IEEE Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits

1. Scope and purpose

The purpose of this document is to provide guidance on applying surge testing to ***ac power interfaces***[1] of equipment connected to ***low voltage*** (up to 1000 V rms) ac power circuits that are subject to transient overvoltages. These transients may be defined by any applicable document, such as IEEE Std C62.41-1991[2] or IEC 664-1 (1992). While frequent reference is made to these documents, the application of this guide is not limited to them.

In IEEE Std C62.41-1991, a description is given of the surge environment that can be expected to prevail in low-voltage ac power circuits where no special precautions have been taken to limit transient overvoltages; in IEC 664-1 (1992), a recommendation made to establish a ***controlled overvoltage situation*** is justified if there is compliance with appropriate interface requirements, so that maximum overvoltage levels in a descending staircase can be assigned according to a specified ***overvoltage category*** where such a category generally reflects the configuration of the power system within a building.

The environment description of IEEE Std C62.41-1991 provides guidance on the ***waveforms*** of current as well as voltage surges that can be selected as representative of the environment for different ***location categories***. The recommendations of IEC 664-1 (1992), provide the basis for ***insulation coordination***. Other standards or specifications for surge withstand capability might also require surge testing to be performed, for which the guidance of the present document may also be applicable.

Regardless of the specification, equipment connected to the power system has to be capable of satisfactory operation or survival, or both, under these surge voltages, with or without additional protection. Surge testing is therefore required to demonstrate this capability. The flow chart of figure 1 shows the basic considerations involved in planning and performing surge tests in accordance with the scope of this guide.

Note that the assignment of surge ***withstand levels*** to various equipment is not included in the scope of this guide. Signal and data lines are also not included in the scope of this guide, but should not be overlooked in the complete evaluation of specific equipment.

2. References

In this document, two types of sources are cited: those that are directly related to the subject being discussed (listed as “References” in this clause) and those that provide supporting information to the subject being discussed (listed under “Bibliography” in Annex D).

References contain information that is implicitly adopted in the present document; complete implementation of the test procedures described in this guide requires the reader to consult those sources for the details of a particular subject. They are cited in the text by their standards organization designation.

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[1]See Annex C for discussion of terms appearing in ***bold italics***.

[2]Information on references can be found in clause 2.

