IEEE Std C62.45™-2002
(Revision of
IEEE Std C62.45-1992)

IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits

Sponsor

Working Group on Surge Characterization
of the
Surge-Protective Devices Committee

Approved 11 November 2002

IEEE-SA Standards Board

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Abstract: The scope of this recommended practice is the performance of surge testing on electrical and electronic equipment connected to low-voltage ac power circuits, specifically using the recommended test waveforms defined in IEEE Std C62.41.2™-2002. Nevertheless, these recommendations are applicable to any surge testing, regardless of the specific surges that may be applied.

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

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Introduction

[This introduction is not part of IEEE Std C62.45-2002, IEEE Draft Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage (1000 V and Less) AC Power Circuits.]

This recommended practice is the result of ten years of use as a guide, and it incorporates only minor additions or updates of the original 1987 document, which was revised in 1992. These earlier versions were published independently, and not concurrently with their intended companion, IEEE Std C62.41-1991, with the result that a “catch-up” situation was created as each document was separately updated.

With the approval of the Surge-Protective Devices Committee, the companion IEEE Std C62.41-1991 was split into two separate documents, IEEE Std C62.41.1-2002 and IEEE Std C62.41.2-2002. Together with the present recommended practice, the two IEEE Std C62.41.1-2002 and IEEE Std C62.41.2-2002 present a “Trilogy” concerning the occurrence, characterization, and testing of surges in low-voltage ac power circuits, to be published concurrently and thus avoid the previous ambiguities of the catch-up updates.

CAUTION

Surge testing of electrical equipment presents potentially hazardous situations for both personnel and equipment. Safety directives promulgated by the laboratory where testing takes place must be observed. Additional precautions are suggested in 4.8 and 6.4.

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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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1. Overview

This recommended practice is divided into 11 clauses. Clause 1 provides an overview of this recommended practice, including its scope and its context with respect to other IEEE standards directly related to the subject. Clause 2 lists references to other standards that are useful in implementing the recommendation of the present document. Clause 3 provides definitions of common English words, but with a specific meaning in the context of this recommended practice. No new technical definitions have been generated in connection with this recommended practice. Clause 4 provides the necessary information for the planning of surge testing, a prerequisite to the performance of tests. In Clause 5, information is provided on the equipment to be used in performing the tests. Clause 6 provides general recommendations on test procedures, with further details in Clause 7 and Clause 8. Clause 9 provides a description of Standard Surge Test Waveforms. Clause 10 provides a similar description of Additional Surge Test Waveforms. Clause 11 provides guidance on evaluating results and offers some concluding remarks.

This recommended practice also contains four informative annexes. Annex A provides information on Surge-Protection Devices (SPD) Class I test parameters. Annex B provides additional information on surge-related issues. Annex C provides practical hints on surge testing. Annex D provides the listing of citations.

1.1 Scope

The scope of this recommended practice is the performance of surge testing on electrical and electronic equipment connected to low-voltage ac power circuits, specifically using the recommended test waveforms defined in IEEE Std C62.41.2™-2002.[1] Nevertheless, these recommendations are applicable to any surge testing, regardless of the specific surges that may be applied.

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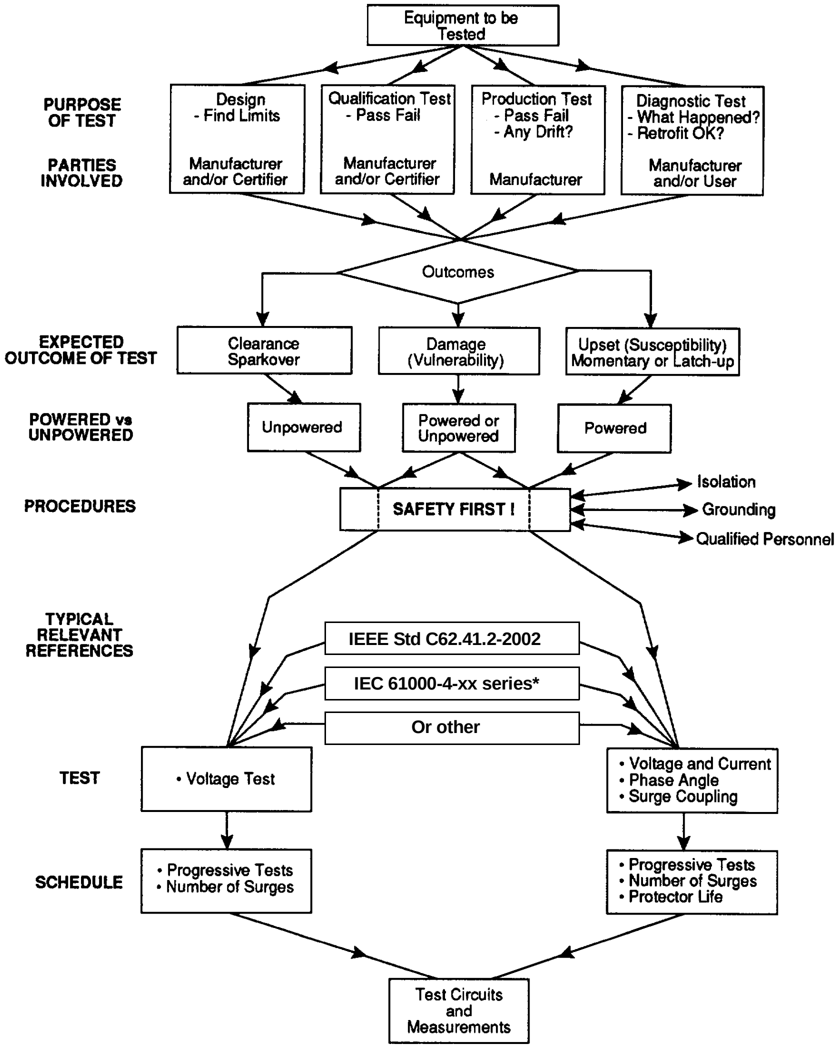
[1] Information on references can be found in Clause 2.

1.2 Purpose

This recommended practice, the third document in a Trilogy of three IEEE standards addressing surges in low-voltage ac power circuits, focuses on test procedures, using representative surge waveforms developed on the basis of the two other documents of the Trilogy. 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 in IEEE Std C62.41.2-2002. This classification provides a practical basis for the selection of waveforms and amplitudes for surge-voltages and surge-currents that may be applied to evaluate the surge ***withstand level***[2] capability of equipment connected to these power circuits. It is important to recognize that proper coordination of equipment capability and environment characteristics is required: each environment and the equipment to be protected have to be characterized and the two have to be reconciled.



*See Annex D for bibliographic citations of several IEC standards on test methods.

Figure 1—Guiding considerations for surge testing

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[2] See Annex B for complementary notes on items appearing in ***bold italics*** in the text.

Regardless of the particular surge specification, equipment connected to the power system have to be capable of satisfactory operation, or at least survival, under these surge voltages or surge currents, with or without additional protection as the case may be. The assignment of withstand level remains the prerogative and responsibility of the users of this document. Surge testing is therefore required to demonstrate this capability. To illustrate the process of surge testing procedures, Figure 1 shows a flow diagram of the guiding considerations that are essential to obtaining reliable test results while enhancing operator safety.

Note that the assignment of withstand levels for equipment is not included in the scope of this recommended practice. Surge testing on signal or data interfaces is also not included in the scope of this recommended practice, but should not be overlooked in the complete evaluation of specific equipment.

2. References

In this document, two types of “references” are used: those that are directly related to the subject being discussed and often necessary to consult when using this guide—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 described below.

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 for the details of the subject. This first type is introduced in the text as (Document identity), and the listing is provided below, in this clause.

The second type, bibliographic citations, is not essential to implementation of a recommendation or comprehensive validation, but it is provided for the use of readers seeking more detailed information or justification. This second type is introduced in the text as (Author, date [B#]), and the listing is provided in Annex D.

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.

IEC 60060-2 (1994), High voltage test technologies—Part 2: Measuring systems.[3]

IEEE Std 4™-1995, Standard Techniques for High Voltage Testing.[4, 5]

IEEE Std C62.41.1™-2002, IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits.

IEEE Std C62.41.2™-2002, IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits.

NFPA 70®-1999, National Electrical Code®.[6]

UL Std 1449, Standard for Safety—Transient Voltage Surge Suppressors, Second Edition, 1996.[7]

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[3] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

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[6] NFPA publications are published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA (http://www.nfpa.org/).

3. Definitions

3.1 Technical terms

The definitions of the terms used in this recommended practice are those found in *The Authoritative Dictionary of IEEE Standards Terms,* Seventh Edition [B11][8], or in IEC 61643-1 [B10]. No new definitions have been generated in developing this document. However, as a reference for the reader and for tutorial purposes, some already existing definitions and related comments may be found in the Glossary provided as Annex C of IEEE Std C62.41.1-2002.

3.2 Special word usage

The words listed below are used in this recommended practice in accordance with the *IEEE Standards Style Manual*, the IEC/ISO Directives, or specific limitation of a term in general use; they convey the following meanings:

3.2.1 will: Conveys the certain occurrence of an event.

3.2.2 can, cannot: Conveys (im)possibility or (in)capability, whether material, physical, or causal.

3.2.3 may, may not: Conveys that a course of action by the equipment user or test operator is permissible (not permissible) within the limits of the present recommended practice, or that it is (im)possible to exercise a choice at the discretion of the sponsor. *See:* **might**.

3.2.4 might: Conveys the possible occurrence of a situation or phenomenon, without intervention from the user or test operator, with actual occurrence uncertain. *See:* **may**.

3.2.5 must: Conveys the necessity of a course of action by the test operator in order to obtain reliable results or observe appropriate safety precautions.

3.2.6 reader: The person using this document for any purpose.

3.2.7 shall: Conveys requirements to be strictly followed to conform to a specification or stipulation, from which no deviation is permitted.

3.2.8 should, should not: Conveys a preference among several possibilities, but not necessarily a requirement. In the negative form, conveys deprecation, but not prohibition, of a course of action.

3.2.9 sponsor: The entity for which the tests are being performed in accordance with the present recommended practice.

3.2.10 user: The occupant, owner, or operator of the power system or premises where the equipment under test (EUT) is intended to be installed.

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[7] UL standards are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (http://global.ihs.com/).

[8] The numbers in brackets correspond to those of the bibliography in Annex D.

4. Planning of surge testing: Basic objectives

4.1 General

This clause outlines the basic objectives to be considered for planning surge testing, as shown in Figure 1. Detailed discussions of these considerations are provided in Annex B. Although the scope of this recommended practice addresses only the power port of equipment, the intended application and multiple ports of the ***equipment under test (EUT)*** should also be considered.

Six ports (see Figure 2), through which electromagnetic disturbances can be coupled into equipment, can be identified as follows:

- Enclosure port (radiated disturbance only)
- AC power port
- DC power port
- Process measurement and control port
- Signal port
- Earth port

Radiated coupling of disturbances through the envelope is clearly outside the scope of the present recommended practice and is addressed in other documents related to electromagnetic compatibility. The scope of this recommended practice specifically excludes signal and data lines and, by implication, the dc power port. However, the sixth port, referred to as *earth port* (*earth* being the term used by the IEC, and *ground*, the term used in the USA), should be recognized. (See discussion of ***grounding practices*** in B.5 and B.23.) The issue is that equipment connected to different systems can be exposed to different reference voltages through their separate connection to those different systems. (In many systems, the reference point is a grounded conductor that, during a ***surge event***, experiences changes of potential.) Subclause 4.4 of IEEE Std C62.41.1-2002 provides a detailed description of this issue. Thus, while planning surge testing for the ac interface of the equipment, a complete evaluation of the equipment performance under surge conditions requires recognition of the occurrence of surges on all ports.

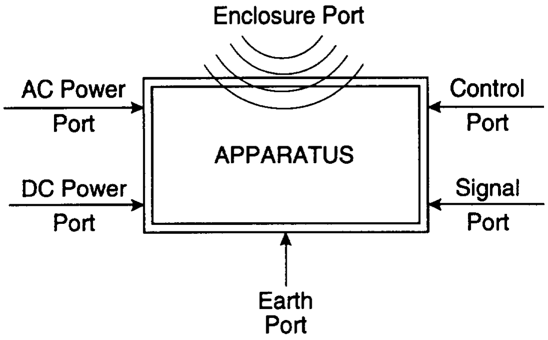


Figure 2—Six ports for coupling of disturbances

4.2 Surge environment

Surge testing is generally performed to determine the surge withstand capability of specific equipment that will be exposed to known or unknown surge environments. Therefore, the first decision or assumption that must be made in planning a surge test concerns the nature of the surge environment. IEEE Std C62.41.1-2002, IEC 60664-1 (2000) [B8], or some other applicable document will be used to define the environment.

Although the test procedures discussed in this recommended practice should be relevant to most surge tests, the major concern here is with switching-induced and lightning-induced surges. Surges associated with nuclear electromagnetic pulse (NEMP) and electrostatic discharges (ESD) involve rise times in the order of a few nanoseconds, requiring instrumentation of different characteristics from those discussed here. In the case of the electrical fast transient (EFT) tests, ***monitoring*** the pulses within the EUT might be counterproductive or cause difficulties, as discussed in 5.5.3. Furthermore, high-frequency ***noise***, generally at amplitudes much less than twice the normal system voltage, is the subject of other documents concerned with electromagnetic compatibility.

4.3 Types of tests

Figure 1 shows a branching point involving the purpose of the surge test. Four types of tests are identified, with their purpose and interested parties, as follows:

Design tests are performed by an equipment manufacturer for establishing or demonstrating to others design margins, and for optimizing the design. These tests may involve pushing the stresses to the limits until a failure is observed.

Qualification tests are performed by the manufacturer, purchaser, or independent test laboratory for demonstrating compliance with specifications. These tests generally are limited to a pass-fail criterion, but are more comprehensive than are tests carried out on a routine basis on production products.

Production tests are performed by an equipment manufacturer for verifying conformity and consistency of the production process. These tests generally involve some statistical evaluation.

Diagnostic tests are performed by the manufacturer or user for investigating difficulties encountered in service. These tests generally involve attempts at laboratory reproduction of the failure modes observed in the field, followed by applying the same test on equipment that has been redesigned or provided with retrofit protection.

Prior to conducting these tests on an EUT, acceptance criteria should be defined in accordance with the considerations of Figure 1, such as purpose of the test and expected outcome.

4.4 Results and consequences of the test

Although surge-protective devices are generally provided for damage avoidance, they can also serve to prevent upset in the operation of an EUT. Therefore, a treatise on surge testing must include subject matter dealing with the evaluation of the test results. Any given surge test will produce one of four results:

- Upset (***susceptibility***)
- Damage (***vulnerability***)
- No observed change
- An ***unforeseen consequence*** elsewhere in the equipment environment

The last result actually involves consideration of circumstances external to the EUT proper that might be overlooked or considered irrelevant to the scope of surge testing in the laboratory. Setting aside any consideration of ***unforeseen consequences*** on that basis would be a severe error. The discussion of unforeseen consequences (B.45) gives some scenarios that illustrate this concern.

Depending on the nature and function of the EUT, seven different outcomes of a surge test should be evaluated whenever direct, local results are noted:

- Outcome 1: No apparent response in the EUT—neither upset nor damage
- Outcome 2: Temporary upset of the EUT operation

- Outcome 3: Upset with trip-out or latch-up of the EUT circuits
- Outcome 4: Flashover of clearances without apparent permanent damage
    a) With no ***follow current*** or with a self-clearing follow current, which might seem to be a benign occurrence
    b) With follow current resulting in operation of an overcurrent protective device (fuse or breaker), an occurrence similar to outcome (3)
- Outcome 5: ***Insulation degradation*** or breakdown due to ***partial discharges*** across the surfaces or in solid insulation, or both
- Outcome 6: Degradation of metal-oxide varistors or other types of surge-suppression elements
- Outcome 7: Insulation breakdown or permanent component damage requiring replacement or repair

The first outcome (no ***upset*** or ***damage***) can represent a success from the point of view of acceptance, but yields incomplete information because the actual design margin is not determined until further tests, at higher stress, are performed. It is also possible that an EUT upset might occur only upon rare coincidence of the surge with a clock transition, which would require a large number of surges to be detected.

The next two outcomes (upsets) are mainly concerned with control or data circuits, and they are related to the susceptibility of the equipment. The electrical noise required to produce them can be low; in fact, low-level noise can be sufficient to upset sensitive circuits. The emphasis in this recommended practice, however, is on surges, generally implying voltage levels of at least twice the normal voltage of the system.

The fourth outcome (flashover) might involve both control and power circuits, and it is expected to occur at surge levels significantly above the normal circuit voltages. As long as no permanent damage or ***insulation tracking*** occurs as a result of the sparkover and eventual follow current, this outcome is still in the category of susceptibility. Some EUTs might be insensitive to or unaffected by the flashover, whereas others would definitely be considered as having been upset by the flashover.

The fifth, sixth, and seventh outcomes describe the vulnerability of the equipment.

The fifth outcome (insulation degradation or breakdown) might occur across the surfaces of insulation or within solid insulation as a result of partial discharges, especially if multiple tests are applied.

The sixth outcome (surge-protective-device degradation) might occur as a result of the surge-testing sequence exceeding the single-pulse-current rating of the device or exceeding the number of surges at a lesser current for which it is rated. The result can be a change in the nominal voltage, standby current, or limiting voltage that is not great enough to be considered device failure (generally, a change exceeding ±10%) but might be a sufficient change to indicate that the device is approaching failure.

The seventh outcome (permanent damage) might occur in either control or power circuits as a result of sparkover with or without follow current producing a permanent degradation, or as a result of semiconductor failure or excessive energy deposition leading to component or etch burnout.

Some of the outcomes can occur in combination so that the distinctions made here might not be so clear-cut in reality but are nevertheless useful as starting points. Remember that any surge test is potentially destructive to the EUT, and appropriate precautions should be taken.

4.5 Unpowered testing versus powered testing

Test surges may be applied to the EUT in two ways:

- With normal operating power disconnected from the EUT (***unpowered testing***)
- With normal operating power applied to the EUT (***powered testing***)

The intended purpose of the test will determine whether one approach is sufficient or whether both are advisable.

Unpowered testing is sufficient in situations for which a test outcome does not depend on the evaluation of EUT performance during the surge, and for which follow current is not considered to be a significant factor in regard to vulnerability. For instance, clearance flashover of an electromechanical device may be the selected failure criterion; in that case, there should usually be no need to power the EUT. Unpowered testing is usually necessary as a preliminary to powered testing, for design and diagnostic testing.

Powered testing is necessary in two cases:

- When a test outcome depends on the evaluation of EUT functional performance during the surge. Thus, a test for susceptibility implies normal equipment functioning prior to the surge; therefore, the EUT can only be checked in the powered mode.
- When determination of EUT vulnerability involves the likelihood or consequence of a follow current (which might also depend in part on the ***phase angle*** at which the surge is applied with respect to the line voltage wave).

4.6 Withstand levels

Surge testing is ordinarily carried out at different stages in a product life cycle, such as design, quality control, and protection retrofit. The extent and severity of the test will depend on the particular stage involved. A design test is likely to involve testing to failure, whereas a production test must carefully avoid creating incipient failures. The voltage surge and current surge environment (see IEEE Std C62.41.1-2002) is described only in statistical terms without imposing a fixed ***withstand level***.

The withstand levels should be expressed in terms of voltage for equipment exhibiting high impedance to a surge; for those EUTs that contain a surge-protective device, the withstand level should be expressed in terms of current in order to give consideration to energy deposition, as discussed in 6.2. A requirement that an undefined, generic device should withstand a specified energy deposition is not meaningful because the energy deposited in a particular device results from the combination of the surge generator impedance and the device dynamic response (Standler 1989 [B30]).

4.7 Voltage and current waveforms

The nature of the EUT will affect its response to an applied test surge. A high-impedance EUT, such as a winding, a clearance, or a semiconductor in the blocking mode, will be stressed by a voltage surge. The energy associated with the surge is not significant here. A low-impedance EUT, such as a circuit containing filter capacitors or surge-diverting protective devices, will be stressed by a current surge. The energy deposited in the components is a significant factor in a low-impedance EUT. A third type of EUT, such as a system with several ground reference points, will be stressed by a current surge applied between different reference points. This test can also provide essential information on the EUT capability. Although this third aspect of surge testing is not directly within the scope of ***low-voltage*** ac power circuits, it should be recognized. Some discussion is provided in B.9. Therefore, the ***waveform*** for both voltage and current tests should be included when specifying a test procedure. IEEE Std C62.41.2-2002 makes such a distinction between current and voltage tests.

The specific selection of withstand levels, for voltage as well as current, depends on the exposure to transients as well as on the consequences of a failure to withstand the transient. This recommended practice provides some perspective in selecting appropriate levels, but the final choice must be made by the user of this document.

For the power port, IEEE Std C62.41.2-2002 recommends consideration of three standard waveforms and two additional waveforms. Table 1 presents a summary of the waveforms, and the location categories to which they apply. Clause 9 and Clause 10 present details on definitions, specifications, tolerances, and equations for these five waveforms. The rare case of a direct flash to the building is presented as an option for surge-protective devices (SPDs) involved in the exit path of the lightning current, as discussed in IEEE Std C62.41.2-2002.

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

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

[a] Refer to Clause 9 for details on the standard waveforms.
[b] Refer to Clause 10 for details on the EFT and Long Wave additional waveforms.
[c] Nearby lightning flashes can induce surges into circuits contained within the building.
[d] For specific cases in which front-of-wave response or software upset might be a concern.

These various waveforms present features that influence the test equipment (generator, coupling, and instrumentation) necessary to perform the tests. The tolerances are intended to help assure reproducible waveforms among different laboratories and to provide a realistic perspective on the limitations of generation and measurement of test surges. The equations are intended for computer simulations of surge protection circuits and for design of surge generators. The history of the definitions of these waveforms is discussed in Standler 1989 [B29].

The fact that five waveforms are listed in IEEE Std C62.41.2-2002 should not be construed as a requirement that all equipment be subjected to all five types of surges. The 100 kHz Ring Wave and the Combination Wave are recommended as basic design and test surges. The additional waveforms (the EFT Burst and the 10/1000 µs Long Wave) need to be included in a test program by mutual agreement only when sufficient evidence is available to warrant their use.

4.8 Safety

CAUTION

Surge testing of electrical or electronic equipment presents potentially hazardous situations for both personnel and equipment. The surge test equipment can generate potentially lethal voltage surges. Furthermore, a catastrophic failure of the EUT might result in a fire or explosion. Only qualified personnel should perform the tests, with safety precautions enforced according to all national codes as well as the applicable safety directives and prescriptions of the organization where the tests are being performed. Testing should not be performed unattended. More specific aspects of safety precautions are discussed in 6.4.

5. Implementation of surge testing: Test equipment

5.1 General

Implementation of surge testing can proceed after the considerations discussed in Clause 4 have been addressed. This clause provides guidance on the major aspects of the equipment requirements, for generating and applying the surge as well as for ***monitoring*** the performance of the ***EUT*** (Figure 3). Occasional users might encounter difficulty and should obtain guidance from qualified sources. Test equipment that does not meet the requirements of applicable standards might give misleading results (Martzloff 1983 [B15]; Buschke 1988 [B4]).

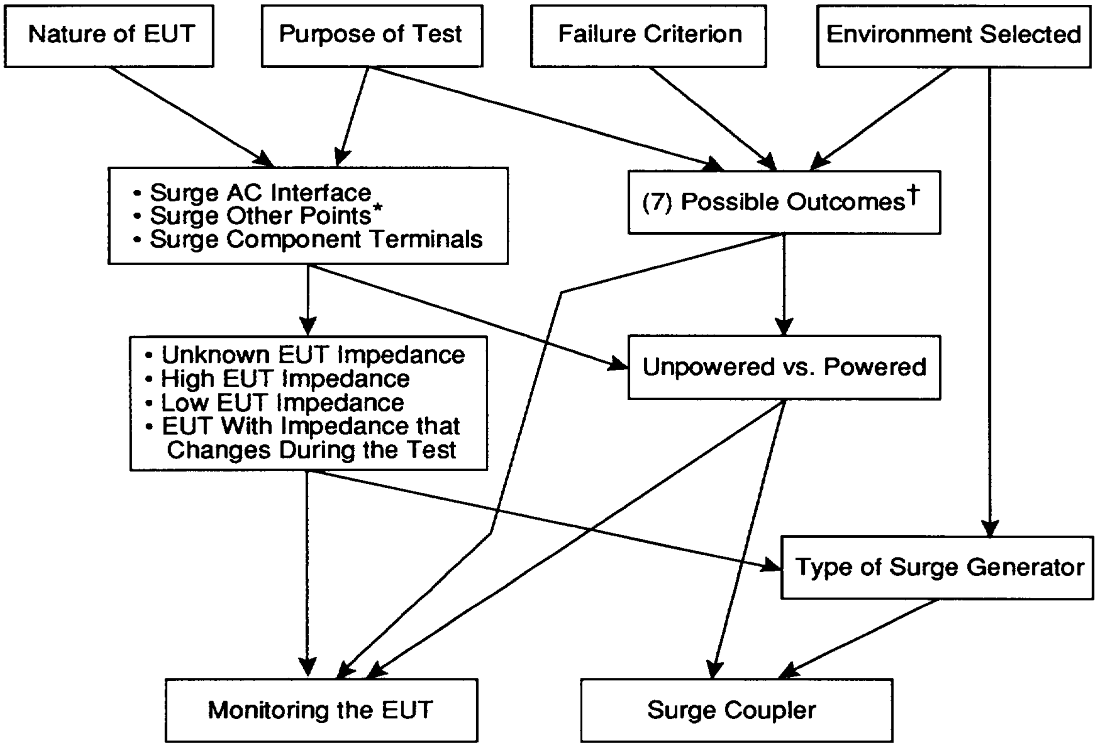
5.2 Surge generators

The test surge to be applied to the EUT will be produced by a surge generator capable of delivering the specified ***waveform*** at any specified ***phase angle*** of the ac voltage sine wave at the EUT terminals. Capability for bidirectional surge polarity simplifies the general test procedure.

A number of commercial surge generators are available with specific waveforms that meet the various standards in existence. High-voltage laboratories are also generally equipped and staffed so that the generation of a test wave is not a problem. Surge testing of electronic equipment is different from a simple dielectric test on an insulation system or a simple surge current test on an individual surge-protective component. Further discussion of component testing is given in B.16.

