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IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits

IEEE Power Engineering Society

Sponsored by the
Surge Protective Devices Committee



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Sponsor

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IEEE Power Engineering Society**

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Abstract: This is a guide describing the surge voltage, surge current, and temporary overvoltages (TOV) environment in low-voltage [up to 1000 V root mean square (rms)] ac power circuits. This scope does not include other power disturbances, such as notches, sags, and noise.

Keywords: lightning surges, low-voltage ac power circuit, surge environment, surge testing, surge withstand level, switching surges

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Introduction

[This introduction is not part of IEEE Std C62.41.1-2002, IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits.]

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

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

- 1) The reduction of a complex database to two representative surges: a new “Ring Wave” featuring a decaying 100 kHz oscillation, and the combination of the classical, well-accepted 1.2/50 μ s voltage waveform and 8/20 μ s current waveform into a “Combination Wave” to be delivered by a surge generator having well-defined open-circuit voltage and short-circuit current.
- 2) The concept that location categories could be defined within an installation where surge voltages impinging upon the service entrance of an installation or generated within an installation would propagate, unabated, in the branch circuits, while the associated currents, impeded by (mostly) the inductance of the conductors, would be reduced from the values observed in circuits located close to the service entrance to lower values observed in circuits located at the end of long branch circuits.

The 1991 version, based on additional data as well as experience in the use of the 1980 guide, maintained the concepts of the location categories and the recommendation of representative surge waveforms.

The two seminal surges, Ring Wave and Combination Wave, were designated as “standard surge-testing waveforms,” and three new “additional surge-testing waveforms” were added to the “menu.” Meanwhile, a companion document, IEEE Std C62.45™-1992, IEEE Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits, was developed, outlining procedures for error-free application of the waveforms defined by IEEE Std C62.41™-1991 while enhancing operator safety.

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

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

- A guide on the surge environment in low-voltage ac power circuits (the present document)
- A recommended practice on characterization of surges in low-voltage ac power circuits (IEEE Std C62.41.2™-2002)
- A recommended practice on surge testing for equipment connected to low-voltage ac power circuits (IEEE Std C62.45™-2002)

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

Participants

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

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Contents

1.	Overview	1
1.1	Scope	1
1.2	Purpose	2
1.3	Contents	3
2.	References	4
2.1	General	4
2.2	Reference documents	4
3.	Definitions	4
4.	The origins of surge voltages and surge currents	4
4.1	General	4
4.2	Lightning surges	5
4.3	Switching surges	8
4.4	Multiple-system interaction overvoltages	11
5.	Propagation, dispersion, and inherent mitigation of surges	13
5.1	General	13
5.2	Current dispersion	13
5.3	Voltage surge propagation	14
5.4	Location categories—Scenario I	15
5.5	Scenario II—Direct flash to the structure	16
6.	Summary of the database	17
6.1	General	17
6.2	Notations and definitions	19
6.3	Site surveys of power quality	20
6.4	Effect of SPD proliferation on survey results	22
6.5	Equipment field experience	22
6.6	Summary of surge characteristics in Scenario I	23
6.7	Surge characteristics in Scenario II	29
7.	TOVs	31
7.1	General	31
7.2	Magnitude of TOVs due to medium-voltage and low-voltage faults	31
7.3	Probability of occurrence	33
7.4	TOVs' impact on SPDs	34
8.	Development of recommended selection of representative surges	34

Annex A (informative) Detailed database 35

Annex B (informative) Complementary information 81

Annex C (informative) Glossary..... 110

Annex D (informative) Annotated bibliography 116

Index 150

IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits

1. Overview

This guide is divided into eight clauses. Clause 1 provides the scope of this guide 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 assessing the surge environment described in this guide. Clause 3 states that no new definitions have been generated for this guide; however, for the convenience of the reader, important definitions already in existence are cited in the glossary (Informative Annex C). Clause 4 provides a tutorial description of the origins of surge voltages and surge currents. Clause 5 provides information on the propagation of surges. Clause 6 provides a summary of the database, drawn from the comprehensive data listed in Informative Annex A. Clause 7 provides basic information on the occurrence of temporary overvoltages (TOVs). Clause 8 suggests how this complex database can be simplified toward selecting a few representative surge waveforms that will be more specifically defined in the recommended practice IEEE Std C62.41.2[™]-2002,¹ which is a companion to this guide within the Trilogy.

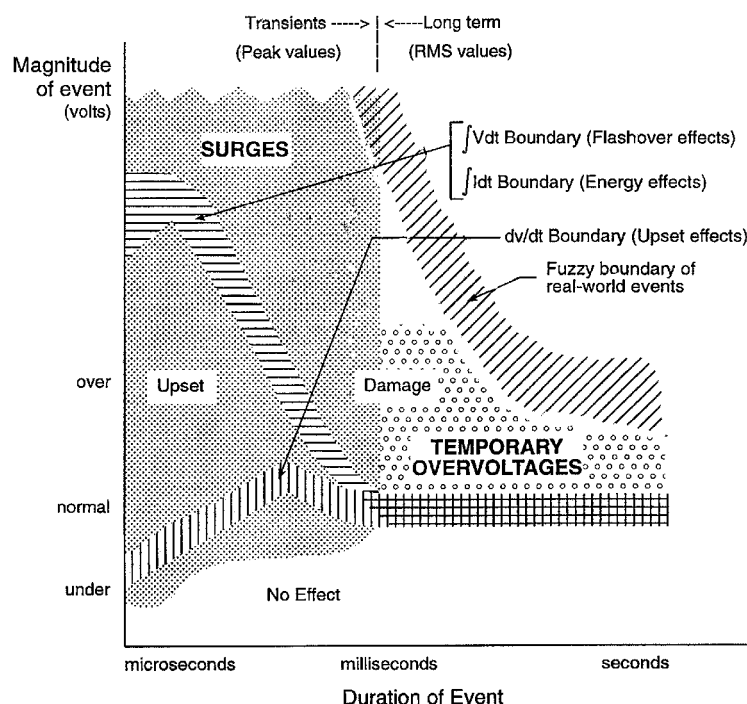
This guide also contains four informative annexes. Informative Annex A describes the results of surge measurements performed in the field, as well as the results of numerical simulations performed to supplement the recording of surge events. Useful inferences on the surge environment that can be drawn from equipment field success and failures are also discussed in this annex. Informative Annex B provides further tutorial information on the occurrence and propagation of surges. Informative Annex C lists some well-established definitions of terms used in this guide, complemented by further comments. Informative Annex D is an annotated listing of bibliographic references used to develop this guide and provides suggestions for further detailed reading on the surge environment.

1.1 Scope

This is a guide describing the surge voltage, surge current, and TOV environment in low-voltage [up to 1000 V root mean square (rms)] ac power circuits. This scope does not include other power disturbances, such as notches, sags, and noise.

¹Information on references can be found in Clause 2.

The surges considered in this guide do not exceed one-half period of the normal mains waveform (fundamental frequency) in duration. They can be periodic or random events and can appear in any combination of line, neutral, or grounding conductors. They include surges with amplitudes, durations, or rates of change sufficient to cause equipment damage or operational upset (see Figure 1). While surge protective devices (SPDs) acting primarily on the amplitude of the voltage are often applied to divert the damaging surges, the upsetting surges may require other remedies. The rationale for including a description of TOVs in this guide on the surge environment is given in 1.2.



NOTES

- 1—The graph shows the relative position of effects and the order of magnitude of the amplitude and duration. Do not attempt to read numerical values from this graph.
- 2—The scope of the guide is shown by the two dot-pattern areas. The fine pattern relates to surges, the prime scope of this guide. The coarse pattern relates to TOVs, the secondary scope of this guide. For surges, the upper limit for the duration is one half-cycle of the applicable power frequency. Swells—overvoltage events longer in duration than a surge, but lasting only a few seconds—are considered to be a subset of TOVs.
- 3—The values or positions of the boundaries between “no effect” and “upset” and between “upset” and “damage” vary with the withstand characteristics of the equipment exposed to the surges.
- 4—The boundary between “upset” and “damage” in the microsecond range is shown as the integral of V/dt to reflect the upturn in the volt-time characteristic of sparkover. Equipment responses that do not involve a sparkover are more likely to be influenced by the simple magnitude of voltage V .
- 5—This figure shows only one measure of surge severity emphasizing voltage and time relationships. Other possible measures include current peak and duration, rise time, and energy transfer.

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

1.2 Purpose

This guide, the first of a Trilogy of three IEEE standards addressing surges in low-voltage ac power circuits, focuses on the surge environment and on the TOV environment. This part provides readers with basic information on the occurrence of surges, as a database for the second document of the Trilogy, IEEE Std C62.41.2-2002 where recommendations are presented on the selection of representative surge

parameters to be considered in assessing equipment immunity and performance of SPDs. The third document of the Trilogy, IEEE Std C62.45™-2002, presents recommendations on surge testing procedures for obtaining reliable measurements and enhancing operator safety.

Including a description of TOVs in a document that has surges as its principal topic is necessary for the following reason: Correct application of SPDs—a topic not addressed directly in this Trilogy—does require knowledge of the TOVs to which these SPDs will be exposed to ensure compatibility of the SPDs with the TOV-related stresses. Thus, this information will serve as an input for other documents addressing the application of SPDs in the environment of low-voltage ac power systems.

1.3 Contents

In addition to Clause 1, this guide includes the following clauses and informative annexes:

- **Clause 2, References**, lists the documents supporting some of the basic concepts of the present document. This clause is not a bibliography, but a list of key documents. For the purposes of this guide, it may be unnecessary to have these references immediately available when using this guide, but it is useful to have access to these references. In contrast, Informative Annex D is a bibliography with annotations on the contents of the documents listed in the annex.
- **Clause 3, Definitions**, is included only to point out that no new definitions have been created for this document. For the convenience of the reader, important existing definitions are provided in the glossary (Informative Annex C).
- **Clause 4, The origins of surge voltages and surge currents**, presents a tutorial overview of the mechanisms leading to the occurrence of surges. These include lightning phenomena and switching under normal or abnormal power system operations.
- **Clause 5, Propagation, dispersion, and mitigation of surges**, presents considerations on these aspects of the surge environment that lead to the concept of “location categories” and the “transitions” between the categories. According to this concept, the surge environment depends on the position within a low-voltage ac power system, offering a way to simplify a complex and boundaryless environment.
- **Clause 6, Summary of the database**, presents an overview of the available database, with a discussion of the limitations and the resulting assumptions or simplifications that will have to be made for developing a definition of a representative generic environment—the latter being the scope of the companion recommended practice IEEE Std C62.41.2-2002.
- **Clause 7, TOVs**, provides the necessary information to assess the stresses that will be imposed on equipment, SPDs in particular, during these unavoidable ac power system disturbances.
- **Clause 8, Development of recommended selection of representative surges**, presents a brief discussion of how the description of the surge and TOV environment offered in this guide will lead to the companion recommended practices, IEEE Std C62.41.2-2002 and IEEE Std C62.45-2002.
- **Informative Annex A, Detailed database**, contains information presented to enhance credibility of the environment description and its summary presented in Clause 6. It is divided in four parts:
 - 1) Recordings of surge events in the field;
 - 2) Numerical simulations and relevant laboratory research;
 - 3) Inferences on the surge environment drawn from analysis of equipment field experience;
 - 4) Discussion of the database
- **Informative Annex B, Complementary information**, provides detailed background and information that would burden the reader if included in the clauses of the main body of this guide.
- **Informative Annex C, Glossary**, provides definitions (drawn from various sources) and complementary discussions in support of the recommendations presented in the document.
- **Informative Annex D, Annotated bibliography**, provides a list of published documents for further reading on recorded events, computed simulations of surge occurrences, surge propagation, and related standards not considered as required reference documents for Clause 2.
- **An index** is also provided for key words.

2. References

2.1 General

In this document, two types of citations are used: those that are directly related to the subject being discussed that might be 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 follows:

The first type, references, contains information that is implicitly adopted in the present document and the listing is provided in 2.2.

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

2.2 Reference documents

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

IEEE Std C62.41.2-2002, IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V or less) AC Power Circuits.^{2, 3}

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

3. Definitions

The definitions of the terms used in this guide are found in *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B12], or the IEC *Multilingual Dictionary of Electricity* [B3]. No new definitions have been generated in developing this document. However, for the convenience of the reader and for tutorial purposes, some existing definitions are listed in the glossary (Informative Annex C).

4. The origins of surge voltages and surge currents

4.1 General

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

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³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

- a) **Lightning surges.** Lightning surges are the result of a direct flash to the power system, to the structure of interest and nearby structures, or to the soil. Distant lightning flashes can also induce voltage surges in the circuits of an installation.
- b) **Switching surges.** Switching surges are the result of intentional actions on the power system, such as load or capacitor switching. They can also be the result of unintentional events, such as power system faults and the subsequent corrective actions.
- c) **Multiple-system interaction overvoltages.** Overvoltages can occur between different systems during the flow of surge currents in one of the systems. By definition, these extend beyond a strict interpretation of the scope as being limited to ac power systems; however, their occurrence can impact multiport equipment connected to the mains and, therefore, needs to be described.

4.2 Lightning surges

Lightning is a natural and unavoidable event that affects low-voltage systems (power systems as well as signal and communication systems) through several mechanisms. The obvious effect is a direct flash to the power system or to the building of interest, but other coupling mechanisms into overhead or buried power circuits can also produce overvoltages and associated surge currents.

Figure 2 gives examples of such events and provides a qualitative description of the concepts of “direct,” “near,” and “far” applied to the point of strike with respect to the installation of interest. The concepts of “near flash” and “far flash” involve several attributes and associated effects as shown in Table 1. Significant lightning parameters include waveforms, amplitudes, and frequency of occurrence.

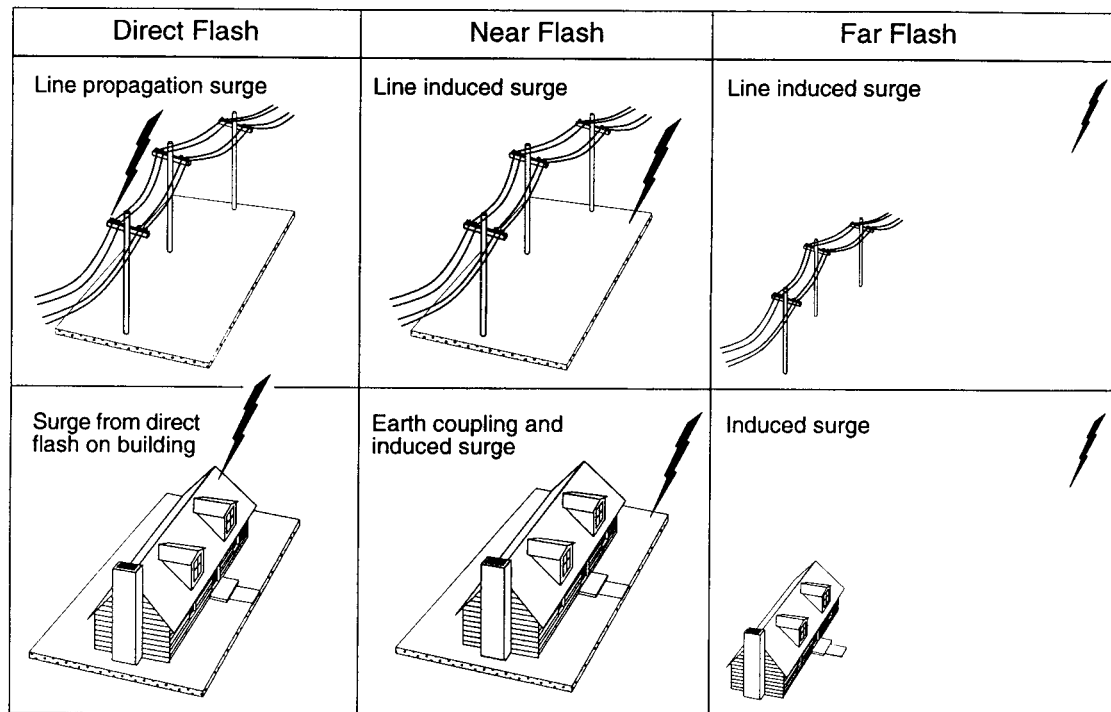


Figure 2—Examples of lightning flash coupling mechanisms

These lightning surges can be described under two distinct scenarios:

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

In the overall description of the surge environment, the information given in 4.3 on switching surges generated outside of the structure and impinging at the service entrance is also included in Scenario I.

