

C62.45™

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

IEEE Power Engineering Society

Sponsored by the
Surge Protective Devices Committee



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Surge Protective Devices Committee
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Power Engineering Society

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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 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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Contents

1.	Overview	1
1.1	Scope	1
1.2	Purpose	2
2.	References	3
3.	Definitions	4
3.1	Technical terms	4
3.2	Special word usage	4
4.	Planning of surge testing: Basic objectives	5
4.1	General	5
4.2	Surge environment	5
4.3	Types of tests	6
4.4	Results and consequences of the test	6
4.5	Unpowered testing versus powered testing	7
4.6	Withstand levels	8
4.7	Voltage and current waveforms	8
4.8	Safety	10
5.	Implementation of surge testing: Test equipment	10
5.1	General	10
5.2	Surge generators	10
5.3	Point of test surge application	11
5.4	Coupling the surge to the EUT	11
5.5	Monitoring the EUT	13
6.	Performance of surge testing: Test procedures	15
6.1	General	15
6.2	Limiting stresses	15
6.3	Nature of the EUT	15
6.4	Safety	16
7.	Applying the test surge: Coupling and decoupling circuits	17
7.1	General	17
7.2	Requirements for surge coupling	17
7.3	Impedance considerations	19
7.4	Requirements for surge decoupling	19
7.5	Surge coupling	20
8.	Grounding	24
8.1	Grounding precautions	24
8.2	Grounding practices in EUTs	26

9.	Standard surge tests waveforms.....	26
9.1	General.....	26
9.2	Standard waveforms	27
9.3	Test procedures	31
9.4	Equations for standard waveforms	32
10.	Additional surge test waveforms	34
10.1	General.....	34
10.2	Additional waveforms.....	34
10.3	Equations for additional waveforms	40
11.	Evaluating test results	40
Annex A	(informative) SPD Class I test parameters	42
Annex B	(informative) Complementary notes.....	44
Annex C	(informative) Practical hints on surge testing.....	77
Annex D	(informative) Bibliography	84

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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.

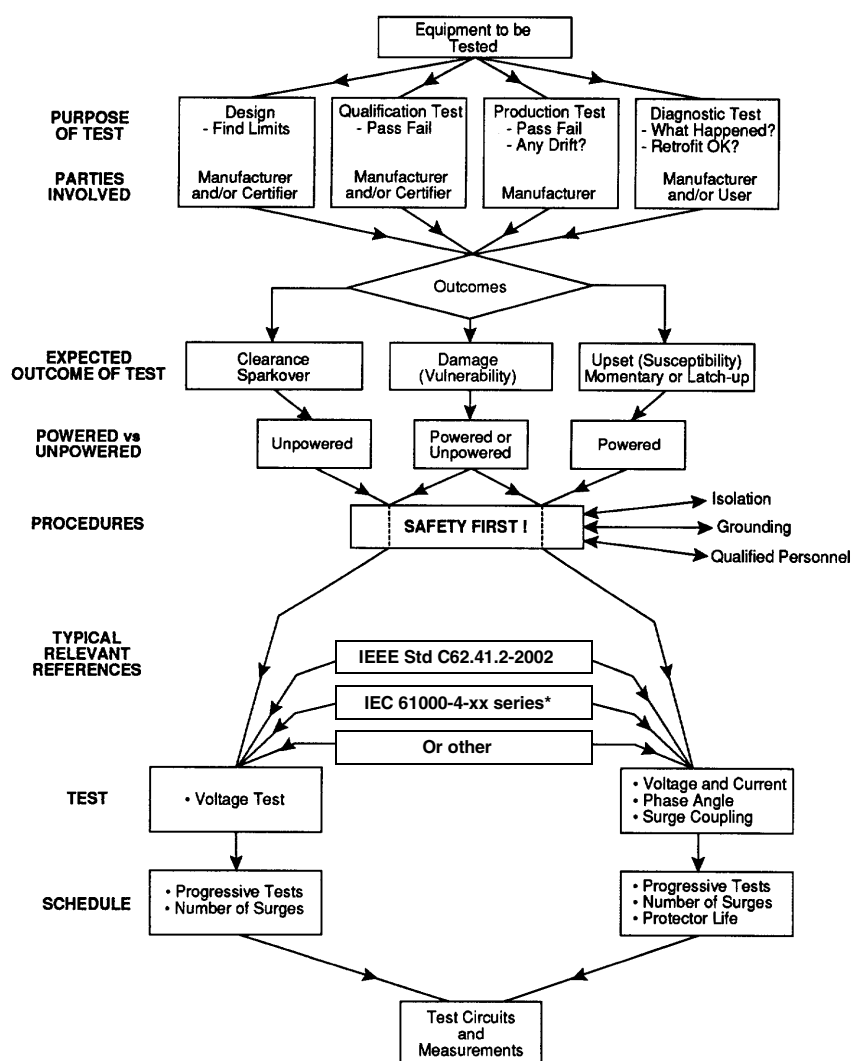
1.1 Scope

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.