Classical surge generators, based on discharging stored energy into a waveshaping network and coupling the resulting surge into a powered EUT, require a ***back filter*** to allow application of the power-frequency voltage and current to the EUT, while blocking the surge from being fed back to the laboratory power system. Such an arrangement works well for surges such as the Ring Wave or Combination Wave, but not for waves of longer duration, such as the 10/1000 µs Long Wave, a capacitor-switching transient wave, or the Scenario II optional 10/350 µs wave.

Some laboratories have acquired high-power linear amplifiers and arbitrary-waveform generators, which can be used for producing both the power-frequency supply and the surge, at the appropriate instant of the power sinewave, and with the appropriate amplitude and available surge current delivery capability. This point is discussed in greater detail in Clause 10, in connection with the description of test procedures for the 10/1000 µs Long Wave and the capacitor-switching transient waves.



* See 5.3.
† See 4.4.

Figure 3—Surge testing equipment considerations

An EUT that contains a surge-protective device or that might experience an insulation breakdown during the test will exhibit an impedance change during the surge. A surge generator inherently capable of delivering a specified voltage or a specified current during a single surge test as required by the EUT impedance will yield information on the EUT performance that cannot be obtained by two separate generators in two successive tests, one for voltage, the other for current (Richman 1983 [B22]; Vance et al. 1980 [B33]). Further discussion of these considerations is given in B.49.

5.3 Point of test surge application

According to the scope of this guide, the ***ac interface*** of an EUT is the point of application of the test surge. In the process of evaluating the performance of the EUT, other terminals may also be subjected to surges. Interconnected or distributed systems might have to be broken into separate subsystems, or the whole system might have to be treated as an EUT. Therefore, the nature of the EUT will affect the points at which the surge is to be applied and, thus, the method of coupling the surge.

5.4 Coupling the surge to the EUT

In the case of ***unpowered testing***, the coupling is simple. The input port of the EUT is merely connected to the output terminals of the surge generator, but further precautions are required. All other terminals or outputs of the EUT, including its ***equipment grounding conductor(s)***, should be isolated to prevent damage to other equipment.

In the case of ***powered testing,*** the coupling becomes a complex matter, which is discussed in detail in Clause 7. This complexity is the result of the need to apply the surge to the power supply line of the EUT, maintaining the specified waveform, but without feeding the surge back into the laboratory ac power supply, where it might damage other loads in the laboratory.

Thus, a ***back filter*** is needed to prevent this feedback. In addition, there is a need to isolate the power supply line, lest it load the surge generator, thereby reducing the generator output below the required levels. The availability of a separate power supply generator, often used in specialized laboratories, can alleviate some of these problems.

Conversely, the quality of the voltage waveform of the ac mains used to supply power to the test circuit should be evaluated, and corrected if found wanting, so that artifacts will not be introduced in the test results by an unusually distorted or disturbed ac mains supply. The back filter, intended to block test surges in the direction from EUT to mains, can also provide some degree of filtering disturbances in the direction from mains to EUT. If L-G or N-G surges are to be applied, ascertain that the back filter will block the selected waveform in the L-G and N-G modes.

In the case of long-duration waveforms, such as the 10/1000 µs surge, it could be difficult to provide a back filter with sufficient blocking capability for the surge and, at the same time, the capability to provide power-frequency current of sufficient amplitude to the EUT. Some schemes have been developed to provide isolation of the test circuit from the power supply circuit by blocking diodes and thyristors with appropriate timing of their conduction periods.

For these long-duration waveforms that generally involve lower voltages than do the standard waveforms, another possible strategy is to obtain the complete waveform (power-frequency voltage before and after the surge, as well as total surge) from a digital waveform generator, with amplification by a high-power linear amplifier. This method requires that the amplifier be capable of delivering either voltage or current peaks during the surge (depending on the EUT impedance, in a manner similar to the Combination Wave), as well as the normal load current of the EUT before, during, and after the surge. This approach would be a radical departure from the classical method of using the discharge of stored energy into the EUT. It would offer the advantage, once the resource of such a system becomes available to a user, of making other test waveforms, such as swells, easy to implement.

In the case of the EFT, the test procedures described in detail by IEC 61000-4-4 [B9] include the use of discrete coupling capacitors for the power-supply lines (called *coupling network* in IEC 61000-4-4) or the use of a coupling clamp, which is in effect a capacitor involving all conductors at the same time.

Thus, both methods of coupling the EFT result in having a capacitive divider (consisting of the coupling capacitance and the internal capacitance of the EUT) that applies the EFT pulses to the port of the EUT (Martzloff and Leedy 1990 [B19]). The actual value of the EFT pulse applied to the EUT port is influenced by the internal design of the EUT; it is not a fixed parameter imposed on the EUT. The external arrangement of the EUT, including cable dressing, enclosure position with respect to the reference ground plane, and in some cases the presence of the operator near the EUT, will affect the capacitive coupling and thus the outcome of the test. The configuration of the ground reference plane can affect the results; for that reason, IEC 61000-4-4 [B9] describes in detail the test setup. The waveform of the EFT generator output before connection to the EUT should be clearly specified, a need not identified in the IEC standard (Richman 1991 [B24]). Thus, the configuration of an EFT test setup must be clearly defined and documented.

Isolated components or simple two-terminal devices can be subjected to the surge in a simple configuration; multiterminal devices, including a simple balanced two-input EUT with ground, require careful attention to specifying which terminals are surged with respect to which others. This aspect of the coupling techniques is treated in greater detail in Clause 7.

5.5 Monitoring the EUT

Both the applied surge and the output, as appropriate, of the EUT need to be monitored; monitoring could also be required within the EUT. Current, as well as voltage, should be monitored to provide complete information on the EUT performance (Richman 1983 [B22]).

The need to monitor the input surge is axiomatic because this will verify the characteristics of the applied surge, both open-circuit and modified by the load. For simple failure modes of isolated components, such as insulation breakdown or permanent semiconductor damage, monitoring the applied surge also reveals a failure because the observed applied voltage wave will appear chopped. On the other hand, a surge applied to an EUT being powered from the ac mains might show extensive distortion or ringing (Martzloff 1983 [B15]). This distortion, therefore, makes diagnosis by simple waveform inspection nearly impossible.

Checking a complex EUT for ***susceptibility*** to surges requires more extensive instrumentation in order to detect misoperation. (That instrumentation must be immune to the electromagnetic disturbances created in the area by production of the test surge.)

Monitoring within the EUT can also be necessary in order to understand the failure mechanism under the surge, to control one or more critical voltages within the EUT, or to check the amount of ***surge remnant*** or ***surge let-through*** reaching specific critical components.

In the case of EUTs that are shunt-connected surge protectors, the measurement of the surge response voltage should be made to include the effect of any leads or configuration normally used to connect the EUT to the mains, so that the impact of the surge suppressor in actual service conditions will be characterized, rather than an intrinsic (but not attainable in practice) value. To avoid misleading data, specific mention of the lead dress should be included when reporting results. See B.1 for further comments.

5.5.1 Monitoring with voltage probes

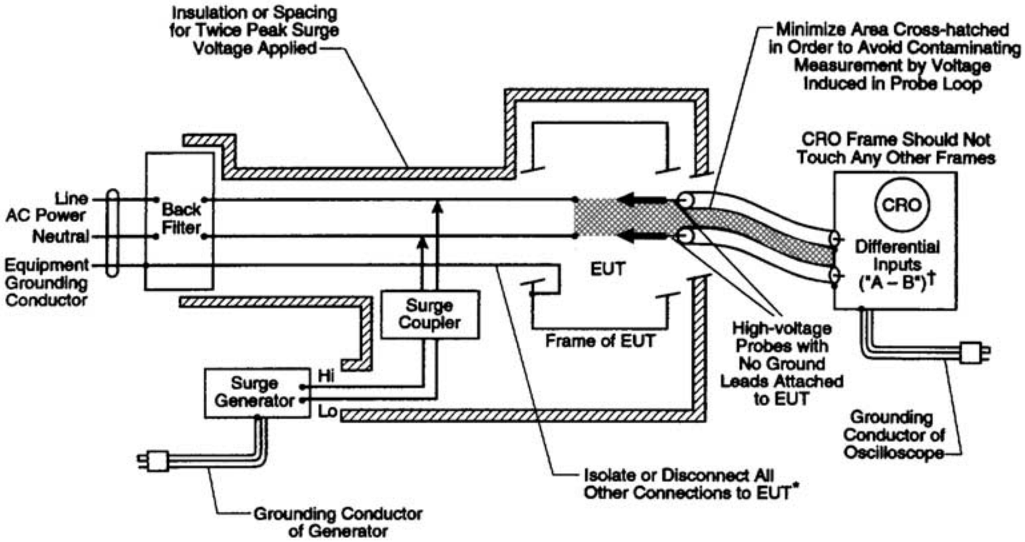
A reliable and safe method for monitoring voltages within the EUT is to use a ***differential connection*** of two matched voltage probes (Figure 4). This type of connection, shown in the figure for the case of a surge applied between line and neutral of the EUT, enables the use of a safely grounded oscilloscope. The high-voltage probes have no ground leads attached to the EUT, whereas the chassis of the instruments are safely grounded by the equipment grounding conductors of their power cords.

Common high-voltage probes must be properly compensated for the parasitic input capacitance of the oscilloscope or digitizer that is used to measure the voltage (Standler 1989 [B32]). Paired differential probes with a 50 Ω output impedance that need no compensation can also be used (Senko 1987 [B26]).

5.5.2 Monitoring with current transformers

Properly applied ***current transformers*** can be useful for monitoring surge currents. It is often desirable, if not necessary, to monitor current during application of a voltage surge, in order to detect breakdowns or to verify EUT performance. A current transformer enables complete isolation of the current-monitoring channel of the oscilloscope, in contrast with a current-viewing coaxial shunt, which can only be inserted very near the grounding reference point. Most commercial “current transformers” are actually current-to-voltage transducers that incorporate a suitable burden to deliver a voltage signal to the oscilloscope.

Voltages can also be monitored with a current transformer: a high resistance is connected between the two points where voltage is to be monitored and a current transformer is used to monitor the current in the resistor, hence, the voltage difference at its points of connection. (Note that the resistance should be implemented with a noninductive resistor with appropriate surge voltage rating.)

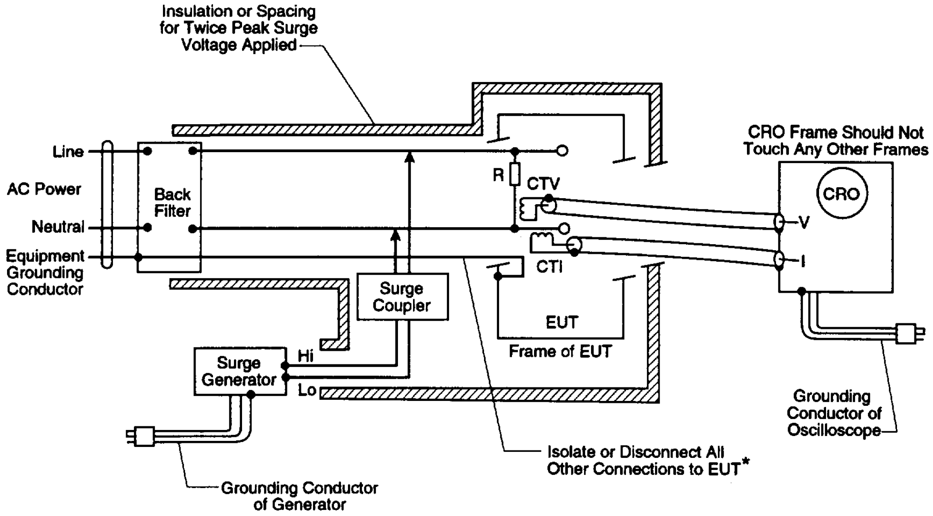


* For the case of an isolated EUT. For systems, refer to 7.5.2 and figure 11

† Or suitable differential probe/amplifier.

Figure 4—Monitoring within surged equipment with voltage probes in differential connections

Figure 5 shows these two applications of current transformers or current-to-voltage transducers. Note, however, that special precautions are required to provide valid measurements, which are discussed in detail in B.10. See also Standler 1989 [B32] for a review of the physics of current transformers.



* For the case of an isolated EUT. For systems, refer to 7.5.2 and Figure 11.

Figure 5—Monitoring within surged equipment with current transformers

5.5.3 Monitoring the EFT test

The high frequencies involved in the EFT Burst make it difficult to monitor the surges within the equipment, because the probe conductors act as an antenna capturing the radiated fields and inject the signal into the EUT, causing an upset that would not occur without this probe. The present EFT procedure, as described in IEC 61000-4-4 (1995) [B9], requires verifying only the waveform of the pulses produced by the generator when connected to a 50 Ω load (Richman 1991 [B24]), while the outcome of the test is observed as the occurrence or absence of a disturbance in the operation of the EUT. The steep front of the EFT pulse raises the issue of the bandwidth of analog instrumentation and of under-sampling in digital techniques (Standler 1989 [B32], pp. 369–375). See also C.1.7 on digital resolution.

6. Performance of surge testing: Test procedures

6.1 General

This clause is intended primarily for the guidance of those individuals involved in performing surge tests. Those who do the testing are presumed to be familiar with safety procedures and with the general techniques of high voltage and high-frequency (impulse) instrumentation. Specific guidance is therefore aimed at the specialized aspects of surge techniques.

a) A surge test is a single event. Thus, once the surge has been applied to the ***EUT***, any damage that occurs has to be repaired and the most probable cause determined before the next surge test is run, possibly at a lower level. (This remark does not apply to the EFT Burst procedure.)
b) Voltage and energy levels required to duplicate the equipment surge environment are necessarily high enough to be a personnel hazard.
c) The performance of virtually all surge-protective devices is highly dependent on the waveform of the applied surge.

6.2 Limiting stresses

Pass/fail ***qualification tests*** and ***production tests*** may consist of a single surge application. On the other hand, ***design tests*** or some qualification tests are generally applied by increasing the surge levels in several steps starting from the operating voltage level and increasing to the goal, in order to obtain meaningful data and reveal any possible ***blind spots***. However, these many steps result in an accumulation of energy deposition that needs to be recognized and possibly limited.

All surge protectors have not only surge performance specifications but also maximum ***average power*** limitations. Furthermore, a series of repeated tests can consume (expend) part of the protector life. Therefore, it is very important that consideration be given to limiting integrated stress in ***multiple surge*** tests as well as to ***life consumption,*** average power, and ***repetition rate***, especially when making repeated tests for blind spot checking.

In the absence of specific information on the failure modes of the EUT, several surges may be required of each polarity and at each selected ***phase angle*** to ensure that the failure will leave a mark or that ac ***follow current*** will finally cause an arcing fault. Thus, efforts should be made to reduce a large number of surges by considering the failure modes and applying good engineering judgment.

6.3 Nature of the EUT

The nature of the EUT has an influence on the test procedure. Single components, or simple systems without multiple built-in protective devices, can be tested with a few increasing steps, often in an unpowered configuration. On the other hand, complex systems, especially those containing several successive protective devices, require more comprehensive test procedures. There can be blind spots in the protection; that is, satisfactory performance at high stress does not guarantee satisfactory performance at lower stresses, or for different wave shapes. Additionally, some EUTs might be sensitive to the phase angle of the applied surge with respect to the power supply.

6.4 Safety

CAUTION

Many of the tests indicated in this recommended practice are inherently hazardous. Observing the precautions for personnel and property described in this clause are important for reducing safety risks. Even more important is observing existing national safety codes and the applicable safety directives and prescriptions of the organization where the tests are being performed.

Surge testing is best conducted only in an area dedicated solely to that purpose. The boundaries of the area must be clearly defined and appropriately marked. Where possible, the area should be fenced in and provided with electrical or mechanical interlocks, or both, on all entrances into the test area and removable barrier panels. All metal fences or barriers, or both, must be grounded. Care must be taken to ensure that all of the EUT is within the assigned area.

Testing should not be conducted unattended. Consideration must be given to the possibility of the surge flashing over to circuits or metallic parts that are not intended to be surged. The surge test area must be kept free of all meters, test setups, and flammable liquids, such as alcohol or cleaning solvents that are often found in an engineering environment, but not are associated with the surge test being conducted.

When the EUT can be enclosed within an effective barrier, the preceding requirements are easier to satisfy. This barrier can be sufficient separation—including separation from the floor, which should be presumed to contain conduit or some metal. Alternatively, the entire barrier can be made up of physical insulation. In either case, the barrier should be complete except where penetrated by input or output lines and measurement probes, and it must be safe for a peak voltage equal to at least twice the peak of the incident test surge. (Circuits in breakdown at or near the surge peak can oscillate at high frequencies. Such oscillatory flashovers can thereby increase effective applied peaks by a factor approaching two.) Interlocks (for the surge as well as the ac mains) must be provided to allow safe access between tests.

Capacitors used in the filter or ***coupler*** can retain a trapped charge; suitable bleeders or short-circuiting must be provided to ensure operator safety against any such trapped charge after application of the test surge.

Consideration must also be given to the possibility of ignition or explosion within the EUT. Where an examination of the EUT indicates a likelihood of ignition, factors to be considered are

a) The amount of combustible materials present
b) The probable rate of propagation
c) The consequences of such propagation, that is, the probability of extension beyond the EUT

Appropriate precautions must be taken to keep these factors within manageable limits. These precautions may include suitable extinguishing agents in sufficient quantity, physical separation from other combustibles, and other appropriate measures. In evaluating the possibility of explosion, consideration must be given to component failure whenever hazardous materials are available in sufficient quantity to create an explosive atmosphere.

All surge testing must be conducted by technically qualified personnel who are aware of the hazards of such testing. The voltage and current levels generally associated with surge testing are well above those considered lethal. Some considerations are the possibility of an accidental discharge of the surge generator, the consequences of a flashover to an unfavorable circuit, the possibility of a charge being trapped in the EUT, or the consequences of a violent component failure.

Testing personnel should never stand in the line of sight of components on printed circuit boards or panels with the enclosure open during EUT surge testing. On occasion, a component will fail in an explosive manner during surge testing. Fragments of the ruptured case and the component might cause injury to personnel in the vicinity. If visual observation is desired, a suitable transparent barrier of sufficient thickness must be provided. Ear protection must also be considered in case of possible violent failure modes. See C.5 for additional suggestions in this regard.

The importance of conducting surge tests in a prudent manner cannot be overstressed; safeguarding the test personnel must be the prime consideration.

7. Applying the test surge: Coupling and decoupling circuits

7.1 General

For independent equipment, the test surges will be applied to the power lines supplying the ***EUT***. For interconnected or distributed systems, the testing of the individual units should be evaluated with regard to the rest of the system.

Testing a complete system might not be possible or economical. Each unit comprising the system may be tested as an independent unit, provided its functional integrity can be monitored during the test. The test surges are to be applied to the cable ports that are connected to cables that are routed to other areas. All ac power inputs and outputs within an interconnected system should be surge tested. Although signal and data lines are not included in the scope of this recommended practice, they should not be overlooked (Martzloff 1990 [B16]; Key and Martzloff 1994 [B12]); see 7.5.2 and the discussion of ***ac interface*** (B.1) and ***communications interface*** (B.6).

7.2 Requirements for surge coupling

Three basic methods can be used for coupling the surge:

a) Direct coupling—As the name implies, it is a direct connection between the unpowered EUT and the test surge generator (Figure 6).
b) Series coupling—Couples the test surge generator to the EUT by injection of the surge in series with the conductor being surged (Figure 8).
c) Shunt coupling—Couples the test surge generator to the EUT by injection of the surge across a combination of conductors (Figure 7).

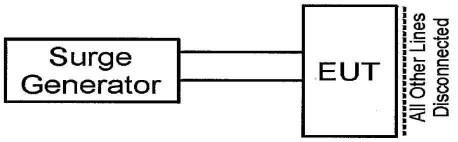
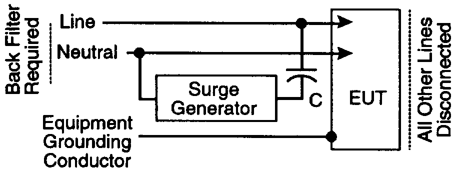
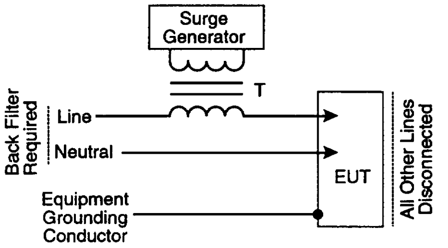


Figure 6—Direct coupling of surge (unpowered tests only)



C = Surge Coupling Capacitor

Figure 7—Elementary diagram of shunt coupling



T = Surge Coupling Transformer

Figure 8—Elementary diagram of series coupling

A fourth method of applying a surge to the EUT—which requires neither the coupler nor the back filter discussed in 7.4 and 7.5—is to provide both the ac power and the superimposed surge, generated by an arbitrary waveform generator, and amplified by a linear amplifier of suitable voltage and current delivery capability (Figure 9). This method makes it possible to apply surges of durations longer than what can be effectively blocked by the back filter in a powered test.

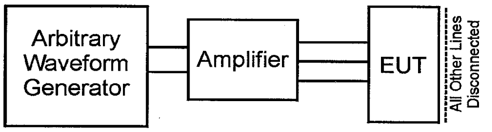


Figure 9—Elementary diagram of arbitrary waveform generator

Advantages and disadvantages of these methods are discussed further in B.39.

To apply the output of a test surge generator to a powered EUT, it is almost always necessary to use a surge coupling device, also called a ***coupler.*** The coupler should conduct the surge energy, with reasonable ***waveform*** fidelity, from the test surge generator into the EUT.

The requirements for appropriate coupling include the following:

a) Minimizing cross-loading and power dissipation in the surge generator output network. Appropriate impedances in the coupler should be provided.

b) Permitting the EUT to function normally before and after the test surge. ***Coupling gaps*** can also be used to provide coupling of the generator only during the surge.
c) Permitting different modes of coupling, as required by the test schedule.
d) Providing bleeder action to discharge any residual voltage trapped inside the EUT after the test.

7.3 Impedance considerations

In general, the output impedance of a test surge generator will be that of its output wave-shaping network as seen through the coupler. Because such networks usually involve inductors and capacitors, the output impedance will be complex, involving both a real and an imaginary component.

For convenience, an ***effective output impedance*** is defined for a surge generator and its coupler, if appropriate, by calculating the ratio of peak open-circuit output voltage (OCV) to peak short-circuit output current (SCI), or as an OCV/SCI ratio at the injection points. Ideally, this impedance, when combined with the ***back filter*** impedance, should represent the ac power system impedance for the incoming surge (Bull 1975 [B3], Standler 1989 [B30]). Typical values range from near 0 Ω at the power-line frequency to 200 Ω above 100 kHz.

In the case of the EFT test, however, the present test procedure (IEC 61000-4-4) [B9] does not call for an available short-circuit current or source impedance, but only for a verification of the waveform when connected to a 50 Ω load.

7.4 Requirements for surge decoupling

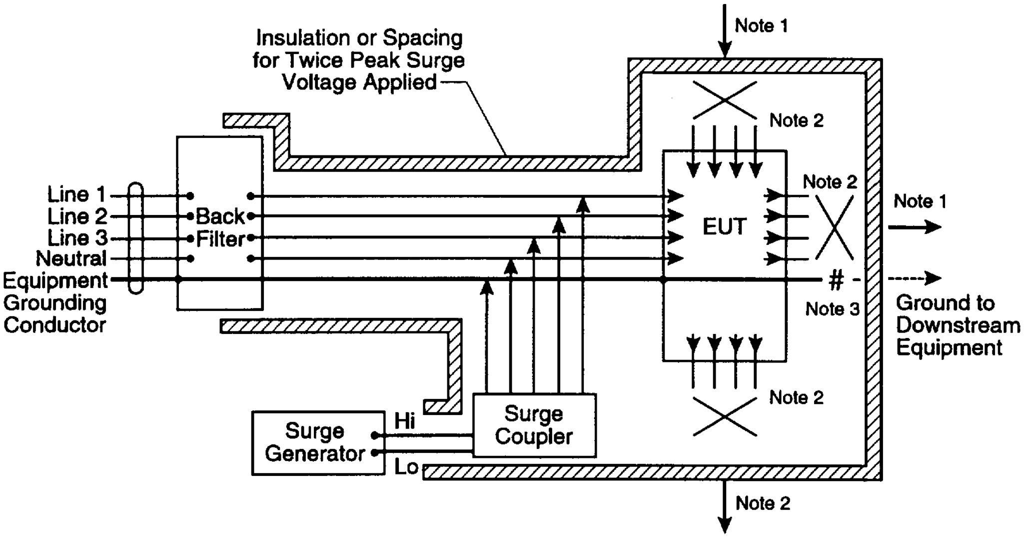
The simplified surge coupling of Figure 8 and Figure 7 shows the requirements of back filters and decoupling. Without these devices, the low line impedance of the ac supply would load the generator and prevent it from delivering the full voltage. Furthermore, all other equipment connected to the same power line would be subjected to the surge, with attendant equipment damage and personnel hazard resulting. Further yet, some other equipment connected to the line might include a surge-protective device, defeating the test. Thus, surge decoupling, generally in the form of surge filters in the power line (referred to as ***back filter*** or decoupling network), is required to eliminate these limitations. However, the insertion of a filter raises the question of reduced available ***fault current*** because of the added impedance of filters.

It is necessary to use back filters in all lines into and out of the EUT, excluding the ***equipment grounding conductor***, that will not be disconnected for the surge tests. Note that the EFT Burst procedure calls for including the “protective earth” (PE in Figure 18) conductor in the decoupling network. To avoid possible damage to interconnected equipment, leads to such equipment should be disconnected, and the associated EUT port should be terminated with a representative equivalent circuit.

The neutral conductor is treated just like the other lines; that is, the back filter should decouple it from ground during testing. This conductor might, in fact, be the most susceptible of the connections to the EUT. In practice, the neutral is bonded to the grounding conductors at the service panel of the facility so that any perturbation suffered by the neutral wire is transmitted to some degree to the equipment grounding conductor either by direct connection or by induction, or both.

Although the signal lines into or out of the EUT are technically outside of the scope of this recommended practice, their presence should be recognized. As shown in Figure 10, they should be disconnected, back filtered, or reterminated with impedances or grounds that simulate operating conditions.