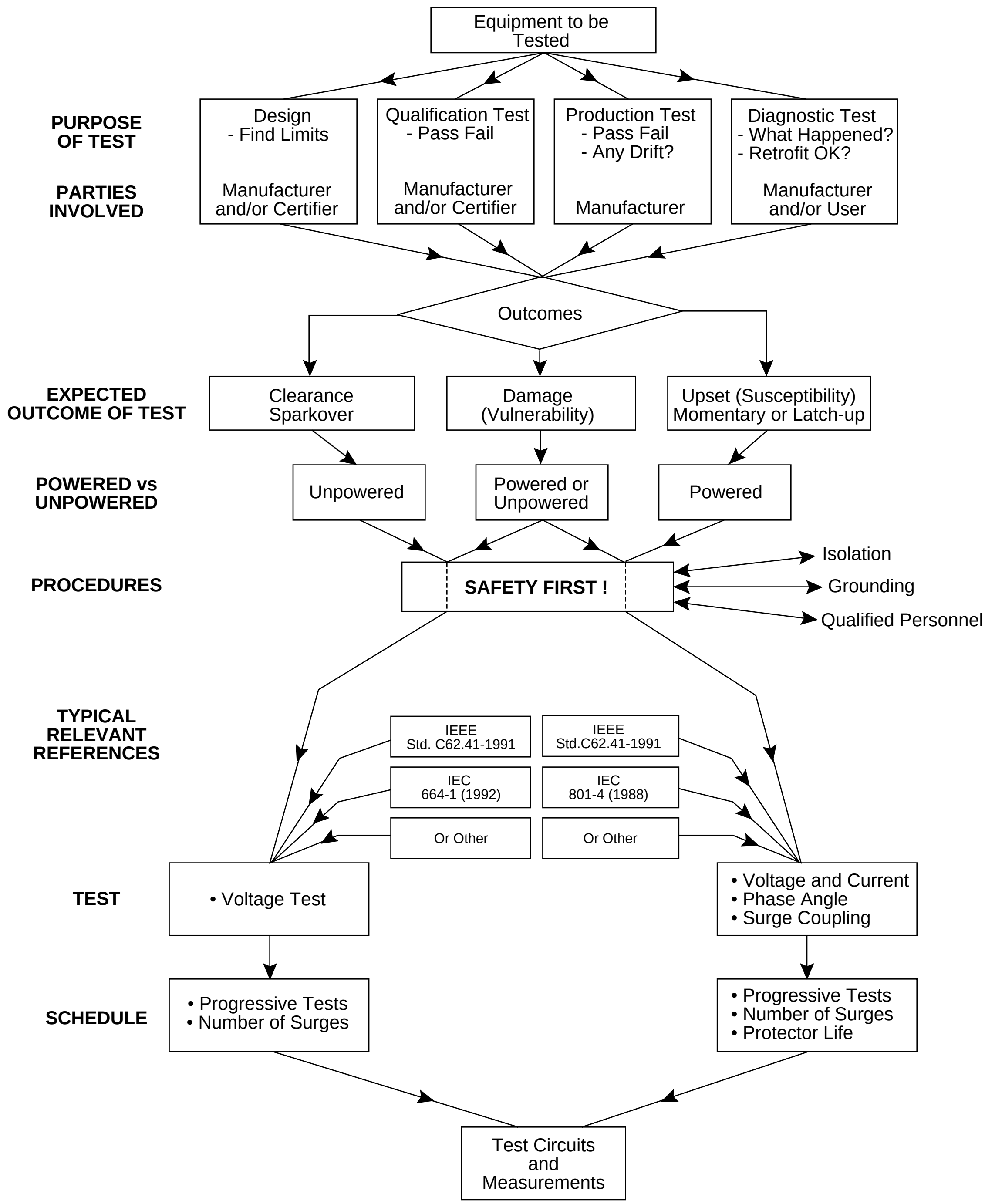

Figure 1—Guiding considerations for surge testing

Bibliographic sources are not essential to implementation of the procedures, but are provided for the use of readers seeking more detailed information or justification. They are cited in the text by either their standards organization designation or by author and date, followed by [B#].

Accredited Standards Committee C2-1993, National Electrical Safety Code.[3]

ANSI/NFPA 70-1993, National Electrical Code.[4]

IEC 664-1 (1992), Insulation coordination for equipment within low-voltage systems including clearances and creepage distances for equipment, Part 1: Principles, requirements and tests.[5]

IEC 801-4 (1988), Electromagnetic compatibility for industrial-process measurement and control equipment, Part 4: Electrical fast transient/burst requirements.

IEEE Std C62.31-1987, IEEE Standard Test Specifications for Gas-Tube Surge-Protective Devices (ANSI).[6]

IEEE Std C62.32-1981 (Reaff 1987), IEEE Standard Test Specifications for Low-Voltage Air Gap Surge-Protective Devices (Excluding Valve and Expulsion Type Devices) (ANSI).

IEEE Std C62.33-1982 (Reaff 1989), IEEE Standard Test Specifications for Varistor Surge-Protective Devices (ANSI).

IEEE Std C62.35-1987, IEEE Standard Test Specifications for Avalanche Junction Semiconductor Surge-Protective Devices.

IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits (ANSI).

3. Definitions

3.1 Technical definitions

Annex C provides more detailed discussions of the concepts associated with the following definitions. This annex may be found useful to readers requiring more in-depth information. When a term covered by such a discussion appears for the first time in each clause, it is printed in bold italics.

3.1.1 Existing definitions

The following definitions appear in IEEE Std 100-1992 [B4][7] but are repeated here because of their importance and frequent use in the present guide:

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[3]The National Electrical Safety Code (NESC) is available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[4] NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

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

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

[7]The numbers in brackets preceded by the letter B correspond to those of the bibliography in Annex D.

3.1.1.1 back filter: A filter inserted in the power line feeding an equipment to be surge tested; this filter has a dual purpose: (1) To prevent the applied surge from being fed back to the power source where it may [*might*, according to the word usage in this guide] cause damage. (2) To eliminate loading effects of the power source on the surge generator. *See:* **decoupling network.**

3.1.1.2 blind spot: A limited range within the total domain of application of a device, generally at values inferior to the maximum rating. Operation of the equipment or of the protective device might fail in that limited range despite the device's demonstration of satisfactory performance at maximum ratings.

3.1.1.3 coupler: A device, or combination of devices, used to feed a surge from a generator to powered equipment while limiting the flow of current from the power source into the generator. *See:* **coupling network.**

3.1.1.4 equipment grounding conductor: The conductor used to connect the non-current-carrying metal parts of equipment, raceways, and other enclosures to the service equipment, the service power source(s) ground, or both.

3.1.1.5 equipment under test (EUT): A representative component, unit, or system to be used for evaluation purposes.

3.1.1.6 surge let-through: That part of the surge that passes by a surge-protective device with little or no alteration. *See:* **surge remnant**.

3.1.1.7 surge remnant: That part of an applied surge that remains downstream of one or several protective devices. *See:* **surge let-through** and **surge response voltage**.

3.1.1.8 susceptibility: The inability of a device, equipment, or system to resist an electromagnetic disturbance.

NOTE—Susceptibility is the lack of immunity.

3.1.1.9 vulnerability: The characteristic of a device for being damaged by an external influence, such as a surge.

3.1.2 New definitions

3.1.2.1 coupling network: Electrical circuit for the purpose of transferring energy from one circuit to another. *See:* **coupler.**

3.1.2.2 decoupling network: Electrical circuit for the purpose of preventing an electrical fast transient (EFT) signal applied to the equipment under test (EUT) from affecting other devices, equipment or systems that are not under test. *See:* **back filter.**

3.1.2.3 surge-protective device: The generic term used to describe a device by its protective function, regardless of technology used, ratings, packaging, point of application, etc.

