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(Revision of IEEE C62.41-1980)

IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits

Sponsor
**Surge-Protective Devices Committee
of the
IEEE Power Engineering Society**

Approved February 25, 1991
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Abstract: A practical basis is provided for the selection of voltage and current tests to be applied in evaluating the surge withstand capability of equipment connected to utility power circuits, primarily in residential, commercial, and light industrial applications. The recommended practice covers the origin of surge voltages, rate of occurrence and voltage levels in unprotected circuits, waveshapes of representative surge voltages, energy, and source and impedance. Three locations categories are defined according to their relative position from the building service entrance. For each category, representative waveforms of surge voltages and surge currents are described, organized in two recommended “standard waveforms” and three suggested “additional waveforms.”

Keywords: ac power circuits, current tests, surge monitoring, surge test waveforms, surge voltages, surges, test waveforms, voltage tests, wave shape

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Foreword

(This Foreword is not a part of IEEE C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits.)

Transient surge voltages occurring in ac power circuits can be the cause of operational upset or product failure in industrial and residential systems and equipment. These problems have received increased attention in recent years because of the widespread application of complex semiconductor devices that are more sensitive to voltage surges than vacuum tubes, relays, and earlier generations of semiconductor devices.

Logical and economical design of circuits to protect vulnerable electronic systems from upset or failure requires knowledge of or an estimate of:

- 1) Transient voltage and current waveforms,
- 2) Frequency of occurrence of transients with various energy levels,
- 3) Particular environmental variations such as amplitudes, and
- 4) Upset or failure threshold of the particular equipment to be protected.

The previous edition of this document, IEEE C62.41-1980, “IEEE Guide for Surge Voltages in Low-Voltages AC Power Circuits” (also known as IEEE Std 587-1980), contained similar information about the surge environment. Most of the voltage surge recordings for the 1980 edition were made prior to 1975, when electronic instrumentation for surge monitoring was not readily available. Instrumentation and data-base information, while still limited in some parameters such as very short rise time and frequencies, have vastly improved, as reflected in this edition.

This document provides updated and expanded information relevant to a typical surge environment based upon location within the building, power-line impedance to the surge, and total wire length. Other parameters often adding to the surge environment include proximity and type of other electrical loads, type of electrical service, wiring quality, and geographic location.

New information on probability of surges has been added. A new waveform incorporating a shorter front and two new waveforms incorporating longer durations supplement the two standard waveforms. A new section consisting of a “how-to-use” guide has also been added to allow the reader to develop a rational approach to equipment protection by following the recommendations of this document.

It must be noted that a recommendation of test waveforms alone is not an equipment performance specification. Other documents based on the waveforms recommended herein have been or will be developed to describe the performance of equipment or protective devices in low-voltage ac power circuits.

Some manufacturers have advertised that their protective device “meets the requirements” of IEEE Std 587-1980 or IEEE C62.41-1980. Such a statement is a misuse of the document, since the document only describes surges and does not specify any specific safe level or performance of equipment during application of a test waveform. The levels given in this document reflect typical environment conditions and provide a menu from which equipment designers and users can select the values appropriate to a specific application. Any statement that a protector “meets the requirements of” or “is certified to” this document is inappropriate and misleading.

The Summary given after this Foreword is intended only for a rapid overview and therefore is not included as part of the recommended practice.

Suggestions for improvements of this recommended practice will be welcomed. They should be sent to the Secretary, IEEE Standards Board, Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

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Summary

(This Summary is not a part of IEEE C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits.)

This document describes the occurrence of surges in low-voltage ac power circuits and provides guidance on the simplification of a complex data base into a limited set of representative surges. This simplification will assist designers of equipment in providing the appropriate degree of withstand capability in their designs, allow users of equipment to specify appropriate levels of withstand requirements, and provide test equipment suppliers and test laboratories with a recommended practice for a limited number of well-defined test waveforms.

Protection from surge voltages in ac power circuits can best be achieved through the application of protective devices matched to the environment and to the operational requirements of the equipment. Environmental conditions can be represented by two selected voltage-current waveforms, described as standard waveforms, with amplitude and available energy dependent upon the pertinent location within the power system or distance from the surge source. Circumstances may be encountered where other waveforms, described as additional waveforms, may be appropriate to represent surges caused by less frequent mechanisms or by the presence of equipment recognized as the cause of longer or shorter disturbances.

Standard Waveforms

For practical purposes, locations are divided into three categories. Surge characteristics, that is, rates of occurrence, waveforms, source impedances, and amplitudes, are discussed for each category of location and exposure.

- 1) Locations
 - Category A:* Long branch circuits, receptacles (indoor)
 - Category B:* Major feeders, short branch circuits, service panel (indoor)
 - Category C:* Outdoor overhead lines, service entrance
- 2) Exposure
 - Low Exposure:* Systems in geographical areas known for low lightning activity, with little load-switching activity.
 - Medium Exposure:* Systems in geographical areas known for medium to high lightning activity, or with significant switching transients, or both.
 - High Exposure:* Those rare installations that have greater surge exposure than those defined by Low Exposure and Medium Exposure.

3) Recommended Values

Recommended values are given for the waveforms, voltage amplitude, and current amplitude of representative surges in line-to-neutral, line-to-line, and neutral-to-ground configurations.

Additional Waveforms

Special situations have been identified in which additional waveforms may be appropriate; these have been added to the standard waveforms initially defined in the 1980 version of this document. These special situations include the presence of large banks of switched capacitors or the operation of fuses at the end of long cables. These cases warrant consideration of additional waveforms that have the capability of depositing substantial energy in a surge-diverting protective device and causing failure of devices not sized for that occurrence. However, the characteristics of these phenomena are closely related to the specifics of the situation, so that it is difficult to provide generally applicable recommendations. For that reason, this document presents information on these surges as a range of values rather than specific numbers.

The presence of nearby equipment involving load switching can couple bursts of fast transients that have the capability of interfering with logic circuits and causing upsets. This situation has been recognized, and test procedures have been defined by other organizations to demonstrate immunity of equipment that may be subjected to these bursts. This document endorses the recommendations made by these organizations and includes the fast-transient burst where applicable.

Guidance Versus Specification

The recommendations given in this document are provided as the basis for selecting specifications appropriate to the needs of equipment designers and users, depending on the particulars of the situation. While recognizing the desirability of sweeping general specifications, this document cautions the reader against such practice. The specification of equipment withstand capability, and of test levels to prove this capability, remains the responsibility of equipment suppliers and equipment users, based on an understanding of the situation that this document is attempting to provide. While short-term monitoring of an individual site often gives some useful information, the environment is so dynamic that the analysis of a brief period may not give a good prediction of the future environment.

Readers are also warned on the economic fallacy of specifying unrealistic complexities of test procedures or excessive withstand capability in an attempt to obtain greater reliability. The complexity of the surge environment is such that no set of test waveforms will ever completely simulate the environment, and a slightly higher level of surges can always be proposed to boost equipment withstand. This document was prepared with the intent to avoid such unrealistic requirements.

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IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits

1. Scope

The purpose of this recommended practice is to provide information on surge voltages in low-voltage¹ ac power circuits. With this information, equipment designers and users can evaluate their operating environment to determine their need for surge-protective devices. The document characterizes electrical distribution systems in which surges exist, based upon the data that have been recorded in interior locations on single-phase and three-phase residential, commercial, and industrial power distribution systems.

There are no specific models that are representative of all surge environments; the complexities of the real world need to be simplified to produce a manageable set of standard surge tests. To this end, a surge environment classification scheme is presented. This classification provides a practical basis for the selection of surge-voltage and surge-current waveforms and amplitudes that may be applied to evaluate the surge withstand capability of equipment connected to these power circuits. It is important to recognize that proper coordination of equipment capability and environment characteristics is required: each environment and the equipment to be protected has to be characterized and the two reconciled.

The surges considered in this document do not exceed one-half period of the normal mains waveform in duration. They may be periodic or random events and may appear in any combination of line, neutral, or grounding conductors. They include those surges with amplitudes, durations, or rates of change sufficient to cause equipment damage or operational upset (see Fig 1). While surge-protective devices acting primarily on the amplitude of the voltage are often applied to divert the damaging surges, the upsetting surges may require other remedies.

Test procedures are described in IEEE C62.45-1987 [8],² as a companion to the present document. Other surge-related standards are identified in Section 4; the present document is intended to complement these standards.

¹Note that “low voltage” is defined by the IEEE and IEC as up to 1000 V rms.

²References in the text, shown as [x], are listed in Section 4. Citations shown as [Bx] are found in Appendix C.

2. How to Use This Document

2.1 General

The purpose of this section is to assist the reader in applying the recommendations of this document to each particular case of interest. The 1980 edition of this document, although presented as a guide, has sometimes been misinterpreted as a performance standard, leading to statements such as “meets the requirements of IEEE Standard 587,” which are inappropriate and misleading. To avoid such misinterpretation, this section presents guidance on parameters of application, with a brief outline of the document and the corresponding actions to be taken by the user in achieving the goal of satisfactory surge protection.

2.2 Achieving Practical Surge Immunity

No performance requirements are specified in this recommended practice. What is recommended is a rational, deliberate approach to recognizing the variables that need to be considered simultaneously, using the information presented here to define a set of representative situations.

For specific applications, the designer has to take into consideration not only the rates of occurrence and the waveforms described in this document, but also the specific power system environment and the characteristics of the equipment in need of protection. Therefore, generalized and specific performance requirements cannot be included in this recommended practice.

As an example, the following considerations are necessary to reach the goal of practical surge immunity:

- Protection desired
 - Hardware integrity
 - Process immunity
- Specific equipment sensitivities
- The power environment
 - Surge characteristics
 - Electrical system
- Performance of surge protective devices
 - Protection
 - Lifetime
- The test environment
- Total and relative costs

Answers may not exist to all of the questions raised by the considerations listed above. In particular, those related to specific equipment sensitivities, both in terms of component failure and especially in terms of processing errors, may not be available to the designer. The goal of the reader may be selection among various surge-protective devices and equipment protected by them. Subsets of the parameters in this section may then apply, and the goal of the reader may then be the testing of various surge-protective devices under identical test conditions. The following may guide the reader in identifying parameters, seeking further facts, or quantifying a test plan.