Table 1—Attributes and impact of lightning flashes

Attributes	Direct stroke	Near stroke	Far stroke
Impact—Mechanical	Structure		
Impact—Thermal	Structure and circuits		
Energy	Service-entrance SPDs (High stress)	Service-entrance SPDs (Medium stress)	Installation SPDs (Low stress)
Rate of current change	Adjacent circuits	Nearby circuits	Large loop circuits
Earth potential rise	Adjacent circuits	Nearby circuits	
Magnetic coupling	Adjacent circuits	Nearby circuits	Large loop circuits
Capacitive coupling	Adjacent circuits	Nearby circuits	
Direct coupling	Connected circuits	Nearby circuits	
Conducted by line propagation	Service-entrance SPDs (High stress)	Service-entrance SPDs (Medium stress)	Service-entrance SPDs (Low stress)

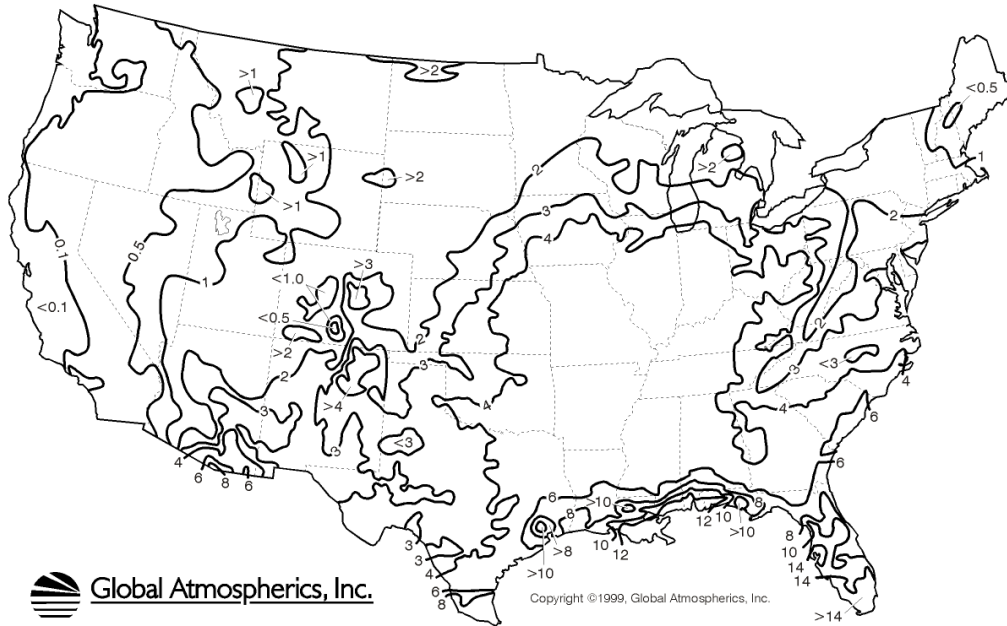
Emerging availability of global lightning detection systems is replacing the traditional isokeraunic maps by flash density maps. Instead of merely indicating the number of “thunderstorm days,” these new maps describe the density of ground flashes on a monthly or yearly basis (Cummins et al. 1998 [B61]); 1998 [B149]. Figure 3 shows an example of such maps, for which detailed location statistics can be provided by various organizations involved in collecting the data.

Because this type of information is frequently updated and is typically color-coded for display as a Web site on a computer screen, the black-and-white medium of this guide would not do justice to the ever-increasing quality of these maps. This activity is expanding and additional information should be found by browsing likely Web sites for the region of interest. A search on the phrase “lightning detection network” or the combination of phrases, such as “flash density” and “lightning,” will generally turn up possible sources.

For a given flash, the severity of the surges appearing at the end-user facility reflects the characteristics of the coupling path, such as distance and nature of the system between the point of flash and the end-user facility, earthing practices and earth connection impedance, presence of SPDs along the path, and branching

1989 – 1998 Average U.S. Lightning Flash Density flashes / km² / year

Lightning data provided by the U.S. National Lightning Detection Network®
(Measured Lightning Flash Density Corrected for NLDN Detection Efficiency)



(Reproduced with permission)

Figure 3—Typical flash density map for the United States

out of the distribution system. All of these factors vary over a wide range according to the general practice of the utility as well as local configurations. Further information on lightning-induced surges can be found in Informative Annex A, with highlights incorporated in the summary of Clause 6. Therefore, the response of an electrical system to the lightning event is an important consideration in assessing the threat in a particular environment.

In the case of a direct flash to the electrical system, the threat is the flow of lightning current in the installation. The effective impedance of the lightning channel is high (a few thousand ohms). Accordingly, the lightning current impinging upon the installation can practically be considered as an ideal current source, unaffected by the configuration of the installation circuits (i_s , Figure 4). Depending upon the relative impedances and connections of the circuits in the installation, this **direct coupling** can result in current surges (i_2 , Figure 4a) or in voltage surges (v_2 , Figure 4a). In addition, the flow of lightning current in down-conductors produces an **indirect coupling** by inducing voltages in adjacent circuit loops (v_i , Figure 4b).

In the case of a near flash, the threat is similar to that of a direct flash, except that the direct coupling effect is reduced by the fact that only a fraction of the total lightning current is involved in entering the building, and the inductive coupling is also reduced by the greater distance between the lightning channel and the affected circuit loops.

In the case of a far flash, the threat is limited to induced voltages (Figure 4b) and the associated stresses are much lower than those associated with the first two cases because of the much greater distance.

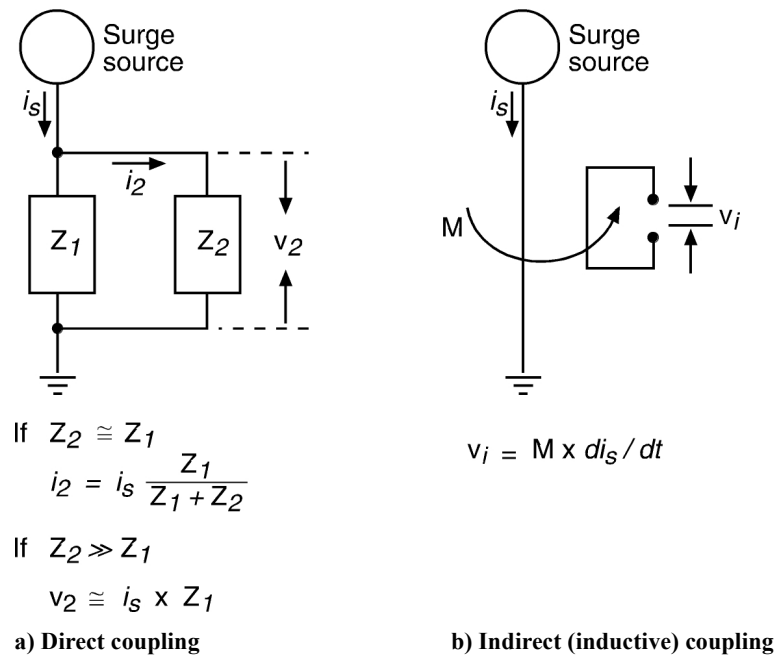


Figure 4—Direct and indirect coupling of lightning surges

4.3 Switching surges

Generally, any switching operation, fault initiation, interruption, etc. in an electrical installation is followed by a transient phenomenon in which overvoltages can occur. The sudden change in the system can initiate damped oscillations with high frequencies (determined by the resonant frequencies of the network), until the system is again stabilized to its new steady state. The magnitude of the switching overvoltages depends on many parameters, such as the type of circuit, the kind of switching operation (closing, opening, restriking), the loads, and the type of switching device or fuse. In this subclause, the phenomenon is described in principle, utilizing simple examples to present a basic description. More information is presented in Informative Annex A (Figure A.10 through Figure A.24).

Figure 5 shows an elementary circuit where an RLC load is being switched on by a circuit breaker and Figure 6 shows typical transients associated with this switching. The frequencies and number of oscillations of the switching transient are determined by the characteristic values of inductance, capacitance, and resistance found in the power system. Transients of this nature are typically stabilized within one cycle. The peak voltage of the switching transient is dependent on the characteristic values and on the voltage of the power system at the time of occurrence.

The maximum voltage is determined by the closing instant of the breaker in relation to the voltage of the supply system. The highest high-frequency overvoltage usually occurs when the breaker is closed at the maximum of the voltage (not to be confused with the offset power-frequency current, which is highest for closing at zero volts).

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

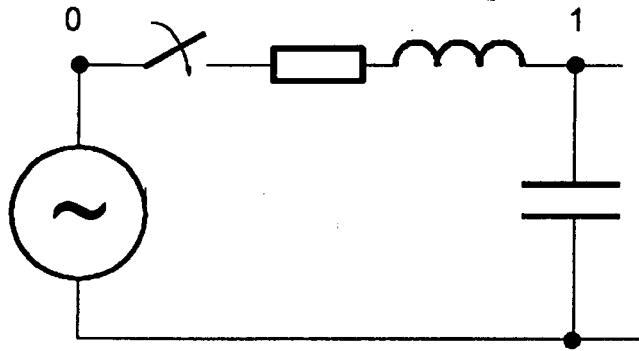
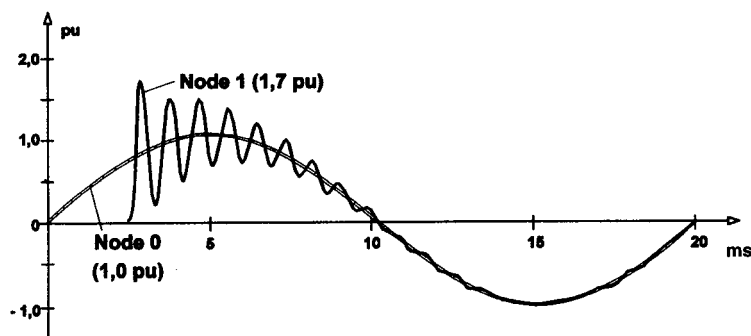
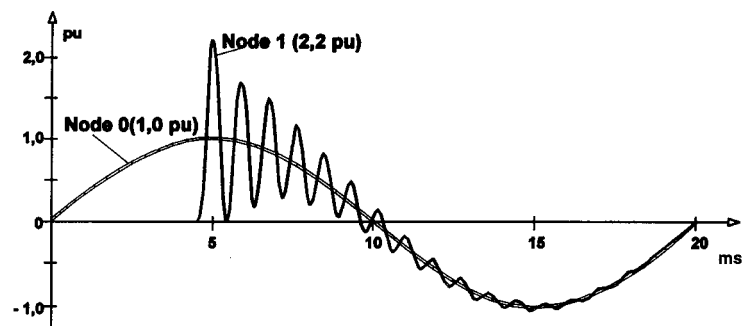


Figure 5—Generation of overvoltage by switching an RLC circuit



a) Closing 2 ms after zero crossing of the supply voltage



b) Closing instant near the peak of the supply voltage

Figure 6—Typical switching overvoltages

The frequency of the oscillations during switching operations is determined by the system characteristics, and sometimes resonance phenomena can occur. In such cases, high overvoltages can be produced. The probability of resonance with harmonics of the power frequency of the system is usually low. The typical shape of switching surges is determined by the response of the low-voltage installation. This situation results in most cases in a ringing wave as shown in Figure 6. System switching transients can be divided into transients associated with normal or abnormal conditions, as described in 4.3.1 and 4.3.2.

4.3.1 Normal operations

Switching is a normal part of the operation of a power system, performed for an intended purpose, but which can have unintended and unavoidable side effects resulting in voltage or current surges. Four examples of such operations and side effects are described below.

- a) **Minor switching** near the point of interest, such as periodic or random turn-off of an appliance in a household or turn-off of other loads in the individual system. Another example is the simple turn-on of an incandescent lamp, where the high inrush current in the branch circuit to supply the cold filament produces a transient almost equal to half of the line voltage in the active conductor (voltage drop) and in the neutral (voltage rise). These phenomena are generally benign, but can quickly overwhelm disturbance recorders set with too low a detection threshold.
- b) **Voltage notching** that occurs each cycle during the commutation in electronic power converters. The voltage notch is caused by a momentary phase-to-phase short circuit with a rapid change in voltage, lasting in the 100 μ s range. This phenomenon can interfere with some electronic loads, but is not within the area of concern associated with “surges.”
- c) **Multiple reignitions** or restrikes during a switching operation. Air contactors or mercury switches can produce, through escalation, surge voltages of complex waveforms and of amplitudes several times greater than the normal system voltage. This is the phenomenon that plagued new electronic controls in the 1970s and 1980s, and one of the motivations for the development of standards focusing on electromagnetic compatibility (EMC) (IEEE Std 518™-1982 [B16]) and of the IEC 801 series, now incorporated in IEC 61000-4-4:1995 [B8].
- d) **Major power system switching** of components such as capacitor banks, reactors, transformers, lines, or cables. Transient overvoltages associated with switching of capacitor banks on the utility systems have levels, at least in the case of restrike-free switching operations, of generally less than twice the normal voltage. However, when capacitor banks are installed on the low-voltage installations, surge magnification can occur. These transients can occur daily, and their waveforms generally show ringing oscillations of longer durations than normal capacitor-switching oscillatory transients. These amplified transients could be as high as four times the normal system voltage but generally are around two times the normal system voltage. If multiple reignitions or restrikes occur in the capacitor switching device during opening, then the transient overvoltages can exceed three times the normal system voltage and involve high energy levels. See a detailed description in B.2.

4.3.2 Abnormal operations

Abnormal, unintended conditions in a power system can produce surges. The intended (corrective) response of a power system to abnormal conditions can also produce side effects resulting in current or voltage surges. Examples of such conditions are described below.

