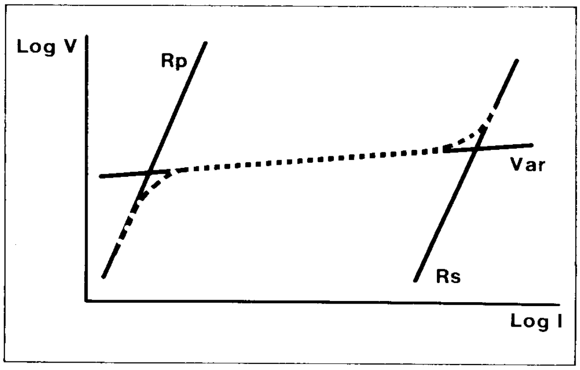
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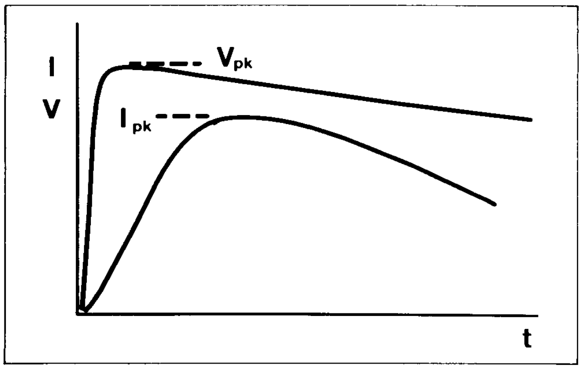
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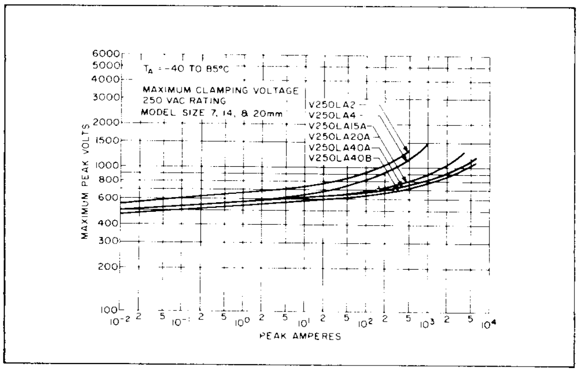
TA = -40 TO 85°C
MAXIMUM CLAMPING VOLTAGE
250 VAC RATING
MODEL SIZE 7, 14, & 20mm
V250LA2
V250LA4
V250LA15A
V250LA20A
V250LA40A
V250LA40B
MAXIMUM PEAK VOLTS
6000
5000
4000
3000
2000
1500
1000
800
600
400
300
200
100
10-2
2
5
10-1
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101
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102
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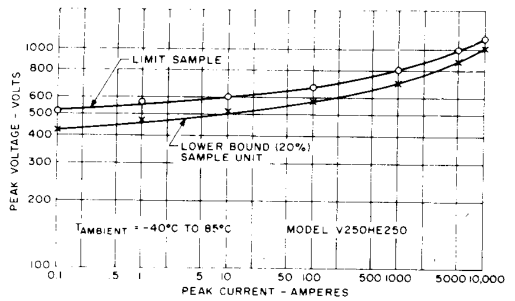
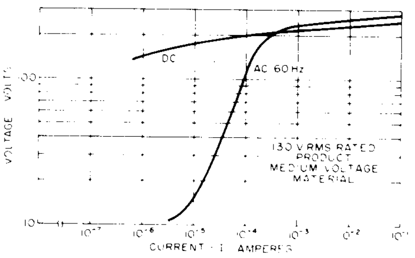
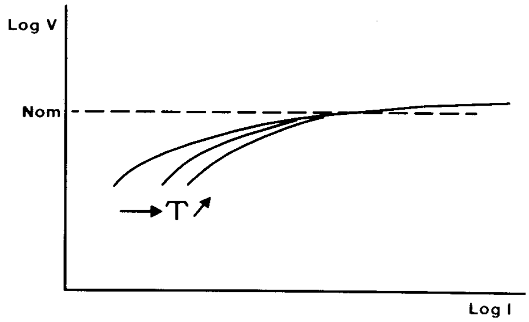
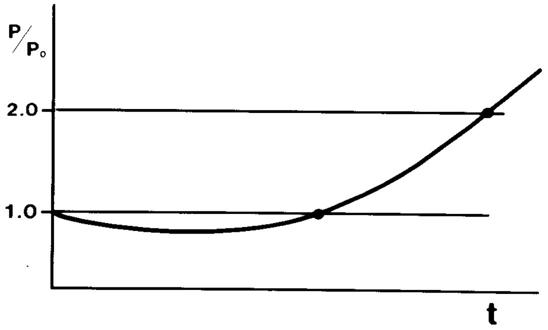
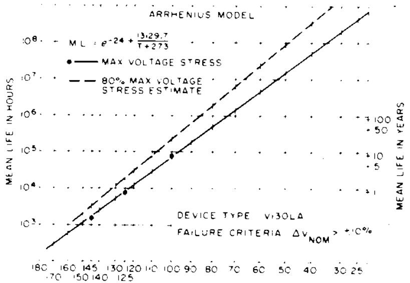
103
2
5
104
PEAK AMPERES

