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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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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 µs voltage waveform and 8/20 µs 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:

Hans Steinhoff, *Chair*
James Funke, *Co-Chair*
Raymond Hill, *Secretary*
François D. Martzloff, *Technical Editor*

Richard Bentinger
William Bush
Ernie Gallo
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Other individuals who contributed review and comments in developing this recommended practice are

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W. J. Zischank

The following members of the balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

Richard Bentinger
James Case
Chrys Chrysanthou
Bryan R. Cole
Bill Curry
Douglas C. Dawson
E. P. Dick
Clifford C. Erven
Ernie Gallo
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Mark S. Simon
Hans Steinhoff
Antony J. Surtees
Donald B. Turner
S. Frank Waterer
James W. Wilson
Jonathan J. Woodworth
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At the time this document was sent to ballot, the Accredited Standards Committee on Surge Arresters, C62, had the following members:

Joseph L. Keepfinger, *Chair*

S. Choinski, *Secretary*

Vacant, *NEMA Co-Secretary*

Naeem Ahmad, *IEEE Co-Secretary*

Organization Represented	*Name of Representative*
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	J. L. Koepfinger
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	J. J. Woodworth
Association of American Railroads (AARR)	W. Etter
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Canadian Standards	D. M. Smith
International Electrical Testing Association (NETA)	A. Peterson
	M. R. Jordan
NIST	F. D. Martzloff
Rural Electrication Administration (REA)	E. Cameron
Telecommunications Information Systems (TCIS)	C. Chrysanthou
Underwriters Laboratories	D. Jennings-Conner
Individuals	J. Osterhout
	S. G. Whisenant
	H. J. Steinhoff

When the IEEE-SA Standards Board approved this standard on 11 November 2002, it had the following membership:

Also included is the following nonvoting IEEE-SA Standards Board liaison:

Contents

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.

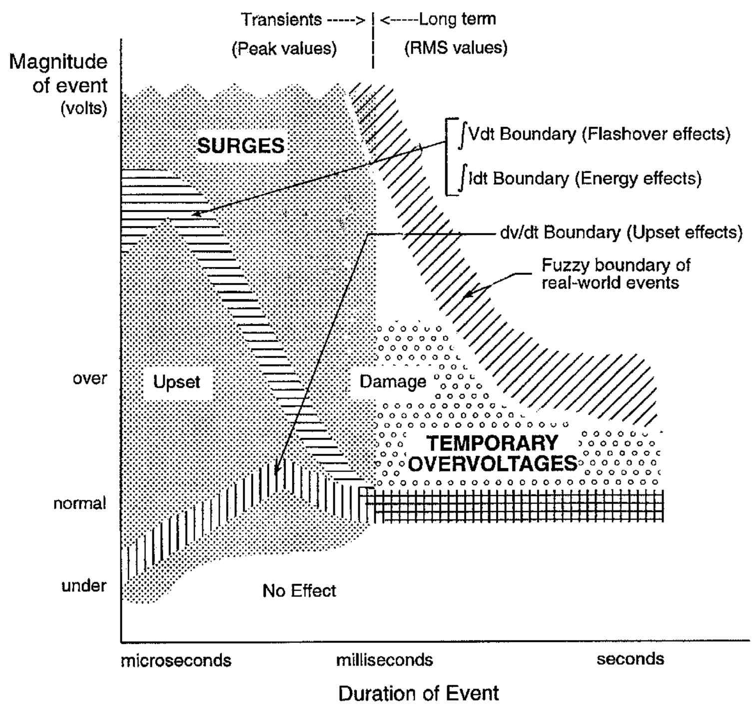
This guide also contains four informative annexes. Informative Annex A describes the results of surge measurements performed in the field, as well as the results of numerical simulations performed to supplement the recording of surge events. Useful inferences on the surge environment that can be drawn 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.

[1]Information 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.

[2]The IEEE standards or products referred to in Clause 2 are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.
[3]IEEE 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.

