IEEE Standards

C62.41.2™

IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits

IEEE Power Engineering Society

Sponsored by the
Surge Protective Devices Committee

IEEE

Published by
The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

11 April 2003

Print: SH95031
PDF: SS95031

Recognized as an
American National Standard (ANSI)

IEEE Std C62.41.2™-2002

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Approved 10 March 2003

American National Standards Institute

Approved 11 November 2002

IEEE-SA Standards Board

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Abstract: The scope of this recommended practice is to characterize the surge environment at locations on ac power circuits described in IEEE Std C62.41.1™-2002 by means of standardized waveforms and other stress parameters. The surges considered in this recommended practice do not exceed one half-cycle of the normal mains waveform (fundamental frequency) in duration. They can be periodic or random events and can appear in any combination of line, neutral, or grounding conductors. They include surges with amplitudes, durations, or rates of change sufficient to cause equipment damage or operational upset. While surge protective devices (SPDs) acting primarily on the amplitude of the voltage or current are often applied to divert the damaging surges, the upsetting surges might require other remedies.

Keywords: low-voltage ac power circuit, surge testing, surge withstand level

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The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Published 11 April 2003. Printed in the United States of America.

Print: ISBN 0-7381-3393-0 SH95031
PDF: ISBN 0-7381-3394-9 SS95031

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Introduction

[This introduction is not part of IEEE Std C62.41.2-2002, IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits.]

This recommended practice is the result of 20 years of evolution from the initial 1980 document, IEEE Std 587™, IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits, which promptly became IEEE Std C62.41™ with the same title. The guide was updated in 1991 as IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits, reflecting new data on the surge environment and experience in the use (and misuse) of the original guide. The purpose of the document was and still is to provide information on the surge environment and offer recommendations to interested parties involved in developing test and application standards related to surge protective devices (SPDs) as well as recommendations to equipment designers and users.

The 1980 version, based on data available up to 1979, proposed two novel concepts:

a) The reduction of a complex database to two representative surges: a new "Ring Wave" featuring a decaying 100 kHz oscillation, and the combination of the classical, well-accepted 1.2/50 µs voltage waveform and 8/20 µs current waveform into a "Combination Wave" to be delivered by a surge generator having a well-defined open-circuit voltage and short-circuit current.

b) The concept that location categories could be defined within an installation where surge voltages impinging upon the service entrance of an installation or generated within an installation would propagate, unabated, in the branch circuits, while the associated currents, impeded by (mostly) the inductance of the conductors, would be reduced from the service entrance to the end of long branch circuits.

The 1991 version, based on additional data as well as experience in the use of the 1980 guide, maintained the concepts of the location categories and the recommendation of representative surge waveforms. The two seminal surges, Ring Wave and Combination Wave, were designated as "standard surge-testing waveforms," and three new "additional surge-testing waveforms" were added to the "menu." Meanwhile, a companion document, IEEE Std C62.45™-1992, IEEE Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits, was developed, outlining procedures for error-free application of the waveforms defined by IEEE Std C62.41™-1991 while enhancing operator safety.

The perceived need to justify the expansion of the two-only waveforms to a menu of five led to the growth in the document volume, from the 25-page IEEE Std 587-1980 to the 111-page IEEE Std C62.41-1991.

Additional data collected toward an update of the 1991 version (which was reaffirmed in 1996) would have increased further the volume of the document. Instead, a new approach was selected: to create a "Trilogy" by separating the information into three distinct documents, making their use more reader-friendly while maintaining the credibility of the recommendations:

- A guide on the surge environment in low-voltage ac power circuits, including a broad database (IEEE Std C62.41.1™-2002)
- A recommended practice on characterization of surges in low-voltage ac power circuits (the present document)
- A recommended practice on surge testing for equipment connected to low-voltage ac power circuits (IEEE Std C62.45™-2002)

In this manner, interested parties will have a faster, simpler access to the recommendations for selecting representative surges relevant to their needs. A comprehensive database will be available for parties desiring to gain a deeper understanding of the surge environment and an up-to-date set of recommendations on surge testing procedures.

Participants

At the time this recommended practice was completed, the Working Group on Surge Characterization on Low-Voltage Circuits had the following membership:

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Contents

IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and less) AC Power Circuits

1. Overview

This recommended practice is the second document in a Trilogy of three IEEE standards addressing surges in low-voltage ac power circuits; the other two companion documents are described in 1.4. This recommended practice is divided into eight clauses. Clause 1 provides the scope of this recommended practice and its context with respect to other IEEE standards directly related to the subject. Clause 2 lists references to other standards that are necessary for full implementation of the recommendations. Clause 3 is limited to a statement referring to existing dictionaries since no new definitions have been generated for this document. Clause 4 provides a summary of the surge environment described in detail in the database of the companion guide IEEE Std C62.41.1™-2002.[1] Clause 5 proposes how this complex database can be simplified toward selecting a few representative surge waveforms that will be more specifically defined in this recommended practice. Clause 6 presents the recommendation for two standard waveforms that should cover the majority of cases. Clause 7 presents suggestions for additional test waveforms that might be appropriate for particular cases, including the rare event of a direct lightning flash to the structure of interest. Clause 8 offers some concluding remarks. Informative Annex A provides a discussion of the stress parameters associated with a direct flash to the building of interest.

Many citations appear, in support of a statement or recommendation, or for greater details. These citations refer to Informative Annex B of this recommended practice. Also, a synopsis of these citations is provided in Informative Annex D of the companion guide IEEE Std C62.41.1-2002. That guide also contains an Informative Annex B that provides further tutorial information on the background of the surge waveform selection process. Also as further information to the reader of the three documents of the Trilogy, Informative Annex C of IEEE Std C62.41.1-2002 contains some relevant definitions and discussions concerning the definitions.

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 waveforms and amplitudes of surge voltages and surge currents that may be applied to evaluate the surge withstand capability of equipment connected to these power circuits. It is most important to recognize that

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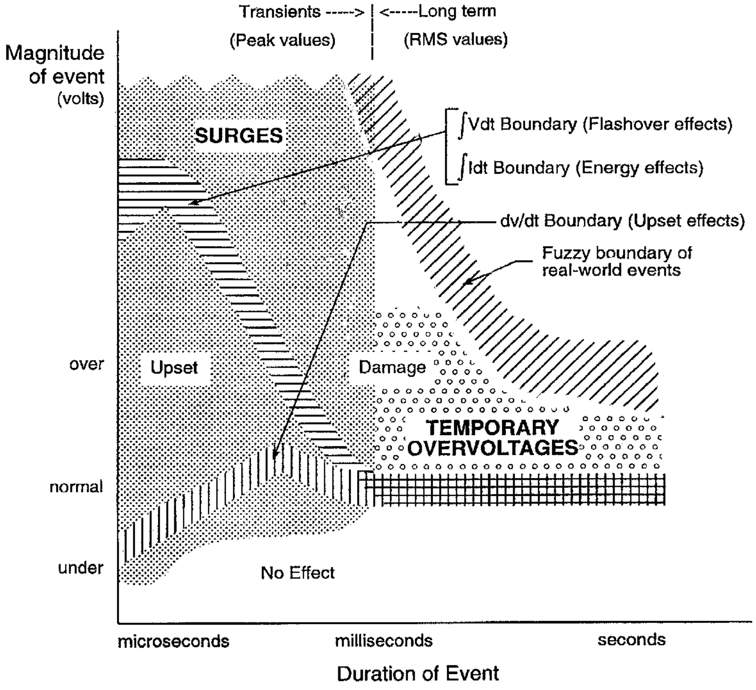
[1] Information on references can be found in Clause 2 and in 2.2.

proper coordination of equipment capability and environment characteristics is required: each environment and the equipment to be protected have to be characterized and the two reconciled.

1.1 Scope

The scope of this recommended practice is to characterize the surge environment at locations on ac power circuits described in IEEE Std C62.41.1-2002 by means of standardized waveforms and other stress parameters. The surges considered in this recommended practice do not exceed one half-cycle of the normal mains waveform (fundamental frequency) in duration. They can be periodic or random events and can appear in any combination of line, neutral, or grounding conductors. They include surges with amplitudes, durations, or rates of change sufficient to cause equipment damage or operational upset (see Figure 1). While surge protective devices (SPDs) acting primarily on the amplitude of the voltage or current are often applied to divert the damaging surges, the upsetting surges might require other remedies.



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 guide is shown by the two dot-pattern areas. The fine pattern relates to surges, the prime scope of this guide. The coarse pattern relates to temporary overvoltages, the secondary scope of this guide. For surges, the upper limit for the duration is one half-cycle of the applicable power frequency. Swells—overvoltage events longer in duration than a surge but lasting only a few seconds—are considered to be a subset of temporary overvoltages.

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—The boundary between "upset" and "damage" in the microsecond range is shown as the integral of Vdt to reflect the upturn in the volt-time characteristic of sparkover. Equipment responses that do not involve a sparkover are more likely to be influenced by the simple magnitude of voltage V.

5—This figure shows only one measure of surge severity emphasizing voltage and time relationships. Other possible measures include current peak and duration, rise time, and energy transfer.

Figure 1—Simplified relationships among voltage, duration, rate of change, and effects on equipment

1.2 Purpose

The purpose of this recommended practice is to offer to equipment designers and users a set of standard and additional surge-testing waveforms and stress levels derived from the surge environment described in the companion guide IEEE Std C62.41.1-2002. The selection and specification of which waveform and what stress level should be considered for specific equipment remain the prerogative and responsibility of designers and users. This recommended practice is only the basis for making an informed decision made possible by a simplification of a complex database. This simplification will then allow consistent, repeatable, and cost-effective specification of surge performance for equipment connected to low-voltage ac power circuits.

1.3 How to use this document

1.3.1 General

The purpose of this subclause 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, was sometimes misinterpreted as a performance standard, leading to statements such as "*(this product) meets the requirements of IEEE Standard 587 ...,*"—which are inappropriate and misleading. The same misapplication occurred for the 1991 version of the document, then elevated to the status of a recommended practice (IEEE Std C62.41™-1991), complemented by a "How to Use This Document" section similar to the present subclause. Nevertheless the same misinterpretation occurred, albeit less frequently among better informed users. To avoid continuing such misinterpretation, this version presents further recommendations on applying surge protection and the corresponding actions to be taken by the user in achieving the goal of satisfactory surge protection.

The database on the surge environment that was included in the 1991—and perhaps created too voluminous a document—has been separated into the companion guide IEEE Std C62.41.1-2002, thus allowing a shorter, more focused recommended practice on the selection of appropriate surge test waveforms.

1.3.2 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 equipment designer has to take into consideration not only the rates of occurrence and the waveforms described in this recommended practice, 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. Nevertheless, the considerations listed below are necessary to reach the goal of practical surge immunity. Clearly, most are beyond the scope of this recommended practice, but it is useful to recite them for the purpose of defining the context and the purpose of this recommended practice.

These consideration include

- Protection desired
- Worst-case or typical-case scenario
- Hardware integrity (no damage)
- Process immunity (no upset)
- Specific equipment sensitivities

- The power environment
  - Surge characteristics
  - Other power system parameters
- Interactions with communications or other systems
- Performance of SPDs
  - Protection
  - Durability
  - Failure mode
- The test environment
- Total and relative costs

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

a) ***Protection desired***. The protection desired can vary greatly depending upon the application. For example, in applications not involving on-line performance, protection might be desired merely to reduce hardware failures by a certain percentage. In other cases, such as data processing, critical medical processes, or manufacturing processes, any interruption or upset of a process is likely to be unacceptable. Hence, the designer should quantify the desired goal with regard to the separate questions of hardware failure and process upset. Another consideration is the need to make an informed decision either to provide protection by and survival of all SPDs for the rare event of a direct lightning flash to the structure of interest or, alternately, to limit such protection for the common occurrence of surges (including remote lightning, but not a direct flash).
b) ***Equipment sensitivities.*** Specific equipment sensitivities should be considered 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 downstream of a mitigation device, waveform or energy sensitivity, etc.
c) ***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 in this recommended practice, as well as consideration of surges associated with a direct lightning flash to the structure. This latter scenario is mentioned in 7.4, with further information and background presented in Informative Annex A.
d) ***Power environment—electrical system.*** The magnitude of the root-mean-square (rms) power-line voltage, including any anticipated variation, should be quantified. Power system voltages are generally regulated to comply with ANSI C84.1-1989 [B2].[2] 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 SPDs requires taking into consideration these occasional abnormal occurrences. Appropriate selection of the limiting voltage, switching voltage, and maximum continuous operating voltage (MCOV) ratings is essential.
e) ***Performance of SPDs.*** Evaluation of an SPD should verify a long life in the presence of both the surge and electrical system environments described above. At the same time, the remnant voltage of the SPD should provide a margin from the withstand levels of the equipment in order to achieve the desired level of protection. It is essential to consider all of these parameters concurrently. For example, the use of a protective device rated very close to the nominal system voltage might provide attractive remnant values, but can be unacceptable when a broad range of occasional abnormal

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[2] The numbers in brackets correspond to the numbers of the bibliography in Informative Annex B. Additional information on these citations can be found in Informative Annex D of IEEE Std C62.41.1-2002.

deviations in the amplitude of the mains waveform are considered. Durability or overall performance of the SPD should not be sacrificed for the sake of a low remnant. Possible failure mode scenarios need consideration.

f) ***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 including simultaneous short-circuit current capability is meaningless. To avoid this pitfall, this recommended practice provides both voltage and current descriptions. Details on test procedures are given in the companion recommended practice IEEE Std C62.45™-2002.

g) ***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.