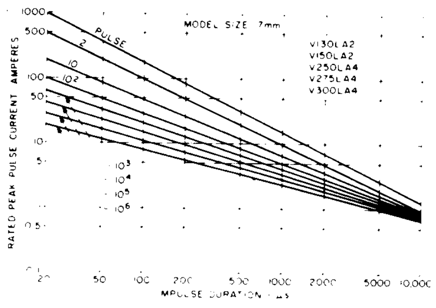




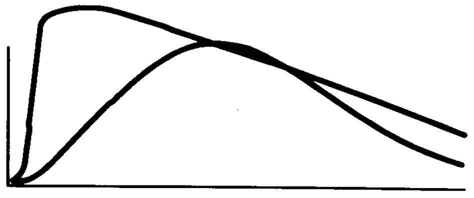


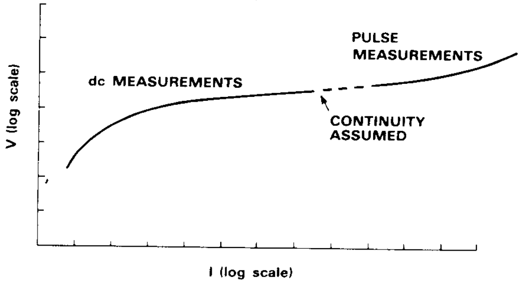


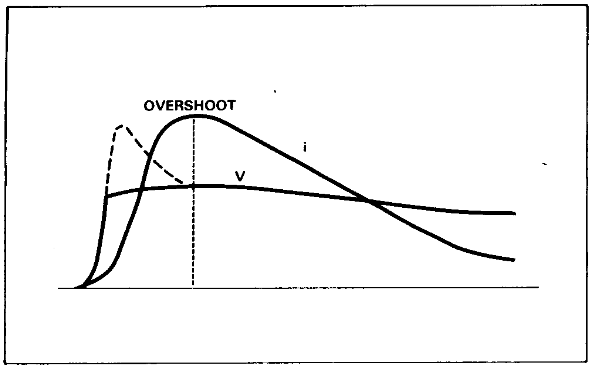


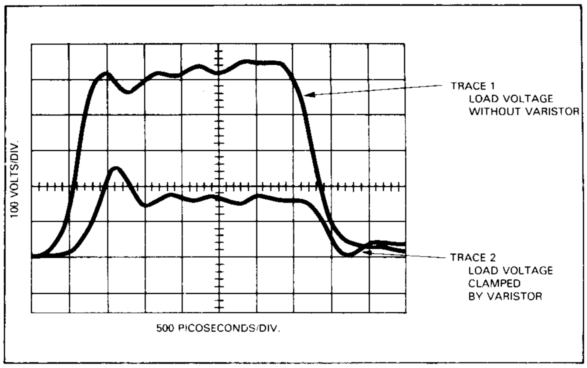


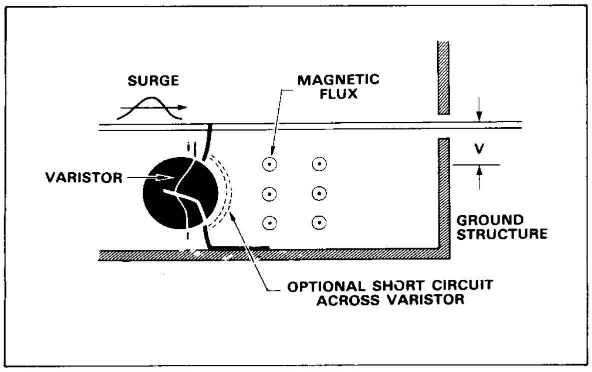
VARISTOR OVERSHOOT
- A LEAD EFFECT -

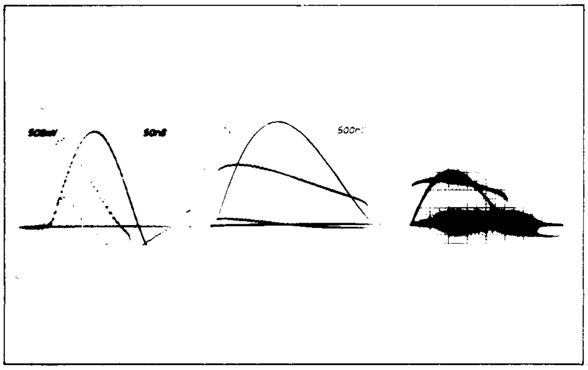


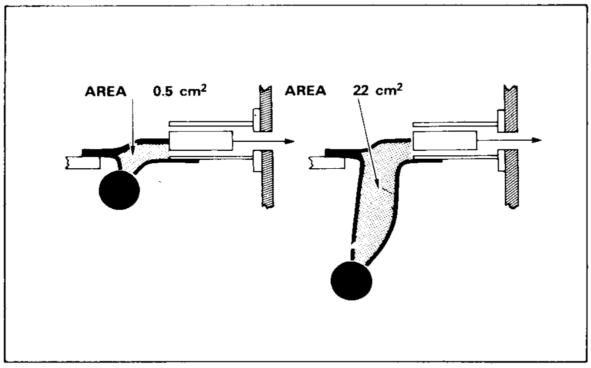




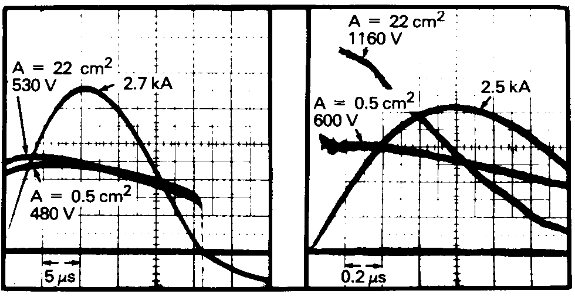




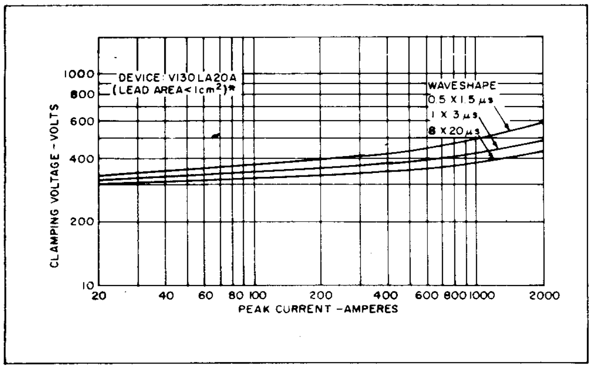




(a) Minimal Loop Area (b) Excessive Loop Area



(c) Current Rise of 8 μs (d) Current Rise of 0.5 μs



FAILURE MODES

FAIL-SAFE - NO NO

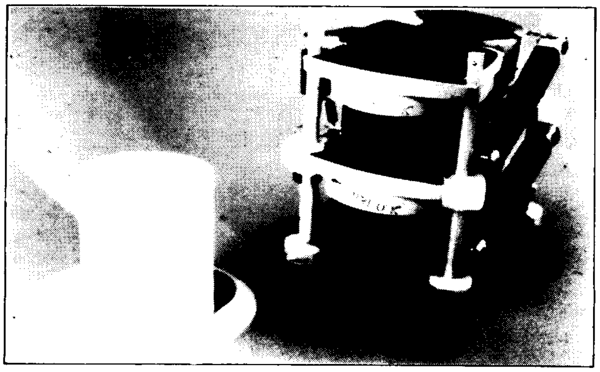
FAIL OPEN - ✓

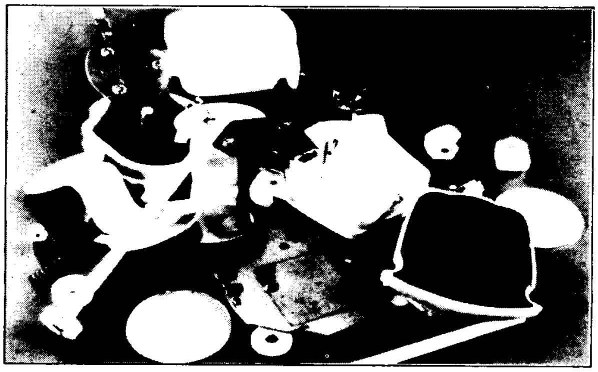
FAIL SHORT - ✓

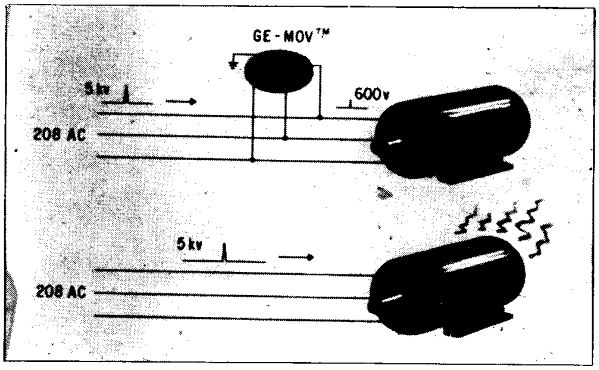
COMPARISONS

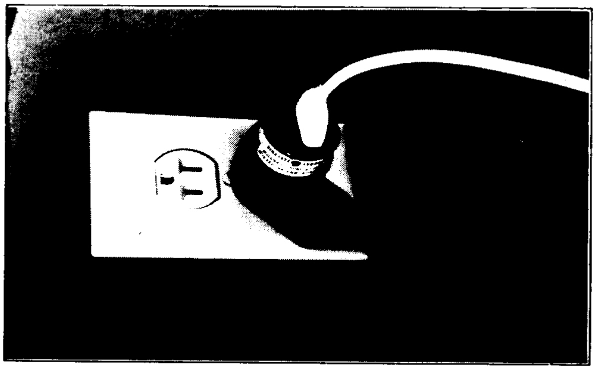
LINEAR VS NONLINEAR
GAP VS VARISTOR
AVALANCHE DIODE VS VARISTOR
GAP VS GAPLESS ARRESTER

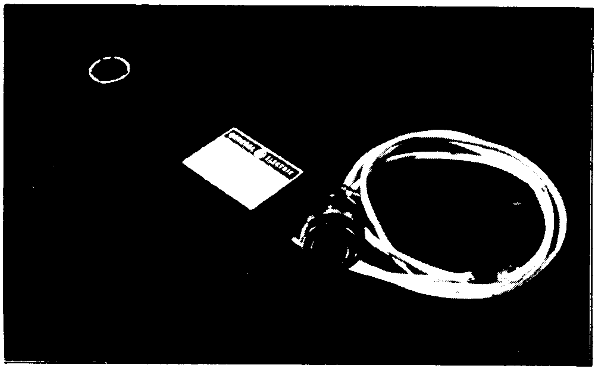
GAPS	VARISTORS (DIODES)
LOW IMPEDANCE ARC: HIGH CURRENT	CLAMPING VOLTAGE: POWER DISSIPATION
LOW CAPACITANCE	NO ABRUPT CHANGE
POWER - FOLLOW	NO POWER FOLLOW

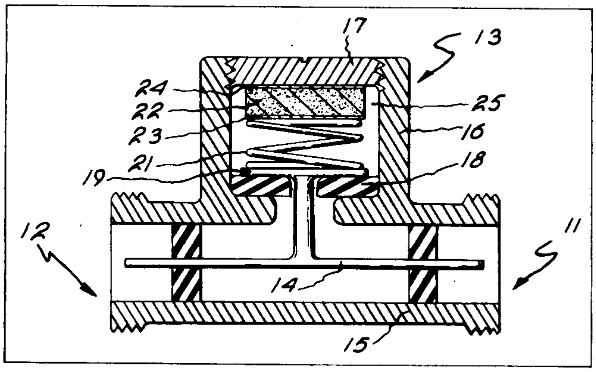


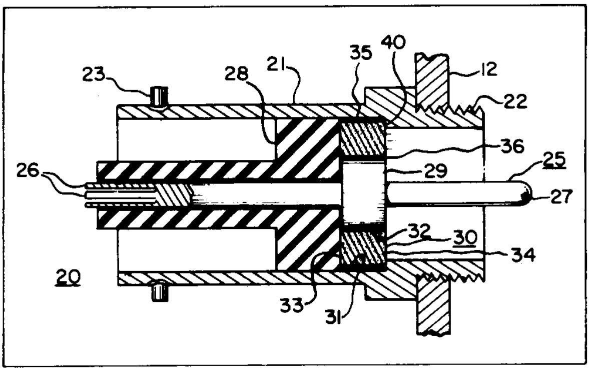








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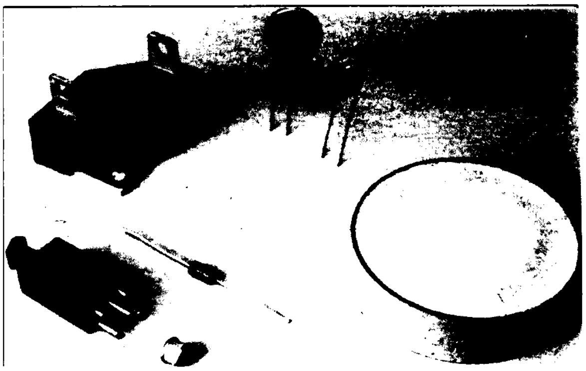


APPLICATIONS OF TRANSIENT PROTECTION

INTRODUCTION

Applications of surge protective devices for transient protection involve two situations: the retrofit of protection into an appliance or system found vulnerable in the field (too often the common situation) and the initial design of protection in a new product (hopefully the result of seminars such as this). Before looking into some specific examples of applications, it is worthwhile for us to examine a concept which could solve the problem of transient protection: the Transient Control Level system proposed to the electrical and electronics community in the U.S.A. (1) and in Europe (2). We shall then examine three fields where transient protection schemes have been applied with different devices and different degrees of success, and conclude with an appeal for the coordination of protective devices on a system-wide basis.

THE TRANSIENT LEVEL CONTROL CONCEPT

Until recently there did not appear to be a clear approach for achieving compatibility between the transient withstand capability of devices and the transients to which such devices are exposed. This situation was somewhat like that which prevailed many years ago in the electric power industry. Transients produced by lightning frequently caused failure of such vital and expensive power equipment as transformers and generators. Those transient problems were solved by engineering design guided by the concept of insulation coordination and the establishment of a series of Basic Insulation Levels (BILs). At present the Transient Control Level concept of testing and coordination promises a solution to the problem of compatibility.

According to the Transient Control Level concept, instead of retrofitting protective devices into a finished product or design, the first step is to determine at what level the transients occurring in the system can be limited by suitable protective devices. It is then sufficient to build the equipment to withstand only that level established by the protective device. The result is a well-defined situation, with adequate margins between the maximum level of transients and the demonstrated withstand capability of the equipment. The specific proposals made in that concept are the following.

1. That there be defined for electronic equipment (and other low-voltage equipment) a standard transient voltage similar in concept to, but different in waveshape from, the 1.2/50 μs wave used in the coordination of insulation in high-voltage power apparatus.

2. That there be defined for electronic equipment (and other low-voltage equipment) a series of TCLs similar in concept to the BILs.

3. That a start be made on assigning one of these standard levels to individual electronic components and electronic devices.

4. That individual protective devices be rated in terms of their ability to control transients to levels no greater than, and preferably lower than, one of the above levels.

5. That equipment and procedures be developed by which equipment may be tested by vendors to determine which TCL is appropriate to assign to individual components and equipment.

6. That TCLs begin to be used in purchase specifications.

7. That such equipment and procedures be used by purchasers to evaluate vendor-supplied equipment to determine its compliance with such purchase specifications.