- a) **Arcing faults** result as insulation systems deteriorate and typically originate as a ground fault. Although smaller in magnitude than bolted faults, arcing faults can generate high heat and arc pressures, thereby escalating the carbonization of insulation material and progressing further to a phase-to-phase fault. In ungrounded systems, the inherent stray capacitance of the system permits high frequency transients on the order of 2 to 3 times the peak line-to-ground voltage to be impressed across equipment. Under resonant conditions, these surge magnitudes can be much greater.
- b) **Fault clearing** by current-limiting fuses or fast-acting breakers that are capable of current chopping leave inductive energy trapped in the circuit upstream. If no low-impedance path is offered for the current flowing in the inductance at the time of current interruption, high voltages are generated. The resultant voltage surge applied to loads connected in parallel with the loads where the fault is being cleared can be exposed to surges of relatively long duration (hundreds of microseconds).
- c) **Power system recovery** following a fault sometimes occurs with phase-by-phase reclosing. Operation of a single fuse in a three-phase system also produces single-phasing in the remaining

circuits. Such abnormal conditions, while not producing surges as defined in this guide (twice the normal voltage and less than a half-cycle), need to be recognized and are discussed in more detail in Clause 7.

Further information on the mechanisms of switching surges and examples of recordings made in the field can be found in A.1 and B.2.

4.4 Multiple-system interaction overvoltages

4.4.1 General

The title of this guide might imply that its scope, narrowly interpreted, is limited to describing only surges occurring within ac power systems. However, it is also necessary to consider another type of overvoltage associated with interactions between the ac power system and another system, such as the ac power system and a communications system, in particular during the flow of surge currents in one of the systems.

This consideration of a system interaction is necessary because field experience has demonstrated that equipment failures are often summarily—and incorrectly—attributed to a surge impinging on the power port of multiport equipment, a “power-line surge” in the language of the media. The stress on the equipment that produced the failure (upset can also occur at lower stress levels) is the result of the flow of surge current in one of the systems, either inherently or as a side effect of the flow of surge current resulting from the intended diverting action of an SPD.

Understanding the nature of the phenomenon is important because the system-interaction stress can occur even if both ports of the equipment—power and communications—are “protected” by SPDs, one at each port or upstream in the systems, raising expectations of adequate surge protection being provided. When failure or upset of the equipment still occurs, questions are then raised on the adequacy of the existing SPDs.

However, the answer to these questions will be found not in providing “improved” SPDs installed *separately* on each of the ports, but by understanding the interaction scenario and providing effective remedial measures to address that stress.⁴

Unfortunately, the published quantitative database on this subject is scarce. One semi-quantitative anecdote is cited in A.1.2.6, as an example of what levels of stress might be expected.

4.4.2 Interaction between power system and communications system

More and more electronic equipment are entering the home and business environment, and these equipment often involve a communications port as well as their usual power-cord port. Typical examples involving a connection to the power system and the telephone system are a personal computers (PCs) with modem connection or fax machines. Although each of the power and communications systems might include a scheme for protection against surges, the surge current flowing in the grounding system causes a difference of potential between the power and telecommunications ports that can cause upset or damage to equipment.

Figure 7 illustrates the example of a PC equipped with a modem, and powered from a branch circuit that includes an equipment grounding conductor (“protective earth” in IEC language), with a three-wire cord that establishes the potential of the chassis as that existing at the grounding (earthing) point of the service panel. The modem is connected to a telephone jack in the room, wired to a primary protector generally installed by the telephone company at the telephone service entrance, called network interface device (NID) in North American practice.

⁴An understanding of grounding practices applied in accordance with local jurisdictions or IEEE recommendations, such as IEEE Std 1100™-1999 (Emerald Book) [B17] or IEEE Std 446™-1995 (Green Book) [B15], assists in surge characterization. Brief references to this topic are included in B.22.

For a worst-case but common scenario, the power service and the telephone service enter the house at opposite ends of the house. In such a situation, the connection of the primary protector is made to the nearest point of the grounding system in accordance with the provisions of National Electric Code[®] (NEC[®]) (NFPA 70-2002) [B19].⁵ However, many older installations were made using other arrangements for the grounding and still exist (“grandfathered”). In either case, the length of this earthing connection can be substantial. The resulting voltages induced in the loop by the fast-changing surge currents flowing in the grounding system can cause a large voltage difference between the power port and the telecommunications port.

This scenario applies to other equipment, such as a fax machine or an answering machine. A difference might be that a PC/modem might be assembled from uncoordinated elements obtained from different manufacturers, while the fax machine or answering machine are designed from the start as one unit and might be expected to have this possible interaction recognized and dealt with by the designers. Field experience, however, indicates that problems still occur.

A very similar scenario can develop for a TV receiver or VCR, with the power supplied from a branch circuit and the video signal supplied from a cable TV system or a satellite dish located outside of the house. The difference would be that instead of the symmetrical and balanced configuration of a telephone pair, the video signal is carried by a coaxial cable for which the shield would be the prime carrier of any surge current. The same observation made in the preceding paragraph applies to the TV or VCR, the product of an integrated design rather than uncoordinated assembly of separate components and, therefore, expected to have been designed to survive the occurrence of these interport stresses. Nevertheless, with the fast-paced evolution of satellite antenna systems for consumer applications, coordination of earthing practices appears a difficult goal to reach. The frequent, albeit anecdotal, occurrence of failures of cable-connected video equipment is an experience-based indication that the phenomenon is real. Many case histories and proposals for remedial measures can be found in the literature; see D.7 and D.8 for a listing of citations.

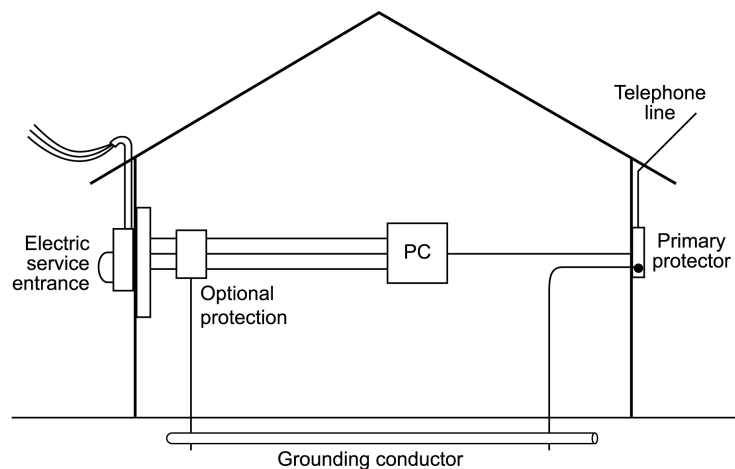


Figure 7—Scenario for interaction between power and telephone systems

⁵National Electrical Code[®] and NEC[®] are both registered trademarks owned by the National Fire Protection Association, Inc.

5. Propagation, dispersion, and inherent mitigation of surges

5.1 General

Clause 4 discussed the mechanisms at the origin of surges. This clause takes the mechanisms one step further to examine how these surges propagate and disperse in a power system and thus might be inherently mitigated in the process. To do so, it is necessary to recognize a fundamental dichotomy on how a surge should be defined: is it a **voltage event**, or is it a **current event**. This dichotomy arises because the local situation of interest to the user is only part of the complete and complex power system involved in a surge event. Rigorous analysis of the event would require considering the complete system where all parameters of the circuit are defined: impedances of the circuit, and amount of energy released into this system by the surge source, in which case, of course, the relationships between current, voltage, and impedance are completely defined by circuit theory. Because that knowledge is not available from the point of view of the user, a possible simplification is to consider the surge source either as a current source or as a voltage source, as illustrated in Figure 4.

Lightning surges, as discussed in 4.2, are the consequence of a direct flash, a near flash, or a far flash. In simplifying analyses, the resulting surge is as a voltage source or as a current source. The current source is usually considered for analyzing direct flashes and some of the near-flash effects while the voltage source is usually considered for analyzing some of the near-flash effects and the far-flash effects. On the other hand, switching surges, as discussed in 4.3, have been considered by the various authors discussing the phenomenon as a voltage source—often without any reference to the impedance of that source, which should be known for a rigorous analysis.

5.2 Current dispersion

For the analysis of a lightning event involving the conductors of the building (lightning protection system or power wiring in the building—damage to the masonry or structural parts is not in the scope of this guide), two cases of lightning seen as a current source may be considered:

- 1) A direct flash to the structure of interest, where the phenomenon is one of the lightning current seeking dispersion among the earthing impedances within the building as well as outside of the building via the utility power supply network;
- 2) A direct flash to the power system outside of the building or to nearby structures or nearby flashes to earth, where the phenomenon is one of the total lightning current seeking part of its dispersion through the available paths to earth within the building.

Ongoing research studies are attempting to measure the dispersion of actual (triggered) lightning in a simple installation (Fernandez et al. 1998 [B105]; Mata et al. 1998 [B129]; Rakov et al. 2001 [B136]). Unavoidably, these studies can only offer specific and limited examples; but, once completely analyzed and understood, these measurement results should become a powerful validation of the other research tool—modeling the dispersion of the lightning current (IEC 62066:2002 [B11]; Mansoor and Martzloff 1998 [B116]; Martzloff 2000 [B127]; Mata et al. 2000 [B130]).

In both cases 1 and 2 above, simulations have postulated, as a starting point, that the current source and the available paths to earth are such that no insulation breakdown occurs. Clearly, if an imposed (postulated) current encounters a high impedance, such as the wiring inductance during the initial rise of the current surge, a high voltage is developed across that impedance. In an actual installation, this high voltage might exceed the withstand level of clearances at the point of injection of the current and thus abort further propagation of the surge current into the building (Mansoor and Martzloff 1997 [B115]). Such an insulation

breakdown might not be a welcome scenario—hence the time-honored, but not universal, provision of SPDs at the service entrance to offer a harmless path for the earth-seeking lightning current.⁶

A distinction should be made between the scenario of a lightning flash striking the building itself (or the earth very close to the structure) on the one hand, Scenario II, and, on the other hand, the scenario of a lightning flash striking the power system outside the building or nearby structures supplied by the same distribution transformer, Scenario I. The first case will involve large current surges, but its probability is low; based on typical flash density values and the building not being a “tall building,” where lightning flashes can be initiated from the ground up. This probability is in the range of perhaps once every hundred years⁷ (see B.9). The second case, more frequent, will involve current surges of lesser amplitude that appear at the service entrance of the building of interest. It is important to keep in mind that the lightning parameters reported in the literature (Berger et al. 1975 [B54]; Anderson and Eriksson 1980 [B48]) are measurements of total stroke currents, not the measurement of current or charge transfer in the wiring of low-voltage ac power systems.

5.3 Voltage surge propagation

Lightning-induced voltage surges appearing in a local circuit can be the result of direct coupling or inductive coupling. Both mechanisms produce a voltage that, for practical purposes, can be considered as voltage sources. These are most likely the surges that have been reported in the various surveys conducted at locations that were not directly struck by lightning.

Direct coupling involves the connection of a part of the local circuit to an external, larger circuit in which the (fixed) lightning current flows, as shown in Figure 4a. The local circuit is presumed to have a higher total impedance than the smaller, common path between the external circuit and the local circuit. Accordingly, the voltage appearing across the common impedance and thus injected in the local circuit is the voltage surge that should be considered in assessing further propagation of the surge in the local circuit.

Inductive coupling involves the induction of a voltage in a circuit loop embracing the flux created by the lightning current, be it near or far, as shown in Figure 4b. Included in this scenario would be induction of voltage surges in local circuits even if the lightning strike would be a direct flash to the building power system, but initially involving only its extraneous metallic parts (structural steel, miscellaneous piping and conduits). Subclause A.2.2.3 offers quantitative examples of such effects.

Another case of inductive coupling, as discussed in 4.4, prevails when the “loop” consists of the conductors belonging to two different systems, such as a branch circuit of the power system and the internal conductors of a communications system.

As mentioned above, a practical and inherent limit exists to the induction of high voltages in the circuits as insulation flashover will occur, mostly across the clearances of wiring devices. Typical hardware design practices or mandated requirements result in relatively high limits for outdoor circuits and lower limits for indoor circuits. The 1980 edition of IEC 664 [B6] attempted to translate this reality into the concept of “installation category,” but more recent versions of that report, now identified as IEC 60664:1992 [B6], have associated the concept with equipment withstand categories, which are only indirectly related to the location of the equipment in a building.

⁶The path of the lightning current as it divides among available paths is often presented as originating from the cloud and flowing into the earth. It should be noted, however, that for a cloud-to-earth stroke, the significant lightning current is a return stroke, originating **from the earth**—not “into the earth,” with charges flowing toward the cloud.

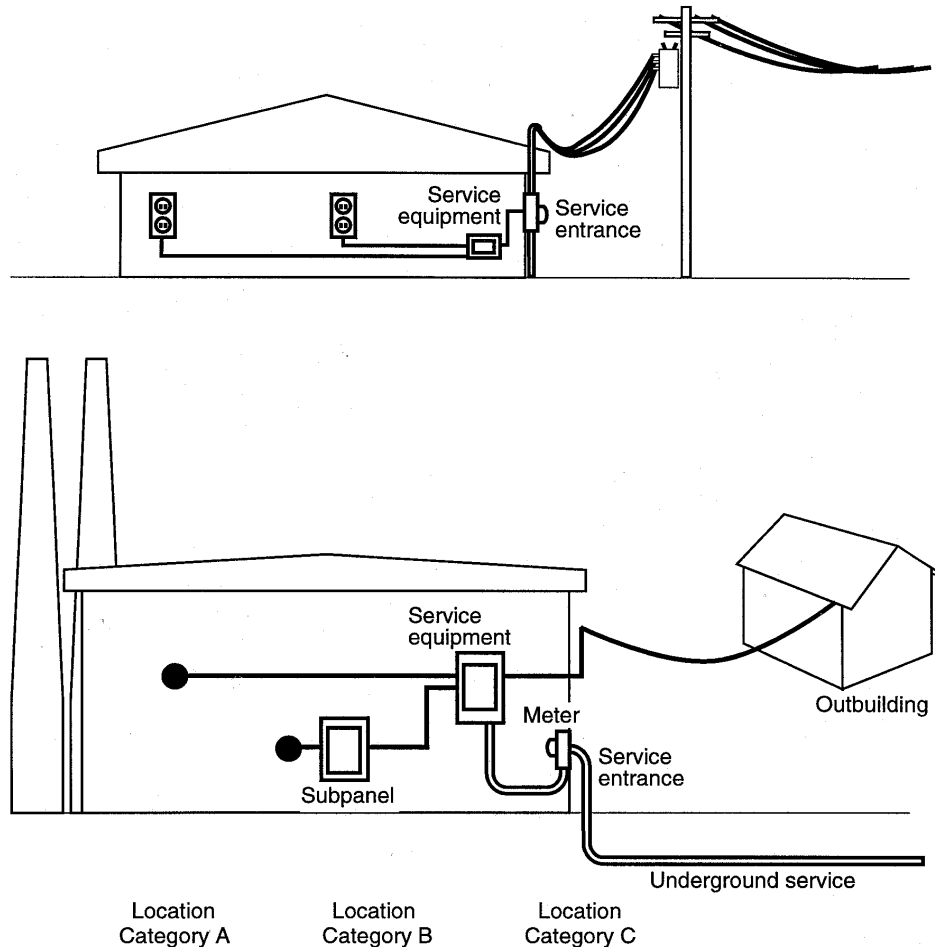
This distinction may be a fine point to make, but it can serve as reminder that the dispersion simulations are only as good as the assumptions made for earth conductivity near the grounding electrodes (Mata et al. 1998 [B129]).