1.4 Context and contents

This recommended practice, the second document of the Trilogy, focuses on the selection of representative surge parameters to be considered in assessing equipment immunity and performance of SPDs. The first document of the Trilogy, IEEE Std C62.41.1-2002, presents basic information on the occurrence and propagation of surges, serving as a database for the selection process of this recommended practice. The third document of the Trilogy, IEEE Std C62.45-2002, presents recommendations on surge test procedures for obtaining reliable measurements and ensuring operator safety. In addition to this first clause, this recommended practice includes the following clauses:

- ***Clause 2, References***, lists the documents supporting some of the basic concepts and recommendations of the present document. This clause is not a bibliography, but a list of key documents. While not imperative to have these references immediately available when using this recommended practice, it is useful to have easy access to these references.
- ***Clause 3, Definitions***, is included only to point out that no new definitions have been created for this document. For the convenience of the reader, some existing definitions are provided in the glossary (Informative Annex C) in the companion guide IEEE Std C62.41.1-2002.
- ***Clause 4, Summary of the surge environment***, provides a summary of the surge environment described in detail in the database of the companion guide IEEE Std C62.41.1-2002. Two distinct scenarios are described:
  - ***Scenario I:*** Surges impinging onto the structure from outside wiring. These surges include lightning phenomena (other than a direct flash) and switching under normal or abnormal power system operations. Specific data on surges associated with system interactions are not included, although the phenomenon is mentioned, lest its implication be overlooked.
  - ***Scenario II:*** Surges resulting from a direct lightning flash to the structure or from a flash to earth very close to the structure. These include surges coupled into the ac power circuits by resistive coupling, by inductive coupling, or by operation of a SPD and surges coupled into circuit loops as the earth-seeking lightning current is dispersed among the available paths to earth.
- ***Clause 5, Development of recommended selection of representative surges***, proposes how this complex database can be simplified toward selecting a few representative surge waveforms that will be more specifically defined in this recommended practice.
- ***Clause 6, Definition of standard surge-testing waveforms***, presents two standard waveforms that should cover the majority of cases:
  - A “Combination Wave” with 1.2/50 µs voltage and 8/20 µs current
  - A 0.5 µs–100 kHz “Ring Wave”

- ***Clause 7, Definition of additional surge-testing waveforms***, presents suggestions for additional test waveforms that might be appropriate for particular cases, two in Scenario I, and one in Scenario II.
  - A 5/50 ns “EFT Burst” (Scenario I)
  - A 10/1000 µs “Long Wave” (Scenario I)
- ***Clause 8, Concluding remarks***, revisits briefly the considerations discussed in detail in Clause 4 and Clause 5, as a recapitulation of the recommendations offered in this document.
- ***Annex A, Scenario II parameters***, provides background and information on the IEC Class I test parameters.
- ***Annex B, Bibliography***, provides the listing of citations made in the text.
- ***An index*** is also provided for key words.

An annotated bibliography, which is a common resource for all three documents of the Trilogy, can be found as Informative Annex D in IEEE Std 62.41.1-2002. Likewise, IEEE Std C62.41.1-2002 includes other common resources for all the Trilogy documents: Informative Annex B, Complementary Information, and Informative Annex C, Glossary.

2. References

2.1 General

In this document, two types of citations are used: those that are directly related to the subject being discussed and often necessary to consult when using this recommended practice—true 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 to look up the citation, yet have some indication on what matter is being referenced, “references” and “citations” are briefly identified in the text, as follows:

The first type, references, contains information that is implicitly adopted in the present document. Complete implementation of any recommendations or validation of a statement made in this recommended practice would require the reader to consult that reference document for details on the subject. The listing is provided in 2.2.

The second type, bibliographic citations, is not essential to implementation of a recommendation or comprehensive validation, 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 [Bx]) and the listing is provided in Informative Annex B of this recommended practice.

2.2 Reference documents

This recommended practice shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revisions shall apply.

IEEE Std C62.41.1-2002, IEEE Guide on the Surge Environment in Low-Voltage (1000 V or less) AC Power Circuits.[3], [4]

IEEE Std C62.45-2002, IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits.

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3. Definitions

The definitions of the terms used in this recommended practice are found in *The Authoritative Dictionary of IEEE Standards Terms,* Seventh edition [B19], or the IEC *Multilingual Dictionary of Electricity* [B11]. No new definitions have been generated in developing this document. However, for the convenience of the reader and for tutorial purposes, some existing definitions for important terms used in the Trilogy in general and this recommended practice in particular are listed in the glossary (Informative Annex C) of the companion guide IEEE Std C62.41.1-2002.

4. Summary of the surge environment

4.1 General

Surge voltages and surge currents occurring in low-voltage ac power circuits originate from two major sources, lightning and switching. A third phenomenon that needs recognition is the occurrence of surge voltages resulting from interactions between different systems, such as the power system and a communications system, during surge events occurring in one of the systems.

4.2 Lightning surges

Lightning surges are the result of a direct flash to the power system, to the structure of interest and nearby structures, or to the soil. Distant lightning flashes can induce voltage surges in the circuits of an installation.

Lightning surges, as discussed in IEEE Std C62.41.1-2002, are the consequence of a direct flash, a near flash, or a far flash. The resulting surge can be described as a current source (direct flashes and some of near-flash effects) or a voltage source (some of near-flash effects and far flashes). This duality will be reflected in the selection process for test waves, in which recommendations are made to consider both current and voltage waveforms.

A meaningful and cost-effective selection of representative waveforms for assessing surge immunity involves a risk analysis that is beyond the scope of this recommended practice and in fact is the prerogative and duty of equipment manufacturers. The situation can be simplified by considering two cases, involving quite different stresses, that will be referred to as “scenarios” in this recommended practice.

- ***Scenario I***. In the event of a lightning flash not directly involving the structure, two different coupling mechanisms occur:
  - Surges coupled into the power system, either directly or indirectly,[5] and impinging at the service entrance of the building of interest, such as a direct flash to the outside power system or to adjacent buildings supplied from the same utilization voltage transformer.
  - Electric and magnetic fields penetrating the structure and coupling inductively in the building wiring.
- ***Scenario II.*** In the less common event of a direct flash to the structure (or a flash to earth very close to the structure), several coupling mechanisms exist:
  - Surges coupled into the ac power circuits by direct coupling;
  - Surges coupled into the ac power circuits by inductive coupling;
  - Surges associated with local earth potential rise causing operation of a service-entrance SPD.

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[5] Including the relatively rare case of a direct flash to an adjacent building with resulting dispersion into the power system. While a direct flash to a structure is a rare event (see B.7 of IEEE Std C62.41.1-2002), any structure surrounded by others that are powered by the same low-voltage supply will be subjected to some portion of the lightning current as the earth-seeking current in the struck building is dispersed among all available paths, including the earthing electrodes of adjacent buildings (Birkl et al. 1996 [B6]; Mansoor and Martzloff 1998 [B24]).

In the overall description of the surge environment, switching surges generated outside of the structure and impinging at the service entrance is also included in Scenario I. More details on these two scenarios are given in Clause 6 and Clause 7.

4.3 Switching surges

Switching surges are the result of intentional actions on the power system, such as load or capacitor switching. They can also be the result of unintentional events, such as power system faults and their clearing. Unfortunately, switching surges, as discussed in IEEE Std C62.41.1-2002, have been considered or measured by the various authors discussing the phenomenon as a voltage source—often without any reference to the impedance of that source, which should be known for a rigorous analysis. This recommended practice attempts to improve this situation by presenting a set of standard and additional waveforms where representative source impedance values are proposed.

In most cases, the maximum overvoltage is in the order of less than twice the peak amplitude of the system voltage, but higher values can occur, especially when switching inductive loads (motors, transformers) or capacitive loads. Also, interruption of short-circuit currents can cause high overvoltages. If current chopping or restrike occurs, relatively high energy can be stored in inductive loads, and oscillations can occur on the load side of the opening switch or fuse.

One of the standard waveforms described in this recommended practice represents switching events typical of switching operations within the local power system, excluding major utility switching events. Capacitor-switching surges can occur frequently for systems where such capacitor banks are switched. However, they should not be considered to be the general case, and their amplitude is generally less than twice the system voltage. Therefore, they are generally not a problem for the utility equipment. However, electronic power conversion equipment can be disturbed, and SPDs with low limiting voltage can be overstressed because the energy available from these events can be substantial. A case-by-case assessment is necessary to describe the stress that can be associated with capacitor-switching surges.

4.4 Systems-interaction overvoltages

As more and more electronic equipment enter the home and business environment, these equipment often involve a communications port as well as their usual power-cord port. Although each of the power and communications systems might include a scheme for protection against surges, the surge current flowing in the surged system causes a shift in the potential of its reference point while the reference point of the other, non-surged system remains unchanged. The difference of potential between the two reference points appears across the two ports of the equipment and can cause upset or damage.

Overvoltages can occur between different systems during the flow of surge currents in one of the systems. By definition, these overvoltages extend beyond a strict interpretation of the scope as being limited to ac power systems. However, their occurrence can impact multiport equipment connected to the mains and, therefore, needs to be mentioned. This consideration of an interaction is necessary because field experience has demonstrated that equipment failures are often summarily—and incorrectly—attributed to a surge impinging on the power port of multiport equipment, a “power-line surge” in the language of the media. In reality, the stress on the equipment that produced the failure (upset can also occur at lower stress levels) is the result of the flow of surge current in one of the systems, either inherently or as a side effect of the flow of surge current resulting from the intended diverting action of an SPD.

Understanding the nature of the phenomenon is important because the system-interaction stress can occur even if both ports of the equipment—power and communications—are “protected” by SPDs, one at each port or upstream in the systems, raising expectations of adequate surge protection being provided. When failure or upset of the equipment still occurs, questions are then raised on the adequacy of the existing SPDs. However, the answer will be found, not in providing “improved” SPDs installed ***separately*** on each of the ports, but by understanding the ***interaction*** scenario and providing effective remedial measures to address that stress. Consensus has not yet been reached on what representative waves and values should be recommended for that mechanism; therefore, this recommended practice does not include these waves and values in its scope.

4.5 Location categories—Scenario I

As a first step toward a reduction of the complex database on surge occurrences for Scenario I, the concept of location categories is proposed here. Figure 2 shows a pictorial description, including the transitions provided by the physical characteristics and components of the power system. Table 1 presents recommendations on the applicable representative waveforms, and Table 2 through Table 7 present stress levels that might be expected in each category. ***As emphasized repeatedly in this recommended practice, this process remains a simplified description of the environment, not an equipment specification.***

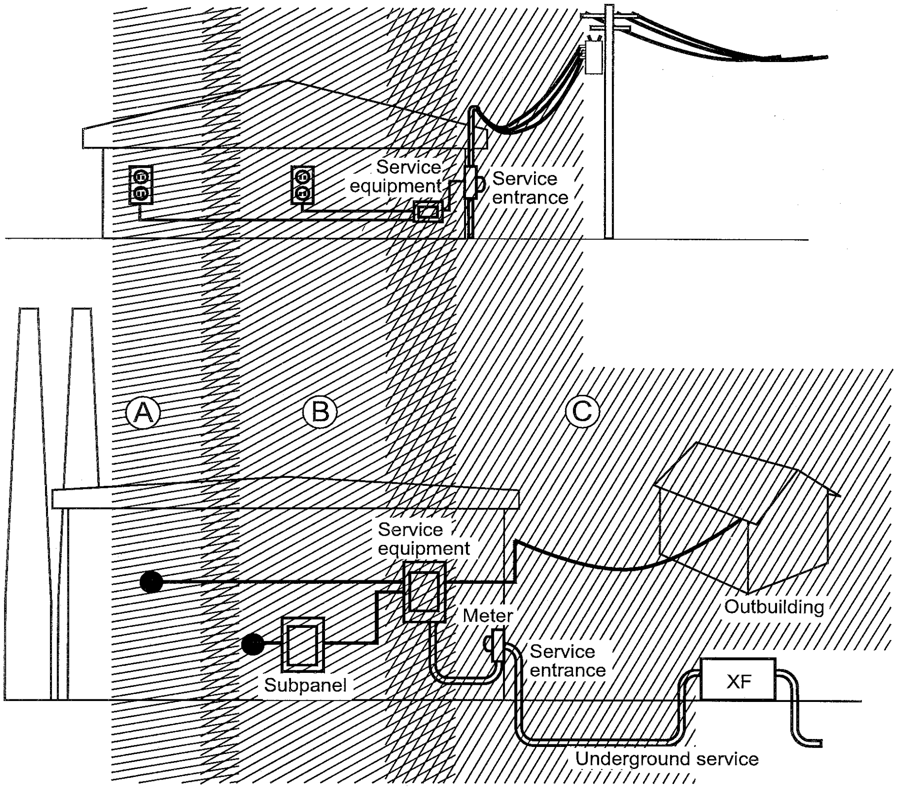
According to this concept, Location Category A applies to the parts of the installation at some distance from the service entrance. Location Category C applies to the external part of the structure, extending some distance into the building. Location Category B extends between Location Categories C and A. Because the reality of surge propagation is clearly a continuous situation, separating the categories by sharp conceptual boundaries would be an arbitrary and debatable process. Instead, the concept of location categories recognizes the existence of transition bands that connect the categories by overlapping. These transitions can be associated with the presence of an identifiable device or component: a clearance can provide a limiting of voltage by flashover; and a surge current can be reduced by diversion through an SPD or impeded by the impedance of the wiring.