8. That such TCLs begin to appear in regulatory specifications for consumer apparatus in which the consumers cannot make the appropriate tests or prepare appropriate specifications.

The engineering community in the U.S.A. responded favorably to the proposal, and some of the concepts found their way into the IEEE Working Group Guide discussed in the first section of this Seminar (3). With the writing of Application Guides by the IEEE as well as the IEC, there is an opportunity to advance the proposal further.

EXAMPLES OF APPLICATIONS

Communications

The communications systems, primarily the telephone installations, were successful in protecting the subscriber as well as the central station equipment against overvoltages as long as mechanical switching equipment was used. However, the increasing use of semiconductors creates a potential problem which is recognized by most equipment manufacturers and telephone operators but which has not been solved at this time.

The long success story of spark gaps, carbon blocks or gas tube protectors, has created a situation where specifications of environment and device capability are intermeshed to the point where one is not quite sure which came first. Therefore any proposal to apply new protective devices in these circuits is likely to confront a requirement for meeting specifications to fit the capability of spark gaps but not necessarily the capability (and limitations) of the candidate replacement. Nevertheless, there is a great need to apply surge protective devices capable of clamping surges at voltages well below the capability of the old-time spark gaps used to protect old-time electromechanical equipment.

Carbon block protectors are still widely used in telephone systems. The reasons for this continued use are technical as well as economic. Technically, the carbon block has provided satisfactory performance in protecting the equipment, and the line voltage and short-circuit current conditions after the crowbar action of the block allow clearing of the circuit. This would not be the case with a power line. Economic reasons include the cost of replacing on a large scale an existing device, still obtainable at low cost, by a technically better device which may be more expensive. Nevertheless, there is a trend to replace carbon blocks by gas tubes, and some telephone companies make it a routine procedure to substitute a gas tube protector for the old carbon block whenever a serviceman is on the premises for some other reason.

The unsettled controversy over two-electrode versus three-electrode gaps remains. The issue is that different sparkover voltages of two separate two-electrode gaps used to protect a two-wire system can transform a common-mode transient impinging on the circuit into a more damaging line-to-line transient during the interval separating sparkover of the first gap and sparkover of the second gap. Three-electrode gaps avoid the problem because both lines are almost instantly connected to ground whenever one of the two line-to-ground gaps contained in the same envelope sparks over. The problem would disappear if varistors were used for this protective function.

One of the requirements for protectors in the telephone systems is that the power-frequency current associated with fallen wires or induced voltages be conducted through the protector for a specified time, or a specified I^2t, corresponding to the melting of the wire connecting the incoming cable to the main frame. This requirement is often met by providing a heat-sensitive element in combination with the protective device. The combination produces a direct short circuit and removes the protective device from the current path, either in a resettable mode or in a destructive mode making the protector expendable but protecting the equipment while failing. Such a combination has the strength of successful experience with carbon blocks, but it has yet to be tried with realistic goals for varistors. Current requirements in the U.S.A. vary from a few amperes for several seconds to a few hundred amperes for a few cycles. In Europe the CCITT recommends 3 levels, 5, 20, and 50 A, for repeated durations of 1s at each current level (4).

Of course a significant part of the telephone plant exposure involves the power supplies connected to the power system. These are not essentially different from any electronic system supplied by the power grid; the discussion for that subject is given under the heading "Mains."

Another exposure involves the growing number of customer-owned terminal equipment (teletypes, computer terminals, recorders, and dialers) connected on one side to the telephone line and on the other side to the local mains. Insufficient withstand capabability of this equipment on the mains side could present some risk to the telephone system, so that, in the U.S.A. for instance, strict withstand requirements have been specified by the Federal Communications Commission: 2.5 kV, 1/10 μs, with a short-circuit capability of 1 kA (5).

As solid-state electronics are applied in the switching equipment, well inside the central station system, surge protective devices are also applied to the inputs of these circuits. This additional protective device, downstream from the protective device at the cable entrance, is generally referred to as a secondary protection, the primary protection being at the cable entrance. A potential problem exists if the secondary protection has such a low voltage level that it will prevent the primary protection from sparking over and thus become subjected to the full surge current. Examples of coordination approaches will be given later in this section to illustrate the concept.

Automotive Circuits

Overvoltages occurring in automotive circuits (6, 7) have durations ranging from microseconds to minutes. Overvoltage can be a steady state condition in the case of a regulator failure or quasi-steady state with 24 V booster starts. Clearly, no voltage-clamping device can limit these overvoltages, nor would a crowbar allow operation of the system while it is being short circuited by the crowbar. From a list of overvoltages published by the Society of Automotive Engineers (SAE) (8), the longest duration which may be amenable to treatment as a transient overvoltage is the so-called load dump, which is the accidental disconnection of the battery while charging is proceeding at a high rate. Voltages in the order of 125 V can occur, involving energy depositions of 10 J or more. Such high depositions occur infrequently but often enough to mandate that protection be provided. At the other end of the range, repetitive transients occur in the ignition circuit, with only a few volts but with high repetition rates.

Two examples of protection against these extreme cases are described in detail in the *Transient Voltage Suppression Manual* (9) and thus will be mentioned only briefly here. For the convenience of the reader, the detailed calculations have been included in the Appendix. Figure 1 shows the circuit of a solenoid driver, for which the most harmful overvoltage would be the load dump condition. Varistors could be connected in Positions A or B; analysis for each position involves simple calculations of the current flowing in the varistor and the resulting clamping voltage, with consideration of the impulse duration and number of expected occurrences in the lifetime of the system.

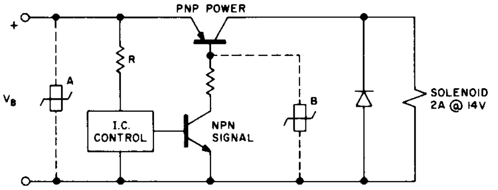


Figure 1. Protection of a Solenoid Driver with Two Candidate Locations

After evaluating the two positions with several candidate varistors, the designer reaches the conclusion that Position B is the preferred location, with a recommendation of a V24ZA50 or V24ZA60 varistor.

Figure 2 shows the circuit for a typical electronic ignition circuit where the switching transistor needs to be protected against overvoltages associated with the energy stored in the ignition coil. Detailed numerical analysis, starting with the coil current parameters, yields a specific recommendation for a candidate varistor protection, a V220MA2A or a V270MA4B varistor in this example.

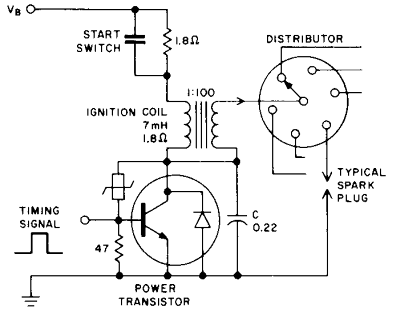


Figure 2. Typical Electronic Ignition Circuit

Protection Against Transients in the Mains

Protection against transients in the mains is the field in which varistors have found their most effective role, and at this time a large fraction of varistor production is applied to this function (10, 11). Even in the high-voltage electric utility field the advent of metal oxide varistors is expected to have considerable impact (12), but a detailed discussion of high-voltage surge arresters (diverters) is beyond the scope of this Seminar.

A major reason for the effectiveness of protection by varistors is the absence of the power-follow problem, a problem which makes the application of gaps impossible on circuits having high power-frequency short-circuit currents. The bilateral conduction of varistors, as opposed to the polarized single direction of avalanche diodes, also makes them cost-effective in ac power circuits.

At the present time, there is no mandatory protection specification on low-voltage mains, in contrast to the BIL concept mentioned earlier for the primary utility systems. Should the Transient Level Concept become standard practice on all low-voltage distribution systems, the situation would be quite different, but the problem is that each appliance or each industrial load may require individual protection as long as there is no central protective device installed at the service entrance. Publications such as the *Guide on Surge Voltages* (3) can provide guidance to manufacturers of electronic appliances or instruments that will be connected to the mains, in making an economic tradeoff between no system protection – with some attendent expected failure rate – and protection for each piece of equipment – at an appreciable cost but with a substantially lower expected failure rate.

The result of the present uncontrolled situation may be a proliferation of surge protective devices in a given household or industrial circuit, for each equipment manufacturer may assume that he alone is to provide protection – that is, that he cannot depend on the user to provide central protection and therefore he must build protection into his equipment. This proliferation is not only an obvious waste but also a potential problem because the protective device installed in a piece of equipment – similar to the secondary protection of the telephone – might assume the role of primary protection if its clamping voltage is lower than that of the device (if any) installed at the service entrance. Thus, proper coordination of protective devices in low-voltage circuits should be a high-priority goal in the efforts of standardizing bodies, manufacturers, and regulatory agencies.

The situation is made more confusing by the role played by the sparkover of wiring devices in limiting the transient overvoltages in low-voltage systems. There is evidence that the clearances in wiring devices in some systems can spark over, providing protection without producing a power-follow fault. Thus the field experience is influenced by this unintentional protective function which occurs in some installations but not in others. Relying on uncontrolled sparkover for protection is hazardous because there are three possible outcomes to a clearance sparkover:

1. A power-follow current occurs with destructive effects on the components.
2. A power-follow current occurs, but overcurrent protection (breaker or fuse) limits the damage. The system can be restored to operation after a mere nuisance interruption.
3. No power-follow current takes place; the overvoltage protective function of the system can be considered as accomplished.

The concept of protecting solid insulation by allowing clearances to spark over first is actively promoted by the Low Voltage Insulation Coordination Subcommittee of the International Electrotechnical Commission (13). The concept is worth attention because cost reductions and system reliability can be obtained but only where it is properly applied.

PROTECTION COORDINATION

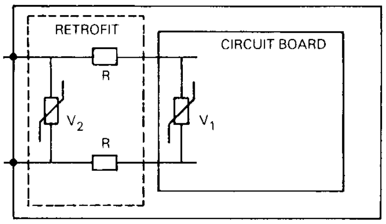
By protection coordination we mean a deliberate selection of two or more protective devices used with the goal of reliable protection at minimum cost. With the present situation of unregulated and uncoordinated application of protective devices, this may seem an unattainable goal for complete systems. In specific cases, however, it is fully attainable, as the three examples that follow 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 independant 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 combined approaches, a series impedance is sometimes added in the circuit, but only after a low-impedance diverting path has first been established.