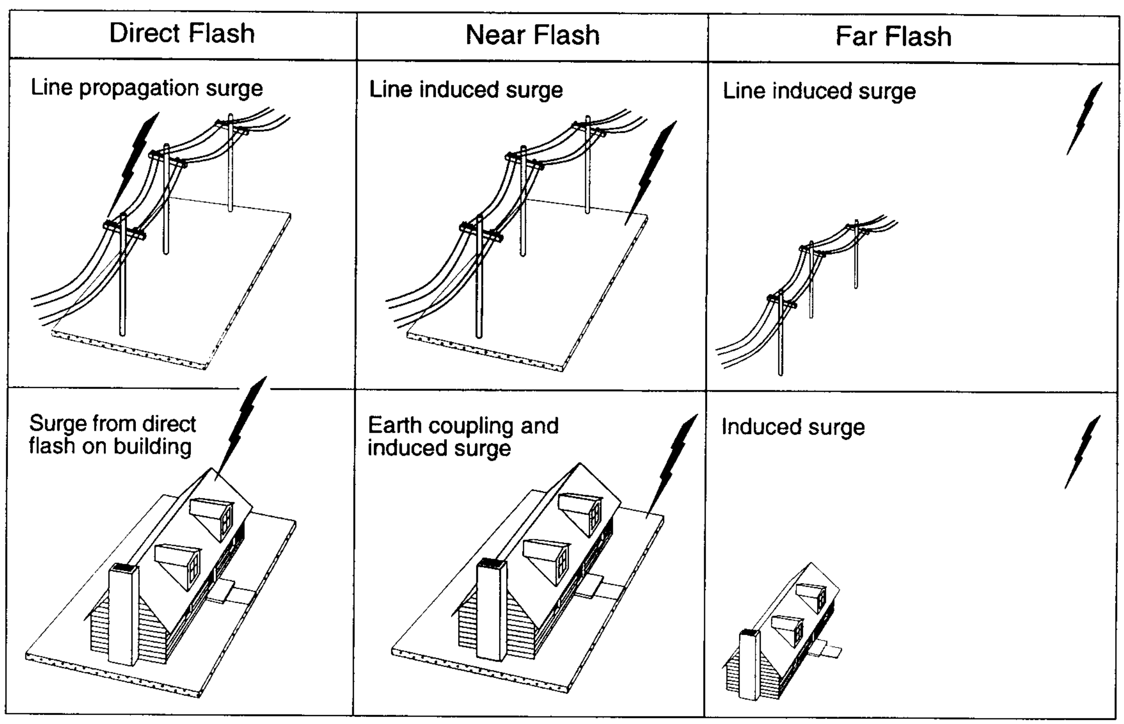


Figure 2—Examples of lightning flash coupling mechanisms

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.