The presence of these filters or connections might produce some interference with ***ground fault protection*** systems in the test laboratory, a possibility that should be recognized.



NOTES
1—Signal or power conductors, or both, to other equipment
2—The symbols (X) indicate one or more of the following:
  a) Complete disconnect of the conductors
  b) Insertion of a surge filter similar to the back filter
  c) Disconnect of the conductors, with addition of a representative termination
3—The symbol (#) indicates disconnection of grounding conductors to downstream equipment in order to avoid passing on a surge. However, a grounding connection to that downstream equipment must be re-established, bypassing the EUT test setup, except in the case shown in Figure 11.

Figure 10—EUT being surge tested, showing required interfaces, filters, or reterminations

7.5 Surge coupling

For a given number of lines in the mains, there are several ways that a test surge may be applied. The type of the coupling also affects the selection of the lines to which the surge is applied.

For shunt coupling, as shown in Figure 7, the surges can be applied between any group of conductors:

- Line(s) to neutral
- Line(s) to line(s)
- Line(s) to ground
- Neutral to ground
- [Line(s) and neutral] to ground
- Line(s) to [neutral and ground]

For test purposes, usually the low terminal of an ungrounded test surge generator is connected directly to one of the power lines or to the equipment grounding conductor. The surge generator high terminal is then connected to the other power line(s) via capacitors. A separate capacitor is used for each line. Note that the use of capacitors presents the hazard of trapped charges after the test; bleeders or discharge interlocks should be provided.

For series coupling, the surges can be applied in series with one conductor, as shown in Figure 8, by inserting the secondary of the coupling transformer in the line or some other conductor.

In all cases, surge testing should be performed with both polarities.

Tests should be performed with surges applied between each group of conductors to evaluate the capability of an EUT to withstand the surges in all possible coupling modes that can be encountered in its field application. In the case of a test for the EFT Burst, the coupling of the surge will be limited to various combinations of conductors with respect to the ground reference plane.

7.5.1 Testing a single piece of equipment

It is necessary to use back filters in all lines into and out of the EUT, excluding the equipment grounding conductor, that will not be disconnected for the surge tests. (Note that the EFT Burst procedure calls for including the protective earth conductor in the decoupling network.) To avoid possible damage to interconnected equipment, leads to such equipment should be disconnected, and the associated EUT port should be terminated with a representative equivalent circuit.

As indicated in Figure 10, when surge testing the EUT by itself, the interconnections to other equipment must be removed to eliminate the possibility of damaging them. This arrangement is the usual practice in the initial evaluation of new designs. If the connections are necessary for the proper operation of the EUT, filters similar to the back filters may be used or special filters may be employed that afford surge isolation but do not corrupt the operation of the communications required by the EUT. It might be necessary to terminate some input/output (I/O) connections with representative equivalent circuits.

Although the signal lines into and out of the EUT are technically outside the scope of this recommended practice, their presence should be recognized. This recommended practice does not consider signal lines that leave the immediate environment of the host system. This recommended practice does consider the intra-system signal lines among the components of the system that are essentially connected to the same power distribution and grounding system within the same building or location.

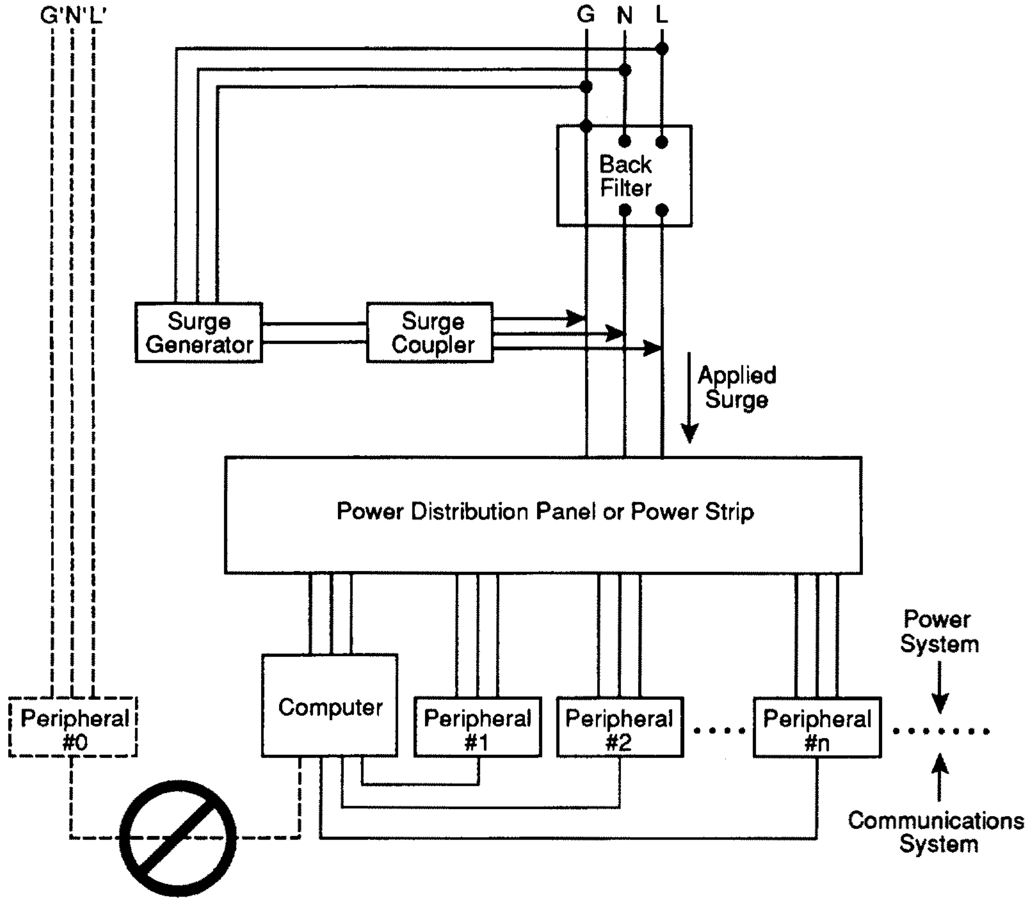
7.5.2 Testing a system

The information in 7.5.1 is applicable to the surge testing of an individual assembly or module that can be part of an interconnected system. In order to evaluate the surge withstand capability of a complete system, such as a computer together with its terminals, printers, and other peripherals, it is necessary to configure the system with back filters in the power lines only, as shown in Figure 10. In this configuration, the surge is applied to all the modules simultaneously.

Lightning-induced surges usually involve all modes of coupling on all conductors of the mains. These surges perturb all the lines in the system power distribution, including the grounding conductors. The resulting voltage perturbations stress both the input power circuits and the interface circuits that are connected to the communications cables. Experience in the field has shown that in a majority of cases, the communications interface circuits are the most susceptible to surges on the input power lines or the ground, or both (Martzloff 1990 [B16]). This test evaluates primarily the ***susceptibility*** of the complete computer-based system to a power-line surge and its impact on the internal communications lines interface circuits.

The typical system shown in the schematic of Figure 11 does not include a modem, local area network (LAN) interface, nor similar connections to external systems. These other interfaces very often introduce an additional ill-defined grounding point into the system under test. They also bear a significant burden when the input power lines or grounding conductors are subjected to the normal lightning-induced voltage surges or ground voltage differentials. The telephone lines might be equipped with surge protectors, but the ***surge remnant*** levels of the latter could be too high to protect the low-voltage communications circuits in modems.

Although some actual field installations might be implemented with the configuration shown for Peripheral #0 in Figure 11(at some risk to the equipment), such a configuration is not recommended for surge testing. For surge testing (as well as for field installation), other methods of connecting Peripheral #0 to the rest of the system should be used.



NOTES

1—Power lines and communication cables in the test setup should be at their maximum specified length for the application.

2—The system equipment layout should approximate an installed working system.

3—The connection of Peripheral #0 would introduce a different set of power-line voltage references, and the absence of back filter on the power line would be a hazard. Such a configuration is not recommended for surge testing.

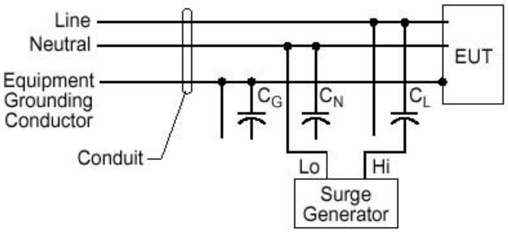
Figure 11—Configuration for surge testing a complete system

7.5.3 Single-phase system

In single-phase power systems, the EUT is powered either by two wires, line and neutral (see Table 2), or by two lines plus a center-tapped neutral (see Table 3). In both cases, an equipment grounding conductor might or might not be present.

Tests marked “Basic” in Table 2 and Table 3 should generally be performed. Tests marked “Supplemental” in Table 2 and Table 3 may be performed to obtain additional information on ***vulnerability*** of the EUT to surges. The tests marked “Diagnostic” in Table 2 and Table 3 may be performed in the course of a major investigation (Richman 1979 [B21]).

Table 2—Selected coupling for single-phase systems (one line and neutral with equipment grounding conductor)

	Connection of generator			**Example of connection diagram for shunt coupling, Basic 2**
Test type	**Ground**	**Neutral**	**Line**	
Basic 1 Basic 2	L_O	H_N L_O	H_H H_H	
Supplemental 1 Supplemental 2	L_O L_O	H_N	 H_H	
Diagnostic 1 Diagnostic 2	H_G H_G	H_N L_O	L_O H_H	

LEGEND

L_O = Connection to surge generator low (Lo)

H_G = Connection to surge generator high (Hi)

H_N = Connection to surge generator high (Hi) by coupling capacitor C_N

H_H = Connection to surge generator high (Hi) by coupling capacitor C_1

NOTES

1—For each test type shown in the table, the surge generator is to be connected as indicated in the “Connection of Generator” columns. The connection diagram shown in the table shows an example of the jumpers required to obtain the shunt coupling for test Basic 2.

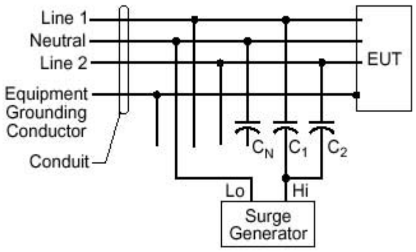
2—When several Hs appear on one horizontal line of the table, shunt coupling requires several capacitors, shown as C_G, C_N, and C_1, between each of the conductors indicated and the surge generator high, in order to apply the surge simultaneously to all the conductors involved.

Table 3 does not show a full complement of ***diagnostic tests***. Additional diagnostic tests can be useful in testing specific EUTs (see B.13 and B.14).

7.5.4 Three-phase system

In three-phase systems, from three to five wires might be involved. Tests marked “Basic” in Table 4 should generally be performed. Tests marked “Supplemental” may be performed to obtain additional information on vulnerability of the EUT. Tests marked “Diagnostic” in Table 4 may be performed in the course of a major investigation. Table 4 does not show a full complement of diagnostic tests. Additional diagnostic tests can be useful in testing specific EUTs (see B.13).

Table 3—Selected coupling for single-phase systems (two lines and neutral with equipment grounding conductor)

	Connection of Generator				**Example of connection diagram for shunt coupling, Diagnostic 1**
Test type	**Ground**	**Neutral**	**Line 1**	**Line 2**	
Basic 1	L_O	H_N	H_1	H_2	
Basic 2		L_O	H_1		
Basic 3		L_O		H_2	
Supplemental 1	L_O	H_N			
Supplemental 2	L_O		H_1		
Supplemental 3	L_O			H_2	
Diagnostic 1		L_O	H_1	H_2	
Diagnostic 2	L_O		H_1	H_2	

LEGEND

L_O = Connection to surge generator low (Lo)

H_N = Connection to surge generator high (Hi) by coupling capacitor C_N

H_1 = Connection to surge generator high (Hi) by coupling capacitor C_1

H_2 = Connection to surge generator high (Hi) by coupling capacitor C_2

NOTES

1—For each test type shown in the table, the surge generator is to be connected as indicated in the "Connection of Generator" columns. The connection diagram shown in the table shows an example of the jumpers required to obtain the shunt coupling for test Diagnostic 1.

2—When several Hs appear on one horizontal line of the table, shunt coupling requires several capacitors, shown as C_N, C_1, and C_2, between each of the conductors indicated and the surge generator high, in order to apply the surge simultaneously to all the conductors involved.

8. Grounding

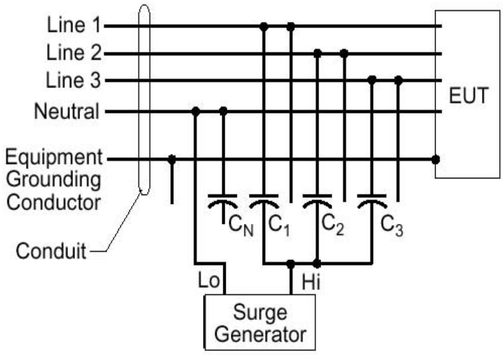
8.1 Grounding precautions

CAUTION

Because the voltages involved in surge testing are hazardous, appropriate precautions are required for grounding equipment other than the *EUT* and for personnel.

One basic precaution is the correct application of ***equipment grounding conductors*** in the test setup. Barriers or separation between the EUT and other parts accessible to personnel can be used; however, the most effective protection is obtained by grounding surrounding objects and having one point of the test circuit maintained at this safety ground potential.

Table 4—Selected coupling for three-phase systems (three-phase wires and neutral with equipment grounding conductor)

	Connection of Generator					Example of connection diagram for shunt coupling, Diagnostic 1
Test type	**G**	**N**	**Line 1**	**Line 2**	**Line 3**	
Basic 1	L_O	H_N	H_1	H_2	H_3	
Basic 2			L_O	H_2		
Basic 3				L_O	H_3	
Basic 4			H_1		L_O	
Supplemental 1	L_O	H_N				
Supplemental 2	L_O		H_1			
Supplemental 3	L_O			H_2		
Supplemental 4	L_O				H_3	
Diagnostic 1		L_O	H_1	H_2	H_3	
Diagnostic 2	L_O		H_1	H_2	H_3	

LEGEND

L_O = Connection to surge generator low (Lo)

H_N = Connection to surge generator high (Hi) by coupling capacitor C_N

H_1 = Connection to surge generator high (Hi) by coupling capacitor C_1

H_2 = Connection to surge generator high (Hi) by coupling capacitor C_2

H_3 = Connection to surge generator high (Hi) by coupling capacitor C_3

NOTES

1—For each test type shown in the table, the surge generator is to be connected as indicated in the “Connection of Generator” columns. The connection diagram shown in the table shows an example of the jumpers required to obtain the shunt coupling for test Diagnostic 1.

2—When several Hs appear on one horizontal line of the table, shunt coupling requires several capacitors, shown as C_N, C_1, C_2, and C_3, between each of the conductors indicated and the surge generator high, in order to apply the surge simultaneously to all the conductors involved.

Figure 4 and Figure 5, discussed in Clause 5, show the recommended test circuit configurations for applying and ***monitoring*** the surge, with safe connections of the oscilloscope (no ground connection of the probe).

In test facilities where there are permanently connected equipment grounding conductors, always check for possible defects in the ground system before each surge test. For instance, in U.S. installations regulated by the NEC ®[9] (ANSI/NFPA 70-1999), all grounding should comply with this Code. The equipment grounding conductors and the neutral conductors must be bonded together at the output of every separately derived source. This bond must not be broken. See also Figure B.8(b) in B.18.

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[9] NEC ® is a registered trademark of the National Fire Protection Association, Inc.

All other connections to equipment that are not part of the EUT must be removed (see Figure 10 and Figure 11). If it is not possible to do so, then the connections should be filtered like the lines actually being surged, because flashover occurring within the EUT might be conducted to any port. To ensure proper testing of internal insulation, these terminals might have to be locally reterminated with impedances or grounds that simulate operating conditions.

The test equipment must include a ***back filter*** or decoupling network to prevent surges from disturbing the power line. If a ground fault circuit interrupter (GFCI) is used, the filters are likely to cause operation of the GFCI. An isolation transformer might be required to avoid this problem. However, the safety ground is to be bonded to the EUT grounding stud or equivalent.

8.2 Grounding practices in EUTs

Electronic circuits are grounded for three basic reasons:

1) *Safety.* Safety grounds with low impedance provide return paths to the current source for ***fault currents***, thereby ensuring the rapid and reliable operation of overcurrent protective devices. The application of common grounds also provides equalization of equipment potentials to improve personnel protection.
   When this function is associated with ac power faults, the term *earth ground* is sometimes used to distinguish the safety ground of the EUT from other usages of the generic term *ground*, and the establishment of such a connection between equipment chassis and earth ground may be called *earthing*.
2) *Signal Voltage Reference*. The concept of a signal, circuit, or logic ground relates to a common equipotential reference against which the various circuit components operate, thereby ensuring that the intended signal voltage levels are consistently and properly recognized throughout the equipment. The relationship between this common reference and the equipment chassis or frame is a function of the equipment design and its intended operating conditions.
3) *Static Charges*. Grounding provides a means for bleeding off electrostatic charges.

In surge testing, safety precautions are of prime importance because surge testing involves the use of potentially dangerous voltages along with the necessity of making accurate measurements. For these reasons, it is imperative that the grounding configuration, not only of the EUT, but also of the entire test setup, be understood.

Unfortunately, the two requirements for grounding are not always compatible. Power safety grounds (also known as “equal potential grounds” or “protective earth”) are often very noisy, thereby limiting their use as signal references. Also, signal reference grounds are sometimes required to be at some potential other than earth, whereas power safety ground is generally referenced to earth. Equipment grounding configurations found in EUTs tend to fall into one or some combination of three general schemes: floating reference, single-point ground, and multiple-point ground. These considerations are discussed in detail in B.23.

9. Standard surge tests waveforms

9.1 General

From the wide range of test waveforms proposed or specified in the literature, only the five identified in IEEE Std C62.41.1-2002 are defined in Clause 9 and Clause 10. Waveforms other than those mentioned in this recommended practice might be required for specific situations, in which case an appropriate definition should be obtained from the sponsor specifying that waveform. The six waveforms defined in this recommended practice are the following:

Clause 9:

- The 100 kHz Ring Wave (standard waveform)
- The Combination Wave (two standard waveforms)

Clause 10:

- The EFT Burst (additional waveform)
- The 10/1000 µs Long Wave (additional waveform)

Informative Annex A:

- A 10/350 µs (optional waveform), cited as a possible representation of the Class I test parameters

Experience has shown that improvised surge generators, while they can produce stresses useful for in-house immunity evaluation (Buschke 1988 [B4]), do not produce waveforms that can be easily reproduced in other laboratories. The output waveforms of improvised generators built from a published circuit are often dominated by parasitic components and do not produce the desired waveforms. Improvised generators might also lack critical safety features. Therefore, this recommended practice provides precise information on desired waveforms, but it does not provide descriptions of circuits for surge generators.

It is important to recognize that the open-circuit voltage waveforms and short-circuit waveforms given in the definitions of the surge test waveforms will generally not be obtained when a load is connected to the surge generator. In particular, the presence of an effective surge-protective device will drastically alter the voltage waveform (Standler 1989 [B29]).

9.2 Standard waveforms

The two standard ***waveforms*** recommended by IEEE Std C62.41.2-2002 are the 100 kHz Ring Wave and the 1.2/50 µs–8/20 µs Combination Wave (the latter involving two waveforms, one for voltage and the other for current). Plots of the three nominal waveforms (one for the Ring Wave, two for the Combination Wave) are shown in Figure 12, Figure 13, and Figure 14. Criteria for selection of the peak voltages and currents corresponding to various environmental exposures are discussed in IEEE Std C62.41.1-2002 and IEEE Std C62.41.2-2002.

The implications for ***test conditions*** are discussed in B.44. Detailed descriptions, including tolerances and equations for these two standard waveforms, are given in the two following subclauses.

9.2.1 The 0.5 µs–100 kHz Ring Wave

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

- Rise time: 0.5 µs ± 0.15 µs
- Ringing frequency: 100 kHz ± 20 kHz

The amplitude will decay so that the amplitude ratio of adjacent peaks of opposite polarity is as follows: The ratio of the second peak to the first peak is between 40% and 110%. The ratio of the third peak to the second peak and of the fourth peak to the third peak is between 40% and 80%. A plot of the nominal 100 kHz Ring Wave is shown in Figure 12.

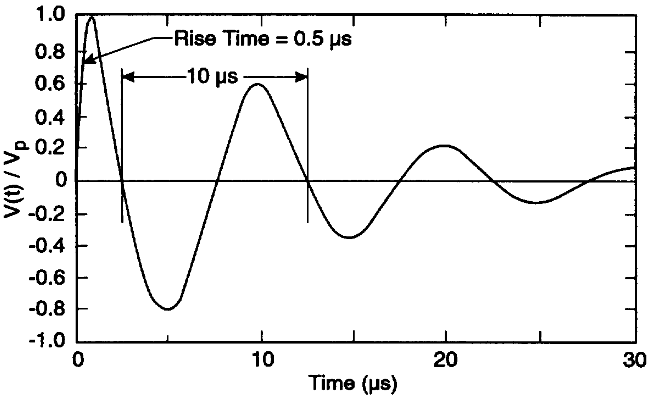


Figure 12—Nominal waveform of the 100 kHz Ring Wave

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, within a tolerance of ±10%.

The ratio V_p / I_p is specified as 12 Ω ± 3 Ω for simulation of the Location Category B environments or 30 Ω ± 8 Ω for simulation of the 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 defined according to the location category. Because the purpose of this Ring Wave is not to provide high-energy stress to the ***equipment under test (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 *di/dt*, 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 IEEE Std C62.41 specified a nominal decay rate of amplitude of 60% between adjacent peaks of opposite polarity, but no tolerances were specified. It is not possible to obtain the 60% ratio of amplitude of the second to the first peak, while also obtaining the 60% ratio between subsequent peaks with a simple damped cosine waveform (Standler 1988 [B28]). As a result, the wave shape of the first cycle of the Ring Wave varied dramatically among different models of commercially available surge generators (Standler 1989 [B29]), because different circuit designs of the waveshaping network were used in an attempt to meet the specifications for the nominal waveform.

When tolerances were added to the 1991 edition of IEEE Std C62.41, 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 Ring Wave generators use the damped cosine waveform defined by the equation in Table 5.

There is no requirement set on the amplitude of the Ring Wave beyond the fourth peak. The amplitude of the fifth and following peaks is so much smaller than the initial peak that they should have little effect on even the most vulnerable or susceptible equipment.

The frequency of oscillation of this waveform might 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.

9.2.2 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 to which the surge is applied. A plot of the nominal open-circuit voltage is shown in Figure 13 and a plot of the nominal short-circuit current is shown in Figure 14.

Open-circuit voltage waveform:

- Front time: 1.2 µs ± 0.36 µs
- Duration: 50 µs ± 10 µs

The front time for voltage waveforms is 1.67 ($t_{90} - t_{30}$), where t_{90} and t_{30} are the times of the 90% and 30% amplitude points on the leading edge of the waveform, as defined in IEC 60060-2 (1994) and IEEE Std 4-1995.

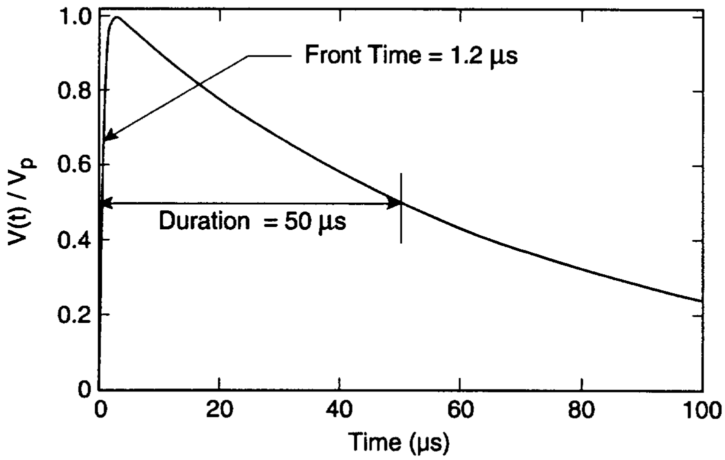


Figure 13—Combination Wave, open-circuit voltage

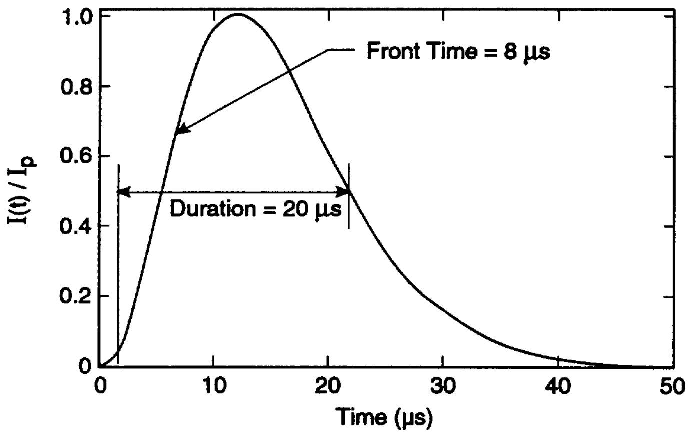


Figure 14—Combination Wave, short-circuit current

The duration is defined as the time between virtual origin and the time of the 50% 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.

Short-circuit current waveform:

- Front time: 8 µs (+1.0, –2.5) µs
- Duration: 20 µs (+8, –4) µs

The front time for current waveforms is 1.25 $(t_{90} - t_{10})$, where t_{90} and t_{10} are the times of the 90% and 10% amplitude points on the leading edge of the waveform, as defined in IEC 60060-2 (1994) and IEEE Std 4-1995.

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. Figure 15 shows these features of the nominal 8/20 µs waveform.

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, with a tolerance of ±10%.

The effective source impedance, the ratio V_p/I_p, is specified as 2.0 Ω ± 0.25 Ω. This ratio determines the behavior of the waveform when various loads, such as surge-protective devices, are connected to the generator.

Traditionally, the 1.2/50 µs voltage waveform was used for testing the basic impulse level of insulation (BIL), which is approximately an open circuit until the insulation fails. The 8/20 µs current waveform was used to inject large currents into surge-protective devices. 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 (Richman 1983 [B21], Wiesinger 1983 [B34]).