3.1.2.4 surge protector: The term used to refer to a specific complete device [generally the equipment under test (EUT) in the context of the present guide], as opposed to a component of the surge protector or a generic surge-protective device.

3.1.2.5 surge response voltage: The voltage profile appearing at the output terminals of a surge-protective device and applied to downstream loads, during and after a specified impinging surge, until normal, stable conditions are reached.

3.2 Special word usage

The words listed below are used in this guide in accordance with the IEEE Standards Style Manual, the IEC/ISO Directives [B2], 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 guide, 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 guide.

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.

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 C. Though the scope of this guide 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 guide and is addressed in other documents (see Ott 1989 [B36], IEEE 518-1982 [B5], and MIL-STD-461 [B7]). The scope of this guide 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 US), should be recognized. (See discussion of ***grounding practices*** in C.5 and C.24 of Annex C.) 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 which, during a ***surge event***, experiences changes of potential.) Section B23 of Appendix B in IEEE Std C62.41-1991 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.

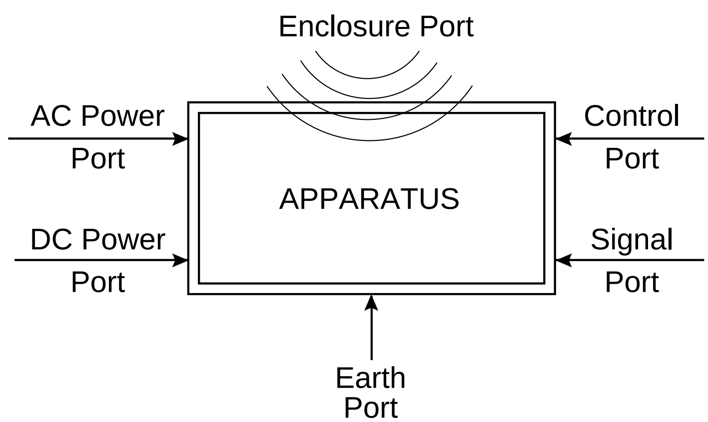


Figure 2—Six ports for coupling of disturbances

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 C62.41-1991, IEC 664-1 (1992), or some other applicable document will be used to define the environment.

While the test procedures discussed in this guide should be relevant to most surge tests, the major concern here is with switching- 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 (see IEEE Std 518-1982 [B5]; MIL-STD-461 [B7], and NEMA ICS 2-1988 [B8]).

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 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 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 (see UL 1449 [B9], and Smith and Standler 1992 [B47] for examples of test plans).

4.4 Results and consequences of the test

While 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 (C.50 in Annex C) gives some scenarios that illustrate this concern.

Depending upon the nature and function of the EUT, seven different outcomes of a surge test should be evaluated wherever 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 since 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 are related to the susceptibility of the equipment. The electrical noise required to produce them can be quite low; in fact, low-level noise can be sufficient to upset sensitive circuits (see IEEE Std 518-1982 [B5], MIL-STD-461 [B7], and NEMA ICS 2-1988 [B8]). The emphasis in this guide, 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 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, while 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 clamping 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***), and
— 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 while a production test must carefully avoid creating incipient failures. The voltage surge environment (see IEEE Std C62.41-1991) is described only in statistical terms without imposing a fixed ***withstand level***.

On the other hand, IEC 664-1 (1992), which covers ***insulation coordination***, sets forth maximum levels for the various ***overvoltage categories*** and system voltages in a ***controlled overvoltage situation*.** Thus, if equipment is to be classified as suitable for various overvoltage or location categories, establishing durability or withstand levels for comparison purposes is desirable.

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 [B48]).

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. While 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 Annex C under C.10, ***Current surging***. Therefore, the ***waveform*** for both voltage and current tests should be included when specifying a test procedure. IEEE Std C62.41-1991 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 guide 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 C62.41-1991 recommends consideration of two standard waveforms and three additional waveforms. Table 1 presents a summary of the waveforms, and the location categories to which they apply. Annex A and Annex B present details on definitions, specifications, tolerances, and equations for these five waveforms.

Table 1—Summary of applicable standard* and additional† waveforms for location categories A, B, and C

Location Category	100 kHz Ring Wave	Combination Wave	5/50 ns EFT Burst	10/1000 µs Wave	5 kHz Ring Wave
A	Standard	None	Additional	Additional	Additional
B	Standard	Standard	Additional	Additional	Additional
C	None	Standard	None	Additional	Additional

*Refer to Annex A for details on the standard waveforms.
†Refer to Annex B for details on the additional waveforms.

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 [B52].

The fact that five waveforms are listed in IEEE Std C62.41-1991 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, the 10/1000 µs Wave, and the 5 kHz Ring Wave) need to be included in a test program only when sufficient evidence is available to warrant their use.