2.2.1 Protection Desired

The protection desired may vary greatly depending upon the application. For example, in applications not involving on-line performance, protection may be desired merely to reduce hardware failures by a certain percentage. In other cases, such as data processing or critical medical or manufacturing processes, any interruption or upset of a process may be unacceptable. Hence, the designer should quantify the desired goal with regard to the separate questions of hardware failure and process upset.

2.2.2 Equipment Sensitivities

Specific equipment sensitivities should be defined in concert with the above-mentioned goals. The sensitivities will be different for hardware failure or process upset. Such definitions might include: maximum surge remnant amplitude and duration that can be tolerated, waveform or energy sensitivity, etc.

2.2.3 Power Environment—Surges

The applicable test waveforms recommended in this document should be quantified on the basis of the location categories and exposure levels defined herein.

2.2.4 Power Environment—Electrical System

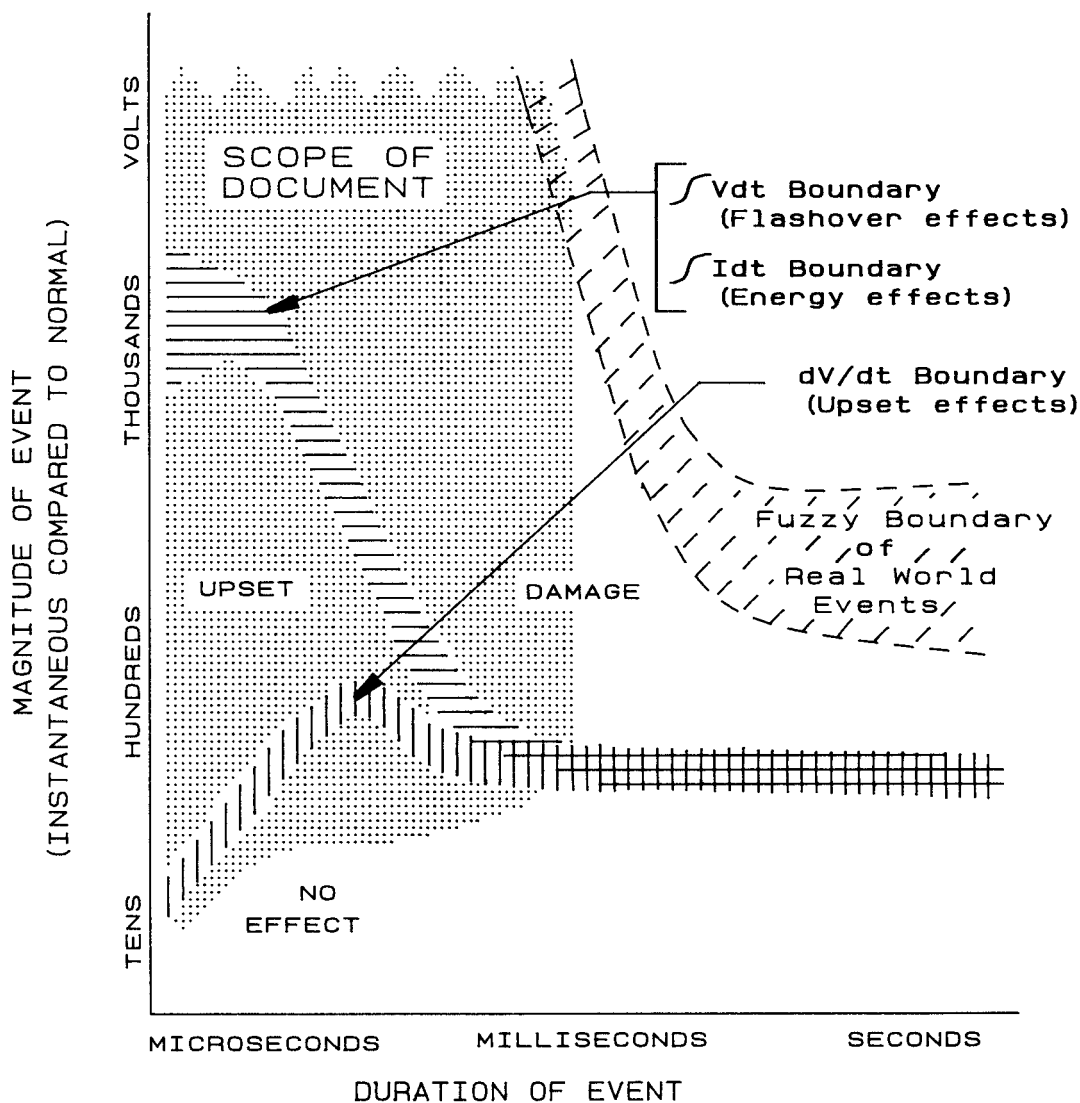
The magnitude of the rms power-line voltage, including any anticipated variation, should be quantified. Power system voltages are generally regulated to comply with ANSI C84.1-1989 [1]. That standard specifies two ranges (A and B) of service and utilization voltages and explicitly acknowledges the occurrence of abnormal conditions that cause these voltages to be exceeded. Successful application of surge-protective devices requires taking into consideration these occasional abnormal occurrences. Appropriate selection of the clamping voltage and continuous mains voltage ratings is essential.

2.2.5 Performance of Surge-Protective Devices

Evaluation of a surge-protective device should verify a long life in the presence of both the surge and electrical system environments described above. At the same time, its remnant and voltage levels should provide a margin from the sensitivity levels of the equipment to achieve the desired protection. It is essential to consider all of these parameters simultaneously. For example, the use of a protective device rated very close to the nominal system voltage may provide attractive remnant figures, but may be unacceptable when a broad range of occasional abnormal deviations in the amplitude of the mains waveform are considered. Lifetime or overall performance of the surge-protective device should not be sacrificed for the sake of a low remnant (Martzloff and Leedy, 1989 [B46]).

2.2.6 Test Environment

The surge test environment should be carefully engineered with regard to the preceding considerations and any other parameters felt important by the user. A typical test-environment description will include definitions of simultaneous voltages and currents, along with demonstrations of proper short-circuit currents. It is important to recognize that specification of an open-circuit voltage without simultaneous short-circuit current capability is meaningless.



NOTES: (1) The graph shows the relative position of effects and the order of magnitude of the amplitude and duration. Do not attempt to read numerical values from this graph.

(2) The scope of the document is shown by the dotted pattern. The upper limit for the duration is one half-cycle of the applicable power frequency.

(3) The values or positions of the boundaries between "no effect" and "upset," and between "upset" and "damage," vary with the withstand characteristics of the equipment exposed to the surges.

(4) This figure shows one measure of surge severity. Other possible measures include peak current, rise time, and energy transfer.

Figure 1—Simplified Relationships Between Voltage, Duration, Rate of Change, and Their Effects on Equipment

2.2.7 Costs

The cost of surge protection can be small, compared to overall system cost and benefits in performance. Therefore, added quality and performance in surge protection may be chosen as a conservative engineering approach to compensate for unknown variables in the other parameters. This approach can provide excellent performance in the best interests of the user, while not significantly affecting overall system cost.

2.3 Document Outline

To achieve the goal of satisfactory surge protection in specific situations, the equipment user has to quantify the variables discussed in the preceding sections. The following description of each section should aid the user in that process.

Section 3, Definitions, presents the definitions of terms for which the IEEE Std 100-1988 [9] does not already provide a definition, or when a special application or extension is made from an existing definition.

Section 4, References, lists the documents supporting some of the basic concepts and recommendations of the present document. It is not a bibliography but a list of key documents; Appendix C is a bibliography with annotations presented for detailed information or further reading material.

Section 5, Origin of Surge Voltages, presents a brief overview of the mechanisms leading to the occurrence of surge voltages. A more detailed discussion of these mechanisms is presented in Section 7, leading to the selection of representative environments.

Section 6, Summary of Data Base, presents an overview of the available data base, with a discussion of the limitations and the resulting assumptions or simplifications made to develop a definition of a representative generic environment.

Section 7, Recommended Selection of Representative Environments, presents a rationale for going from the limited data base on the complex environment to a manageable set of a few representative surge waveforms. Two standard waveforms are specified, and three additional waveforms are proposed to represent the environment, but discussion of the selection of levels is deferred until Sections 9 and 10. The concept of ***Location Categories***³ is presented in this section. A discussion is also presented on the fallacy of assigning an energy content to a surge regardless of source or load-sharing considerations. Understanding this process of simplification is essential to avoiding the pitfall of blind dependency on a performance specification—which this document is not. In other words, the selection of a representative environment when designing for surge immunity, no matter how carefully made, cannot yield 100% assurance that surge problems will not occur.

Section 8, Recommended Planning for Surge Immunity, presents a discussion of the tradeoffs necessary to reconcile the equipment surge withstand capability with the environment, recognizing statistical and economic realities. Issues of surge test equipment are discussed.

Section 9, Definition of Standard Surge Testing Waveforms, provides precise information on the standard waveforms proposed in Sections 7 and 8, including tolerances. Recommendations are given in the form of tables proposing severity levels for various environments.

Section 10, Definition of Additional Surge Testing Waveforms, provides the same type of information given in Section 9 for the additional waveforms.

Appendix A, Detailed Data Base, contains information presented to enhance credibility of the environment description and simplification process.

³Those terms appearing in bold italics in the text are discussed further in Appendix B.

Appendix B, Additional Information, provides detailed background and information that would burden the reader if included in the main sections.

Appendix C, Annotated Bibliography, provides the user with a list of published documents for further reading on recorded occurrences and computed simulations; propagation, attenuation and mitigation; reviews and discussions; measurement techniques and test methods; and related standards.