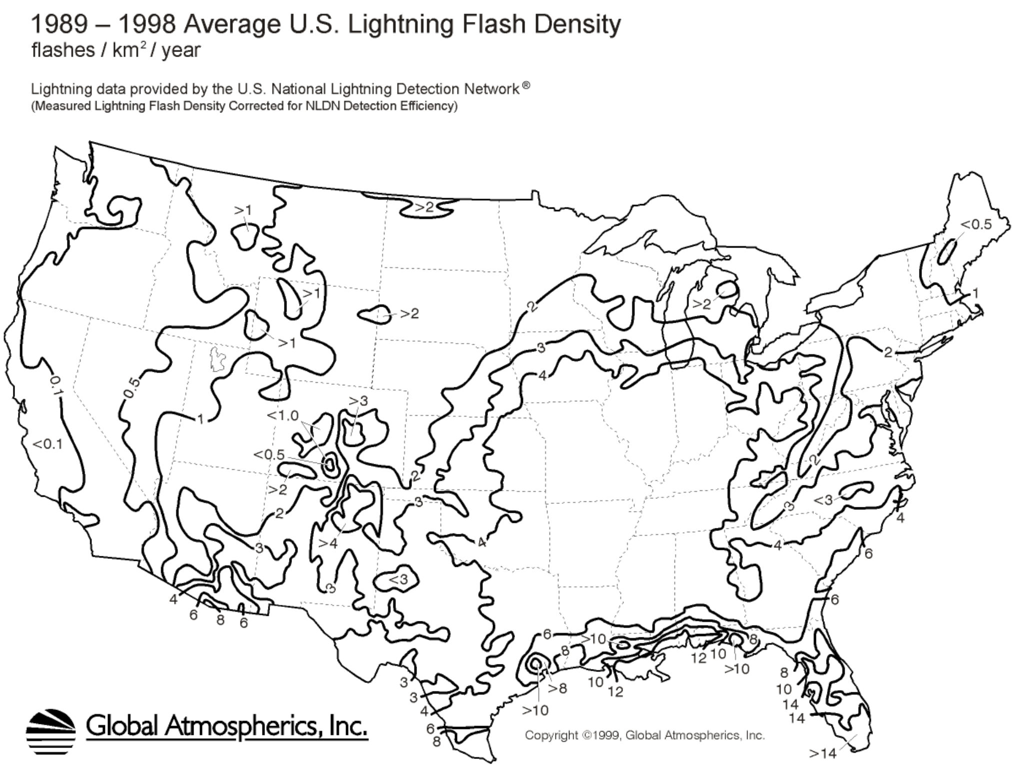
Table 1—Attributes and impact of lightning flashes

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



(Reproduced with permission)

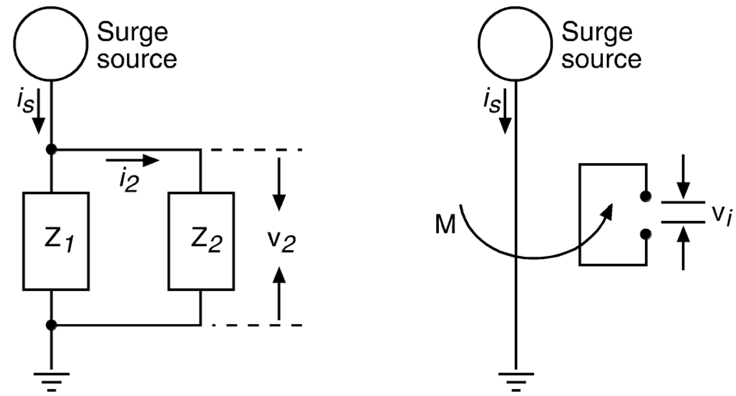
Figure 3—Typical flash density map for the United States

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.



If $Z_2 \cong Z_1$

$$i_2 = i_s \frac{Z_1}{Z_1 + Z_2}$$

If $Z_2 \gg Z_1$

$$v_2 \cong i_s \times Z_1$$

a) Direct coupling

$$v_i = M \times di_s / dt$$

b) Indirect (inductive) coupling

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.