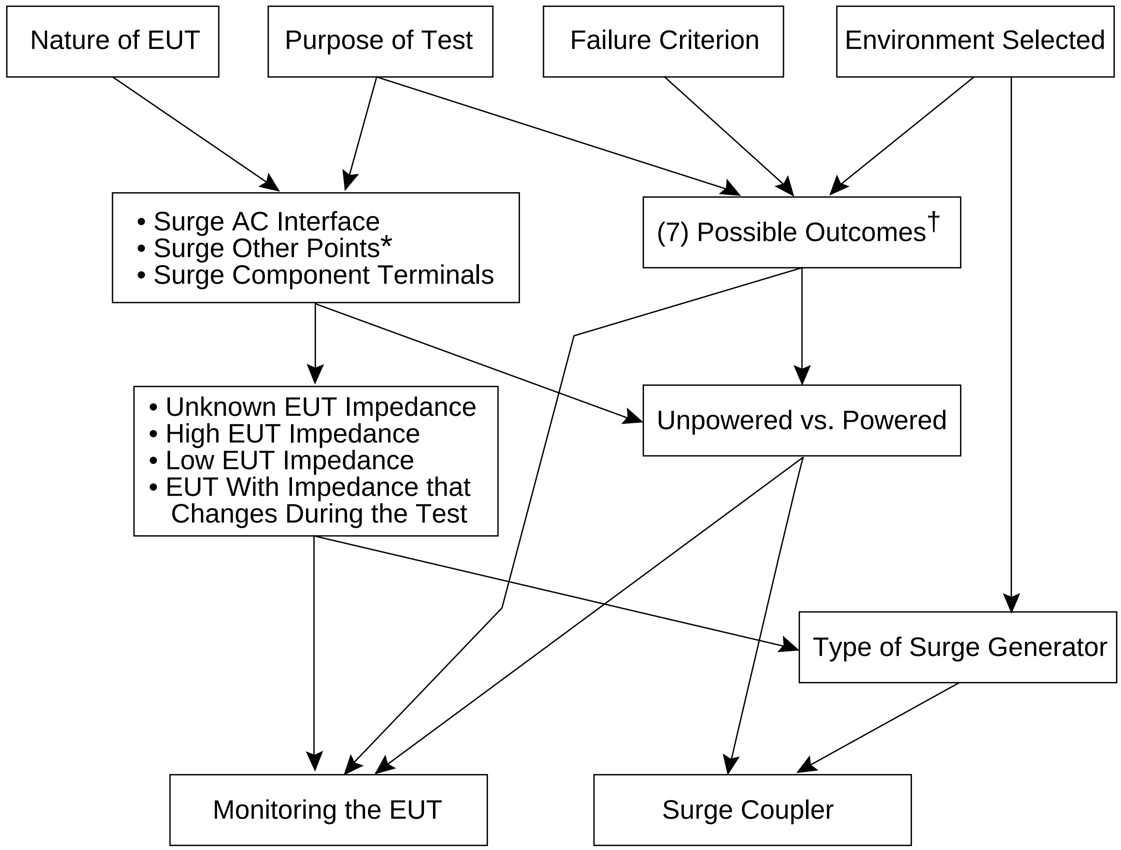
4.8 Safety

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 national codes as well as the normal safety directives of the organization conducting the test. 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 [B31]; Buschke 1988 [B13]).



* See 5.3.
† See 4.4.

Figure 3—Surge testing equipment considerations

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 Annex C under C.16, ***Environment test versus component specification test***.

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 tests, one for voltage, the other for current (Richman 1983 [B43]; Vance, Nanevicz, and Graf 1980 [B58]). Further discussion of these considerations is given in Annex C under C.53, ***Waveform: Voltage versus current***.

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 quite 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 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 801-4 (1988) include the use of discrete coupling capacitors for the power-supply lines (called *coupling network* in IEC 801-4 (1988)) or the use of a coupling clamp, which is in effect a capacitor involving all the 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 [B33]). 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 801-4 (1988) 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 IEC 801-4 (1988) (Richman 1991 [B41]). 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 [B43]).

The need to monitor the input surge is axiomatic since 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 [B31]). This distortion, therefore, makes diagnosis by simple waveform inspection nearly impossible.