The tolerances for the 8/20 µs current waveform are broader than those in IEC 60060-2 (1994) and IEEE Std 4-1995. The tolerances in those standards are for an 8/20 µs current waveform without specifying the open-circuit voltage. These other standards also do not include the effects of a ***back filter*** and coupling network, as required here.

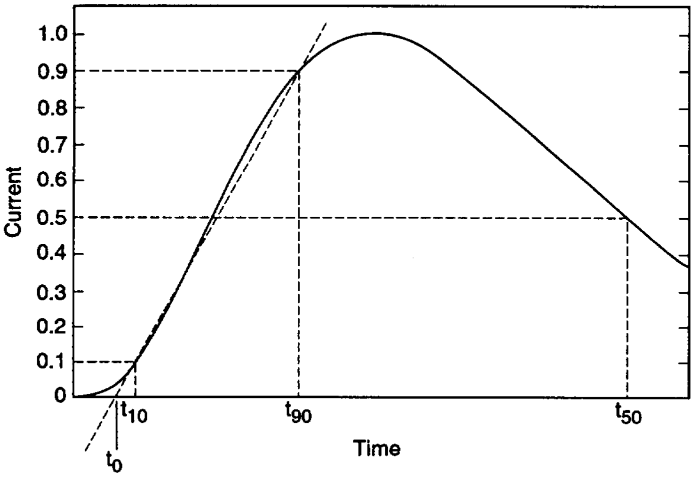


Figure 15—Features of the nominal 8/20 µs waveform: Front time, virtual origin, and duration

9.3 Test procedures

Because of the effects produced by the back filter and the coupling network, it is necessary that the surge ***waveform*** specifications for both the 0.5 µs–100 kHz Ring Wave and the 1.2/50 µs–8/20 µs Combination Wave be verified with back filter connected and coupling network used to apply the surge. An initial verification should be made of the following conditions:

a) The surge generator is connected to the ***back filter*** via the coupling network in the relevant coupling mode.
b) All of the conductors of the mains connection that supply the back filter, including protective ground, are disconnected from the mains and shorted together at a point upstream from the back filter.

By shorting the mains upstream from the back filter (prior to the actual powered test), the effects caused by differing impedances of the mains from one laboratory to another are avoided. Allowing the ac supply mains to be disconnected and simulating the low impedance of the mains by shorting the conductors together is the recommended procedure to determine peak voltage and current.

In this manner, the available short-circuit surge current and the open-circuit surge voltage (as defined in 9.2.1 and 9.2.2) at the ***EUT*** power-line interface can be readily verified. Note, however, that this procedure establishes the voltage peak of the surge alone.

During testing of powered equipment or components, the surge waveform may be applied at any specified phase angle of the normal mains waveform. The timing of the surge application with respect to the power-frequency sine wave will then determine the peak of the total surge. Because this total surge is the significant parameter in the response and stress of a clamping type of surge-protective device, this effect must be recognized in setting the surge amplitudes for low-level surge testing. With surge levels in the kilovolt range, the variation introduced by the value of the sine-wave voltage at the instant of the surge application is less significant.

In tests where the value of *di/dt* is large (such as the 8/20 µs current waveform or the 100 kHz Ring Wave with its relatively short rise time), it is particularly important to use short lengths of conductors and maintain minimum conductor loop area between the surge generator and device under test.

9.4 Equations for standard waveforms

Mathematical representations of the nominal ***waveforms*** are given in Table 5. These equations, and the value of the time constants, are useful for designing surge generators and for simulations of surge performance on digital computers (Standler 1988 [B28]).

A test waveform in the laboratory will, of course, not exactly match the waveform given by the equations for the nominal waveform, due to the tolerances of components in pulse-forming networks and parasitic inductances and capacitances in the components of both generators and test fixtures.

The loading by the ***EUT*** might cause appreciable discrepancy between the preset nominal open-circuit voltage or short-circuit current and the actual voltage across or current in the load. This effect is the reason why surge waveform parameters are not specified with the EUT connected. In computer simulations, some of the loading effects can be taken into account by including the ***effective output impedance*** V_p/I_p with the ideal voltage or current source.

Typical generators for the Combination Wave, especially when the connections to the EUT add some inductance, produce an “undershoot” in the current delivered to a typical EUT, rather than the textbook critically damped unidirectional impulse of the 8/20 µs waveform. When performing numerical simulations with cross validation by an actual test, it may be more appropriate to use a highly damped sine wave, which can be defined by an equation that will mimic the undershoot produced in the laboratory by the [surge generator + EUT] circuit.

However, a simple damped sine wave has an abrupt start—*di*/*dt* at the origin is not zero, a situation that can produce artifacts in numerical simulations. To alleviate this situation, proposals have been made (Mansoor and Martzloff 1997 [B13]) to add a factor $\{1 - e^{(-t)}\}$ to the 8/20 µs equation, which produces a “gentle toe” on the wave. Such a waveform is closer to real-world surges than is the abrupt simple sine wave. For instance, to simulate the injection of a 3 kA 8/20 µs surge with undershoot and a gentle toe, the equation becomes [Equation (1)]:

$$I = 4200 \times \sin(0.126t) \times e^{(-t/28.1)} \times [1 - e^{(-t)}] \tag{1}$$

With I in amperes and t in microseconds.

Table 5—Equations for standard waveforms

0.5 µs–100 kHz Ring Wave

$$V(t) = AV_p\left(1 - \exp\frac{-t}{\tau_1}\right)\exp\left(\frac{-t}{\tau_2}\right)\cos(\omega t)$$

where

τ_1	is 0.533 µs
τ_2	is 9.788 µs
ω	is 2 ¼ 10^5 rad/s
A	is 1.590

8/20 µs Wave

$$I(t) = AI_p t^3 \exp\left(\frac{-t}{\tau}\right)$$

where

τ	is 3.911 µs
A	is 0.01243 $(\mu s)^{-3}$

1.2/50 µs Wave

$$V(t) = AV_p\left(1 - \exp\frac{-t}{\tau_1}\right)\exp\left(\frac{-t}{\tau_2}\right)$$

where

τ_1	is 0.4074 µs
τ_2	is 68.22 µs
A	is 1.037

NOTE—In all the equations above:

t	is time
V_p	is maximum or peak value of the open-circuit voltage
I_p	is peak value of the short-circuit current

10. Additional surge test waveforms

10.1 General

This clause involves the additional ***waveforms*** defined in IEEE Std C62.41.2-2002. The specific discussion of standard waveforms is given in Clause 9. See 9.1 for a general discussion of test waveforms.

10.2 Additional waveforms

The two additional ***waveforms*** are the EFT Burst and the unidirectional 10/1000 µs Long Wave. Each of these waveforms has a unique domain of application (respectively, contactor interference, fuse operation, and load switching). Consequently, the waveform definition and the test procedures are discussed separately for each waveform. Plots of the nominal waveforms are shown in Figure 16, Figure 17, and Figure 21.

Another family of additional test waveforms may also be considered for the case of capacitor switching. As discussed in 10.2.3, capacitor switching should be a case-by-case subject.

10.2.1 The EFT Burst

This waveform consists of repetitive bursts, with each burst containing individual unidirectional pulses. This waveform has been proposed 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. They should not be construed as actual voltage levels occurring in the mains.

The characteristics of this waveform and the corresponding test procedures are summarized in the following paragraphs, based on the specifications of IEC 61000-4-4 (1995) [B9]. However, readers are cautioned that IEC documents are subject to periodic revision. Therefore, any detailed plan for specific tests calling for the EFT should be based on the current edition of the IEC document, not on the description provided herein.

10.2.1.1 Waveform definition

The individual EFT pulses within a burst are defined as follows:

- Rise time: 5 ns ± 1.5 ns
- Duration: 50 ns ± 15 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 ± 3 ms. Within each burst, the repetition rate of pulses is specified as a function of the peak open-circuit voltage, as follows:

- For peaks ≤ 2 kV: 5 kHz ± 1 kHz
- For peaks > 2 kV: 2.5 kHz ± 0.5 kHz

These two values of the repetition rate are specified in IEC 61000-4-4 (1995) [B9] and reflect only limitations in inherent performance of pulse generators, not a characteristic of the environment.

The period of the repeated bursts is 300 ms ± 60 ms. A plot of a single pulse is shown in Figure 16, and the burst pattern is shown in Figure 17.

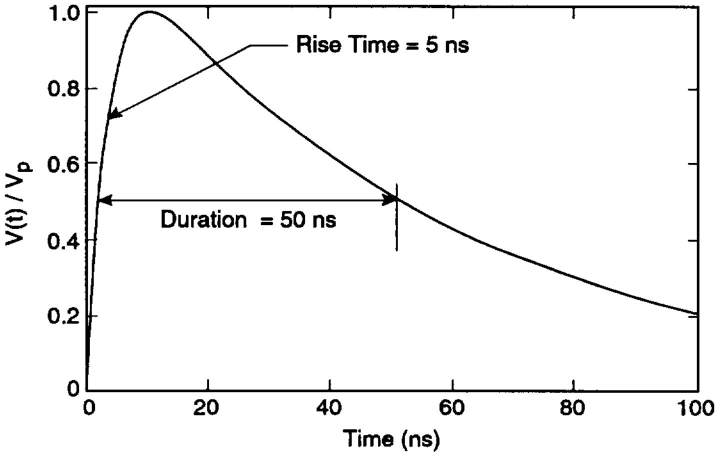


Figure 16—Waveform of the EFT pulse

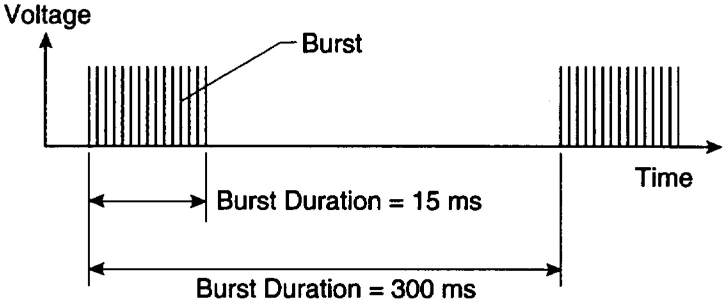


Figure 17—Pattern of EFT Bursts

10.2.1.2 Amplitude

The amplitude of the EFT pulses is specified by IEC 61000-4-4 (1995) [B9] in an open-circuit condition, but the waveform is specified for a generator connection to a 50 Ω load. The generator is defined as having a 50 Ω source impedance between 1 MHz and 100 MHz. However, the voltage without the 50 Ω load is not defined (Richman 1991 [B24]).

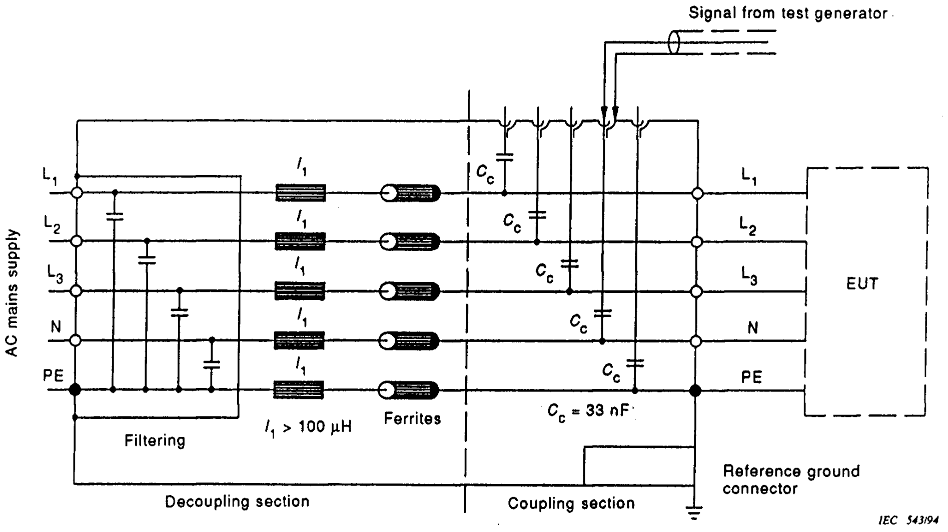
The resulting current, when the pulses are applied to the ***equipment under test (EUT)*** according to the methods described below, is not defined because it will depend on the impedance exhibited by the EUT at the frequencies associated with the EFT waveform. Because the purpose of the test is to evaluate interference immunity, not energy capability, the specification of a current amplitude is not essential. Given this definition of the test level, the specific value is to be selected by the parties involved according to the severity desired, with a tolerance of ± 10%.

In IEC 61000-4-4 (1995) [B9], 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. Because the additional waveforms defined in IEEE Std C62.41.2-2002 are only suggestions, the provision that other levels may be selected is implicit.

10.2.1.3 Test procedures

The coupling methods for the EFT test are specified in IEC 61000-4-4 (1995) [B9], from which the essential characteristics are cited in the following paragraphs. Two coupling methods are specified, depending on the nature of the EUT interface cable.

One method, in particular for single and polyphase ac interfaces, uses direct coupling to each of the cable conductors selected by discrete capacitors (Figure 18). The other method uses a “coupling clamp” that in fact also produces capacitive coupling to the interface cable on which the clamp is installed, in a global coupling mode (Figure 19).



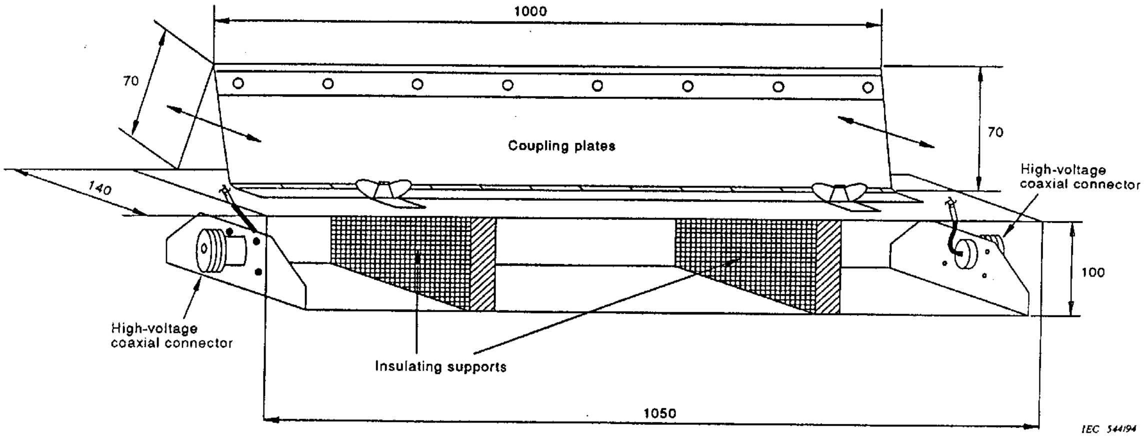
(Example: Construction for three-phase lines, d.c. lines/terminals shall be treated in a similar way.)

Warning: The construction and application of the coupling/decoupling network shall be such that existing national safety regulations will not be violated.

Source: IEC 61000-4-4:1995

Figure 18—Direct coupling of EFT pulses into the ac mains connection of the EUT

Thus, both coupling methods result in having a capacitive divider (coupling capacitor and internal capacitance of the EUT) that applies the pulses at the port of the EUT (Martzloff and Leedy 1990 [B19]). The actual value of the pulse applied at the EUT port is influenced by the internal design of the EUT (Figure 20); it is not a fixed parameter imposed on the EUT. Even the external arrangement of the EUT, including cable dressing and enclosure position with respect to the reference ground plane, will affect the capacitive coupling. The configuration of the test setup, therefore, must be clearly specified and documented.



Dimensions in millimetres

Warning: The distance of the coupling section to all other conductive constructions except to the cable under test and the ground plane shall be more than 0,5 m.

Source: IEC 61000-4-4:1995

Figure 19—Coupling clamp for EFT test

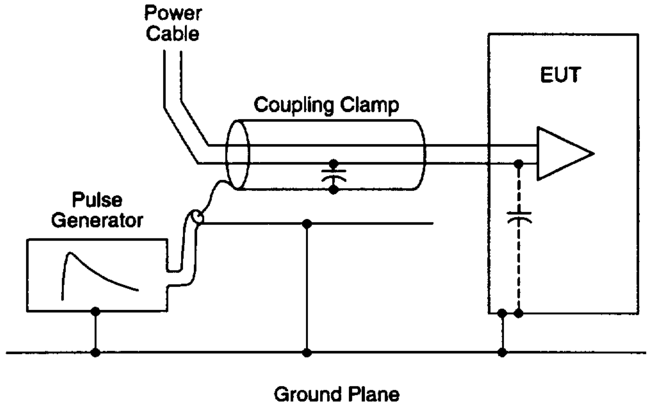


Figure 20—Capacitive divider effect in EFT test

10.2.2 The 10/1000 µs Long Wave

10.2.2.1 Waveform definition

The front time and duration of this wave are the following:

Open-circuit voltage:

- Front time: 10 µs (+0, –5) µs
- Duration: 1000 µs (+1000, –0) µs

Short-circuit current:

- Front time: 10 µs (+0, –5) µs
- Duration: 1000 µs ± 200 µs

See 9.2.2 for definitions of front time and duration.

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 [B28]). Because the major purpose of this waveform, in the present context, is to provide an energy stress, the differences between rise time, time to peak, and front time are negligible. A plot of the nominal current is shown in Figure 21.

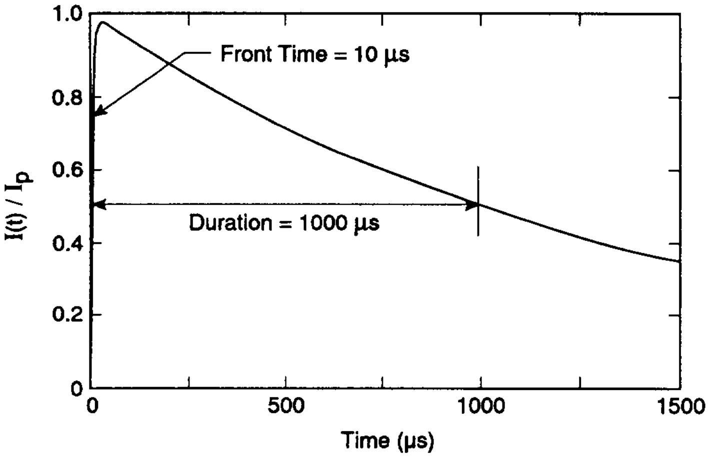


Figure 21—Waveform of the 10/1000 µs current surge

10.2.2.2 Amplitude

There is a major difference in the application of this waveform compared with that of the two standard waveforms: the concept of location categories in IEEE Std C62.41.2-2002 that was used for the standard waveforms is no longer applicable. (That concept is based on the limiting effect of the inductance of branch circuits at the frequencies associated with the two standard waveforms, presumed to have a decreasing severity as distance from the service entrance increases.) The long duration of the 10/1000 µs waveform reduces the effect of inductance. However, depending on the environment exposure of the site, there is still a range of levels to be considered, as discussed in IEEE Std C62.41.2-2002.

The amplitude of the peak open-circuit voltage is to be selected by the parties involved, according to the severity desired, with a tolerance of ±10%.

It should be noted, however, that the relatively low peak voltage of this waveform, compared with clamping levels of surge-protective devices in common use (Martzloff and Leedy 1989 [B18]), has important implications on the outcome of a test involving such nonlinear devices. The combination of a ±10% tolerance on the applied surge and the manufacturing tolerance on the surge protector can spell the difference between survival or failure of the device (Fenimore and Martzloff 1992 [B5]). Therefore, a careful review of the tolerance combinations when planning for a 10/1000 µs test is imperative.

10.2.2.3 Test procedures

The preferred test method for standard waveforms is ***powered testing***, as discussed in this recommended practice and in IEEE Std C62.41.2-2002. However, the 10/1000 µs test waveform is suggested primarily for its high-energy characteristic, stressing any surge-protective device that an EUT might contain. The long duration of the wave makes a conventional ***back filter*** difficult to implement.

As discussed in 7.2 of IEEE Std C62.41.2-2002, two different approaches may be considered for testing with the 10/1000 µs Long Wave:

a) **Unpowered test:** This is the most likely purpose, aimed at evaluating the energy-handling capability of an SPD. This test may be conducted by using a conventional surge generator—capable of delivering the specified open-circuit voltage or short-circuit current, in a direct coupling mode (Figure 6). However, the outcome of such a test does not address concerns such as pre-surge stress, additive effect of the mains voltage and specified surge (a phase-dependent effect), failure modes, or the need to have the EUT operational.

b) **Powered test:** This test may be performed to evaluate the performance of an SPD or load equipment, while connected to the ac mains, to alleviate the limitations of an unpowered test. Because it cannot be conducted with a conventional surge generator and a back filter, the test method would be to provide an amplified arbitrary waveform (Figure 9) where the power amplifier has the capability of delivering the specified open-circuit voltage or short-circuit current. To remain under a reasonable envelope for the power rating of the amplifier, this capability may be limited to one parameter only at a time, voltage or current, depending on the effective impedance of the EUT under the surge condition.

The arbitrary waveform with amplifier method is a radical departure from the classical method of using a stored-energy surge generator. It offers the advantage, once the resource of such a system becomes available to a user, of making other test waveforms easy to implement, for instance, a tailored capacitor switching surge, or the application of a temporary overvoltage to an EUT.

10.2.3 Capacitor-switching ring waves

As indicated in IEEE Std C62.41.2-2002, no across-the-board waveform has been recommended for capacitor-switching surges, in view of the case-by-case nature of the phenomenon. The choice of appropriate waveform, voltage level, and source impedance is therefore left to the interested parties. However, the following points should be noted when making such a choice.

The low frequencies considered as representative of the phenomenon make it impractical to use the method of a surge generator injecting a well-defined test wave into the EUT via a coupler/back filter. Three test methods may be considered:

a) Generation of an arbitrary waveform and linear amplifier at the EUT power level
b) Emulation of the phenomenon by switching a capacitor bank in the laboratory
c) Staged field tests at a site allowing switching of power-system banks

The concept of Location Categories, based on the fact that impedance values increase as the point of interest is moved further into the building, is not applicable at the low frequencies associated with capacitor switching surges. However, the concept of system exposure is still useful in making decisions for a realistic stress level.

The peak surge voltage can be expected to be less than twice the system voltage, except for a case in which voltage magnification might be expected.

10.3 Equations for additional waveforms

Mathematical representations of the nominal ***waveforms*** are given in Table 6. These equations, and the value of the time constants, are useful for designing surge generators and for simulations of surge performance on digital computers (Standler 1988 [B28]).

A test waveform in the laboratory will, of course, not exactly match the waveform given by the equations for the nominal waveform, due to the tolerances of components in pulse-forming networks and parasitic inductances and capacitances in the components of both generators and test fixtures.

The loading by the EUT can cause appreciable discrepancy between the preset nominal open-circuit voltage or short-circuit current and the actual voltage across or current in the load. This effect is the reason why surge waveform parameters are not specified with the EUT connected. In computer simulations, some of the loading effects can be taken into account by including the ***effective output impedance*** V_p/I_p with the ideal voltage or current source.

Table 6—Equations for additional test waveforms

10/1000 µs Wave	
$I(t) = AI_p\left(1 - \exp\frac{-t}{\tau_1}\right)\exp\left(\frac{-t}{\tau_2}\right)$	
where	
t_1	is 3.827 µs
t_2	is 1404 µs
A	is 1.019
EFT Pulse	
$V(t) = AV_p\left(1 - \exp\frac{-t}{\tau_1}\right)\exp\left(\frac{-t}{\tau_2}\right)$	
where	
τ_1	is 3.5 µs
τ_2	is 55.6 µs
A	is 1.270
NOTE—In all of the equations above:	
t	is time
V_p	is maximum or peak value of the open-circuit voltage
I_p	is peak value of the short-circuit current

11. Evaluating test results

Reporting and evaluating results of surge tests is an essential part of the procedure. Tests performed by independent laboratories at the request of a sponsor are generally covered by an official, certified test report. In-house tests performed by manufacturers become an intrinsic part of the design data. Round-robin tests performed by a group of interested parties must be thoroughly documented because, by definition, they are performed by different organizations.

The purpose or nature of the test, as discussed in Clause 4, will determine how the numerical test results are eventually turned into an engineering statement or conclusion. Thus, it is important that both the purpose and evaluation criteria be defined *before* the test program is initiated. Examples of test programs and evaluation of their results can be found in various documents. See also C.6, which offers recommendations for making ongoing checks of the results as the test program is progressing.

A sponsor might be inclined to oversimplify for economic reasons and be interested only in whether a percentage of a specimen population passes or fails the test(s). However, subtle details of the ***EUT*** behavior during the test might convey useful information to the equipment designer and user. A particularly important issue is that of realizing the impact of tolerance combinations (generated ***waveform***, instrumentation, and manufacturing tolerances) when testing nonlinear devices.

Annex A

(informative)

SPD Class I test parameters

A.1 General

As explained in IEEE Std C62.41.1-2002, surge-protective devices (SPDs) involved in the exit path of the lightning current in the case of a direct lightning flash to the building of interest can be subjected to severe stresses. The earth-seeking lightning current divides among the available paths to earthing electrodes, one of them being the power supply connection where SPDs might be installed. In recognition of this application, IEC 61643-1 (2002) [B10] has defined, among the classes of tests applicable to SPDs connected to low-voltage power distribution systems, a Class I test involving high stress. Annex A of IEEE Std C62.41.2-2002 provides details on the background and numerical values of the parameters for this Class I test, which are summarized below.

A.2 The IEC Class I test for SPDs

According to IEC 61643-1 (2002) [B10], the “test impulse current” of the Class I test is defined by its peak value and charge transfer. A further stipulation is that the specified peak current and charge transfer be reached within 10 ms. Because these stresses are substantial, several levels of peak current values are tabulated in that IEC standard, allowing a case-by-case decision on selecting the appropriate level. The standard also states that a typical waveshape that can achieve these parameters is that of a “unipolar impulse current.” A proposed additional note states that one of the possible waveshapes meeting these parameters may be the 10/350 µs waveshape defined in the IEC documents dealing with lightning protection. Accordingly, A.3 provides a graphical description of this waveshape (called waveform in the Trilogy) and the corresponding equation to be used for test or numerical simulations. For this waveform, as well as for the Standard Waveforms (Clause 9) and the Additional Waveforms (Clause 10), this recommended practice does not stipulate any particular level, but just the parameters of the waveform. Selecting Class I level values remains the prerogative of users, based on their requirements, with guidance on realistic levels provided in Annex A of IEEE Std C62.41.2-2002.