⁷Tall buildings will experience a higher rate of occurrence, from attracting cloud-to-ground strokes within their so-called “protective area” as well as by initiating ground-to-cloud flashes. Such buildings deserve special consideration in assessing their surge environment beyond the generic information offered in this guide.

From all of these considerations emerges the practical concept of location categories presented in 5.4.

5.4 Location categories—Scenario I

As a first step toward a reduction of the complex database on surge occurrences, the concept of “location categories” is proposed here to describe the scenario of surges impinging at the service entrance or generated within the building, exclusive of those associated with a direct lightning flash to the structure. The latter are described under the heading of Scenario II, in 5.5. At this conceptual stage, location categories are described only in qualitative terms, as illustrated in Figure 8 where the exact separation or transition from one category to the next is left undefined.



NOTE—There can be differences in the configuration and distance between the revenue meter and the service equipment. This schematic is only an example to illustrate the concept of location categories. (The NEC [B19] states in Article 230-70 “The service disconnecting means shall be installed at a readily accessible location either outside of a building or structure, or inside nearest point of entrance of the service conductors.”)

Figure 8—The concept of location categories as a simplification approach

The propagation of voltage surges and current surges is a phenomenon that does not recognize arbitrary boundaries, but will be influenced by the characteristics of the physical components of the installation. A quantitative description is presented as part of the recommended practice IEEE Std C62.41.2-2002, which is a companion to the present guide.

According to this concept, Location Category A applies to the parts of the installation at some distance (defined in IEEE Std C62.41.2-2002) from the service entrance. Location Category C applies to the external part of the building, extending some distance into the building (also defined in IEEE Std C62.41.2-2002). Location Category B extends between Location Categories C and A.

The concept of location category rests on the considerations discussed in 5.2 and 5.3 on dispersion and propagation of surge currents and surge voltages. For surge currents presented at the service entrance of a building, the increasing impedance opposing (impeding) the flow of surge currents further into the building (with or without the crowbar effect of a flashover that can occur at the meter or in the service-entrance equipment) reduces the surge current that can be delivered along the branch circuits. In contrast, a voltage surge, with an amplitude below the point of flashover of clearances and presented at the service entrance of a building, can propagate, practically unattenuated, to the end of a branch circuit when no low-impedance load (equipment or local SPD) is present along the branch circuit.

Therefore, the location category concept can also be described as a staircase of surge voltages and a down-hill slope of currents, as illustrated in Figure 9. In this conceptual figure, the specific levels and nature of the waveforms have not yet been defined, although some voltage values are shown to help illustrate the concept. The precise numerical definition is in the scope of the recommended practice IEEE Std C62.41.2-2002. It should be noted here, however, that the limitation of current surges by the wiring impedance (Standler 1992 [B140]; 1993 [B141]; Mansoor and Martzloff 1997 [B115]) applies only during the fast-changing parts of the surges. For surges with long duration (unidirectional with several hundreds of microseconds, or low-frequency oscillations), this limitation will be substantially reduced or will not apply.

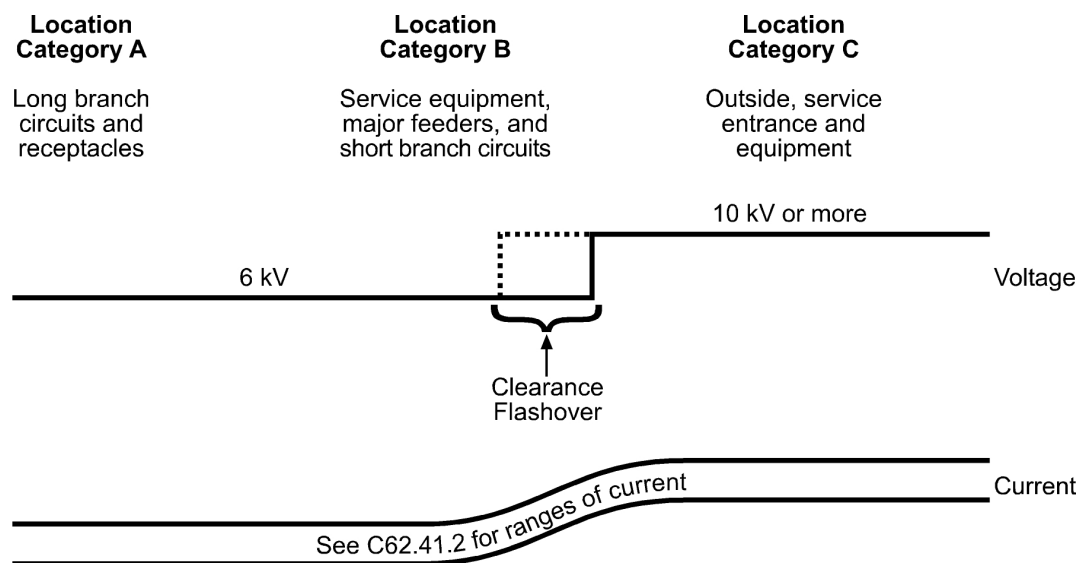


Figure 9—Voltage staircases and current down-slopes according to location category

5.5 Scenario II—Direct flash to the structure

In this scenario, a lightning flash is postulated to involve the flow of lightning current in all the available conductive paths that can disperse the current, from the point of strike to the earth—local earth electrode and any remote earth electrode, intended or opportunistic. In some documents, a distinction seems to be made as to whether a “lightning protection system” has been provided for the structure. The actual flow of lightning current will occur along intentional down-conductors as well as any conductor momentarily bonded by a side-flash and/or extraneous grounded conductive structural elements. This current will “seek” (see

footnote 5 in 5.2) dispersion into any local earth electrode as well as remote electrodes, as shown in Figure 10. The local electrodes include the made earth electrodes of the structure (MEB and MEL) as well as other grounded conductors (OU), such as utility piping (water and gas) or communications links (e.g., telephone, cable TV, backyard dish antenna). The remote electrodes are primarily the made or opportunistic electrodes of the distribution system (PU), now acting as an exit path for the dispersion of the lightning current.

In a multiple-grounded neutral configuration, the preferential path (least impedance) for the dispersion of the lightning current toward the distribution system is the neutral conductor and its many earth electrodes. However, the phase conductors of the incoming power supply also offer a path, through the very SPDs installed in the service-entrance equipment for protection against the impinging surges of Scenario I, as shown in Figure 10. These SPDs installed at the service-entrance equipment become involved in dispersing a share of the lightning current exiting via the phase conductors of the utility connection. During the initial part of the lightning impulse, where rapid changes occur, the dispersion will be in inverse ratio of the inductance to earth and, during the later part of the impulse, in inverse ratio of the earthing resistances. It might seem that the inclusion of the phase conductors in dispersing the current, which involves an SPD connected phase-to ground, while the neutral path does not involve an SPD in typical North American practice, would make some difference. In reality, the difference is small because the added voltage drop across the SPD is almost negligible compared to the large voltage differential developed between the local earth bonding point and the remote earth electrodes (Mansoor and Martzloff 1998 [B116]). For the late part of the lightning current, where most of the charge transfer occurs, the critical factor is the relative values of the resistive paths—multiple-grounded neutral compared to phase conductors. The two examples of modeling in A.2.2.1 and A.2.2.2 illustrate this situation.

In addition to the dispersion of direct lightning current among available paths to earth, the Scenario II also involves the coupling of surge voltages in the conductors of the ac power system within the building. This coupling involves two mechanisms:

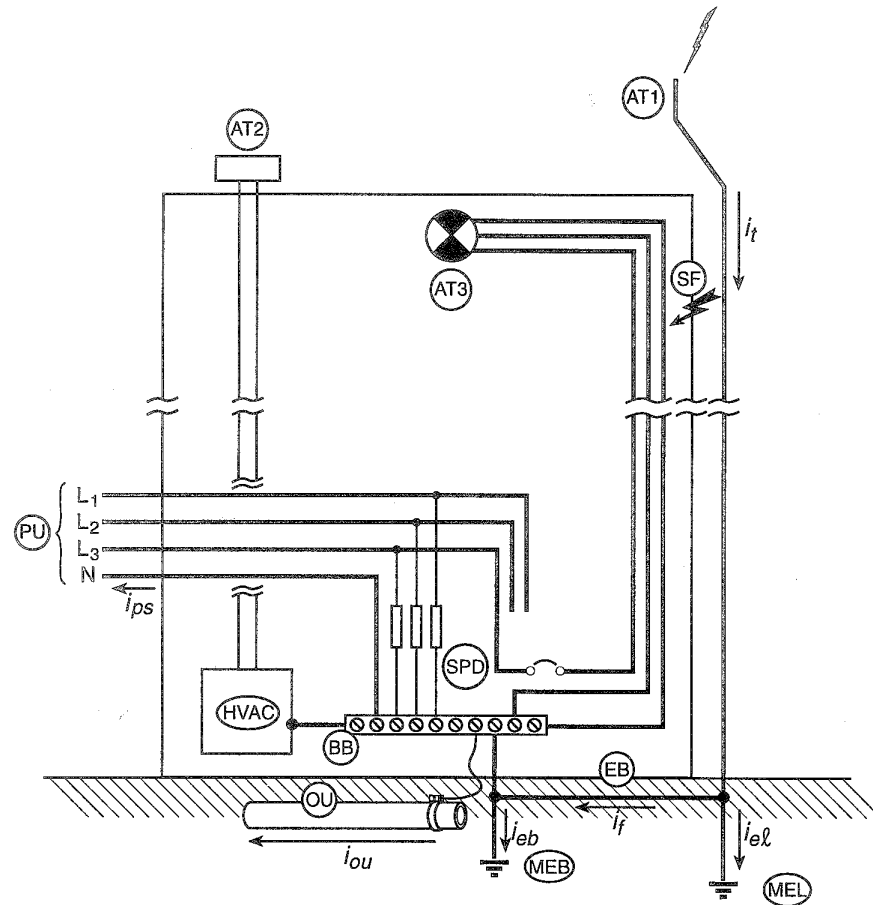
- Shifts in the potential of conductors by the rise in ground potential
- Induction of voltage or current in circuit loops by the electromagnetic fields of the lightning.

These two types of surges involve considerably less energy-delivery capability than those associated with the direct dispersion of the lightning current. Nevertheless, they still represent a significant threat and should be recognized. In the absence of published measurements made during these rare events, it is difficult to assign, in IEEE Std C62.41.2-2002, precise quantitative recommendations to describe these two types of surges. The potential shift might be represented by a long, unidirectional impulse, while the induced voltage might be represented by an oscillatory (“Ring Wave”) waveform. The long wave would reflect the effect of the long tail of the lightning current, while the Ring Wave would reflect the electromagnetic coupling associated with the steep front of the lightning current.

6. Summary of the database

6.1 General

Disturbances on low-voltage ac power circuits (“mains”) can be classified in many ways, such as a voltage increase or reduction from the nominal rms value, a voltage or current wave shape variation, and surge waveform characteristics (IEEE Std 1159™-1995 [B18]). The latter include amplitude, duration, rise time, frequency of ringing, polarity, energy-delivery capability, amplitude spectral density, position with respect to the phase of the mains waveform, and frequency of occurrence. The primary scope of this guide is limited to surges—disturbances that have a duration of less than one half-cycle of the normal mains waveform. Consequently, the issues of disturbances caused by other events, such as sags, outages, swells, and harmonic distortions, are not addressed in this discussion of the database, regardless of their importance or rates of occurrence compared to those of surges.



- (AT1) Intended air terminal of "lightning protection system."
- (AT2) Unintended, but likely air terminal (e.g., ventilation, air conditioning).
- (AT3) Unintended, but possible air terminal if no others available.
- (SF) Side flash from down-conductor in the absence of bonding.
- (BB) Facility bonding bar.
- (EB) Earthing bonding.
- (MEB) Made earth electrode for building.
- (MEL) Lightning earthing electrode.
- (HVAC) Heating, ventilation, air conditioning equipment.
- (SPD) SPDs installed in the service entrance equipment.
- (PU) Power utility incoming connection.
- (OU) Other utilities (e.g., communications, water).
- i_t Total lightning current.
- i_f Portion of lightning current into facility wiring.
- i_{el} Portion of lightning current into lightning earthing electrode.
- i_{eb} Portion of lightning current into building made electrode.
- i_{ps} Portion of lightning current exit via electric power utility.
- i_{ou} Portion of lightning current exit via other utilities.

Figure 10—Dispersion of direct flash current among available paths to earth

It is difficult to assign minimum or maximum values to some of the surge characteristics because the effect and hence the significance depend on the nature of the equipment subjected to the surge. Some of these disturbances occur without causing any equipment problem, some can cause equipment upset, and others can cause equipment damage as illustrated in Figure 1 (in Clause 1).

Surge voltage amplitude alone is not the sole criterion for immunity in the design and testing of equipment. However, the data available at the time of the 1980 version (IEEE Std 587™) of this guide were based on the general use of peak-reading instruments, with only a few oscilloscopes. (The latter became progressively more suitable for monitoring.) Hence, the information on waveform was more limited than the information on peak amplitude.

When attempting to correlate the data collected by many researchers over the years, no agreement is found on the voltage amplitude below which the surges lose significance. Different perceptions on what should be considered as “noise” in contrast to a “surge” are found among different user categories. As a result, different researchers assigned different levels to the threshold above which they included a surge in their data, so that the “relative frequency of occurrence” expressed in percent of recorded events is affected by this threshold selection. An insidious effect of this selection process is found in summaries (pie charts) of power quality surveys where the relative percentage of all the recorded disturbances (surges, swells, and sags) is affected by the threshold selection as pointed out in Gruzs 1986 [B186].

Characterization of surges is further complicated by diverse perceptions of the significance of other parameters, such as the rate of change of the surge voltage and the amplitude spectral density of the surge, the energy-delivery capability of the surge, the threshold of the susceptible circuits, and the threshold level of the instrument used to collect the data. This aspect is discussed in greater detail in the database of A.1. From this database, the recommendations presented in the companion recommended practice IEEE Std C62.41.2-2002 were developed by consensus.

In the 1970–1980 data, the highest confidence level was found in the expected peaks and rates of occurrence. Other data on the surge environment had a narrower basis, but could still be used for guidance until broader data would be published and integrated as an international effort. However, as discussed later in this clause, the emergence of ubiquitous low-voltage SPDs radically changed the situation, to the point that the results of the most recent surveys limited to surge **voltage** measurements might be misleading if interpreted as an indication of only few surge-generating events.

6.2 Notations and definitions

A surge on the ac mains is generally described as a time-domain phenomenon. Of course, terms used to describe a particular event should use definitions applicable to all measurements. The reader should review the definitions and the notes in Informative Annex C for the refinements or changes to commonly used terms.

Design of equipment for surge immunity requires knowledge of how the surge is presented to the equipment: the designer needs to know the surge mode of coupling. Unfortunately, many publications are not explicit on this point. For instance, the community of insulation coordination engineers tends to imply that the significant surges are those occurring between active conductors and ground (e.g., ground, chassis). On the other hand, electronic equipment designers are generally more concerned with surges occurring between active conductors—line-to-neutral or line-to-line. The summary of surveys presented in Table 2 shows (when it was explicitly stated in the cited paper) how that perception directed the connection mode of the instruments.