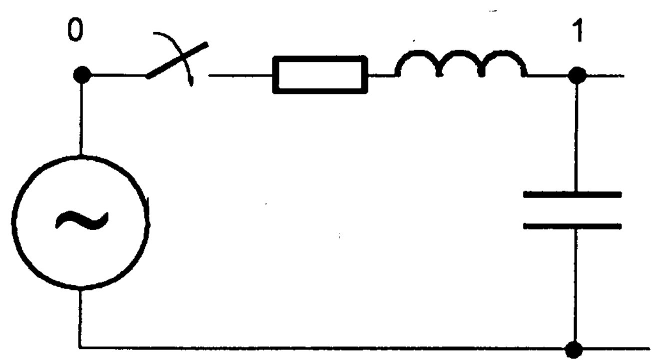
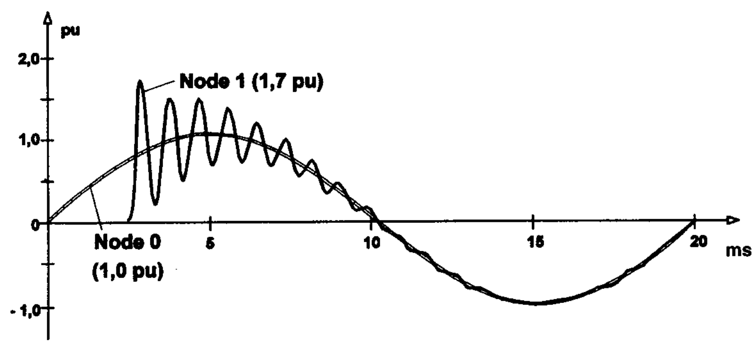
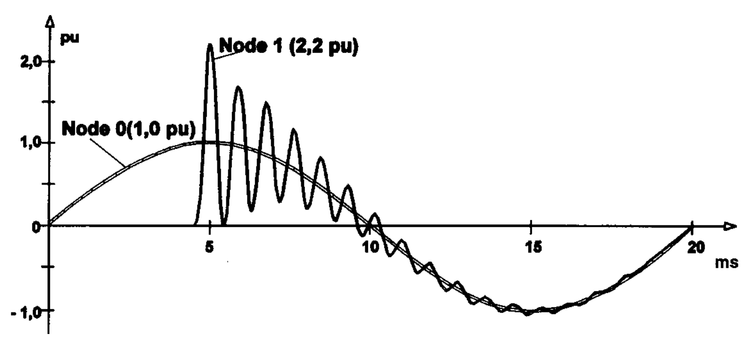


Figure 5—Generation of overvoltage by switching an RLC circuit



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 µs 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.

[4]An 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.

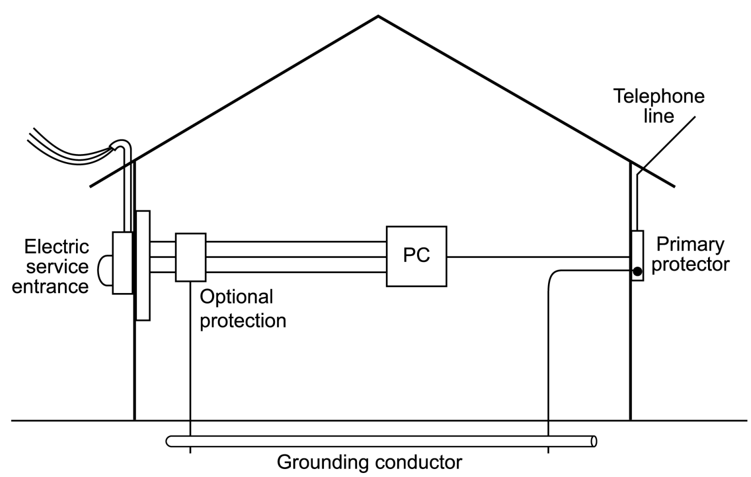


Figure 7—Scenario for interaction between power and telephone systems

[5]National 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 years[7] (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.