The concept of location category rests on the considerations discussed in 5.2 and 5.3 in IEEE Std C62.41.1-2002 on dispersion and propagation of surge currents and surge voltages. For surge currents presented at the service entrance of a building, the increasing impedance opposing (impeding) the flow of surge currents further into the building—with or without the crowbar effect of flashover at the service entrance—reduces the surge current that can be delivered along the branch circuits (Mansoor and Martzloff 1997 [B23]). In contrast, a voltage surge presented at the service entrance of a building (unless limited by clearance flashover) can propagate, practically unattenuated, to the end of a branch circuit when no low-impedance load (equipment or local SPD) is present there (Martzloff 1983 [B25]; 1986 [B26]; 1990 [B27]; 1991 [B28]).

In Figure 2, Location Categories A, B, and C correspond to the scenario of surges impinging on the service entrance or generated within the building. A direct flash to the structure produces by induction voltage and current surges in the circuits of the building. However, such induced surges occur during the initial rise of the lightning current and, therefore, can be represented by relatively short-duration surges involving relatively low energy deposition capability, such as the 100 kHz Ring Wave. The resistively coupled surges resulting from a direct flash (Scenario II) involve long tails, so that their dispersion is not affected by the wiring inductance after the initial part of the surge, which is the significant parameter in the location category concept.

4.6 Direct flash to the structure—Scenario II

Scenario II has been proposed to describe the special case of a direct flash to the structure or of a flash to earth very close to the structure. Significant factors include the flash density for the area of concern, the effective collection area of the structure, the statistical distribution of peak amplitudes, the relationship between first stroke and subsequent strokes, and the dispersion of the lightning current in the available paths to ground. There are two related phenomena occurring with a direct strike to the facility. One effect is the induction of surges into the surrounding circuits by the high electromagnetic field produced by the high-current, fast-rising lightning flash. The resulting surges can be represented by a Ring Wave, as described in 6.3.1. The other effect is the direct injection of current into the ground system. Briefly summarized here, it is discussed in more detail in 5.5 of IEEE Std C62.41.1-2002. In that subclause, data are given on flash density



NOTE—There can be differences in the configuration and distance between the revenue meter and the service equipment. This schematic is only an example to illustrate the concept of location categories. [The National Electrical Code® (NEC®) (NFPA 70-2002) [B32] states in Article 230-70 "The service disconnecting means shall be installed at a readily accessible location either outside of a building or structure, or inside nearest point of entrance of the service conductors."]

Figure 2—The concept of location categories and transitions as simplification approach

maps, and in C.7 of IEEE Std C62.41.1-2002 an example is given of computation of the average annual frequency of direct flashes to a specified structure. Indeed, an important aspect of Scenario II is its low probability of occurrence for a particular building, although lightning flashes are globally frequent events. In the case of a flash to earth very close to the structure, a significant part of the current can disperse directly into the soil, while the remainder is likely to flow into the earthing system of the structure, as if injected by a direct flash, but with some reduction of the amplitude. Therefore, a specific risk analysis, taking in consideration the function of the building, should be performed before discounting or mandating the need for adequate surge protection in this rare scenario for one specific installation.

The lightning current parameters defined in IEC publications are based on the results of Study Committee 33 of CIGRE (International Conference on Large High Voltage Electric Systems) (Berger et al. 1975 [B5]; Anderson and Eriksson 1980 [B1]). ***Note that these studies characterized the lightning flash itself, not the resulting lightning surges in the ac power circuits of the struck building.***

The first stroke of a flash is characterized by three parameters:

- Current amplitude
- Stroke charge
- Specific energy

For the first stroke of a natural lightning flash, its parameters have been characterized in IEC 61312-3:2000 [B16]. The dispersion of the flash current among available paths reflects the relative impedances of these paths, which can vary over a wide range, as discussed in IEEE Std C62.41.1-2002. Numerical simulations (Birkl et al. 1996 [B6]; Mansoor and Martzloff 1998 [B24]) have shown that the waveform of the portion of the stroke current passing through service-entrance SPDs to exit the building is not very different from that of the flash current if the model postulates comparable values of the resistance of the earthing electrodes for all conductors. In the case of a power system with multiple-grounded neutral, the substantially lower resistance offered by the multiple earthing electrodes reduces considerably the portion of the lightning current carried by SPDs involved in the exit path. Therefore, when making a risk analysis, it is very important to consider the grounding practices of the power system.

Subsequent strokes in a flash have lower amplitudes but steeper fronts. Therefore, they are significant for the mechanism of inducing voltages in circuit loops. Examples of computations for this effect are given in A.2 of IEEE Std C62.41.1-2002. For practical purposes, given the oscillatory response of these circuits to an impulsive stimulus, the 100 kHz Ring Wave may be considered as representative of the environment for the case of internal circuits exposed to a Scenario II event.

4.7 Exposure level

The description of the database first given in the 1980 version of this document (IEEE Std 587™) included a figure showing the rate of occurrences versus voltage levels ***at unprotected locations***, in support of introducing the concept of exposure levels. In the post-1990 environment, there are very few locations left without the presence of an SPD somewhere, so that “unprotected locations” are scarce. The level of exposure of a particular environment and location category would be better described by a diagram showing the frequency of occurrence of surge currents as a function of their amplitude (or perhaps energy-delivery capability). Unfortunately, available data do not provide that information, and the concept of exposure levels remains qualitative. The 1991 version of this recommended practice attempted to quantify, by a consensus process, the impact of exposure by means of tables where the numerical values for the three location categories were divided into three subcategories. This attempt was deemed cumbersome by some readers, and many specifiers used only the largest value. Consequently, the tables appearing in this recommended practice show only one row of values for Category A and Category B. Because of the width of the transition band connecting Location Category B to Location Category C (spanning over the service equipment), two levels of exposure have been maintained for Location Category C.

5. Development of recommended selection of representative surges

5.1 Approach

The wide variety of surges that can be expected to occur in low-voltage ac power systems has been described in the database of IEEE Std C62.41.1-2002. Evaluation of the ability of equipment to withstand these surges, or of the performance of SPDs in dealing with this variety of surges, can be facilitated by a reduction of the database to a few representative stresses. It is unnecessary and not cost-effective to require subjecting equipment to surges that would duplicate field-measured surges, since these measurements are site dependent and are likely to change with time (Martzloff and Gruzs 1988 [B30]). This approach was proposed with the concept of transient control levels (Fisher and Martzloff 1976 [B9]) and can be stated in the form of an axiom, as shown below.

> The criterion of validity of an environment standard is not so much how closely it duplicates reality but rather how well equipment designed in accordance with this standard perform in the field. If equipment designed in accordance with the standard perform well in the field, while equipment ignoring the standard do not perform well, the chances that the standard is a good standard are pretty good.

The reduction process should lead 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. A combination in the selection of location category and exposure level (including typical conducted surges versus direct flash surges), as proposed in this recommended practice, will then provide the appropriate degree of compromise between a conservative overdesign and a cost-conscious reduction of margins.

5.2 Worst-case design and economic trade-off

Excessively conservative design for surge immunity will drive the requirements toward specifying the largest number of possible types of surge waveforms and the highest levels of stress, presumably to achieve maximum reliability of the equipment. In general, a trade-off based on risk analysis is an inescapable element of equipment design and specification. Furthermore, the level of immunity of any specific equipment within a particular design (catalog number and vintage) is not a single-value parameter, but is represented by some statistical distribution. In addition, the amplitude of the surges that can be expected on the mains is also a statistical distribution. Therefore, reconciling the equipment susceptibility with the surge environment level involves the probabilistic intersection of two distributions, as illustrated by Figure 3.

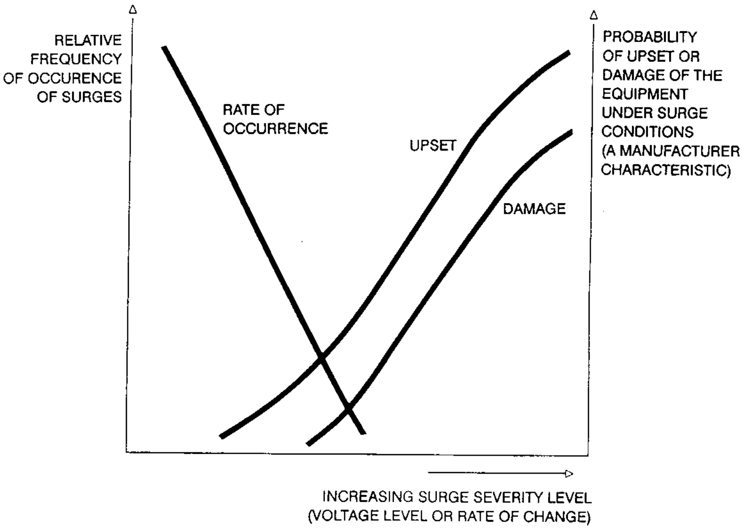


Figure 3—Probabilistic concept of surge immunity

This recommended practice provides a matrix, in the form of specific tables, from which a selection can be made; therefore, a common base of reference can be made 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 the 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 involving different significant parameters should be considered as follows.

   Case 1: When equipment are 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 equipment are 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.

The range of electromagnetic environments in which a particular piece of equipment will be called to operate can vary widely. Some equipment are intended for a specific environment while other equipment can be applied in a variety of environments. In addition, the particular environment can change over time, as a function of a number of factors, including geographic, seasonal, and annual changes in local lightning incidence. Another change over time concerns the existing complement of nearby electric and electronic equipment that can generate interfering or damaging surges.

For industrial equipment, industry groups and various standardizing bodies often provide guidance in the selection of electromagnetic interference severity levels that the equipment have to endure (IEC 61000-2-5:1995 [B13]), of which the surge environment discussed here is a subset. In both areas of commercial and consumer goods, however, manufacturers often make their own trade-offs between excessive malfunctions or damage on the one hand and excessive costs on the other. One solution to this ongoing dilemma is to design products whose basic surge immunity is coordinated with low or medium exposure levels, while offering options, upgrades, or additional protection for more hostile environments.

Independently from the immunity level built in or supplied optionally to provide performance without upset or damage, protection of some kind is often included to guard against so-called consequential damage, such as fires or explosions, while nevertheless allowing the victim equipment itself to fail. It is to assist in making evaluations among these and other alternatives, for equipment of all types, that this section on planning for surge immunity has been prepared.

It is not the purpose of this recommended practice to specify levels for equipment immunity or SPD surge-handling capability. A distinction should be made between equipment in general (which might contain SPD components at their power port) and SPDs designed specifically to serve for the purpose of diverting surges. Surge testing of equipment in general is intended to assess the response of a piece of equipment to the surge environment. For that purpose, the concept of representative surges is applicable, and the test will consist of applying these surges to the equipment specimen and observing its response (no apparent disturbance, upset, or damage). Surge testing of SPDs is intended to determine their characteristics (protection level and surge-handling capability) and eventually compare the performance of different designs. For that purpose, consistent characterization requires applying a set voltage and a set current to the SPD specimen. However, it is important to note that the values suggested in this recommended practice, while reflecting the expected environment, should not be construed as product specifications.

Consequently, the recommendations presented in Clause 6 and Clause 7 show two kinds of tables:

- Surges expected in the various environments and location categories that will impinge on equipment.
- Test surges that may be applied as appropriate to characterize the performance of SPDs.

5.3 Surge effects

The nature and functional purpose of the equipment influence the judgment of what will be considered an acceptable or unacceptable effect of a surge. When the consequences of a failure are not safety-related, but represent only an economic loss, it may be appropriate to trade off the cost of protection against the likelihood of a failure caused by a rarely encountered surge with high energy-delivery capability. This rarity can take two different aspects: “when?” or “where?”

- During operation of the vast majority of equipment in service, surges with relatively high levels of voltage or current can occur on rare occasions, such as those caused by lightning or multiple restrikes during de-energization of capacitor banks—the question is ***when***?
- Among all equipment in service everywhere, a few rare installation sites are frequently and consistently afflicted by surges like local switching surges, for instance, power-factor correction capacitor banks—the question is ***where***?

