LINE CONDUCTED DISTURBANCES — ORIGINS AND CONTROL

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National Bureau of Standards, May 1984

Significance
Part 6: Tutorials, Textbooks, and Reviews

This invited lecture was presented at a forum organized by the National Bureau of Standards (NBS) under the auspices of the same organization that developed the publication FIPS PUB 94 "***Guideline on Electrical Power for ADP Installations,***" a widely disseminated and often-cited tutorial document in the eighties and nineties. My subjects were presented within the broad scope of the forum, with emphasis naturally given to surge protection.

Delivering this lecture at NBS marked a turning point in my career because it catalyzed the establishment of a program aimed at surge protection and EMI control which I joined in 1985, allowing me to continue my work in this area within the supporting environment of NBS (soon to become NIST) until my retirement in 2003. Such support for 18 years of original research and dissemination of results via contributions to IEEE, IEC, and UIE standards is gratefully acknowledged.

Power and Grounding for a Computer Facility
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THE ORIGINS OF TRANSIENT OVERVOLTAGES

Transient overvoltages in power systems originate from one cause, energy being injected into the power system, but from two sources: lightning discharges, or switching within the power system. However, in communication and data systems, there is another source of transients: the coupling of power system transients into the data system.

Lightning discharges may not necessarily mean direct termination of a lightning stroke onto the power system. A lightning stroke terminating near a power line, either by hitting a tree or the bare earth, will create a very fast-changing magnetic field that can induce voltages – and inject energy – into the loop formed by the conductors of the power system. Lightning can also inject overvoltages in a power system by raising the ground potential on the surface of the earth where the stroke terminates, while more distant "ground" points remain at a lower voltage, closer to the potential of "true earth." The literature and other presentations in this conference provide information on the characteristics of lightning discharges.[1–6]

Surges from power system switching create overvoltages as a result of either trapped energy in loads being switched off, or restrikes in the switchgear. These will be examined in greater detail in the following paragraphs.

SWITCHING TRANSIENTS

A transient is created whenever a sudden change occurs in a power circuit, especially during power switching – either the closing or opening of a circuit. It is important to recognize the difference between the intended switching (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. In medium-voltage switchgear, pre-strikes can occur just before the contacts close, with a succession of clearings at the high-frequency current zero, followed by restrike. Similarly, 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 by converting it 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 which fuses or which circuit breakers can force when clearing a circuit prior to the natural current zero of the power system. 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. Restrike occurs following the initial 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 1). At 180° after interruption, the switch has to support twice the amount of system voltage, a stress it might not be able to withstand with its contacts not completely 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

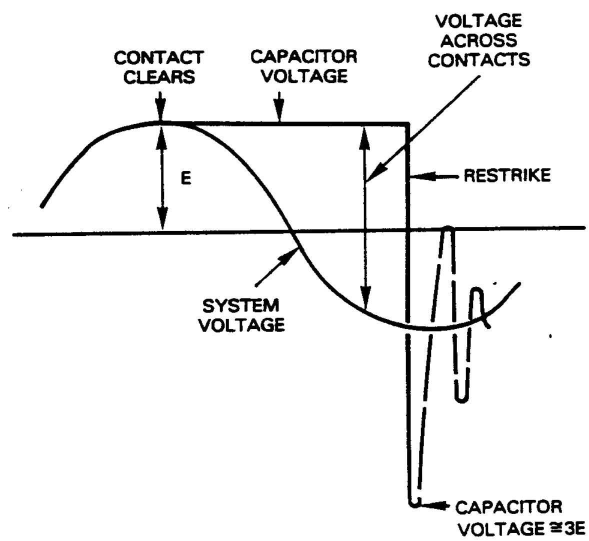


Figure 1. Restrike Mechanism on Capacitor Switching

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 then 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 behavior of a circuit element. Lightning-induced transients are much less predictable because there is a wide range of coupling possibilities. Moreover, one user, assuming that his system will not be the target of a direct hit, may take a casual view of protection, while another, fearing his system will experience a "worst case," may demand the utmost protection.

In response to these concerns, various committees and working groups have attempted to describe ranges of transient occurrences or maximum values occurring in power circuits. Three such attempts will be discussed now.

STANDARDS ON TRANSIENT OVERVOLTAGES

Several standards or guides have been issued or proposed in Europe by VDE, IEC, CECC, Pro-Electron, CCITT, and 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. The IEEE has recently published a new standard describing the environment in low-voltage ac power circuits.[8] The Low-Voltage Insulation Coordination Subcommittee SC/28A of IEC has also completed a report, IEC 664, 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 reviewed in the pages that follow. Greater emphasis will be placed on the first cited above 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 innovations in transient protection:

- The specified waveshape of the voltage is oscillatory waveshape, not the historical unidirectional waveshape.
- A source impedance, a characteristic undefined in many other documents, is defined.
- The concept that all lines to the device under test must be subjected 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 recommendations of this document 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 the application.

The IEC 664 Report

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 1). The table specifies that it is applicable to a *controlled voltage situation*, which 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 withstand concerns of the group that prepared the document. 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.

Table I

IEC Report 664

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	12000

The IEEE Guide on Surge Voltages (IEEE Std 587-1980)

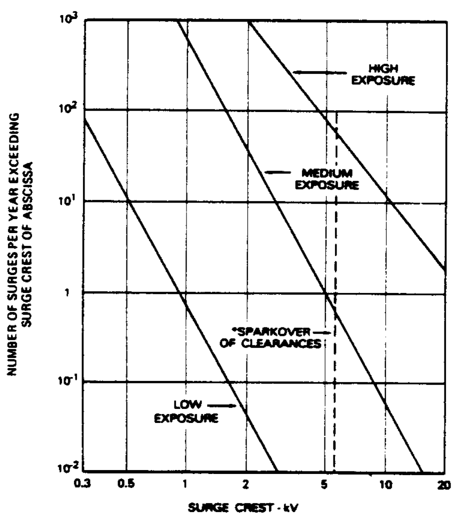
Voltages and Rate of Occurrence

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 2). These exposure levels are defined in general terms as follows:

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

The two lower lines of Figure 2 have been drawn at the same slope since the data base shows reasonable agreement among several sources on that slope. All lines may be truncated by sparkover of the clearances, at levels depending on the withstand voltage of these clearances. The *high exposure* line needs to be recognized, but it should not be indiscriminately applied to all systems. Such application would penalize the vast majority of installations where the exposure is lower.

Rate of Surge Occurrences versus Voltage Level at Unprotected Locations



***In some locations, sparkover of clearances may limit the overvoltages (see 8.3).**

Figure 2. Rate of Surge Occurrence versus Voltage Level *(Reprinted with permission from IEEE Std 587-1980, "IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits.")*

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 one 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 to 240 V systems have sparkover levels of about 6 kV; this 6 kV level, therefore, can be selected as a typical cutoff for the occurrence of surges in indoor power systems.

The voltage and current amplitudes presented in the Guide attempt to provide for the vast majority of lightning strikes but none should be considered "worst case," as this concept cannot be determined realistically. It is necessary to think in terms of the statistical distribution of strikes, and to accept 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.

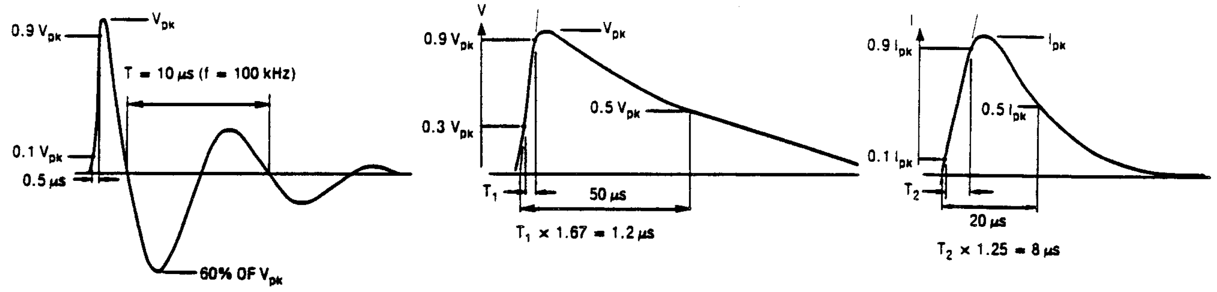
Waveshape of the Surges

Many independent observations[11–13] 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 that is generally described as 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 Guide specifies an oscillatory waveshape inside buildings, a unidirectional waveshape outside buildings, and both at the interface (Figure 3).

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.



Open-Circuit Voltage, Current Defined by Table II
Indoor Environment

Open Circuit Voltage **Discharge Current**
Outdoor and Near-Outdoor Environment

Figure 3. IEEE Std 587 Transient Overvoltages and Discharge Currents

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 664 report, either ignore the issue or indicate values applicable to limited cases, such as the SWC test for high-voltage substation equipment. The IEEE 587 standard attempts to relate impedance to categories of locations but unavoidably remains vague on their definitions (Table 2).

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 Location 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.

Category C is likely to be exposed to substantially higher voltages than Category B because the limiting effect of sparkover might not be available. The *high exposure* rates of Figure 2 could apply, with voltage in excess of 10 kV and discharge currents of 10 kA or more. Installing unprotected load equipment in 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 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—16] 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.

Table 2
Surge Voltages and Currents Deemed to Represent the Indoor Environment and Recommended for Use in Designing Protective Systems

Location Category	Comparable to IEC No 664 Category	Impulse: Waveform	Impulse: Medium Exposure Amplitude	Type of Specimen or Load Circuit	Energy (Joules) Deposited in a Suppressor* with Clamping Voltage of 500V (120 V System)	1000V (240 V System)
A Long branch Circuits and outlets	II	0.5 µs-100 kHz	6 kV	High impedance†	—	—
			200 A	Low impedance‡, §	0.8	1.6
B Major feeders, short branch circuits, and load center	III	1.2 X 50 µs	6 kV	High impedance†	—	—
		8 X 20 µs	3 kA	Low impedance‡	40	80
		0.5 µs-100 kHz	6 kV	High impedance†	—	—
			500 A	Low impedance‡, §	2	4

*Other suppressors having different clamping voltages would receive different energy levels.
†For high-impedance test specimens or load circuits, the voltage shown represents the surge voltage. In making simulation tests, use that value for the open-circuit voltage of the test generator.
‡For low-impedance test specimens or load circuits, the current shown represents the discharge current of the surge (not the short-circuit current of the power system). In making simulation tests, use that current for the short-circuit current of the test generator.
§The maximum amplitude (200 or 500 A) is specified, but the exact waveform will be influenced by the load characteristics.

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PROPAGATION OF SURGES

Voltage surges propagate in wiring at speeds in the order of 2/3 the speed of light, i.e., about 200 m/μs. Thus, for short lengths of wiring, the classical transmission line behavior of reflections is not applicable: with surges having a rise time of 1 μs, many round-trips between the sending end and the far end can occur during the rise, so that the final voltage is not affected by the reflections; only during the rise can one notice a small difference between the two ends (Figure 4).

Figure 4 also illustrates the fact that a line with an unloaded end does not attenuate the voltage. This fact prevails over the misconception that the wiring system in a building, for instance, inherently produces a progressive attenuation of surges from the service entrance to the locations inside the building.[9]

Likewise, suggestions are sometimes made that an "isolating transformer" can attenuate surges. This is true only if the transformer is fully loaded. It is not difficult to imagine a scenario where the transformer will operate at very light load, for instance, with only an electronic control energized during the off-cycle of the power circuit. Figure 5 shows how an impinging 0.5 μs-100 kHz transient of 6 kV (IEEE 587) produces a 7 kV output at the unloaded secondary terminals. The second reprint in these notes, "The Propagation and Attenuation of Surge Voltage and Surge Currents in Low-voltage AC Circuits," presents more detailed discussions of these concerns.

THE TRANSIENT CONTROL LEVELS (TCL) 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 to 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 levels* concept of testing and coordination promises a solution to the problem of compatibility.

According to the transient control levels 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 United States responded favorably to the proposal, and some of the concepts found their way into the IEEE Guide discussed in the first section of these notes. With the writing of Application Guides by the IEEE as well as by the IEC, there is an opportunity to advance the proposal further. A reprint of the original paper presenting this proposal is included in the notes.