3. Definitions

The definitions of the terms used in this document are those found in IEEE Std 100-1988 [9], the *IEC Multilingual Dictionary of Electricity* [3], or the IEC International Electrotechnical Vocabulary [B95]. In some instances, the IEEE definition in the current dictionary may be either too broad or too restrictive; in such a case, an additional definition or note is included in this section.

mains: The ac power source available at the point of use in a facility. It consists of the set of electrical conductors (referred to by terms including “service entrance,” “feeder,” or “branch circuit”) for delivering power to connected loads at the utilization voltage level.

surge (surge-protective device): A transient wave of current, potential, or power in an electric circuit.

NOTE — The use of this term to describe a momentary overvoltage consisting of a mere increase of the mains voltage for several cycles is deprecated. See **swell**.

swell: A momentary increase in the power frequency voltage delivered by the mains, outside of the normal tolerances, with a duration of more than one cycle and less than a few seconds. See **surge**.

wave shape designation:

NOTE — On wave shape designation, IEEE Std 100-1988 [9] states that the units used in a wave shape designation are microseconds; to avoid confusion in this document where other units are necessary, units—ns, μ s, or ms—are shown after all wave shape designations.

4. References

In this document, two types of “references” are used: those that are directly related to the subject being discussed—references—and those that provide supporting information to the subject being discussed—bibliographic citations. For the convenience of the reader in not breaking the pace of reading, “references” and “citations” are briefly identified in the text as described below.

The first type, references, contains information that is implicitly adopted in the present document; complete implementation of the recommendations made in the present document would require the reader to consult that reference for the details of the subject. This first type is introduced in the text as (Document identity, [xx]), and the listing is provided below, in this section.

The second type, citations, is not essential to implementation of the recommendations, but is provided for the use of readers seeking more detailed information or justification. This second type is introduced in the text as (Author, date [Byy]) and the listing is provided in Appendix C.

This recommended practice shall be used in conjunction with the following publications:

[1] IEEE Std C84.1-1989, American National Standard Voltage Ratings for Electric Power Systems and Equipment (60 Hz).⁴

[2] ANSI/NFPA 70-1990, National Electrical Code.⁵

[3] IEC Multilingual Dictionary of Electricity. Institute of Electrical and Electronic Engineers, 1983.⁶

[4] IEC 664 (1980), Insulation Coordination Within Low-Voltage Systems Including Clearances and Creepage Distances for Equipment.

[5] IEC 801-4 (1988), Electromagnetic Compatibility for Industrial Process Measurement and Control Equipment—Part Four: Electrical Fast Transient/Burst Requirements.

[6] IEEE Std C37.90.1-1989 IEEE Standard Surge Withstand Capability (SWC) Tests for Protective Relays and Relay Systems.⁷

[7] IEEE C62.1-1984, IEEE Standard for Gapped-Silicon Carbide Surge Arresters for AC Power Circuits.

[8] IEEE C62.45-1987, IEEE Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits.

[9] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronic Terms.

[10] IEEE Std 518-1982, IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources.

5. The Origins of Surge Voltages

5.1 General

Surge voltages occurring in low-voltage ac power circuits originate from two major sources: lightning effects (direct or indirect) on the power system and system switching transients.

5.2 Lightning

Models of lightning effects consistent with available measurements have been made in order to yield predictions of surge levels, even if the exact mechanism underlying the production of any particular surge is unknown. The major mechanisms by which lightning produces surge voltages are the following:

- 1) A nearby lightning strike to objects on the ground or within the cloud layer produces electromagnetic fields that can induce voltages on the conductors of the primary and secondary circuits.
- 2) Lightning ground-current flow resulting from nearby cloud-to-ground discharges couples onto the common ground impedance paths of the grounding network, causing voltage differences across its length and breadth.

⁴ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

⁵NFPA publications are available from Publications Sales, National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA.

⁶IEC publications are available from IEC Sales Department, Case Postale 131, 3 rue de Varembe, CH 1211, Geneve 20, Switzerland/Suisse. IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

⁷IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

- 3) The rapid drop of voltage that may occur, when a primary gap-type arrester operates to limit the primary voltage, is coupled through the capacitance of a transformer and produces surge voltages in addition to those coupled into the secondary circuit by normal transformer action.
- 4) A direct lightning strike to high-voltage primary circuits injects high currents into the primary circuits, producing voltages by either flowing through ground resistance and causing a ground potential change or flowing through the surge impedance of the primary conductors. Some of this voltage couples from the primary to the secondary of the service transformers, by capacitance or transformer action or both, thus appearing in low-voltage ac power circuits.
- 5) Lightning strikes the secondary circuits directly. Very high currents and resulting voltages can be involved, exceeding the withstand capability of equipment and conventional surgeprotective devices rated for secondary circuit use.

5.3 Switching Transients

System switching transients can be divided into transients associated with normal or abnormal conditions, as follows:

- 1) Minor switching near the point of interest, such as an appliance turnoff in a household or the turnoff of other loads in the individual system.
- 2) Periodic transients (voltage notching) that occur each cycle during the commutation in electronic power converters. The voltage notch is caused by a momentary phase-to-phase short circuit with a rapid change in voltage, lasting in the 100 μ s range.
- 3) Multiple reignitions or restrikes during a switching operation are another example. Air contactors or mercury switches can produce, through escalation, surge voltages of complex waveforms and of amplitudes several times greater than the normal system voltage.
- 4) Major power system switching disturbances, such as capacitor bank switching, fault clearing, or grid switching. Transient overvoltages associated with switching of power-factor correction capacitors have levels, at least in the case of restrike-free switching operations, of generally less than twice the normal voltage, though the levels of the transients often can be 1.5 times normal (that is, the absolute value may be 2.5 times the normal peak). These transients can occur daily, and their waveforms generally show longer time durations, such as several hundred microseconds, compared to typical durations on the order of microseconds to tens of microseconds for other switching events and lightning-induced transients. If multiple reignitions or restrikes occur in the capacitor switching device during opening, then the transient overvoltage can exceed three times the normal system voltage and involve high energy levels.
- 5) Various system faults, such as short circuits and arcing faults. One type of switching transient, for example, results from fast-acting overcurrent protective devices such as current-limiting fuses and circuit breakers capable of arcing times of less than 2 μ s. These devices leave inductive energy trapped in the circuit upstream; upon collapse of the field, high voltages are generated.

The most visible effect of a switching surge is generally found on the load side of the switch and involves the equipment that is being switched, as well as the switching device. In the case of the equipment being switched, the prime responsibility for protection rests with either the manufacturer or the user of the equipment in question. However, the presence and source of transients may be unknown to the users of this equipment. This potentially harmful situation occurs often enough to command attention.

6. Summary of Data Base

6.1 General

Disturbances on low-voltage ac power circuits ("mains") can be classified in many ways, such as a voltage increase or reduction from the nominal rms value, a voltage or current wave shape variation, and the surge waveform characteristics. The latter include amplitude, duration, rise time, frequency of ringing, polarity, energy delivery

capability, amplitude spectral density, position with respect to the phase of the mains waveform, and frequency of occurrence.

The scope of this document is limited to disturbances that have a duration of less than one half-cycle of the normal mains waveform. Consequently, the issues of disturbances caused by other events such as sags, outages, swells, and harmonic distortions are not addressed in this discussion of the data base, regardless of their importance or rates of occurrence compared to those of surges.

It is difficult to assign minimum or maximum values to some of the surge characteristics because the effect and hence the significance depends on the nature of the equipment subjected to the surge. Some of these disturbances occur without causing any problem with the equipment, some can cause equipment upset, and others can cause equipment damage (Fig 1).

Surge amplitude alone is not the sole criterion for immunity in the design and testing of equipment. However, the data available at the time of the 1980 version of this document were based on the general use of peak-reading instruments, with few oscilloscopes. Hence, the information on waveform was more limited than the information on peak amplitude. When attempting to correlate the data collected by many researchers over the years, no agreement is found on the voltage amplitude below which the surges lose significance. Different perceptions on what should be considered as “noise” in contrast to a “surge” also exist (IEEE C62.45-1987, [8]; IEEE Std 518-1982 [10]).

Characterization of surges is further complicated by diverse perceptions of the significance of other parameters, such as the rate of change of the surge voltage and the amplitude spectral density of the surge (Rhoades, 1980 [B64]; Goedbloed, 1987 [B14]), the energy delivery capability of the surge (Martzloff, 1986 [B22]), the threshold of the susceptible circuits (Rhoades, 1981 [B65]), and the threshold level of the instrument used to collect the data (Goldstein and Speranza, 1983 [B15]; Martzloff and Gruzs, 1987 [B61]).

In this section, a summary discussion of the data base is presented. A more detailed description of the data base is presented in Appendix A. From this data base, the recommendations presented in Sections 7, 8, 9, and 10 were developed by consensus.

The highest confidence level is found in the expected peaks and rates of occurrence; other data on the surge environment have a narrower basis, but can still be used for guidance until broader data are published and integrated as an international effort.

6.2 Notations and Definitions

A surge on the ac mains can be described as a time-domain phenomenon; terms used to describe such an event should have definitions applicable to all measurements. The reader should review the definitions given in Section 3 and the notes in Appendix B for the refinements or changes to commonly used terms. In particular, note that units will be shown after the designation of a waveform, for example, 5/50 ns.

Design of equipment for surge immunity requires knowledge of how the surge is presented to the equipment: the designer needs to know the surge mode of coupling. To avoid the ambiguities that may occur when using the term “common mode” (see Appendix B5), the following notations are used in this document:

- L-N:** Measurement from phase(s) to neutral for both single- and three-phase systems.
- L-L:** Measurements from phase to phase in a polyphase system, or from one line to the other line in a single phase system.
- L-G:** Measurements from phase to equipment grounding conductor at the line terminals of utilization equipment. In North American single-phase systems and three-phase five-wire systems, the equipment grounding conductor is bonded to the neutral conductor at the service entrance.
- N-G:** Measurements from neutral to equipment grounding conductor at the line terminals of the utilization equipment.