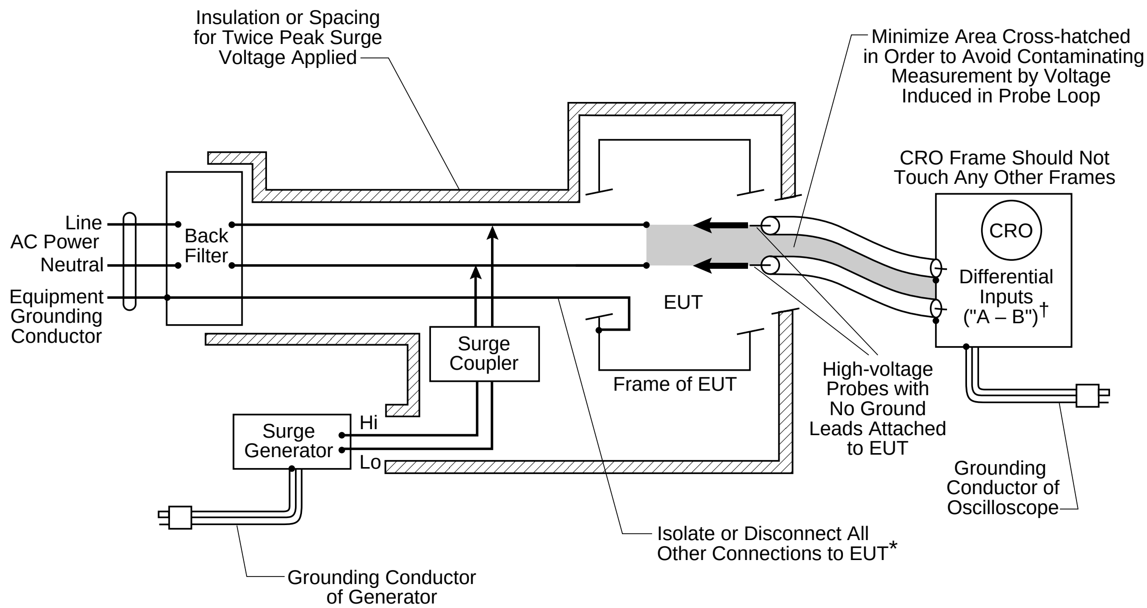
Checking a complex EUT for ***susceptibility*** to surges requires more extensive instrumentation in order to detect misoperation. (That instrumentation itself must be immune to the electromagnetic disturbances created in the area by production of the test surge.)

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.

5.5.1 Monitoring with voltage probes

A reliable and safe method for monitoring voltages within the EUT is to use a ***differential connection*** (C.14) 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, while the chassis of the instruments are safely grounded by the equipment grounding conductors of their power cords.



* For the case of an isolated EUT. For systems, refer to 7.5.2 and figure 9.
† Or suitable differential probe/amplifier.

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

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 [B52]). Paired differential probes with a 50 Ω output impedance that need no compensation can also be used (Senko 1987 [B45]).

5.5.2 Monitoring with current transformers

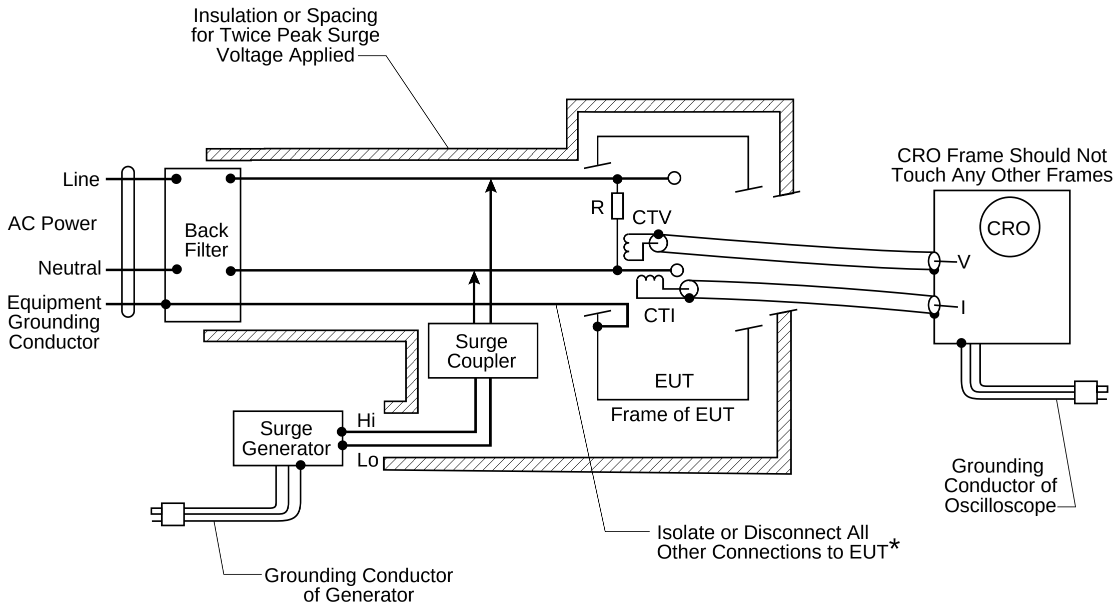
Properly applied ***current transformers*** can be useful for monitoring surge currents. It is often desirable, if not necessary, to monitor current during application of a voltage surge, in order to detect breakdowns or to verify EUT performance. A current transformer enables complete isolation of the 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.

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.)

Figure 5 shows these two applications of current transformers. Note, however, that special precautions are required to provide safe and valid measurements, which are discussed in detail in C.11 of Annex C. See also Standler 1989 [B52] for a review of the physics of 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, IEC 801-4



* For the case of an isolated EUT. For systems, refer to 7.5.2 and figure 9.

Figure 5—Monitoring within surged equipment with current transformers

(1988), requires verifying only the waveform of the pulses produced by the generator when connected to a 50 Ω load (Richman 1991 [B41]), 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 [B52], pp. 369–75).

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 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 upon 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 (see device test specification standards listed in clause 3).

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. Likewise, some EUTs might be sensitive to the phase angle of the applied surge with respect to the power supply.