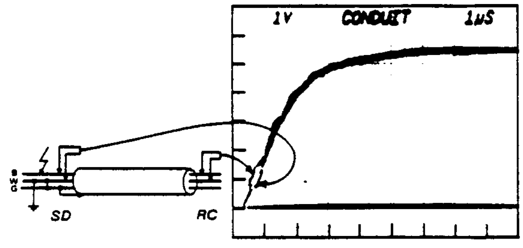

Figure 4. Sending and receiving end voltage with 1.2/50 μs impulse applied to wiring in metal conduit.

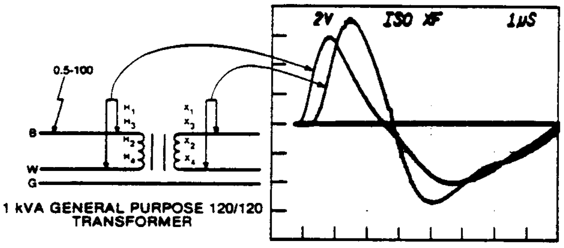

Figure 5. Propagation of a 0.5 μs-100 kHz ring wave through an isolating transformer.

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.

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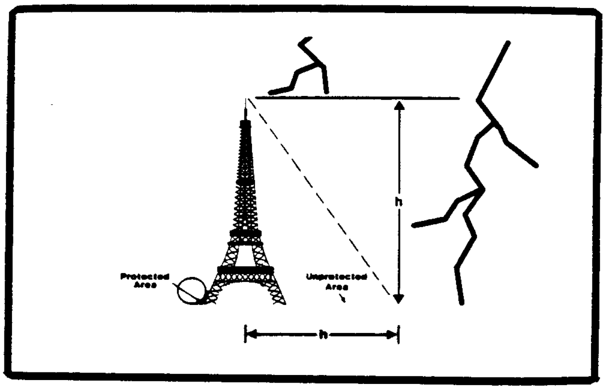
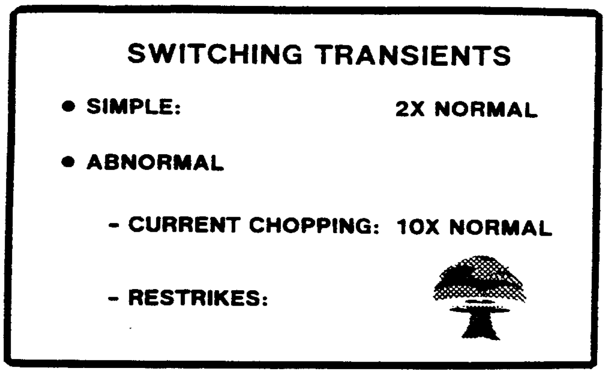
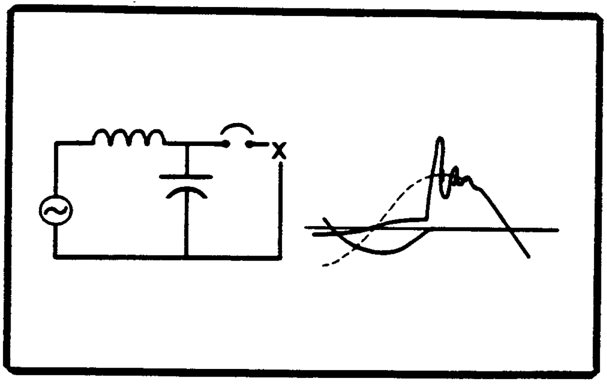
SLIDE NOTES



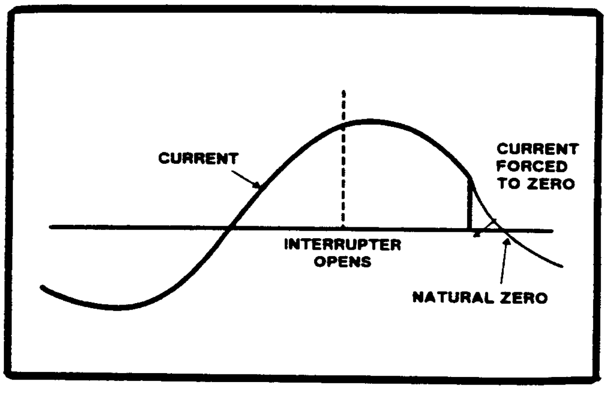
The traditional "cone of protection," revised with the "rolling ball" concept based on striking distance.



There are many ways to get into trouble from the "benign" to the horrendous.

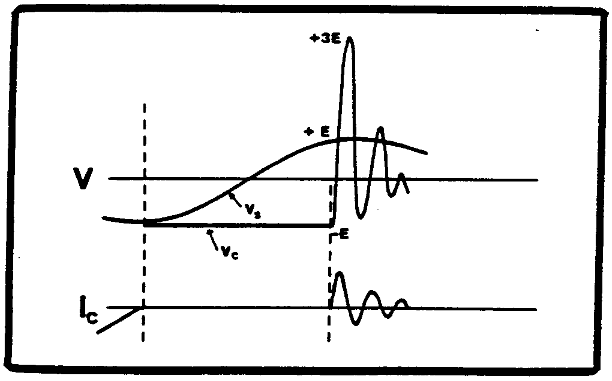


A simple switching transient in an LC circuit, undamped, can reach 200%, or 2 per unit, for instance during fault clearing by a circuit breaker.

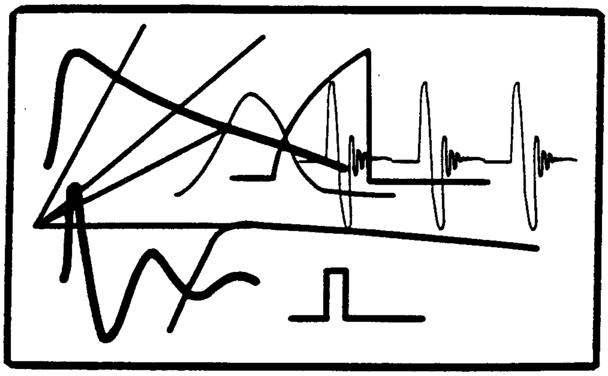


Current chopping produces steep di/dt, thus high L di/dt voltages.

SLIDE NOTES



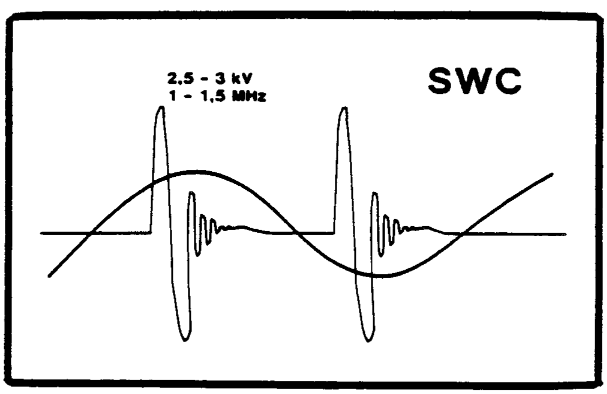
The restrike phenomenon can escalate to very high voltages. Here is the mechanism for going from one per unit to three per unit. The next go-round can reach 5, then 7 . . .



All these various mechanisms produce all kinds of transient waveforms -- which one to choose?

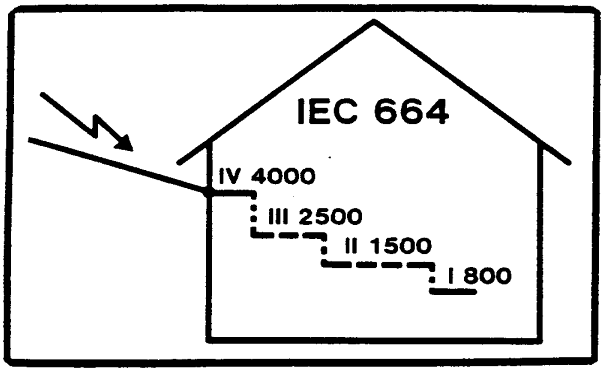
STANDARDS ON TRANSIENT OVERVOLTAGES

Many national and international groups are concerned, and prepare standards; some of these are not always compatible.

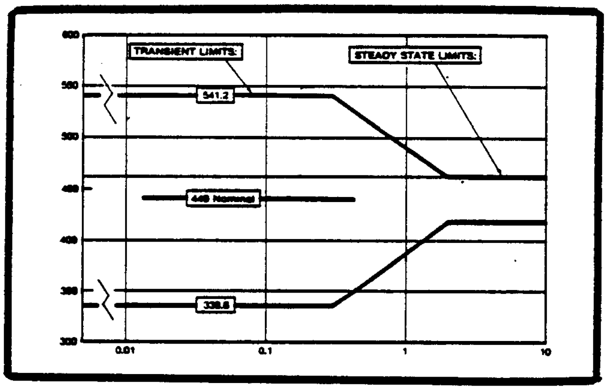


The "Surge Withstand Capability" test was among the first published for low-voltage equipment -- in high-voltage substations.

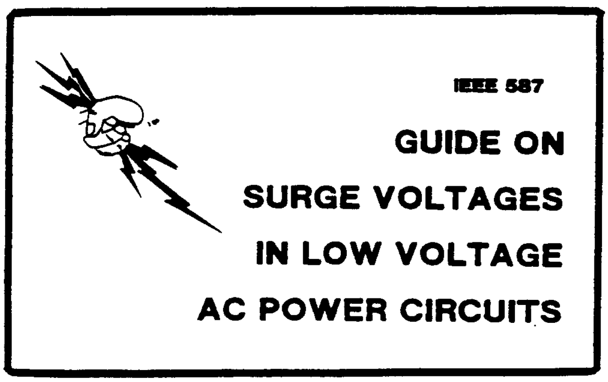
SLIDE NOTES



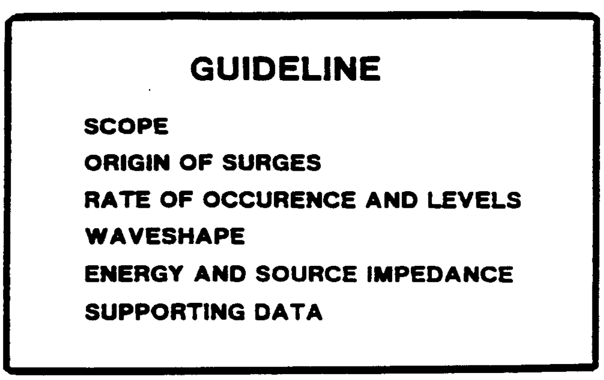
The International Electrotechnical Commission is recommending the application of a staircase of descending voltages from the service entrance onward.



Military precision in an imprecise world: 4-digit specifications.

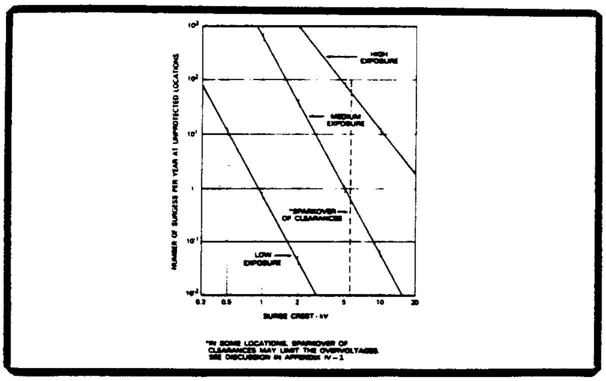


One of the more recent attempts to describe the real world.

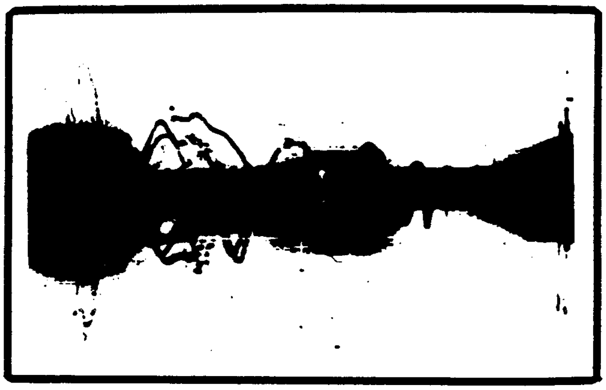


The contents of IEEE Std 587-1980.