6.3 Site Surveys of Power Quality

Monitoring of mains voltage is in some cases a logical first step to determine the power quality at a specific site. However, the results are only a snapshot of the quality because the characteristics of the measured surges vary over time as loads and system configurations change. Seasonal variations and geographic location also influence the results, in particular for lightning effects. Past site surveys of power quality can help determine the probabilistic external transients. A chronological review of several site surveys is shown in Table 1.

Early site surveys were limited by instrument bandwidth in the measurements of highamplitude, fast rise-time transients. With improving detection capability in the instrumentation resulting in some changes in the recorded results, this original limitation could lead to the false conclusion that power quality has degraded over the years.

About 1960, researchers began to measure the surge transients on low-voltage lines as the transition from vacuum tubes to semiconductor design occurred and semiconductor failures became an issue. Because the monitoring instruments reflected technology available at the time of measurement, the early data are very limited.

Early site surveys had several limitations:

- 1) They were only differential mode measurements (L-N or L-L)
- 2) They did not always record the highest surge peak in an event
- 3) They rarely recorded the surge waveform or duration
- 4) They did not record the surge ringing period
- 5) They did not give any data on the repetition rate of surge bursts
- 6) They did not provide critical parameters of rate of rise, rate of voltage change, or energy delivery capability

6.4 Field Experience

In addition to site surveys, observations of failure rate can also provide data on the occurrence of surges. For instance, as detailed in Appendix A, three observations have been reported:

- 1) A 100 to 1 reduction occurred in the failure rate of some clock motors when their voltage withstand was raised from 2 000 V to 6 000 V (Martzloff-Hahn, 1970 [B22]). Because of the large sample and duration of the observation, this ratio in failure rate and, therefore, the relative occurrence of the two levels, has high credibility.
- 2) Many incandescent light bulbs typically fail by internal flashover when subjected to surges above 1500 V. Since this failure level does not produce an unacceptable rate of premature failure among millions of light-bulb users, there has to be a corresponding upper bound on the rate of occurrence of surges above 1500 V at the locations of light-bulb sockets.
- 3) Metal oxide varistors of 20 mm diameter or less, installed at some service entrances, have been informally reported to fail occasionally, while their performance within a building has been reported as acceptable. To the extent that these failures can be attributed to surge energy deposition in excess of the varistor rating (Martzloff and Leedy, 1989 [B46]), this observation can be used to obtain a gross estimated magnitude of energy-delivery capability of surges at these two locations, supporting the concept of **Location Categories** presented in this document.

6.5 Summary of Surge Characteristics

The combination of data from published surveys, anecdotes, and observed failure rates yields information used to develop the qualitative and quantitative recommendations of Sections 7, 8, and 9, as well as the suggestions of Section 10. In the following paragraphs, a summary is presented on the aspects of amplitude versus rate of occurrence, surge duration, ringing frequency, rate of voltage change, energy delivery capability, and effects of leading conditions.

6.5.1 Peak Amplitude Versus Rate of Occurrence

The peak amplitude versus occurrence of surges depends on the type of service and on the location where measurement is made (IEEE Committee Report, 1970 [B57]; Rheades, 1979 [B63]). Overhead distribution lines usually have the highest surge amplitude (5 kV to 20 kV), whereas surge amplitudes within a building may be limited by flashover of clearances (IEC 664 (1980) [4]) or by the propagation characteristics of the wiring system (Martzloff, 1990 [B48]).

Table 1—Summary of Site Surveys

Survey	Period	Locale	System Voltage	System Type*	Instrument	Connection Mode	Power Frequency Filtered Out
B-N	Circa 1962-1963	Great Britain	240	Industrial and residential	Analog multithreshold	Not stated	Yes
M-H	1963-1967	US	120/240 277/480	Residential and industrial	Analog single-threshold Oscilloscope and Camera	L-N	No
Can	Circa 1969-1970	US Navy	120 450	Shipboard	Oscilloscope and Camera	L-L (ungrounded)	No
A-S	1969-1972	US	Not stated	Computer sites	Screen storage oscilloscope Oscillograph Digital multiparameter	Not stated	Not clear
G-S	1977-1979	US	120/208	Telephone facilities	Digital multiparameter	L-N	Yes
WBB	Circa 1982-1983	Sweden	220/380	Industrial	Digital multiparameter Digital storage oscilloscope	Common (unclear)	Yes
AEM	1982-1983	US (Alaska)	120/240	Isolated systems	Digital multiparameter	L-N	Yes
O-B	1982-1983	US	120/240 120/208 277/480	Industrial and computer sites	2-point digital V & I: Peak amplitude and time. Time to 50% of peak	L-N (V) Series (I)	No (V) Yes (I)
Goe	Circa 1983-1984	Europe	220/380	Industrial and miscellaneous	Two digital waveform recorders (fast and slow)	L-G	Yes

Source: Martzloff-Gruzs [B61]

LEGEND:

B-N= Bull-Nethercot [B6]
M-H= Martzloff-Hahn [B22]
Can= Cannova [B7]
A-S= Allen-Segal [B2]
G-S= Goldstein-Speranza [B15]
WBB= Wernström et al. [B34]
AEM= Aspnes et al. [B3]
O-B= Odenberg-Braskich [B28]
Goe= Goedbloed [B14]

*Principal type stated first.

Seasonal and time-of-day variations can also affect the occurrence (Allen and Segall, 1974 [B2]). Most high-amplitude surges are caused by lightning, so that geographic location and time of the year affect the rate of occurrence (Martzloff and Hahn, 1970 [B22]; Haruki et al., 1989 [B16]). However, these published site surveys contain few occurrences specifically identified as lightning-related.

As an example of survey results, Fig 2 shows an average number of occurrences per year from several sites. As expected, the number of events decreases for higher peaks. Observe that from 100 V to 400 V, the events almost follow a V^{-4} slope, then a lower and almost linear rate (V^{-1}) from 400 V to 1200 V, and finally above 1200 V, the events follow a V^{-2} slope. Furthermore, plotting the frequency of occurrence versus peak values from many surveys yields the remarkable result of comparable slopes, but different specific numbers of occurrences (see Fig 3).

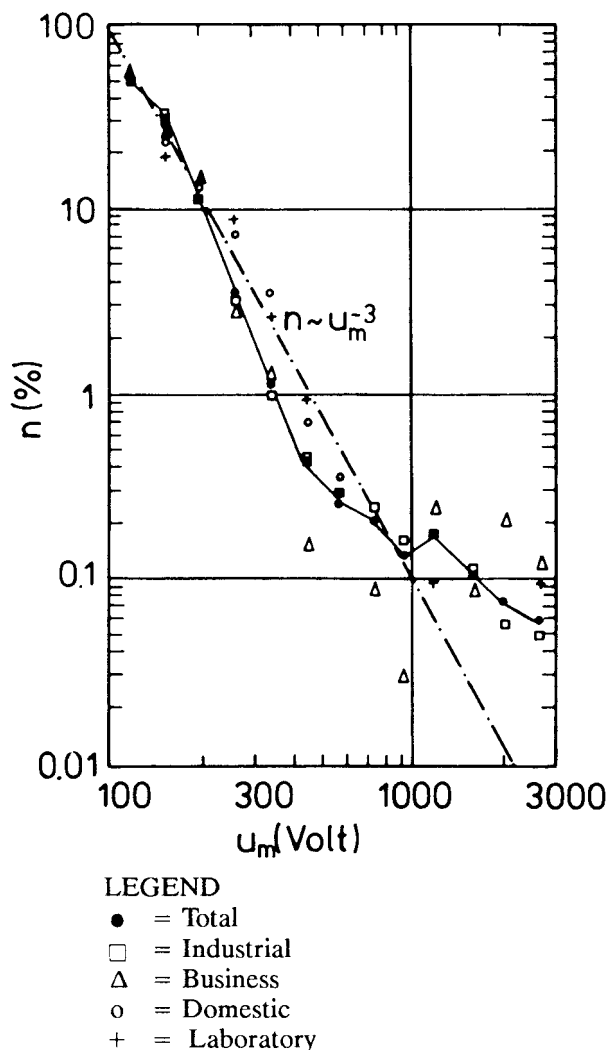
In conclusion, all events from early to late surveys show that the number of surge events decreases with increasing crest voltage, at the power of V^{-a} , where a varies from 1 to 4. From Fig 2 and Fig 3, the relationship is typically $N = V^{-3}$, where N is the relative number of surges. Thus, a probabilistic analysis is required to determine the expected crest amplitude for a specific location, and the decision to provide a specific level of equipment immunity and margin can only be made on a risk analysis tradeoff.

6.5.2 Duration

Those surveys that report complete waveform recordings show a wide range of durations, ranging from a fraction of a microsecond (Wernström et al., 1984 [B34]) to a few milliseconds (Meissen, 1983 [B25]) for unidirectional or quasi-unidirectional waveforms. Oscillatory waveforms, with ringing frequencies discussed below, have been observed with durations of one or two cycles to about ten cycles of the ringing frequency. Examples of these durations are given in Appendix A.

6.5.3 Ringing Frequency

The ringing frequencies cited in surveys cover the range of relatively low frequencies, a fraction of a kilohertz, up to one megahertz. The lower frequencies result from capacitor bank switching transients, while the higher frequencies are the result of the natural oscillation of local circuit elements or of multiple reflections in a wiring system of limited dimensions (Standler, 1989 [B68]). Fig 4 shows one example of report from a recent survey, expressed in ***amplitude spectral density***.

