The Protection of Industrial Electronics and Power Conversion Equipment Against Power Supply and Data Line Disturbances

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Significance
Part 6: Tutorials, textbooks and reviews

Tutorial presentation including a description of surge origins and standardization projects to characterize them, including the now-abandoned IEC 664 concept of "Installation Categories" – as contrasted with the IEEE C62.41 concept of "Location Categories." Brief discussions of issues such as the limitations of transmission-line analysis, pitfalls in shield grounding practices, comparisons of voltage-switching vs. voltage-limiting devices, and fusing options for failure modes.

Three examples are given in an Appendix on the erroneous expectation that an isolating transformer can be a one-type-fits-all surge mitigation approach, on the implications of possible configurations of SPD connections, and a case history of shifting reference voltages with retrofit of an appropriate remedy.

THE PROTECTION OF INDUSTRIAL ELECTRONICS AND POWER CONVERSION EQUIPMENT AGAINST POWER LINE AND DATA LINE DISTURBANCES

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Abstract

The irresistible trend toward distributed computing systems for the control of industrial power electronic equipment is adding new dimensions to the old problem of surge protection. Harmful surges may be produced by lightning, power switching, or by differences in ground potentials. The objective of the paper is to provide increased awareness and better understanding of the fundamentals of protection as well as the characteristics of protective devices.

1. Introduction

The continuing development of power conversion equipment, further promoted by the success of microelectronics in controlling this equipment, raises the question of vulnerability to surge voltages or surge currents appearing at the power or control input terminals of the equipment. The very origin of these surges (lightning, switching, electrostatic discharges) makes it somewhat difficult to predict with accuracy their characteristics, so that surge protection has sometimes been presented as "art rather than science." There is, however, enough practical experience and data available to apply good engineering judgment in developing an understanding of the practical aspects of surge protection based on fundamental concepts and on protective device characteristics. The present paper is offered as a contribution toward better surge protection, neither as an art nor as a science, but as a no-nonsense, sound, and cost-effective engineering practice.

The paper presents first a discussion of the various and complex origins of lightning and switching surges (electrostatic discharges are acknowledged but not addressed in a limited space discussion). The paper also shows how standards can help simplify the application of protection. A brief discussion is given on aspects of the propagation of these surges, followed by a presentation of some fundamental approaches to protection. Basic characteristics of protective devices are outlined. Three examples are given on how this knowledge and engineering judgment can be applied to answer specific questions and to avoid pitfalls.

2. 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. In communication or data systems, there is another source of transients: the coupling of power system transients into the system. Furthermore, all systems involving several connections to the environment have the potential risk of transient overvoltages associated with ground potential rise during the flow of surge currents. As stated previously, static discharge problems are not treated in this paper.

Lightning discharges may not necessarily mean direct termination of a lightning stroke onto the system. A lightning stroke terminating near a power line, either by hitting a tall object 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 system. Lightning can also inject overvoltages in a 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 provides information on the characteristics of lightning discharges [1-6].

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

2.1 Transients in Power Systems

A transient is created whenever a sudden change occurs in a power circuit, especially during power switching – either the closing or opening. 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. Prestrikes can also occur just before the contacts close, with a succession of clearings at the high-frequency current zero, followed by restrikes. Similarly, during an opening sequence of a switch, restrikes can cause electrical closing(s) of the circuit.

Simple switching transients [7] include circuit closing transients, transients initiated by the clearing of 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. Without a surge protective device, the current flowing just before switching is available to charge the circuit capacitances at whatever voltage is required to store the inductive energy of the current by converting it into capacitive energy.

Several mechanisms are encountered in practical power circuits that 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.

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.

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 are described in the next section. Figures 1, 2, and 3 show typical examples of transients recorded in power systems.

3. Standards on Transient Overvoltages in Power Lines

Several standards or guides have been issued or proposed in Europe and in the United States, 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. Three of these are briefly discussed here.

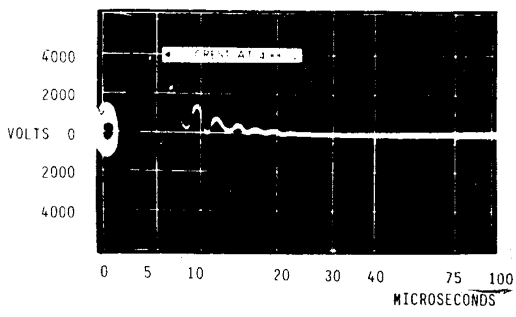

Figure 1. Lightning surge recorded on a 120 V overhead distribution system

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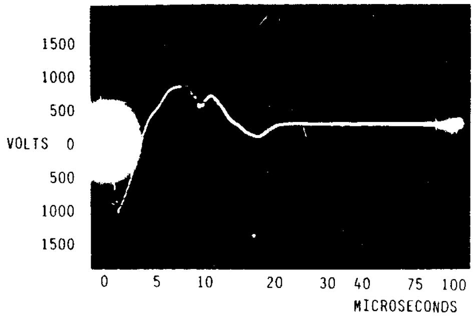


Figure 2. Switching surge recorded on a 120 V residential wiring system

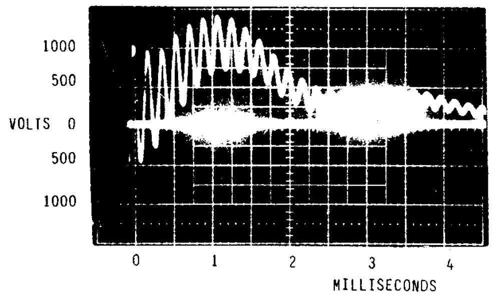


Figure 3. Capacitor switching transient recorded on a 460 V system

3.1 The IEEE Surge Withstand Capability Test (SWC) [8]

One of the earliest published documents which addressed 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.

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. The revised version of this standard, soon to be issued, recognizes the problem and attempts to be more specific (and restrictive) in its scope. 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.

3.2 The IEC 664 Report [9]

The Insulation Coordination Committee of IEC 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 its applicability to a *controlled voltage situation*, which implies that some surge-limiting device has 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 primarily addresses the concerns of insulation coordination; 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 will be reviewed in detail.

3.3 The IEEE Guide on Surge Voltages (ANSI/IEEE Std C62.41-1980) [10]

3.3.1 Voltages and Rate of Occurrence. Data collected from a number of sources led to plotting a set of lines representing a rate of occurrence as a function of voltage for three types of exposures (Figure 4). These exposure levels are defined in general terms as follows:

- *Low Exposure* — Systems in geographical areas known for low lightning activity, with little load switching activity.
- *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 4 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.

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.