To avoid the ambiguities that may occur when using the term *common mode*, which is in common usage (see B.5), the following notations are used in this guide to describe the recorded surges.

- **L-N:** Measurement from phase(s) to neutral for both single- and three-phase systems.
- **L-L:** Measurements from phase to phase in a polyphase system or from one line to the other line in a single-phase, midpoint neutral system.
- **L-G:** Measurements from phase to equipment grounding conductor at the line terminals of utilization equipment. In North American single-phase systems and three-phase five-wire systems, the equipment grounding conductor is bonded to the neutral conductor at the service entrance.
- **N-G:** Measurements from neutral to equipment grounding conductor at the line terminals of the utilization equipment.

6.3 Site surveys of power quality

Monitoring of mains voltage is a logical first step to determine the power quality at a specific site. Power quality surveys, an increasingly prevalent undertaking, do generally include some sections on the occurrence of surges. However, the results are only a snapshot of the quality because the characteristics of the measured surges vary over time as loads and system configurations change. Seasonal variations and geographic location also influence the results, in particular for lightning effects. A chronological review of several site surveys is shown in Table 2, which clearly shows the wide range of choices of recorded parameters made by the researchers on reporting their results.

Table 2—Summary of site surveys

Survey author (See D.2 for citation)	Period	Locale	System voltage	System type	Instrument	Connection mode	Power frequency filtered out
Bull & Nethercot	1962–1963	Great Britain Undefined	240	Industrial and residential	Analog with multiple thresholds	Not stated	Yes
Martzloff and Hahn	1963–1967	USA Residence and industry	120/240 277/480	Residential and industrial	1. Analog with single threshold 2. CRO and camera	L-N	No
Cannova	1969–1970	US Navy	120 & 450	Shipboard (Ungrounded)	CRO and camera	L-L	No
Allen and Segall	1969–1972	USA	Not stated	Computer power supply system	1. Storage CRO 2. Oscillograph 3. Digital multi-parameter	Not stated	Not clear
Goldstein and Speranza	1977–1979	USA	120/208	Telephone facilities	Digital multi-parameter	L-N	Yes
Wernström et al.	1982–1983	Sweden	220/380	Industrial	1. Digital multiparameter 2. Storage CRO	“Common mode”	Yes
Aspnes et al.	1982–1983	Alaska	120/240	Isolated rural systems	Digital multi-parameter	L-N	Yes

Table 2—Summary of site surveys (continued)

Survey author (See D.2 for citation)	Period	Locale	System voltage	System type	Instrument	Connection mode	Power frequency filtered out
Odenberg and Braskich	1982–1983	USA	120/240 120/208 277/480	Industrial and computer sites	Two-point digital, V & I Peak: amplitude and time Duration: to 50% of peak	V: L-N I: In series with load	V: No I: Yes
Goedbloed	1983–1984	Western Europe	220/380	Industrial and miscellaneous	Two digital recorders, one fast and one slow	L-G	Yes
Standler	1988–1989	USA	120	Residential Single phase	Digital oscilloscope	L-N	No
Meissen	1983–1994	Germany	220/380	Industrial		L-G	Not stated
Dorr	1990–1994	USA and Canada	120	Industrial, commercial residential	Digital 5 kHz–1 Mhz	L-N	Yes
Hughes and Chan	1990–1992	Canada	120/240 120/208 347/600	Residential Commercial Industrial	Digital 5 kHz–1 Mhz	L-N	Not stated
Sabin	1996	USA	4 kV–34 kV	Distribution systems	Digital 5 kHz–1 Mhz	Not stated	Not stated
Ackermann et al.	1997	Germany	220/380	Industrial, rural residential, commercial	Digital oscilloscope	L-G	Not stated

Early site surveys were limited by instrument bandwidth in the measurements of fast rise transients. With improving detection capability in the instrumentation resulting in some changes in the recorded results, this original limitation could lead to the false conclusion that power quality has degraded over the years (Goldstein and Speranza 1982 [B69]; Martzloff and Gruzs 1988 [B192]).

About 1960, researchers began to measure the surge transients on low-voltage systems as the transition from vacuum tubes to semiconductor design accelerated and semiconductor failures became an issue. Because the monitoring instruments reflected technology available at the time of those measurements, the early data are very limited. Early site surveys had several limitations:

- They were only differential mode measurements (L-N or L-L);
- They did not always record the highest surge peak in an event after being momentarily disabled by a first, mild surge preceding a subsequent larger surge;
- They rarely recorded the surge waveform or duration;
- They did not record the period of an oscillatory surge;
- They did not give any data on the repetition rate of surge bursts;
- They did not provide parameters of rate of voltage change or energy-delivery capability.

6.4 Effect of SPD proliferation on survey results

All of the considerations listed above were formulated during the development of the original version of this guide (IEEE Std 587-1980) and its successor (IEEE Std C62.41™-1991). The 1991 version of the database included measurement surveys conducted until the mid-1980s. Since that time, a very significant change has taken place in the surge environment of low-voltage ac power circuits, namely the proliferation of SPDs in equipment as well as in installations.

Furthermore, the proliferation of switch-mode power supplies in electronic appliances effectively connects substantial capacitors across the mains, producing a further reduction in the level of recorded voltages—but not in the occurrence of a current surge (Mansoor et al. 1999 [B33]).

This proliferation has produced a new situation where monitoring surge **voltages** can lead to erroneous conclusions on the surge environment. In the present new situation, the surge environment and its threat to equipment, including SPDs, would be better characterized by measuring the capability of this environment to deliver a surge **current**. More information on this situation is presented in B.3.

6.5 Equipment field experience

In addition to site surveys, observations of failure rates (including alarming rates in some instances and satisfactory performance in other cases) can also provide data on the occurrence of surges. Conversely, field experience on equipment, SPDs in particular, for which the stress withstand characteristics have been well established, can also provide information on the surge environment. A tenet of standards development can be expressed as follows:

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

This tenet can be applied to assess the validity of imposing over-conservative requirements on the specifications of SPDs. For instance, five observations have been reported formally or anecdotally on voltage levels versus frequency of occurrence or on surge energy-delivery capability of surge sources versus energy-handling capability of equipment (more details in A.3):

- 1) In the 1960s, a 100:1 reduction occurred in the failure rate of some clock motors when their voltage withstand was raised from 2000 V to 6000 V (Martzloff and Hahn 1970 [B78]). Because of the large sample and duration of the observations, this ratio of failure rate and, therefore, the relative occurrence of the two levels, even as it is now mostly historical interest, still has high credibility.
- 2) Many incandescent light bulbs typically fail by internal flashover when subjected to surges above 1500 V (Bachl et al. 1997 [B24]). Since this failure level did not produce an unacceptable rate of premature failure, before the SPD proliferation, among millions of light-bulb users, there had to be a corresponding upper bound on the rate of occurrence of surges above 1500 V at the locations of light-bulb sockets. Again, this observation might be only historical at this point, but still represents useful data.
- 3) Single metal-oxide varistors (MOVs) of 20 mm diameter or less, installed at some service entrances, have been informally reported to fail occasionally, while their performance within a building has been reported as acceptable. To the extent that these failures can be attributed to surge energy deposition in excess of the varistor surge rating (excluding occurrences of TOVs), this observation can be used to obtain a gross estimated magnitude of energy-delivery capability of surges at these two locations, supporting the concept of location categories and exposure levels presented in this guide.

- 4) An IEC standard (IEC 1000-4-1, 1990 edition) at one point suggested a 100/1300 μs “high-energy surge” as a routine requirement for industrial equipment. Such a test applied to these ubiquitous 20 mm varistors invariably produced their failure, thereby indicating that the proposed 100/1300 μs requirement was inconsistent with the observed low failure rate of these 20 mm varistors (Fenimore and Martzloff 1992 [B26]). The present “menu” of the IEC 61000-4 series no longer includes this 100/1300 μs test requirement.
- 5) Distribution arresters and low-voltage SPDs designed and tested in accordance with the specifications of IEEE Std C62.11™-1993 [D.1.1] (Revised 1999 [D.1.2]) have very low failure rates (Goedde et al. 2000 [B27]), an indication that the stresses associated with worst-case Scenario II conditions are rarely encountered. A likely explanation for this situation is the reduction of stresses applied to exit-path SPDs resulting from the use of multiple-grounded neutral systems.

6.6 Summary of surge characteristics in Scenario I

The combination of data from published surveys, anecdotes, and observed failure rates yields information used to develop the qualitative and quantitative recommendations of the companion recommended practice IEEE Std C62.41.2-2002. To facilitate the transition from this guide to the recommendation of specific surge waveforms, the characteristics of typical surges occurring for Scenario I in the low-voltage ac power circuit environment are summarized in this subclause. The case of Scenario II is addressed in 6.7.

From measurements and simulations on the propagation of surges in a low-voltage installation, it has been demonstrated that surge **voltages** impinging at the service entrance experience very little attenuation as they propagate inside the building (Martzloff 1983 [B119]; 1990 [B124]; Martzloff and Gauper 1986 [B120]).

For the circuit lengths found in typical buildings (less than a few hundred meters), the surge front is long compared to the travel time so that the reflections effects have damped out by the time the voltage surge reaches its peak. An exception to this situation is the case of transients with very steep front, such as the IEC Electrical Fast Transient (EFT) Burst, which is rapidly attenuated as it propagates in the wiring (Martzloff and Wilson 1987 [B122]; Martzloff and Leedy 1990 [B123]). Another possible cause of attenuation would be the presence of low-impedance components (load equipment or SPDs), which, combined with the high-frequency impedance of the wiring, might produce an attenuation at the far end of a branch circuit. However, such an attenuation should not be taken for granted and, therefore, a conservative and realistic view should consider that the parameters of **voltage** surges are not significantly changed with the location within the building, as shown in Figure 9. In contrast, the propagation of **current** surges in an installation is affected by the impedance it encounters along its path, which is one of the reasons that led to the concept of location categories.

- a) **Current surges.** Because there are so few published results of surge current recordings (Odenberg and Braskich 1985 [B84]; Standler 1989 [B94]), the data on what currents might be expected to be are mostly the product of inferences from successful field experience of equipment, SPDs in particular, that were designed for specific current stress levels. These are the “classical” surge currents defined in various SPD-oriented standards, in particular the 8/20 μs short-circuit part of the Combination Wave and the short-circuit current of the 100 kHz Ring Wave. (See IEEE Std C62.41.2-2002 for a complete definition of these waveforms.) Interest in making recordings of available surge currents, while acknowledged (Martzloff 1996 [B157]), has not yet resulted in a sufficiently broad database to derive “representative” values. Instead, the companion recommended practice will draw on the “classical” current waveforms.
- b) **Voltage surges.** Because the historical development of surge measurements focused on recording voltages rather than current, there is a fairly well developed body of data, which is summarized in 6.6.1 through 6.6.6 for the following topics:
 - Voltage peak amplitude versus rate of occurrence;
 - Voltage surge duration;
 - Ringing frequency;

- Rate of voltage change;
- Energy-delivery capability;
- Effects of location, loads, and mode of coupling.

6.6.1 Voltage peak amplitude versus rate of occurrence

As discussed in 5.4, a record of voltage levels is no longer an indication of the level of actual threat to equipment. Nevertheless, this now historical information is still useful in providing a perspective on the relationship between severity and rate of occurrence of surge events.

The peak amplitude of voltage surges versus occurrence of surges depends on the type of service and on the location where the measurements were made (AIEE Committee Report 1961 [B46]; Rhoades 1979 [B197]). Overhead low-voltage distribution lines usually experience the highest surge amplitudes (5 kV to 20 kV, limited by SPDs or by flashover of the insulation system), whereas surge amplitudes within a building can be limited by flashover of clearances (IEC 664-1980 [B6]; Mansoor and Martzloff 1997 [B115]) or by the propagation characteristics of the wiring system (Martzloff 1990 [B124]). Seasonal and time-of-day variations can also affect the occurrence (Allen and Segall 1974 [B47]). Most high-amplitude surges are caused by lightning, so that geographic location and time of the year affect the rate of occurrence (Martzloff and Hahn 1970 [B78]; Haruki et al. 1989 [B72]). However, these published site surveys contain few occurrences specifically identified as lightning-related (Lenz 1964 [B76]). It should also be noted that the external origin of lightning surges produces surges that are independent of the system voltage (clearance flashover levels are not very different for wiring devices rated for 120 V or 480 V). In contrast, switching surges reflect the operating voltage of the system. Consequently, survey results that do not differentiate the origin—and few do—contain a mixture of absolute values (lightning) and relative values (switching).

As an example of survey results, Figure 11 shows an average number of occurrences per year from several sites. Note, however, that these recordings were all made before the proliferation of SPDs in low-voltage circuits, as mentioned in 6.4. As expected, the number of events decreases for higher peaks. Observe that from 100 V to 400 V, the events almost follow a V^{-4} slope, then a lower and almost linear rate (V^{-1}) from 400 V to 1200 V, and finally above 1200 V, the events follow a V^{-2} slope. Furthermore, plotting the frequency of occurrence versus peak values from many surveys yields the remarkable result of comparable slopes, but different specific numbers of occurrences. This relationship has been elevated to the status of “third power law” in some publications (Pfeiffer and Gräf 1994 [B134]; IEC 62066:2002 [B11]).

In conclusion, all events from early to late surveys show that the number of voltage surge events decreases with increasing crest voltage, at the power of V^{-a} , where a varies from 1 to 4. From the lines of Figure 11, the relationship is typically

$$N = V^{-3}$$

where

N is the relative number of surges.

Thus, a probabilistic analysis is required to determine the expected crest amplitude for a specific location, and the decision to provide a specific level of equipment immunity and margin can only be made on a risk analysis tradeoff, which neither this guide nor its companion, IEEE Std C62.41.2-2002, can undertake because such a risk analysis is the prerogative and responsibility of equipment manufacturers and purchasers, according to their immunity requirement for a given mission.