6.4 Safety

Many of the tests indicated in this guide are inherently hazardous; the safeguards for personnel and property described in this clause are essential in reducing safety risks. Chapter 24 of Standler 1989 [B52] gives some practical hints on safety in a high-voltage laboratory. Observance of the prescriptions of the National Electrical Code (NEC) (ANSI/NFPA 70-1993) and the National Electrical Safety Code (NESC) (C2-1993) is, of course, a requirement.

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 unattended. Consideration must be given to the possibility of the surge flashing over to circuits or metallic parts that were 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 often found in an engineering environment, that are not 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 itself 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, it 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 passage 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 consist of suitable extinguishing agents in sufficient quantity, physical separation from other combustibles, or 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.

The importance of conducting surge tests in a prudent manner cannot be overstressed; safeguarding 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. Signal and data lines are not included in the scope of this guide, but should not be overlooked (Carroll and Miller 1980 [B15], Carroll 1980 [B14], Martzloff 1990 [B28]); see 7.5.2 and the discussion of ***ac interface*** (C.1 of Annex C) and ***communications interface*** (C.6 of Annex C).

7.2 Requirements for surge coupling

Two basic methods can be used for coupling: ***series coupling*** connects the test surge generator in series with the conductor being surged (figure 6), and ***shunt coupling*** connects the test surge generator in parallel with one or several lines (figure 7). The most frequently used method is shunt coupling, but both have advantages, as discussed in C.43 and C.44 of Annex C.

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 ***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 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. Since 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 [B12], Rhoades 1980 [B37], Standler 1989 [B48]). 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 801-4 [1988]) does not call for an available short-circuit current, but only for a verification of the waveform when connected to a 50 Ω load.

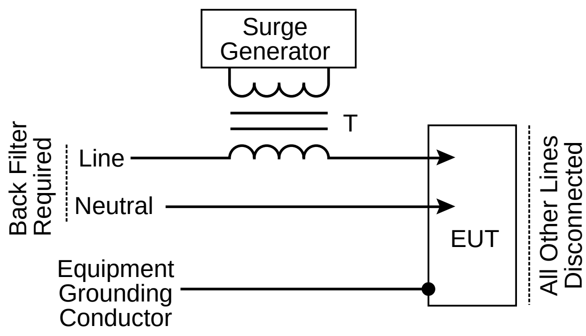
7.4 Requirements for surge decoupling

The simplified surge coupling of figure 6 and figure 7 shows the requirements of back filters and decoupling. Without these devices, the low line impedance 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 procedure calls for including the “protective earth” (PE in figure B3) 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.

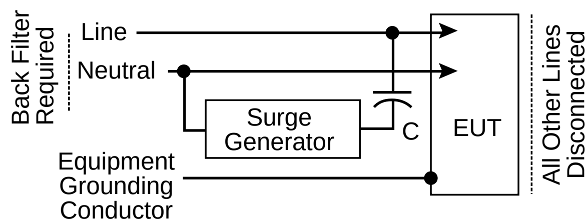
The neutral conductor is treated just like the other lines; that is, the back filter should decouple it from ground during testing. This conductor might, in fact, be the most susceptible of the connections to the EUT. In practice, the neutral is connected to the grounding conductors at the entrance power panel 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.

While the signal lines into or out of the EUT are technically outside of the scope of this guide, their presence should be recognized. As shown in figure 8, they should be disconnected, back filtered, or reterminated with impedances or grounds that simulate operating conditions.