A.3 Parameters for a 10/350 µs waveform

Figure A.1 shows the nominal parameters of a 10/350 µs waveform suggested as one way to achieve the Class I test parameters. Because of the latitude expressed in the time elements of this waveform, unlike the standard and additional waveforms of this recommended practice, no precise tolerances are suggested for the front time and for the duration. The corresponding equation for the nominal parameters is given in Table A.1.

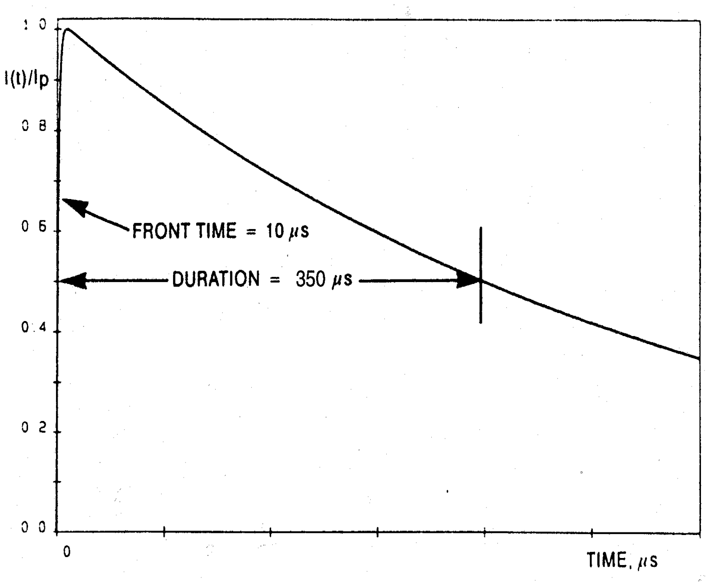


Figure A.1—Waveform of the 10/350 µs current surge

Table A.1—Equation for the 10/350 µs waveform

$$I_t = AI_p\left(1 - \exp\left(\frac{-t}{\tau_1}\right)\right)\exp\left(\left(\frac{-t}{\tau_2}\right)\right)$$

where

τ_1	is 4.103 µ s
τ_2	is 470.1 µ s
A	is 1.051 µ s
t	is time
I_p	is peak value of the applied short-circuit current

Annex B

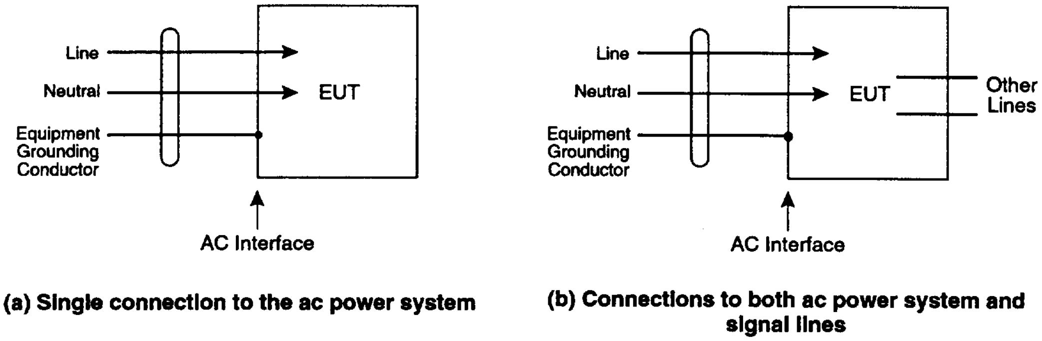
(informative)

Complementary notes

B.1 AC power interface (ac power port)

The scope of this recommended practice limits the ***equipment under test*** **(EUT)** to that which is connected to low-voltage ac power circuits. Available data on the occurrence of surges, whether measurements or specifications, concern surge voltages or surge currents imposed on the EUT at its connection to the ac power supply.

In the case of EUTs that are simple loads, the ac power interface can be understood as the connection to the power system, and the surges to be taken into consideration are those appearing among the line(s), neutral, and ***equipment grounding conductors*** of the EUT ac power supply [Figure B.1(a)]. These surges can be applied in a variety of conductor combinations, but they are limited to the combinations of conductors on that ac power supply connection.



(a) Single connection to the ac power system

(b) Connections to both ac power system and signal lines

Figure B.1—Connections of the EUT with the environment

In the case of EUTs that are shunt-connected surge protectors, surge response voltage measurements should be made on the integral leads or wires normally used to connect the device to the premises wiring. The exact configuration (lead dress, distance from the exit of the device housing) has an effect on the measurement results and must be documented. (See C.1.1.)

There is, however, another category of equipment that involves signal or data lines in addition to the ac power supply [Figure B.1(b)]. Typical examples of these EUTs are an industrial process control system with remote sensors and actuators, a TV set with community antenna input, a computer system with remote terminals, and telephone equipment such as answering machines, facsimile machines, or cordless set base stations.

For these types of EUTs, the ac power interface concept includes not only all of the possible combinations involved in the Figure B.1(a) connection, but also the surge voltages that might appear between the ac connection (power port), on the one hand, and the connection to the signal line (signal/control port), on the other hand. This type of surge exposure is now recognized as one of the major sources of problems (Martzloff 1990 [B16], Key and Martzloff 1994 [B12], Martzloff et al. 1995 [B20]).

Readers, sponsors, and users should not ignore the possible problems of surges appearing between the ac power port and the signal port, although the scope of this recommended practice does not cover such surges.

B.2 Average power (overstressing)

It is possible to inadvertently exceed the rated maximum average power of protectors that might be in use within an EUT if the interval between test surges is too short. Thus, although surge generation at a rate of once every few seconds might be an available instrumentation capability, it is unlikely that all types of protectors that might be used within an EUT will be able to withstand such treatment for very many surges (Standler 1989 [B30]).

Tests should take into consideration realistic intended use of the EUT. A life test should not be compressed with an excessive test-surge ***repetition rate*****,** for the sake of saving test time, if stresses caused by excessive average power would result in an apparent failure of an otherwise adequate design of the protective EUT.

The stress level—voltage, current, or energy—of each individual test surge is no guide to the rate at which the test may be repeated. What is significant is the relationship of that stress level to the average power ratings of the internal EUT protectors. For example, consider an EUT protected for the current surge and typical energy levels of Category B. If the EUT is tested to the Category A levels, the repetition rate can be higher than if the test was made to a Category B level.

Note that service requirements for the EUT can include ***multiple surges*****.** For instance, during a single lightning flash, there might be several strokes; in the case of switching surges, several can occur within a fraction of a second when abnormal switch behavior is involved.

B.3 Back filter

A ***back filter*** is defined in this document as a filter inserted into the ac power line supplying the equipment to be surge-tested (called *decoupling network* in IEC 61000-4-4 (1995) [B9]). Such a filter is required to prevent the surge (assumed coupled in shunt to the ac line input terminals of the EUT) from traveling upstream toward the power source, where it might damage other devices connected to the same power source. In addition, in the absence of the filter, the low impedance of the power source (Bull 1975 [B3]) would load the surge generator, which might therefore be unable to deliver the high peak voltage that is required by the test plan to the EUT.

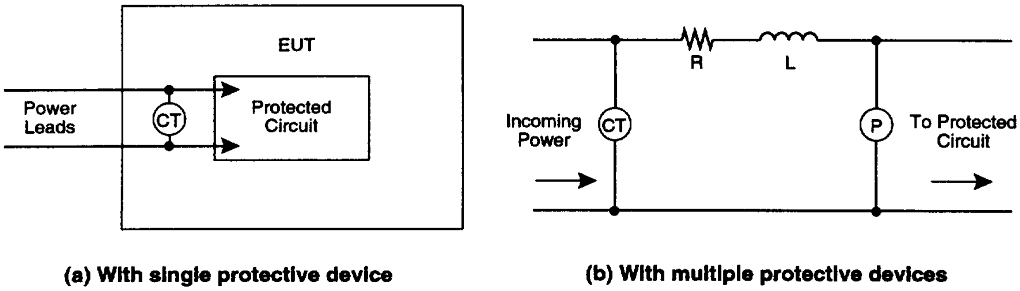
A compromise is necessary, however, between having a filter that presents an adequately high impedance to the surge, particularly if the surge is of long duration (Richman 1985 [B23]), and a filter of low impedance that would not excessively limit the power-frequency current. Both the normal operating power-line current drawn by the EUT and the ***fault current*** that is available in the event of internal EUT flashover are significant factors to be taken into account when ***test conditions*** are set up. For examples of back filters, see Figure B.9 and Figure B.10 in B.19, and Figure B.11 under B.21.

B.4 Blind spots

Blind spots can exist in ***EUTs*** that contain surge-protective devices. The protective device performs well at maximum stress (voltage, current, rise time), but at some intermediate level, the protective device might not perform as intended and the circuits expected to be protected might in fact be subjected to greater stress than at the maximum surge levels.

As a first example, consider the EUT of Figure B.2(a), which contains a voltage-switching protective device (the term *crowbar* is now deprecated), CT. Assume that an impulse voltage of up to 6000 V is to be applied to the EUT and that the voltage-switching device has a breakdown voltage of 1000 V. The application of a 6000 V test impulse operates the voltage-switching device on the leading edge of the surge; only a small ***surge remnant*** reaches the protected circuit and the equipment survives the test. On the other hand, a test voltage of 950 V does not operate the voltage-switching device; a large ***surge let-through*** reaches the protected circuit and the equipment might be damaged. A similar situation, with large surge let-through, can occur at higher test voltages than the voltage-switching device breakdown if the protected circuit has too low an impedance to allow the voltage-switching device to operate.

As a second example, consider the multiple protective device arrangement of Figure B.2(b) with a voltage-switching device CT and a voltage-limiting protective device P, separated by a series combination of resistance R and inductance L.



(a) With single protective device

(b) With multiple protective devices

Figure B.2—Examples of blind spot conditions

This combination can be implemented in a single package incorporated to the EUT, or it can be implemented as separate components working together, but actually some distance apart for a complex EUT. When the proper components are selected for an application with a specified surge current amplitude and ***waveform***, the voltage drop across R and L added to the limiting voltage of P becomes sufficient to cause sparkover of CT, relieving protector P from diverting the full surge current. However, at some intermediate surge current amplitude or at some slow rise of the current, the voltage developed across R and L might be insufficient to produce sparkover of CT so that clamp P would then have to carry the full current surge, an event that might not have been foreseen if the design or test parameters were limited to maximum values.

Therefore, it is recommended to test the EUT over the complete range of impulses for the system, whenever possible, in order to reveal such blind spots.

B.5 Common mode (and normal mode)

The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition [B11], gives the following definitions of common mode and normal mode (and information on the mechanisms leading to the coupling of these unwanted signals):

> “Common-mode noise (longitudinal) (cable systems in power generating stations). The noise voltage that appears equally and in phase from each signal conductor to ground.”
> “Normal-mode noise (transverse or differential) (cable systems in power generating stations). The noise voltage that appears differentially between two signal wires and acts on the signal sensing circuit in the same manner as the desired signal.”

In the context of describing surges in ac power distribution systems, it is useful to examine how the concepts first defined in communications circuits can be applied to power circuits. Consider the circuit shown in Figure B.3(a), which is a simplified typical balanced circuit in which the sender and receiver transformer windings have a grounded center tap.

Note that no metallic conductor is explicitly provided between the two ground connections. A surge current external to this circuit along a path, including the two points of ground connection, can couple simultaneous impulses on the two transmitting conductors. The voltmeter V_1, connected as shown, will not read a voltage difference, whereas the voltmeter V_2 will. This is classified as common-mode coupling.

On the other hand, if a surge is coupled onto only one wire, as shown in Figure B.3(b), then all the V_1 and V_2 voltmeters will read a voltage difference. This situation is classified as normal-mode coupling.

There is a difference in the common mode between ac power circuits, in which an ***equipment grounding conductor*** is provided, and balanced communications circuits, in which it is not. When simultaneous impulses are coupled into the circuit of Figure B.3(c) by an external surge, all conductors are involved.[10]

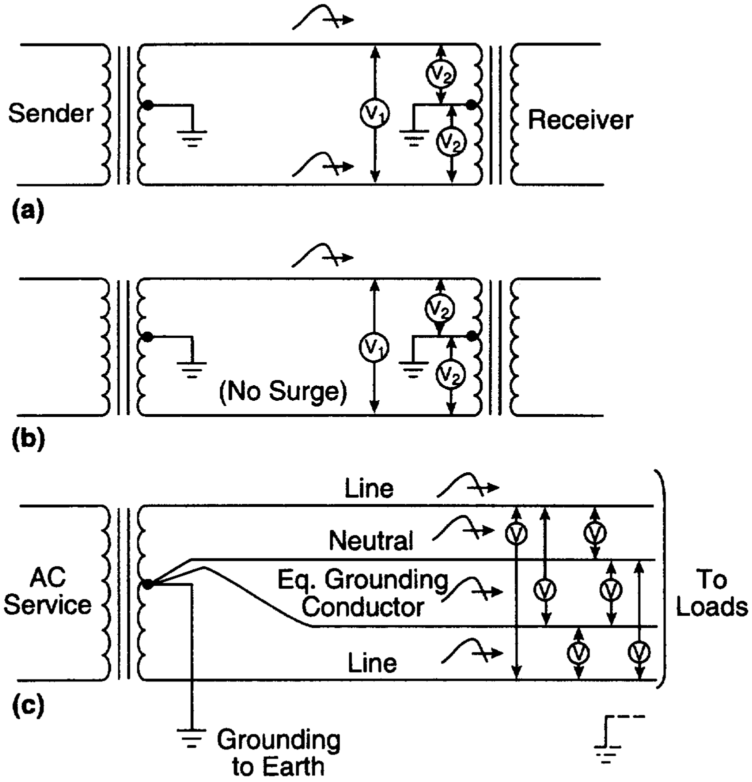


Figure B.3—Common mode and normal mode in communications circuits and in power circuits

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[10] This example is provided for illustrating this discussion. The absence of a bond of ground conductors across the transformers should not be construed as suggesting a violation of the prescriptions of the National Electrical Code®.

In this situation, simplified here by assuming equal coupling with all conductors, none of the voltmeters shown would read a voltage difference. This situation is in contrast with the case of Figure B.3(a), where both V_2 voltmeters would show a voltage difference. On the other hand, if a remote ground was provided, as shown by the dotted line in Figure B.3(c), then one could have the same definition for common mode as that given for Figure B.3(a).

For normal-mode coupling, the same definition can be applied to communications and to power circuits.

A surge-protective device installed at the end of a long line for protecting the equipment at the end of the line can produce a voltage between the neutral conductor and the equipment grounding conductor, in addition to the limiting voltage between line and neutral, when a surge current is flowing in the line (Figure B.4). The inductive voltage drop, *L di/dt*, caused by the surge current in the line and neutral conductors, can elevate the neutral terminal of the equipment above the equipment grounding conductor potential and cause stress of neutral-to-ground insulation.

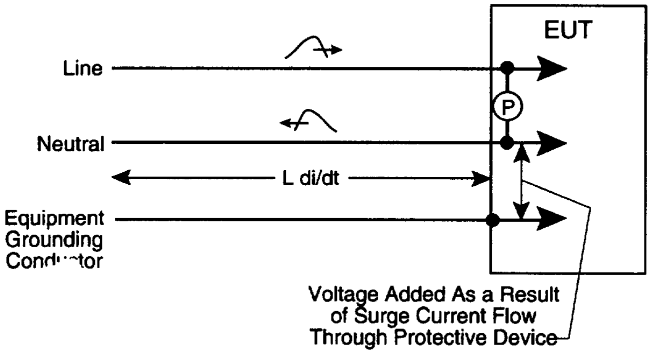


Figure B.4—Voltage difference between the neutral conductor and the equipment grounding conductor resulting at line end from surge applied at line beginning

In such a situation, the addition of a protector between the neutral conductor and the equipment grounding conductor will limit this voltage (Martzloff 1983 [B15]). Adding such an N-G protective device in this location, as distinct from the alternative of adding it from the line conductor to the equipment grounding conductor, minimizes the amount of standby current injected into the ground plane of the equipment to which the equipment grounding conductor is connected.

Notes of caution, however, are appropriate:

a) Connecting a protector from neutral to ground might cause a disturbance to the ***EUT***.
b) Should the protector fail in the short-circuit mode, neutral current might appear on the equipment grounding conductor.
c) The additional impedance of a ***back filter*** might add some steady-state N-G voltage to the EUT.

B.6 Communications interface (control/signal port)

Although the power-line environment of equipment might be in a low or moderate exposure or duty level, the addition of signal lines with undefined “ground” potential changes constitutes an additional threat to survival of the system in its normal environment. Examples of this situation are a TV set with a cable TV signal input, a process computer with long sensor lines, and communication equipment powered by the ac line and connected to the telephone lines.

Therefore, tests limited to impinging transients (surges) on the power port might not ensure adequacy of the system (see B.1). A central project or system responsibility should be provided to guard against uncoordinated practices and incomplete test specifications.

B.7 Coupler

The coupler is a device, or combination of devices, used to feed a surge from a generator into powered equipment, at the same time limiting the flow of current from the power source into the surge generator. Typically, capacitors are used to perform the coupling function. These capacitors should be noninductive, capable of carrying the pulse currents involved, and have appropriate voltage ratings. Precautions are necessary to ensure operator safety against any trapped charge that might exist in these capacitors after they have coupled the test surge.

The coupling method (device) can have an effect on the sharing of the energy stored in the surge generator among the elements of the test circuit and, hence, the energy deposited in the ***EUT***. Careful analysis is required when comparing test results obtained with different types of couplers (Senko 1991 [B26]).

B.8 Coupling gap

A convenient method for coupling the surge generator to the ***EUT*** only during the surge is to use a gap that sparks over during the initial rise of the pulse. The gap subsequently provides direct coupling and disconnects the generator from the EUT after the surge.

However, it should be recognized that this method applies to the EUT a voltage wave with a very steep front as the gap sparks over. Some EUTs might respond to this unintended steep front in a manner that could be misleading—for example, a logic circuit upset caused by the steep front. Selecting a gap with very low sparkover voltage and fast response will minimize the problem. Note also the discussion in the preceding clause, B.7, concerning the effect of the nature of the coupling device on the energy deposited in the EUT.

B.9 Current surging

Surge current flow, especially in ground and neutral conductors, can have particularly severe effects on connected equipment. Damage is usually due to the fact that several interconnected circuits or devices are not grounded at the same point. Although this aspect of surge testing is not directly related to the explicit scope of surges impinging from the ac power-line interface, experience has shown that one of the causes of ***common-mode*** voltages appearing on ac lines is lightning ground current flow that couples into the ac system. Explicit ground and neutral current surge testing can be a separate requirement in many cases, therefore, during the testing of distributed subsystem, such as circuit boards and other subsystem elements.

Figure B.5 shows one of the ways in which a surge generator can be used to simulate ground current flow. Two devices, EUT #1 and EUT #2, are interconnected by signal or power leads, or both. In addition, they are connected to a common system ground at G_1 and G_2.

Significant ground current can flow due to an external surge. This current may be simulated by applying the output of a surge generator between points G_1 and G_2 on the ground system after first disconnecting all other equipment not included in the test. The voltage E_G between points G_1 and G_2 on “ground” will be a function of the resistance R_G and the inductance L_G in the line between these points and the surge current I_S, that is [Equation (B.1)]:

$$E_G = R_G I_S + L_G\left(\frac{dI_S}{dt}\right) \tag{B.1}$$

The test surge current should be a function of the location category in which the EUT is assumed to be located, as well as the values selected to represent L_G and R_G in Figure B.5. In the present state of knowledge, these parameters are not well defined.

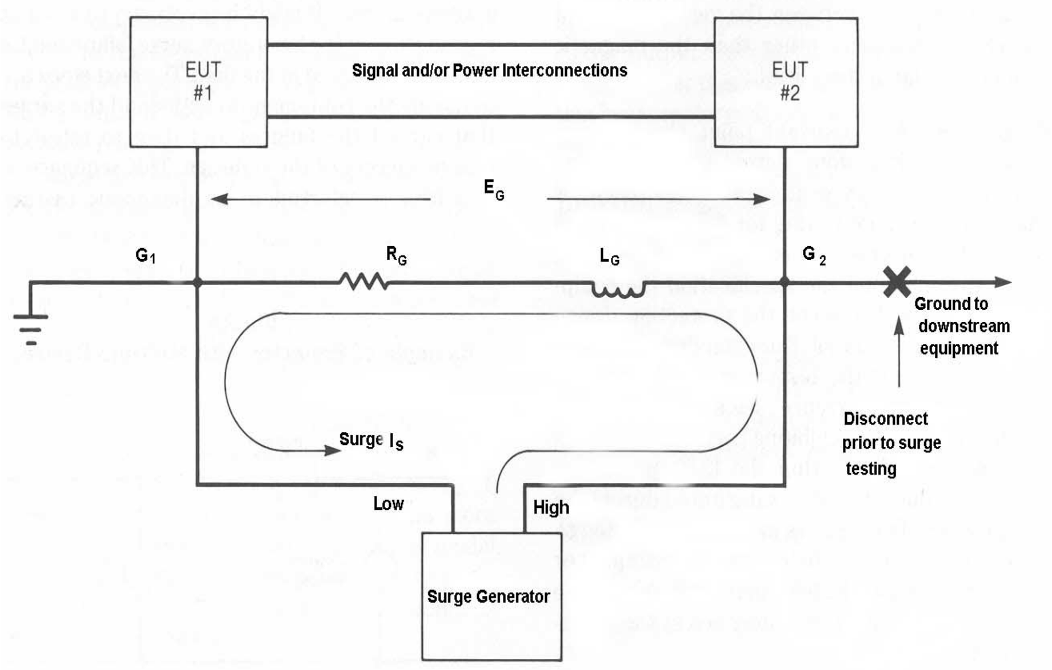


Figure B.5—Current surge test example: Surging ground or common

B.10 Current transformers

As described in 5.5.2, current transformers or current-to-voltage transducers offer the advantage of isolation of the ***monitoring*** oscilloscope from the test circuit. However, the current transformer used in this case must have adequate response and be inserted in the ***EUT*** with adequate insulation for the voltages involved in the surge test.

These requirements include the following:

a) The transformer has adequate response time to assure that the surge will be faithfully transmitted.

b) The transformer will not overload (saturate) because of the high current encountered.

c) Adequate insulation is provided between the wire carrying the current to be measured (primary lead) and the viewing coil (secondary lead).

d) Adequate insulation is provided between the viewing coil case to any other nearby component or lead at high voltage.

e) No undesired magnetic or capacitive coupling should exist between the viewing coil and the EUT component.

B.11 Damage

The term *damage* can take on different meanings and degrees of severity depending on the context and the circumstances. For instance, the IEC publications on immunity tests (61000-4 series) list outcomes of the test, with the last (and most severe) defined as:

4) Degradation or loss of function which is not recoverable due to damage of equipment (components) or software, or loss of data.

This description indicates that “damage” includes not only physical damage to the EUT, but also an irreversible and unacceptable change in software or data base.

The third outcome listed in the 61000-4 series reads as:

3) temporary degradation or loss of function or performance which requires operator intervention or system reset.

Depending on the extent and time expended for the intervention, a conservative view might be that, for practical purposes, the EUT has been “damaged.” (See also B.47.)

B.12 Design test

An important point about design testing when it is done during the engineering design phase of an equipment development is that it may include testing for failure as well as testing for success. By extending the applied surge stress beyond the specification the equipment is required to meet, the protection design margin can be evaluated. This extended stress may also include repetitive tests to establish the ***EUT*** limits on stress recurrence (see B.2).

When protectors exhibiting performance variations are included within the EUT, protectors with limit values should be substituted during the test program. Limit values are usually selected to be at the 3 Σ point in their expected limiting or switching ranges, at the 99th percentile, or at some other worst-case level recommended by the manufacturer.

Example. Figure B.6 illustrates the need for performing tests with well-characterized samples of protective devices. A protective scheme is shown, with a voltage-switching device as primary protector, followed by an impedance and a secondary protector, which could be an avalanche junction device or a varistor. This scheme is predicated on the expectation that, for large currents, the limiting voltage of the secondary protector plus the voltage drop in the impedance will reach the sparkover voltage of the primary protector.

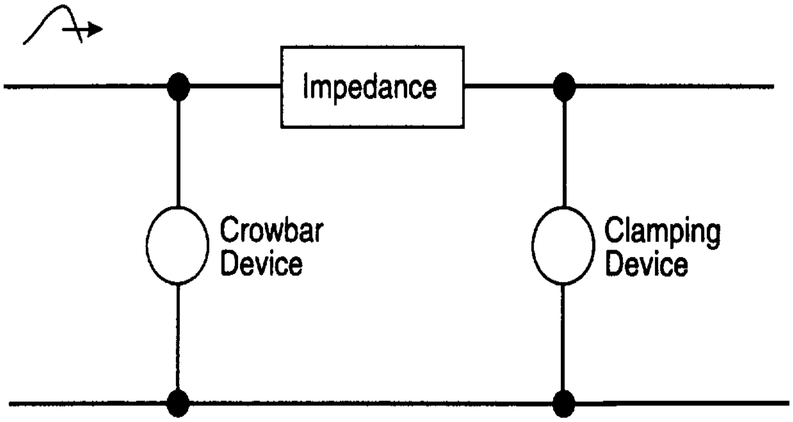


Figure B.6—Example of protector with multiple devices

This coordination requires evaluation with the primary protector at the upper limit of the tolerance band and the secondary protector at the lower limit in order to reveal any ***blind spot*** in the coordination (Martzloff 1980 [B14]). A test made with the reverse situation (low primary with high secondary) might provide misleading, optimistic results. This situation parallels the concern discussed under B.4. A volt-time curve would also be useful to define the circuit performance.

The selection of sample protectors at the limit of tolerance band might not always be possible. An alternative approach is to determine from manufacturers' data the level of the ***surge remnant*** at the upper limits, remove the randomly selected protector from the circuit, and apply from a test generator a voltage ***waveform*** and level duplicating the remnant voltage determined above. This approach is a significant simplification of the test program, provided that reliable information on the surge remnant is available.