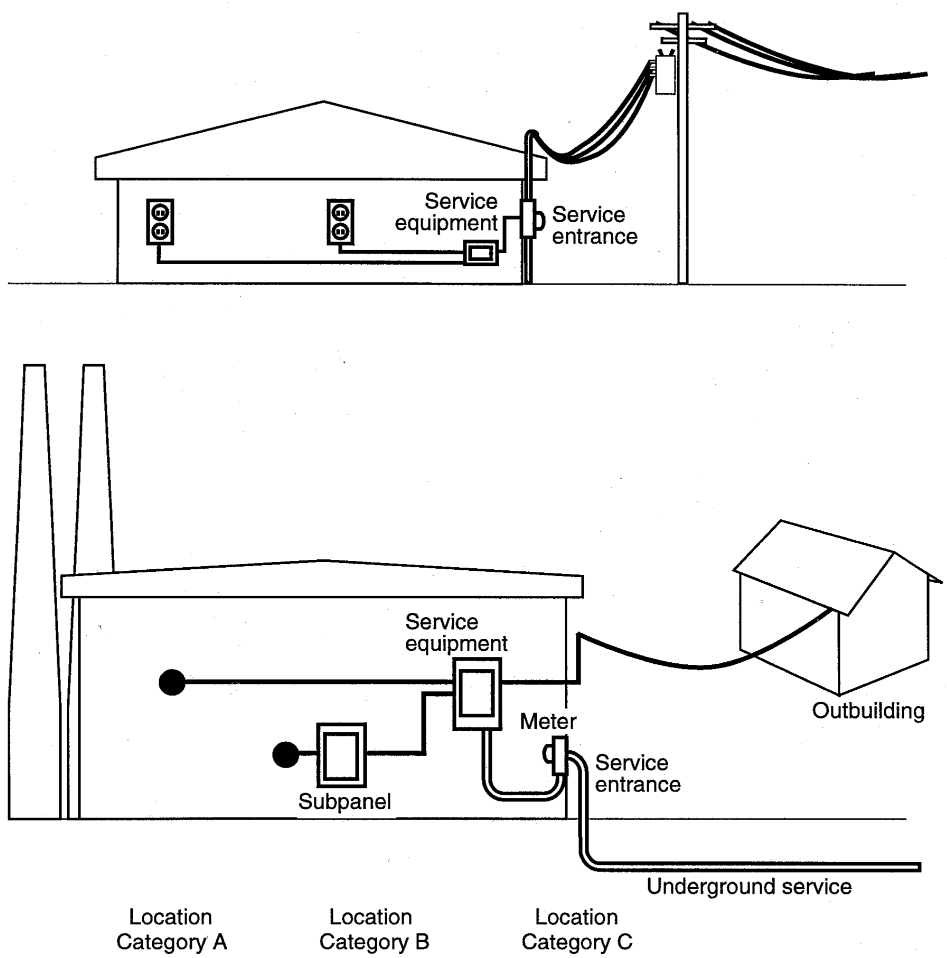
[6]The path of the lightning current as it divides among available paths is often presented as originating from the cloud and flowing into the earth. It should be noted, however, that for a cloud-to-earth stroke, the significant lightning current is a return stroke, originating **from the earth**—not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

[7]Tall 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 downhill 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.

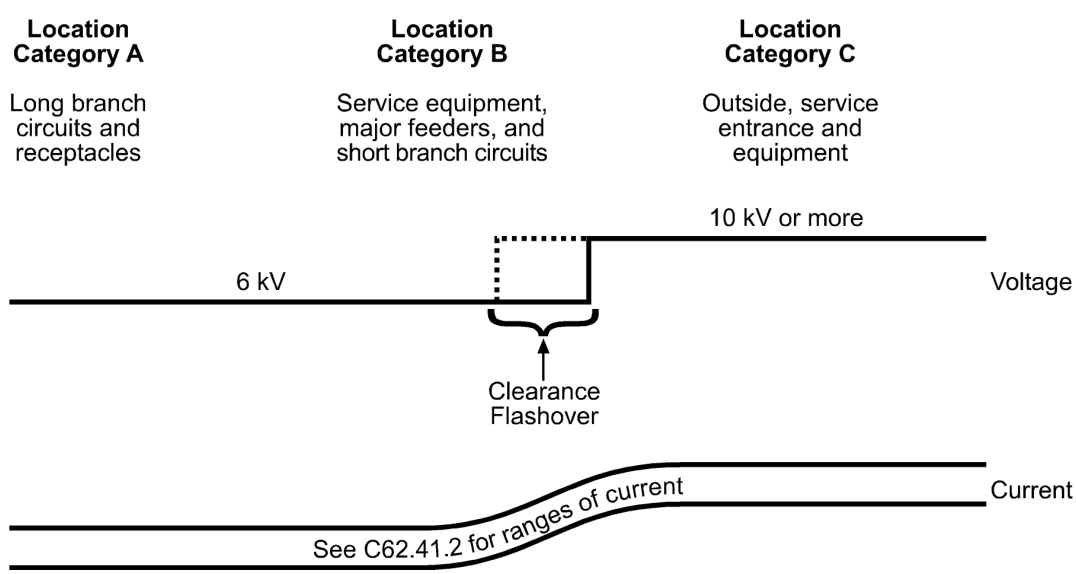


Figure 9—Voltage staircases and current down-slopes according to location category