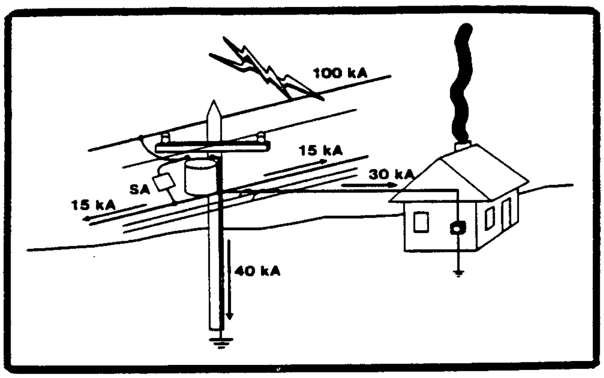
SLIDE NOTES



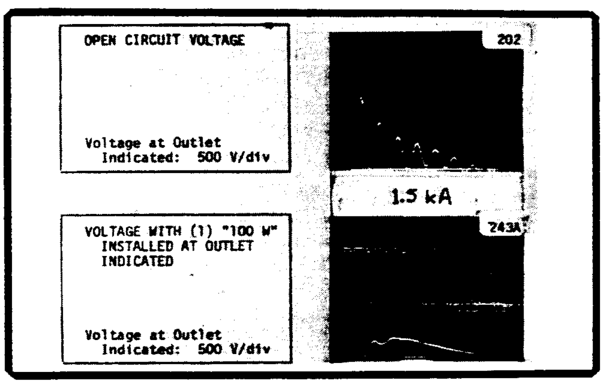
The occurrences of surges has statistical distribution at any location, and locations and exposures vary.



An extreme case of surge occurrences over a period of 24 hours, due to switching surges in a house.

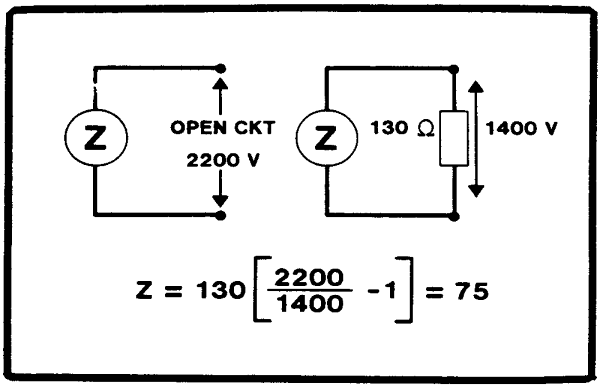


Scenario for the division of lightning current toward ground, along ground conductors.

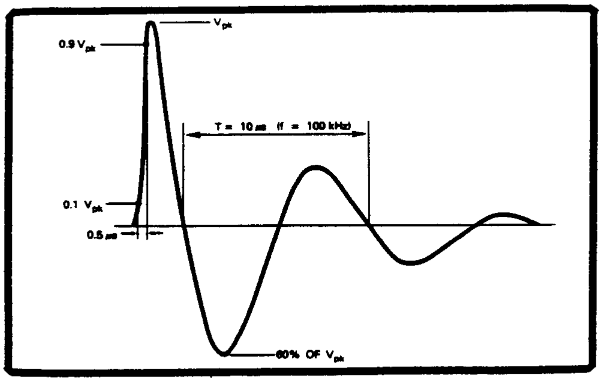


The result of a ground current of only 1.5 kA is 2200 V induced line-to-neutral on unloaded circuits.
With a moderate load, the voltage is reduced to 1400 V.
Note the oscillatory voltages from a unidirectional current pulse.

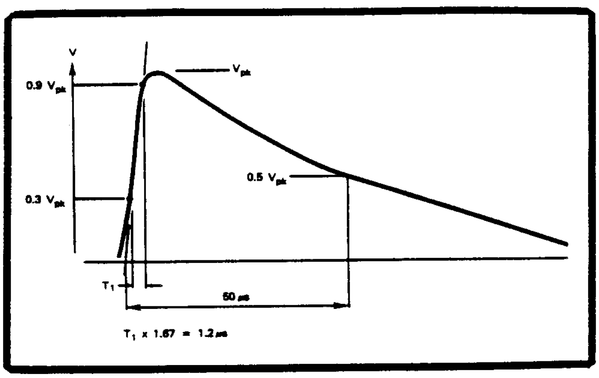
SLIDE NOTES



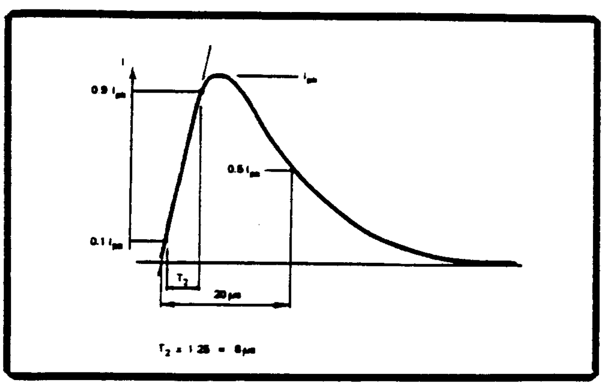
Is the source impedance of the above scenario 75 Ω ?



First representative waveform from IEEE Std 587 — voltage and current. The "0.5 μs-100 kHz Ring Wave."

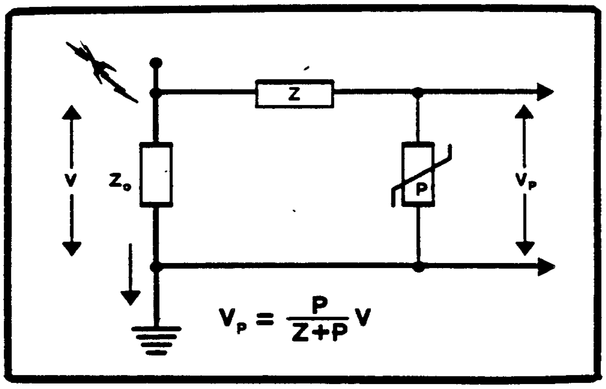


Second IEEE Std 587 waveform — voltage for high impedance — 1.2/50 μs.

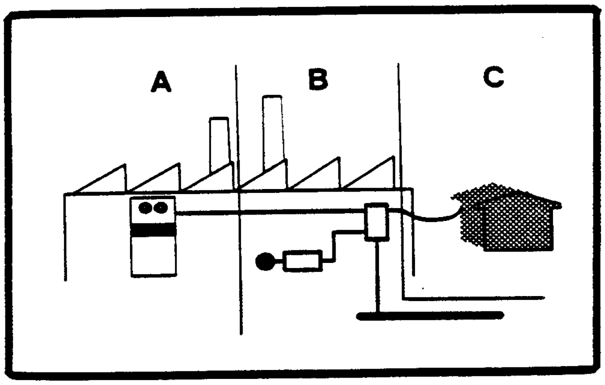


Third IEEE Std 587 waveform — current for low impedance — 8/20 μs.

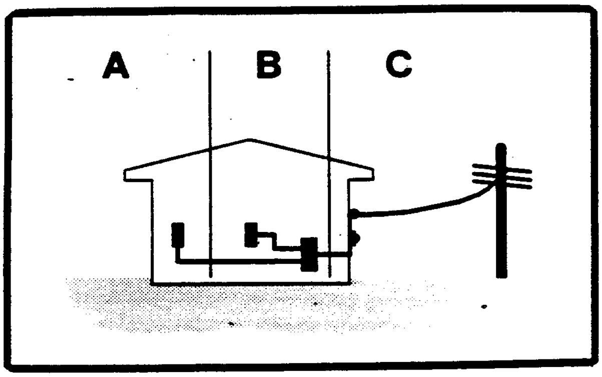
SLIDE NOTES



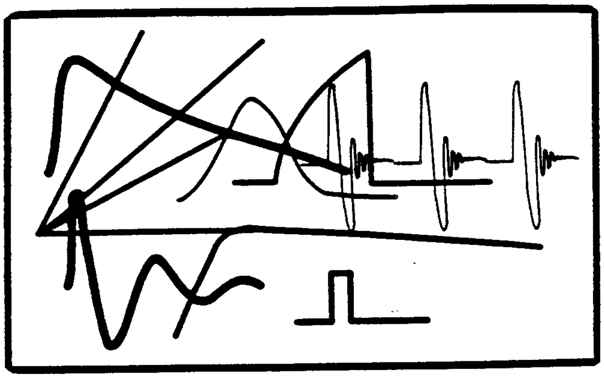
Clamping surge protective devices work only if there is a finite source impedance.



Location categories in an industrial system.



Location categories in a residential system.

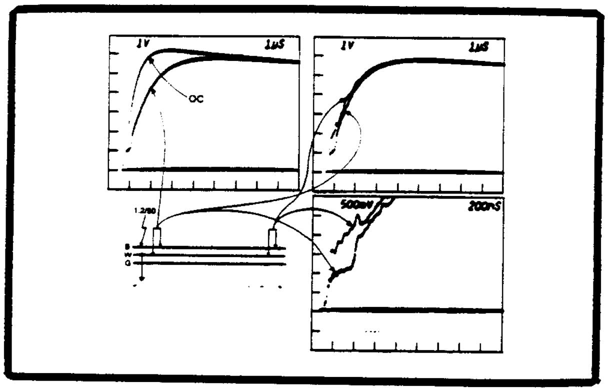


Now we know which one to pick.

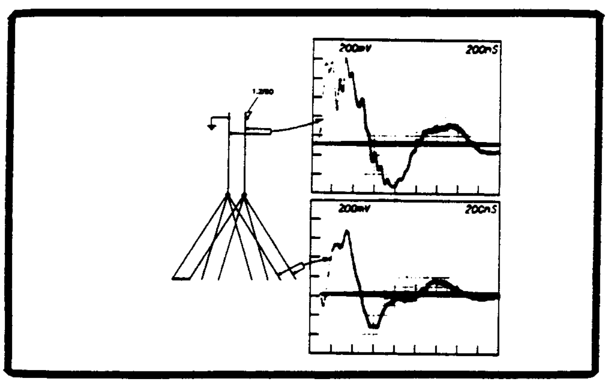
SLIDE NOTES

PROPAGATION OF SURGES

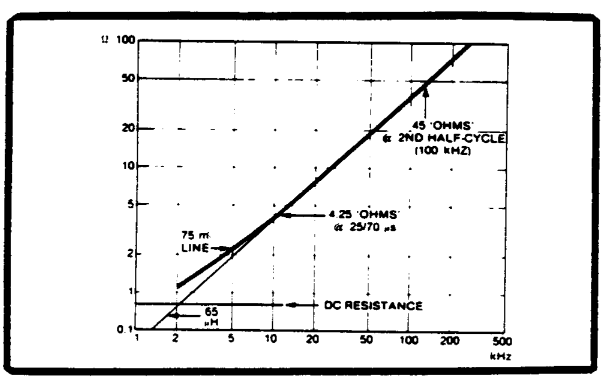
More about this in the reprint section.



Reflections at line ends are not significant if the travel time is shorter than the rise time.



Clean test waves are quickly confused by complex circuits.



Typical wiring impedance.

SLIDE NOTES

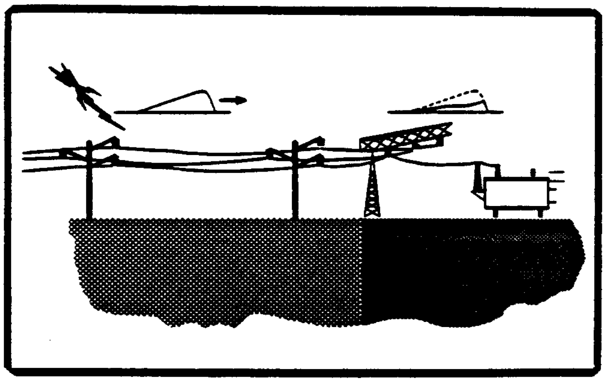
TRANSIENT CONTROL LEVELS

A noble objective, but perhaps the world is not quite ready, or the presently scrambled situation can no longer be unscrambled?