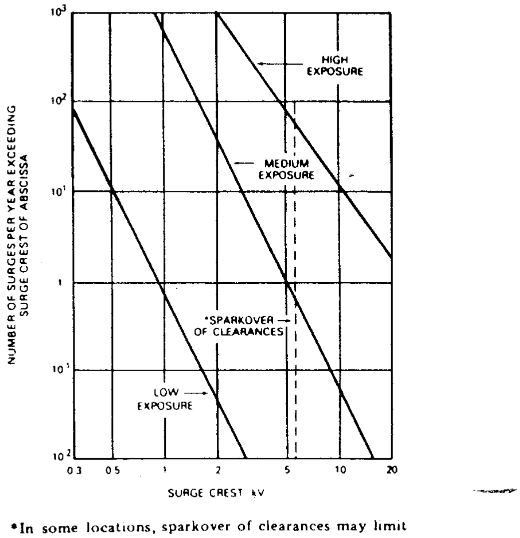
* Forthcoming revisions to the IEC Report will include a change from "Installation Category" to "Overvoltage Category."

Table 1

IEC Report 664

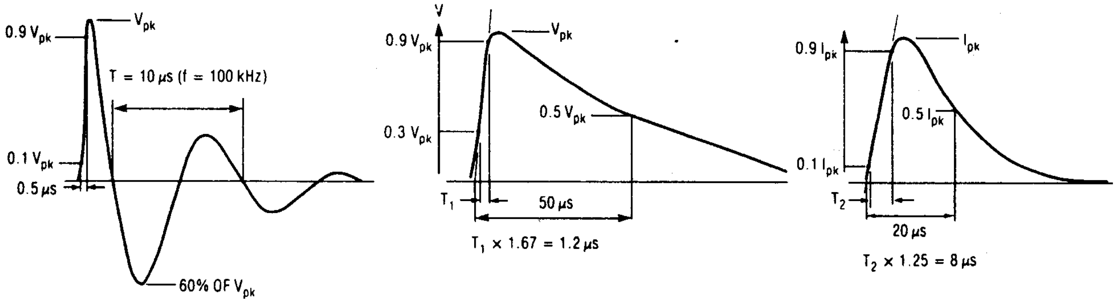
PREFERRED SERIES OF VALUES OF IMPULSE WITHSTAND VOLTAGES FOR RATED VOLTAGES BASED ON A CONTROLLED VOLTAGE SITUATION

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



*In some locations, sparkover of clearances may limit the overvoltages

Figure 4. Frequency of occurrence versus level from ANSI/IEEE Std C62.41-1980



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

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

Figure 5. Surges defined for power lines by ANSI/IEEE Std C62.41-1980

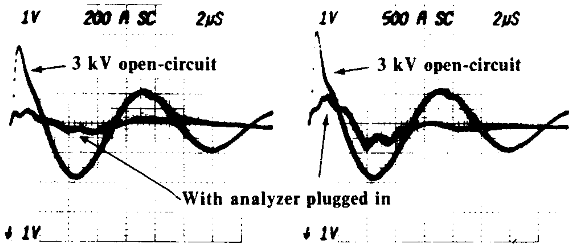
3.3.2 Waveshape of the Surges. Many independent observations [11-13] have established that the most frequent type of transient overvoltage in ac power systems is a decaying oscillation, with frequencies between 5 and 500 kHz. This finding is in contrast to earlier attempts to apply the unidirectional 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 5).

The oscillatory waveshape simulates those transients affecting devices that are sensitive to dv/dt and to voltage reversals during conduction [14], 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.

3.3.3 Energy and Source Impedance.* The energy involved in the interaction of a power system with a surge source and a surge protctive 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, e.g., in a resistor added in series with the gap for limiting the power-follow current, or on the impedance of the circuit upstream of the protective device. In an energy-absorber protective device, by its very nature, a substantial share of the surge energy is dissipated in the suppressor, but its clamping action does not involve the power-follow energy resulting from the short-circuit action of a gap. It is therefore essential to the effective use of surge protective devices that a realistic assumption be made about the source impedance of the surge whose effects are to be duplicated.

Unfortunately, not enough data have been collected on what this assumption should be for the source impedance of the transient. Standards and recommendations, such as MIL STD-1399 or the IEC 664 report, either ignore the issue or indicate values applicable to limited cases, such as the SWC test for high-voltage substation equipment. ANSI/IEEE Std C62.41-1980 attempts to relate impedance to categories of locations but unavoidably remains vague on their definitions (Table 2).

3.3.4 New Reports on Transient Occurrence. The importance of defining the environment has motivated a number of workers to install recording devices on their power systems, and thus created a market for commercial transient recorders in the last several years. Unfortunately, at least one such recorder contains a surge suppressor in its own power supply (Figure 6).



(a) 200 A short-circuit current **(b) 500 A short-circuit current**

Figure 6. Effect of connecting a "Disturbance Analyzer" on a power system subjected to the ANSI/IEEE C62.41 ring wave

* Note the difference between *surge impedance* of the line, also called characteristic impedance, and the *impedance to the surge, Z_1 of Figure 8, defined in terms of R, L, C at the frequency corresponding to the surge.*

Table 2
Description of Surge Environment in ANSI/IEEE Std C62.41-1980

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.

Consequently, if the line being monitored is that in which the analyzer has its power cord plugged, the transients that occurred on the line before the analyzer was installed disappear. This irony makes my facetious remark of 1969, ". . .the best surge suppressor is a surge monitor," [12] the truth. Therefore, some of the recently published surveys on the occurrence of surges may show a lower number of surges than actually occur, and therefore data should be examined with caution until the ambiguity caused by this cord-connected suppressor is resolved.

4. Surge Propagation

4.1 The Limitations of Arbitrary Division into Categories

The standards cited in the preceding paragraphs describe surges which may be expected at specific points of a wiring system; the implication is that the surges will proceed downstream, at the same amplitude, until some interface somehow produces a decrease in amplitude down to the next lower level of voltage or to the next lower level of current specified by the next downstream category (Figure 7).