¹Information 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

²See 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

³IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, 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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⁶NFPA 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.

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

⁸The 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.

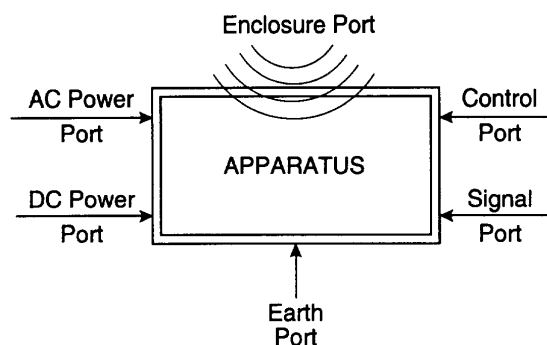


Figure 2—Six ports for coupling of disturbances

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 $\pm 10\%$) 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 (Sandler 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 impinging 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 μ s 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	—		

^aRefer to Clause 9 for details on the standard waveforms.

^bRefer to Clause 10 for details on the EFT and Long Wave additional waveforms.

^cNearby lightning flashes can induce surges into circuits contained within the building.

^dFor 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 μ s 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]).

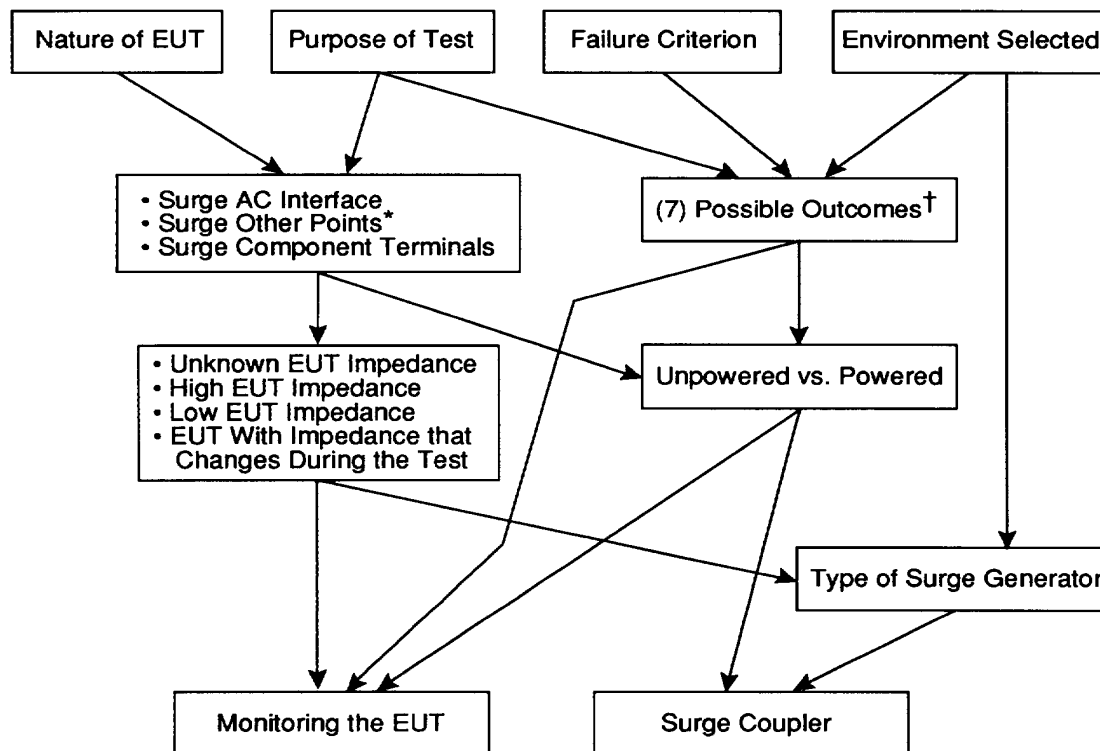
5.2 Surge generators

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 μ s Long Wave, a capacitor-switching transient wave, or the Scenario II optional 10/350 μ s 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 μ s 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 μ s 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

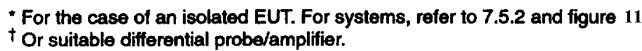
A reliable and safe method for monitoring voltages within the EUT is to use a *differential connection* of two matched voltage probes (Figure 4). This type of connection, shown in the figure for the case of a surge applied between line and neutral of the EUT, enables the use of a safely grounded oscilloscope. 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.