HOW THINGS STAND NOW

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

. . . is a backward situation.



The electric utilities long ago developed the Basic Insulation Level (BIL) concept.

FUNDAMENTALS OF PROTECTION

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 ensuring 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 the fundamental techniques which are most effective and economical when implemented at the outset.

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 present much more serious problems than the same system confined in a single building.

For the system components or 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 or a search for inherent immunity 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 was 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, in particular common mode noise reduction – 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 associated with common mode *noise* coupling 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 voltages that otherwise would be induced in the circuits.

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 but close 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. In the case of underground conduit runs, the most frequent practice is to use plastic conduit, which unfortunately breaks the continuity. System designers would be well advised to require metal conduits where the circuits are sensitive or, at a minimum to pull a shielded cable in the plastic conduit where the shield is used to maintain continuity between the above-ground metal conduits. That additional cost, then, is the insurance premium, which is well worth accepting.

Bonding

We have 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 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 expected from the point of view of surge protection.

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, voltages 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 connect the wires to the local ground 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 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 the neutral. The intent is to increase the reliability of 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 possible 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.

FOR FURTHER READING

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Valazquez, R.S., V. Gerez, D. Mukhedar, and Y. Gervais, "Probabilistic Calculations of Lightning Protection for Tall Buildings," *IEEE Transactions on Industry Applications 1A-18 (3)*, May/June 1982, pp. 252-259.

Appendix

BASIC CONSIDERATIONS ON SURGE CONTROL FOR ELECTRONIC SYSTEMS

(From Surge Protection of Electronics, University of Wisconsin, March 1979, Conference Notes)

Frank A. Fisher, General Electric Company

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 ensures that, at 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 in Figure A-1. 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 (O) between the electronic ground system and the building ground system.
8. Electronic cables are generally carried between locations in cable trays. These trays, although 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 nonmetallic conduits, however, must have the overall shield.

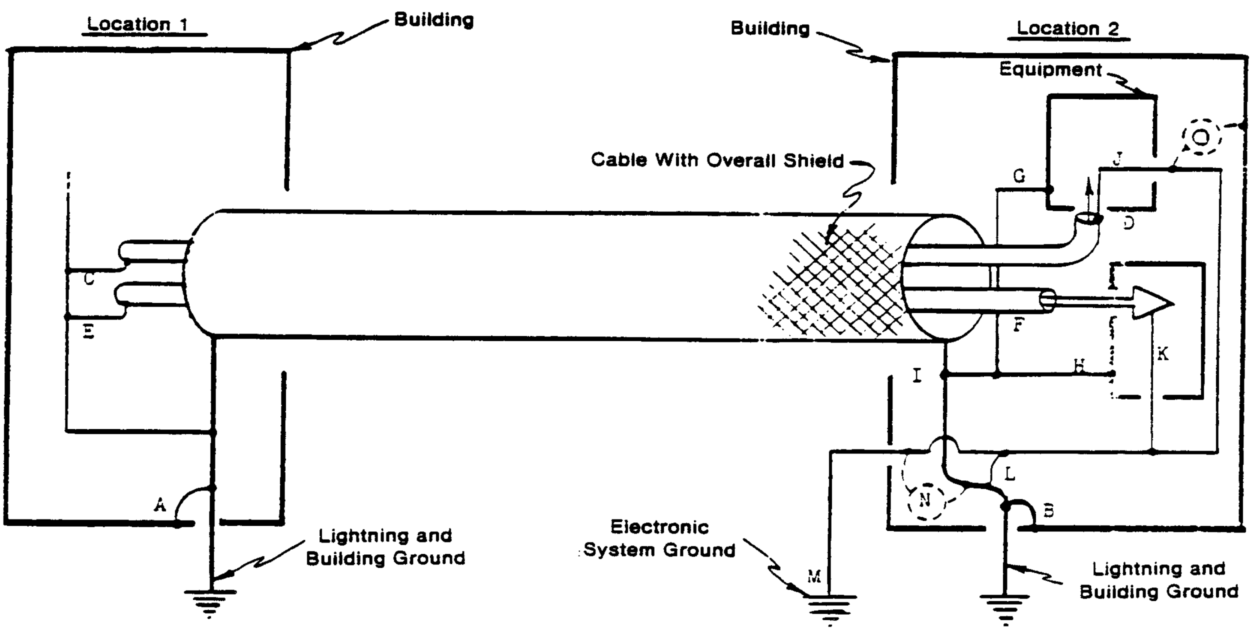
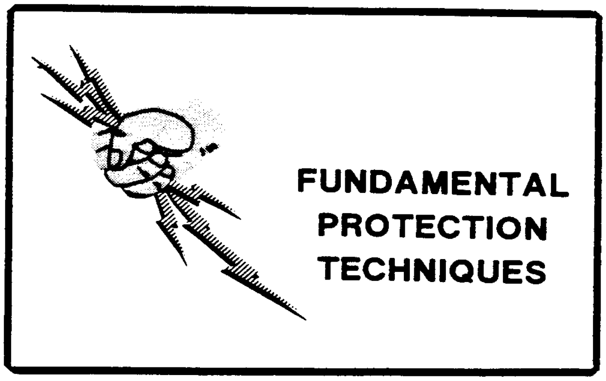
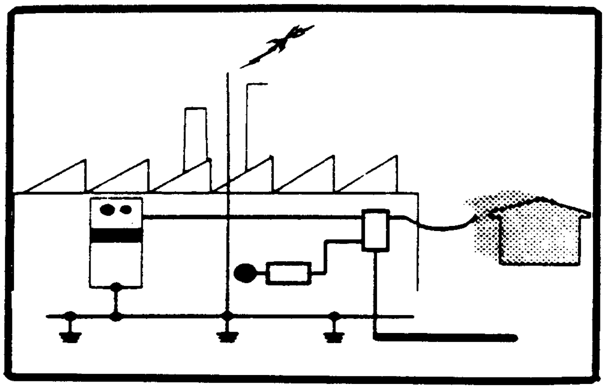


Figure A-1. Lightning Protection Measures Which Provide Minimum Disruption to Steady-State Operation

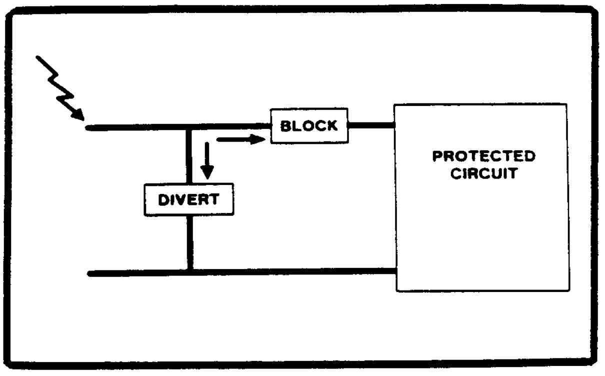
SLIDE NOTES



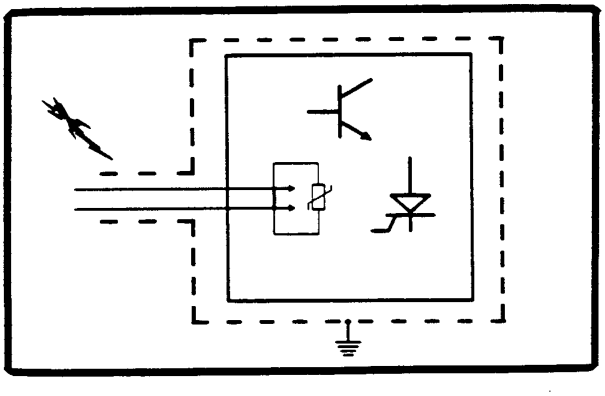
What can we do to prevent problems?



Lightning and electronics do not mix with good results, but simple precautions can go a long way.



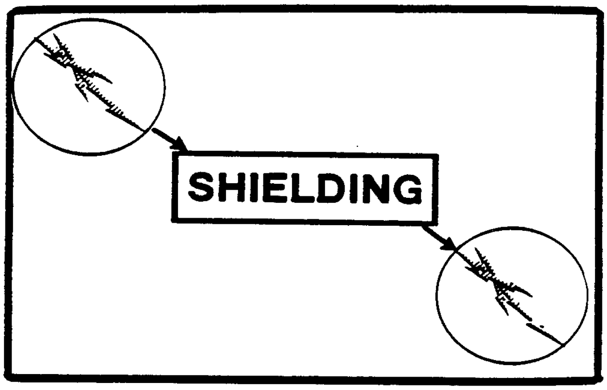
The basic protection philosophy.



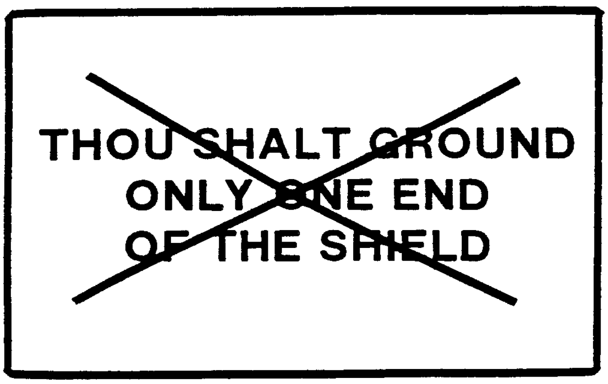
Surge protective devices at the black box level can deal with limited energy.

SLIDE NOTES

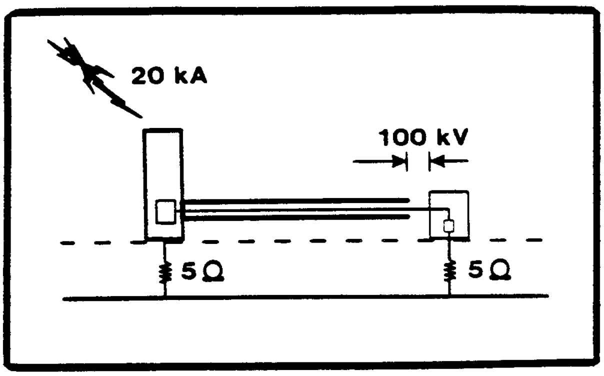
Three very powerful protective measures.



The first technique.

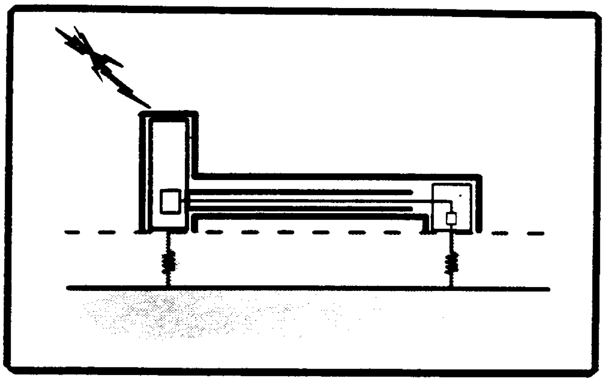


The 13th Commandment of "electronikers."

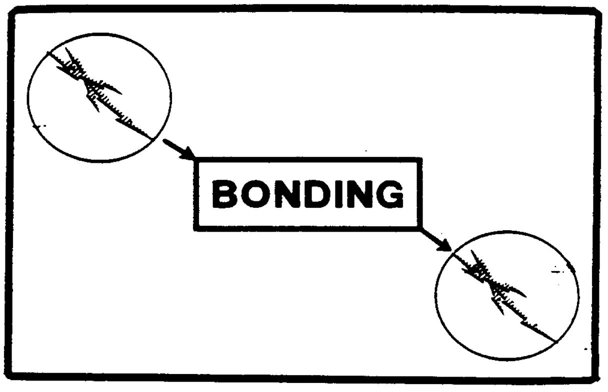


The consequence of the 13th Commandment.