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:

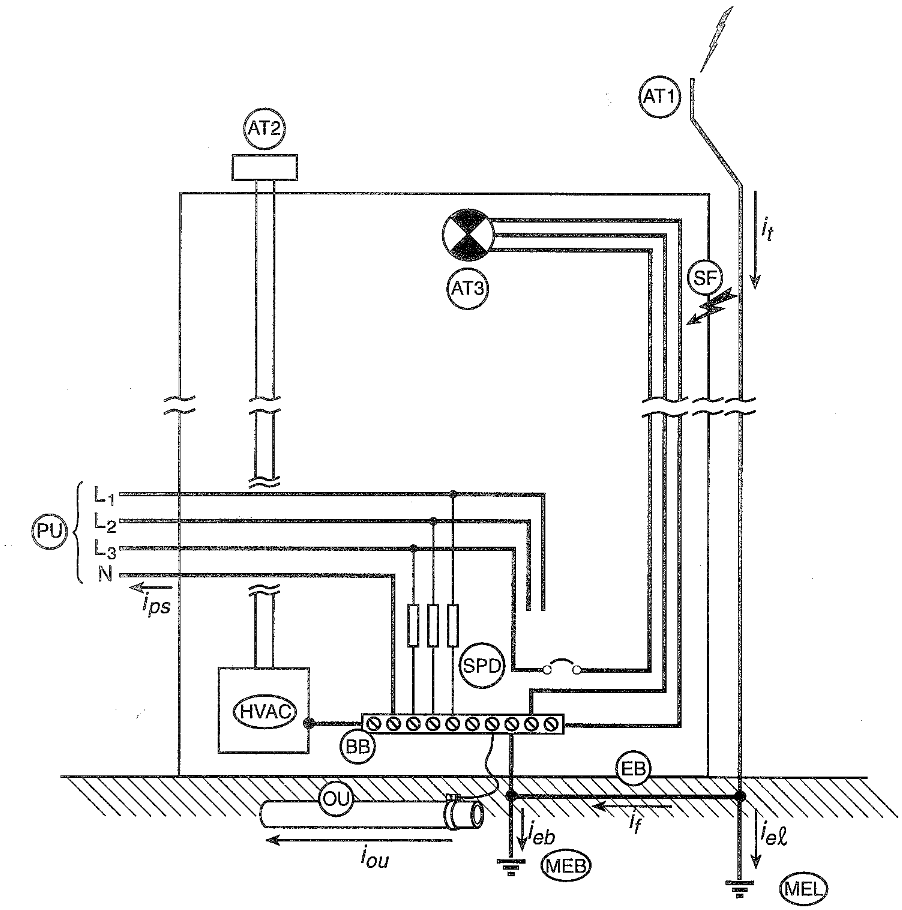
- Shifts in the potential of conductors by the rise in ground potential
- Induction of voltage or current in circuit loops by the electromagnetic fields of the lightning.

These two types of surges involve considerably less energy-delivery capability that 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.
$i_{e\ell}$	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 thresh-olds	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 multipa-rameter 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.