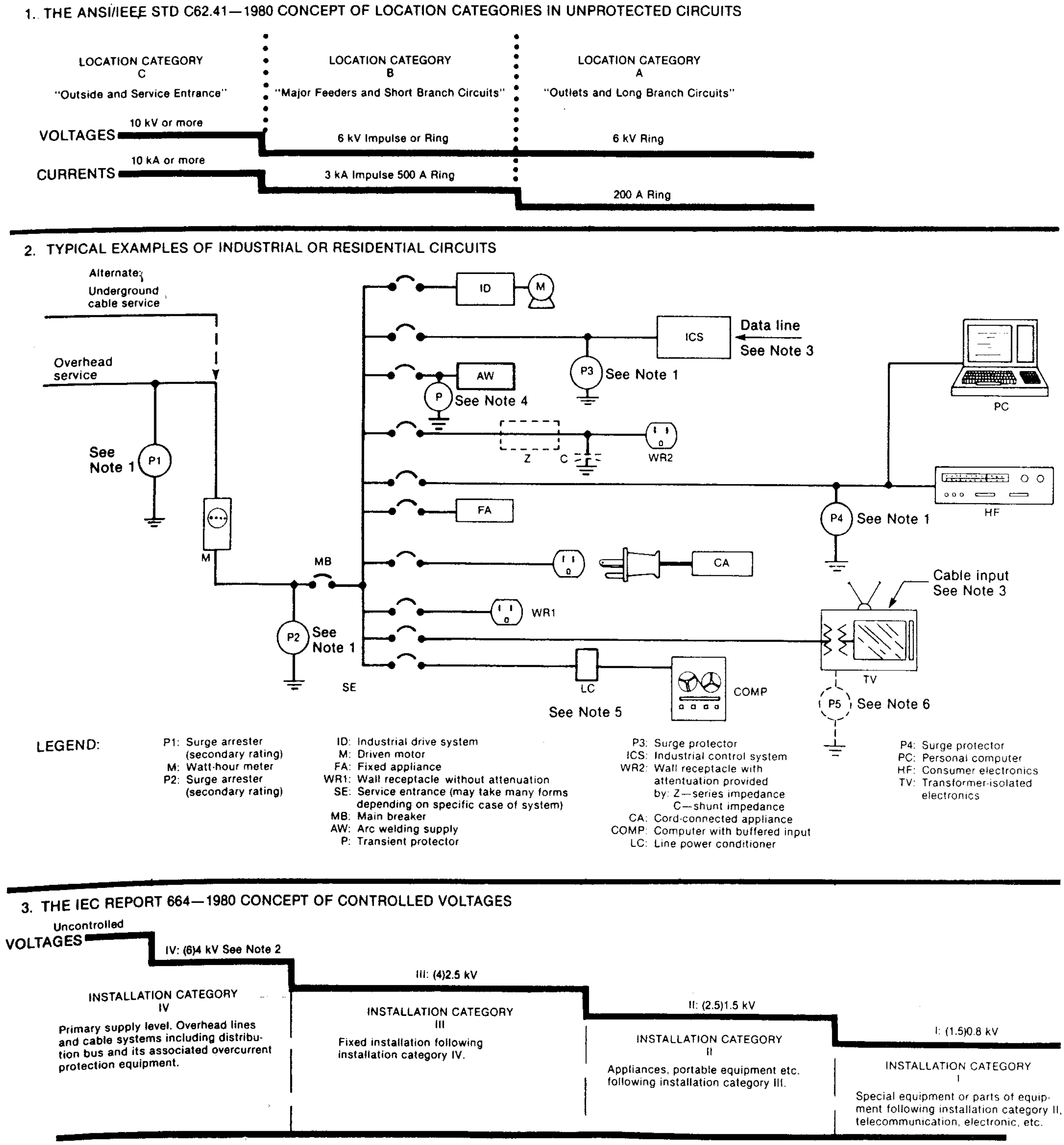


Figure 7.
Similarities and differences between the location categories concept of ANSI/IEEE Std C62.41-1980 and the installation categories concept of IEC Report 664-1980, applied to a typical example

Table 3
(Notes for Figure 7)

1. THE ANSI/IEEE Std C62.41-1980 CONCEPT OF LOCATION CATEGORIES IN UNPROTECTED CIRCUITS

(a) The voltage levels shown in the three location categories represent high impedance circuit conditions: light loading and no surge protective devices P1, P2, P3 or P4. The 10 kV voltage of Category C is reduced to a maximum of 6 kV in *both* Categories B and A by the likely sparkover of clearances, should a 10 kV surge impinge on the service entrance.

(b) The current levels shown in the three location categories, in a descending staircase from C to A, represent low impedance circuit condition for surges, such as the installation of one or more surge protective devices P1, P2, P3 or P4. Another low impedance condition is the case of equipment sparkover (installed equipment in an actual system or EUT during a test).

(c) If multiple surge protective devices are installed on the system, the current waveform imposed on the downstream protective device is influenced by the clampling characteristics of the upstream device.

2. TYPICAL EXAMPLES AND THE IEC REPORT 664 CONCEPT NOTES:

(1) The Controlled Voltage Situation of IEC Report 664 requires the presence of interfaces: these can be surge protective devices such as P1, P2, P3 or P4, or the existence of well-defined impedance networks such as Z and C shown in the circuit diagram upstream of WR2.

Surge arresters or protectors P1, P2, P3 and P4 may be any protective device suitable for the surge current levels expected at that point of the system. P1 and P2 are shown connected line-to-ground. P3 and P4 may be connected line-to-neutral, or be a combination of line-to-neutral with additional neutral-to-ground.

Surge arrester P2 may also be connected on the load side of the main circuit breaker MB. In that case, MB would then be considered to be in Installation Category IV.

(2) Voltage levels following the designation of Installation Category (IV, III, II or I) are shown in parentheses for a system with 300 V phase-to-ground voltage, and next for 150 V phase-to-ground voltage. The voltages shown are implied as 1.2/50 μs impulses.

Example: IV:(6)4 means: 6 kV 1.2/50 μs for a 240 V system, 4 kV 1.2/50 μs for a 120 V system. See IEC Report 664-1980 [9] for the complete table of levels corresponding to system voltages from 50 to 1000 V.

(3) This diagram makes no allowance for the possibility of surges associated with ground potential differences that may occur, for instance, with a sensor connection to the ICS control system, a cable TV connection to the line-isolated TV set, etc., or the flow of ground current in the impedance of the grounding conductors.

(4) Transient protector P in the line feeding the welder AW (a typical example of transient generator internal to the system) is intended to protect the system from the welder, rather than to protect the welder from the system.

(5) Power line conditioner LC, while performing the major task of conditioning the power supply to the computer, may perform a function similar to that of the protector P at the welder in blocking conducted interference from the load toward the system.

(6) Many appliances or electronic devices might be equipped with internal surge protective devices and therefore be suitable for installation in other categories than II.

This staircase representation is useful to simplify the real world into a manageable set of assumptions, but it is a simplification that can mask the reality. Surges will propagate in the system starting at the point of entry; voltage surges will be attenuated to the extent that the series impedance between the point of interest and the source (Z_1, Figure 8) and the shunt impedance (Z_2), form a voltage divider. If the series impedance is low and the shunt impedance is high (light loading of the system), the voltage divider does not produce high attenuation of the voltage surges. Conversely, current surges, if they are the result of a current source such as a lightning strike, will produce high voltages unless a low-impedance diverting path is offered to the flow of current. If the current surge in a system is the result of a combined current source and multipath to ground (Figure 9), there is then a division of the current among the paths that is governed by the inverse ratio of the impedances. If a user has control over only one of the paths, he can decrease the amplitude of the current surge in his path only by forcing a greater share of the total current to flow through the other paths; thus, surge *blocking* is likely to be an exercise in passing the problem from one point of the system to another. The solution lies in surge *diversion*, offering to the surge a path where the current flow can occur harmlessly.