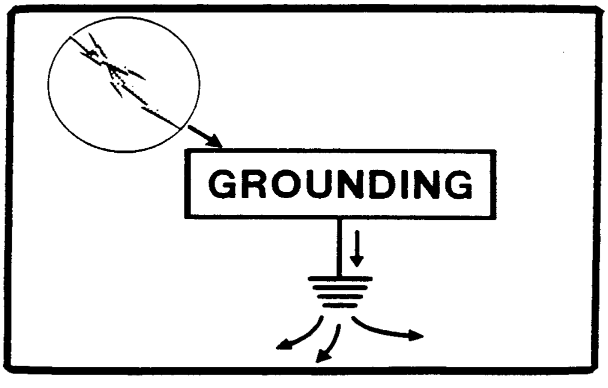
SLIDE NOTES



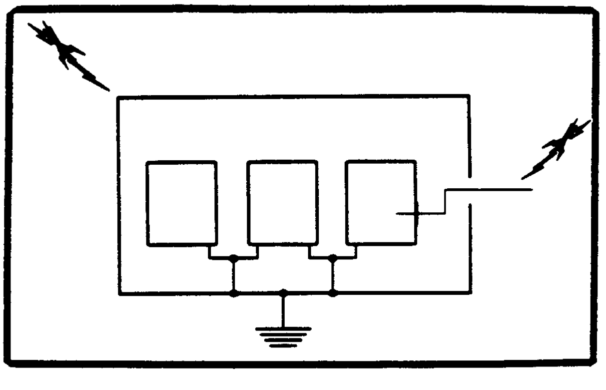
A simple solution to reconcile two contradictory requirements.



The second technique.

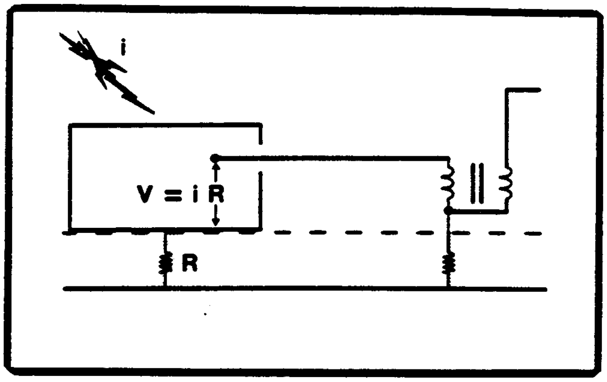


Last, but not least, the third technique.

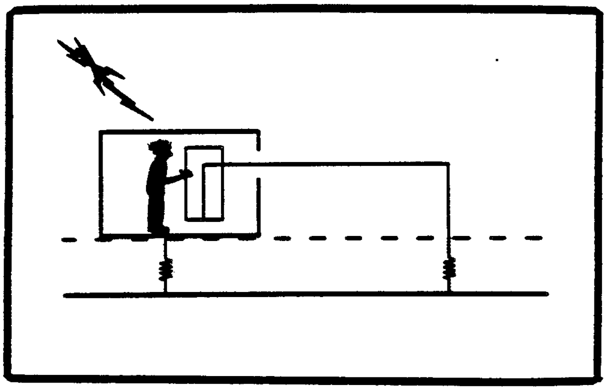


Grounding alone is not enough.

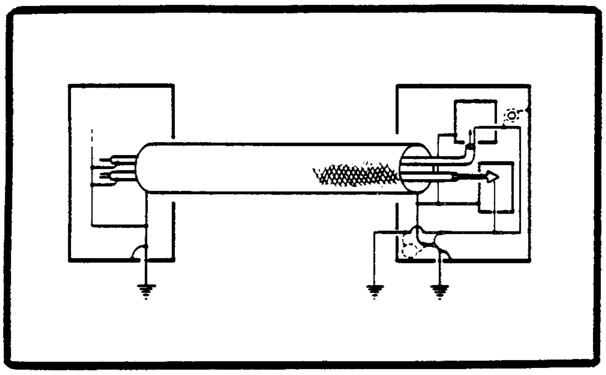
SLIDE NOTES



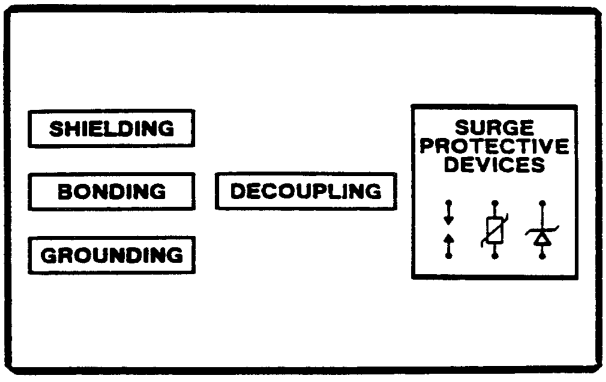
Ground potential differential rise.



Dangerous scene.



One way to reconcile everybody.



The total picture.

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 ethem 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 many 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 (Figure 1). Thus, we are primarily interested in the diverting devices. These diverting devices can be of two kinds: voltage-clamping devices or 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.

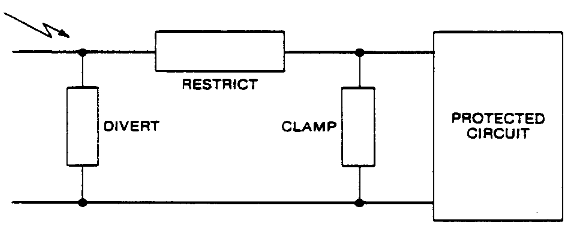


Figure 1. Multi-stage Protection

Because the 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. 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 a control circuit senses the rising voltage and turns on the power-rated device 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 cost.

The crowbar device, however, has three 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 occurs to the arc mode of conduction, by avalanche breakdown of the gas between the electrodes. 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.

The second limitation is associated with the sharpness of the sparkover, which produces fast current rises in the circuits and, thus, objectionable noise. A classic example is found in oscillograms recording the sparkover of a gap where the trace exhibits an anomaly *before* the sparkover (Figure 2). This anomaly is due to the delay introduced in the oscilloscope circuits to provide an advanced trigger of the sweep. What the trace shows is the events delayed by a few nanoseconds, so that in real time, the gap sparkover occurs while the trace is still writing the pre-sparkover rise.

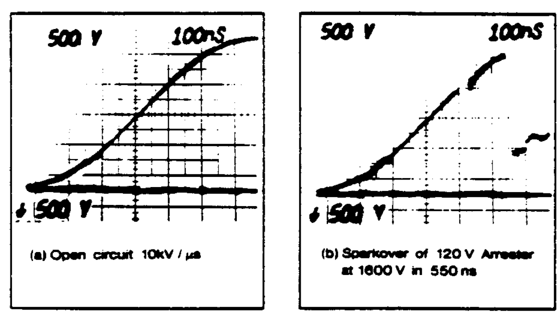


Figure 2. Anomaly in Oscilloscope Recording

Another, more objectionable effect of this fast current change can be found in some hybrid protective systems. Figure 3 shows the circuit of such a device, as found in the commerce. The gap does a very nice job of discharging the impinging high energy surges, but the magnetic field associated with the high di/dt induces a voltage in the loop adjacent to the secondary suppressor, adding what can be a substantial spike to the expected secondary clamping voltage.

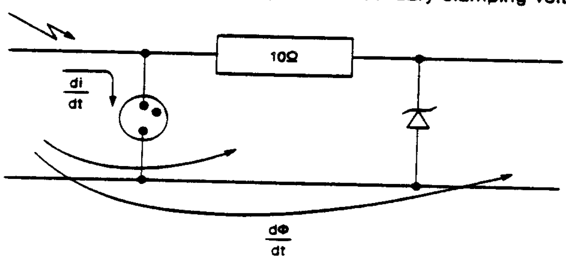


Figure 3. Hybrid Protector with Gap

A third 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 *R*. 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. 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 essentially 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 surge voltage attempts to rise results in voltage-clamping action. Nonlinear impedance is the result if this current rise is greater 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. If the source impedance is very low, the ratio is low, and eventually the suppressor could not work at all with a zero source impedance (Figure 4). In contrast, a crowbar-type device effectively short circuits the transient to ground, but, once established, this short circuit will continue until the current (the surge current as well as any power-follow current supplied by the power system) is brought to a low level.

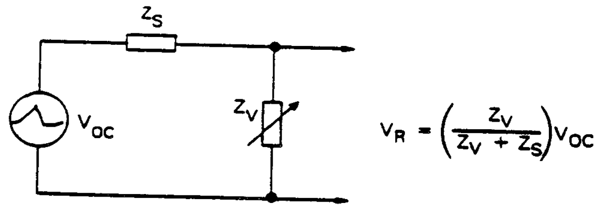


Figure 4. Voltage Clamping Action of a Suppressor

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

AVALANCHE DIODES

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

The advantage of the avalanche diode, generally a P-N 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.

Characteristics of Avalanche Diodes

Silicon avalanche diodes are available with characteristics tailored to transient suppression. These should not be confused with regulator-type Zener diodes although many engineers tend to use the generic term "Zener diode." May Zeus help them if they misapply a regulator-type Zener, expecting to achieve good protection!

Figure 5 shows a typical family of *V-I* characteristics for one product. The parameter *I* is the peak of a specified current waveform, generally the 10/1000 μs double exponential preferred by communication engineers in contrast to the 8/20 μs wave preferred by power engineers. These curves are remarkably flat from 1 to 20 amperes, with clamping voltages low enough to protect sensitive electronics.

Manufacturers of avalanche diodes generally rate their devices in terms of maximum peak power for a specified pulse duration. Although the power decreases with increasing pulse duration, this does not occur at constant energy (Figure 6). A two-decade increase in pulse duration reduces the power by only about one decade, primarily because of increasing heat transfer for longer pulses.

Since the junction is very thin, the capacitance of an avalanche diode is appreciable. This can be a concern. It is possible to minimize this effect by using series combinations with low capacitance diodes (Figure 7).

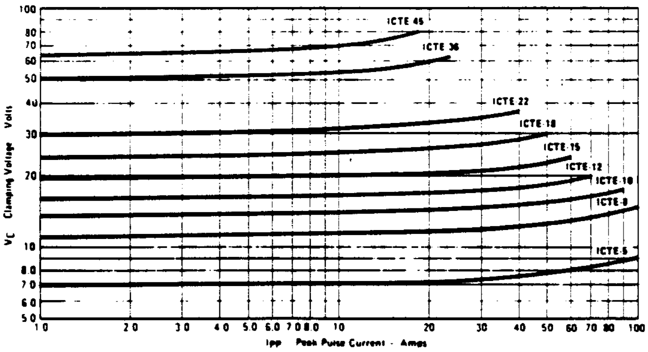


Figure 5. Typical V-I Characteristics

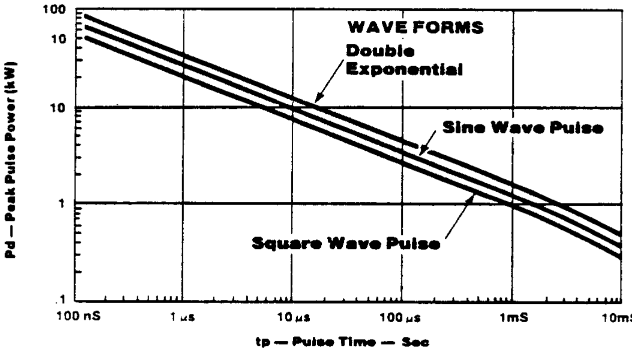


Figure 6. Peak Pulse Power Curve versus Pulse Time

Properly packaged and wired avalanche diodes exhibit a quick response to steep, front pulses, and have been widely used for NEMP protection of electronic equipment. However, this quick response can be completely obliterated by improper wiring (lead length). The effect of lead length, discussed in detail in the next section, is applicable to any transient suppressor.