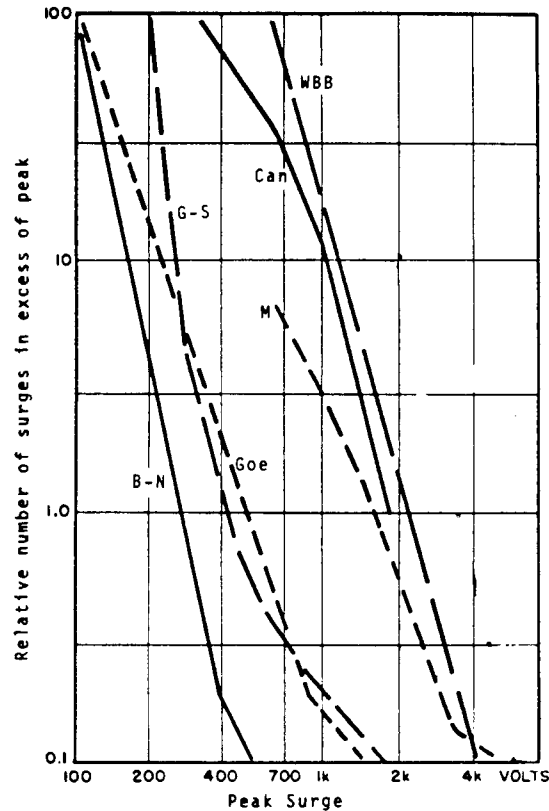


Figure 11—Comparison of the slopes of the frequency of occurrence versus peaks of the voltage surges among different surveys

6.6.2 Voltage surge duration

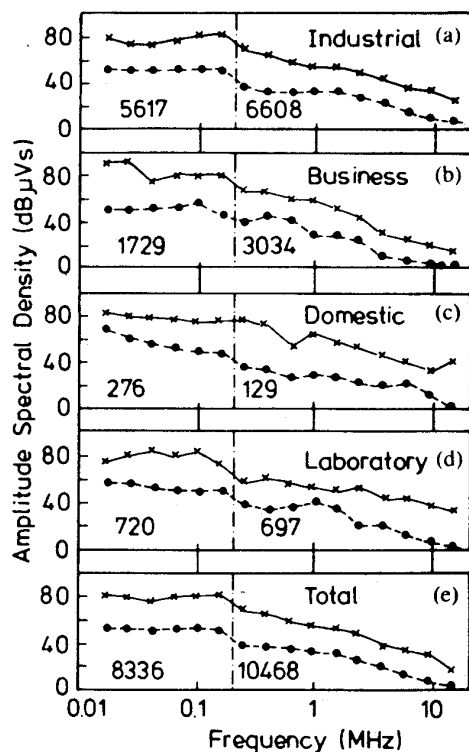
Surveys that report complete voltage waveform recordings show a wide range of durations, ranging from a fraction of a microsecond (Wernström et al. 1984 [B96]) to a few milliseconds (Meissen 1983 [B81]) for unidirectional or quasi-unidirectional waveforms. Oscillatory waveforms, with ringing frequencies discussed in 6.6.3, have been observed with durations of one or two cycles to about ten cycles of the ringing frequency. Examples of these durations are given in A.1.

6.6.3 Ringing frequency

The ringing frequencies cited in surveys cover the range of relatively low frequencies, a fraction of a kilohertz, up to one megahertz. The lower frequencies result from capacitor bank switching transients, while the higher frequencies are the result of the natural oscillation of local circuit elements or of multiple reflections in a wiring system of limited dimensions (Standler 1989 [B203]). Figure 12 shows one example of report from a survey, expressed in *amplitude spectral density*.

6.6.4 Voltage rate of change

Some surveys have presented the results in the form of statistical distributions relating rate of rise (dv/dt) to other parameters of the surges. Typical data for sites without lightning transients are shown in Figure 13. In that figure, the upper limits of the rate of change are above 100 V/ns, even at low peak voltages such as 500 V. This form of data presentation will be helpful to designers of circuits sensitive to coupled disturbances, but the present database is still limited.



NOTES

1—For each site, the number of reported events is shown below and above a 200 kHz boundary in the frequency scale and spectral density (Standler 1989 [B203]).

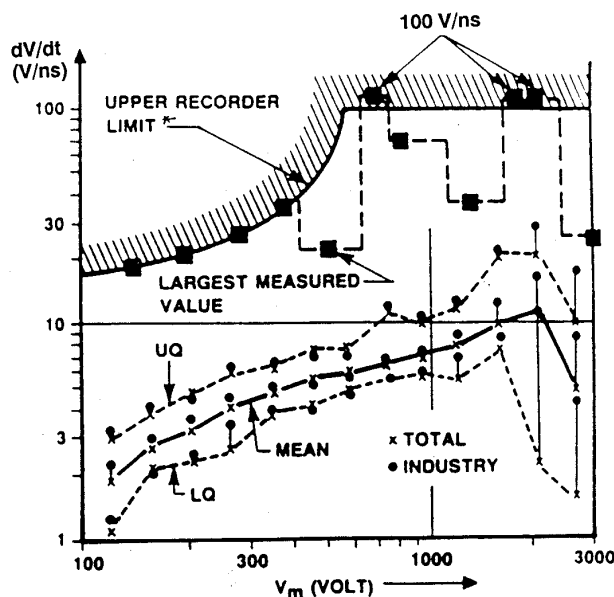
2—When many surges and sites are combined, such as in this figure, the result is a broad and declining distribution.

3—Therefore, a distinction should be made between single events, as they impact a specific piece of equipment having specific frequency response, and the composite result shown in this figure.

4—Individual surges and individual sites of specific Ring Wave frequency produce a peaked distribution of amplitude

Upper lines: 99.8%
Lower lines: 50% (mean)
(for 3 sigma levels)

Figure 12—Amplitude spectral density at four sites



NOTE—Upper limits of the rate of change shown in this graph were added to the original data from Goedbloed 1987 [B67]. The recorder did not always measure the value of the maximum value of dv/dt .

Figure 13—Statistical evaluation of recorded dv/dt data, as a function of the maximum transient amplitude

6.6.5 Energy-delivery capability

Some surveys have addressed the issue of energy-delivery capability in various manners. The significant parameter is not the “energy contained in the surge,” but the actual energy that can be deposited in a surge-absorbing device. One survey author (Goedbloed 1987 [B67]) proposed an “energy measure” parameter, defined as the product of the voltage squared by the time duration of the voltage. That approach is justifiable for a resistive load, where the power dissipated in the resistor is V^2/R . For a nonlinear SPD, the relationship is not so simple. Furthermore, the concept of recording the “energy measure” may promote the arbitrary reporting of “surge energy” by assuming a value for the impedance and then quoting results in joules—a misleading statement.

While there is definite merit in an attempt to describe the capability of a surge for delivering energy to circuit components, readers should realize that “energy” reports have to be evaluated with a clear understanding of the underlying assumptions. The “energy in the surge” cannot be determined from measurements of voltage alone (Standler 1989 [B174]; Lindes et al. 1997 [B154]). As progress continues in the development of power-system disturbance monitors, the database could be expanded by making appropriate measurements of the surge current diverted by generic SPDs installed at the point of monitoring (Martzloff 1985, in discussion of Odenberg and Braskich 1985 [B84]; Standler 1987 [B170]; Martzloff 1996 [B157]).

A distinction should be made between surges of high amplitude with short duration and surges of high amplitude with long duration. The former have the potential of upsetting equipment operation, but involve little energy, while the latter have the potential for high levels of energy deposition.

6.6.6 Effects of location, loads, and mode of coupling

Surge voltage recording results can be affected by the location of the disturbance monitor within a building, because changes in the loads will affect the response of a system to impinging surges. The mode of coupling is important and, as noted in 6.2, has not been well defined in the earlier surveys. In addition to the issue of citing results as L-L, L-N, L-G, or N-G voltage measurements, another issue that has not been addressed is that of voltage differences appearing between the power-system conductors and conductors from other systems, such as a communication system, a control system, or even building steel. Voltage differences between systems can occur during power-system faults and lightning discharges; the present database does not recognize these. See B.22 for a more comprehensive discussion of utilities interconnections and interactions.

6.6.7 Surge current amplitude and duration

Very few surveys report surge current measurements; those that did had a narrow database from which it would be difficult to draw general conclusions (Odenberg and Braskich 1985 [B84]; Standler 1987 [B170]). Instead, according to the philosophy that successful field experience of equipment that passes a given surge current test provides an indirect validation of the selected test parameter, the “standard” surge waveforms can be offered as representing a stress that is realistic. This philosophy is another application of the concept that field failure experience provides information on the surge environment.

a) *The standard surge current waveforms*

- There is a long experience in the application of an 8/20 μ s current test to SPDs in the high-voltage arena, and in 1980, this current waveform was introduced in IEEE Std 587-1980 in combination with a 1.2/50 μ s voltage waveform, under the designation of “Combination Wave.” The detailed rationale for the combination is given in IEEE Std C62.41.2-2002.
- In recognition of the fact that most waveforms recorded in low-voltage installations were oscillatory, a 100 kHz Ring Wave was also introduced in IEEE Std 587-1980.

Both these waveforms have been broadly accepted by other standards-writing bodies and by industry, and while initially presented as a guide (IEEE Std 587-1980), they were later elevated to the status of recommended practice (IEEE Std C62.41-1991).

- b) **Additional waveforms.** The menu of waveforms proposed in the 1991 version of this guide (IEEE Std C62.41) included three “additional waveforms” in recognition of proposals made by other standards or research results (see A.1). Only one of these, the 10/1000 μ s Long Wave, specifically addressed both voltage and current waveforms. More information on additional waveforms can be found in the companion recommended practice, IEEE Std C62.41.2-2002. Subclause A.1.2.5 reports results of fast transients being induced into building wiring by lightning events occurring outside of the building.

6.6.8 Frequency of occurrence and exposure

As shown in Figure 11, the results of many of the early surveys were summarized as a plot of frequency of occurrence as a function of (voltage) surge peak. The intention was to place the phenomena in perspective and eventually allow equipment designers to make a risk analysis on the levels of immunity they would use as acceptable targets. As discussed above, this type of statistic can no longer be compiled from recent surveys because of the proliferation of SPDs and switch-mode power supplies. Nevertheless, a plot of the potential severity of surges and their associated frequency of occurrence is still a useful description of the surge environment.

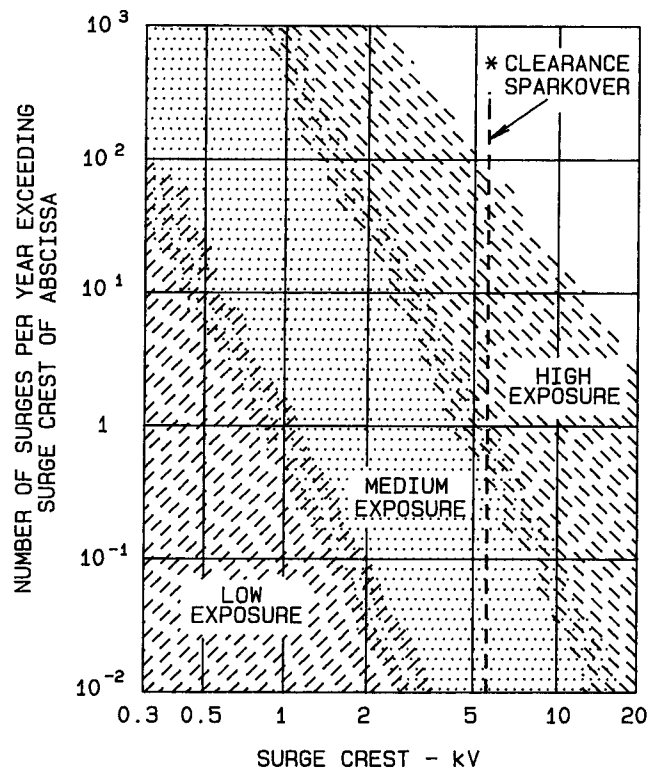
Another factor in the risk assessment is the exposure of the circuit, reflecting regional characteristics (lightning flash density) as well as power system conditions [frequency and intensity of switching surges, nature of the power distribution system (PDS) such as overhead open lines, overhead twisted lines, cables, and grounding practices] that will also influence the level of these surges. The frequency of occurrence and level of load-switching surges depend on the nature and impedance of the adjacent loads being switched, as well as their electrical distance from the point of interest (see surge impedance and source impedance in B.17), rather than the geographic situation or the utility practice.

All of these factors can be integrated in a qualitative description of “exposure,” which was offered in the 1991 version of this guide (IEEE Std C62.41), as follows:

- **Low exposure.** Systems in geographical areas known for low lightning activity with little load or capacitor switching activity.
- **Medium exposure.** Systems in geographical areas known for medium to high lightning activity or with significant switching transients. Both or only one of these causes may be present, as it is difficult to separate them in reviewing the results of monitoring disturbances.
- **High exposure.** The rare installations that have greater surge exposures than those defined by low exposure and medium exposure. The more severe conditions result from extensive exposure to lightning or unusually severe switching surges. The high-exposure level needs to be recognized, but it should not be indiscriminately applied to all systems. Such general application would penalize the majority of installations, where the exposure is lower.

The concepts of exposure level and the relative frequency of occurrence as a function of voltage have been combined in the plot of Figure 14. It is important to note that this plot is by now historical data because it represents the **peak voltages at unprotected locations**, and unprotected locations are now rare. As an indicator of surge environment severity, it is useful as a qualitative description; in particular the boundaries of exposure levels are now shown as fuzzy, in contrast with the initial plot of the 1980 version of this guide where fine lines separating the ranges of exposure were sometimes taken as a reference for a quantitative specification.

Thus, the exposure levels shown in Figure 14 cover a wide range of situations and represent relative rather than absolute levels. The sparkover of wiring devices indicates that while a 6 kV withstand capability might be enough to ensure device survival indoors, a withstand capability of 10 kV or greater might be required outdoors. This limitation effect has sometimes been misconstrued as the basis for stating that surges up to 6 kV do occur (frequently) in low-voltage ac power circuits. The real meaning is that surges in excess of 6 kV are unlikely to be found (at unprotected locations), which indeed is not to say that 6 kV is a typical occurrence.



NOTES

1—In some locations, sparkover of clearances can limit overvoltages (dashed line at 6 kV).

2—This figure shows peak voltage as a measure of surge severity.

3—Other possible measures include peak current, rise time, and energy transfer.

Figure 14—Rate of surge occurrences versus voltage level at *unprotected* locations

6.7 Surge characteristics in Scenario II

There are few if any published data on measured surge currents flowing in the many paths of the grounding system of a building, during a direct lightning flash to the structure. One reason for this lack of specific or generic information is the difficulty of inserting a current-sensing probe in all possible paths during the dispersion of the lightning current, once it has involved a building in a direct strike. Two reports commissioned by ELECTRA of measurements made directly of the lightning current itself, not of the dispersion among the available paths, have been widely used in defining lightning parameters (Berger et al. 1975 [B54]; Anderson and Eriksson 1980 [B48]). Parameters such as those shown in Figure 15 and Figure 16 were derived from the ELECTRA papers. It is important to note that these measurements of total stroke currents are not the measurement of current or charge transfer in the wiring of low-voltage power systems.

A less widely distributed statistic from the same ELECTRA papers is shown in Figure 17, where some information can be gleaned on the impulse duration, although the authors make it clear that these waveforms are drawn from a limited number of recordings.

Another source of data is provided by the lightning detection network where peak amplitudes, but not waveforms, are reported, computed from the electromagnetic fields detected by the network (Cummins et al. 1998 [B61]). An example of the statistics from that database for southeastern United States is shown in A.1.2.4.

A study of the characteristics of lightning surges on distribution systems (Barker et al. 1993 [B51]) provides statistics for the medium-voltage system, from which inferences may be made by assuming that the values recorded on the distribution lines (through a modified arrester serving as a transducer) can represent the values that would have occurred for a direct flash to a building.