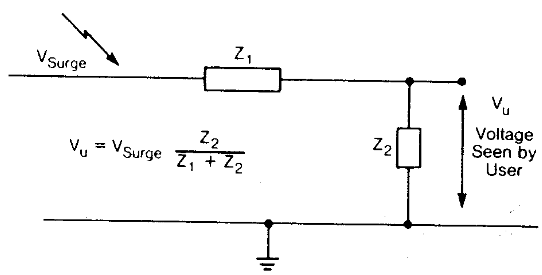
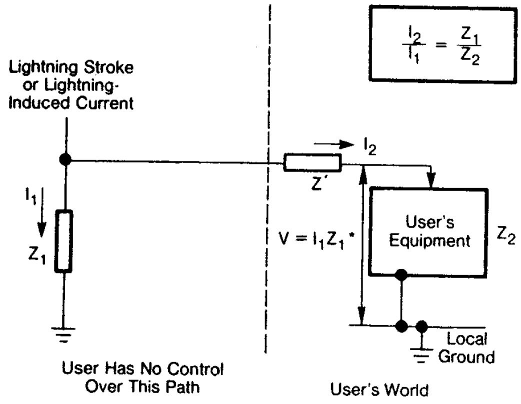


Figure 8. Voltage divider effect

4.2 The Limitations of Transmission Line Analysis

In qualitative discussions of surge propagation, the classical behavior of a transmission line is often called upon to provide explanations of the situation. In particular, the theoretical reflections occurring at the end of a line are cited: doubling the impulse if the line is open-ended, returning an inverse impulse if the line is shorted. However, these discussions sometimes lose sight of the fact that the concept can be



* or $V = I_1Z_1 - I_2Z'$ if Z' is Significant

Figure 9. Multipath current division

applied only if the line length is sufficient to contain all of the surge front. If the surge has a rise time longer than the propagation time along the line, the point is moot and, by the time the surge reaches its peak, the voltage at the receiving end of the line does not differ from the voltage applied at the sending end. Figure 10 illustrates this situation showing the voltage at the sending end (SD) and the voltage at the receiving end (RC) of a conduit-enclosed three-wire line (B: black or phase conductor, W: white or neutral conductor, G: green or grounding conductor). There is a minor difference during the rise, where the initial front is doubled at the receiving end, but the crests are the same. Thus, for many installations in buildings, the line lengths are short compared to the length required to contain, say, a 1 μs front traveling at a typical speed of 200 m/μs.

A more detailed report describing some of the aspects of the propagation of surges and their implications is given in Reference 15.

4.3 Common Mode or Normal Mode?

Another aspect of the propagation of surges concerns the dichotomy normal mode/common mode. In other words, the issue is whether significant surges occur line-to-line (black-to-white, or phase-to-neutral), the situation described by "normal mode," or whether they occur between any – or both – of the lines and ground (black-to-green, white-to-green, or [black-and-white]-to-green), the situation described by "common mode."

The answer to that dichotomy is that, in most cases, both modes must be considered, since one often converts into the other, depending upon the coupling, the wiring practices, and the attempts made at suppressing the mode perceived as the greatest threat. Here again, the pervasive and pervert reality is too often that a solution aimed at suppressing one effect only displaces the problem. Examples 1 and 2, in the Appendix, show how controversies on the method of suppressing a surge assumed to occur between two wires can lead to partial or misleading solutions when the realities of the situation are not recognized.

5. Fundamental Protection Techniques

The protection of a power conversion system or 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 space and scope has the risk of becoming an inventory of a bag of tricks; yet, there are a few fundamental principles and fundamental techniques that can be useful in obtaining transient immunity, especially at the design stages of a computer system or circuit. All too often, the need for protection becomes apparent at a late stage, when

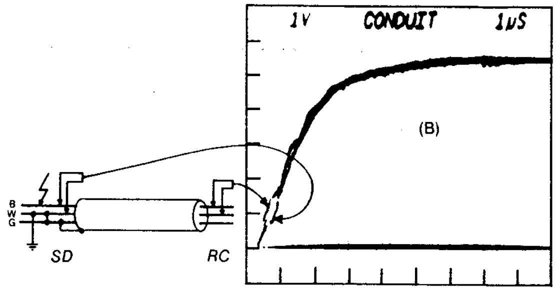


Figure 10. Voltages at sending and receiving ends of a line

it is much more difficult to apply the fundamental techniques which are most effective and economical when implemented at the outset.

5.1 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 system depending on low-voltage signals, high-impedance circuits, and installed over a wide area would present much more serious problems than the same system confined to a single building or a single cubicle.

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. While surges are unavoidable, one can attempt to block them, divert them, or strive to withstand them; the latter, however, is generally difficult to achieve alone.

5.2 Shielding, Bonding, and Grounding

Shielding, bonding, and grounding are three interrelated methods for protecting a circuit from external transients. Shielding consists of enclosing the circuit wiring in a conductive enclosure, which theoretically 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. Many texts and papers discuss the subject at length, so that a detailed discussion is not necessary here, with one exception, which follows.

5.3 Ground One End or Both Ends of the Shield?

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. Difficulties also arise 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 miles 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. This concept is exemplified in the terminology of shielded cable users, when they describe the shield construction of some cable design as having a foil plus *drain wire*, as if there were *electrostatic* charges that needed to be removed *(drained)*. Indeed, electrostatic charges can be drained by connecting only one end of the shield. Furthermore, if the two ends of the shield of a cable spanning some distance are connected to the local ground at each end, there is a definite possibility that some power frequency current may flow in the shield. For low-level signals, this current would produce noise (hum) in the signals. For that reason, many system designers will insist on the one-end-only grounding rule, and they are correct from that point of view. 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. Worse yet, in the case of a lightning stroke injecting current into the earth in the area spanned by the one-end-only grounded shield, the potential of one end of the cable defined as "ground" is not the same as the "ground" at the other end of the cable. Very high voltages can be developed (Figure 11) between the floating end of the shield and the local ground. No practical insulation can withstand these levels, and breakdown will occur, allowing surge currents to flow in spite of the designers' intent to prevent them; the path of these currents will be determined by the components most likely to fail when the voltage rises – the low-level logic circuits, of course. In contrast, 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, and the currents will follow a well-defined path that can be designed to provide harmless effects.

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. In many installations, however, 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. Example 3 in the Appendix shows the consequence of the misapplied "ground one end only" rule.

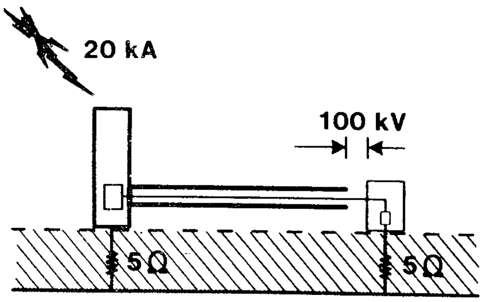


Figure 11. Voltage developed by a lightning stroke at the ungrounded end of a shield

6. Transient Suppressors

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

There are two categories of transient suppressors: those that block transients, preventing their propagation toward sensitive circuits, and those that divert transients, limiting residual voltages. Since many of the transients originate from a current source, the blocking of a transient may not always be possible; thus, diverting the transient is more likely to find general application. 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 – an 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 12). 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 the current increases, or an abrupt switching as the voltage increases.