VARISTORS

The term *varistor* is derived from its function as a *vari*able resistor. It is also called a *voltage-dependent resistor*, but that description tends to imply that the voltage is the independent parameter in surge protection. This concept will be contested repeatedly during the conference. Two very different devices have been successfully 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 higher 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

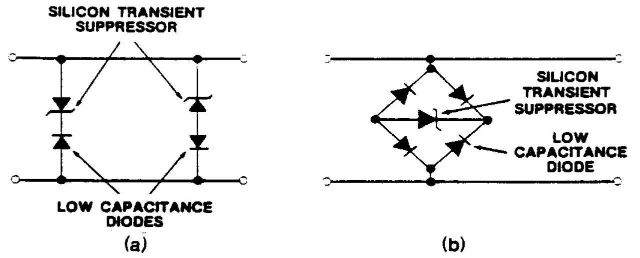


Figure 7. Examples of Low-Capacitance Protectors

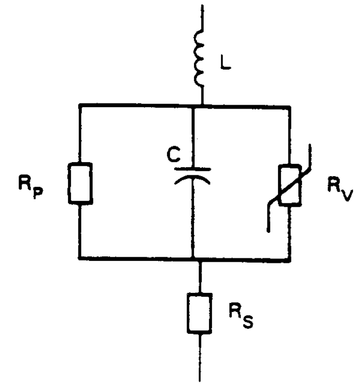


Figure 8. Equivalent Circuit of a Varistor

the material, successful as it is, has remained an art. It appears that the process takes place at the tips of the grains of silicon carbide which are 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, accidentally 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. The physics of the nonlinear conduction mechanism have been described in the literature;[1-10] in these application notes, we will be more concerned with the behavior of the varistors as a two-terminal electrical component.

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 8. The major element is the varistor proper, R_v, whose V-I characteristic is assumed to be the perfect power law $I=kV^a$. 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.

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 the V-I characteristic is plotted on a log-log graph, the curve of Figure 9 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.

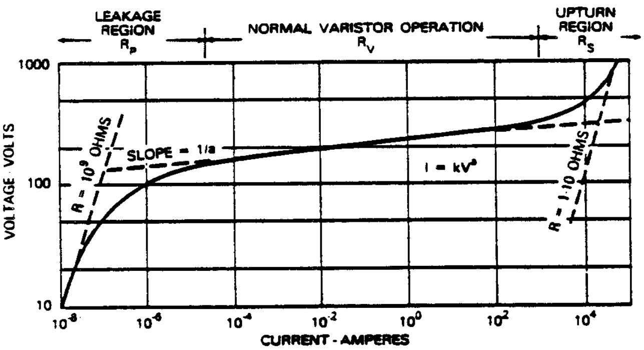


Figure 9. Typical V-I Characteristic

The 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:

- Selection of the appropriate nominal voltage for the line voltage of the application
- Selection of energy-handling capability (including consideration of the source impedance of the transient, the waveshape, and the number of occurrences)
- Heat dissipation
- Proper installation in the circuit (lead length).

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 10(a) and 10(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 10(c) and 10(d). With a slow current front of 8 μs, 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 in Figure 10(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.

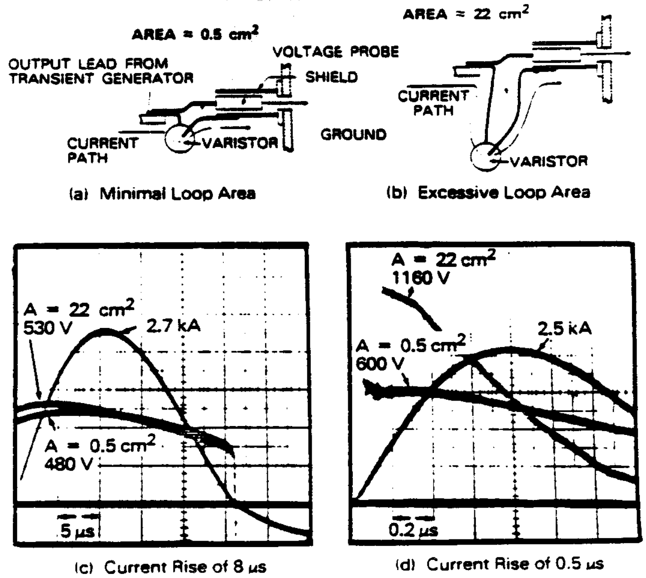


Figure 10. Effect of Lead Length on Overshoot

PROBE CONNECTIONS

When making voltage measurements across a clamping device, e.g., for evaluating its performance, one must recognize possible difficulties requiring special precautions. Two precautions must be taken:

1. Use two probes in a differential mode to make a mesurement directly at device terminals.
2. Avoid contaminating the true device voltage by the additional voltage caused by magnetic coupling.

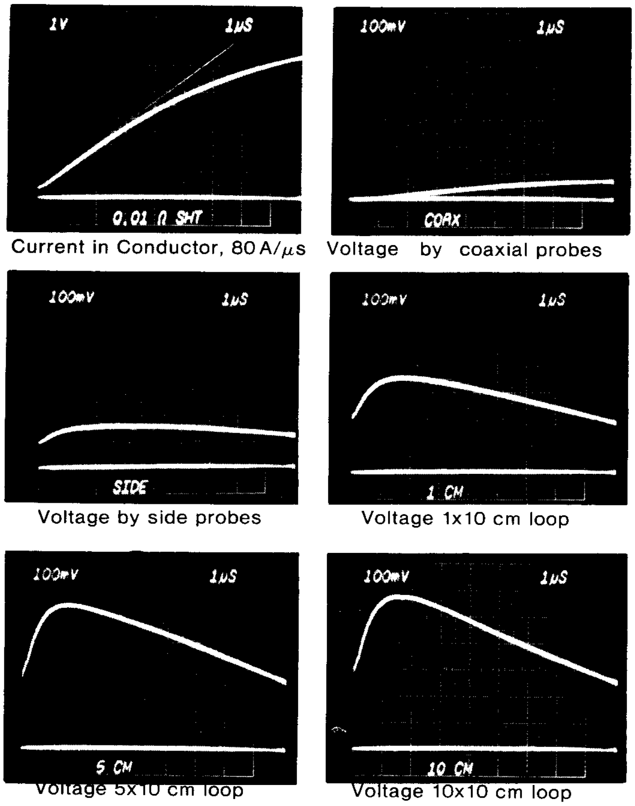
Commercial oscilloscope preamplifiers offer a wide choice of differential mode operation, either through an [add + invert one] mode of two-channel preaplifiers, or through a differential amplifier built specifically for high common-mode rejection, sometimes at the expense of bandwidth. Thus, careful attention must be given to this aspect of measurements.

The voltage measured by the two probes is the sum of the actual clamping voltage existing across the device and a spurious voltage caused by magnetic coupling. This spurious voltage is induced into the loop formed by the clamping device length and the two probes by the changing magnetic field of the current flowing in the device.

To further illustrate this situation, the measurement circuit shown in Figure 11 was set up in the output circuit of a generator producing a 8/20 μs impulse. The "device" was a hollow conductor, with a hole at the center through which a twisted pair was fed, one wire of the pair branching out to each end of the conductor, separated by 10 cm. At the same 10 cm separation, but outside of the hollow conductor, two thin wires were also soldered, brought to the midpoint of the hollow conductor and in close contact with the conductor; from the midpoint outward, they were twisted in the same manner as the inside pair. A third set of wires were soldered at the end points of the hollow conductor, and arranged to form a rectangle, the hollow conductor being one side of that rectangle. Several widths could be set up for the rectangle, and each time the measured voltage was recorded. Figure 13 shows the measured voltage versus radial distance of the opposite side of the rectangle, plotted from the oscillograms of Figure 12.

This example shows that not only one must connect the probes as close as possible to the terminals of a clamping device, but still strive to minimize the area established by the probes close to the device.

In this case of a low-voltage suppressor, it would be better to solder short leads to the device terminals, bring them together while tightly hugging the device, then twist them in a pair and connect the oscilloscope probes some distance away from the device.



Current in Conductor, 80 A/μs — Voltage by coaxial probes

Voltage by side probes — Voltage 1x10 cm loop

Voltage 5x10 cm loop — Voltage 10x10 cm loop

Figure 12. Voltages Recorded for Various Probe Connections

This example also shows the importance of wire layout in making the connections of a protective device in an actual circuit. As discussed in Case History No. 1, creating a loop near the protective device is an invitation to induce additional voltages in the output of the protective device, thus losing some of its effectiveness.

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.

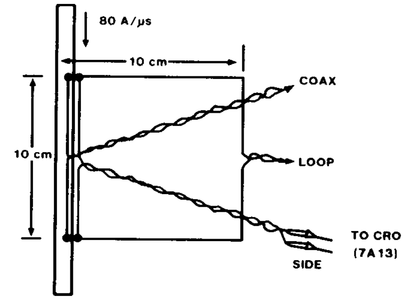


Figure 11. Circuit Configuration

COMPARISONS OF PROTECTIVE DEVICES

Linear Versus Nonlinear Devices

When a protection scheme is designed for an electronic system operating in an environment which is not completely defined, 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 are dramatically different between a linear protective device and a nonlinear protective device, as illustrated in a simplified comparison of the two suppressor devices (see box).

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, compared to the lower levels inherent with the crowbar action of a gap, can be deposited in a varistor, then a high capacity surge arrester near the service entrance may be combined with a lower clamping voltage varistor installed farther into the circuit. This combined protection, however, requires adequate coordination between the two suppressors (see reprint F79 635-4 in this section).

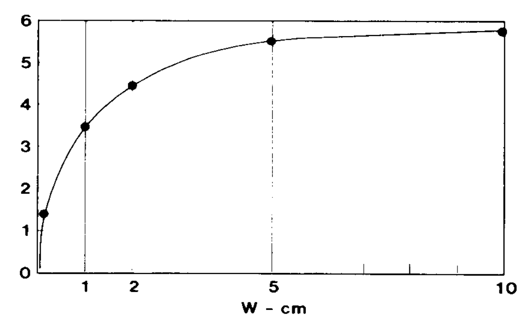
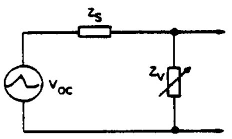


Figure 13. Voltage versus Area

A SIMPLIFIED COMPARISON BETWEEN PROTECTION WITH LINEAR AND NONLINEAR SUPPRESSOR DEVICES

Assume an open-circuit voltage, V_{oc}, of 3000 V (see the figure).



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

1. Assuming a source impedance of $Z_s = 50\ \Omega$

   - With a suppressor impedance of $Z_v = 8\ \Omega$, the expected current is

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

     Therefore,

     $$V_R = 8 \times 52\ A$$

     $$= 416\ V.$$

   - Working back from an assumed 52 A current but now considering a varistor, the maximum voltage appearing across the terminals of a typical nonlinear V150LA20A varistor at 52 A is 285 V (from characteristic curve).

     Note that:

     $$Z_s \times I = 50 \times 52 = 2600\ V$$

     $$V_R = 8 \times 52 = 385.\ V$$

     Therefore,

     $$V_{oc} \cong 3000\ V.$$

     The identity between this result for V_{oc} and the assumed 3000 V justifies the trial selection of 52 A in the circuit.

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

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

   $$= 1850\ V$$

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

   $$Z_s \times I = 5 \times 500 = 2500\ V$$

   $$V_R = 450\ V$$

   Therefore,

   $$V_{oc} \cong 3000\ V.$$

   The identity between this result for V_{oc} and the assumed 3000 V justifies the trial selection of 500 A in the circuit.

3. Conclusions:

   - With a linear resistor, a change of source impedance from 50 Ω to 5 Ω would produce a change in the protective level from 416 V to 1850 V.
   - With a varistor, the same change of source impedances produces a protection level change of only 385 V to 450 V.

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 the specified discharge voltage and discharge current, the standby current at the normal voltage would 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 conditions. The series gap can thus be eliminated, thereby producing three considerable improvements:

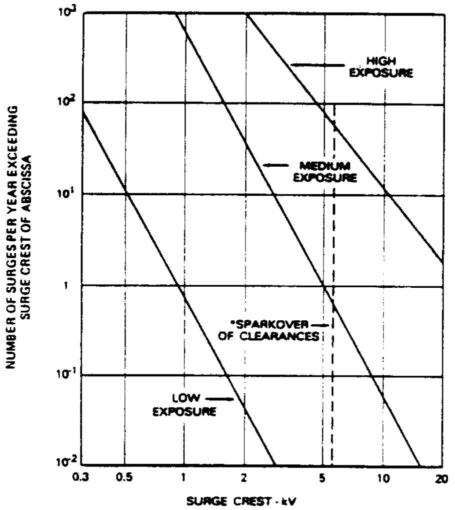
- Performance (elimination of abrupt sparkover)
- Reliability (elimination not only of the gap and all trigger circuitry but also of the parallel voltage-grading varistors)
- Contamination withstand (elimination of effects of leakage current on the outer shell).