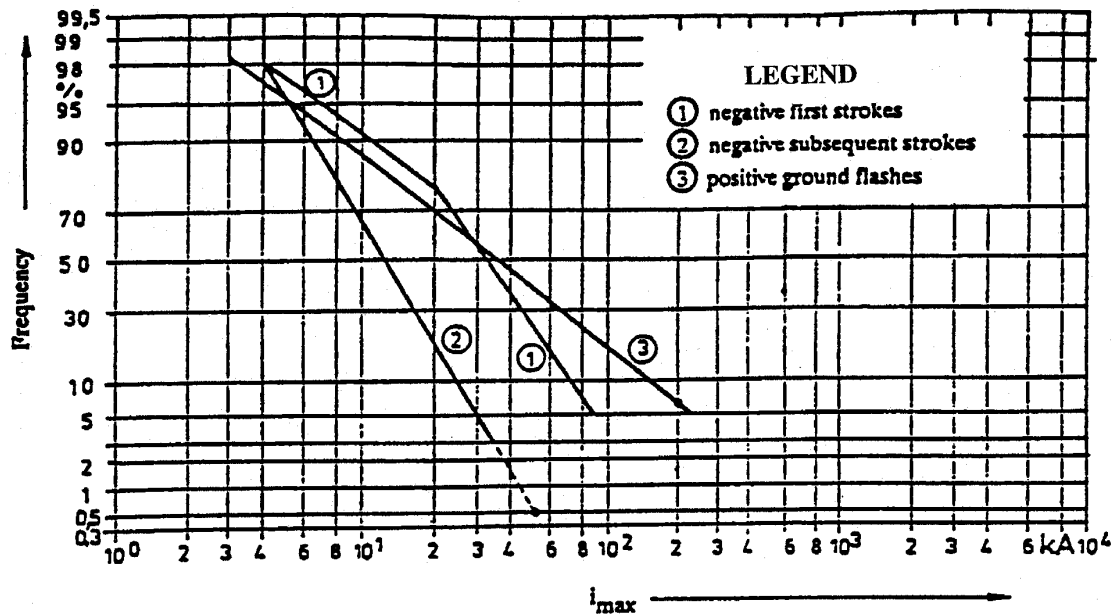


Figure 15—Frequency distribution of peak currents for three types of lightning events

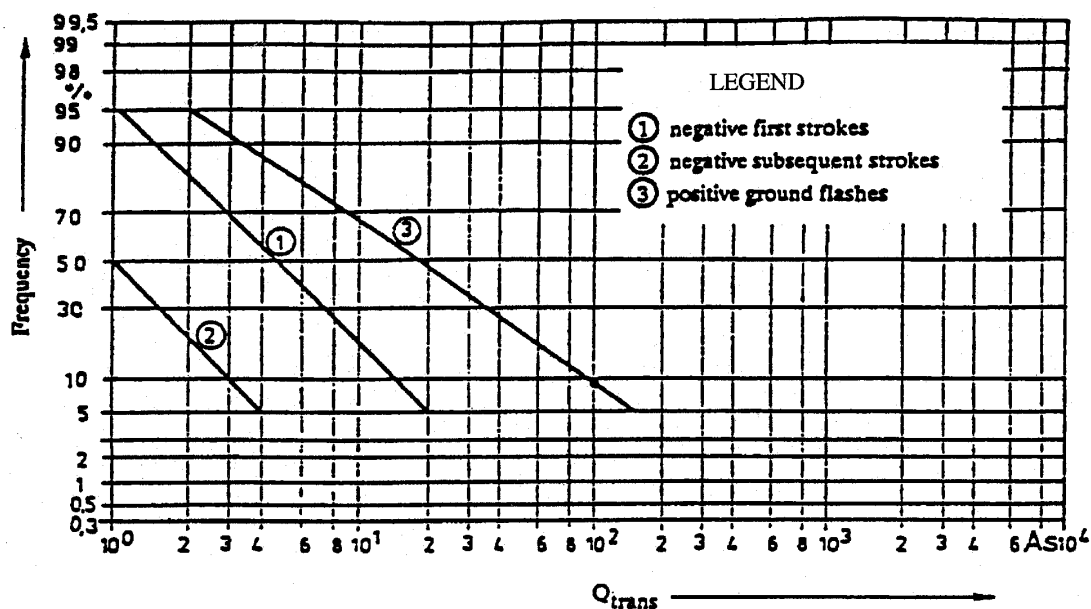


Figure 16—Frequency distribution of the transient lightning charge Q_{trans}

To obtain some information on the surge currents in the ac power circuits within a building that might occur during a direct strike, researchers have resorted to numerical simulations by postulating the impedances involved (resistance as well as inductance) and the lightning stroke parameters. The simulations of the dispersion are performed using numerical methods such as PSPICE (Birkel et al. 1996 [B97]) or EMTP (Mansoor and Martzloff 1998 [B116]). Subclause A.2.2 shows two examples of such simulations. It should be noted, however, that the results of these simulations might be affected by the nonlinearity of the earthing electrodes impedance, which is generally not included in the simulations (Mata et al. 1998 [B129]).

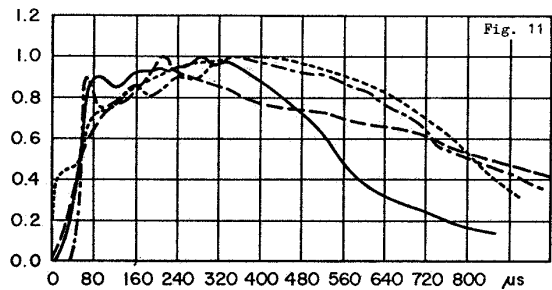


Figure 11
Formes de courant typiques – Impulsions positives
Typical current shapes – positive strokes

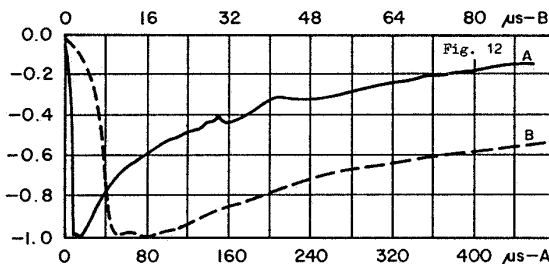


Figure 12
Forme de courant moyenne Premières impulsions négatives
A – échelle des temps inférieure B – échelle des temps supérieure
Mean current shape Negative first strokes
A – lower time scale B – upper time scale

Source: Berger et al. 1975 [B54]

Figure 17—Example of lightning current waveforms

7. TOVs

7.1 General

A wide range of phenomena, either resulting from normal system operation or from accidental conditions can produce TOVs, which should be distinguished from the switching surges discussed in 4.3. These overvoltages occur at the power system frequency and generally require operation of some existing protective overcurrent equipment to clear the circuit, should some equipment fail under that stress. Note, however, that equipment is generally designed to withstand TOV stresses. SPDs at the present state of technology—as applied for protection against lightning and switching surges—do not have the energy-handling capability that would be required for limiting these TOVs. Therefore, the following information on TOVs (which might be considered as being outside of the scope of this guide) is presented for consideration in the application of SPDs, a topic addressed in other documents of the IEEE Std C62™ series.

7.2 Magnitude of TOVs due to medium-voltage and low-voltage faults

TOVs can appear in a system following a fault condition. They are, in general, originated by insulation faults or loss of a supply conductor in the medium-voltage or low-voltage electrical installation. Product standards take into account these phenomena by appropriate insulation requirements and tests. IEC 60364-4-442:1999 [B5] provides some information and data, which are summarized here. Additional information is also given in B.9.

NOTE—In systems with medium-voltage and low-voltage lines mounted on the same poles, or systems with two different medium-voltage levels also mounted on the same poles, accidental commingling of the systems can occur, causing substantial overvoltages on the low-voltage system. In the application of SPDs to low-voltage systems, consideration of commingling is generally not included because such accidents are rare. However, if such exceptional events are to be considered, special SPDs need to be applied to survive the event or at least fail in an acceptable manner (Goedde et al. 1999 [B211]).

7.2.1 TOVs due to faults between medium voltage and ground

Depending on the configuration of the grounding of the medium-voltage and low-voltage networks, the medium-voltage fault current flows into one or more ground electrodes and generates ac overvoltages in the low-voltage system by ground coupling.

The main parameters that influence the value and the duration of the overvoltages are listed below. All of these are determined by the designers of the power system, rather than from SPD application considerations.

- a) The configuration of the ground electrodes of the medium-voltage and low-voltage network:
 - One, two, or three distinct ground electrodes
 - Common grounding electrodes or separated grounding electrodes for medium-voltage and low-voltage networks
 - The values and the number of ground electrodes of the low-voltage distribution system
- b) The type of system grounding of the medium-voltage network:
 - Isolated
 - Resonant-grounded
 - Grounded through an impedance
 - Solidly grounded
- c) The method used to clear the medium-voltage fault:
 - Long time for isolated resonant-grounded or impedance-grounded types
 - Short times (< 5 s) for low-impedance grounded types
 - Shorter time for solidly grounded types

TOVs appear at different places and apply in different ways:

- In the medium-voltage/low-voltage substation, the overvoltage stresses the insulation of the low-voltage equipment between live parts and exposed conductive parts if there is no common medium-voltage/low-voltage grounding.
- In multiple-grounded, four-wire systems the TOV that occurs on the medium-voltage side is transformer-coupled to the low-voltage side, resulting in L-L and L-N TOVs.
- In the low-voltage electrical installation, the overvoltage stresses the insulation of low-voltage equipment, between live parts and exposed conductive parts, if the neutral is not connected to the local grounding electrode.
- An overvoltage appears between the local ground of the low-voltage installation and remote ground. That overvoltage can stress, for example, the double insulation of Class II equipment used outside of a building or service entrance, which would not be connected to the main grounding terminal.

7.2.2 TOVs due to a short circuit between line and neutral conductors

After the transient situation, the magnitude of the short-circuit current is limited only by the impedances of the supply and building wiring. The currents involved can be very high, ranging between one hundred and tens of thousands of amperes. A protective device operates to clear the fault. During this period of a few milliseconds to a few hundred milliseconds (but in all cases less than 5 s), a TOV can occur in the unfaulted lines of the affected power circuit. The value of the overvoltage can be calculated from the impedances of the supply and building wiring. The value of $1.45 U_0$ (U_0 being the phase-to-neutral voltage) is considered to be a representative upper limit (see IEC 60364-4-442:1999 [B5]).

7.2.3 TOVs due to low-voltage ground faults

After the transient situation, a TOV occurs during such a fault. In power systems generally used in North America, specifically, TN systems (see B.9 for a description of the IEC codes IT, TT, and TN), ground faults can produce overvoltages comparable to those occurring in circuits where the fault is between phase and neutral. Indeed, the return path to the neutral of the transformer consists of a cross-section comparable to that of the phase conductors.

7.2.4 TOVs due to the loss of a live conductor

In three-phase systems, loss of any conductor can give rise to various conditions, such as unbalance, faults, and TOVs, which can indirectly result in transients. For example, loss of a neutral conductor in an unbalanced star-connected supply can result in a TOV where two phases attain the phase-to-phase voltage with respect to ground. This can cause a fault and possible transients associated with initiation or clearing of the fault. In that case, it is generally considered that the permanent stress voltage is the line-to-line voltage.

7.3 Probability of occurrence

7.3.1 TOVs due to faults between medium voltage and ground

Medium-voltage ac insulation faults to ground are likely to occur on overhead medium-voltage lines during thunderstorms or due to other incidents. When lightning strikes the medium-voltage system, operation of an SPD located on the medium-voltage side initiates a current flow through the corresponding ground electrode. In some existing networks, SPDs might still be of the air-gap type, and the surge current starts the flow of a medium-voltage fault current at the power frequency, which is not interrupted at the first zero crossing. The same chain of events unfolds in case of an insulator flashover. Medium-voltage system configurations are well-defined so that their ground-fault currents can be predicted by calculation even though they vary depending on the location of the ground fault.

If SPDs are installed on the medium-voltage side, close to a medium-voltage/low-voltage substation, they normally decrease the number of ground faults. The current flow through the SPD to ground is restricted to a short surge if the surge arrester is of the metal-oxide type. In case of gapped arresters, a short-duration ac current follows. In case of gaps alone, an ac follow-current occurs, to be cleared by the medium-voltage protective devices after a duration that depends on the type of device used.

Finally, the immunity specification of an item that is likely to be subjected to TOVs depends on its mode of application. An SPD, for instance, is permanently energized, whereas, at the lower end of the severity scale, a portable tool is connected to the low-voltage system only for a very short fraction of its life time; in the latter case, the probability of coincidence with a medium-voltage ground fault in the substation is then extremely low and the immunity specification is likely to be correspondingly low.

7.3.2 TOVs due to faults in the low-voltage installation

The likelihood of low-voltage insulation faults cannot be neglected in normal installations. The possibilities of faulted conditions increase in older installations and equipment that are not properly maintained or are exposed to hazardous or polluted environments. Generally, insulation faults are more likely to occur between active conductors and grounded conductive parts than between the active conductors considered hereafter. The effects of these ground faults (voltage drops and in particular overvoltages) affect the SPDs. These effects are determined by the location of the fault and, in the case of a fault to ground in TT systems, the impedance to earth of the ground electrodes.

If the SPD has been selected with a maximum continuous operating voltage (MCOV) lower than the overvoltage generated by the low-voltage insulation failures or the loss of a supply conductor, the current flowing through the SPD increases very quickly and thermal destruction of the SPD occurs. The effects of this failure might be limited to the SPD if appropriate coordinated thermal protection is incorporated. This SPD failure can then leave the installation or equipment without other overvoltage protection.

For the remaining cases, when the possibility of a loss of surge protection is deemed acceptable, other risks have to remain covered; in particular, an appropriate protection against short-circuits should be specified by the manufacturer and requested by the end-user.

Concerning the loss of the neutral conductor, the overvoltage is independent of the grounding system, but can reach values close to three times the phase to phase voltage in a three-phase system, applied between line conductors. The overvoltage can reach twice the phase-to-phase voltage in a single-phase, three-wire system whenever the loads in each side of the neutral are not balanced; this overvoltage is then applied across an SPD intended for surge protection of loads connected line to neutral. In the case of the loss of the neutral conductor, damage to the SPDs might be a small event in comparison with the damages suffered by other equipment in the installation, as long as the SPD failure occurs in an acceptable mode, for instance, by appropriate thermal protection.

7.4 TOVs' impact on SPDs

TOVs are a type of abnormal event that is difficult to prevent—if not impossible—in the normal course of operation of a power system. The probability of such occurrence and the levels of overvoltages that can be reached depend on the design of the power system. This design is generally determined by overriding system constraints other than the consequences of applying a TOV to an SPD.

Therefore, SPDs have to suffer the consequences of a TOV, and various scenarios are possible, ranging from an SPD selected with a high MCOV that will make it immune to most TOVs (but at the price of diminished surge protection) down to a low MCOV selected by a wish to provide surge protection with low limiting voltage for loads perceived as needing such low limiting voltage, but at a greater risk of destruction under TOVs (Martzloff and Leedy 1989 [B219]).

8. Development of recommended selection of representative surges

The database summarized in Clause 6, along with anecdotal information, illustrates the wide variety of surges that can be expected to occur in low-voltage ac power systems. Evaluation of the ability of equipment to withstand these surges, or of the performance of SPDs in dealing with this variety of surges, can be facilitated by a reduction of the database to a few representative stresses. It is unnecessary and not cost-effective to subject equipment to surges that would duplicate field-measured surges, since these measurements are site dependent and are likely to change with time.

The reduction process should lead to selecting a few representative surges that will make subsequent laboratory tests uniform, meaningful, and reproducible. Since the environment is subject to change both for the better and the worse, it would be prudent to use these representative surges as a baseline environment. However, this simplification should not bar any user from performing evaluations for different surge environment conditions if knowledge is available for a particular environment (over a sufficient period of time, such as one or more years) and the requirements warrant the cost and effort of additional tests.