The consequences of a surge impinging on the mains interface can be classified in four broad categories, as discussed in the following list, each having several aspects:

1) ***No observed change***. This absence of visible change would demonstrate that the equipment specimen is actually immune to the surge level in question; however, appearances can be deceiving. The equipment can continue normal performance within specified limits, thus meeting the criterion of “No loss of function or performance.” Yet, significant consequences are possible: degradation of performance still within limits, but foreboding larger degradation, latent failure of a component, or an unforeseen consequence elsewhere in the equipment environment.
2) ***Upset.*** This consequence can be a self-recoverable upset by design of the software and, therefore, not immediately apparent; or it might be a permanent upset requiring operator intervention or programmed automatic action occurring after some time delay. Many documents on test methods suggest three classes for this type of consequence, as follows:
    - Minor: Acceptable temporary loss of function, but no faulty operation.
    - Major: Temporary faulty operation or performance (which is self-recoverable).
    - Critical: Faulty operation or performance that requires operator intervention or system reset. Another consequence that may be classified in this category is an upset caused by sparkover of air clearances without permanent degradation of adjacent solid insulation.
3) ***Damage***. This consequence includes the subtle as well as the obvious. As discussed under category 1, damage might occur without being detected unless special assessment of the equipment condition is performed. One of the most vexing problems in insulation testing is the risk of creating an incipient defect by applying a surge test.
4) ***Consequential damage.*** This consequence includes the possibility that equipment subjected to a surge might cause damage to their surroundings well beyond the importance of the damage or upset done to the equipment. Ignition of a fire or an explosion could occur. Damage might result from unseen hardware upset, during which data become corrupted and might subtly degrade other elements in the database, with the user left unaware of the situation.

Criteria for acceptance or rejection have to take into consideration these different consequences. For instance, upset may be ruled out until a specified level of severity is reached, above which occurrence of an upset is declared acceptable; at some higher severity level, damage may be ruled acceptable, provided that safety is not jeopardized and no consequential damage occurs. In any event, it is imperative that data validity, where applicable, be verified following each test to ensure that database damage has not occurred.

Furthermore, the level at which an upset or damage occurs depends on the mission of the specific equipment. For this reason, universal levels of withstand should not be assigned to all equipment. ***Hence, the values of environment levels proposed in Clause 6 and Clause 7 should not be blindly construed as severity test level requirements applicable to all types of equipment.***

To simplify the wide choice, two types of surge test waveforms are proposed in the following two clauses. The first type, defined in Clause 6 under the label of "standard waveforms," has a long history of successful application in industry and thus may be considered sufficient for most cases of surge immunity tests on the ac port of equipment. However, for special environments or difficult cases, the second type, defined in Clause 7 under the label of "additional waveforms," offers recommendations for selecting additional waveforms as appropriate for the application of interest. Table 1 presents a summary of these waveforms, showing in which location categories and for which scenario they are applicable.

Table 1—Summary of applicable standard[a] and additional[b] surge-testing waveforms for Location Categories A, B, and C (Scenario I only) and parameters for Scenario II

Scenario I **Surges impinging upon the structure from outside[c], and generated within[d]**						**Scenario II** **Direct lightning flash**	
Location Category	**100 kHz Ring Wave**	**Combination Wave**	**Separate Voltage/ Current**	**EFT Burst 5/50 ns**	**10/1000 µs Long Wave**	**Inductive coupling**	**Direct coupling[e]**
A	Standard	Standard	—	Additional	Additional	Category B Ring Wave	Case-by-case assessment[e]
B	Standard	Standard	—	Additional	Additional		
C Low	Optional[f]	Standard	—	Optional[f]	Additional		
C High	Optional[f]	—	Standard	Optional[f]	—		

[a] Refer to Table 2 through Table 5 for details on the standard waveforms (Clause 6).
[b] Refer to Table 6 and Table 7 for details on the electrical fast transient (EFT) Burst and Long Wave additional waveforms (Clause 7).
[c] Refer to discussion of capacitor-switching transients under 7.3 for impinging surges.
[d] Nearby lightning flashes can induce surge voltages into circuits contained within the building.
[e] Refer to discussion of the assessment under 7.4 and Informative Annex A.
[f] For specific cases where front-of-wave response or software upset might be a concern.

6. Definition of standard surge-testing waveforms

6.1 General

The two recommended standard waveforms are the 0.5 µs–100 kHz Ring Wave and the 1.2/50 µs–8/20 µs Combination Wave. The parameters of these two standard waveforms are described in 6.1.1 and 6.1.2. Plots of the three nominal waveforms (one for the Ring Wave, two for the Combination Wave) are shown in Figure 4 through Figure 6.

Criteria for selection of the peak voltages and currents that correspond to various environmental exposures are discussed in 6.2 with reference to Table 2 through Table 5. A more detailed description of these two standard waveforms is given in 6.3. Tolerances to be applied for testing and equations describing the waveforms that might be used in numerical simulations are given in IEEE Std C62.45-2002. For SPD testing applicable to the Category C environment, two separate surge generators may be used to perform respectively a current test and a voltage test.

6.1.1 The 100 kHz Ring Wave

A plot of the nominal Ring Wave is shown in Figure 4, and further details are given in 6.3.1. No short-circuit current waveform is specified for the 100 kHz Ring Wave. A peak short-circuit current amplitude, however, is proposed in 6.2, according to the location category. The nominal ratio of peak open-circuit voltage to peak short-circuit current (effective impedance) is specified to be 12 Ω for simulation of Location Category B environments or 30 Ω for simulation of Location Category A environments. The nominal amplitude of the first peak is selected by the parties involved (see 6.2), according to the severity desired.

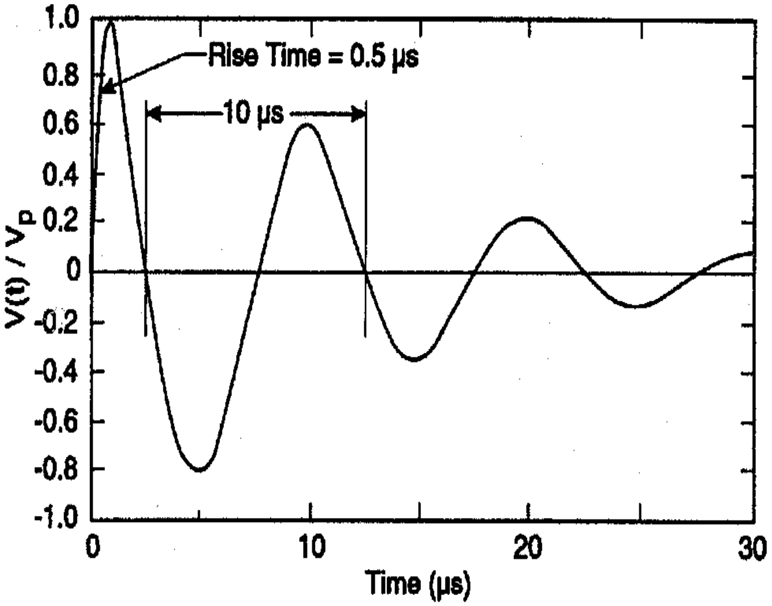


Figure 4—The 100 kHz Ring Wave (voltage and current)

6.1.2 The Combination Wave

The Combination Wave involves two waveforms, an open-circuit voltage and a short-circuit current, shown in Figure 5 and Figure 6, respectively. Further details are given in 6.3.2. The Combination Wave is delivered by a generator that applies a 1.2/50 µs voltage wave across an open circuit and an 8/20 µs current wave into a short circuit. The exact waveform that is delivered is determined by the generator and the impedance of the equipment under test (EUT) to which the surge is applied. The value of either the peak open-circuit voltage or the peak short-circuit current is to be selected by the parties involved (see 6.2), according to the severity desired.

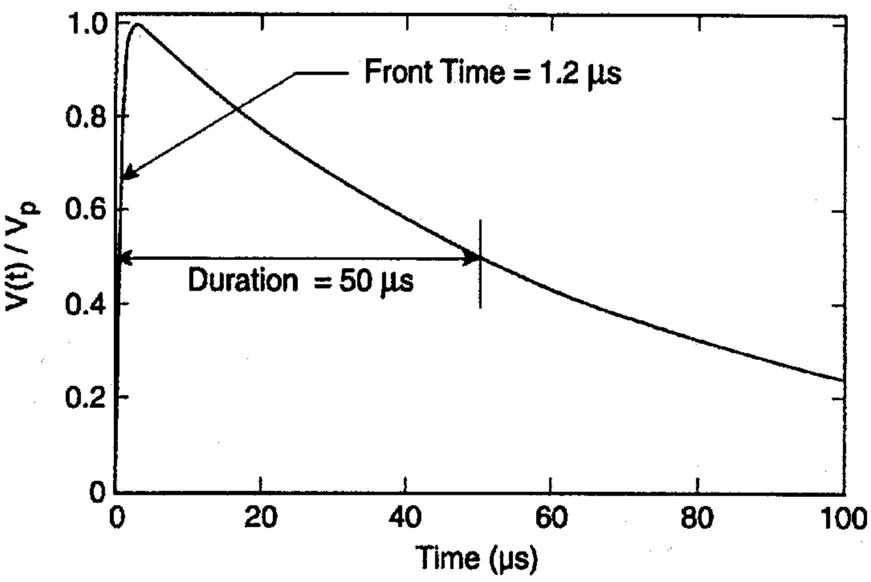


Figure 5—Combination Wave open-circuit voltage

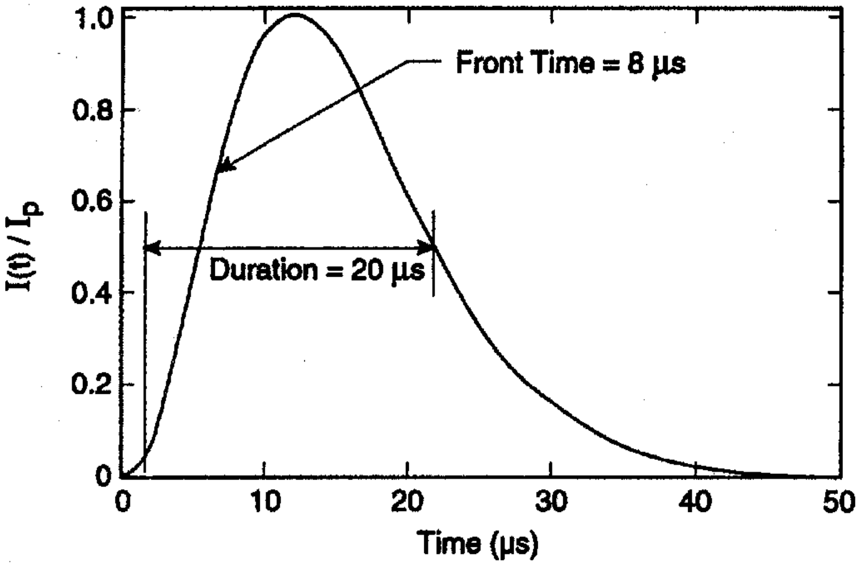


Figure 6—Combination Wave short-circuit current

6.2 Selection of peak values of standard waveforms

Table 2 through Table 5 include a matrix of location categories, types of surges, peak voltages, and peak currents provided as a guide toward the selection of an appropriate set of design parameters or tests. It is emphasized that these parameters in the matrix can only provide a menu. ***They are not intended to be mandatory requirements.***

Table 2—Standard 0.5 μs–100 kHz Ring Wave
Expected maximum voltage and current surges in Location Categories[a] A and B[b]
Single-phase modes[c]: L-N, L-G, and [L&N]-G
Polyphase modes: L-L, L-G, and [L's]-G
(See Table 5 for N-G mode)

Location Category[a]	Peak values[d]		Effective impedance (Ω)[e]
	Voltage (kV)	Current (kA)	
A	6	0.2	30
B	6	0.5	12

[a] See 4.5 for definition and discussion of location categories.

[b] A 100 kHz Ring Wave may be optional in Category C when front-of-wave response is a concern.

[c] See IEEE Std C62.45-2002 for discussion of coupling modes.

[d] The values shown for Location Categories A and B have been set by consensus to provide guidance and uniformity in test procedures and in SPD selection. Other levels may be negotiated between the parties involved, including the particulars of a situation where the transitions between categories can be specifically assessed.

[e] The effective impedance of the surge source (emulated by a test generator) is defined as the ratio of the peak voltage to the peak current. It has the dimension of a resistance, but it is not a pure resistance (see 6.3.1).

Table 3—Standard 1.2/50 μs–8/20 μs Combination Wave
Expected voltages and current surges in Location Categories[a] A and B[b]
Single-phase modes[c] : L-N, L-G, and [L&N]-G
Polyphase modes: L-L, L-N, L-G, and [L's]-G
(See Table 5 for N-G modes)

Location Category[a]	Peak values[d]		Effective impedance (Ω)[e]
	Voltage (kV)	Current (kA)	
A	6	0.5	12 [f]
B	6	3	2

[a] See 4.5 for definition and discussion of location categories.

[b] See Table 4 for Combination Wave application to a low exposure in Location Category C.

[c] See IEEE Std C62.45-2002 for discussion of coupling modes.