Because the technical and trade literature contains many articles on these devices, a discussion of the details will be limited. Some comparisons will be made, however, to point out the significant differences in performance.

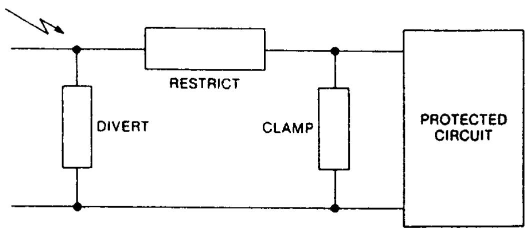


Figure 12. Three-step approach for surge suppression

6.1 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 "reflection" 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. The first limitation concerns the volt-time sensitivity of the breakdown process. As the voltage increases across a spark gap, a 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. In addition, this sparkover voltage 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.

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 13). This anomaly is due to the delay introduced in the oscilloscope circuits to provide an advanced trigger of the sweep. What the trace shows is the event delayed by a few nanoseconds, so that in real time, the gap sparkover occurs and noise enters the oscilloscope by stray coupling while the electron beam is still writing the presparkover rise.

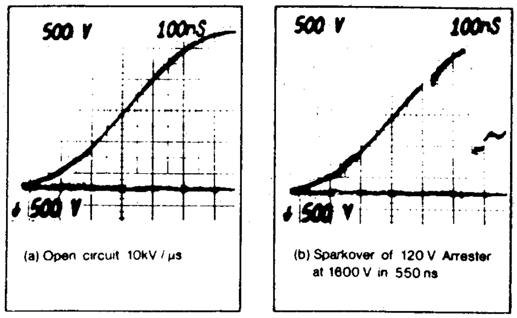


Figure 13. Anomaly in recording showing gap interference

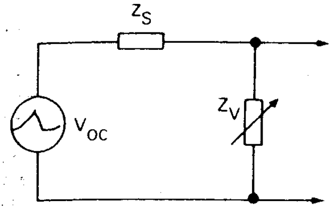
A third limitation occurs when a power current from the steady-state voltage source follows the surge discharge (follow-current, or power-follow). In ac circuits, this power-follow current may or may not be cleared at a natural current zero. In dc circuits, clearing is even more uncertain. Additional 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 nonlinear varistor that limits the power-follow current has been very successful in the utility industry as a surge arrester or surge diverter.

6.2 Voltage-Clamping Devices

Voltage-clamping devices will exhibit a variable impedance, depending on the current flowing through the device or the voltage across its terminals. These components show a nonlinear characteristic — that is, Ohm's law can be applied, but the equation has a variable *R*. Impedance variation is monotonic and does not contain discontinuities, in contrast to the crowbar device, which shows a turn-on action. As far as 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 clamping. A voltage divider action is at work where 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 14). In contrast, a crowbar-type device effectively short circuits the transient to ground; once established, however, this short circuit will continue until the current (the surge current as well as any power-follow current supplied by the power system) is brought to a low level.

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: polycrystalline varistors and single-junction avalanche diodes. Another technology, selenium rectifiers, has been practically eliminated from the field because of the improved characteristics of modern varistors.



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

Figure 14. Voltage divider effect of shunt-connected suppressor

6.3 Avalanche Diodes

Avalanche diodes, or 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 deposited by the surge in the small volume of 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.

6.4 Varistors

The term *varistor* is derived from its function as a *var*iable res*istor*. It is also called a *voltage-dependent resistor*, but that description tends to imply that the voltage is the independent parameter in surge protection. 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.

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 [16-20].

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 15. The major element is the varistor proper, R_v, whose $V-I$ characteristic is assumed to be the perfect power law $I = kV^{\alpha}$. In parallel with this varistor, there is a capacitor, *C*, and a leakage resistance, R_p. In series with this three-component group, there is the bulk resistance of the zinc oxide grains, R_s, and the inductance of the leads, *L*.

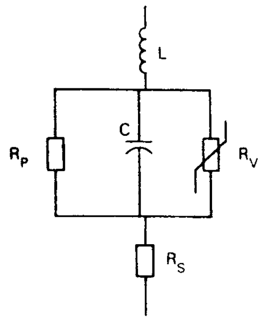


Figure 15. Equivalent circuit of a varistor

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

6.4.1 V-I Characteristic. When the *V-I* characteristic is plotted on a log-log graph, the curve of Figure 16 is obtained. Three regions result from the dominance of R_p, R_v, and R_s as the current in the device goes from nanoamperes to kiloamperes.

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, discussed in detail in the information available from manufacturers, must also be taken into consideration. Some of these factors are:

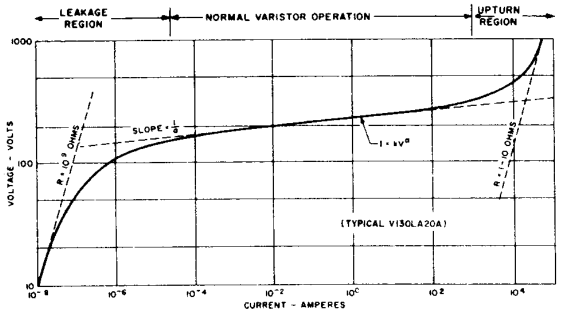


Figure 16. V-I characteristic of a varistor

- Selection of the appropriate nominal voltage for the line voltage of the application
- Selection of the energy-handling capability (including consideration of the source impedance of the transient, the waveshape, and the number of occurrences [21])
- Heat dissipation
- Proper installation in the circuit (lead length) [22]

6.5 Packaged Suppressors

The need for protection and the opportunity to provide packaged protective devices to concerned computer users has prompted the marketing of many packaged suppressors, ranging from the very simple and inexpensive to the complicated (not necessarily much better) and expensive. The field has also seen a number of devices claiming energy savings in conjunction with transient suppression; there is no foundation for such a claim, and the issue hopefully has been settled in a study published by EPRI [23].

Line conditioners using a ferro-resonant transformer are offered primarily as line-voltage regulators, but also provide high attenuation of transient overvoltages, a performance that isolating transformers do not provide. Example No. 2, in the Appendix, gives examples of the poor performance of isolating transformers and of the effective performance of line conditioners in dealing with normal mode transients.

6.6 Failure Modes

Failure of an electrical component can occur because its capability was exceeded by the applied stress or because some latent defect in the component went unnoticed in the quality control processes. While this situation is well recognized for ordinary components, a surge protective device, which is no exception to these limitations, tends to be expected to perform miracles, or at least to fail graciously in a fail-safe mode. The term "fail-safe," however, may mean different failure modes to different users and, therefore, should not be used. To some users, fail-safe means that the protected *hardware* must never be exposed to an overvoltage, so that failure of the protective device must be in the fail-short mode, even if it puts the system out of operation. To others, 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 design 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, e.g., an error made in the assumption, a 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).