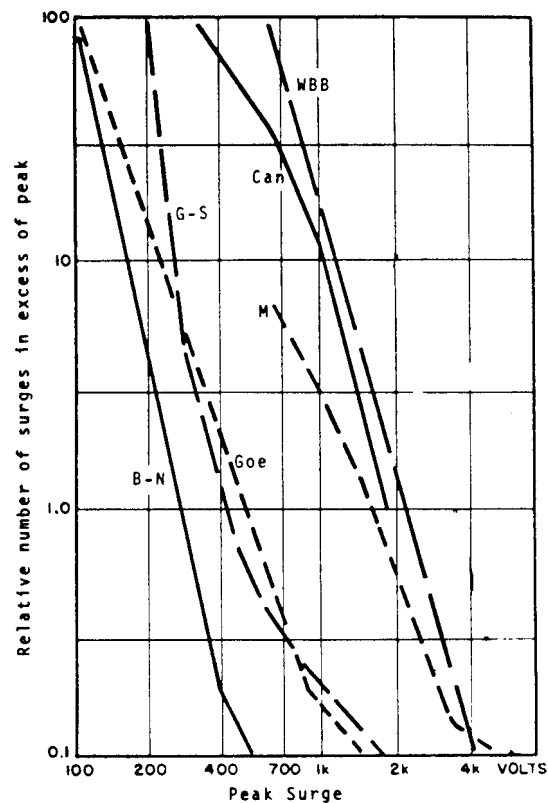


Source: Goedbloed [B14]

Figure 2—Relative Number of Transients as a Function of Amplitude

6.5.4 Voltage Rate of Change

Recent surveys have presented the results in the form of statistical distributions relating rate of rise (dv/dt) to other parameters of the surges. Typical data for sites without lightning transients are shown in Fig 5. In that figure, the upper limits of the rate of change are above 100 V/ns, even at low peak voltages such as 500 V. This form of data presentation will be helpful to designers of circuits sensitive to coupled disturbances, but the present data base is still limited.



LEGEND

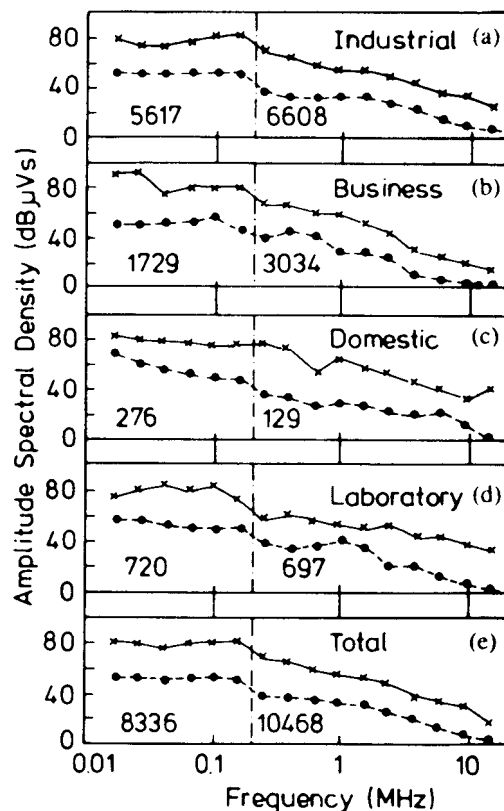
B-N = Bull-Nethercott (composite)
 M = Martzloff
 Can = Cannova
 G-S = Golstein-Speranza
 WBS = Wernstrom et al (upper limit).
 Goe = Goedbloed

Source: Martzloff-Gruzs [B61]

Figure 3—Comparison of the Slopes of the Frequency of Occurrence Versus Peaks of the Surges Among Six Site Surveys

6.5.5 Energy Delivery Capability

Recent surveys have addressed the issue of energy delivery capability in various manners. As discussed in Section 7, the significant parameter is not the “energy contained in the surge” but the actual energy that can be deposited in a surge-absorbing device. One survey author (Goedbloed, 1987 [B14]) proposes an “energy measure” parameter, defined as the product of the voltage square by the time duration of the voltage.

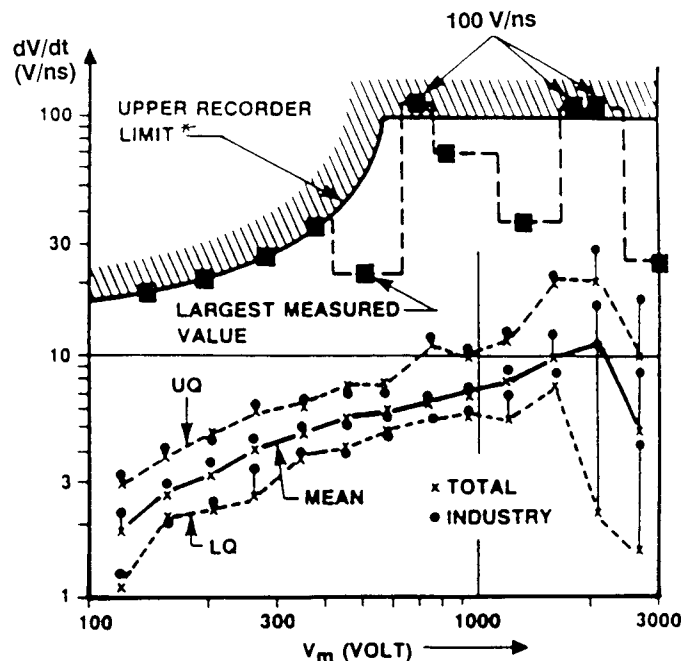


Upper lines: 99.8%
 Lower Lines: 50% (mean)
 (for 3 σ levels)

Source: Goedbloed, 1987 [B14]

Figure 4—Amplitude Spectral Density at Four Sites⁸

⁸For each site, the number of reported events is shown below and above a 200 kHz boundary in the frequency scale. Individual surges and individual sites of specific ring wave frequency produce a peaked distribution of amplitude and spectral density (Standler, 1989 [B68]). When many surges and sites are combined, such as in this figure, the result is a broad and declining distribution. Therefore, a distinction should be made between single events as they impact a specific piece of equipment having specific frequency response, and the composite result shown in this figure.



NOTE: Upper limits of the rate of change shown in this figure were added to the original data from Goedbloed [B14]. The recorder did not always measure the maximum value of dv/dt .

Figure 5—Statistical Evaluation of Recorded dv/dt Data, as a Function of the Maximum Transient Amplitude

This approach is justifiable for a resistive load, where the power dissipated in the resistor is V^2/R . For a nonlinear surge-protective device, the relationship is not so simple. Furthermore, the concept of recording the “energy measure” may promote the arbitrary reporting of “surge energy” by assuming a value for the impedance and then quoting results in joules.

While there is definite merit in an attempt to describe the capability of a surge for delivering energy to circuit components, readers should realize that “energy” reports have to be evaluated with a clear understanding of the underlying assumptions. The “energy in the surge” cannot be determined from measurements of voltage alone (Standlet, 1989 [B83]). As progress continues in the development of power-system disturbance monitors, the data base could be expanded by making appropriate measurements of the surge current diverted by generic surge-protective devices installed at the point of monitoring (Martzloff, 1985 in discussion of [B29]; Standlet, 1987 [B85]).

A distinction should be made between surges of high amplitude with short duration and surges of high amplitude with long duration. The first have the potential of upsetting equipment operation but involve little energy, while the second of these have the potential for high levels of energy deposition.

6.5.6 Effects of Location, Loads, and Mode of Coupling

Disturbance recording results are not very sensitive to the location of the disturbance monitor within a building, with the exception of the fast transients (Martzloff, 1990 [B48]). However, the changes in the loads will affect the response of a system to impinging surges. The mode of coupling is important and has not been well defined in the earlier surveys (Martzloff and Gruz, 1988 [B61]). In addition to the issue of citing results as L-L, L-N, L-G, or N-G voltage measurements, another issue that has not been addressed is that of voltage differences appearing between the power-system conductors and conductors from other systems, such as a communication system, a control system, or even

building steel. Voltage differences between systems can occur during power-system faults and lightning discharges; the present data base does not recognize these. See **utilities interconnections and interactions** in Appendix B23 for a more comprehensive discussion.

7. Recommended Selection of Representative Surges

7.1 General

The data base summarized in Section 6, along with anecdotal information, illustrates the wide variety of surges that can be expected to occur in low-voltage ac power systems. Evaluation of the ability of equipment to withstand these surges, or of the performance of surge-protective devices, can be facilitated by a reduction of the data base.

It is unnecessary to subject equipment to surges that would duplicate field-measured surges, since these measurements are site dependent (Martzloff and Gruz, 1988 [B61]) and are likely to change with time.

The reduction process leads to selecting a few representative surges that will make subsequent laboratory tests uniform, meaningful, and reproducible. Since the environment is subject to change both for the better and the worse, it would be prudent to use these representative surges as a baseline environment. However, this simplification should not bar any user from performing evaluations for different surge-environment conditions if knowledge is available for a particular environment (over a sufficient period of time, such as one or more years) and the requirements warrant the cost and effort of additional tests.

To assist equipment designers and user in making appropriate choices, this recommended practice outlines several exposure levels among several location categories that will be defined further in this section. A combination in the selection of location category and exposure level will then provide the appropriate degree of compromise between a conservative overdesign and a cost-conscious reduction of margins.

The objective of this recommended practice is to lead to an appropriate choice among the levels cited on the basis of the rationale presented here. However, the goal is not to assign arbitrarily any given level to a generic class of equipment. This assignment remains the prerogative and the responsibility of the users and the manufacturers of specific equipment classes.

7.2 Simplification of the Data Base

This recommended practice provides a matrix from which a selection can be made and therefore a common base of reference for specifying equipment performance requirements. Note that the specification of these individual equipment requirements is outside of the scope of this document. However, a first and necessary step in the process of addressing concerns of surge effects on equipment is to determine, by design review or by tests, the susceptibility or vulnerability of the equipment to impinging surges.