[d] The values shown for each location category have been set by consensus to provide guidance and uniformity in test procedures. Other levels may be negotiated between the parties involved, including the particulars of a situation where the transitions between categories can be specifically assessed.

[e] The effective impedance of the surge source (emulated by a test generator) is defined as the ratio of the peak voltage to the peak current. It has the dimension of a resistance, but is not a pure resistance (see 6.3.2).

[f] Nominally, a 12 Ω effective impedance. To allow using a surge generator with 2 Ω impedance, a 10 Ω non-inductive resistor may be added, recognizing that the waveform might be slightly changed.

Table 4—Scenario I tests for SPDs intended for Location Category C[a]

Exposure	Standard tests		Optional test
	1.2/50 µs Voltage generator	**8/20 µs Current generator**	**100 kHz Ring Wave for front-of-wave response evaluation**
	Minimum open-circuit voltage to be applied to SPD	**Current to be driven through the SPD[b]**	
Low	6 kV	3 kA[c]	6 kV
High	10 kV	10 kA	6 kV

[a]The scope of these tests is limited to SPDs, in contrast with all the other recommended tests that may be applied to equipment other than SPDs.

[b]Values shown for the current are applicable for each phase of the SPD. In contrast with a test applied to equipment for the purpose of assessing its response to the surge environment, a test applied to characterize the performance of an SPD requires that the specified current be driven through the SPD. For the low exposure, this can be accomplished with a typical Combination Wave generator. For the high exposure, two separate generators, in two successive tests, must be used to apply the specified values.

[c]For low exposure tests, if a Combination Wave generator is used instead of two separate generators, the generator charging voltage has to be adjusted to obtain the stated current amplitude.

Table 5—N-G mode
Standard representative waveforms and levels for maximum voltage and current surges inside buildings for N-G mode, depending on applicable neutral earthing or bonding practice[a, b, c]

Neutral grounding practice	Distance from service entrance or from surge source	System exposure[d]	Applicable surge			
			0.5 µs–100 kHz Ring Wave		**1.2/50 µs–8/20 µs Combination Wave**	
			Peak voltage (kV)	**Effective impedance[e]**	**Peak voltage (kV)**	**Effective impedance[e]**
Neutral grounded at service entrance	Close	All	None	None	None	None
	Nearby	All	*1*	*30*	None	None
	Far	All	*3*	*30*	None	None
Neutral not grounded at service entrance	All	Low	*2*	*12*	*2*	*2*
	All	Medium	*4*	*12*	*4*	*2*
	All	High	*6*	*12*	*6*	*2*

[a]The values for peak voltage and effective impedance have been set in italic type to emphasize that there is no available database to support these values. Instead, these numbers and waveforms have been selected by consensus to provide uniformity in test procedures. These values are not intended to be mandatory requirements.

[b]Bonding the neutral to the equipment grounding conductor (protective earth) and the building ground at the service entrance, or at a separately derived ac power source, effectively prevents the propagation of external surges in N-G mode. This situation, including that of a separately derived ac power source, corresponds to the requirement of the NEC [B32]. In such installations, N-G surges can still be generated by internal load switching or by mode conversion when surge currents flow in the inductance of the neutral or grounding conductors, or both. The 100 kHz Ring Wave is an appropriate representation of inductive voltages in the wiring.

[c]When the neutral is not bonded to the equipment grounding conductor (protective earth) nor to the building ground at the service entrance, N-G surges can be expected in a manner similar to those defined for the L-L, L-N, or L-G modes, as shown in Table 2 and Table 3. This more severe situation will be encountered in installations not subject to the NEC [B32]. It is standard practice in some countries.

[d]See 4.7 for discussion of system exposure levels.

[e]The effective impedance of the surge source (to be emulated by a test generator) is defined as the ratio of the peak voltage to the peak current. It has the dimension of a resistance, but is not a pure resistance.

The recommendations of the present document address the need to make a deliberate choice, but leave the choice to the parties interested in the issues, who are presumed to have the best available knowledge of the particular situation. Because the system exposure levels may be different with respect to the source of the surges and hence the waveform, separate tables are provided for the Ring Wave and for the Combination Wave. For instance, an installation may be located in an area of high lightning activity, but little switching activity (giving more weight to the Combination Wave), or vice versa.

Making such a choice, however, might be difficult. On the one hand, the nature and mission of the equipment have a strong influence on the choice. Some equipment are likely to be operated in a well-defined environment exposure and location category; others may be operated in a broad variety of exposures and location categories. Furthermore, the consequence of a failure and thus the selection of a degree of margin, are related to the mission of the equipment. On the other hand, when dealing with mass-produced equipment, it would be impractical or unrealistic to tailor the surge withstand specifications of the equipment to a specific environment exposure and location category. In such cases, a selection must be made to cover the typical situation, not the extreme—unless life-support or similar stringent requirements would mandate a very conservative design.

6.3 Detailed specifications of waveforms

6.3.1 The 0.5 μs–100 kHz Ring Wave

A plot of the nominal 100 kHz Ring Wave has been shown in Figure 4.

The open-circuit voltage waveform is defined by the following parameters:

— Rise time:	0.5 μs
— Ringing frequency:	100 kHz

Greater details on applicable tolerances on the detail parameters are given in IEEE Std C62.45-2002.

The amplitude will decay so that the ratio of adjacent peaks of opposite polarity is as follows:

- The ratio of the second peak to the first peak is between 40% and 90%.
- The ratio of the third peak to the second peak and the ratio of the fourth peak to the third peak are between 40% and 80%. There is no requirement set on the amplitude of the Ring Wave beyond the fourth peak. The amplitudes of the fifth and following peaks are so much smaller than the initial peak that they should have little effect on even the most vulnerable or susceptible equipment.
- The rise time is defined as the time difference between the 10% and 90% amplitude points on the leading edge of the waveform. The frequency is calculated from the first and third zero-crossing after the initial peak.
- The nominal amplitude of the first peak of either the open-circuit voltage, V_p, or the short-circuit current, I_p, is to be selected by the parties involved, according to the severity desired.
- The ratio V_p/I_p is specified as 12 Ω for simulation of Location Category B environments or 30 Ω for simulation of Location Category A environments. When the peak open-circuit voltage is adjusted to be exactly 6 kV, the nominal peak short-circuit current will be 500 A for Location Category B environments and 200 A for Location Category A environments. For lower peak voltages, the peak short-circuit current will be proportionately lower, so that the nominal ratio V_p/I_p remains either 12 Ω or 30 Ω
- No short-circuit current waveform is specified for the 100 kHz Ring Wave. A peak short-circuit current, however, is proposed in Table 2, according to the location category. Because the purpose of this Ring Wave is not to provide high-energy stress to the EUT, the precise specification of the current waveform is unnecessary.

The short 0.5 µs rise time of the leading edge of the waveform, together with a large peak current, corresponds to a large value of $\mathrm{d}i/\mathrm{d}t$, which will produce significant inductive effects in the connections of the devices under test. The voltage divider action of the surge generator impedance and the EUT impedance is likely to be significant; it is addressed by specifying the peak short-circuit current.

The 1980 edition of this document (IEEE Std 587) specified a nominal rate of decay of amplitude of 60% between adjacent peaks of opposite polarity, but no tolerances were specified. When tolerances were added, large tolerances were applied to the ratio of the first and second peaks so that a cosine waveform with an exponentially decaying amplitude would meet the requirements for the Ring Wave. Although existing generators are acceptable, it is recommended that new designs for 100 kHz Ring Wave generators use the damped cosine waveform defined by the equations given in IEEE Std C62.45-2002.

The frequency of oscillation of this waveform may excite resonances in the EUT. However, this effect cannot be positively identified with the fixed-frequency Ring Wave; a swept-frequency test would be necessary for that purpose.

6.3.2 The 1.2/50 µs–8/20 µs Combination Wave

The Combination Wave is delivered by a generator that can apply a 1.2/50 µs voltage wave across an open circuit and an 8/20 µs current wave into a short circuit. The exact waveform that is delivered is determined by the generator and the impedance of the EUT and its connections to which the surge is applied. A plot of the nominal open-circuit voltage has been shown in Figure 5, and a plot of the nominal short-circuit current has been shown in Figure 6.

6.3.2.1 Open-circuit voltage waveform

— Front time:	1.2 µs
— Duration:	50 µs

The front time for voltage waveforms is defined (IEC 60060-2:1994 [B12]; IEEE Std 4™-1995 [B21]) as

$$1.67 \times (t_{90} - t_{30})$$

where

t_{90} and t_{30} are the times of the 90% and 30% amplitudes on the leading edge of the waveform.

The duration is defined as the time between virtual origin and the 50% amplitude point on the tail.

The virtual origin is the point where a straight line between the 30% and 90% points on the leading edge of the waveform intersects the $V = 0$ line.

6.3.2.2 Short-circuit current waveform

— Front time:	8 µs
— Duration:	20 µs

The front time for current waveforms is defined (IEC 60060-2:1994 [B12]; IEEE Std 4-1995 [B21]) as

$$1.25 \times (t_{90} - t_{10})$$

where

t_{90} and t_{10} are the times of the 90% and 10% points on the leading edge of the waveform.

Duration is defined as the time between virtual origin and the time of the 50% amplitude point on the tail. The virtual origin is the time that a straight line between the 10% and 90% amplitude points on the leading edge of the waveform intersects the $I = 0$ line.

The value of either the peak open-circuit voltage, V_p, or the peak short-circuit current, I_p, is to be selected by the parties involved, according to the severity desired.

From the peak values of voltage and current specified for the Combination Wave, the effective source impedance, the ratio V_p/I_p, is therefore 2.0 Ω This ratio determines the behavior of the waveform when various loads, such as SPDs, are connected to the generator.

Traditionally, the 1.2/50 µs voltage waveform was used for testing the basic impulse level (BIL) of insulation, which is approximately an open circuit until the insulation fails. The 8/20 µs current waveform was used to inject large currents into SPDs. Because both the open-circuit voltage and short-circuit current are different aspects of the same phenomenon, such as an overstress caused by lightning, it is necessary to combine them into a single waveform when the load is not known in advance or could change during the surge (Richman 1983 [B35]; Wiesinger 1983 [B40]). When the generic load characteristics are known (for instance, an SPD), separate generators may be used for the voltage test and the current test.

7. Definition of additional surge-testing waveforms

The two additional waveforms for Scenario I are the EFT Burst and the unidirectional 10/1000 µs Long Wave. For Scenario II (direct lightning flash), a special test, defined as Class I in IEC 61643-1:1998 [B17] is proposed in Informative Annex A for evaluation of candidate SPDs involved in the exit path. Each of these waveforms has a unique domain of application (contactor interference, fuse operation, capacitor switching, and direct lightning flash). Consequently, the waveform definition and the amplitude selection are discussed separately for each waveform in 7.1 through 7.4. Detailed test procedures are discussed in IEEE Std C62.45-2002. Plots of the nominal waveforms are shown in Figure 7 through Figure 9. The suggested peak voltages or currents, and source impedances that correspond to various environmental exposures are shown in Table 6 and Table 7.

7.1 The EFT Burst

The EFT Burst waveform consists of repetitive bursts, with each burst containing individual unidirectional pulses. This waveform was at first proposed in the IEC as a method for evaluating the immunity of equipment against interference; it is not a “representation” of the surge environment. The amplitude levels proposed for the various degrees of severity have been set by consensus as representing a realistic stress for the typical ***equipment*** exposed to the test. It is important to note that they should not be construed as actual voltage levels occurring in the mains. Consequently, they should not be considered as a stress test for ***components.***

The characteristics of this waveform are summarized in 7.1.1 and 7.1.2. They are based on the specifications of IEC 61000-4-4:1995 [B14] (see EFT Burst test in IEEE Std C62.45-2002 for details). However, readers are cautioned that IEC documents are subject to periodic revision. Therefore, any detailed plan for specific tests calling explicitly for the EFT “per IEC procedures” should be based on the current version of the IEC document, not on the description provided in this recommended practice or in IEEE Std C62.45-2002.

7.1.1 Waveform definition

The individual EFT pulses in a burst are defined as

— Rise time:	5 ns
— Duration:	50 ns

The rise time is defined as the time difference between the 10% and 90% amplitude points on the leading edge of the waveform.

The duration is defined as the full width at half maximum (FWHM), that is, the time difference between the 50% amplitude points on the leading and trailing edge of each individual pulse.

Individual pulses occur in bursts with a duration of 15 ms. Within each burst, the repetition rate of pulses is specified as a function of the peak open-circuit voltage:

— For peaks ≤ 2 kV:	5 kHz
— For peaks > 2 kV:	2.5 kHz

(These two values of the repetition rate are specified in IEC 61000-4-4:1995 [B14] and reflect only limitations in inherent performance of pulse generators, not characteristics of the environment.)

The period of the repeated bursts is 300 ms. A plot of a single pulse is shown in Figure 7, and the burst pattern is shown in Figure 8.