With the failure mode of a suppressor being of the fail-short type, the system protection with fuses can take two forms (Figure 17). For the user concerned with maintaining the protection of expensive equipment, even if failure of the protector means the loss of the function, Alternative A must be selected. Conversely, if the function is paramount, Alternative B must be selected.

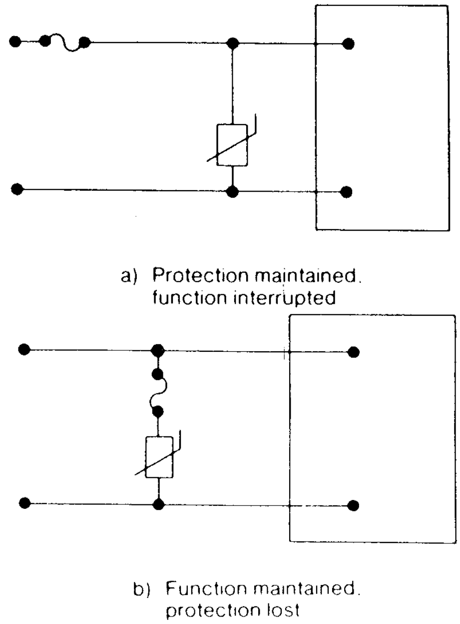


Figure 17. Fusing alternatives for suppressors

7. Conclusions

Power system disturbances can inject damaging overvoltages in power lines as well as data lines. Lightning surges can be equally damaging, by direct termination of a stroke, or by induction or even differences in ground potential caused by the flow of the current. **Beware of differential ground potential rise!**

Fundamental precautions, best applied in the design and construction stages, can provide effective protection at a small cost compared to the alternative of failures and later retrofits. **The cost of insurance premiums always seems high before the accident.**

Shielding, bonding, and grounding are the classical preventive methods at the system and component level. Conflicts between traditional grounding practices for noise reduction can be reconciled with the requirements of surge protection. **Grounding the shields at one end only invites trouble.**

A combined approach of fundamental precautions and protective devices can provide effective protection over the range of natural and man-made disturbances. However, these devices must be applied as part of a concerted effort. **Coordination of protective devices is the key to functional and cost-effective protection.**

Acknowledgments

Motivation for presenting this paper was provided by the reported case histories and the penetrating questions raised by students at the University of Wisconsin annual conferences on surge protection, as well as by discussions with members of the IEEE Surge Protective Devices Committee. Catharine Fisher and Elizabeth Zivanov of CRD contributed valuable reviews and comments toward development of the final text.

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To illustrate the preceding discussion, some practical examples are given in this appendix as the basis for sound design approaches.

Example No. 1 – Does an isolating transformer help? The author has witnessed and engaged in many discussions on the merits of isolating transformers, sparked by the misconception that "spikes are attenuated by transformers" or "spikes do not pass through transformers." Figures 18 and 19 are offered to support the position that these quotations are misconceptions. When properly applied, isolating transformers are useful to break ground loops and reduce common mode effect, but they do not by themselves attenuate spikes that occur line-to-line in the normal mode.

Figure 18 shows the propagation – or worse, the enhancement – of a voltage impulse in a 1:1 isolating transformer. The 6 kV, 0.5-100 kHz impinging wave of ANSI/IEEE Std C62.41-1980 is applied to the primary of the transformer, H_1H_3 to H_2H_4. The output voltage, measured at X_1X_3 to X_2X_4, appears as a 7 kV crest on the secondary side of this "isolating" transformer.

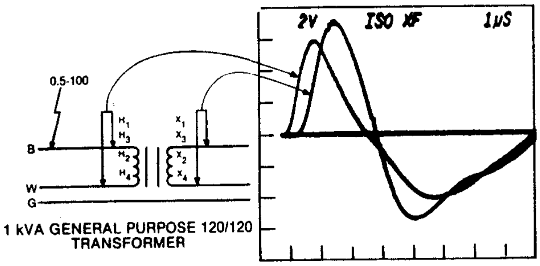

Figure 18. Surge propagation through isolating transformer

Figure 18 was recorded with no load on the transformer secondary, which represents the extreme case of the low-power electronic control in the standby mode. Figure 19 shows the primary and secondary voltages of the transformer with a 10 W (1500 Ω) and a 100 W (150 Ω) load on the secondary side, at the same generator setting as Figure 18. With the 10 W load that might be typical of an electronic control in standby mode, the combined series reactance of the transformer and shunt resistance of the load produce the output shown in Figure 19A, still slightly higher than the input.

With the 100 W load shown in Figure 19B, the attenuation is now apparent, but is only 2:1. Capacitive loads would, of course, produce a greater attenuation than resistive loads for the inductive series impedance of the transformer, at the frequency spectrum of this fast 2 µs-wide spike. For surges of longer duration, the attenuation would be even smaller.

These examples show that, unless a well-defined load is connected to the transformer, expecting attenuation from the transformer may prove to be hazardous to the health of low-power electronics connected on the secondary side of a transformer.

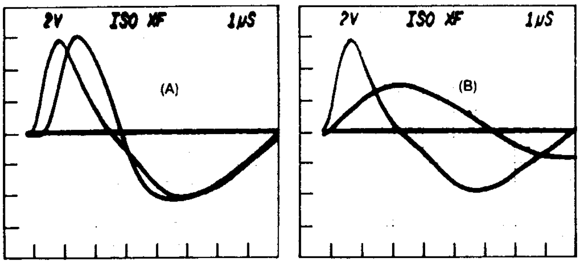

Figure 19. Effect of loading on the secondary side

In contrast, decoupling is possible with a ferro-resonant line conditioner which is primarily intended for line voltage regulation, but which also provides a high degree of surge suppression. Figure 20 shows the 6 kV incoming wave being attenuated to 60 V (100:1) on the secondary side of the unloaded line conditioner, and to 40 V (150:1) with a load of only 10%; at full load, an attenuation to less than 10 V was observed. The nature of the ferro-resonant line conditioner is such that the decoupling improved with loading, while the simple transformer of Figure 18 can only act as linear dividers with load changes. Conversely, the decoupling between primary and secondary sides of the line conditioner is further seen on the oscillogram recorded on the input side of the line conditioner. This oscillogram is, in fact, a photograph of two successive measurements, one with no load on the line conditioner and one with a 100 W load. The input waves are exactly superimposed.

