

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



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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Surge Protective Devices Committee
of the
Power Engineering Society

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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3 Park Avenue, New York, NY 10016-5997, USA

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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 μ s voltage waveform and 8/20 μ s 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

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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.

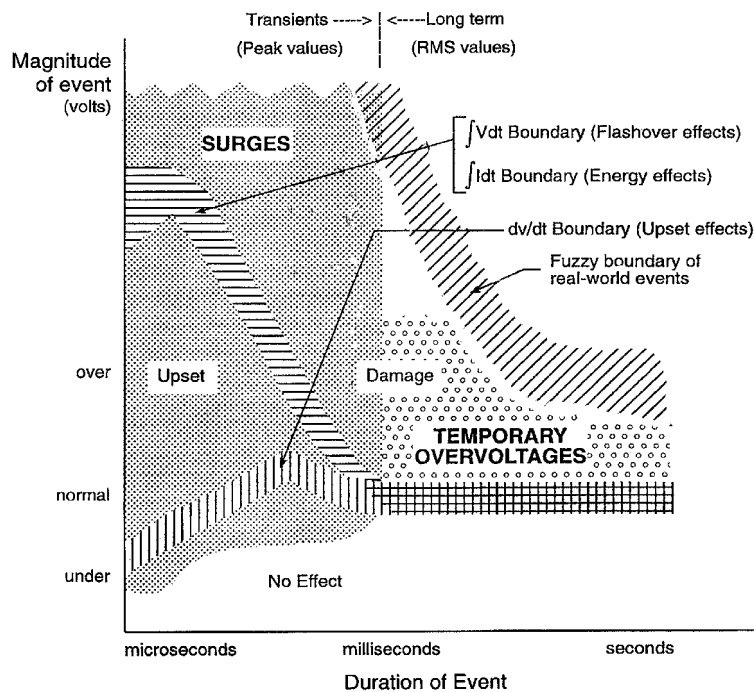
There are no specific models that are representative of all surge environments; the complexities of the real world need to be simplified to produce a manageable set of standard surge tests. To this end, a surge environment classification scheme is presented. This classification provides a practical basis 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

¹Information 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

²The 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 μ s voltage and 8/20 μ s current
 - A 0.5 μ s–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 μ s “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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⁴IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

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.

⁵Including 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 (Birkel et al. 1996 [B6]; Mansoor and Martzloff 1998 [B24]).