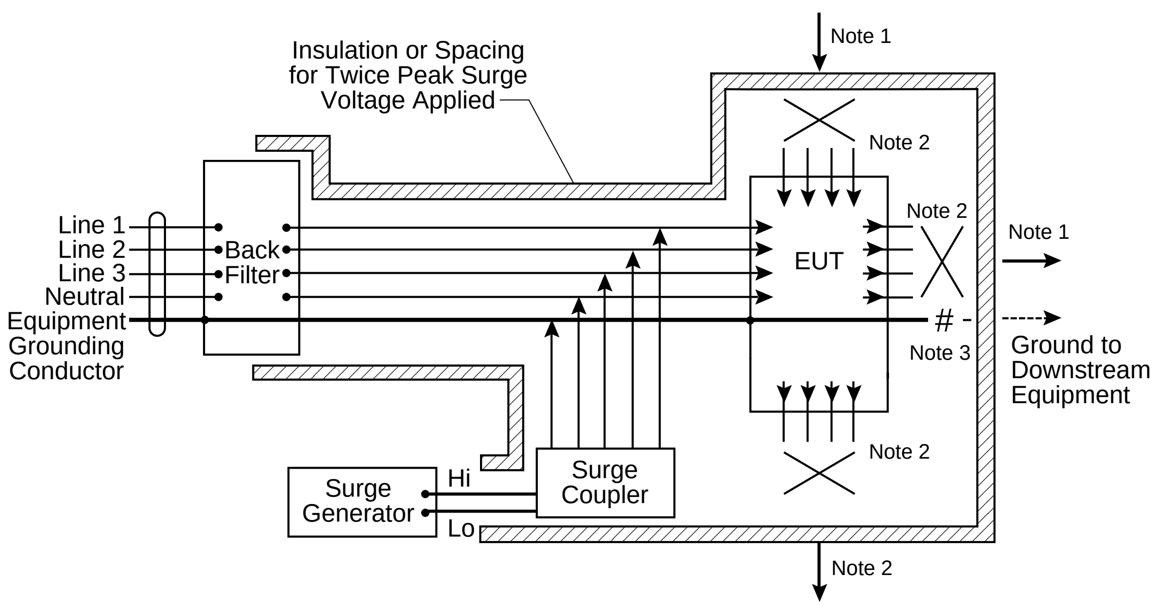
T = Surge Coupling Transformer

Figure 6—Elementary diagram of series coupling



C = Surge Coupling Capacitor

Figure 7—Elementary diagram of shunt coupling



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 9.

Figure 8—EUT being surge tested, showing required interfaces, filters, or reterminations

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.

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 8, 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 6, 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, the coupling of the surge will be limited to various combinations of conductors with respect to the ground reference plane.

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 connected to the grounding conductors at the entrance power panel 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.

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 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 8, when surge testing the EUT by itself, the interconnections to other equipments must be removed to eliminate the possibility of damaging them. This arrangement is the 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.

While the signal lines into and out of the EUT are technically outside the scope of this guide, their presence should be recognized. This guide does not consider signal lines that leave the immediate environment of the host system. The guide 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 8. 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 [B28]). This test evaluates primarily the ***susceptibility*** of the complete computer-based system to a power-line surge and its impact upon the internal communications lines interface circuits.

The typical system shown in the schematic of figure 9 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.

While some actual field installations might be implemented with the configuration shown for Peripheral #0 in figure 9 (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. For field application of a system that has first been successfully demonstrated in the laboratory, refer to publications such as IEEE 518-1982 [B5] or the IEEE Color Book Series, in particular, IEEE Std 1100-1992 [B6].

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 tables 2 and 3 should generally be performed. Tests marked “Supplemental” in tables 2 and 3 may be performed to obtain additional information on ***vulnerability*** of the EUT to surges. The tests marked “Diagnostic” in tables 2 and 3 may be performed in the course of a major investigation (Richman 1980 [B39], Richman 1979 [B40]).

Table 3 does not show a full complement of ***diagnostic tests***. Additional diagnostic tests can be useful in testing specific EUTs (see C.12 and C.13 of Annex C).

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 C.12 and C.13 of Annex C).

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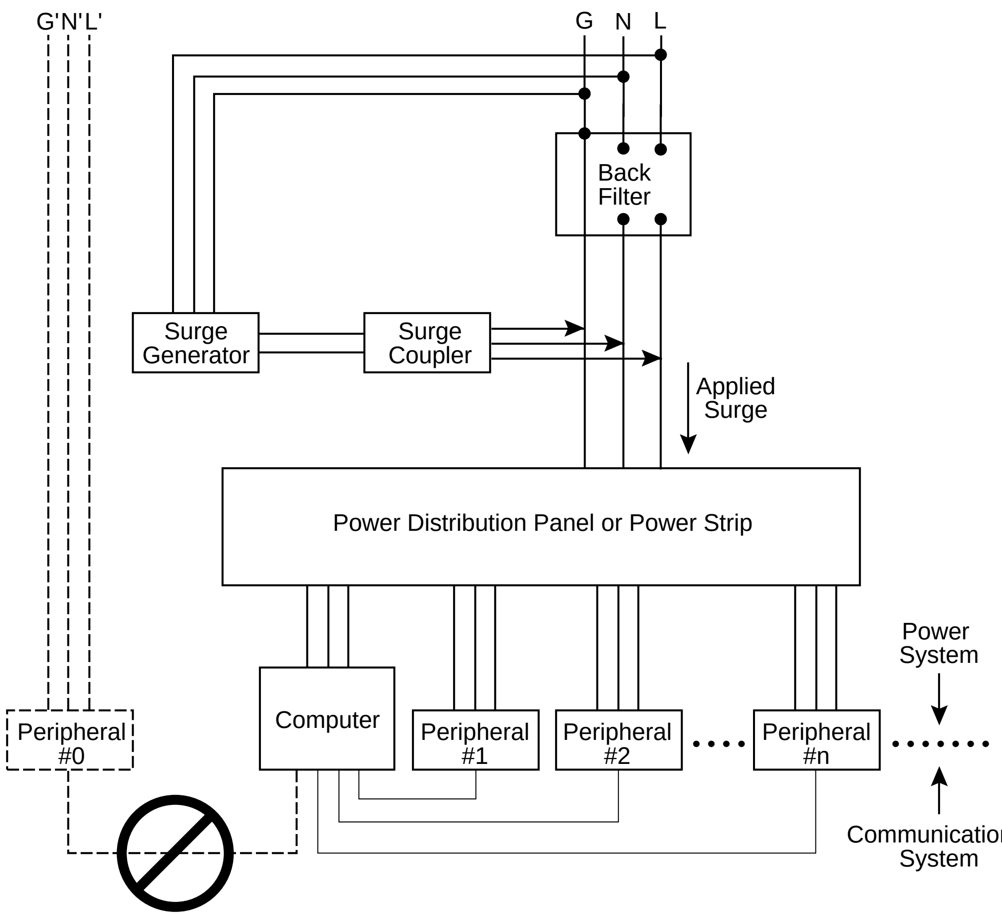