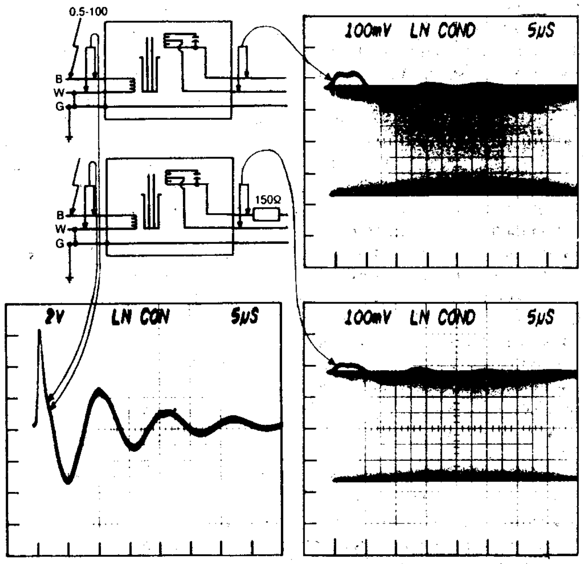

Figure 20. Surge decoupling by ferro-resonant line conditioner

This decoupling reflects the nonlinear behavior of the ferro-resonant line conditioner, which is significant in this case, compared to the linear behavior of transformers: For surge sources of lower impedance than the generator used in these tests, or for frequencies lower than that contained in the 0.5 µs – 100 kHz spike, the transformer attenuation would become lower, in direct proportion to the corresponding impedance change, while the ferro-resonant line conditioner would keep the decoupling unchanged.

For worst-case demonstration, the two oscillograms of the output were recorded with the spike timed to occur at the peak of the 60 Hz line voltage. demonstration. The peak-to-peak amplitude of the line voltage is indicated by the gray band recorded on the oscillograms by photographically superimposing repetitive traces of the line voltage. For timings other than the peak, the small voltage oscillation on the output voltage would be completely contained within the normal peak-to-peak band of the 60 Hz line voltage.

There is at present a trend to an upward spiral in specifying dB's of attenuation in line conditioners. In the author's opinion, the point of citing a 120 dB attenuation is moot because typical installation practice will degrade that level of decoupling.

Example No. 2 – Connections options for suppressors and effects on residual voltages. The author has witnessed lively controversies among various application information sources on the most effective transient suppression configuration to be applied. Taking, as a simplified example, the task of specifying the protection of a single-phase equipment connected at the end of a line with no opportunity to divert the transient closer to the source (for instance, at the service entrance), the options would be to connect one, two, or three varistors between the three wires (black, white, and green) at the end of the line. However, additional information needs to be known: Will the impinging surge be in the normal mode (black-to-white) or in the common mode ([black-and-white]-to-green)? Where in the equipment is the most sensitive component: line-to-line (most likely) or line (black OR white)-to-green? Clearly, the situation is confusing, and there will not be a single, simple answer applicable indiscriminately to all cases. The National Electrical Code [24] specifically allows the connection of *surge arresters* (Article 280-22) if the interconnection occurs only by operation of the surge arrester during the surge. Since the standby current of varistors is very low, this requirement can be met; furthermore, there will not be any interference with the operation of Ground Fault Circuit Interrupters if there is only a small number of protectors.

The set of measurements recorded in Figure 21 shows an example of these many options with increasing protection, albeit at increasing cost, from a single varistor to three varistors. The selection would depend on the vulnerability level and location of the equipment to be protected. The impinging surge is assumed to be black-to-[white-and-green], since white and green are tied together at the service entrance. The line is a 75 m line and the surge is that available from the generator set for a 2000 A 8/20 μs short-circuit impulse. Rather than attempt to modify the setting of the generator for each case in order to maintain constant current crest for the various configurations (an impossible task if wave form is also to be maintained), the generator was left unchanged, to discharge a constant total energy in the system — not a bad hypothesis for the real world. The current crests are all in the range of 300 to 380 A, which is not a significant change for comparing varistor clamping voltages.

If only one varistor is allocated to protect the equipment, the black-to-white varistor connection (first row) affords maximum protection for the electronics which are also likely to be connected black-to-white. However, the voltages between either black or white and green are large; this is the stress that will be applied to the clearances of the equipment. This is a good example of conversion of a normal mode transient into a common mode.

The configuration with varistor black-to-green (second row) does not afford very good protection for components connected black-to-white; therefore, it should be used only if there is a special need to clamp black-to-green at a low voltage with only one varistor available.

An improved protection is obtained with a varistor connected black-to-white, complemented by a second varistor connected white-to-green (third row). The ultimate protection is, of course, one varistor in every position (fourth row), but this should be required only for exceptionally sensitive loads.

Example No. 3 — Ground potential rise on data lines. A distributed computer system had been installed with a central processing unit and remote terminals located in separate buildings. In a span of 5 weeks during the first summer after commissioning the system, three lightning storms occurred in the area; no direct strikes were reported on the buildings, but extensive damage was done to the circuit boards on terminals and CPU inputs.

After the first occurrence, power line surges were suspected and some precautions were applied, when access to the hardware was possible, by pulling out the ac power plugs from the CPU or terminal at the onset of a lightning storm. This did not help. Next, isolating transformers were considered but, again, did not help. At this point, the author was called in for consultation, and the following proposed diagnostic was established: the surges were not coming from the ac lines, but rather were due to differences in the ground potential existing between the separate buildings during flow of lightning currents. The data cables had been run in PVC conduit buried between the buildings and, true to one tenet of steady-state noise prevention, only one end of the shield of the wire pairs had been grounded, with the other left floating. Figure 22 shows how this arrangement can produce high voltage between a floating end of the shield and the local ground, a practice which is bound to produce a flashover and flow of surge currents along unwanted paths in the circuit components. Thus, the problem was *not* power line surges, but differential ground potential. Worse, by pulling out the ac line plugs but leaving the incoming data cables connected, the operators had unwittingly removed the local grounding connection from the hardware frame, leaving only the data cables coming in, with a possibility of raising the complete hardware several thousand volts above local grounds in the room — a dangerous condition.

A solution to the problem could take several approaches. Radical solutions, such as a microwave link or a fiber optics cable, would indeed have eliminated the differential ground potential problems, but were considered too expensive or too long to install.