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.

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.

7. Applying the test surge: Coupling and decoupling circuits

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.

7.2 Requirements for surge coupling

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

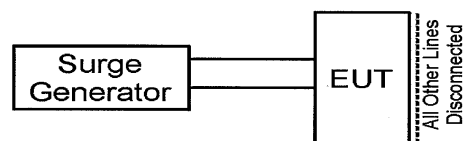


Figure 6—Direct coupling of surge (unpowered tests only)

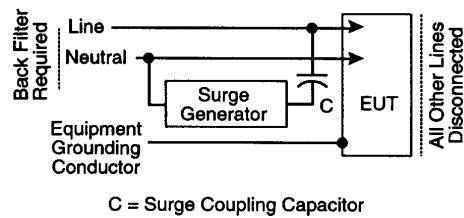


Figure 7—Elementary diagram of shunt coupling

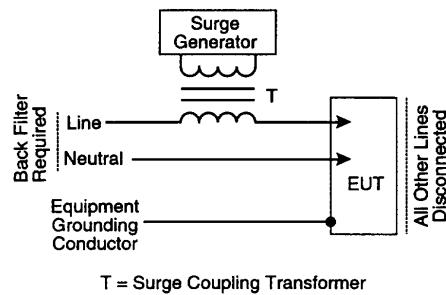


Figure 8—Elementary diagram of series coupling

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.

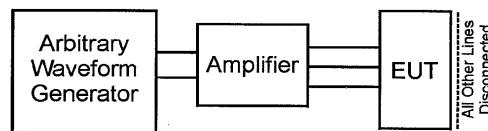


Figure 9—Elementary diagram of arbitrary waveform generator

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

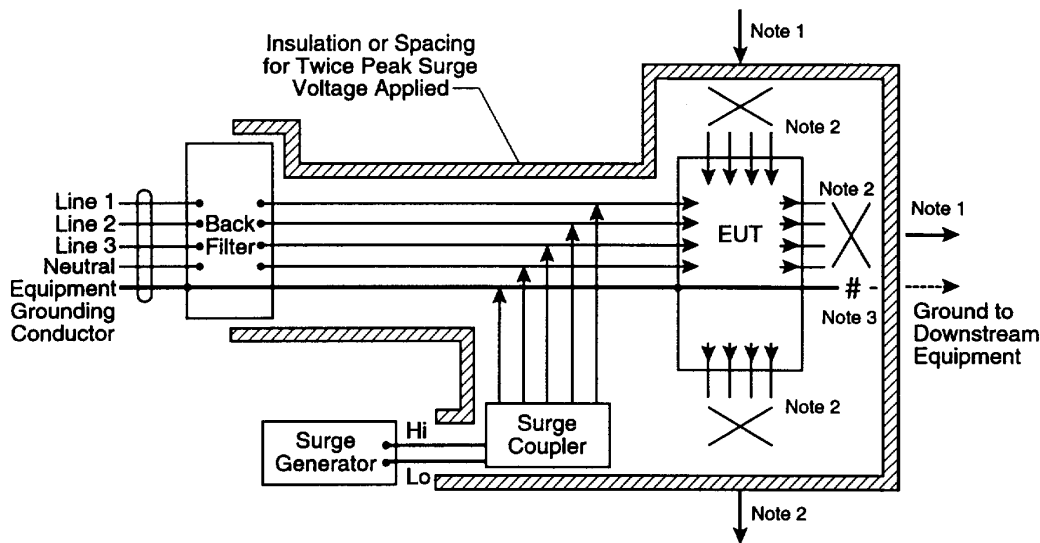
The simplified surge coupling of Figure 8 and Figure 7 shows the requirements of back filters and decoupling. Without these devices, the low line impedance of the ac supply would load the generator and prevent it from delivering the full voltage. Furthermore, all other equipment connected to the same 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.