Retrofit of a Control Circuit Protection

In one retrofit case history, a field failure problem was caused by the lack of awareness, at the time the original circuit was designed, of the hostility of the environment in which the circuit was to be installed. A varistor had been provided on the printed circuit board of the device, to protect the control circuit components, but its capability was exceeded by the surge currents occurring in that location (Category B of the *Guide on Surge Voltages* [3]).

Because 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 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 3). Laboratory proof-test of the retrofit demonstrated the capability of the combined scheme to withstand 6 kA crest current surges (Figure 4A), a 200% margin from the proposed Category B requirement, as well as reproduction of the field failure pattern (Figure 4B). The latter is an important aspect of any field problem retrofit. Simulation in the laboratory of the assumed surges occurring in the field and subsequent verification of the failure mechanism are the first steps to an effective cure. Figure 4C illustrates the effect of improper installation of the suppressor, with 20 cm of leads instead of a direct connection across the input terminals of the circuit.

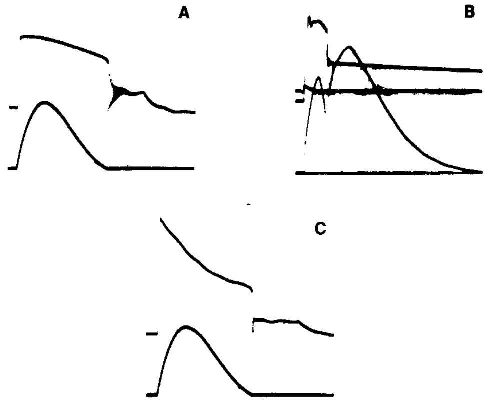


V1: V150LA1 varistor
V2: V150LA20A varistor
R: 10Ω, 1W carbon resistor

Figure 3. Retrofit Protection of Control Circuit

Coordination Between an Arrester and a Varistor

The example described here involves a load circuit for which the maximum transients had to be limited to 1000 V (on a 120 V ac line) although lightning surges were expected on the



A Upper trace: Voltage across V150LA1 varistor on PC board, 200 V/div.
Lower trace: Surge current, 2000 A/div.
Sweep speed: 10 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: 10 µs/div.

C Same as Figure 4A, but with varistor mounted on 20 cm leads from terminal board.

Figure 4. Laboratory Demonstration of Retrofit Effectiveness

incoming service. The only arresters available at the time which could withstand a 10 kA crest, 8/20 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, with 8 m of typical two-wire cable between the arrester and the varistor. The current, approximately 8/20 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 sparks 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.

Lightning Surge Injection into Ground

A lightning surge current flowing in the ground of a power system can induce substantial overvoltages in the phase wires of the system without having these phase wires directly involved in conducting the lightning current. To illustrate this situation, a laboratory simulation circuit was set up (14), under the following valid assumptions:

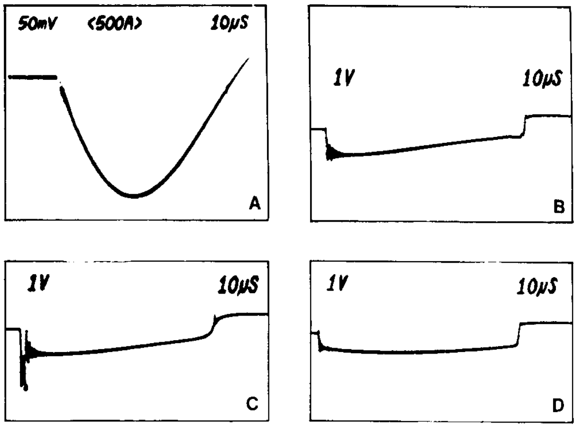


Figure 5. Transfer of Conduction

1. A 100 kA lightning strike terminated on the overhead primary circuit causing flashover to ground or sparkover of an arrester at the pole. This 100 kA represents a severe occurrence, not exceeded in more than 5% of all lightning strokes (15).
2. Seventy percent of this current is assumed to flow into the ground at the pole and into the next two pole grounds, leaving 30 kA to flow into the service entrance in question (Figure 6).
3. The service overhead entrance has the phase wires wrapped around the ground wire.

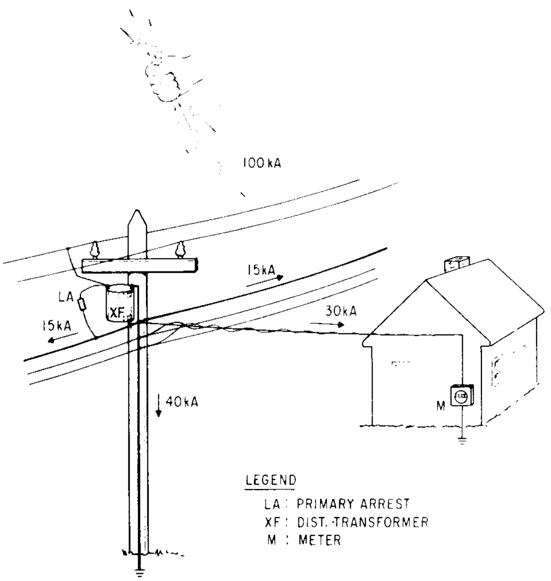


Figure 6. Distribution of Surge Currents

Accordingly, a series of 8/20 current impulses was injected into a representative wiring system, consisting of a service entrance box with circuit breakers and branch circuits terminating at wall receptacles. Provision was made to connect a secondary arrester at the service box or, alternatively, a high-capacity varistor with a low-capacity varistor at the outlet - the latter typical of a consumer's electronic package. Some of the interesting observations made during this test series follow. First, the injection of a unidirectional 8/20 surge current into the ground conductor of the service entrance caused oscillatory voltage transients in the phase-to-ground outlets within the 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., as if a direct lightning stroke occurred in the distribution system outside the building. Table 1 shows some of the values recorded.

Table 1

RESULTS OF SURGE INJECTION TESTS

Current Injected into Ground of Service Entrance	Observations Inside the "Building"
1.5 kA	• With open-circuit, a 2200 V crest at 500 kHz occurs at 6 m from entrance. • With 130Ω load, a 1400 V crest with fast damping occurs at the same point.
10 kA	• 8 kV open-circuit voltage in wiring produces sparkover of the clearances of the wiring devices.
30 kA	• An arrester connected at the service entrance discharges about 3.5 kA between the phase conductors and ground.

From the first and second observations, one can compute an approximate equivalent source impedance for the 1.5 kA surge:

$$
\begin{aligned}
Z &= 130\Omega \left[\frac{2200}{1400} - 1\right] \\
&= 75\Omega
\end{aligned}
$$

The second test level, 10 kA, produced flashover (or sparkover)* at voltage levels which are predictable for the type of wiring devices being used. Ironically, the better the wiring device, the higher the overvoltage imposed on the system; the poorer the wiring device, the lower the overvoltages, provided that this sparkover of the device clearance will not produce a power-follow.

The third test level, representing a very severe occurrence with very low probability at any one location, did not, however, threaten the integrity of an arrester designed to ANSI standards for secondary arresters.

CONCLUSIONS

Applications of surge protectives devices can be retrofit protection following field problems or preventive protection against possible problems.

Although the Transient Control Level concept has not yet gained full acceptance, it should be actively discussed and promoted in order to attain more cost-effective application of protective devices.

Coordination of protective devices will become a more important task as more protective devices are installed in "parallel" across the mains. Effective coordination does require matching the characteristics of protective devices with the source impedance as well as the impedance separating the two protective devices.

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*A distinction may be made between flashover and sparkover, although dictionary definitions are not quite clear. Sparkover tends to imply the action of a controlled device, such as a surge protective device, while flashover tends to imply an undesirable breakdown of the air in a clearance or along the surface of an insulator.

APPENDIX

APPLICATIONS OF VARISTORS TO AUTOMOTIVE CIRCUITS*

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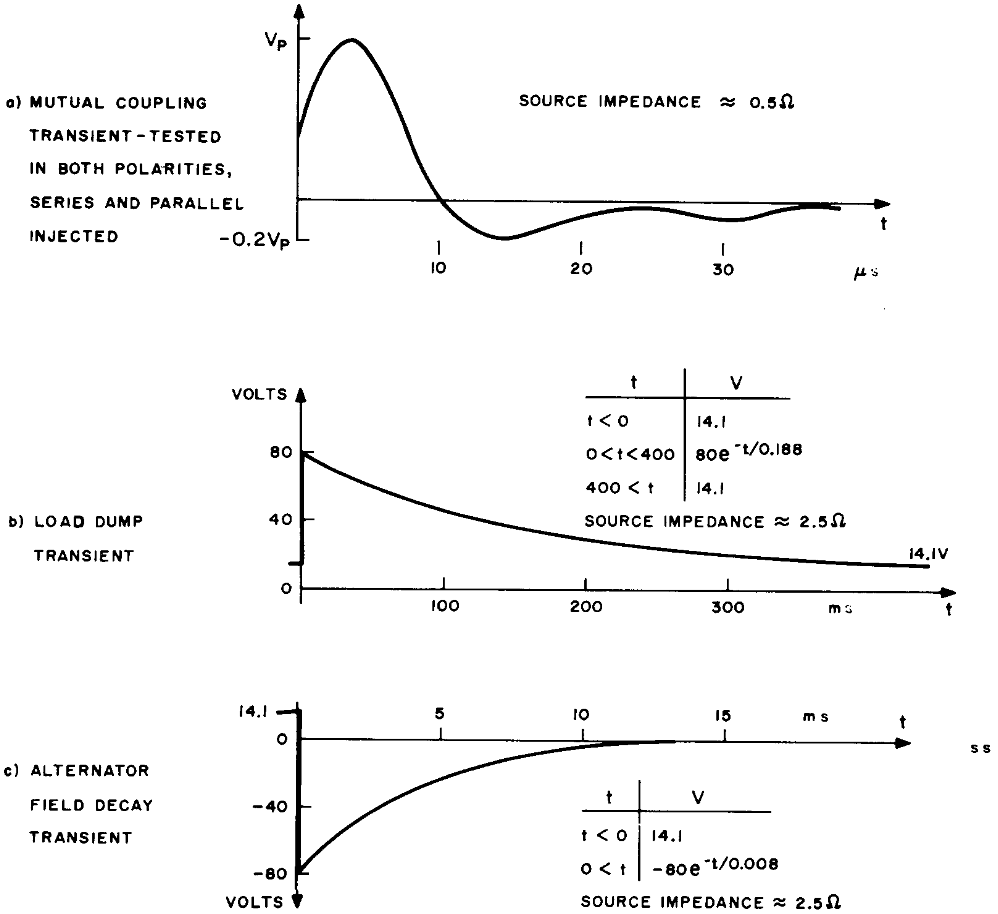
6.2 VARISTOR APPLICATIONS

To illustrate the procedures involved in designing transient protection for automotive electronics, two examples are provided. One example illustrates the protection of a solenoid driver circuit consisting of a logic integrated circuit with power transistor buffer; the second is the protection of an ignition circuit output transistor. These examples also illustrate the difference between protecting against random and repetitive transients. For random transients, energy and clamping vs. standby power dissipation are dominant constraints. For repetitive transients, transient power dissipation places an additional constraint on the choice of the suppression device. The solenoid driver protection circuit also illustrates the conflicting constraints placed on automotive transient suppressors by the low maximum voltage ratings of integrated circuits, the 24V jump start cycle and the load dump transients.



t	V
t < 0	14.1
0 < t < 400	$80e^{-t/0.188}$
400 < t	14.1

t	V
t < 0	14.1
0 < t	$-80e^{-t/0.008}$

NOTE:
Amplitudes, impedances, and time constants vary, depending on the specific electrical system considered and the system loading.