A combination in the selection of location category and exposure level, as proposed in this guide and further defined in the companion recommended practice IEEE Std C62.41.2-2002, will then provide the appropriate degree of compromise between a conservative overdesign and a cost-conscious reduction of margins.

To assist equipment designers and users in making appropriate choices, a companion recommended practice, IEEE Std C62.41.2-2002, IEEE Recommended Practice on Characterization of Surges in Low-Voltage AC Power Circuits, has been developed on the basis of the surge environment described in this guide. A second companion recommended practice, IEEE Std C62.45-2002, IEEE Recommended Practice on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits, has also been developed to provide recommendations for performing surge tests that yield reliable results and enhance operator safety.

Annex A

(informative)

Detailed database

This informative annex provides detailed information in support of the summary presented in Clause 6. The view that “database” means only the results from recordings of surge events would be too narrow. Useful information can be obtained on the surge environment from other sources, hence the four subclauses of this annex, as summarized below.

This database consists of a body of published and unpublished information contributed by many individuals or organizations. These contributions are gratefully acknowledged, and their sources are identified in the text or in footnotes.

- **A.1—Recorded events.** The events recorded in past surveys were characterized as “transient over-voltages” with emphasis on the voltage, because most available instruments, whether custom-made or commercial, could only record voltages, not the currents involved in surge events. As discussed in A.4, this limitation is expected to be alleviated in the future as new surveys are likely to include the current-delivery capability of the surge environment. Thus, the data presented in this subclause are a historical record, with the inference that the surge-generating mechanisms involved in producing these events still exist, albeit masked by the effect of the proliferation of surge-mitigating devices such as SPDs and the power supplies of new electronic appliances. In the first section, A.1.1, the data from recordings included in the 1991 version of this guide (IEEE Std C62.41) are reproduced verbatim. In the second section, A.1.2, new data published or made available (but still unpublished) since 1990 are summarized.
- **A.2—Experiments and computations.** Progress in simulation software has made possible increasingly sophisticated modeling of surge events, including their generation, propagation, dispersion, and eventual mitigation. While mitigation is not in the overall scope of this guide, some of the sources cited in this subclause include suggestions for mitigation after presenting results of the first three aspects of simulation. Laboratory experiments have also been conducted. Some of these were purely experimental, others were conducted in conjunction with numerical modeling, in effect validating each other. For the convenience of the reader, a summary of the papers and reports of such simulations or experiments is given in this subclause. Supporting details can be obtained from the original complete documents.
- **A.3—Inferences from field experience.** Documented statistics on field experience, successful application as well as case histories of equipment failures attributable to surges, provide data, even if merely anecdotal, that can suggest upper and lower boundaries for the range of surge occurrences. As cited in 6.5, a criterion of validity of a standard on the surge environment is the field experience of equipment designed to meet that standard. If the failure level of a category of equipment is known, absence of failure, relatively low rate of failure, or alarmingly high rate of failure for such equipment provides convincing evidence on the absence, low rate, or high rate of occurrence of surges above the corresponding failure level, an indirect reality check on what might be insufficient or excessive performance requirements.
- **A.4—Discussion of the database.** The database obtained by the various methods described in the first three subclauses of this annex merits examination and discussion to enhance its reliability and avoid erroneous conclusions that might be inferred from misinterpretation of the data or from some inherent but not obvious flaw in the measurements.

A.1 Recorded events

This first part of this informative annex includes three stages of recording surge events, as reports became available during the development of this guide, from the mid-1970s to the late 1990s. A first subsection includes the data collected in the 1970s and 1980s, as presented in the 1991 version of this guide (IEEE Std C62.41). The second subsection presents new data obtained during the 1990s, in particular those collected as part of “Power Quality Surveys”—an expanding activity among electric utilities, end-users, and consultants.

A.1.1 1990 database from the 1991 edition of this guide

Oscilloscope recordings and surge-counter data were contributed from several sources, in addition to the surge-counter data obtained by members of the working group. Representative oscillograms and summary statistics are reproduced in this subclause in support of the recommended levels and waveforms proposed in IEEE C62.41.2-2002. The early part of the database, until the mid-1980s, should be seen as representative of systems with few, if any, SPDs installed at those locations, because the proliferation of these devices had not yet started.

A.1.1.1 Recordings by Bell Telephone Laboratories⁸

Typical surge-counter statistics for a 120 V line at the Bell facility in Chester, NJ, during 42 months of monitoring were

146 counts at 300 V to 500 V
14 counts at 500 V to 1000 V
3 counts at 1000 V to 1500 V
3 counts above 1500 V

Oscillograms recorded at various locations of the Bell facilities are shown in Figure A.1

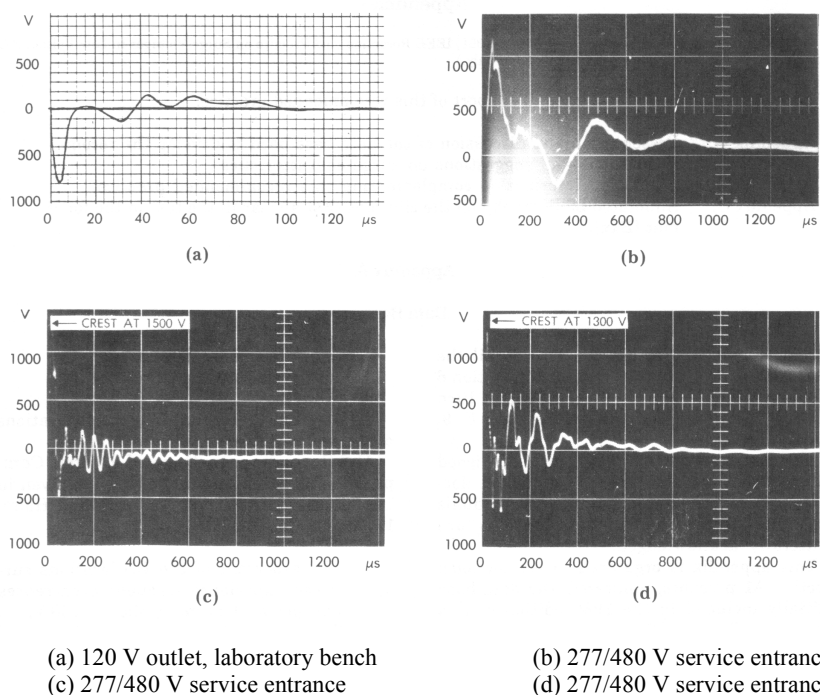


Figure A.1—Typical oscillograms from the Bell data

⁸Data contributed by P. M. Speranza.

A.1.1.2 Recordings by General Electric Company⁹

A simple peak voltage detector and counter was developed in the mid-1960s for deployment in the homes of General Electric engineers in several cities (Martzloff and Hahn 1970 [B78]). Oscilloscopes fitted with a motor-driven camera were deployed at a few locations where high surge activity was suspected. The surge-counter results are given in Table A.1 and Table A.2, and typical oscillograms are shown in Figure A.2.

Table A.1—Number of houses with repetitive surge activity above 1200 V

Location	Number of homes surveyed	Recording period (weeks)	Houses with repetitive surges
Providence, RI	4	2–6	None
Cleveland, OH	28	2–4	None
Auburn, NY	12	2–3	None
Lynchburg, VA	3	2–3	None
Syracuse, NY	8	1–2	1
Chicago, IL	23	1–6	None
Ashland, MA	24	1–2	1
Holland, MI	6	2–10	None
Louisville, KY	10	2–6	None
Somersworth, NH	50	1–2	1
Plainville, CT	5	10	None
Ashboro, NC	24	1–2	None
Fort Wayne, IN	38	1–4	1
DeKalb, IL	14	3–12	None

Table A.2—Surge-counter recordings above 1200 V (spring, summer, and fall)

Location	Number of homes	Total homes (weeks)	Number of surges
Providence, RI	6	60	1
Ashboro, NC	13	85	None
DeKalb, IL	11	60	2
Somersworth, NH	3	48	1
Chicago, IL	12	58	None
Cleveland, OH	8	106	1
Decatur, IL	12	72	2
Holland, MI	7	56	None
Auburn, NY	3	70	None
Springfield, PA	1	24	None
Ashland, MA	6	72	None
Pittsfield, MA	3	60	1
Plainville, CT	3	60	None
Lynchburg, VA	3	15	None
TOTAL	91	846	8 in 8 homes

Additional data from the General Electric investigation indicated that 3% of the US locations surveyed experience frequent occurrences (one per week or more) above 1200 V. An anecdote also reported that there is a 100:1 reduction in clock motor failures when their withstand level was raised from 2 kV to 6 kV.

⁹Data contributed by F. D. Martzloff.

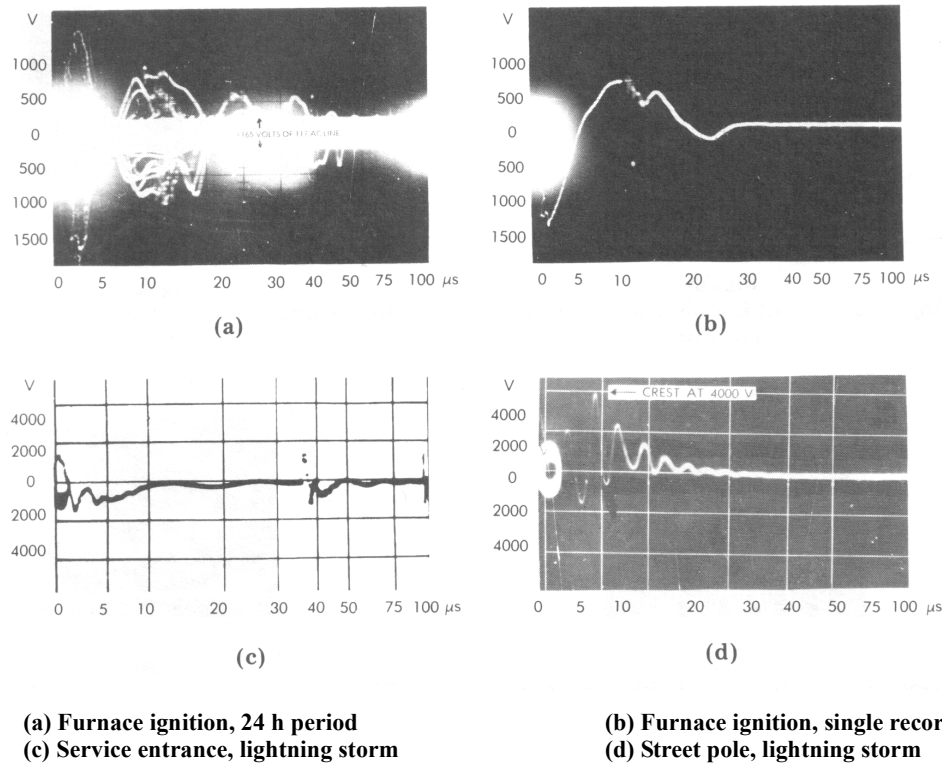


Figure A.2—Typical oscillograms from the General Electric data

From another experiment (Crouch and Martzloff 1978 [B99]; Martzloff and Crouch 1978 [B117]), simulated lightning strokes on a residential power circuit (laboratory model of a system) are shown in Figure A.3 through Figure A.6.

A 1.5 kA current impulse (approximately 8/20 μs) is injected in the ground wire only of a service drop (Figure A.3). Higher currents produce flashover of wiring. The open-circuit voltage at a branch circuit outlet during the 1.5 kA impulse was found to be 2200 V peak, 500 kHz oscillations (Figure A.4). By connecting a 130 Ω load at the same outlet (1 A load), the voltage is reduced to 1400 V peak, with more damping (Figure A.5). For a 30 kA injection (corresponding to an assumed 100 kA lightning strike on the distribution system), the discharge current passing through an arrester installed at the service entrance is 3.5 kA (Figure A.6).

The following conclusions can be drawn from this test series:

- A current of 1.5 kA (moderate for a lightning discharge injected into the ground system) raises the wiring system of the house 2.2 kV above ground. In the case of 4 kA (still a moderate value), this voltage would reach 6 kV, the typical sparkover value of this wiring.
- A discharge current level on the order of 3 kA can be expected in an arrester installed at the service entrance when a very high current, 30 kA, is injected into the ground wire.
- A natural frequency of 500 kHz is excited by a unidirectional impulse.
- In this example, the source of the transient, Z , (from the loading effect of 130 Ω) appears as

$$Z = 130\Omega \left[\frac{2200}{1400} - 1 \right] = 75\Omega$$

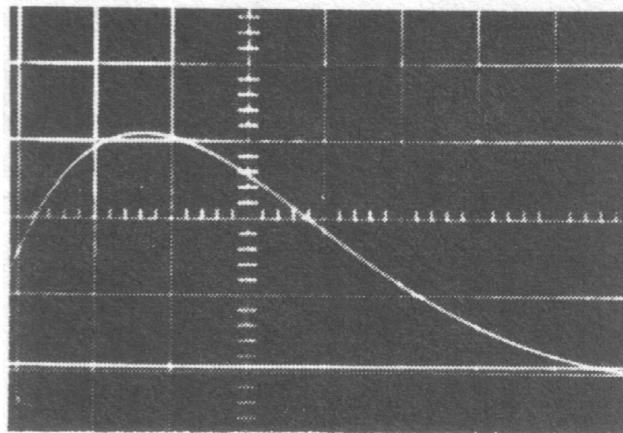


Figure A.3—Injected current: 500 A/div and 5 μ s/div

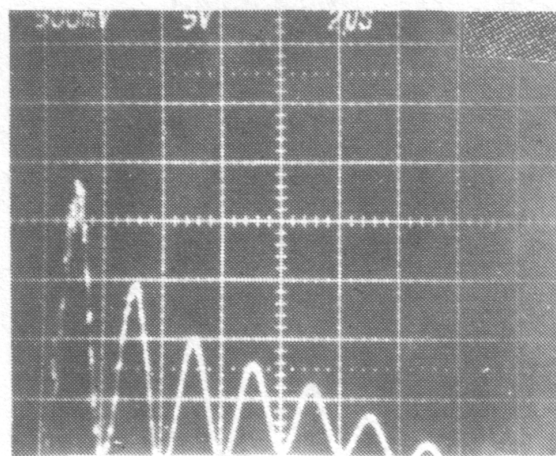


Figure A.4—Open-circuit: 500 V/div and 2 μ s/div

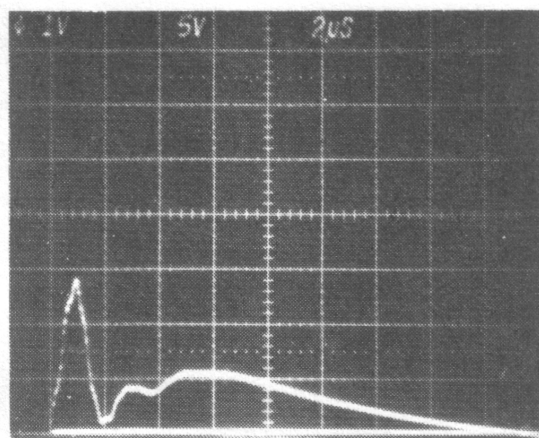


Figure A.5—Recording with 130 Ω load: 500 V/div and 2 μ s/div