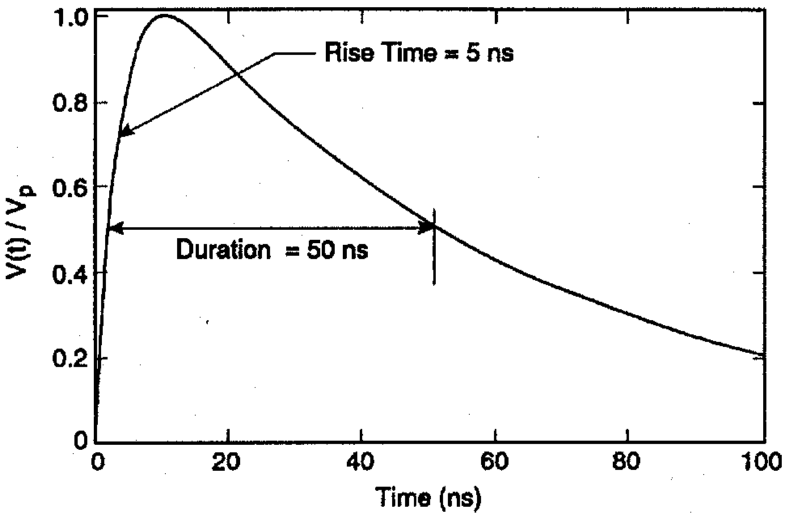


Figure 7—Waveform of the EFT pulse

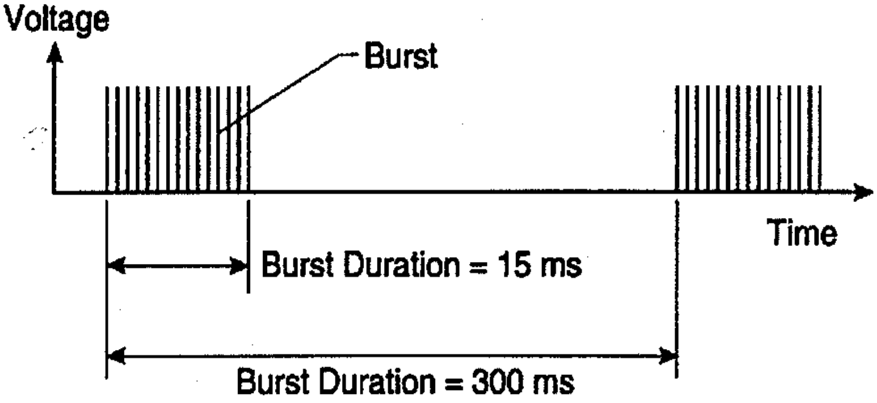


Figure 8—Pattern of EFT bursts

7.1.2 Amplitude

The amplitude of the EFT pulses is specified by IEC 61000-4-4:1995 [B14] as an open-circuit test voltage, while the waveform is defined when the generator is connected to a 50 Ω load. The generator is also defined as having a 50 Ω source impedance between 1 MHz and 100 MHz.

The resulting current, when the pulses are applied to the EUT, is not defined since it will depend on the impedance exhibited by the EUT at the frequencies associated with the EFT waveform. Because the purpose of the test is to evaluate interference immunity, not energy capability, the specification of a current amplitude is not essential. Given this definition of the test level, the specific value should be selected by the parties involved, according to the severity desired.

In IEC 61000-4-4:1995 [B14], five test-severity levels are specified, from 0.5 kV to 4 kV open circuit, with provision of an additional, special level open to negotiations. In keeping with the simplification approach taken in the present recommended practice, only three levels are shown in Table 6. Because the additional waveforms described in the present document are only suggestions, there is always the implicit provision that other levels may be negotiated, as indicated by the fourth row “X” in Table 6.

Table 6—Levels for EFT burst

Test severity	Peak voltage (Open circuit)
Low	1 kV
Medium	2 kV
High	3 kV
X	By agreement

7.2 The 10/1000 µs Long Wave

7.2.1 Waveform definition

The front time and duration are the following:

- ***Open-circuit voltage***
  - Front time: 10 µs
  - Duration: 1000 µs
- ***Short-circuit current***
  - Front time: 10 µs
  - Duration: 1000 µs

Some ambiguity exists in the definitions of this waveform given in other references, depending on the interpretation of the 10 µs "front" specification (Standler 1988 [B39]). Because the major purpose of this waveform, in the present context, is to provide an energy stress, the difference between the rise time, time to peak, or front time is negligible in comparison with the 1000 µs duration. A plot of the nominal current is shown in Figure 9.

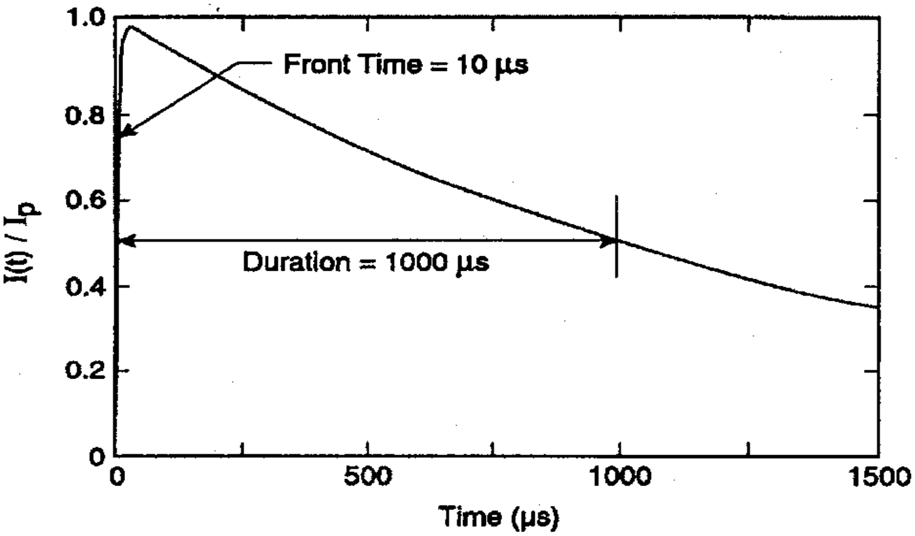


Figure 9—Waveform for the 10/1000 µs current surge

7.2.2 Amplitude

There is a major difference in the application of this waveform compared to that of the two standard waveforms: the concept of location categories that has been applied for the standard waveforms is not applicable here. (That concept is based on the limiting effect of the inductance of branch circuits at the frequencies associated with the two standard pulses, presumed to have a decreasing severity as distance from the service entrance increases.)

The long duration of the 10/1000 µs waveform reduces the overall effect of the wiring inductance. However, depending on the environment exposure of the site, there is still a range of levels to be considered. Therefore, the values shown in Table 7 for the three system-exposure levels are applicable to all location categories.

The amplitude of the peak open-circuit voltage is to be selected by the parties involved according to the severity desired. The corresponding ratios of the peak open-circuit voltage to the peak short-circuit current, V_p/I_p, are shown in Table 7.

Table 7—Levels for the additional 10/1000 µs Long Wave

Exposure	Surge voltage peak [a]	Source impedance [b c d]
Low (residential)	None	
Medium (commercial)	1.0 U_{pk}	1.0 Ω
High (industrial)	1.3 U_{pk}	0.25 Ω

[a] The surge voltage peak is proportional to the system peak voltage, U_{pk}. The values shown in this column are those of the surges alone, to be added to whatever the value of the mains voltage is for the phase angle at which the surge would occur in an actual environment. (See the note [d] concerning powered versus unpowered test.) For instance, the peak total voltage applied to a piece of equipment at the end of a long line, upon clearing of a fault by a fuse and occurring near the peak of the power-frequency sine wave, would be for a 120 V rms L-N system and for a high exposure level

$$\begin{aligned} V_{total} &= 170\text{ V (the sine wave)} + 1.3 \times 170\text{ V (the surge alone)} \\ &= 390\text{ V} \end{aligned}$$

[b] The database does not provide sufficient information to set an impedance value. The values shown in this table have been set by consensus as a reasonable value to provide guidance and uniformity in test procedures and in the selection of a suitable SPD rating.

[c] The effective impedance of the surge source, to be emulated by a test generator, is defined as the ratio of the peak voltage to the peak current. It has the dimension of a resistance, but is not a pure resistance.

[d] The prime purpose of a test conducted with the 10/1000 µs Long Wave is to evaluate the performance of equipment subjected to this surge with a high energy-delivery capability. Thus, it is a ***component*** rather than ***total equipment*** test, and it may be acceptable to perform it as an unpowered test. Such acceptance will make it possible to deliver the surge from a conventional surge generator alone, without the ac power supply and back filter involved in performing powered tests. The long duration of the surge would make the design and construction of a back filter difficult. However, for cases where a powered test would be required, a waveform signal generator and high-power linear amplifier could deliver both the ac power and the superimposed Long Wave, in an arrangement similar to that necessary for performing specific capacitor-switching ring waves.

7.3 The capacitor-switching ring wave

As discussed in IEEE Std C62.41.1-2002, the occurrence of capacitor-switching surges is due to the presence of switched capacitor banks on the distribution system (generally installed on the medium-voltage side), with possible magnification if power-factor correction capacitors are also present on the low-voltage network of the user—an industrial situation rather than a residential or commercial installation. Because this situation reflects specific cases, it is difficult and could be misleading to specify across-the-board waveforms, although there is consensus on the range of frequencies (a few hundred hertz to a few kilohertz).

The levels of these surges, in the absence of magnification, are generally limited to slightly less than 2 p.u. of the system voltage. While such an overvoltage can have impact on the operation and perhaps survival of power-conversion equipment, it is generally less significant for SPDs that do not attempt to provide very low limiting voltages. Some power-conversion equipment might draw excessive current during the overvoltage, tripping the overcurrent device(s). If the system configuration makes it possible that voltage magnification could occur, then there might be implications for the ability of an SPD to mitigate such surges or to survive in case of large banks being switched.

Consequently, it is difficult to recommend specific source impedances for representative capacitor-switching surges. Rather, an assessment of the likelihood of such surges should be made for each specific case or at least for each type of specific case, a task which is beyond the scope of a generic environment description.

Tests conducted to evaluate the energy-handling capability of a candidate SPD or the disturbance-free operation of a power-conversion equipment may be conducted in a laboratory either by switching an actual capacitor bank or by generating an arbitrary waveform consisting of the power frequency voltage plus the switching surge. In the first approach, some meaningful results might be obtained, albeit limited to the particular configuration of the laboratory and, therefore, difficult to replicate. With the use of a waveform generator and power amplifier, replication is possible over a wide range of stress levels.

7.4 Scenario II parameters

As stated in 4.6, the basis of the lightning current parameters quoted in the IEC publications on lightning protection are derived from the CIGRE study committee reports and other papers, which are cited in the database and the bibliography of IEEE Std C62.41.1-2002. For a directly coupled lightning surge, the greatest concern is for the first stroke, due to its large peak current, charge transfer, and specific energy. For an inductively coupled surge, the greatest concern is associated with rate of rise and mutual inductance between the conductors carrying the lightning current (intended down-conductors as well as opportunistic unintended conductors) and the circuit of interest. This difference of behavior and concerns leads to two different sets of parameters, defined in 7.4.1 and 7.4.2.

7.4.1 The Scenario II directly coupled lightning surge

Because the prime concern for a directly coupled surge is energy-handling capability of SPDs involved in the exit path of the lightning current via the power supply connection, IEC 61643-1:1998 [B17] defines a "Class I test" that may be applied to evaluate the energy-handling capability of such SPDs. Details and background information on this Class I Test are provided in Informative Annex A.

7.4.2 The Scenario II inductively coupled lightning surge

For an inductively coupled lightning surge, the greatest concern is with subsequent strokes, due to their high rate of rise (d*i*/d*t*), particularly for their effect in inducing transient overvoltages in nearby circuits. Earlier direct measurements of natural lightning flashes had limited capability, but triggered lightning research has confirmed the steepness of subsequent strokes (Rakov and Uman 1994 [B33]; Fernandez et al. 1998 [B8]; Mata et al. 2000 [B31]; Rakov et al. 2001 [B34]). A 0.25 µs front time has been proposed as representative by IEC 61312-3:2000 [B16]. The first part of the induced voltage would then occur with a peak at some point during the front time (maximum d*i*/d*t*). This part of the wave is of primary importance for simulation studies (see A.2.2.3 of IEEE Std C62.41.1-2002). The decay portion is of minor importance due to its lower rate of change. When considering the combined effects of damping and of the natural frequency of the oscillations for the circuits in which the voltage are induced by the initial fast stimulus, the standard 100 kHz Ring Wave may be used as a practical representation of these inductive effects, as indicated in Table 1 (in 5.3).

8. Concluding remarks

The test waveforms presented in this recommended practice have been selected from the database on surge occurrences to assist designers, manufacturers, and users of equipment connected to low-voltage ac power circuits in defining surge withstand capability for the equipment. ***Once again, it is imperative to note that these descriptions of the environment and test waveform recommendations should be used as the basis for a realistic and successful application, including an appropriate risk analysis, and not as a blind procurement specification.***

The "Scenario I" defined in this recommended practice—the case of surges impinging at the power service entrance or generated within the building—has been confirmed by the successful experience of 20 years since the initial document (IEEE Std 587-1980) was released as a guide and amended as a recommended practice in 1991. This scenario includes two standard waveforms (100 kHz Ring Wave and Combination Wave) applicable for three location categories and two additional waveforms (EFT Burst and 10/1000 µs Long Wave).