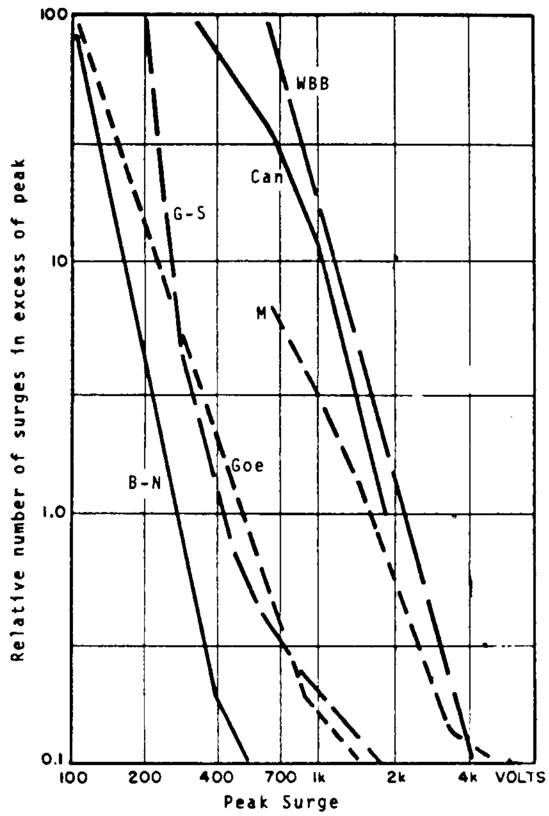


Figure 11—Comparison of the slopes of the frequency of occurrence versus peaks of the voltage surges among different surveys

6.6.2 Voltage surge duration

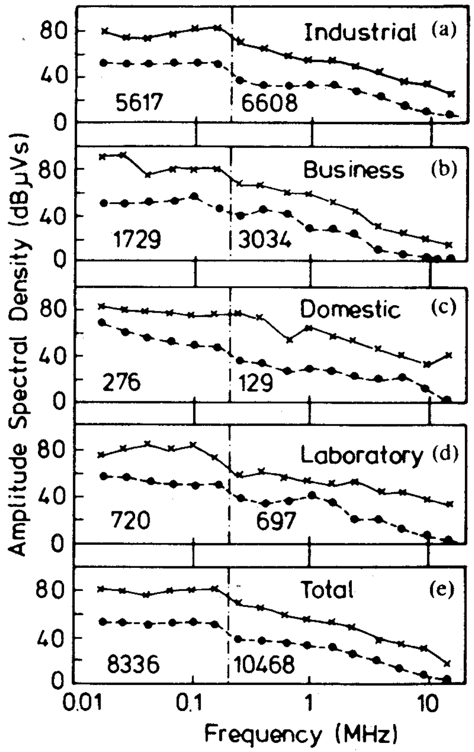
Surveys that report complete voltage waveform recordings show a wide range of durations, ranging from a fraction of a microsecond (Wernström et al. 1984 [B96]) to a few milliseconds (Meissen 1983 [B81]) for unidirectional or quasi-unidirectional waveforms. Oscillatory waveforms, with ringing frequencies 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 (d*v*/d*t*) 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]).

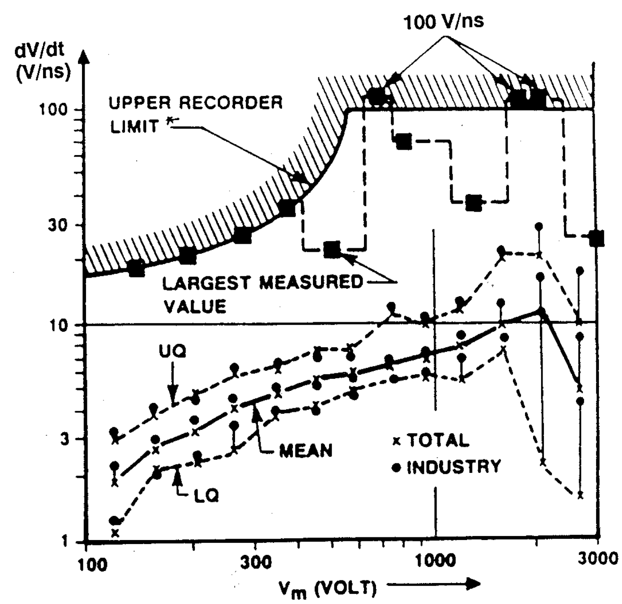
2—When many surges and sites are combined, such as in this figure, the result is a broad and declining distribution.

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 d*v*/d*t*.

Figure 13—Statistical evaluation of recorded d*v*/d*t* 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 µs 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 µs 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 µs 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.