FIGURE 6.2: SEVERE TRANSIENT TEST WAVEFORMS (FROM SAE PROPOSED TEST PROCEDURES[2])

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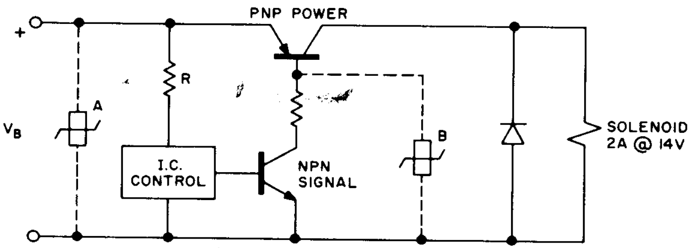
*Section 6.2, Transient Voltage Suppression Manual, Second Edition, Auburn, N.Y. 13201, General Electric Company, U.S.A. 1978, pp. 74-78.

6.2.1 Protection Of A Solenoid Driver

The first example considers a 5 V integrated circuit, with internal shunt regulator, which drives a two-transistor buffer amplifier. The transistors and circuit configuration have been selected to minimize interfacing of the I.C. to sensors and voltage drop to the solenoid. The internal shunt regulator in the I.C. is specified for operation between 10 and 75 mA, which limits the value of R and the maximum transient voltage which can be applied:



SYSTEM SPECIFICATIONS		
CONDITION	V_B	R_{SOURCE}
NORMAL	12V TO 16V	0.1Ω
15 S JUMP START	24V	1Ω
0.18 S LOAD DUMP	80 V	2.5Ω

FIGURE 6.3: EXAMPLE 1
EVALUATE A VS. B FOR VARISTOR EFFECTIVENESS AND COST
SOLENOID DRIVER – CIRCUIT TRANSIENT PROTECTION SELECTION

$$R_{\text{maximum}} = \frac{12-5}{0.01} = 700\,\Omega;$$

which in a standard value becomes 620 Ω ± 5%. This limits the input voltage to R, using the low tolerance extreme value of R, i.e., 589 Ω, to:

$$V_{\text{maximum}} = 5 + 0.075\,(589) = 49 \text{ Volts}$$

Analysis of the system constraints indicates that the load dump transient, the 24 V jump start, and the 16 V "high line" voltage will be the limiting factors on varistor selection, so this example will just consider these conditions. In *Position A,* under load dump, the varistor must clamp to 49 volts maximum at:

$$I_{\text{varistor}} = \frac{80-49}{2.5} = 12.4\text{A}$$

The example assumes a load dump source with a Thevenin equivalent open circuit voltage similar to Figure 6.2b. When load dump transient simulator is loaded by a suppressor device the time constant of voltage decay changes and the new time constant can be calculated as follows. With a circuit source impedance of 2.5 Ω, and assuming that the typical clamping voltage will be 10% below maximum or 44V, the instantaneous resistance of R_v of the suppressor is given by the ratio:

$$\frac{R_v}{R_v + 2.5} = \frac{44}{80}$$

Solution of the above yields a value of 3.1 Ω for R_v. This value changes as the transient current decays, but assume that a representative value occurs at 70% of peak current. The effective value of R_v is then 4.4. The transient simulator discharge circuit consists of an internal capacitor of 0.023F with a parallel internal 16Ω discharge resistor. The parallel external discharge path consists of the effective suppressor resistance, 4.4 Ω, in series with the source impedance, 2.5 Ω. The voltage decay time constant then is calculated to be 0.11s. The suppressor current waveform also will decay in an exponential manner but with a somewhat shorter time constant.

It is now clear that V24ZA50 and V27ZA60 are candidates since they satisfy requirements for maximum clamping voltage, continuous dc voltage rating, and transient dc voltage (jumpstart) rating. It is necessary only to verify that peak current and impulse duration are within the limits shown on the pulse lifetime rating graph of the specifications. To find these values a worst case condition will be assumed by estimating that minimum clamping voltage is 20% below the maximum value shown on transient V-I characteristic curves in the specification sheets. Peak varistor current then can be calculated as illustrated previously. Although the rate of decay of varistor current is not known, the time to half value of peak current can be found from the known decay of simulator voltage, V_o. The instantaneous voltage is:

$$V_o = 80 \exp(-t/0.11)$$

which is also equal to the voltage drop across the source impedance plus the varistor voltage. At half peak current this condition can be expressed as:

$$V_o = 2.5\, I_p/2 + V_c \text{ min.}$$

Impulse duration, t, now can be calculated by combining these two equations and solving for t.

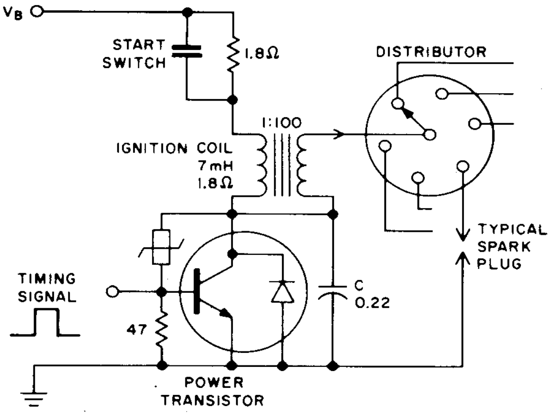
By drawing load lines on the transient V-I characteristic curves and deducting 20% from the maximum clamping voltages, the estimated minimum clamping voltages for V24ZA50 and V27ZA60 are respectively 35V and 38V at peak currents of 17.6A and 16.4A. At half peak current the estimated minimum voltages are respectively 33V and 36V. Solving for impulse duration gives 40ms and 38ms respectively. By placing these values on the pulse lifetime rating graph it is apparent that both types are within rating; however, the V27ZA60 allows somewhat greater margin on the impulse rating as well as on continuous and transient dc voltage ratings. The V24ZA50 would be used where a lower clamping voltage is needed than the example.

In Position B the use of the varistor is analyzed in the same manner. Since the varistor now turns on the PNP power transistor, it carries a lower current and must clamp to about 1 V lower to compensate for the transistors $V_{BE(SAT)}$. Assuming the transistor saturates to a V_{CE} of 1 V or less during the transient, the current loop solution indicates that 5.6A flows through the varistor at 48V, while 6.8A flows through the solenoid. This verifies the saturated condition assumed for the power transistor, as it operates with a forced gain of 1.2. Obviously, this position is preferred for the varistor since the energy of the load dump transient is shared between the varistor and the solenoid. The smaller V24ZA4 varistor also can be examined for possible use in this position. The minimum clamping voltage is estimated at 39V at 10.4A, with a minimum of 36V at half peak current. Impulse duration is calculated to be 52ms. When these values are placed on the pulse lifetime rating graph it is apparent that they are beyond ratings. Therefore, it is concluded that a V27ZA60 or V24ZA50 should be used in this example with position B as the preferred location.

6.2.2 Protection Of Electronic Ignition

In the second example the protection of the output power transistor in an electronic ignition circuit is analyzed. This power transistor performs the current switching function of mechanical distributor points in the usual Kettering ignition, thus avoiding the pitting, burning, and erosion mechanisms associated with the mechanical points. The ignition circuit is illustrated in Figure 6.4.

In normal operation the coil primary current builds up when the power transistor is on, storing energy in the coil inductance. The power transistor is then switched off, and the voltage at the collector rises rapidly as the capacitor, C, charges. Transformer action causes the secondary voltage to rise until the spark plug reaches firing voltage, truncating the transistor collector voltage at a safe value for the transistor. If a spark plug is fouled or disconnected, the collector voltage can rise until either the capacitor contains the stored energy (minus losses), or the transistor breaks down with resulting damage. Since the capacitor is small, transfer of the stored energy of the coil to the capacitor would result in a very high voltage requiring transistor protection. A varistor can be used to turn the transistor on during the period of high voltage, thus dissipating the excess energy safely as heat. The constraints on varistor selection are: clamp voltage must be low enough to protect the transistor; clamp voltage must be high enough to not affect normal spark energy; the power dissipation (with two spark plugs disconnected) must be within varistor ratings for an 8-cylinder, 4-cycle engine at 3300 rpm (misfires at 55 Hz, average). The minimum spark voltage output required is 20,000V, which represents 200V at the transistor collector. The transistor has a breakdown voltage