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

MATCHING VARISTOR CAPABILITY TO THE ENVIRONMENT

Manufacturers of metal oxide varistors publish ratings which include a family of curves, generally described as "Pulse Lifetime," that show the number of surges which a given varistor can absorb before some arbitrary limit of characteristic shift is reached. These curves show numbers of surges of equal amplitudes for a set of waveshapes. The actual occurrence of surges, however, is a full range of values, from the lowest to the highest, and also of different waveshapes.

Attempts to simplify the description of surge occurrences have resulted in the statistical information of IEEE Std 587-1980, where a family of curves has been obtained from actual surge recordings; these curves show the frequency of occurrence of surges as a function of the voltage surge level, for various exposures (Figure 14). Carroll first developed a method(12) whereby the statistical information of IEEE 587 can be combined to predict the effect of the range of surge, as opposed to constant amplitude surges, on the varistor Pulse Lifetime. Korn has shown(13) how a simple set of assumptions and computations based on Figure 14 and Pulse Lifetime curves can provide an estimate of the time required to reach the varistor rated Pulse Lifetime. The last reprint, "Matching Surge Protective Devices to Their Environment," provides a detailed explanation of the method, with two specific examples.



***In some locations, sparkover of clearances may limit the overvoltages (see 8.3).**

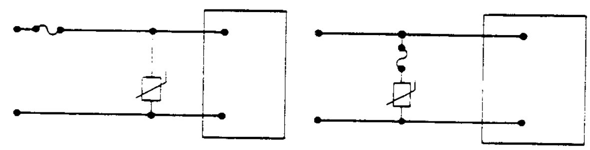
Figure 14. Rate of Surges Occurrence vs. Voltage Level (From IEEE Std 587-1980)

Failure Modes

Failure of an electrical component can occur 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 be exposed to an overvoltage, so that failure of the protective device must be in the fail-short mode, even if it puts the system out of operation. To other users, fail-safe means that the *function* must be maintained, even if the hardware is left temporarily unprotected, so that failure of the protective device must be in the open-circuit mode. It is more accurate and less misleading to describe failure modes as "fail-short" or "fail-open," as the case may be.

When the diverting path is a crowbar-type device, little energy is dissipated in the crowbar, as noted earlier. In a voltage-clamping device, because more energy is deposited in the device, 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, such as an error made in the assumption, human error in the use of the device, or because nature tends to support Murphy's law, 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 quickly cleared by a series overcurrent protective device (fuse or breaker).

When there is a need to provide elimination of a failed protector at the specific equipment level, insertion of the fuse in the line provides protection of the equipment (Figure 15a), while insertion of the fuse in series with the shunt-connected protector provides protection of the function. Albeit with loss of overvoltage protection (Figure 15b).



a. Protection maintained, function interrupted

b. Function maintained, protection lost

Figure 15. Fusing Options for Suppressors.

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.

FOR FURTHER READING

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8. Philipp, H.R., and L.M. Levinson, "Long Time Polarization Currents in Metal Oxide Varistors," 76CRD026, General Electric Company, Schenectady, NY, 1976.
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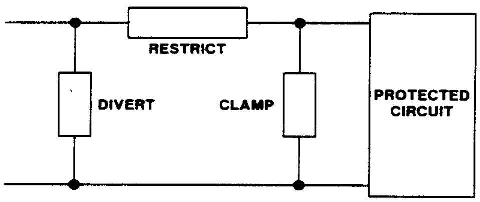
SLIDE NOTES



The basic approach to application of protective devices.

TRANSIENT SUPPRESSORS

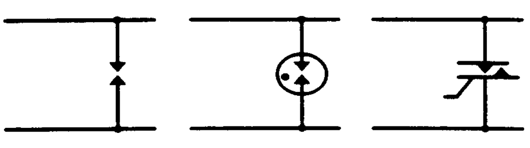
- SUPPRESSORS
- LIMITERS
- CLAMPS
- DIVERTERS
- ARRESTERS
- PROTECTORS
- PROTECTIVE DEVICES

They come under all names . . .

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

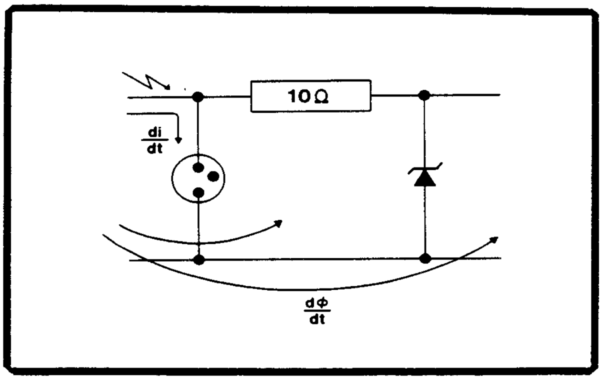
. . . and are of many types.

CROWBAR

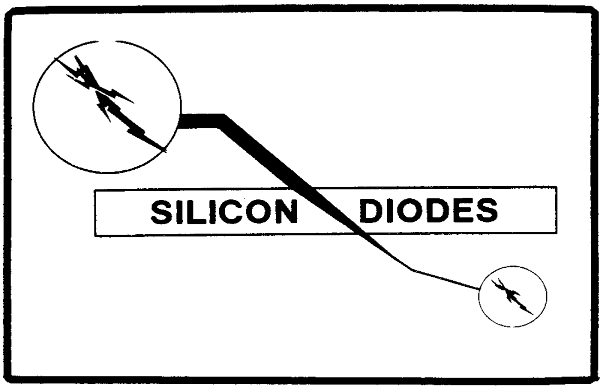


First family: gaps, semiconductor switches.

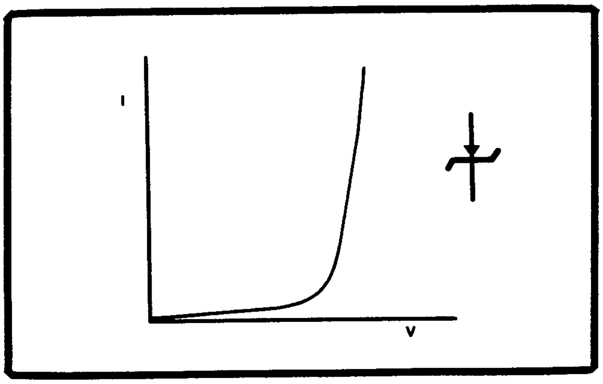
SLIDE NOTES



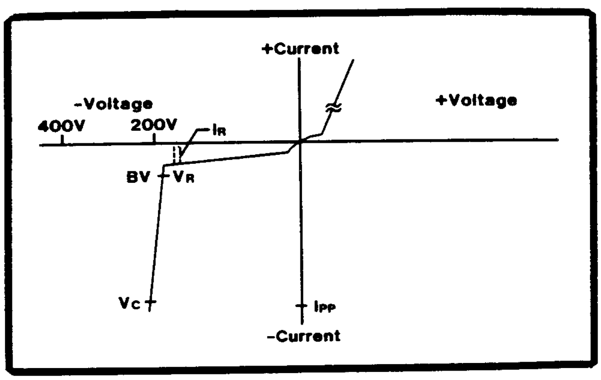
One of the problems introduced by the solution.



Another family: clamps.

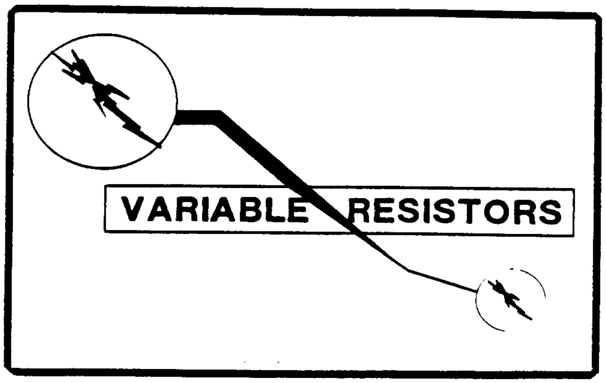


"Zener diode" response.

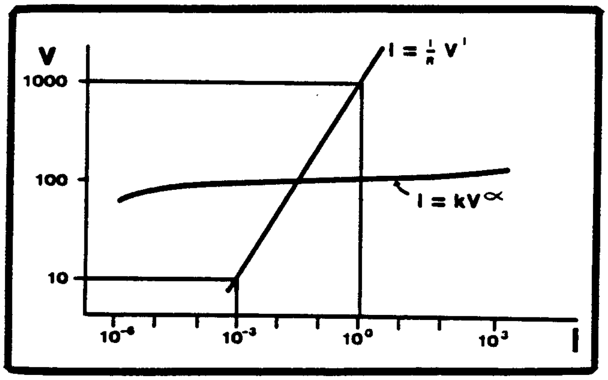


Parameters of an avalanche diode.

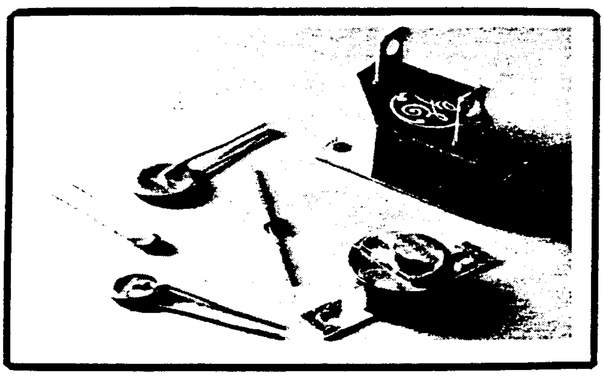
SLIDE NOTES



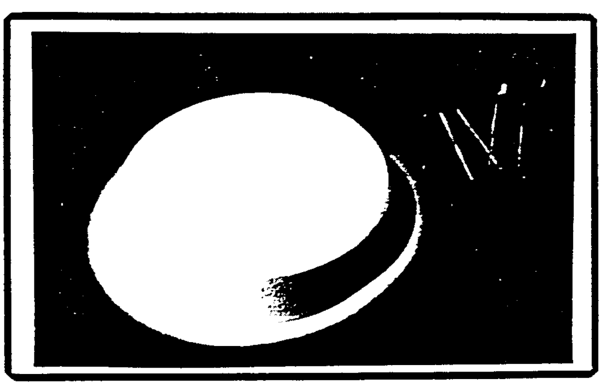
The newest, but well-established.



High exponent I-V characteristic.

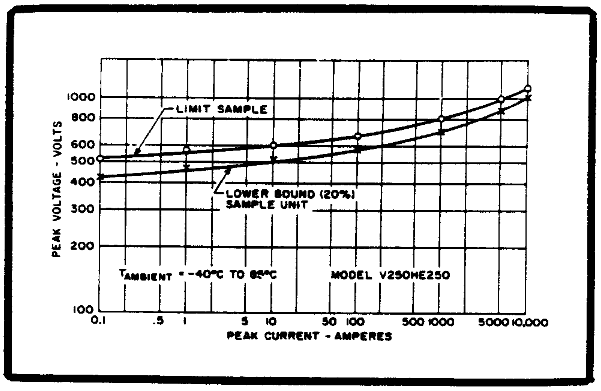


Overview.

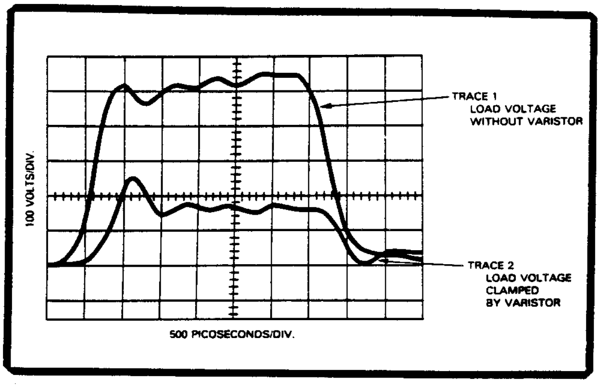


More joules.