The process of simplifying the complex environment involves three further steps:

- 1) Identify the environment (outside or inside building) and operating conditions in unprotected circuits.
- 2) Select a minimum number of surge waveforms that are representative of the postulated environment. This recommended practice provides the basis for this selection.
- 3) The last step will depend on the point of view of the designer or the user of the equipment of interest. Two cases should be considered: *Case 1*: When the equipment is sensitive to voltage or current peaks and durations (equipment upset or damage is the concern here), the significant parameters are primarily the amplitude and duration of the surge.
Case 2: When the equipment is sensitive to the rate of change in the voltage of the mains (equipment upset is the major concern here), the significant parameter is primarily the rate of change. Rate-of-change effects can

cause equipment upset for surge amplitudes far below those involved in hardware damage, even for amplitudes that do not exceed the envelope of the power frequency sine wave.

Fig 1 presents a schematic and simplified view of relationships between time, voltage, current, and the rates of change. An additional concern is the number of occurrences. The rate of occurrences is a significant parameter when the equipment is sensitive to the number of surges occurring in a given time period. Some equipment or its protective circuits may eventually fail as a result of being degraded by multiple surges that, individually, would not cause failure.

The three steps of the simplification process are discussed in detail in 7.3, 7.4, and 7.5. These selections will ultimately be used as the basis for specifying surge tests. Therefore, they should be limited to a reasonable number to avoid impractical test requirements.

7.3 Rate of Occurrence and Voltage Levels in Unprotected Circuits

7.3.1 General

The rate of occurrence of surges varies over wide limits, depending upon the particular power system. Prediction of the rate for a particular system is always difficult and frequently impossible. The rate is related to the level of the surges; low-level surges are more prevalent than high-level surges.

It is essential to recognize that a surge voltage observed in a power system can be either the original surge or the remnant resulting from the sparkover of some clearance or the operation of a protective device in the system. Hence, the term “unprotected circuit” should be understood to be a circuit in which no known low-voltage protective device has been installed, but in which the **sparkover of clearances** will eventually limit the maximum voltage of the surges.

The distribution of surge levels, therefore, is influenced by the surge-producing mechanisms as well as by the sparkover level of clearances (between energized parts, as well as between energized parts and ground) and the operation of unidentified protective devices. It is important to recognize the effect of the increasing number of surge-protective devices installed in and around equipment (see **changes in the environment** in Appendix B3).

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 may have higher clearances, hence higher sparkover levels; 10 kV may be typical, but 20 kV is possible (peak values for a 1.2/50 μ s wave). At the service entrance, watt-hour meters may include protective gaps between phase conductors and ground with sparkover levels in the range of 8 kV. In contrast, most indoor wiring devices used in 120 V, 240 V, and 480 V systems have sparkover levels between phases or between phase and ground of about 6 kV. Therefore, this 6 kV level can be selected as a typical but not a guaranteed limit for the magnitude of surges in an indoor power system.

NOTE — This 6 kV limit is stated as an upper limit that is unlikely to be exceeded in typical low-voltage, indoor environments, for the reasons stated. It is not to be construed as a mandatory surge withstand requirement for all load equipment.

7.3.2 Rate of Occurrence Versus Voltage Level

Data collected from many sources (see the data base in Appendix A) have led to the log-log plot shown in Fig 6. This plot shows the crest values of surges, regardless of their waveform and location of recording, from a composite of all recordings reported in the literature, as indicated in Fig A.9 of Appendix A.

The data reported by many observers at the sites they monitored show decreasing numbers of occurrence for higher crests, with a slope that is independent from the site. The absolute number of occurrences, however, varies from site to site. Thus, if a limited set of recordings can establish the rate of occurrences for the more probable events at low amplitudes, then the events of higher amplitude that are less likely to occur might be extrapolated or estimated from the general slope (Goldstein and Speranza, 1982 [B15]).

The three regions shown in Fig 6 and labeled low, medium, and high exposure present the data in empirical form that is applicable, if some knowledge is available or if some assumption is made on the “exposure level” of the site, as defined below.

7.3.3 Exposure Levels

The exposure level of the environment can be related to exposure of the power system to induced surges. The following descriptions are offered on the exposure levels:

- 1) *Low Exposure.* Systems in geographical areas known for low lightning activity, with little load or capacitor switching activity.
- 2) *Medium Exposure.* Systems in geographical areas known for medium to high lightning activity, or with significant switching transients. Both or only one of these causes may be present, as it is difficult to separate them in reviewing the results of monitoring disturbances.
- 3) *High Exposure.* Those rare installations that have greater surge exposures than those defined by Low Exposure and Medium Exposure. The more severe conditions result from extensive exposure to lightning or unusually severe switching surges.

The high-exposure level needs to be recognized, *but it should not be indiscriminately applied to all systems.* Such general application would penalize the majority of installations, where the exposure is lower (see **amplitudes of strikes** in Appendix B1).

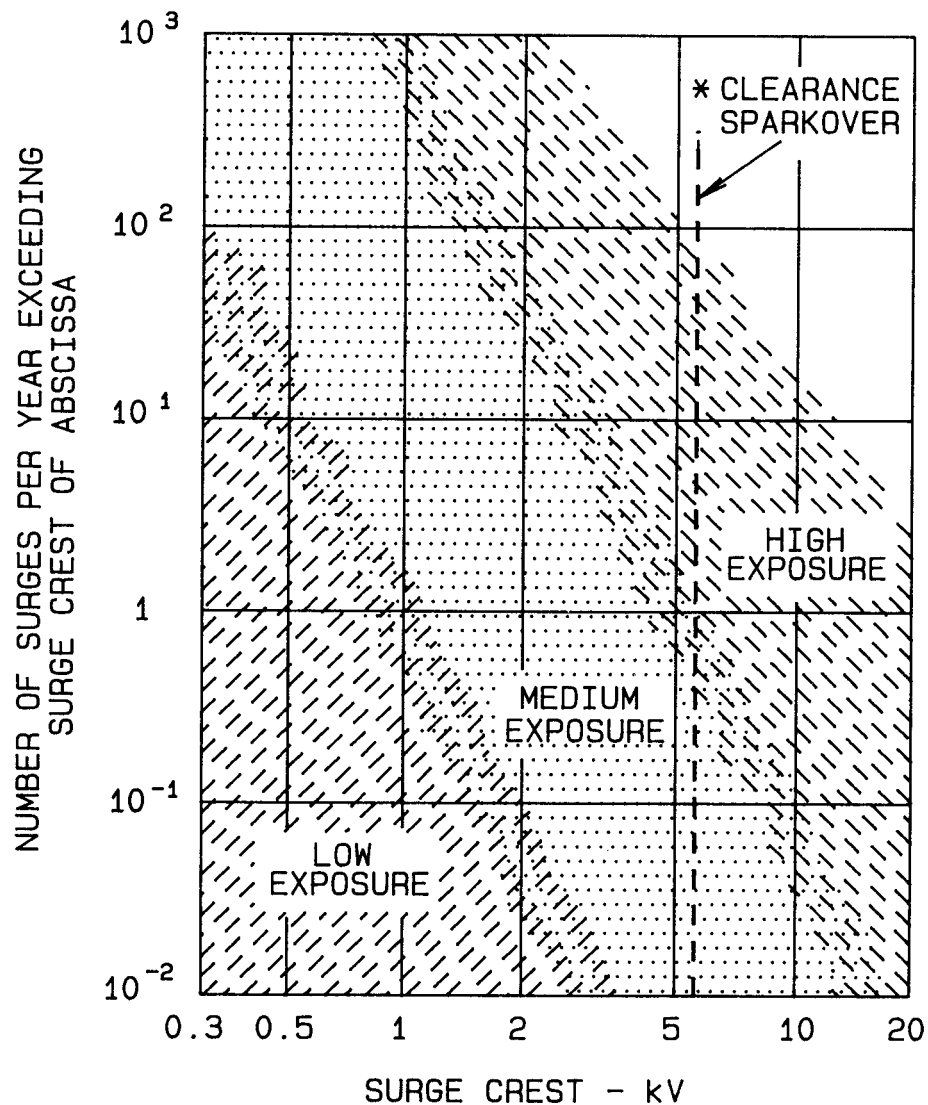
Several major sources of surges have been identified; the definition of “exposure” depends on which source is involved. The frequency of occurrence and level of lightning surges are influenced by isokeraunic levels (Figs 7 and 8) and flash densities.⁹ The nature of the power distribution system (overhead open lines, overhead twisted lines, cables) and grounding practices will also influence the level of these surges.

The frequency of occurrence and level of power-system switching surges depend on the mode of operation of the utility supplying the user. For instance, the presence of switched capacitor banks is likely to affect the level of surges impinging at the service entrance.

The frequency of occurrence and level of load-switching surges depend on the nature and impedance of the adjacent loads being switched, as well as their electrical distance (see **surge impedance and source impedance** in Appendix B19) from the point of interest, rather than the geographic situation or the utility practice.

Thus, the exposure levels shown in Fig 6 cover a wide range of situations and represent relative rather than absolute levels. The sparkover of wiring devices indicates that while a 6 kV withstand capability may be enough to ensure device survival indoors, a withstand capability of 10 kV or greater may be required outdoors. This practical approach has been applied in proposing the matrix of levels in Section 9 for standard waveforms and in Section 10 for additional waveforms.

⁹See expected occurrence of lightning in Appendix B for a discussion of flash density and isokeraunic levels.



NOTES: (1) In some locations, sparkover of clearances may limit the overvoltages.

(2) This figure shows one measure of surge severity. Other possible measures include peak current, rise time, and energy transfer.

Figure 6—Rate of Surge Occurrences Versus Voltage Level at Unprotected Locations

7.4 Recommended Waveforms

7.4.1 General

Progress has been made in techniques for the recording of surges since the 1960s; the greater availability and improvements of waveform-recording instruments will further enhance the data base in the future. At the present time, however, the wide variety of events reported in the data base may be simplified into three types of surges. These three types will be described in detail in the following subsections; briefly, they are categorized as follows:

- 1) Oscillatory surges of relatively high frequency, generally labeled “Ring Wave.” Those at the higher end of the frequency range have limited energy deposition capability, but may have high peak voltages. Those at the lower end of the frequency range may have higher energy deposition capability but lower peak voltages.
- 2) High-energy surges of various waveforms generally accepted as representing appropriate stress levels associated with nearby direct lightning discharges, fuse operation, or capacitor switching.
- 3) Bursts of very fast surges, associated with local load switching, with little energy but capable of producing serious interference or upset.