A new "Scenario II" has been added to take into consideration the rare but possible special case of a direct lightning flash to the building of interest. When such a building has been provided with a properly designed lightning protection system or if opportunistic down-conductors carry the lightning current to the earthing system of the building, the topology of the earthing electrodes and utility services results in a dispersion of the earth-seeking lightning current that can impose substantial stresses on SPDs involved in the exit path of the lightning current via the power supply connection.

The controlled flow of lightning current in the lightning protection system can also induce significant transient voltages in circuit loops within the building. The case of a building with no lightning protection system, or of a flash to unintended but de facto air terminals of a building, is more difficult to characterize (Martzloff 2000 [B29]), but can be expected to produce damaging insulation breakdowns along the uncontrolled lightning current paths, as well as inducing significant transient voltages in circuit loops within the building. A flash to earth very close to the building can also result in the injection of a portion of the lightning current into the earthing system of the building, with subsequent dispersion of that current in a manner similar to a direct injection of the total current into the lightning protection system (the Scenario II proper), but with an amplitude reduced by the insertion of the path in the soil between the point of strike and the earthing system of the building. It is not possible to quantify "very close" because the reduction effect attributable to the insertion of the (short) path depends on local conditions of the earth conductivity and of the configuration of the earthing electrodes.

The energy-related and mechanical stresses on exit-path SPDs associated with Scenario II represent a significant increase compared to those of Scenario I. However, successful field experience based on the standard waveforms defined for Scenario I has confirmed the validity of these recommended Scenario I waveforms (Goedde et al. 2000 [B10]). An appropriate scaling factor may be used to apply a somewhat equivalent stress with the standard 8/20 µs or 4/10 µs current tests (Rousseau and Quentin 1996 [B38]; Rousseau 1989 [B36]).

When concerns arise on the possible occurrence of a Scenario II, an appropriate risk analysis should be conducted before considering the provision of SPDs designed for that scenario. The following parameters should be taken into consideration, including but not limited to, local flash density, building characteristics and exposure, statistics of the lightning current amplitudes and rates of current change, mission of the installation, consequences of a service interruption caused by failure of an SPD, and possible damage to other equipment.

Induction of transient voltages in circuits within the building by distant, nearby, or direct lightning flashes is an unavoidable effect that should be dealt with regardless of the energy considerations associated with the selection of service-entrance SPDs. For practical purposes, this effect may be represented by the 100 kHz Ring Wave, as was suggested in Table 1 (in 5.3).

Annex A

(informative)

Scenario II parameters

A.1 Background on the Scenario II

As explained in IEEE C62.41.1-2002 and in 4.6 and 7.4 of the present recommended practice, the possible event—rare as it might be—of a direct strike to the building of interest is the basis of the Scenario II. In contrast, Scenario I represents the event of surges impinging onto the building by way of the incoming power service connection. The database of IEEE Std C62.41.1-2002 contains convincing and long-standing evidence on the nature and severity of Scenario I events, but Scenario II is at this stage less thoroughly documented and the consensus somewhat limited. For that reason, this informative annex offers background information and details on the consensus-building process.

Essentially, the nature of Scenario II is based on well-documented and well-accepted data on the parameters of the lightning flash itself. However, the resulting surge currents carried by the building conductors (intended or opportunistic) and any SPDs installed in the building rest on ***postulates*** about the dispersion of the flash current. This dispersion process is controlled by the paths that are available to feed the current into many earthing (grounding) electrodes. These electrodes include both those local to the building (intended made electrodes as well as opportunistic electrodes) and distant electrodes accessible by way of the power service connection. Therefore, the difference between Scenario I and Scenario II is worth repeating here, and is essential for understanding the resulting stresses on SPDs. In Scenario I, the SPD stress (threat) is associated with surges that ***impinge upon the building*** via the service connection or are generated within the building. In Scenario II, the stress (threat) is associated with the portions of the lightning current that ***exit the building*** via the service connection.

Two IEC documents were developed in the 1990s to describe the events associated with a direct lightning flash. In the first document developed by Technical Committee 81 on Lightning Protection, IEC 61312-1:1995 [B15], the idealized concept of lightning protection zones (LPZs) is proposed (see Figure A.1). This figure conveys the interpretation that the threat is external to the structure and that protection is achieved by recognizing nested zones with appropriate interface devices (for instance, SPDs) at the boundaries separating the zones. Among several penetrations shown in the figure from the **LPZ 0_A** into the **LPZ 0_B**, one of them—identified as the **power cable**—is similar to the representation of Scenario I in the present Trilogy. The concept is further described by three tables listing the lightning current parameters for the first stroke, for the subsequent stroke, and for the long-duration stroke. Figure A.2 is a reproduction of the table giving the parameters of the first stroke as it appears in IEC 61312-1:1995 [B15].

The second document was developed by a joint working group of Technical Committee 64 on Electrical Installations, IEC 62066:2002 [B18]. That document contains a description, with numerical examples, of the dispersion of the lightning current, in particular the concept of a current that exits the building via the power service connection. Some parts of that document have been included in the database of IEEE Std C62.41.1-2002. The examples given in IEC 62066:2002, as well as the general principles of dispersion, rest on ***postulates*** concerning the impedance (inductance and resistance) of the available earthing electrodes and their connections. If the parameters of the first stroke, as defined in IEC 61312-1:1995 [B15] (Figure A.2) are accepted, then reasonable postulates on the dispersion will yield information on what stresses might be applied to the SPDs involved in the exit paths.

Current research on the dispersion of the current produced by triggered lightning experiments yields information on subsequent strokes for site-specific conditions, in particular the actual values of the earthing resistances (Fernandez et al. 1998 [B7]; Bejleri et al. 2000 [B4]). Such experimental data are extremely valuable to support the postulates made for numerical simulations, but still provide only site-limited examples.

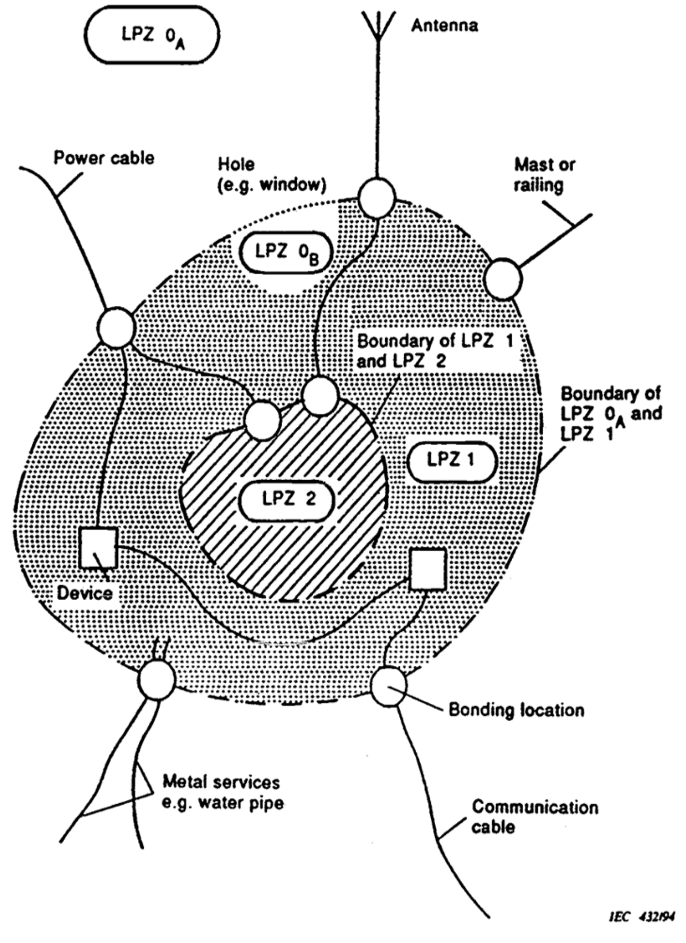


Figure 3 – Principle of the division of a volume to be protected into different lightning protection zones (LPZ)

Source: IEC 61312-1:1995 [B15]

Figure A.1—Principle of LPZs from IEC standard on lightning protection

A.2 Resulting stresses on exit-path SPDs

The process of assimilating the information on lightning current occurrence and dispersion led to two IEC documents in which the titles contain the words "requirement for SPDs."

By chronological order of publication, the first document is IEC 61643-1:1998 [B17], Surge protective devices connected to low-voltage power distribution systems—Part 1: Performance requirements and testing methods. In recognition of the high stresses that might be imposed on some SPDs (but with no specific reference to the location where such SPDs might be installed, a topic that is discussed in other IEC documents on SPD application), the IEC document lists several stress levels according to an "impulse test classification." Figure A.3, reproduced from that document, lists the parameters for Class I tests, which impose the highest stress level in the set of standard tests listed in the document.

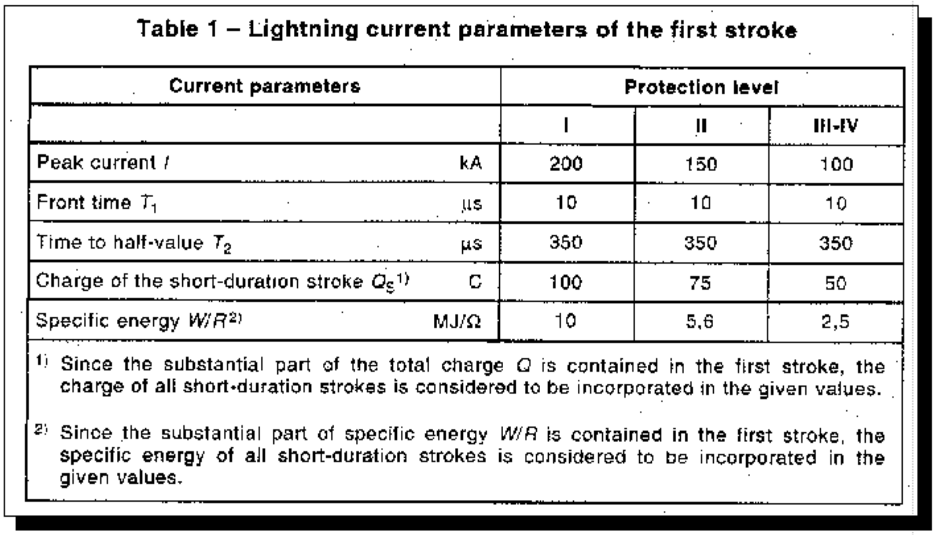


Table 1 – Lightning current parameters of the first stroke

Current parameters		Protection level		
		I	II	III-IV
Peak current I	kA	200	150	100
Front time T_1	µs	10	10	10
Time to half-value T_2	µs	350	350	350
Charge of the short-duration stroke Q_S 1)	C	100	75	50
Specific energy W/R 2)	MJ/Ω	10	5,6	2,5

1) Since the substantial part of the total charge Q is contained in the first stroke, the charge of all short-duration strokes is considered to be incorporated in the given values.

2) Since the substantial part of specific energy W/R is contained in the first stroke, the specific energy of all short-duration strokes is considered to be incorporated in the given values.

Source: IEC 61312-1:1995 [B15] and IEC 61312-3:2000 [B16]

Figure A.2—Parameters of the first stroke defined in IEC 61312 documents

It is noteworthy that neither this table nor the associated text make reference to a waveform, but only to the parameters of peak current, total charge transfer, and maximum time for the transfer (10 ms). A specified rate of energy deposition into the SPD, which Bartkowiak et al. 1999 [B3] report as being significant, is not included either.[6]

The second document is IEC Technical Specification[7] IEC 61312-3:2000 [B16], Protection against lightning electromagnetic impulse—Part 3: Requirements of surge protective devices (SPDs). From the title, it is not clear whether the purpose of the document is to show evidence that a need exists to provide SPDs ("of SPDs") or to define the performance requirements that these SPDs should meet ("for SPDs"). After showing the same table of the first stroke parameters (as in Figure A.2), the document provides a wealth of information on the application of SPDs (35 pages), including several examples of computations for the dispersion of the lightning current among the available earthing electrodes.

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[6] In the parallel European Standard EN 61643-1, an additional stipulation states that the impulse current shall reach ("obtain" in European English) its peak within 50 µs.