B.13 Diagnostic test

It might be necessary to attempt reproducing, in the laboratory, surge failure modes that have occurred in the field. The next steps are to modify the equipment to withstand the surges that caused the failures and then to retest to ensure success of the redesign. This sequence of activities is referred to as *diagnostic testing*. Because diagnostic testing seeks to cure one or more specific surge failure modes, it may involve tests that would not be included in a normal ***qualification test*** program. This recommended practice is therefore intended to be broad enough to serve as a basis for extension from qualification testing to diagnostic testing as might be required.

B.14 Differential connection

Because the “ground” or “common” points within an ***EUT*** are likely to assume different potentials during the flow of surge current, erroneous measurements would be obtained if single-ended input circuitry was used for instruments measuring the surge within the EUT.

Probes with safe peak-voltage margins for at least twice the applied surge peak are required. Ordinary low-voltage oscilloscope probes are inappropriate, even if the protected circuit peak voltages are thought to be just a few hundred volts. This is due to fault conditions, in which an internal EUT flashover, protector failure, or other malfunction might apply enough voltage to destroy the probe, the monitor device input circuits, and possibly even other equipment if the voltage can enter the laboratory ground system via this route. Consult the probe instruction sheet or the manufacturer before using these probes in the test circuit. Commercial high-voltage probes are available with sufficient voltage ratings for surge tests on low-voltage equipment.

Oscilloscope (or other monitor) common-mode rejection should be carefully checked. Checking is best accomplished with both input probes connected to the same point, ***monitoring*** first with the point of application of the surge, and then the EUT ground. In both checks, the oscilloscope or monitor readings should be small compared to the surge amplitude that is finally measured. See C.1.3 for details.

Of the two methods given in Figure 4 and Figure 5 (5.5), the use of current probes (Figure 5) has almost no noise or common-mode pickup. However, the current reading must be converted to voltage, which is subject to errors if the current and voltage are not in perfect phase or the resistance is not a constant value with frequency.

Careful attention to the details of the instrumentation is required in order that the measurements obtained reflect only the electrical signals present at the points of interest, and no more. Oscilloscope probes must be identical in model, length, termination, and compensation; the probe leads should be twisted together to minimize induced error voltage.

Commercial oscilloscope preamplifiers offer a wide choice of differential mode operation. One method is to use a two-channel preamplifier in its add mode, with one channel inverted. This method is limited by the capability of the preamplifier for high-frequency, common-mode rejection.

A preferred method is to use a true differential preamplifier built specifically for high common mode rejection. Many such preamplifiers achieve this objective at the expense of bandwidth; therefore, the preamplifier should be selected from those having both a high common-mode rejection ratio (CMRR) and an appropriate bandwidth for the impulses being monitored at high frequencies as well as at dc. Furthermore, CMRR specifications are sometimes given for dc, so that additional care is required in selecting the preamplifiers. Standler (1989 [B32], pp. 376–378) discusses true differential and pseudo-differential amplifiers. Smith and Standler 1992 [B27] discuss how to avoid ground loops by using differential voltage probes with no ground connection.

The test operator (purchaser of instrumentation) should consult the oscilloscope manufacturer for assistance in making the appropriate choice. Some digital storage oscilloscopes have limited common-mode rejection capability; when first using such an instrument, a useful technique to avoid artifacts is to program the oscilloscope to display each channel and examine the amplitude of each signal before programming the oscilloscope to perform the subtraction that yields the differential measurement. In this manner, large signals that would exceed the common-mode rejection capability of the oscilloscope are readily identified, and the sensitivity of the scope must then be reduced to bring the signal within the range of the oscilloscope storage capability. See C.1.7 for a discussion of digital resolution.

For the measurement to be valid, the two attenuator probes for the differential input must be matched; that is, their attenuation must be equal over the frequency range of interest. Typical high-attenuation probes are provided with a compensation box that, when properly adjusted, makes possible such a match. A complete single-unit differential probe may also be used (Senko 1987 [B26]).

B.15 Effective output impedance

For convenience, an effective output impedance is defined for a surge generator by calculating the ratio of peak open-circuit output voltage (OCV), V_p, to peak short-circuit output current (SCI), I_p, or OCV/SCI, V_p/I_p. Note, however, that this concept is only a convenient simplification because the peaks of the voltage and current waves are generally not simultaneous. For instance, for the Ring Wave and Combination Wave of IEEE Std C62.41.2-2002, these effective output impedances are given in Table B.1.

In the design of the surge generator and test circuit, a judicious addition of circuit reactance, either alone or in combination with nonlinear circuit elements, can be used to eliminate two potential problems:

a) The excessive power dissipation in the network of the surge generator.
b) The unreasonable drain that might be imposed on the power source supplying the ***EUT***. Often, a simple surge-coupling capacitor can perform this function.

Table B.1—V_p / I_p ratio

Category A Ring Wave	6 kV/200 A = 30 Ω
Category B Ring Wave	6 kV/500 A = 12 Ω
Category B Combination Wave	6 kV/3 kA = 2 Ω

For instance, it follows from Table B.1 that although there is a range of 15 to 1 in the OCV/SCI ratio, all of the waves derive from sources that might not tolerate sustained imposition of ac line voltage. With 220 V, for example, the dissipations that would result if the effective output impedances were purely resistive range from over 1.6 kW for the 30 Ω of Category A Ring Wave to over 24 kW for the 2 Ω of Category B Combination wave. These situations would seldom be practical for either the surge generator or the power line.

To illustrate this situation, Figure B.7 shows a simplified test surge generator output waveshaping network. C is the energy storage capacitor, charged to peak voltage E_C. When switch S is closed, the test surge is generated across shunt resistor R_1 with its leading edge shaped by inductor L, and resistor R_2 limits the output short-circuit current to whatever value is required.

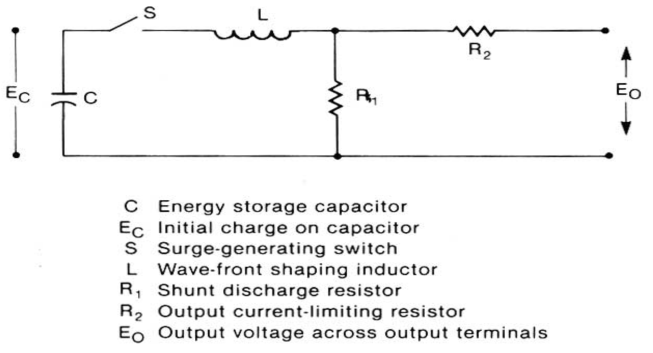


Figure B.7—Simplified output waveshaping network of test surge generator

In Figure B.7, if R_2 is 2 Ω (as in the case of the Category B impulse), and if R_1 is 10 Ω, for example, then the total $R_1 + R_2$ dissipation prior to closure of switch S, due to direct connection of the output E_O across a 220 Vac line, would be one sixth of 24 kW calculated above for the simple 2 Ω output impedance, that is, 4 kW. Thus, isolation of the surge network from the ac line is clearly a requirement.

B.16 Environment test versus component specification test

Load equipment, particularly electronic equipment, connected to low-voltage ac power circuits will be exposed to the surge environment at installation points. Users and manufacturers are interested in the immunity level of this equipment from the point of view of damage as well as the point of view of upset. To demonstrate immunity against upset, clearly the equipment must be in its normal mode of operation, that is, powered and connected to other subsystems associated with its operation, particularly input/output data lines. For equipment containing integral surge-protection components, the issue of recovery of standby condition when in powered mode (for instance, no thermal runaway) is also important. Should a failure occur, the mode of failure and ultimate consequences will be affected by the presence of line voltage at some specified available ***fault current*** level, an issue related to the ultimate safety of the device, as opposed to a simple performance evaluation that might only require passing a certain test severity level without failure.

Generally, the requirement of performing the surge test while in powered mode requires either a ***back filter*** or a fast disconnect–reconnect arrangement to decouple the surge-test circuit from the power-frequency source, when the surge is produced by the discharge of a stored-energy circuit (Fenimore and Martzloff 1991 [B5]).

For the emerging “long duration” surges having relatively lower peak currents, high-power amplifiers can produce the power-frequency voltage and the superimposed surge, starting from an arbitrary waveform generator. However, the necessary power rating of the amplifier can make this approach costly if it requires emulating high values of the available fault current or steady state load current.

On the other hand, only a few large high-voltage laboratories have the capability of producing a surge from a virtual current source, that is, a high open-circuit voltage and a high internal impedance that make the test current independent of the response of the ***EUT***. Furthermore, few laboratories have a facility for applying this surge to an independent source of mains power-frequency, such as a generator/transformer with enough insulation strength to withstand the surges.

For these reasons, a surge test philosophy has evolved among low-voltage equipment users that requires conducting the test under conditions representative of the surge environment (Fisher and Martzloff 1976 [B6]). The approach is to apply an open-circuit voltage for those devices that exhibit a high impedance to the impinging surge, while specifying a short-circuit current relevant to those devices that exhibit a low impedance to the impinging surge.

When testing an equipment of unknown characteristics (the so-called “black-box test”), or equipment where the impedance can shift from one condition to the other (sparkover of a gap, flashover of a clearance, or clamping of a nonlinear device, for instance), it is important that both the voltage and the current be available to track the characteristic of the device. This requirement led to the specification of the Combination Wave (Richman 1983 [B22]), also known in Europe as the *Hybrid Wave* (Weisinger 1983 [B34]).

In this procedure, the test generator circuit is set up with well-defined open-circuit voltage and short-circuit current, with both values accepted as representative of the environment.

In the case of a voltage-limiting device, for instance, the current flowing in the test specimen will be determined by the dynamic impedance of the test specimen in series with the internal impedance of the generator. The resulting current in the specimen will be less than the short-circuit current value selected to represent the environment; this approach of setting the open-circuit voltage of the test generator, then connecting the test specimen without changing the generator setting, has been described as "let it rip" and is viewed as a test that evaluates the performance of the device under specified environmental conditions. In contrast, another approach consists of adjusting the surge generator setting to obtain a specified surge current level with a specific device connected across its terminals, for the reasons described in the next paragraph.

The objective of a test conducted for component specification is to verify (and compare) the performance of a known device under a specified surge current level. The generator setting (open-circuit *voltage*) must then be adjusted as necessary to obtain a specified *current* in the test specimen. For the large surge generators used in testing high-voltage arresters, the test circuit generally contains enough fixed impedance to make the test SPD impedance only a small part of the total, or at least to minimize the effect of minor variations in the impedance from one specimen to the next. In effect, the surge generator acts almost as a perfect current source. The let-it-rip approach generally used in the low-voltage domain does not do so because the dynamic impedance of the test specimen can be a significant part of the total impedance of the test circuit. (In other words, the residual voltage of the arrester reduces significantly the voltage available to drive the current in the circuit.)

Thus, when the objective is a comparison among different designs of SPDs, rather than the performance of a piece of equipment (which could be a test SPD, or include an SPD at its input terminals) in a given real-world environment, it may be desirable that the test current be set at exactly the same level for each test. This constant level is obtained by making a preliminary test on a sample to fine-tune the setting (voltage setting, which determines the charge in the energy-storage capacitor) of the generator. As a result, the final test is then conducted on a specimen that has already been subjected to setup adjustments, or a brand new device must be used, with the underlying expectation that its impedance will be identical to that of the expendable device used in setting up the generator.

This readjustment of the generator initial charge will alter the voltage aspect of the surge test when conducting a current test. The sought-after constant test parameters for both current and voltage is then lost.

In the case of a surge-protective device, knowledge of the generic design of the test specimen can help predict the behavior of the device under the impinging surge. This knowledge could allow separating the voltage test from the current test using in succession two surge generators, one for voltage and the other for current. In such a case, more useful information can be secured on the behavior of the SPD under a Ring Wave than under the classical 1.2/50 μs voltage impulse, while the desired information on the behavior under fixed current discharges can be obtained with the classical 8/20 μs impulse. However, differences in the behavior can creep into the test when the device is a complex assembly involving changes of state at the beginning and during conduction of the surge (Richman 1983 [B22]). This possibility justifies a suggestion that surge protector manufacturers provide, upon request, generic information on the internal design of their devices so that meaningful tests can be performed.

In summary, when testing *equipment*, the surge generator should be preset to a specified open-circuit voltage or short-circuit current level and not be readjusted. In contrast, when testing *individual components*, the generator may be readjusted in order to deliver a fixed current level into the component under test.

B.17 Equipment grounding conductor

The equipment grounding conductor in this text describes the ground return path of the ***EUT***. This conductor might be a copper or aluminum wire or a metallic raceway (conduit, wire tray, etc.) In actual use, normal power current does not flow in this path. Momentary current, from line-to-ground faults or from lightning-induced current, can flow in this path.

Some instances might be encountered where a surge-protective device is connected between the line conductor and the equipment grounding conductor [Figure B.8(a)]. When surge tests are performed on such

EUTs, it is imperative that the equipment grounding conductor be properly connected to the system ground electrode. Failure to provide this proper connection would cause the surge current, diverted as intended by the protective device, to seek a return path in the direction of the EUT chassis rather than in the intended direction of the system ground [Figure B.8(b)]. The result of such unintended routing of the surge current might cause upset or damage to the EUT, which would not occur if the grounding connection were made correctly.

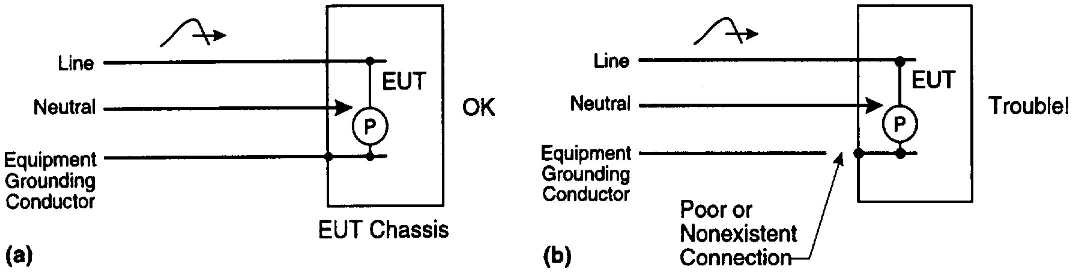


Figure B.8—Effect of poor or missing connection to the equipment grounding conductor

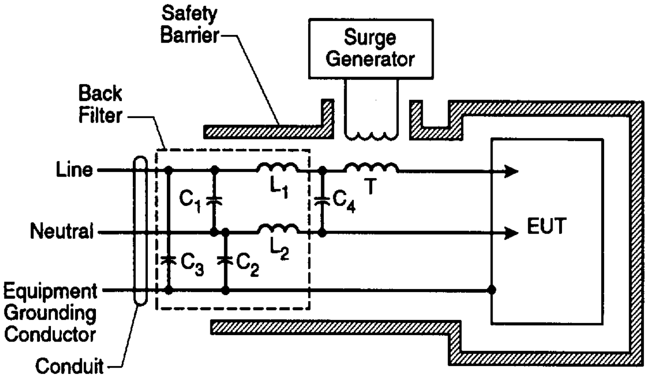
B.18 Equipment under test (EUT)

In this recommended practice, EUT is a shorthand way of describing any piece of electrical equipment or group of electrical equipment that is ready to be exposed to a prescribed series of voltage surges or current surges, or both. Some examples of what an EUT could be follow:

a) A single component
b) A single group of protective devices
c) A known protected or unprotected circuit
d) An unknown circuit (“black box”)
e) Appliances of all types
f) Frames of electrical equipment making up a system or subsystem

B.19 Fault current

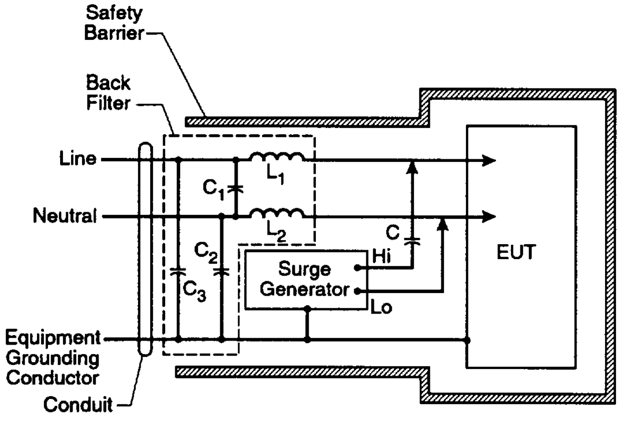
It is conventional in performing stress tests on powered equipment to specify a minimum value of the fault current that will flow from the power line in the event of flashover, an arcing fault, or an internal failure of the EUT. Specified minimum fault currents at the service entrance of residential circuits below 600 V will usually range from 1 kA to 10 kA (and more in some rare cases), with higher requirements for industrial circuits, up to 100 kA and 200 kA or more in rare cases. However, the requirement for filtering during a surge test generally implies the insertion of the series impedance of the ***back filter*** in the line. Typical inductor values for L_1 and L_2 in Figure B.9 and Figure B.10, for example, range from microhenries to a few millihenries.



T	Surge coupling transformer
L_1, L_2	Filter inductors
C_1	Line-to-neutral filter capacitor
C_2	Neutral-to-ground filter capacitor
C_3	(Optional) Line-to-ground filter capacitor
C_4	Surge coupling capacitor

*Details of the filter design may vary among manufacturers.

Figure B.9—Back filter added to series coupler* (line-to-neutral injection mode)



L_1, L_2	Filter inductors
C	Surge generator output coupling capacitor
C_1	Line-to-neutral filter capacitor
C_2	Neutral-to-ground filter capacitor
C_3	(Optional) Line-to-ground filter capacitor

*Details of the filter design may vary among manufacturers.

Figure B.10—Back filter added to shunt coupler*

Even with inductances as low as 0.5 mH, the sum of L_1 and L_2 constitutes a total impedance of 0.377 Ω at 60 Hz. The maximum fault current is therefore only 115/0.377 or about 300 A for a 115 Vac line. For filters with higher series inductance, fault currents will be proportionately lower. Thus, the test schedule should recognize the effect of the filter; some reduction of the available fault current might be unavoidable.

If the back filters include shunt capacitors on the ***EUT*** side of the series inductance of the filters, a flashover in the EUT will cause these capacitors to discharge into the fault. This capacitor discharge might mask the effect that would occur in the normal environment where these shunt capacitors would not be present, and in which only the power frequency fault current would normally flow.

For testing protective devices that involve a ***follow current***, it would be desirable to perform the test with full follow current, that is, the current resulting from the available fault current at the EUT terminals. More powerful surge generators and filters with lower impedance can be used if required.

For EUTs other than SPDs, the available fault current will flow only if the EUT has failed; in which case, the exact level of the fault current could be of secondary concern, unless the purpose of the test is explicitly to investigate failure modes and effects. In this situation, it might be advantageous to perform the test with reduced fault current in order not to completely destroy evidence for the post-mortem.

Another consideration to keep in mind when testing for failure mode is the importance of fault duration as limited by an overcurrent protective device in the actual use of the equipment. Although a large available fault current could seem to be a worst-case scenario, large fault currents produce instantaneous tripping of overcurrent protective devices and, therefore, limit the plasma generation. On the other hand, lower fault currents result in a significant time delay for tripping an overcurrent protective device, therefore, a long period of arcing that might be a fire hazard. This situation is another aspect of the ***blind spot*** concern, where the worst failure mode might, paradoxically, occur at less-than-maximum-available fault current.

Therefore, it is important to recognize the effect of the unavoidable back filters and to make appropriate allowances for the difference between a test with filters inserted into the line with the surge injected downstream (away from the source of power) from the filters, as opposed to performance in actual applications where the surge is coming from the power system.

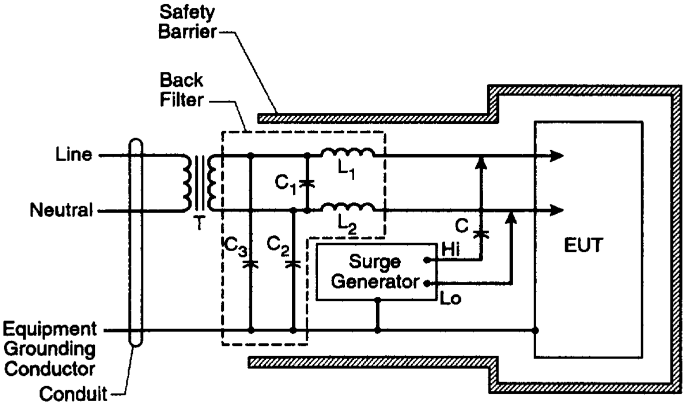
B.20 Follow current

Follow current is defined in *The Authoritative Dictionary of IEEE Standard Terms,* Seventh Edition [B11], as "The current from the connected power source that flows through an arrester during and following the passage of discharge current." For the purposes of this recommended practice, follow current is also used to refer to a similar current from the power source resulting from any sparkover in the ***EUT***—intentional or unintentional.

B.21 Ground fault protection

If ground fault circuit interrupters (GFCIs) are employed in the test laboratory, difficulties might be experienced with the ***back filters*** in the ac power lines. Because normally only a small voltage exists between neutral and ground, a capacitor between them (such as C_2 in Figure B.9 and Figure B.10) will draw far less current than one from line to ground (C_3). If the line-to-ground capacitor is omitted, even tens of microfarads between neutral and ground (C_2) yield an effective imbalance current of only a few milliamperes due to the minimal potential difference normally existing between neutral and ground. By contrast, if the line-to-ground capacitor C_3 is included, values as low as 10 nF to 100 nF can produce a current sufficient to actuate the GFCI due to the line-to-ground potential difference that normally exists. However, for some surge test configurations, omission of the line-to-ground filter capacitor will result in higher residual transients on the nominally unsurged line, unless other capacitor values are increased to compensate.

An alternative configuration to employ in more stringent GFCI applications is shown in Figure B.11. Use of the power-line isolation transformer T permits virtually any degree of capacitor loading on both line and neutral conductors—in this case, the transformer secondary—with no adverse effect on the power-line GFCI. Insertion of the impedance of the isolating transformer, however, decreases the available ***fault current***. GFCIs are also designed to trip out if the neutral conductor (load side) becomes grounded through an impedance of less than 2 Ω to 5 Ω.



T — Isolation transformer
All other components are identical to those of Fig B10.

Figure B.11—Back filter and coupler with isolation transformer for GFCI applications

Most GFCIs sense a grounding of the neutral conductor by use of a high-frequency (5 kHz to 10 kHz) signal induced in the neutral conductor. Therefore, a capacitor connected between the neutral conductor and the ***equipment grounding conductor*** might cause a GFCI to trip (10 µF is about 2 Ω at 7.5 kHz).

B.22 Grounding conductor

See B.17.

B.23 Grounding practices

Equipment grounding configurations found in ***EUTs*** tend to fall into one of three general schemes, or into some combination of them:

a) *Floating reference*. Where the single reference for certain circuits is isolated from earth and power reference (sometimes called “floating ground”).
b) *Single-point ground*. Where only one connection is made to power ground reference.
c) *Multiple-point ground*. Where there are many connections to earth at various points of the power ground reference system.

Each of these grounding configurations presents certain problems that must be dealt with when a surge test procedure is developed.

As described, a “floating ground” is isolated from all other ground references. However, this isolation does not alleviate the need to provide protection. The result is usually a configuration similar to that shown in Figure B.12. Notice that the equipment chassis is bonded to the ***equipment grounding conductor***, providing the necessary safety protection. It is also important to realize that Circuit A is totally isolated from the chassis and the equipment grounding conductor. The important considerations here are the possibilities of flashover between Circuit A and the chassis, along with the unintentional introduction of a ground connection via test equipment probes if these are not used in a ***differential connection*** mode.

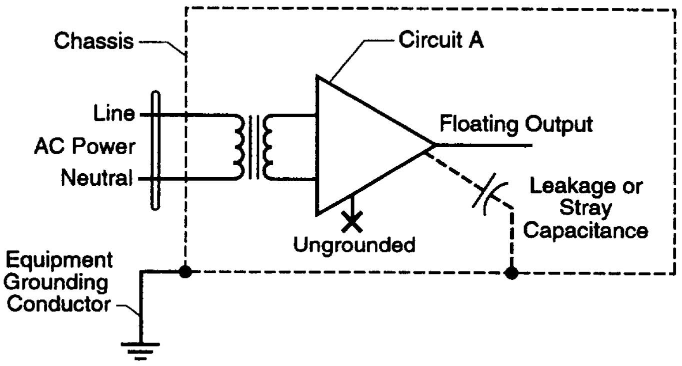


Figure B.12—Floating reference (“floating ground”)

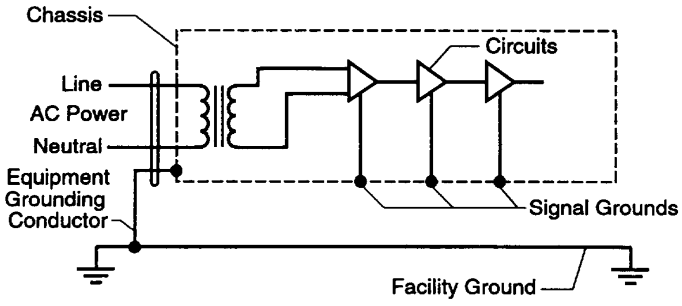
Several schemes are shown in Figure B.13 that illustrate single-point connections to the power ground reference, or earth. In Figure B.13(a), the equipment designer has utilized the chassis as the internal common equipotential reference, and this “chassis ground” is earthed at one point. In Figure B.13(b), the designer has elected to control the structure of the signal-ground distribution within the equipment, bonding it to the chassis at the point selected for earth connection. With this single-point grounding scheme, a surge current flow in the facility ground path does not involve the chassis.

Figure B.14 is a representation of multiple-point ground. As can be seen, ground connections are made to several points in the configuration. The distinction between this and single-point grounding is that the various signal references and ***grounding conductors*** are all tied to different ground points, none of which shares commonality with the chassis ground. Thus, surge currents in the facility ground can flow in and out of such chassis, which permits voltage buildup exposing the circuits in the chassis to flashover, upset, or both.