In this section, a qualitative description and justification is presented for these three types of surges. Section 8 provides recommendations on the planning for surge immunity; Sections 9 and 10 provide precise numerical definitions and waveforms intended for planning surge tests or computer simulations of systems performance under surge conditions.

7.4.2 Ring Waves

Measurements in the field and in the laboratory indicate that most surge voltages propagating in indoor low-voltage systems have oscillatory waveforms (Martzloff and Hahn, 1970 [B22]; Allen and Segal, 1974 [B2]; Wernström et al., 1984 [B34]; Goedbloed, 1987 [B14]). A surge impinging on the system, even if initially unidirectional, excites the natural resonance frequencies of the system (Martzloff, 1990) [B48]. As a result, not only are the surges typically oscillatory, but surges may have different amplitudes and waveforms at different places in the system. The frequency of oscillation of these surges ranges from less than 1 kHz (primarily capacitor switching) to more than 500 kHz (primarily local oscillations).

Thus, more than one ring wave may be necessary to represent this type of surge. In the 1980 edition of this document, a “Ring Wave” was defined with a 0.5 μ s rise time and decaying oscillation at 100 kHz, each peak being 60% of the amplitude of the preceding peak of the opposite polarity. A ring wave with a lower frequency is also proposed as an additional waveform in Section 10.

The fast rate of change of the front of the ring wave can produce the effects associated with nonlinear voltage distribution in windings. Some semiconductors are also sensitive to dv/dt effects, in particular when they are forced into or out of conducting states, or when a transient is applied during a particular portion of the power frequency supply cycle (see **timing of surges** in Appendix B22).

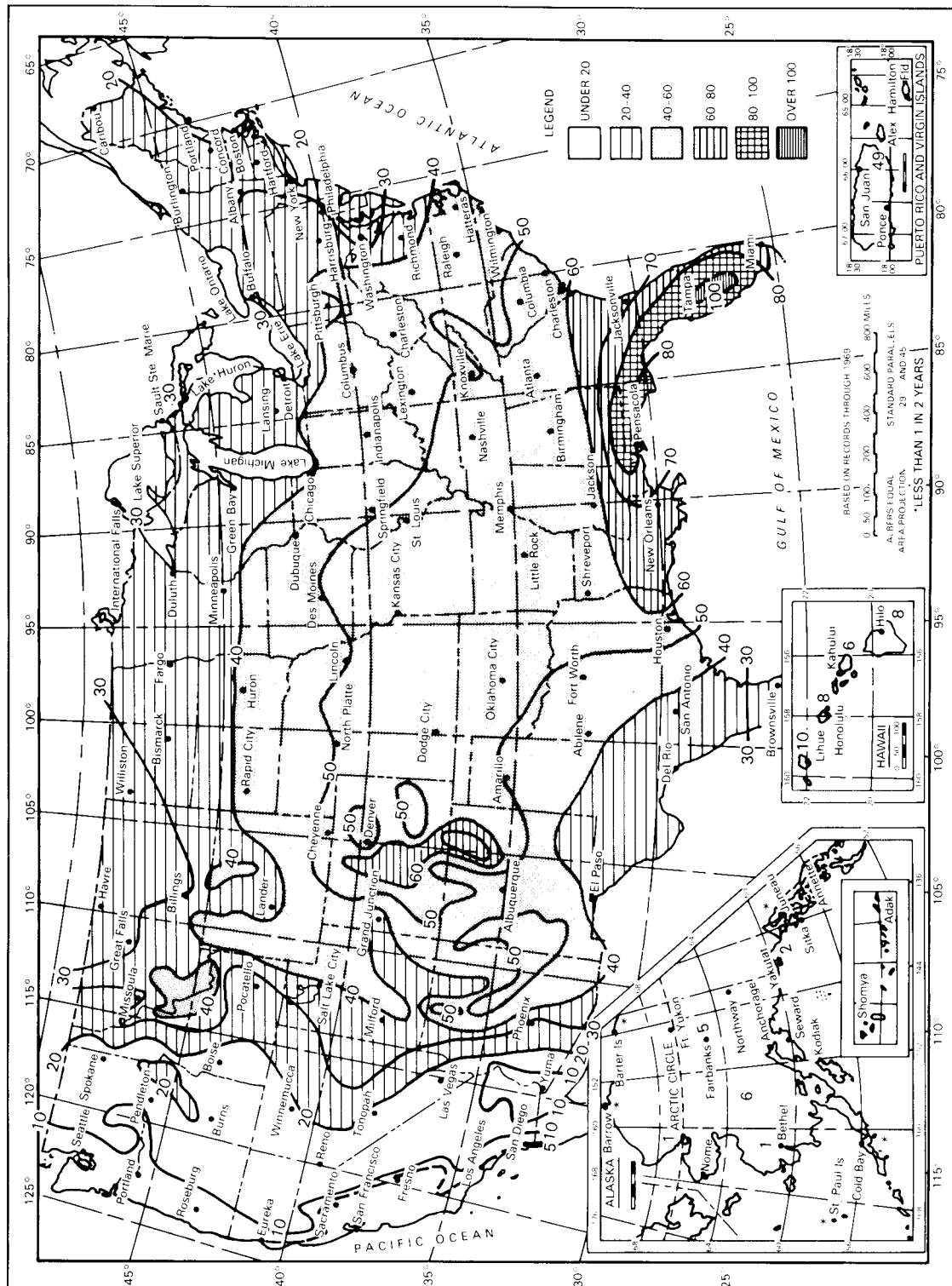
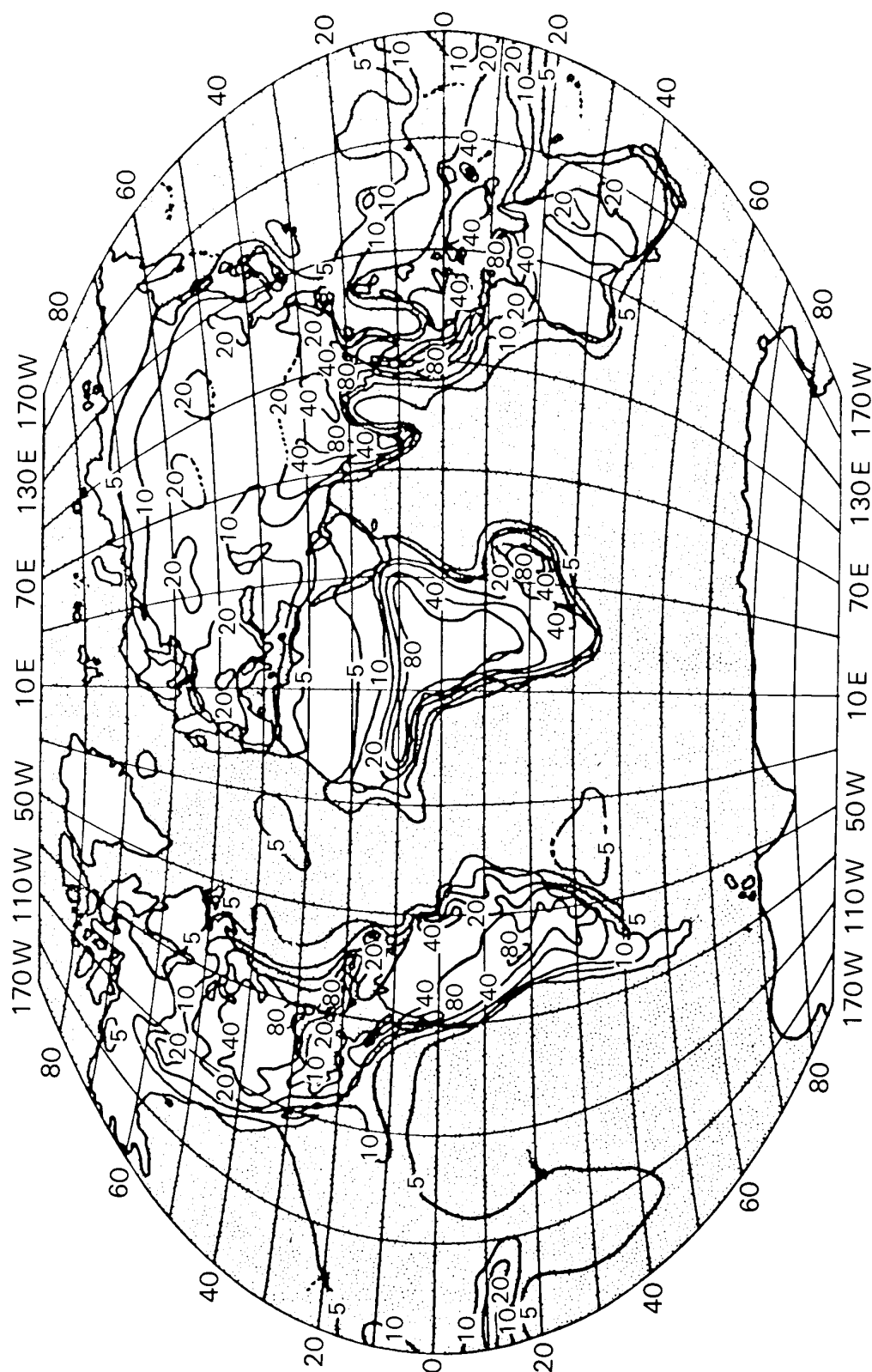


Figure 7—Isokeraunic Levels for the United States



Source: Bodle et al. [B52]

Figure 8—Isokeraunic Levels for the World

Shorter rise times are found in many transients, but as they propagate into the wiring or are reflected from discontinuities in the wiring, the rise times become longer (Martzloff and Leedy, 1990 [B46]; Martzloff, 1990 [B48]).