[7] The IEC/ISO Directives describe a "Technical Specification" as a document which has not reached the recognition or status of a (normative) standard: *"... It is proposed for provisional application so that information and experience of its use in practice may be gathered...."*

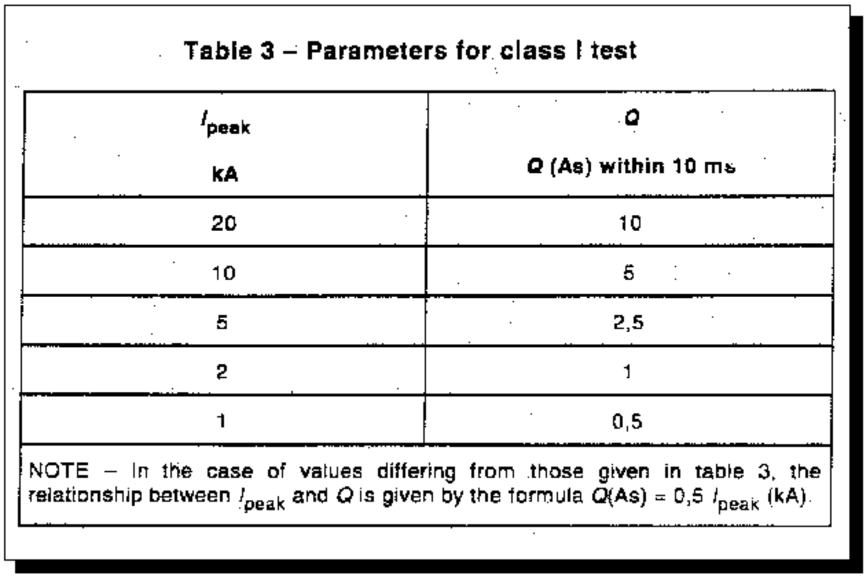


Table 3 – Parameters for class I test

I_{peak} kA	Q Q (As) within 10 ms
20	10
10	5
5	2,5
2	1
1	0,5

NOTE – In the case of values differing from those given in table 3, the relationship between I_{peak} and Q is given by the formula Q(As) = 0,5 I_{peak} (kA).

Source: IEC 61643-1:1998 [B17]

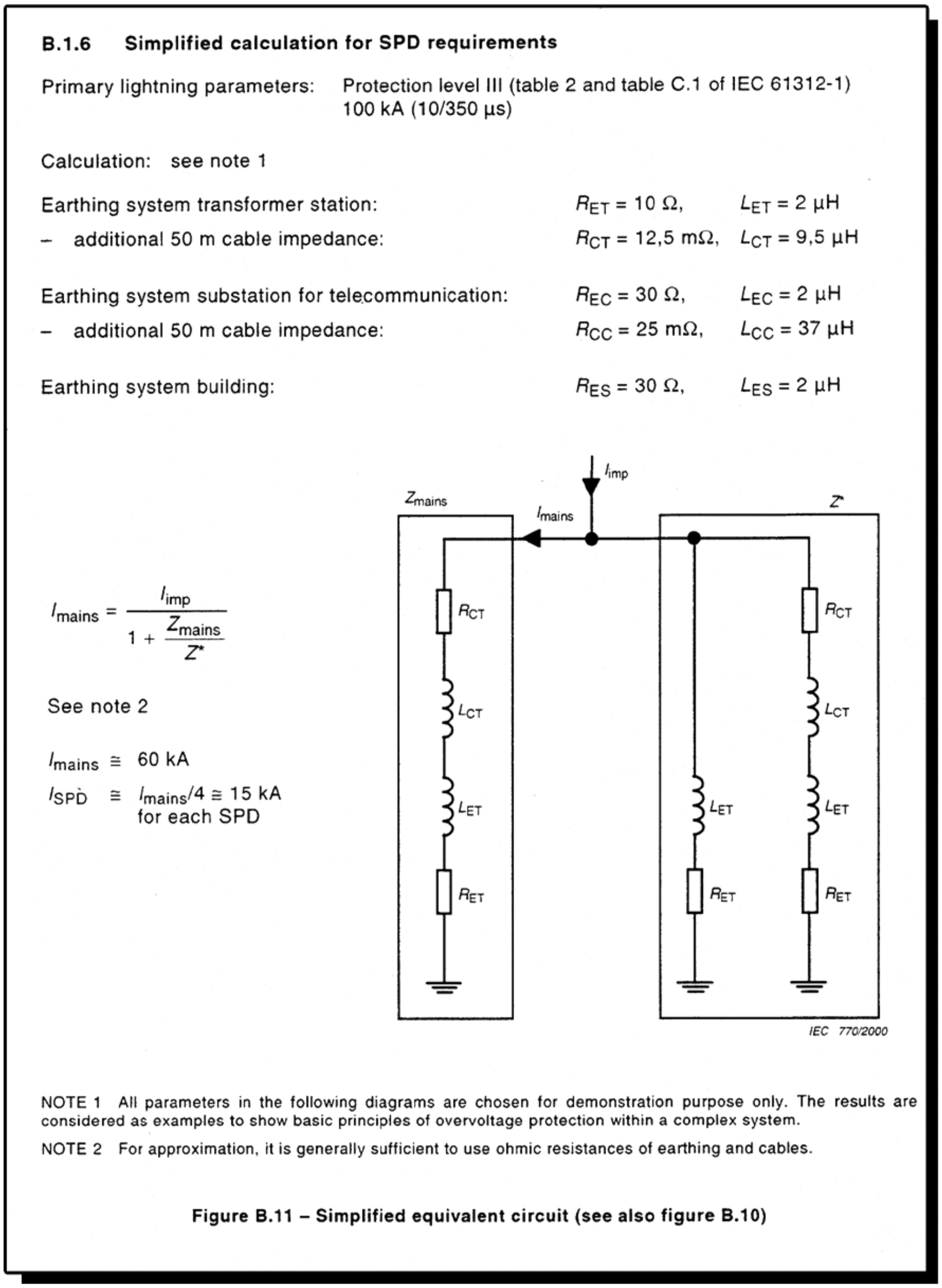
Figure A.3—Parameters for Class I test according to IEC 61643-1

These examples are based on postulates on the impedance of the multiple paths but they are postulates, not recorded natural occurrences. For instance, Figure A.4, excerpted from IEC 61312-3:2000 [B16], is based on a system with no multiple-grounded neutral, and each of the four conductors (three phases and the neutral) bonded to local earth by an SPD. In contrast, the multiple-grounded neutral conductor, typical of North American systems, will carry a large share of the lightning current that is dispersed via the power supply connection, not one-fourth as shown in the IEC example, thereby reducing the stress on the line-to-ground SPDs.

Thus, the case for “high-energy” surge requirements rests on a consensus based on limited data, a matter of some concern when comparing these “requirements” with the field performance of SPDs designed on the basis of the standards of the IEEE C62 family, as discussed next.

A.3 Proposed IEC requirements versus field experience

Accepting the “requirements” defined in the IEC documents cited in this informative annex raises the issue of a possible contradiction between, on the one hand, the successful field experience in North America of SPDs designed in accordance with the parameters identified in the C62 series of IEEE standards, such as IEEE Std C62.11™-1999 [B20] and applied in power systems with multiple-grounded neutral (Rousseau 1989 [B36]; Rousseau and Gumley 1999 [B37]) or on medium-voltage distribution systems (Maciela 1995 [B22]; Goedde et al. 2000 [B10]) and, on the other hand, the higher stresses implied by the proposed IEC requirements. Both families of documents rest on consensus documented by the voting process. IEC documents are voted on by the participating national committees (“P-Members”) on the basis of one country, one vote. IEEE documents are voted on by balloting committees formed of volunteer/designated experts with appropriate balance among manufacturers, users, and general interest. In each case, these organizations have well-defined rules on what percentage of the votes (rarely achieving 100%) makes the document an approved publication. To provide a sense of how pervasive or how limited the consensus was for these various documents, Table A.1 shows the official statistics of the voting results.



B.1.6 Simplified calculation for SPD requirements

Primary lightning parameters: Protection level III (table 2 and table C.1 of IEC 61312-1)
100 kA (10/350 µs)

Calculation: see note 1

Earthing system transformer station:	$R_{ET} = 10\ \Omega$,	$L_{ET} = 2\ \mu H$
– additional 50 m cable impedance:	$R_{CT} = 12{,}5\ m\Omega$,	$L_{CT} = 9{,}5\ \mu H$
Earthing system substation for telecommunication:	$R_{EC} = 30\ \Omega$,	$L_{EC} = 2\ \mu H$
– additional 50 m cable impedance:	$R_{CC} = 25\ m\Omega$,	$L_{CC} = 37\ \mu H$
Earthing system building:	$R_{ES} = 30\ \Omega$,	$L_{ES} = 2\ \mu H$

$$I_{mains} = \frac{I_{imp}}{1 + \frac{Z_{mains}}{Z^*}}$$

See note 2

$I_{mains} \cong 60$ kA

$I_{SPD} \cong I_{mains}/4 \cong 15$ kA for each SPD

NOTE 1 All parameters in the following diagrams are chosen for demonstration purpose only. The results are considered as examples to show basic principles of overvoltage protection within a complex system.

NOTE 2 For approximation, it is generally sufficient to use ohmic resistances of earthing and cables.

Figure B.11 – Simplified equivalent circuit (see also figure B.10)

Source: IEC 61312-3:2000 [B16]

Figure A.4—IEC example of dispersion with neutral earthed only at the distribution transformer

Table A.1—Consensus-building results on IEC and IEEE documents

Document	IEC			IEEE		
	P-members voting	Required percentage for approval	Percentage of approval achieved	Votes cast	Required percentage for approval	Percentage of approval achieved
C62.1 (Reaff 1994)				38	> 75	84
C62.34-1996				27	> 75	82
C62.11-1999				55	> 75	92
61312-1:1995	18	> 67	78			
61643-1:1998	15	> 67	80			
61312-3:2000	19	> 50	68			
62066:2002	26	> 50	92			

Source: IEEE Standards Office and IEC Central Office

A.4 Reconciliation and harmonization

A narrow and overly conservative interpretation of the parameters identified in the IEC documents could lead to counterproductive and not cost-effective application of SPDs involved in the exit path of Scenario II events. Several factors need to be considered to develop a proposal for additional parameters, consistent with the approach taken for the other waveforms included in this recommended practice. These factors include, but are not limited to, the following:

- Probability distribution of peak amplitudes of the first stroke (including negative as well as positive strokes)
- Flash density to be used for the particular locale when making a risk analysis
- Other specific factors included in the risk analysis method (More than one method have been proposed.)
- Range of relative impedances (mostly resistance) of available earthing electrodes, in particular the beneficial effect of multiple ground electrodes on the neutral of the power distribution system
- Consequences of overstressing an SPD in the exit path
- Validity of the concept that the total charge transfer is the single parameter[8]

A.5 Proposed informative alternate waveforms and values

For all the reasons and limitations enumerated in this informative annex, it is difficult, and might be misleading, to propose a unique waveform and a set of values to represent Scenario II events. Instead, Table A-2 has been developed through the consensus process for case-by-case application. The table shows several stress levels that might be considered as applicable to a particular situation, with the additional flexibility of a negotiable level for those applications where the parties would have mutual acceptance of different conditions. One such flexibility is to use an empirical “equivalency scaling factor” relating the stress imposed by a 10/350 µs waveform of a stated peak value to the corresponding stress imposed by an 8/20 µs waveform—with simply a higher peak value. Thus, SPDs intended (or unintended but still involved) for exit

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[8] See Bartkowiak et al. [B3] on the effect of rate of energy/charge deposition.

path application cannot receive a blanket performance requirement with pass/fail criteria. Rather, all the factors enumerated above need be taken into consideration.

Because the prime concern here is energy-handling capability of SPDs involved in exit paths, a 10/350 µs waveform has been proposed as one way to represent the three parameters of the first stroke: peak current, charge transfer, and specific energy according to Table 1 of IEC 61312-1:1995 [B15]. This waveform is intended to represent the imparted energy as well as the electrical and mechanical stresses imposed on SPDs involved in the exit path. Note that this waveform is not intended to represent the entire lightning flash. Subsequent strokes exhibit steeper fronts (see 7.4.2), and multiple strokes involve additional stresses beyond the first stroke, although their amplitude is generally lower than that of the first, as indicated in the notes of Table 1 of IEC 61312-1:1995 [B15]. In this informative annex, four levels of exposure are proposed in Table A.2.

Limited tests conducted by some manufacturers and informally reported have indicated that the stress imposed on metal-oxide varistor (MOV) SPDs by a 10/350 µs test might be equivalent to the stress imposed by a standard 8/20 µs test, with a scaling factor in the order of 10, as shown in the third column of Table A.2. Therefore, by mutual agreement among the parties involved, a Class I test in accordance with Table A.2 might also be appropriate.

Table A.2—Scenario II tests for SPDs involved in exit paths[a, b]

Exposure	All SPD technologies 10/350 µs	Alternative for MOVs[c] 8/20 µs
1	2 kA	20 kA
2	5 kA	50 kA
3	10 kA	100 kA
X [d]	Lower or higher by agreement between parties	

[a] The scope of these tests is limited to SPDs involved in an exit path, in contrast with the other standard and additional tests of this recommended practice that may be applied to equipment other than SPDs.

[b] Values shown for the current are applicable for each leg of a multi-phase SPD.

[c] A scaling factor of 10 has been empirically established for relating peak values for the 10/350 and 8/20 waveforms in the case of MOV SPDs. Scaling factors have not been determined for other technologies.

[d] Successful field experience of SPDs designed for lower values than exposure level 1 support an informed choice of an appropriate level.

Annex B

(informative)

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