SYSTEM CONDITIONS		
CONDITION	V_B	START SWITCH
RUNNING	12V TO 16V	OPEN
STARTING	5V TO 12V	CLOSED

OPERATING TEMPERATURE RANGE
-40°C TO +110°C

FIGURE 6.4: EXAMPLE 2
TYPICAL ELECTRONIC IGNITION CIRCUIT

rating of 400V with the 47Ω base emitter resistor and a current gain over 20. The base emitter on-state voltage, $V_{BE(ON)}$, is between 1.0 and 1.8V, and the collector to emitter saturation voltage is between 0.9 and 1.5V. The varistor clamp voltage range is determined by the 200V needed to supply minimum spark voltage and the 400V rating of the transistor. At 200V the varistor current must be less than:

$$V_{BE(ON)}/47\Omega = \frac{1V}{47\Omega} = 0.02A$$

to prevent unwanted transistor turn-on. The minimum varistor voltage at the 1mA varistor specification point is found by solving the varistor voltage equation:

$$I = kV^{\alpha},$$

assuming a maximum α of 40. The result is 186V. The peak clamping current (at 400V – $V_{BE(MAX)}$) is found from the energy balance equation for the coil, using the peak coil current, I_C. I_C maximum is analyzed under both start and run conditions to determine the worst case:

$$I_{C(start)} \leqslant \frac{12 - 0.9}{1.8} = 6.17A$$

and,

$$I_{C(run)} \leqslant \frac{16 - 0.9}{3.6} = 4.2A$$

The worst case coil current occurs with the start switch closed and will be less than 6.2A. The maximum peak coil current, I_p, when clamping is then:

$$\tfrac{1}{2}L\ I_c{}^2 = \tfrac{1}{2}L\,I_p{}^2 + \tfrac{1}{2}C\ V_p{}^2$$

and with a V_p of 400V:

$$I_{p2} = I_C{}^2 - 400^2\ C/L$$

results in 6.0A starting and 3.6A running. The varistor currents corresponding to this are:

$$I_p/h_{FE} + V_{BE}/47\Omega;$$

which gives 0.34A starting and 0.22A running. Peak varistor voltage must be less than:

$$400V - V_{BE}\ \text{(i.e., 398V at 0.34A)}$$

The varistor power dissipation at 3300 rpm (55 pps), assuming a triangular current waveform with constant voltage and no losses, is found from coil energy balance:

$$\tfrac{1}{2} L (I_p)^2 = V_{MAX} \frac{I_p}{2} t$$

solving for t:

$$t = \frac{7 \times 10^3 \ H (3.6A)}{400V} = 63 \mu s$$

The varistor power dissipation is found to be:

$$V_{MAX.} \frac{I_p}{2} tf = 398V \frac{0.22A}{2} 63 \times 10^{-6} \ s \ (55 \ pps) = 0.15W$$

Observations indicate that the losses in the coil and reflected secondary load will reduce this by half to about 75mW. Using the 110°C ambient temperature derating factor of 0.53, it is found that a varistor of 0.15W dissipation capability is required. The varistor parameters are now defined as V_x of at least 186V at 1mA but less than 398V at 0.34A and capable of at least 0.15W dissipation. The V220MA2A and V270MA4B both fit these requirements.

As these examples have illustrated, the use of the GE-MOV® varistor in automotive circuits for transient protection is both technically and economically sound. Design procedures are identical to the procedures used in the other environments. Experimental verification of the degree of protection can be made using standard waveforms reported by automotive engineering investigators.

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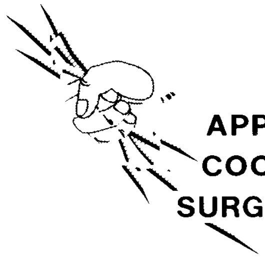


APPLICATION AND COORDINATION OF SURGE SUPPRESSORS

APPLICATIONS

- RETROFIT
- NEW PRODUCT
- TRANSIENT CONTROL LEVEL
- EXAMPLES
- COORDINATION

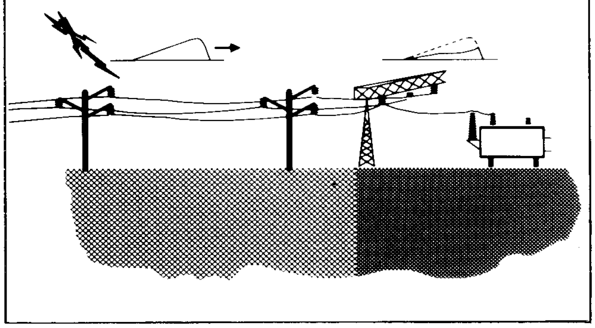
TRANSIENT CONTROL LEVELS

HOW THINGS STAND NOW

- EQUIPMENT IS BUILT
- INSTALLED ..... FAILS
- AH - HA!! - TRANSIENTS -
- ADD SUPRESSORS

QUESTIONS

- SHOULD USER CONTROL TRANSIENTS ?
- SHOULD MANUFACTURER BUILD TRANSIENT-PROOF EQUIPMENT ?
- OR - SHOULD BOTH USER AND MANUFACTURER SHARE THE TASK ?

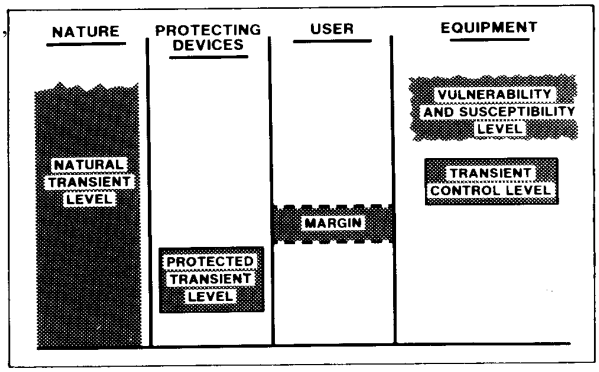


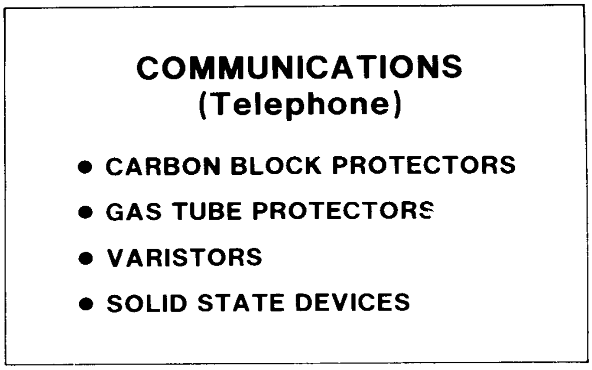
WE PROPOSE (THE PHILOSOPHY)

- TEST TO PROVE DESIGN
- SELECT LEVEL
- VOLTAGE AND CURRENT
- STANDARD WAVE SHAPES
- HOW TO MAKE TEST

WE PROPOSE (THE PROOF TEST)

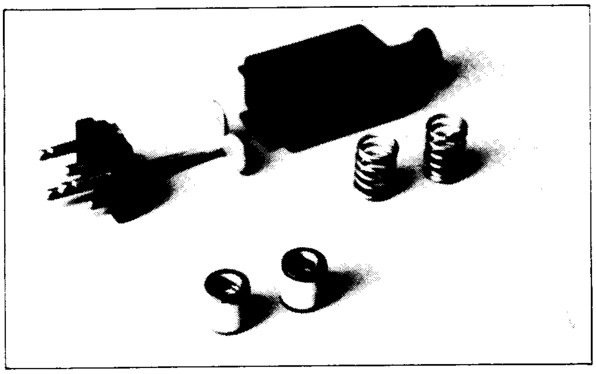
- SERIES OF STANDARD TCL
- LIMITED NUMBER
- ALL INPUT/OUTPUT LINES
- FIT TYPE OF CIRCUIT
- FIT PROTECTIVE DEVICES

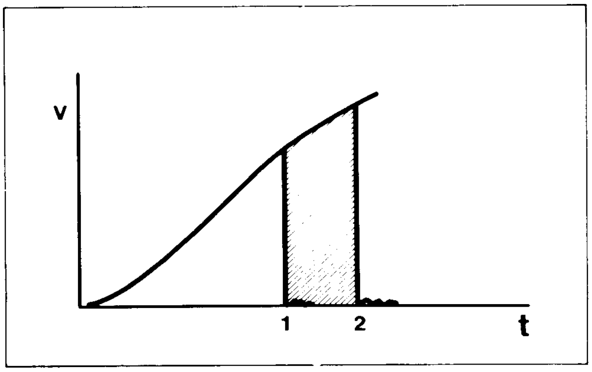


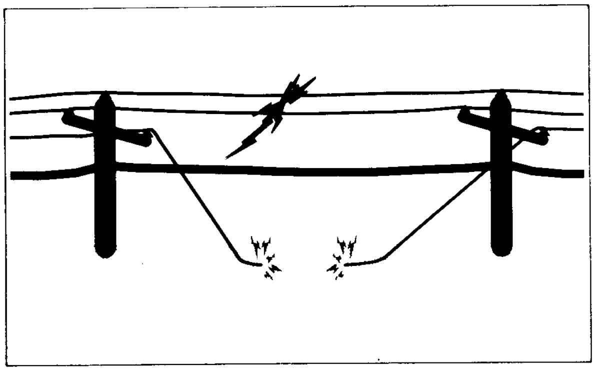


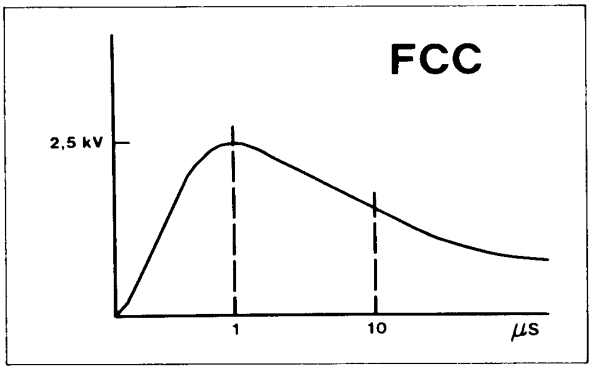
COMMUNICATIONS (Telephone)

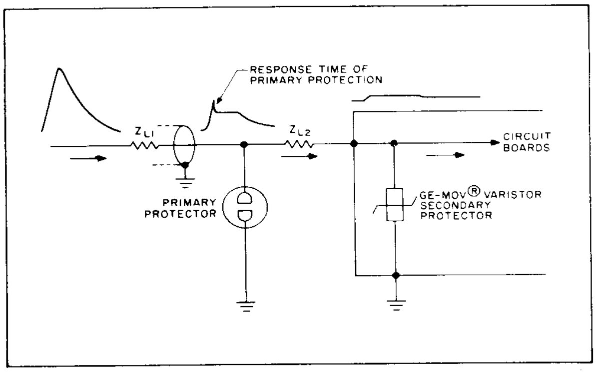
- CARBON BLOCK PROTECTORS
- GAS TUBE PROTECTORS
- VARISTORS
- SOLID STATE DEVICES