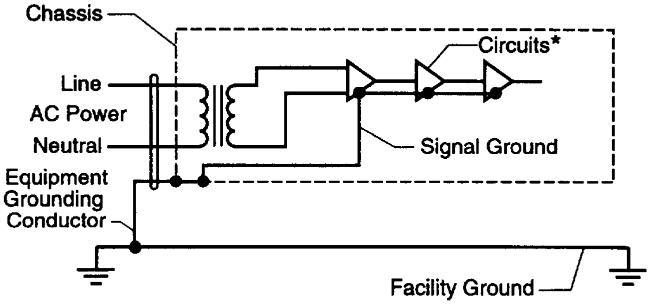
Again, it is emphasized that these descriptions do not aim at recommending any particular scheme for better ***noise*** immunity; rather, they are described to forearm the individual performing surge tests on an existing EUT. Many EUT designers strive to avoid noise problems by controlling the ways by which their circuits are grounded.

B.24 Insulation coordination

Insulation coordination is a concept in which solid insulation in electrical equipment has an impulse withstand voltage level in excess of either the protective voltage level of associated surge-protective devices or the breakdown of the clearances existing in the equipment. This coordination ensures that the surge-protective devices or the clearances in air (a renewable insulation) protect the nonrenewable solid insulation.



(a) Parallel single-point ground



* Note: Removal of center circuits for test purposes can cause an inadvertant break in the ground chain.

(b) Series single-point ground

Figure B.13—Single-point grounding

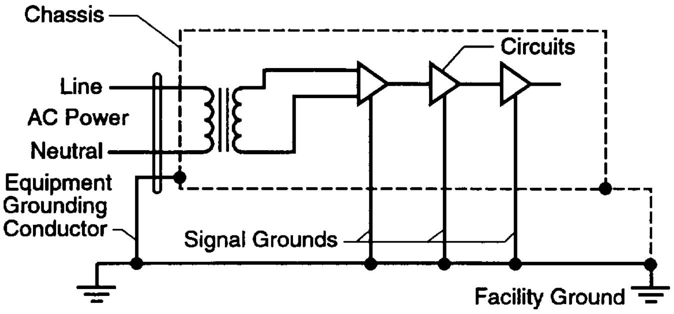


Figure B.14—Multiple-point grounding

A coordinated insulation system implies the selection of the electrical insulation characteristics of equipment with regard to its application and its relation to its surroundings. It is necessary to consider the voltages that can appear within the system, the location and characteristics of the surge-protective devices, the continuity of service desired, and the safety of persons and property, so that the probability of undesired incidents due to voltage stresses is reduced to ensure an economically and operationally acceptable performance.

Many existing low-voltage product standards in the United States, based primarily on experience, specify dimensional requirements for equipment design but do not require tests measuring the actual performance of the equipment insulation. As a result, the insulation systems of various equipment are uncoordinated and the sparkover of clearances or the breakdown of solid insulation can occur at random locations at unknown transient overvoltage levels. New standards such as IEC 60664-1 [B7] are based on the concept of insulation coordination and rely on performance tests rather than on the traditional dimension standards.

B.25 Insulation degradation

The majority of the ***EUT*** failures under a voltage transient may be very broadly considered as insulation failures. This insulation failure can occur in wiring insulation, within the bulk of solid insulation, at the edges of printed circuit boards, within semiconductor material, or along the etch runs of an integrated circuit. Two modes of failure might be encountered:

a) A destructive single flashover that leads to permanent damage, either by the energy of the surge alone or by the energy of the ***follow current*** initiated by the surge sparkover.
b) A progressive loss of quality of the insulation where several successive sparkovers along the surface or ***partial discharges*** within the bulk of the insulation eventually lead to grossly visible and permanent damage.

Therefore, the test criteria should include, as appropriate, an evaluation of this mechanism.

B.26 Insulation tracking

The flashover of a clearance, at the first occurrence or after multiple surges, might affect adjacent solid organic insulation or weaken the long-term withstand capability of the ***EUT*** and, therefore, might not be such a benign occurrence. In addition, a high voltage, either of a transient nature or continuously recurring, might result in ***partial discharges*** within solid insulation or on surfaces of insulation. Repetitive partial discharges might result in degradation of the insulation material.

A post-test examination should be performed to attempt to ascertain the location and effect of a flashover that occurred in the EUT. Observation during the surge will also help in locating a flashover, and a repeat test where flashover would occur at a lower voltage would indicate some change in the EUT. Other components subjected to the surge stress might also be weakened but appear to perform “normally” for some time, whereas others might not even withstand normal line voltage. Therefore, some life testing after surge testing is desirable.

B.27 Life consumption

It is possible that a significant portion of rated protector life might be consumed during a surge test program (see B.30). This consumption is far more likely to occur during the engineering phase of ***EUT*** development than during ***production tests.*** If it does occur, the protector(s) may be replaced by new ones during tests or following test completion, with a small portion of the tests then being repeated.

Performing tests with built-in deliberate defects in the EUT could also provide information on life consumption and integrated stress for the protectors.

B.28 Low voltage

The term *low-voltage* in this document has the same meaning as *low-voltage system (electric power)* in *The Authoritative Dictionary of IEEE Standards Terms,* Seventh Edition [B11], and, that is, up to 1000 V rms for ac circuits. For electronic designers, the term might have a different meaning, but in keeping with [B11], this document uses *low-voltage* only as stated above.

B.29 Monitoring

IEEE Std C62.41.2-2002 defines an open-circuit voltage and a short-circuit current for the waveforms; the impedance of the test circuit determines the choice between voltage and current. Therefore, the monitoring of the applied surge should include both voltage and current capabilities. For instance, if the ***EUT*** is presumed to be a high-impedance circuit, the test would aim at applying a voltage surge at a value set by adjusting the surge generator with the EUT disconnected, following which the EUT would be reconnected without a change in the generator setting. If the EUT is presumed to be a low-impedance circuit (because it includes a surge-protective device expected to operate under the applied surge), the test would aim at exercising that protective device by the injection of a current surge, with an available generator short-circuit current selected on the basis of the IEEE Std C62.41.2-2002 environment. If the EUT contains surge-protective devices with negative impedance characteristics, such as a voltage-switching device, the EUT impedance will switch from high to low during the test, at the time the voltage-switching device operates (see B.49).

Monitoring the test outcome may include such criteria as voltage withstand of the EUT (absence of a breakdown that would otherwise chop the applied wave), absence of corona or ***partial discharge*** in the circuits during the impulse, ***surge let-through*** voltage or ***surge remnant*** passed on to devices connected at the output of the EUT, or any other parameter significant to the evaluation of a specific EUT. In the case of an EFT Burst test, attempts at monitoring voltages within the EUT might introduce disturbances through the probe acting as an antenna, so that monitoring after the initial verifications prescribed by the EFT Burst procedure is generally limited to the observation of any upset in the operation of the EUT.

B.30 Multiple surge

In service, the protectors within the ***EUT*** will be subjected to one or, at most, a few ***surge events*** at a time (including a net of several surges associated with a lightning flash, including subsequent strokes). Typically, a long recovery period of minutes, hours, or even days will follow before they are required to withstand the next surge event. However, during thorough surge testing, it might be necessary to apply a sequence of tens or even hundreds of pulses or surge events. Surging at all network ***phase angles*** versus the ac line and in both polarities on a progressive stress basis might result in a large number of successive test waves.

In ***production tests***, it is important to limit the number of surges applied to devices intended for shipment in order to avoid possible degradation of the product.

It is possible that a component would be stressed during a single surge and continue to perform “normally” for some time. However, the life of this component might be shortened so that it might fail much earlier than it would have without the surge. The device parameters might be altered by the surge, but the device would remain temporarily functional, perhaps even within its specifications. A thermal runaway might be initiated if the device was left powered for a sufficient time after completion of the series of pulse applications. Therefore, some life testing should follow surge testing.

B.31 Noise

This recommended practice on surge testing primarily concerns those surges with amplitudes that typically exceed twice the normal circuit voltages. These surges are mainly caused by lightning and power system switching. It is recognized that the range of amplitudes extends downward, and that switching transients can be injected in ac power lines with low amplitude but very short rise time (that is, below 100 ns). These fast transients can produce severe interference problems and should not be ignored. Another source of interference is mobile communication equipment, which is increasingly used in industrial plants. The electromagnetic compatibility (EMC) literature and standards should be consulted for guidance in this area.

B.32 Normal mode

See B.5.

B.33 Partial discharge

When an electrically stressed dielectric structure exhibits one or more areas of very local field intensification, it is possible that electrical (corona) discharges might be present in the high field regions without the failure of the complete insulation. The most common circumstance leading to the formation of such partial discharges occurs in solid dielectrics in which small cavities exist. Under ac conditions, the electric stress in the gaseous voids will be enhanced because of the ratio of dielectric constants between solid and occluded gas. Discharges in the gas-filled cavity will commence when the voltage on the complete structure reaches a value known as the inception voltage, which will generally be considerably less than that required for complete short-term failure. The magnitude of the discharges, usually measured in picocoulombs, is dependent on cavity dimension, and the ***repetition rate*** of the discharges, on the extent to which the inception voltage is exceeded. Cavities are often present in solid dielectrics as manufacturing defects or by virtue of the operation of thermal or mechanical stresses. In liquid-impregnated systems, partial discharges can occur in bubbles formed in the stressed impregnating fluid. Other forms of stress enhancement, such as conducting inclusions, can also generate partial discharges.

Under dc conditions, the distribution of stress in a solid is determined by the volume resistivity and not by the relative permittivities. Under these circumstances, the time constant for charging the capacitance of a small cavity to a voltage at which it will discharge is large, and thus discharges under dc conditions are much less frequent. For surge voltages, the partial discharge behavior is critically dependent on whether the impulses are unipolar or involve voltage reversals. Because charges might be trapped within a dielectric, reversing the polarity of the applied voltage is much more severe than is a single polarity test.

B.34 Phase angle

Many surge-related equipment failures depend on the phase angle of the ac voltage sine wave at which the surge is applied (Figure B.15). When an ***EUT*** clearance sparks over during an impulse (surge) test, ***follow current*** might occur.

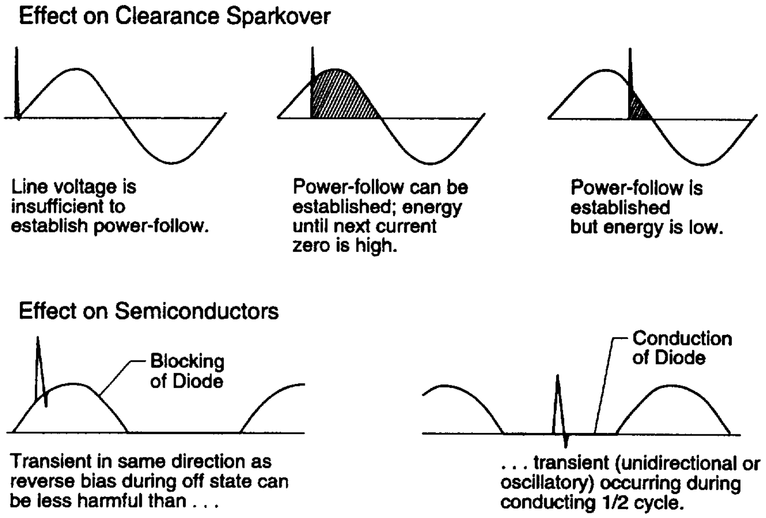


Figure B.15—Phase angle effects

The likelihood of such an occurrence depends on a number of factors, one of which is the instantaneous value of power system voltage at the time of sparkover. If this voltage is low (early or late in the cycle), follow current might not result. If this voltage is sufficient to establish a follow current (later, but not too late in the cycle), the power-frequency current integral is a function of the time remaining in the cycle until current zero. Thus, both the occurrence and consequence of a follow current depend on the phase angle of the surge (Bachl et al. [B2]).

For semiconductors, the phenomenon appears related to the conduction state of EUT semiconductor devices at the time the surge occurs. Semiconductor parameters that might be involved include forward and reverse recovery characteristics and second-breakdown performance. The devices most likely to fail in a phase-related way are semiconductors involved in the power-input circuitry. Others, in different areas of the EUT, might also exhibit such failure modes if the EUT power-input circuits let some or all of the surge pass through to them.

B.35 Powered testing

There are several reasons for performing powered testing:

a) From the standpoint of good practice, it is best to perform laboratory tests in a manner that most closely simulates the actual service environment.

b) It is the applied ac that furnishes the energy following the surge, which can establish sustained arcing faults, tracking on insulation, destruction of printed wiring, and so on (see B.34).

c) The application of normal ac power generally raises the ***EUT*** to an initial level of stress. Without power current following a surge-induced flashover, the resulting defect might not be detected. Even repeated, unpowered surging might not mark the defect well enough to make it obvious.

B.36 Production test

It may be desirable to set up an acceptable quality level (AQL) surge-test program based, as far as possible, on knowledge of ***EUT*** surge sensitivities. In production tests, it is important to limit the number of surges applied to devices intended for shipment in order to avoid any degradation of the product. Tests made on some samples in AQL programs might damage components or the EUT. All samples used in potentially destructive tests should be scrapped.

B.37 Qualification test

It will generally be up to the equipment specifier and manufacturer to agree on which tests will be performed. Tests performed to qualify a new equipment design or a major modification to an existing one will ordinarily be more complete than tests carried out on a routine basis on production products.

B.38 Repetition rate

A maximum allowable surge repetition rate cannot be determined without the evaluation of the ***EUT*** protection design. For this reason, it is strongly recommended that the maximum allowable repetition rate for pulse trains of varying length be incorporated into the test plan. In the absence of other requirements, it is suggested that the wait times of Table B.2 be incorporated in the test protocol.

Table B.2—Suggested wait times

Location category	Waveform type	Power parameters	Numbers of applied surges	Wait time (seconds)
A	0.5 µs–100 kHz Ring Wave	6 kV OCV[a] 200 A SCI[b]	10 to 1000	6 to 20
B	0.5 µs–100 kHz Ring Wave	6 kV OCV 500 A SCI	10 to 1000	10 to 30
C	Combination Wave	6 kV OCV 3 kA SCI	10 to 1000	30 to 120

[a] OCV—Open-circuit voltage
[b] SCI—Short-circuit current

Note that all equipment do not need to follow the wait times of Table B.2, which are suggested mainly for testing new equipment designs. The fact that a particular piece of equipment should be surged more slowly than the table suggests in no way implies that it provides less surge protection in the field. The slower rate is relevant during surge test, where repetitive testing should not be performed at a rate that would produce cumulative heating of the SPD. There might be repetition rate requirements for surges to be withstood in actual service, such as multiple discharges, and these should be determined at the outset if they exist. The repetition capabilities of the surge test generator should also be considered.

In the case of the EUT being a computer system, a very high repetition rate at low energy level might be necessary to check for software ***susceptibility***, whereas a “one-shot” surge would be needed to check for hardware ***vulnerability***. (See further comments under B.31.)

B.39 Surge coupling

B.39.1 Direct coupling

Direct coupling of the surge generator with the EUT (Figure B.16) is applicable for cases in which the purpose of the test is merely to evaluate the surge-withstand capability of the EUT, from the point of view of energy-absorption capability (for SPDs) or insulation assessment (for equipment). Such a test cannot reveal the complete scenario of a failure that the surge might have caused, because the follow-current from the power-frequency source is not present. Any disturbance in the operation of the EUT cannot be revealed either, because the EUT is not operating.

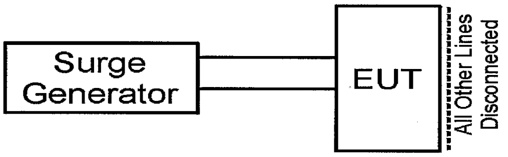


Figure B.16—Direct coupling surge (unpowered tests only, simplified)

B.39.2 Series coupling

Figure B.17 shows, in a simplified manner, an example of the series approach. (The details of the ***back filter*** can vary with manufacturers.) Coupling of transformer T is driven by the surge generator, and its secondary is inserted in series with the line side of the single-phase mains. Note that in this example the line side is, in effect, being surged with respect to both neutral and ground. Series coupling has this property: The line in which the coupling is inserted is always effectively surged with respect to all other lines (power or signal, or both) into and out of the ***EUT***.

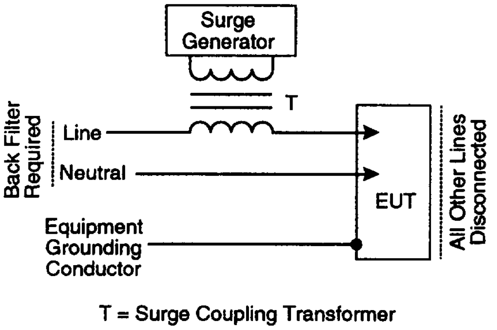


Figure B.17—Series coupling of surge generator (simplified)

B.39.3 Shunt coupling

Figure B.18 shows, in a simplified manner, an example of shunt coupling. (The details of the ***back filter*** can vary with generator or back filter manufacturers.) In this case, called normal mode, the surge is applied via coupling capacitor C between line and neutral. Shunt coupling is therefore different from series coupling. Other lines to the EUT need not be intentionally involved with the surge path. (A flashover during testing might, however, involve these other lines.)

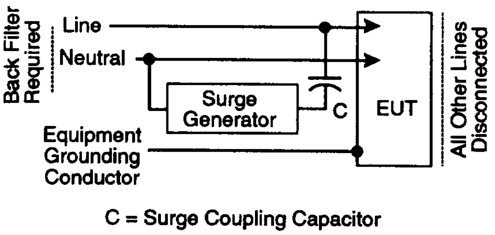


Figure B.18—Shunt coupling of surge generator (simplified)

B.39.4 Arbitrary waveform generator

This method is gaining acceptance as linear power amplifiers are becoming more common in test laboratories (Figure B.19). The advantage is that low-frequencies surges can be superimposed onto the power frequency, without the limitations of a back filter. However, to perform a meaningful and relevant test, the sponsor must specify the complete test parameters, in contrast with the standard waveforms that can be applied by a Combination Wave generator to an EUT applying the “let it rip” principle discussed in B.16.

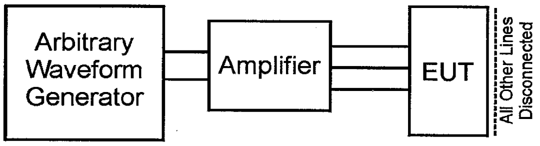


Figure B.19—Injecting surge with arbitrary waveform generator (simplified)

B.40 Surge event

A surge event, in the context of this recommended practice, can be a single pulse or a train of pulses occurring with little time between them (see B.30). Therefore, when testing for power or energy considerations, a train of pulses should be considered. When testing for evaluation of voltage limiting, a single pulse can provide the necessary information.

B.41 Surge let-through

A surge let-through is that part of a surge that passes through a surge-protective device or a power supply, with little or no alteration. For instance, a power supply might be unaffected by a line-to-neutral voltage surge or a current surge along the ***equipment grounding conductor****;* however, if the power supply allows the surge to pass through, the circuit it powers will be subjected to this surge let-through (see B.42).

B.42 Surge remnant

A surge remnant is that portion of the surge that remains downstream of one or more SPDs. The limiting voltage of a protective device, propagating downstream (away from the source of the surge), is a surge remnant. The front part of a surge before a protective device conducts surge current is also a surge remnant.

When an ***EUT*** contains built-in surge-protective devices, the EUT should be surge tested with the stress relevant to the expected performance of the protective device, with the components downstream of the protective device stressed only to the voltage level allowed to pass by the protective device. Whole-system surge tests need be concerned with internal protector remnants only to the extent that, during engineering or ***qualification tests***, or both, it is usually desirable to employ limit protectors. Carrying the process a step further, it is possible then to select the subsequent protector to ensure that it, in turn, is maximally stressed. This extension implies selection of a performance point that will generally be the opposite 3 σ point from that which transmits maximum stress to the protector or circuit that follows in turn. Various combinations of these situations should be employed to ensure a design that will remain valid over the entire range of the anticipated protector performance distribution (see B.4, B.12, and B.41).

B.43 Susceptibility

A test for susceptibility implies normal equipment functioning prior to the surge; therefore, equipment can only be checked in the powered configuration. In order to segment the surge test of a larger system, it might be necessary to use simulations, for inputs as well as for outputs. As a result, an evaluation of misoperation might require measurements to be taken on either simulated outputs (for performance) or on simulated inputs (for unusual loadings). In addition, it is always necessary to consider the possibility that the ***EUT*** might carry some portion of the applied surge to either inputs or outputs, or both, whether or not the EUT demonstrates susceptibility. For instance, a power supply might be insensitive to a surge applied to both of its inputs versus ground, but the ***common-mode*** (see B.5) surge might well pass unattenuated to the circuitry being driven by the supply.

The importance of susceptibility depends on the EUT and its function: An audible click in a telephone voice system might not be important, but bit dropouts with consequent corruption of data in a computer or shutdown of a digital processor might be highly significant.

B.44 Test conditions

B.44.1 Powered testing

During powered testing of equipment that is connected to the mains, it is necessary to interpose a ***back filter*** between the ***EUT*** and the mains and to use a ***coupler*** between the surge generator and the EUT. The presence of the back filter and the coupler, and the low impedance of the mains, will alter the surge waveform compared with that observed at the output terminals of the surge generator alone (Richman 1985 [B23]).

When the intent of surge testing is to apply surges to the mains connection of the EUT while the equipment is operating, the effect of the back filter and the coupling network on the surge ***waveform*** must be included when determining the surge waveform. The expression *open-circuit voltage* means that the EUT is not connected, but the surge coupler and back filter are. They are clearly parts of the surge generator, because they can affect the wave applied to the EUT.

B.44.1.1 Verification of the test generator

As a result of these effects, it is necessary that the surge waveform specifications for both the 0.5 µs–100 kHz Ring Wave and the 1.2/50 µs–8/20 µs Combination Wave be satisfied accordingly. An initial verification should be made of the following conditions:

a) The surge generator is connected to the back filter via the coupling network in the relevant coupling mode.
b) All the conductors of the mains connection supplying the back filter, including protective ground, are disconnected from the mains and shorted together at a point upstream from the back filter.

By shorting the mains upstream from the back filter (prior to the actual powered test), the effects caused by differing impedances of the mains from one laboratory to another are avoided. Allowing the ac supply mains to be disconnected and simulating the low impedance of the mains by shorting the conductors together is the recommended procedure to determine peak voltage and current. The available short-circuit surge current and the open-circuit surge voltage (as defined above) at the EUT power-line interface can be readily verified. Note, however, that this procedure establishes the voltage peak of the surge alone.

During testing of powered equipment or components, the surge waveform may be applied at any specified ***phase angle*** of the normal mains waveform. The timing of the surge application with respect to the power-frequency sine wave will then determine the peak of the total surge. Because this total surge is the significant parameter in the response and stress of a voltage-limiting surge-protective device, this effect must be recognized in setting the surge amplitudes for low-level surge testing. With surge levels in the kilovolt range, the variation introduced by the value of the sine-wave voltage at the instant of the surge application is less significant.

In tests where the value of *di/dt* is large (such as the 8/20 µs current waveform or the 100 kHz Ring Wave with its relatively short rise time), it is particularly important to use short lengths of conductors and maintain minimum conductor loop area between the surge generator and the device under test. (See C.1.1.)

B.44.1.2 Tolerances on the most important parameter

The combination of practical tolerances on the surge generator internal components, operator settings, and instrument calibration uncertainties can produce significant variations in the results of tests performed at different sites. To reduce the effect of these unavoidable differences, the purpose of the test should be recognized when specifying the most important of the voltage or current test parameter for a specified waveform:

a) When testing insulation, the peak open-circuit voltage is the most important parameter. Therefore, the peak open-circuit voltage should be adjusted to the desired level before connecting the EUT to the generator.
b) When testing energy-absorbing nonlinear surge-protective devices, the short-circuit current peak is the most important parameter. According to the concept of testing for demonstration of surge withstand in a specific environment, as defined in IEEE Std C62.41.2-2002, the current flowing in the EUT should NOT be adjusted during the test to obtain a desired level. However, testing for verification of a component specification requires obtaining a set value of surge current. See further discussion of this duality in B.16.

B.44.2 Unpowered testing

When the 1.2/50 µs–8/20 µs Combination Wave is used to test unenergized components, the same generator, with back filter in place, may still be used. However, the mains should be disconnected upstream from the back filter and all of the input power conductors shorted together and to ground.

Alternatively, the back filter and the coupling network may be removed from a surge generator that has an internal circuit to determine the presence or absence of a back filter/coupling network and to make the appropriate adjustments in the waveform. Such circuits are included in many commercially available surge generators.

B.45 Unforeseen consequences

An unforeseen consequence might be the outcome of a surge test performed in the laboratory, or of a surge occurring in the field and impinging a device for which this type of outcome might not have been previously recognized, despite the fact that surge tests had been performed during the design phases of that device. Some examples follow:

a) A power supply is not damaged by the surge, but passes it downstream causing failure of connected equipment in the field, a consequence that was not recognized during a test focusing only on the ***EUT***.
b) A device deemed most likely to be installed in a Category A location might in fact be installed in a Category B environment where it might fail in an unacceptable mode.
c) A solid-state power-control EUT fails in a mode that leaves power on full; hence, a motor overspeed, a load burnout, and so on.
d) A surge-protective device fails under long-term exposure (failure to reseal, thermal runaway, etc.)

The phenomenon is systemic in nature and results from testing an EUT as an isolated device rather than testing it in its intended application. Downstream damage can result from excessive ***surge let-through***, which is not observable unless system-level testing is performed.

B.46 Unpowered testing

As a precaution against severe damage of the test piece that might be difficult to analyze, unpowered testing should always precede powered testing. For some types of ***EUT***, where it is judged that powered testing would not provide additional insights on the outcome, unpowered testing only is quite appropriate. For instance, in an ***insulation coordination*** test, a clearance sparkover is sufficient to signal a failure without the more complicated powered test.

B.47 Upset

The term *upset* can take on different meanings and degrees of severity depending on the context and the circumstances. For instance, the IEC publications on immunity tests (61000-4 series) list outcomes of the test, two of which can be characterized as “upset”:

2) temporary degradation or loss of function or performance which is self-recoverable.

3) temporary degradation or loss of function or performance which requires operator intervention or system reset.

As discussed in B.11, for critical applications tolerating no interruption, outcome 3) might be considered as damage from a conservative point of view.

B.48 Vulnerability

Vulnerability refers to ***EUT*** damage that has to be repaired before the normal equipment function can be reestablished. It might involve components such as semiconductors, or it might result in open runs (conducting paths) on a printed circuit board, in arcing between runs that leaves a heavy conductive carbon track, or in other destructive phenomena that prevent normal EUT performance. In the context of IEEE Std C62.41.2-2002 and IEC 60664-1 (1992) [B7] testing for vulnerability is always required.