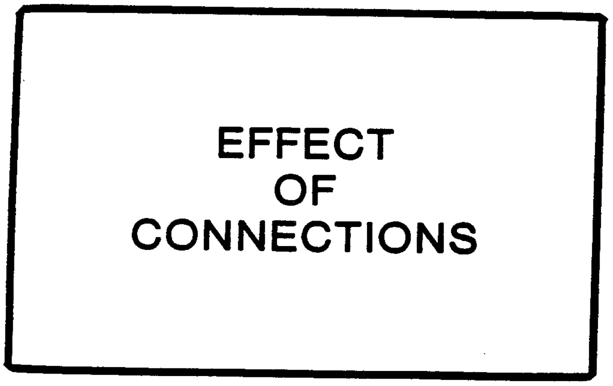
SLIDE NOTES



The "upturn" at high current density makes current sharing possible.

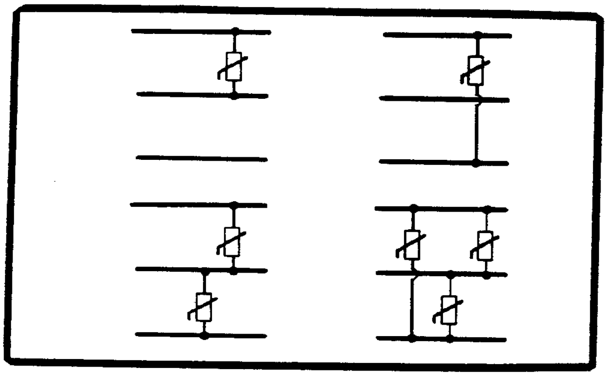


Actual response in a very low special inductance (VLSI) test circuit.

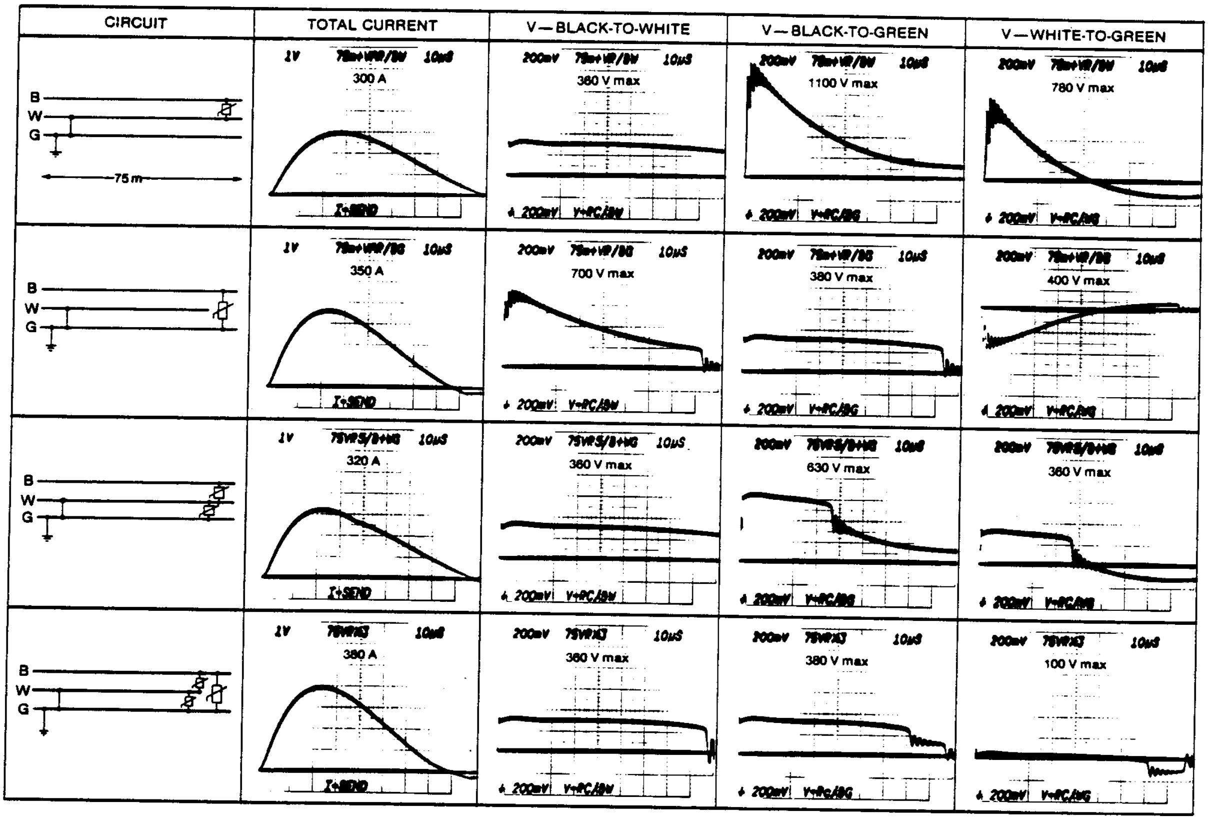


Two effects:

- Measuring device characteristics
- Applying the devices correctly



Connection options for 3-wire service.

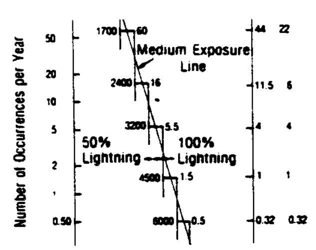


The clamping voltages and voltages between other conductors for various connection options (see propagation paper in reprint section).

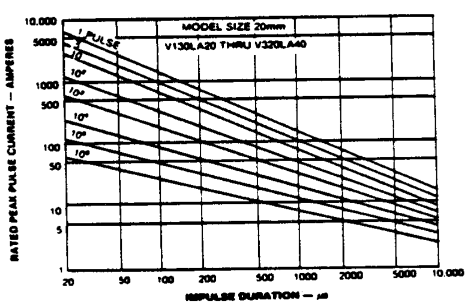
SLIDE NOTES

MATCHING THE ENVIRONMENT

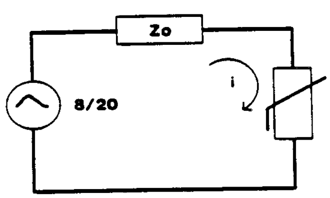
More of this in the reprint section.



Histogram with allocation of lightning surges (8/20 μs) vs. switching surges (Ring Wave).

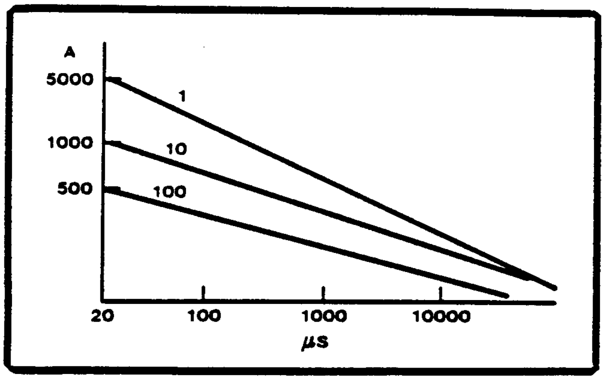


Published pulse lifetime characteristics.



Calculating the current in the varistor.

SLIDE NOTES



Simplified pulse lifetime.

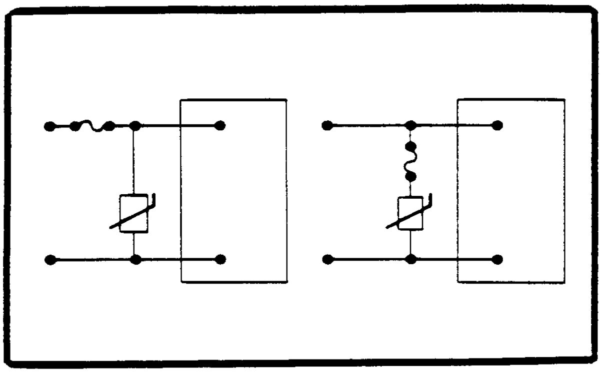
- **NUMBER OF OCCURRENCES AT 8/20**
- **SUBTRACT CLAMPING VOLTAGES**
- **DIVIDE BY IMPEDANCE**
- **LOOK UP RATED NUMBER OF PULSES**
- **COMPUTE YEARLY CONSUMPTION AND TOTAL**

The sequence of operations.

FAILURE MODES

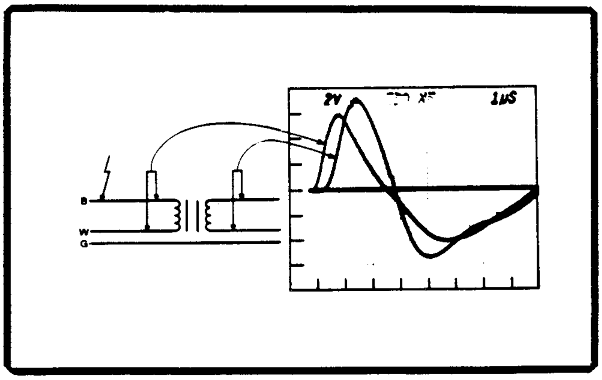
FAIL-SAFE	-	**NO NO**
FAIL OPEN	-	✓
FAIL SHORT	-	✓

Word usage.

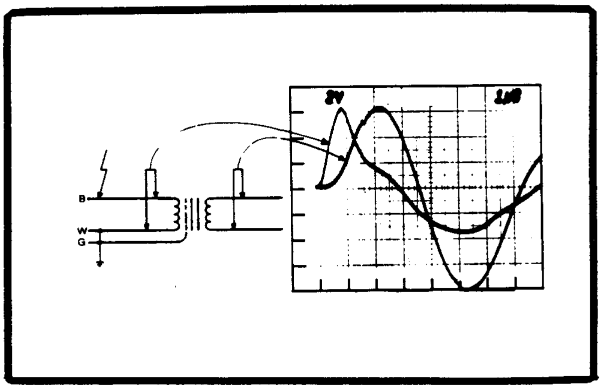


Two options for fusing, depending on mission objective.

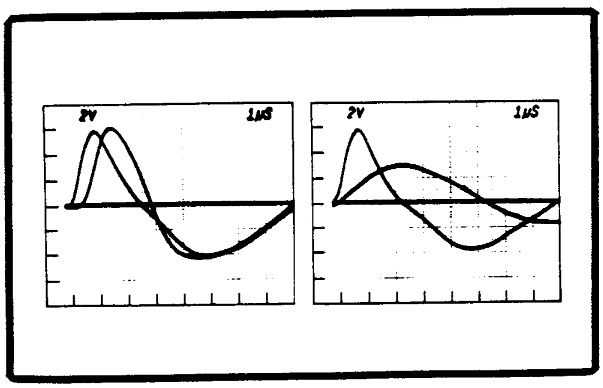
SLIDE NOTES



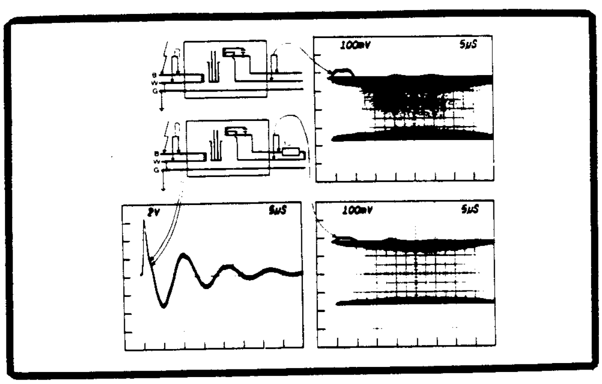
How a perfectly good isolating transformer -- for common mode -- fails to decouple normal mode surges.



Low interwinding capacitance does not do any better -- perhaps worse.



Loading the transformer secondary helps, but is not sufficient.



The ferroresonant line conditioner not only regulates and provides 1/2 cycle ride-through, but decouples the surges