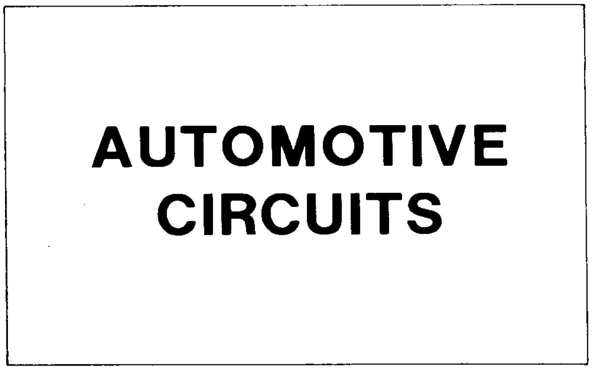




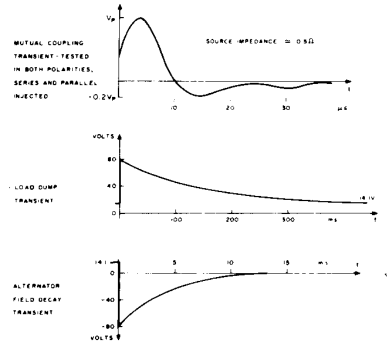


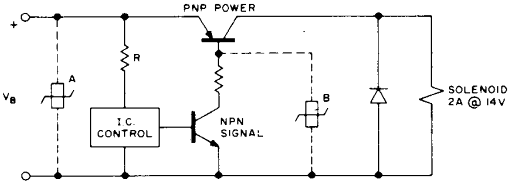


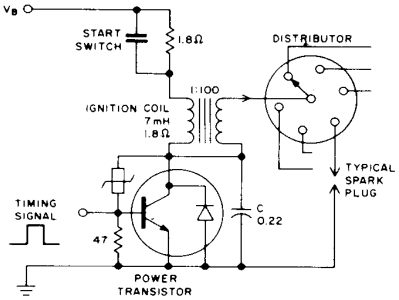


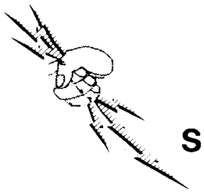


AUTOMOTIVE CIRCUITS

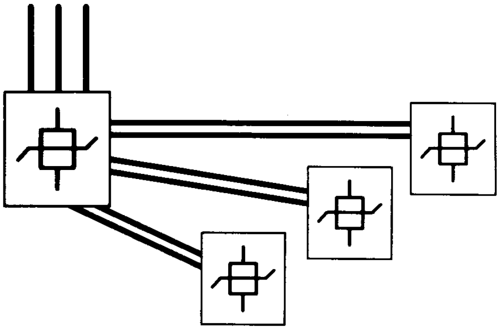


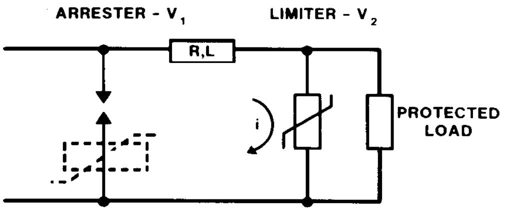






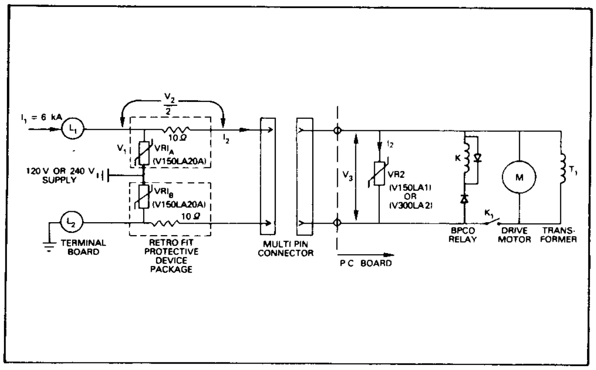
SURGE VOLTAGES
IN
AC POWER CIRCUITS

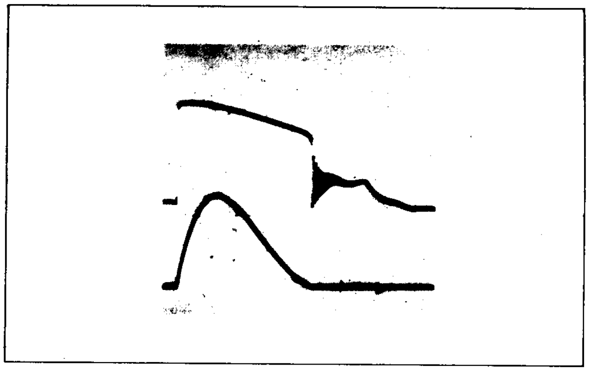


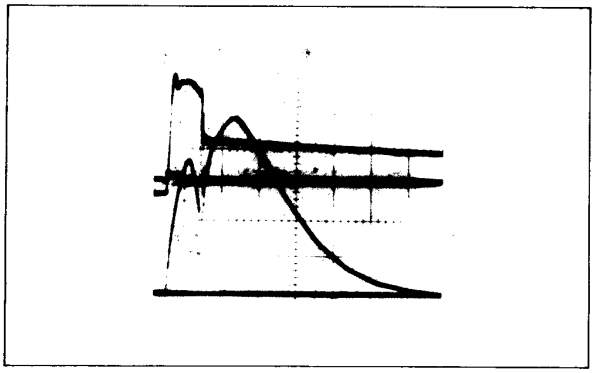


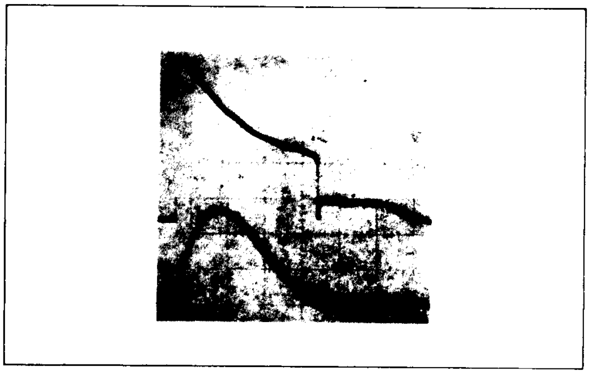
$$V_1 = V_2(i) + Ri + L\frac{di}{dt}$$

RECORDER
PROTECTION
RETROFIT

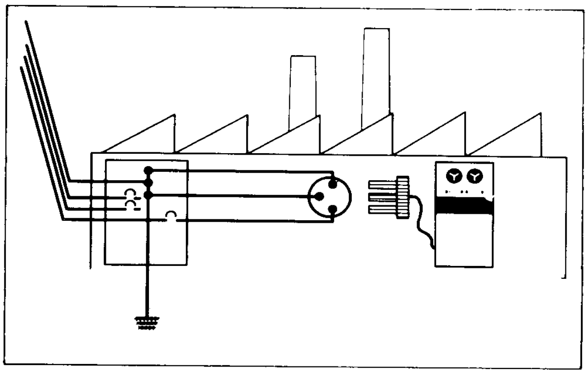


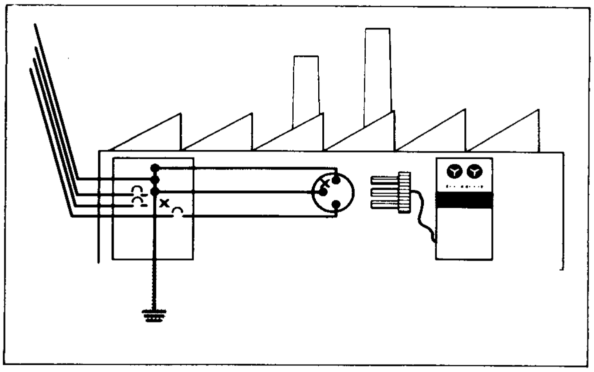


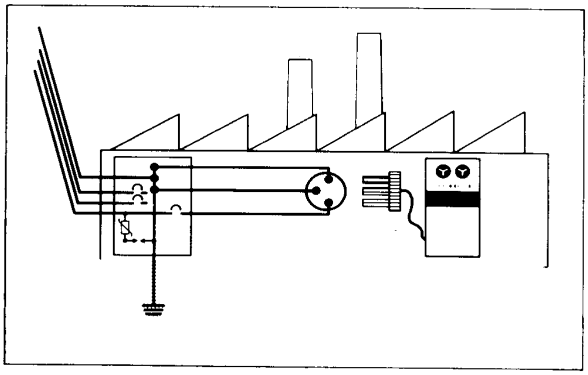


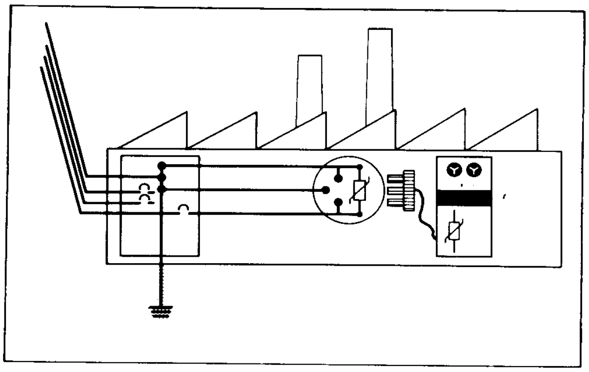


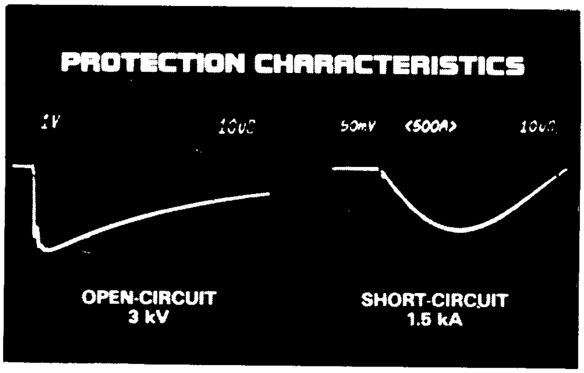
ARRESTER
&
VARISTOR







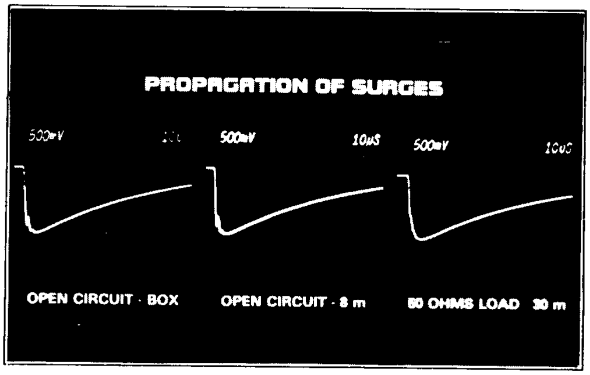




PROTECTION CHARACTERISTICS

OPEN-CIRCUIT
3 kV

SHORT-CIRCUIT
1.5 kA

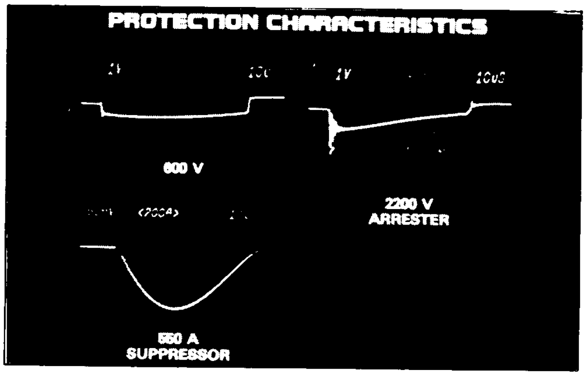


PROPAGATION OF SURGES

OPEN CIRCUIT - BOX

OPEN CIRCUIT - 8 m

50 OHMS LOAD 30 m

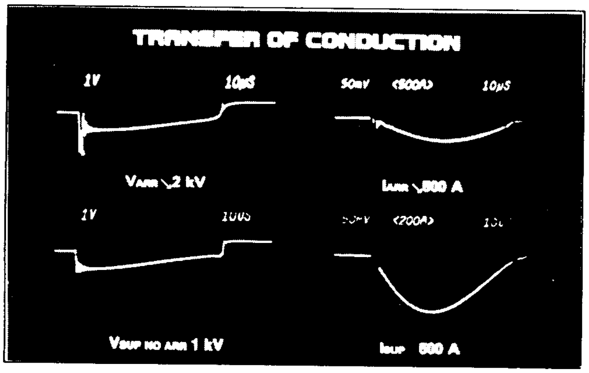


PROTECTION CHARACTERISTICS

600 V

2200 V
ARRESTER

550 A
SUPPRESSOR



TRANSFER OF CONDUCTION

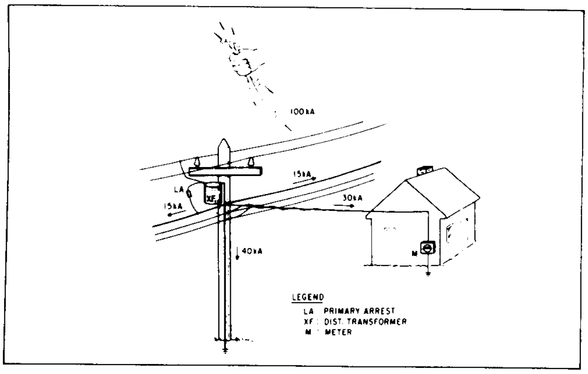
V_{ARR} ≈2 kV

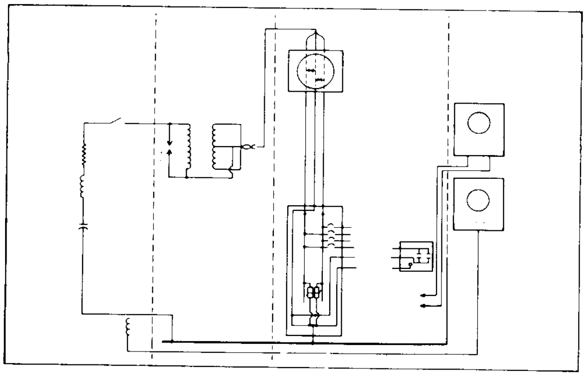
I_{ARR} ≈500 A

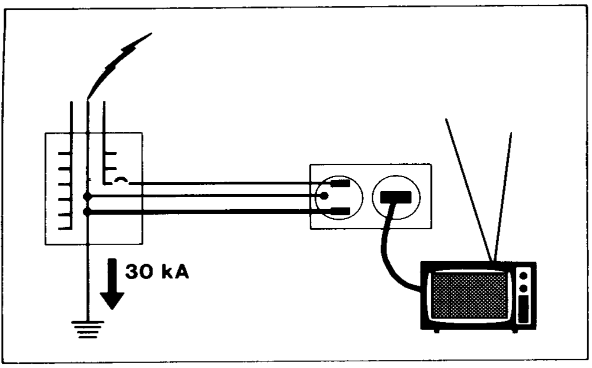
V_{SUP} NO ARR 1 kV

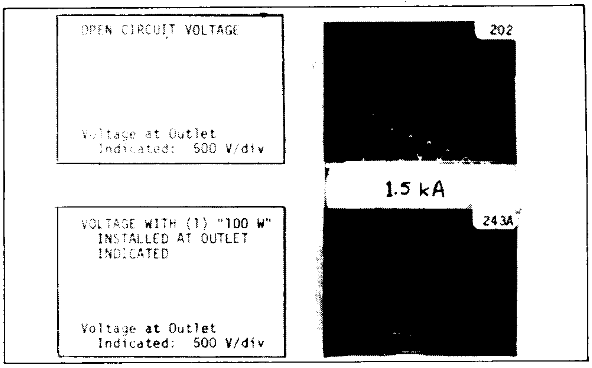
I_{SUP} 600 A

GROUND
CURRENT
INJECTION





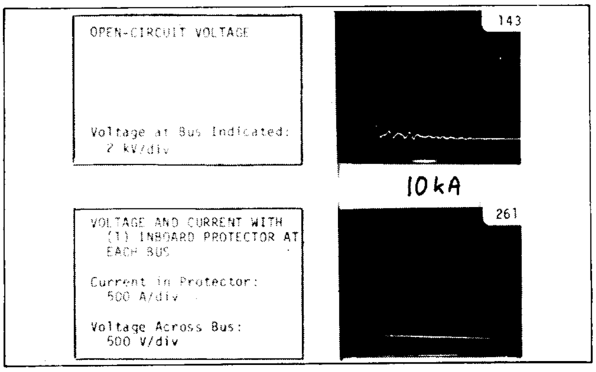



OPEN CIRCUIT VOLTAGE

Voltage at Outlet
Indicated: 500 V/div

VOLTAGE WITH (1) "100 W"
INSTALLED AT OUTLET
INDICATED

Voltage at Outlet