On the other hand, testing for ***susceptibility*** is elective, and the need for it should be decided by the user or designer of the EUT, or by both, taking into consideration its application; many criteria other than surge testing are defined in electromagnetic compatibility (EMC) standards.

B.49 Waveform: Voltage versus current

IEEE Std C62.41.2-2002 proposes two standard voltage waveforms with associated current waveforms, and three additional waveforms, depending on the ***location category*** of interest and the nature of the ***EUT*** (high or low impedance). If the particulars of the application warrant it, a different waveform, longer or shorter, may also be appropriate.

If the characteristics of the specific EUTs are known, the sponsor may specify the appropriate test wave, voltage, or current, depending on the input impedance of the EUT under surge conditions. Pass-fail acceptance tests on insulation, for instance, are not concerned with events following the insulation breakdown, and therefore, the simple voltage test should be sufficient. Other tests are so concerned, because the EUT impedance might be affected, temporarily or permanently, by the very test surge being applied. The following aspects of surge testing electronic systems are relevant to the selection of a test method:

a) Testing for failure modes that involve flashover are influenced by the surge current that would flow after flashover (Bachl et al. 1997 [B2]).
b) The ***surge let-through*** of a protective device depends on the applied voltage front, and the ***surge remnant*** depends on the ensuing discharge current.
c) The surge current front and magnitude after operation of a voltage-switching device can affect the coupling of additional voltages in downstream (away from the source of the surge) circuits.
d) The response of a voltage-switching device, subjected to an intended current test, will be influenced by the voltage front applied by the generator, which senses a high-impedance test piece, until operation of the voltage-switching device.
e) The voltage compliance of an intended current test generator will influence the surge remnant of a voltage-limiting device.

Therefore, the generator should be capable of a dual role:

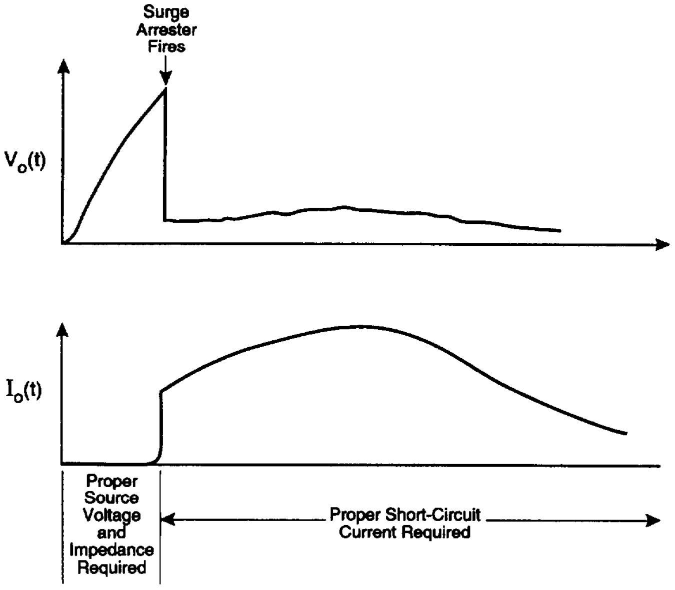
First, for what is nominally a voltage test, such as the 1.2/50 µs wave of IEEE Std C62.41.2-2002, a sudden impedance drop must be accompanied by a minimum, specified, surge current to ensure both that failure will leave a mark and that ***follow current*** will be initiated. It is also desirable that the short-circuit current waveform (such as the 8/20 µs wave) be the prescribed value for the same reason.

Second, for what is nominally a current test (such as the 8/20 µs wave), the voltages involved should be held between a low and a high limit in order to respectively initiate current flow by a sparkover-type device, while not exceeding an appropriate upper limit. The prescribed open-circuit voltage waveform (or at least rise time, such as 1.2 µs) is preferable to ensure operation of a voltage-switching device or internal flashover at a repeatable level.

Such tests can be accomplished with a surge generator having the inherent capability of applying a selected voltage wave to a high-impedance specimen and of delivering a selected short-circuit current wave into a very low-impedance test specimen. Although the need for providing conditions a and b above might not always be apparent, ignoring these conditions can lead to meaningless testing, for instance, where a surge generator of high internal impedance or low stored energy would be applied to conduct a voltage test on an EUT having relatively low input impedance.

Further reference to this need for providing the dual capability, if and when the test piece experiences flashover, voltage-limiting or voltage-switching action, can be found in Richman 1983 [B22], and Vance et al. 1980 [B33]). Figure B.20, excerpted from [B33], illustrates the case in which the test piece is a protector containing at least a gas tube, with the following descriptive comments:

However, if we examine the test requirements more carefully, we observe that these lines are usually provided with spark-gap surge arresters that fire at a few kilovolts. After the surge arrester fires, it behaves somewhat as a voltage regulator; the most important parameter, then, is the current delivered to the surge arrester. Thus, as illustrated in the figure, it is necessary to simulate the proper impedance and voltage for these protected lines only until the surge arrester fires; thereafter, only the current need be simulated.



Source: Vance, Nanevicz, and Graf [B33]

Figure B.20—Excitation of nonlinear parameters

If a generator with dual capability is not available, separate current and voltage surge tests need to be performed in succession with two separate generators. However, such an approach might not detect performance limitations such as ***blind spots*** and energy-sharing difficulties in multiple-device protective systems (Martzloff 1980 [B14], Richman 1983 [B22]).

On the other hand, it might be desirable to limit the surge current after a breakdown under a voltage surge test in order to avoid complete destruction around the breakdown path to the point where diagnosis might be difficult (this is a different purpose from that of the test for failure modes and effects). The person conducting the test should select the waveform or combination of waveforms that represents the type of surges to which the EUT should be subjected. Both the nature of the EUT and the nature of the surges should be considered in making that selection.

B.50 Withstand level

As pointed out in the Introduction and in Clause 1, assignment of specific withstand levels is not the purpose of this recommended practice. The selection process will be performed with agreement among the concerned parties, typically by technical committees concerned with specific products, or by the sponsor on the basis of the specific situation. Note also that the selection of withstand levels, when clearance flashover is involved, requires consideration of altitude effects both in specifying the level and in performing the tests.

In evaluating the results of a test for withstand level, it is necessary to recognize the statistical aspects of the ***EUT*** behavior. The assumption is that if a single specimen is being tested (a frequent situation when the EUT is a complex and expensive piece of equipment), the specimen has been selected at random from the population of interest. Typically, this single piece of equipment is subjected to increasing voltage tests until the failure criterion is observed; the test result is then a single number, either the voltage surge or the current surge that produced the failure.

The result for a single random sample provides a statistical best estimate of the characteristic in question for the sampled population. This result, of course, provides no information about the variability of this characteristic from equipment to equipment. Therefore, unless other relevant prior information about variability is available, it is not possible to make any statement concerning how close the values of the individual pieces of equipment in the population are to that of the single unit that was sampled or, more generally, about the statistical distribution of such samples. To obtain such information about variability, additional samples are required.

Annex C

(informative)

Practical hints on surge testing

This informative annex provides some practical hints—or even more imperative advice—derived from the experience in performing the tests as described in the 1992 version of IEEE Std C62.45. Although these might seem obvious or just common sense to individuals steeped into surge testing, to the point that they might appear unnecessary, experience has also shown that they are sometimes overlooked. More important, these hints should help make those not directly involved in the test aware of the issues, so that adequate support can be provided for the personnel performing the tests at a pace that will ensure adequate precautions and timely documentation.

C.1 Surge measurements

C.1.1 Connections

a) To minimize departure from the ideal test waveforms, it is essential that the connections between the surge generator and the EUT introduce as little impedance as possible:
    1) A high-voltage coaxial cable is the best, but admittedly sometimes awkward to connect.
    2) Next, a twisted pair of leads, AWG #12 minimum, is acceptable
    3) Separate open wires are not acceptable.[11]
b) Minimize the separation of the two conductors when threading one of them through the window of the current transducer.
c) Minimize the coupling between the two unavoidable loops formed at the EUT terminals on the one hand by the connection to the surge generator, and on the other hand by the end-leads of the probes. Both connections, from the generator to the probes, must be twisted as much as possible, and separated from each other only enough to reach the EUT terminals.

Many references are found in the literature stating that *lead length* has an undesirable effect by adding the voltage caused by the inductance of the connecting lead to the measurement, or to the protective level achieved by an SPD. Actually, the measured voltage in a test, or the protective voltage in equipment, is the voltage established by the limiting action for the SPD, augmented by the voltage induced in the *loop area* formed by the connecting leads (Figure C.1). Therefore, when conducting a test to evaluate the performance of an SPD provided with connecting leads, the issue is not so much the additional length of the leads, but the loop area into which the additional voltage can be induced. Twisting the leads, whatever their length, will substantially reduce the effect.

NOTE—For the example represented in Figure C.1, with a typical standard impulse wave of 8 µs front time, *di/dt* is highest near the beginning of the impulse. A similar situation, but even more prevalent, will occur if the test wave is the 100 kHz Ring Wave with its 0.5 µs front time.[12]

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[11] An exception may be made for a test in which a specified current is forced into the test specimen; in which case, the impedance of the connections is merged with that of the waveshaping network.

[12] See the discussion of the “gentle toe” and corresponding equation in 9.4.

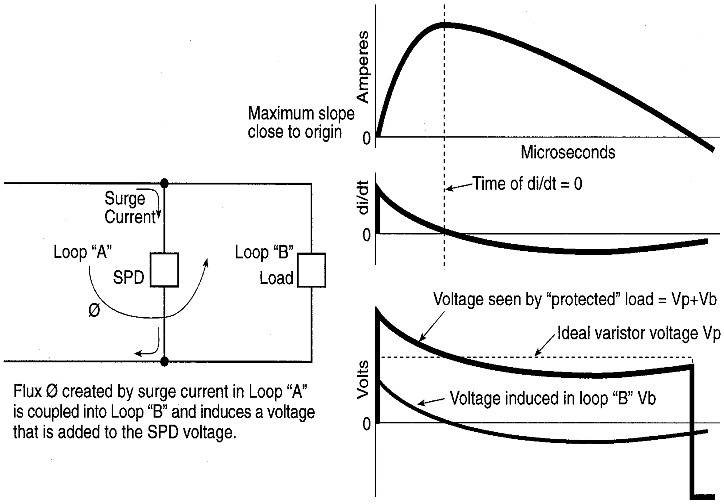


Figure C.1—Effect of mutual inductance coupling on the measured or protective voltage level

C.1.2 Noise check

a) Make sure that the power-frequency voltage is not applied to the EUT.

b) Without disturbing the position of the probes and EUT, disconnect the two probe end-leads from the terminals of the EUT, connect them together and place the probes and their leads to the digital signal analyzer (DSA) in the same relative position as they would be if connected to the EUT terminals (see Figure C.2).

c) Set-up the DSA to trigger from the signal, not from a trigger output from the surge generator, at a trigger level of about 5% of the expected surge level.

d) Energize the EUT with the power-frequency voltage.

e) Apply the surge to the EUT as it would be done for a measurement, and verify that if triggered, the DSA displays a signal of tolerable amplitude to allow neglecting it when the actual measurement will be performed.

f) Now obtain the trigger signal from the surge generator and verify again that the signal displayed by the DSA has a tolerable amplitude.

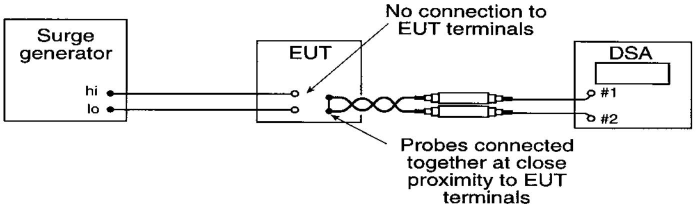


Figure C.2—Arrangement of differential probes for noise check

C.1.3 Common Mode Rejection Check

a) Make sure that the power-frequency voltage is not applied to the EUT.
b) With the probes still connected to each other and located as for the noise check, bring the ends of the two probe end-leads to the EUT terminal, which is connected to the “Lo” side of the surge generator (See Figure C.3).
c) Set-up the DSA to trigger from the signal, not from a trigger output from the surge generator, at a trigger level of about 5% of the expected surge level. Arrange the display mode to show both channels and their difference.
d) Energize the EUT with the power-frequency voltage.
e) Apply the surge to the EUT as it would be done for a measurement, and verify that if triggered, the oscilloscope displays a differential signal of tolerable amplitude to allow neglecting it when the actual measurement will be performed. Verify that each channel produces a display that is within the screen limits.
f) Now obtain the trigger signal from the surge generator and verify again that the differential signal displayed by the DSA has a tolerable amplitude.
g) Repeat the procedure with the two probe end-leads connected to the “hi” terminal of the EUT.

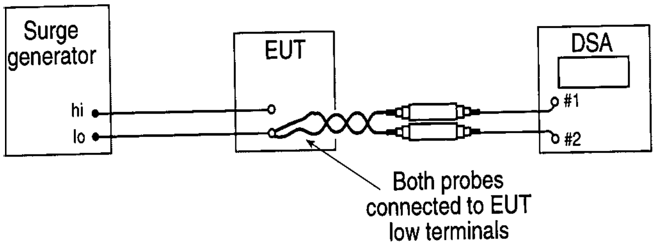


Figure C.3—Arrangement of differential probes for common mode rejection check

C.1.4 Test Set-Up Check

a) Make sure that the power-frequency voltage is not applied to the EUT.
b) Connect the two end-leads of the probes to their intended terminals at the EUT, and install a short lead across the EUT terminals (see Figure C.4).
c) Set-up the DSA to trigger from the signal, not from a trigger output from the surge generator, at a trigger level of 5–10% of the expected surge level.
d) **DO NOT** energize the EUT with the power-frequency voltage.
e) Apply the surge to the EUT as it would be done for a measurement, and verify that if triggered, the oscilloscope displays a signal of tolerable amplitude to allow neglecting it when the actual measurement will be performed.
f) Now obtain the trigger signal from the surge generator and verify again that the signal displayed by the DSA has a tolerable amplitude.
g) If a current-viewing transducer (current transformer with burden) has been inserted in the leads connecting the surge generator to the EUT, the same surge application may be used to verify the delivery of the short-circuit current. If the surge to be used has a long duration (such as the 10/1000 µs), check that the current viewing transducer does not saturate (see C.1.6).
h) See further hints on point of application and trial run in C.2 and C.3.

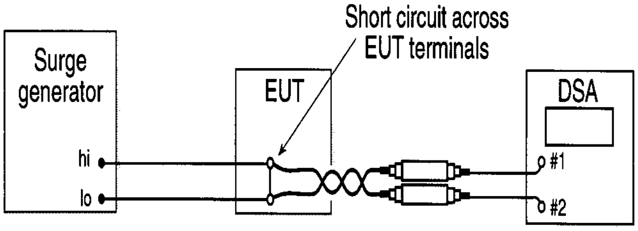


Figure C.4—Arrangement of differential probes for set-up check

C.1.5 Attenuator Check

Coaxial 50 W attenuators are generally found in any laboratory. However, several types exist, with different power ratings. Occurrences have been noted that attenuators intended for low-level testing have insufficient power dissipation rating for the signals delivered by the current viewing transducers typically used in surge testing. Such insufficient power rating has been found to produce a drift in their rated attenuation. Depending on the laboratory experience, a reliable brand of attenuator must be selected, and it will be prudent to check the attenuators in constant use to ascertain that they have not been abused, mechanically or electrically. Precious test time can be wasted in an attempt to optimize trigger levels when difficulties arise in obtaining a trigger signal, but the real culprit is an unsuspected damaged attenuator not included in the routine calibration procedure.

C.1.6 Saturation check

Current-viewing transducers (commonly called “current transformers,” which is not quite accurate because they have an internal burden that produces a voltage output for a current input) have a limited capacity, related to their core cross section, to accept long-duration surges without saturation of the iron (ferrite) core. The manufacturer of the transducer does provide application information, enabling the user to predict the limit, but this limitation is sometimes forgotten.

Symptoms can be found on the recordings, as shown in Figure C.6, where one trace (I_2) was recorded with a relatively large transducer (80 A/division, obtained by inserting attenuators at the input of the digital signal analyzer (DSA) while the other trace ($I_1 + I_2$) was recorded with a smaller transducer (50 A/div). The alert test operator will notice and question the collapse of the recorded current in a test in which smooth decay should be expected, illustrating once again the need for careful examination of the records as they accumulate, not after the test series has been completed.

To avoid the problem, perform the following check:

a) Insert the candidate transducer in the loop formed by the connecting leads from the surge generator, which have been bonded together (shorted) instead of being connected to the EUT.
b) Apply a surge at 10% of the maximum amplitude of the longest waveform expected during the test. Record the output of the transducer as displayed on the DSA.
c) Increase by steps of about 20% (no need for accuracy) the charging voltage of the generator and apply the surge again. Watch for an abrupt change in the decay of the current trace, as shown in Figure C.5, which would be the indication of saturation. In that case, change to a transducer with higher capability.

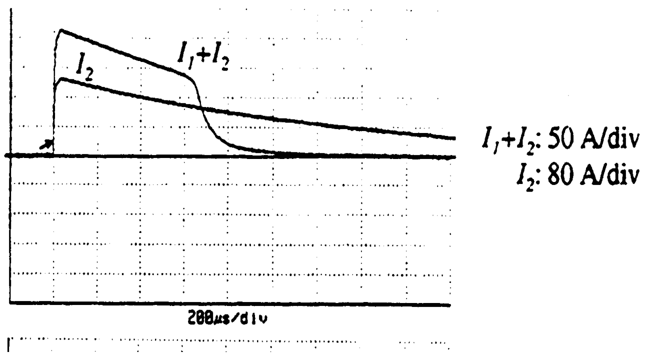
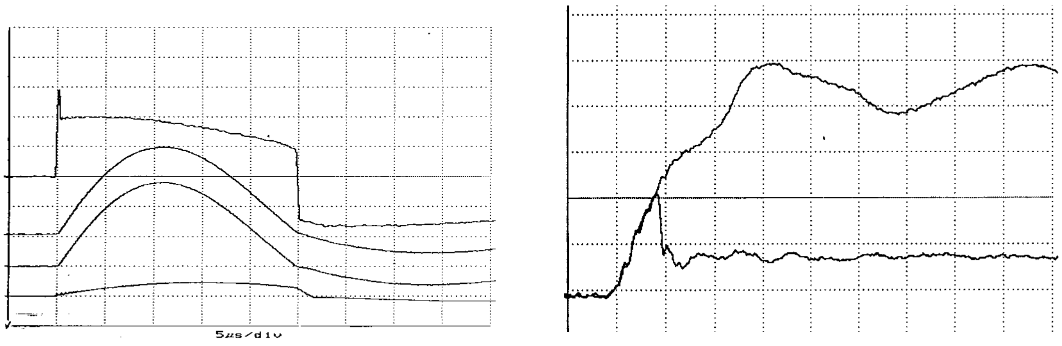


Figure C.5—Example of current-viewing transducer saturation

C.1.7 Digital resolution

Digital oscilloscopes (also called DSAs) display traces that are a succession of data points collected at a sampling rate, which is related to the time-width of the display. For events with very fast changes occurring within a relatively wide window selected to gain knowledge on the complete event, a situation can occur in which the peak of the event is not displayed. Figure C.6 shows an example of this phenomenon.

Some digital oscilloscopes have an enhanced resolution setting that can be employed on single captured recordings. In effect, it is a digital low-pass filter, and it increases the amplitude resolution of the waveform, but it does so by reducing the bandwidth of the recording. Users need to exercise caution here as the resulting smoother-looking waveform might not show the true peak of the original captured recording.



Recordings with an oscilloscope setting of 200 V/div and sweep of ***5 ms/div***, intended to show the full event. The appearance of the top trace, which is the voltage across the EUT, would lead one to erroneously conclude that the peak voltage is only 600 V.

Recording with an oscilloscope setting of 500 V/div and sweep of ***200 ns/div***. The top trace is recorded with no EUT, to show the full applied surge. The lower trace is the response to the same EUT as the left top trace (a), and reveals an actual peak of 1100 V, not 600 V.

Figure C.6—Misleading display (a) and fully resolved display (b) showing the need for providing enough data points with a digital oscilloscope

C.2 Point of surge application and measurement

C.2.1 One-port SPDs

The test surge should be applied to the appropriate pair of the SPD terminals (L-N, L-G, N-G as directed by the tables included in the test procedures for the particular test—see Table 2, Table 3, and Table 4 in Clause 7) and the surge response voltage determined by connecting the differential probes to the same pair of terminals. Thus, the voltage measurement produces at the same time, with only one set of differential probes and one differential channel of the oscilloscope, both the applied surge and the surge response voltage.

C.2.2 Two-port SPDs

The test operator is presented with a device having an “input” port and an “output” port. There might be some series impedance, deliberate or inherent, between the two ports of the device.

In the case of a deliberate two-stage design, the principle of operation is based on having the surge impinge on the “input” port, as the SPD might not work as intended if the direction of the surge through the SPD was reversed. This situation has several consequences for the test procedure:

a) A plug-in or cord-connected SPD for ac power circuits designed to provide two-stage mitigation will have a male input connector for the input and a female receptacle for the output. Thus, there is no ambiguity on which is which.
b) A permanently connected SPD might have simple wire terminals or a terminal strip, making it less obvious about which is which, although one should expect the manufacturer to have provided appropriate markings.
c) The surge should be applied to the input terminals, at the pairs specified in the table of the test procedures for the particular test (see Table 2, Table 3, and Table 4 in Clause 7).
d) The surge voltage response appearing at the output terminals is likely to be different from the voltage appearing at the input terminals when the surge is applied there. Consequently, two sets of differential probes are necessary, one at the input port and one at the output port.
e) The test record must then show both measurements.

C.3 Trial run on components

When testing an SPD for the first time, its response is not always predictable. The oscilloscope parameters might have been set at less than optimum levels so that the record might be useless. For a test series on a limited number of available specimens, this could prove embarrassing. Thus, in addition to the precaution given in the procedures specifying starting at 40% of the target stress, it would be prudent to make a trial run on an expendable component that would have characteristics similar to the front-end SPD component in the total SPD package. This precaution will allow verifying the oscilloscope settings and general test procedure, and provide an opportunity to become acquainted with the likely response of the SPD.

C.4 Cheesecloth specifications

The cheesecloth used for wrapping SPDs during failure mode tests is specified in UL 1449-1996, Section 30.3) as follows (sequence of units shown here are verbatim quote from UL 1449-1996):

Bleached cheesecloth running 14-15 yd^2/lb *(approximately 26-28* m^2/kg*) and having what is known as a count of 32 by 28, that is, for any square inch, 32 threads in one direction and 28 threads in the other direction (for any square centimeter, 13 threads by 11 threads)*

One of the expected results of the failure mode test is that no charring of the cheesecloth should occur. Charring is interpreted as the condition immediately preceding burning, but not brought to inflammation, characterized by a substantial weakening of the threads. This condition is to be distinguished from blackening caused by the filtering action of the cheesecloth when soot is emitted from openings in the SPD housing, a condition that leaves the strength of the threads unchanged—and is not indicative of a fire hazard.

C.5 Smoke, sights, and sounds

The trend toward increasing stress levels being applied to EUTs, SPDs in particular, and the emerging scrutiny of failure modes points out the need for additional precautions if not already included in the normal practices of the laboratory. See also 4.8 and 6.4 for other considerations in the planning stages of a test series.

C.5.1 Smoke

Pushing the test stress until failure of the SPDs occurs can result in the emission of large amounts of smoke, which can be annoying at best (objectionable smell or unnecessary trigger of smoke alarm in the building), and a health concern at worst, if released in the atmosphere of the laboratory. It is prudent to perform such tests in a well-ventilated enclosure.

C.5.2 Sights and sound

The flash and loud report associated with failure of an SPD, especially with the higher stress levels now considered under some scenarios, can be startling for personnel not directly involved in the test but working in the same area of the laboratory. One way of avoiding such disruptive interactions would be to sound off, a few seconds before applying the surge (with a fixed time interval known to other personnel), a suitable, nonstartling signal such as a gentle chime or muffled horn.

C.6 Does it make sense?

Last but not least, a leitmotif of these hints has been the need to examine the records as they accumulate. Simply entering test results in a preformatted table and going on to the next step will not do. This examination includes several aspects, as follows.

C.6.1 Results vs. expectations

From what the test operator knows about the EUT design (always a desirable situation, “black box testing” notwithstanding), some expectations can be formulated on what the recordings will show. Any deviation from these expectations should be seen either as a symptom of some aberration in the test procedure or in the instrument settings, or perhaps as an indication that some abnormal behavior in the response of the EUT.

Any and all of these deviations require explanation, and correction if necessary, before proceeding further with the test.

C.6.2 Programmed instrumentation computations

Typical modern oscilloscopes—“digital signal analyzers”—have the capability of performing computations on the digitized signals either before or after the traces have been displayed. For instance, an energy computation might be called for in some tests, involving the multiplication of current by voltage, followed by integration over a set time. The digital signal analyzer is then programmed in advance to perform these computations, taking into consideration all the parameters of the set-up, such as voltage probe attenuation, current transducer volt/ampere ratio, additional attenuators, and so on. It might seem trivial to perform a reality check at this stage of sophistication, but the old-fashioned method of “counting squares” to verify the order of magnitude of an integrated area, such as the power trace displayed by the analyzer, as experience has frequently shown, can help detect errors in the computation instructions entered into the oscilloscope software.

C.6.3 Trends while incrementing

Typical responses of SPDs, by the very nature of the devices, are highly nonlinear; that is, the current will increase much faster than, say, the charging voltage of the surge generator. This nonlinearity can result in large signals that can exceed the range of the oscilloscope. Most of the time, such a situation will produce an anomaly in the display, and the need for correction is obvious.

More insidious is the possibility that as oscilloscope settings are changed, notations on the records might not be entered to reflect these changes. Another scenario might be a progressive change in the EUT characteristic that would not produce a large difference of appearance in the recordings. For these two reasons, and especially when exploring new designs of EUTs, it is useful to make an informal ***plot*** of the responses as the stress is incremented during the test shots: Anomalies in the progression of the results will provide a timely signal for the operator that something might be amiss and call for a repeat of the shot or a verification of the settings before going on to the next step increment.

Annex D

(informative)

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