NOTES
1—Power lines and communication cables in the test setup should be at their maximum specified length for the application.
2—The system equipment layout should approximate an installed working system.
3—The connection of Peripheral #0 would introduce a different set of power-line voltage references, and the absence of back filter on the power line wuld be a hazard. Such a configuration is not recommended for surge testing.

Figure 9—Configuration for surge testing a complete system

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

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

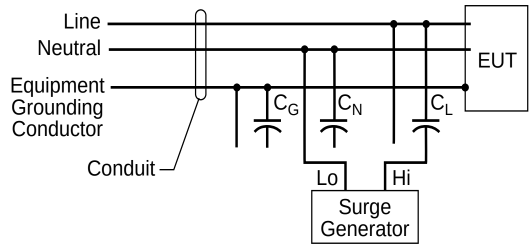
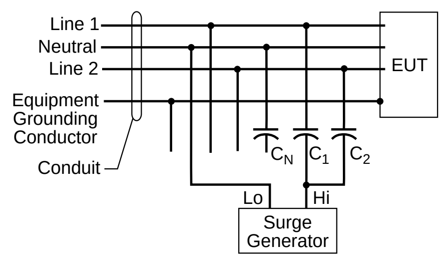


Table 3—Selected coupling for single-phase systems (two lines and neutral with equipment grounding conductor)

Test type	Connection of Generator: Ground	Connection of Generator: Neutral	Connection of Generator: Line 1	Connection of Generator: Line 2	Example of connection diagram for shunt coupling, Diagnostic 1
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	



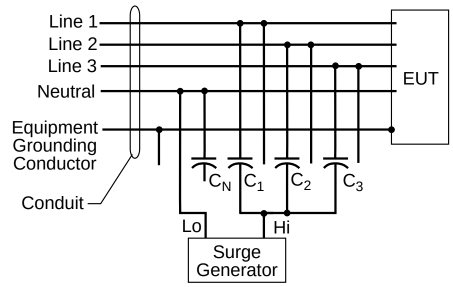
NOTES for tables 2 and 3:

L_O = Connection to surge generator low (Lo)
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_H
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

For each test type shown in the tables, 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.

When several H’s appear on one horizontal line of the table, shunt coupling requires several capacitors, shown as C_G, C_N, C_L, C_1, or C_2, between each of the conductors indicated and the surge generator high, in order to apply the surge simultaneously to all the conductors shown.

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

Test type	Connection of Generator: G	N	Line 1	Line 2	Line 3	Example of connection diagram for shunt coupling, Diagnostic 1
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	

NOTES for table 4:

L_O = Connection to surge generator low (Lo)
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
H_1 = Connection to surge generator high (Hi) by coupling capacitor C_2
H_2 = Connection to surge generator high (Hi) by coupling capacitor C_3

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 in table 2 shows an example of the jumpers required to obtain the shunt coupling for test Basic 2; for table 3, the example is for test Diagnostic 1.

When several H’s appear on one horizontal line of the table, shunt coupling requires several capacitors, shown as C_N, C_L, C_1, or C_2, between each of the conductors indicated and the surge generator high, in order to apply the surge simultaneously to all the conductors shown.

8. Grounding

8.1 Grounding for safety

Since the voltages involved in surge testing are hazardous, appropriate precautions are required for equipment other than the ***EUT*** and for personnel. One basic precaution is the correct application of ***equipment grounding conductors*** in the test setup. See 6.4 for general safety considerations. 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.

Figures 4 and 5, discussed in Section 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 US installations regulated by the NEC (ANSI/NFPA 70-1993), 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 C8(b) in Annex C under C.17, Equipment grounding conductor.

All other connections to equipment that is not part of the EUT are to be removed (see figure 8 and figure 9). If it is not possible to do so, then the connections should be filtered like the lines actually being surged, since 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 EUT

Electronic circuits are grounded for three basic reasons:

a) *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 ensure personnel protection.
   When this function is associated with ac power faults, the term *earth ground* is frequently used to distinguish the safety ground from other usages of the generic term *ground*, and the establishment of such a connection between equipment chassis and earth ground is called *earthing*.
b) *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.
c) *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 of the entire test setup, be understood.

Unfortunately, the two requirements for grounding are not always compatible (Graf and Vance 1982 [B22]; Morrison 1967 [B35], Ott 1989 [B36], Vance 1980 [B57]). Power safety grounds 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 Annex C under C.24, ***Grounding practices***.

9. 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 since, 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, such as UL 1449 [B9], Standler 1989 [B52], and Steinhoff 1991 [B54]).

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 tolerance) when testing nonlinear devices.