Indicated: 500 V/div

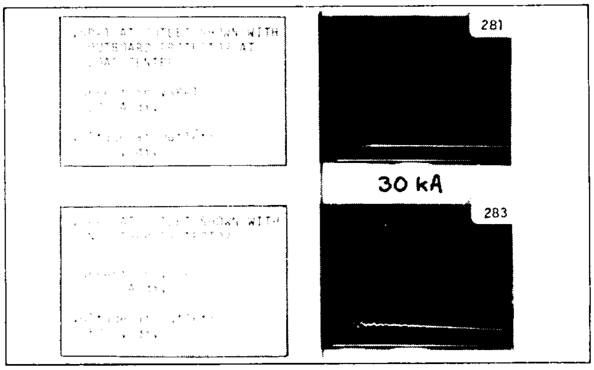

OPEN-CIRCUIT VOLTAGE

Voltage at Bus Indicated:
2 kV/div

VOLTAGE AND CURRENT WITH
(1) INBOARD PROTECTOR AT
EACH BUS

Current in Protector:
500 A/div

Voltage Across Bus:
500 V/div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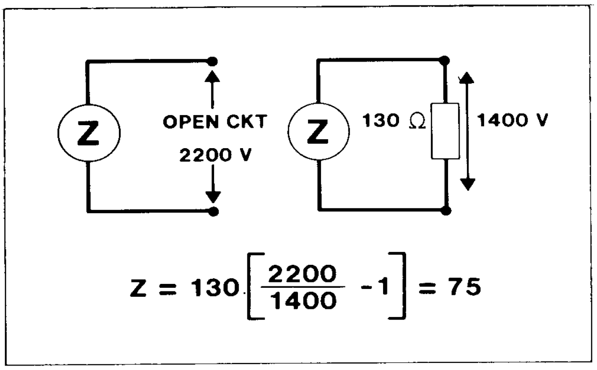
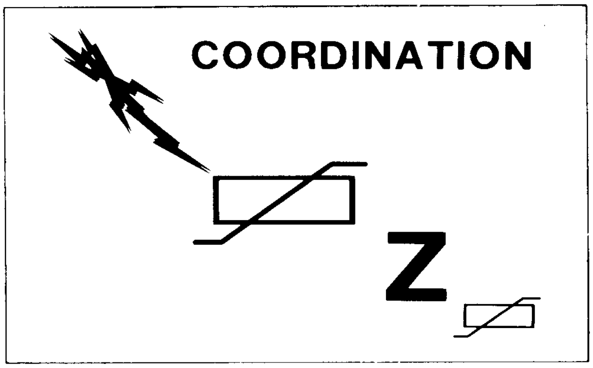
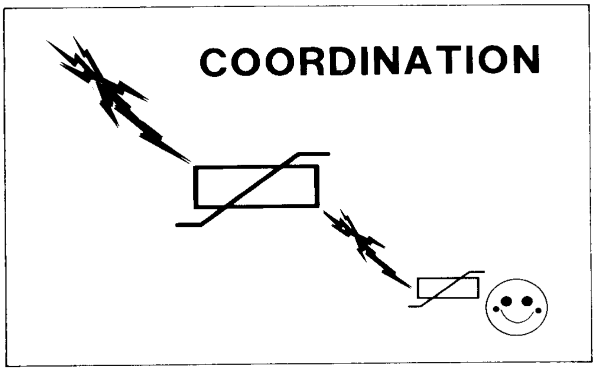


$$Z = 130\left[\frac{2200}{1400} - 1\right] = 75$$


COORDINATION


COORDINATION

EPILOGUE

This Seminar, starting with the origin of transient overvoltages, presented basic concepts on protection techniques and protective devices, and gave specific examples of the application of protective schemes and surge generating equipment. Condensing the field in a brief handout and a one-day presentation was a challenge. Surely the author has failed to bring out *all* the relevant facts; for this he accepts full responsibility, and he will sincerely welcome comments from the readers.

This epilogue presents an opportunity to acknowledge the support of International General Electric in sponsoring this Seminar, the participation of the Heafely Company and KeyTek Instrument Corporation in demonstrating equipment, and also to thank Catharine Fisher for editing these notes.

The author expresses his appreciation to the Seminar participants for their attention. As one who has experienced the problems caused by transients and the satisfaction of solving them, the author extends to the protection engineer his best wishes for success through the effective application of protective techniques and devices.

François D. Martzloff
Schenectady, N.Y., July 1979