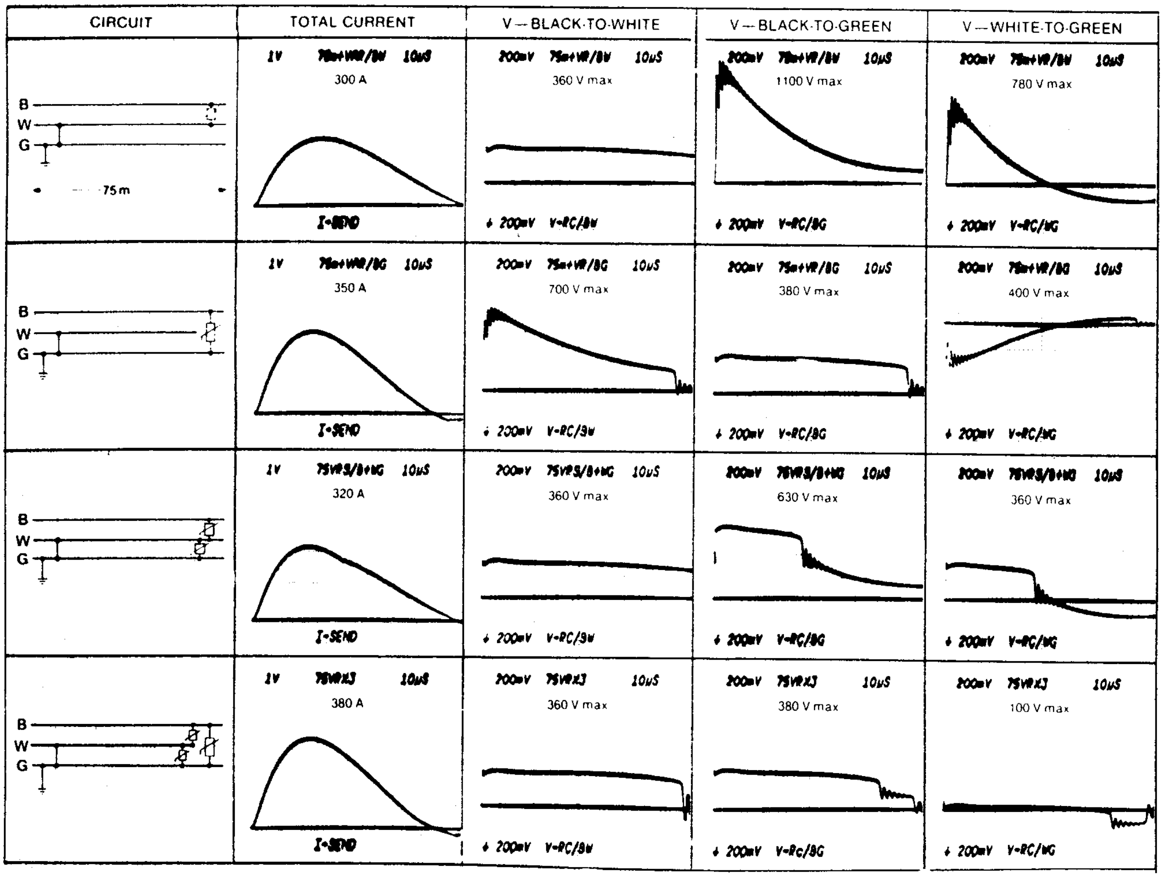

Figure 21. Connections options and effect on common mode or normal mode overvoltages

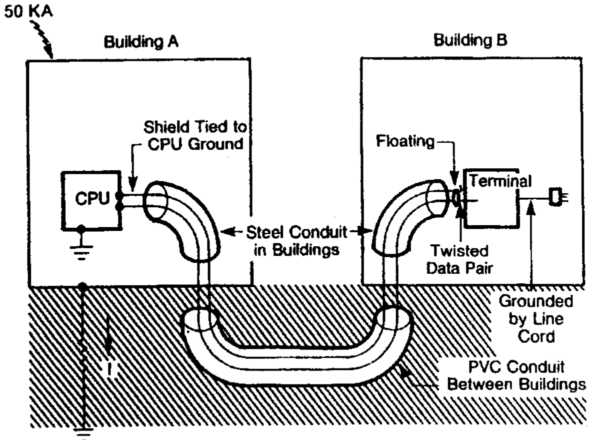

Figure 22. ***2004 correction, caption should have read:***
Problem of single-ended shield

Incidentally, part of the original puzzlement at the failures was the notion that opto-isolators provided in the data link route should have avoided problems. Close scrutiny of the circuits, however, disclosed that the opto-isolators had been provided for some other purpose; in fact, the ground potential loop was closed by the power supply to the opto-isolator feeding the amplifiers from a local source rather than the remote source, negating the isolation function.

Another solution, really the most simple and effective, would have been the replacement of the plastic underground conduit by a continuous steel conduit linking the steel conduits used inside the buildings. This would have provided equalization of the ground potentials along the data cable, while allowing the desired use of shields with one end only at ground. However, that solution was not acceptable to the plant facility organization.

In this particular location, a spare conduit had been buried next to the data line conduit. This offered the possibility of pulling a heavy ground cable in this conduit, close to the data cables, which could then tie the two corners of the buildings at the point of entry of the data cables, as a first step toward reducing differential ground potentials. At first, this concept was somewhat difficult to sell to plant facilities: because there is a ground grid tying to two buildings for 60 Hz faults, further ties between the two buildings did not seem necessary. However, our thesis was that this grid would have too high an impedance to serve the purpose, and furthermore that the data cable run, located away from the ground grid, would form a flux-collecting loop with the ground grid. After lengthy discussions, the thesis was accepted and the cable was installed.

Simultaneously, the concept of tying the two ends of the cable shields to ground was proposed, with the provision of a barrier that would avoid the circulation of power-frequency currents [25]: inserting an array of diodes (Figure 23) at one end of the shields reconciled the needs of noise prevention under normal operation and the requirement of grounding at both ends during lightning events. The forward drop of the two diodes in series (1.5 V) was enough to block any 60 Hz

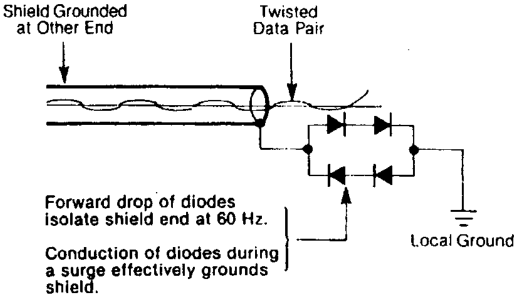

Figure 23. ***2004 correction, caption should have read:***
Single-ended shield corrected by second bond with diodes

circulating current that would inject noise in the data cables. During a lightning strike, however, the diodes would allow flow of current to compensate and cancel the ground potential differences.

These two cures were implemented during the first summer, and no further problems occurred for the rest of the lightning season. While these two solutions might have been sufficient, the concern over another possible failure of the system was sufficient to motivate the design of further protection: the insertion of a voltage clamp in each data pair. This solution required some design and acceptance testing from the system manufacturer, so that it was not implemented until the next lightning season. Thus, the system survived the remainder of the first lightning season with only the first two remedies.

Experience has shown that conclusions on the effectiveness of lightning protection schemes should wait perhaps as much as 10 years before being proclaimed, because of the large variations in lightning activity. However, after three summers of trouble-free operation compared to three major failures in 5 weeks, the cure would seem effective. Hopefully, these words will not have to be eaten by the author in a few years.

In retrospect, then, the following recommendations can be drawn from this horror tale, for retrofits or new installations:

1. Data cables linking separate buildings or spanning beyond a single room within one building should have a shield tied to local ground at both ends of the cable. If the first shield provided with the cables must be left with one end floating by *diktat* of the system vendor, then these cables should be installed within a *continuous* metal shield. This continuous shield can be either a double shield of the flexible cable, or simply a metal conduit, *with both ends grounded.*
2. Substantial relief can be obtained in retrofits by grounding both ends of existing shields through a low-voltage clamp, such as a diode array, that will block noise-inducing power frequency currents, but will allow the flow of ground-potential equalizing currents during surges.
3. The ultimate protection may be the insertion of surge-protective devices in each line. However, this solution requires careful design so that degradation of the signals does not occur, and residual spikes are not allowed to pass through