The peak voltage can produce insulation breakdown in connected components and equipment, even if the energy involved in the 100 kHz Ring Wave is small. Surges with higher energy deposition capability will be represented by other waveforms.

7.4.3 High-Energy Surges

Although the data base on energy is limited, there is a need to acknowledge the occurrence of high-energy surges capable of depositing more energy than that associated with the 100 kHz Ring Wave.

Anecdotal field experience shows that surgeprotective devices with limited current handling capability installed at the service entrance have a significant failure history, while applications of the same device further inside a building are generally successful. From the energy and source impedance factors discussed under 7.5, it becomes apparent that the 100 kHz Ring Wave will not deposit enough energy in surge-protective devices to produce the observed failures.

Several types of events can be the origin of high-energy surges capable of delivering significantly more damaging energy:

- 1) Lightning surges on overhead distribution systems (A)
 - 2) Lightning surges originating on overhead lines and traveling in cables (B)
 - 3) Surges generated by fuse operation involving trapped energy in the power system inductance (C)
 - 4) Surges generated by power-factor correction capacitor switching (D)
- A) Lightning surges on overhead lines have long been represented by a voltage surge of 1.2/50 μ s and a current surge of 8/20 μ s (IEEE C62.1-1984, [7]), which is described as “impulse” in IEC Document 99 [B97], and as the Combination Wave in the present document. These two waveforms have long been used, are readily generated in many laboratories, and are an appropriate simplification of the environment near the service entrance of a building connected to an overhead distribution system. They also have substantial energy deposition capability, when applied from a generator with inherent capability to supply a voltage as well as a current waveform (IEEE C62.45-1987 [8]), to provide representative stress to connected equipment. Because of the relatively short front time of 8 μ s, such a postulated current surge would not propagate very far into a building. The voltage drop associated with the propagation of a high-amplitude current surge front (thus high di/dt) in the inductive impedance of the wiring would require a driving voltage at the service entrance high enough to cause sparkover of the clearances (Martzloff, 1983 [B43]). This limitation sets the basis of the selection of waveforms associated with the location categories discussed in 7.7 and makes their maximum amplitude less dependent on the system voltage than on the actual clearances.
- B) Lightning surges traveling in underground systems involve longer durations. Lightning surges that have traveled along a long cable have wave fronts with a slope less steep than that of the initiating wave, as a result of the propagation characteristics of the cable. The peak of the initiating surge is likely to reflect the operation of a surge arrester at the interface of the overhead system and the cable.
- C) Surges generated by fuse operation involving long cables are unidirectional surges lasting several hundred microseconds, depending on the inductance of the cable and the transformer feeding the fault being cleared by the fuse (Meissen, 1983 [B25]).
- D) Capacitor switching surges and some other switching surges involve damped oscillations at low frequency (a few hundred hertz to a few kilohertz) lasting for a few milliseconds at most (Boehne and Low, 1969 [B5]; Wiitanen et al., 1971 [B35]; Martzloff, 1986 [B22]). From the point of view of energy exchange, such a long oscillation could be simplified as the envelope of the oscillation. Such an envelope would have a duration in the same order of magnitude as the surges generated by fuse operation.

These last three types of surges, (B), (C), and (D), have maximum amplitudes reflecting the system voltage rather than clearances, in contrast to the (A) surges. A simplified common representation might be adequate for these three phenomena.

For instance, the 10/1000 μs unidirectional waveform has long been specified for surge protection requirements in the communications and process control industries (IEEE Std 518-1982, [10]), and a 100/1300 μs waveform has been recommended in several IEC draft documents on electromagnetic compatibility. Thus, the present recommended practice added two additional waveforms of longer duration: a unidirectional surge (10/1000 μs) and a low-frequency 5 kHz Ring Wave if the application warrants such waveforms.

It is not uncommon for the frequency of a capacitor switching surge to be much less than 5 kHz, as low as 300 Hz. The lower the frequency, the greater the available energy. This energy may be too great for a surge-protective device attempting to clamp that surge, particularly if the switching device should restrike during opening and little impedance exists between the switching device and the protective device.

The difficulty, however, is that the data base on these longer waveforms is limited concerning representative source impedances or available currents for these long-duration surges. Meaningful testing can be achieved only if source impedance or short-circuit current are defined in addition to a voltage waveform.

Therefore, at the present state of knowledge, this recommended practice can only urge designers and users to consider the specific application environment and call for additional waveforms if their knowledge of the environment justifies the added complication of testing for these additional waveforms.

In the absence of measurements on actual occurrences, some theoretical considerations on **surge impedance and source impedance** provide guidance on what the appropriate values may be for the source impedance or the available current.

For long waves in power-system cables, with travel times longer than the front time of the surge, the source impedance would be the characteristic impedance of the cable, typically 10 Ω to 100 Ω for power-system cables, as opposed to higher values for overhead openwire lines. However, if the travel times are shorter than the front time of the surge, then the inductive impedance would prevail, and its value may be as low as a fraction of an ohm at the lower frequencies implied by such long waves.

For surges generated by fuse operation, the maximum fault current involved in the trapped energy ($1/2 Li^2$) has the value corresponding to the let-through current of the fuse in question (not the available fault current), as well as the system inductance, including the cable and the transformer feeding the fault. The let-through current is typically between 100 and 1000 A in residential or commercial circuits and possibly higher in industrial circuits.

For capacitor switching surges, the impedance of the complete circuit would be the combined impedance of the capacitor bank (source) and the series impedance between the point of switching and the point of interest (not the characteristic impedance). A few examples of this situation may be found in the literature.

7.4.4 Fast Transients

Circuit opening by air-gap switches (relays and contactors) has long been recognized as producing a succession of clearings and reignitions that generate bursts of fast-ringing surges in the circuits being switched (Mellitt, 1974 [B26]; Minegishi et al., 1989 [B27]). These transients have sometimes been associated with arcing phenomena under the label of “showering arc.” Under the name of “Electrical Fast Transients (EFT),” IEC 801-4 (1988) [5] requires a test involving bursts of surges with 5 ns rise time and 50 ns duration at various severity levels.

The new version of surge withstand capability (SWC) tests (IEEE C37.90.1-1989 [6]), intended for protective relays and relay systems, also includes a fast transient specification. The waveform for the SWC test calls for a rise time of less than 10 ns and a duration of 150 ns, not very different from the 5 ns and 50 ns of the EFT. (The upset aspects are primarily associated with the rise time, so that the difference between a duration of 50 ns and 150 ns should not be a significant difference.)

Furthermore, the SWC test is primarily intended for the high-voltage substation environment, while the EFT test is intended for general industrial equipment. Therefore, this recommended practice encourages the use of the EFT test

over the SWC test. Actually, when tolerances are taken into consideration, differences in the effect of one waveform versus the other may not be very significant. Adopting the EFT waveform to represent the environment next to switching devices appears to be a reasonable choice of selection, in harmony with international standards, for equipment subjected to that environment.

In contrast to the other waveforms discussed previously, the duration of these fast transients is short compared to the travel time in building wiring systems (50 ns is the time required to travel 10 m). Therefore, transmission line concepts are applicable to describe the propagation of these transients in building wiring and large equipment. This fact has two implications in including these fast transients in the description of the surge environments:

- 1) The characteristic impedance of low-voltage wiring systems inside a building is typically 100 Ω to 300 Ω for L-N or L-L configurations, and typically 25 Ω to 75 Ω for LL-G or LN-G configurations (see Appendix B5 for a discussion of the terms ***differential mode and common mode*** in the context of this document). This impedance will limit the current associated with these fast transients.
- 2) After only a short distance traveling in the wiring, the amplitude, as well as the rate of rise, of these fast transients is attenuated (Martzloff and Wilson 1987 [B45]; Martzloff and Leedy, 1990 [B47]). Furthermore, even a small resistive or capacitive load at the end of the transmission line can reduce the arriving surge (Martzloff, 1990 [B48]). Thus, the design of the equipment and its method of connection to the mains, as well as the internal capacitance to ground, has a greater effect on the equipment withstand capability than changes in the waveform and amplitude of the impinging fast transients.

Therefore, fine detail in the specification of a fast transient waveform is not significant to the actual performance of the equipment; the only justification for a specific description of the waveform is the acknowledged need for uniformity in test procedures. The EFT seeks to emulate a phenomenon that occurs in repeated groups of pulses that may vary in amplitude and duration over an indefinite period of time. It is not an attempt to reproduce the surges as they appear on the mains interface, as other surges waveforms do; it is a practical compromise for evaluating equipment immunity to fast transients.

This recommended practice emphasizes the importance of maintaining a clear distinction between the concepts of a *description* of a surge occurrence and a *test specification*. The preceding discussion of how the EFT test relates to the environment but is not to be taken as “representing” the environment is a good example of the need to maintain this distinction.

NOTE — Endorsing the EFT test procedure should not lead to the misinterpretation that there are such frequent and widespread fast transients with 4 kV peaks in low-voltage ac power circuits.

The only prevailing consideration is that passing the EFT test, when required for equipment acceptance, seems to result in improved equipment reliability. A good example for the need to consider fast transients is the case of two pieces of electronic equipment operating from the same receptacle, thus closely coupled. Disconnecting power from one while maintaining power to the other can subject the powered equipment to high-frequency transients such as the EFT (see ***description versus specification*** in Appendix B4).

Thus, a recommendation for considering the EFT as an additional waveform is directly related to a test demonstrating equipment immunity to upset by fast transients, rather than an inference that this specific waveform can be found in the environment. Fast transients do occur during contact arcing, and digital circuits are fast enough to respond (in an unwanted manner) to these fast transients. Detailed specifications on the test procedure are given in IEC 801-4 (1988) [5]. Waveforms are described in Sections 8 and 10; some implications of the test procedure are discussed under ***EFT test*** in Appendix B6.

7.5 Amplitude, Energy, and Source Impedance

For each waveform selected as one of the possible representations of the surge environment, the peak open-circuit voltage and the peak short-circuit current should be stated to provide a complete and meaningful description.