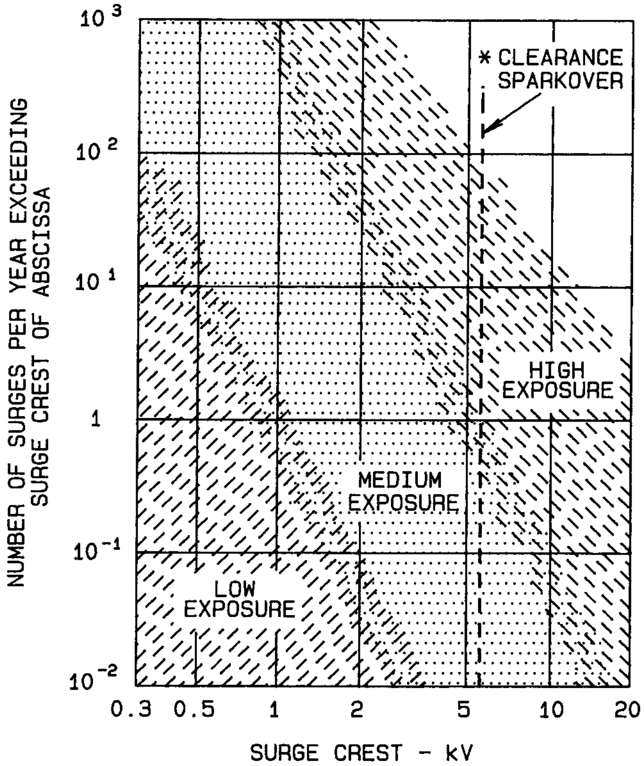
Another factor in the risk assessment is the exposure of the circuit, reflecting regional characteristics (lightning flash density) as well as power system conditions [frequency and intensity of switching surges, nature of the power distribution system (PDS) such as overhead open lines, overhead twisted 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.

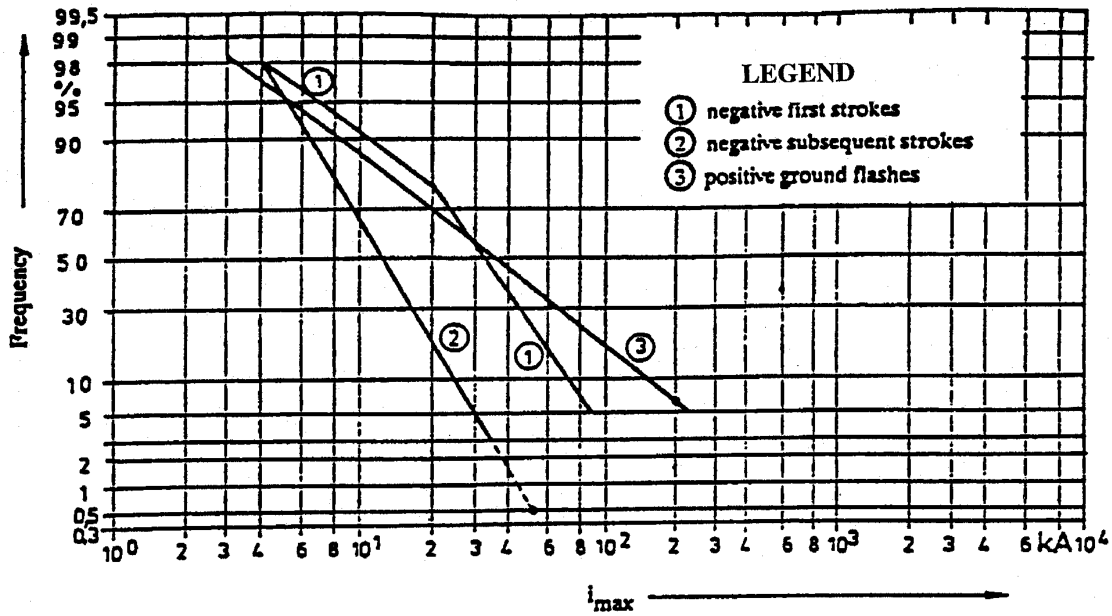


Figure 15—Frequency distribution of peak currents for three types of lightning events

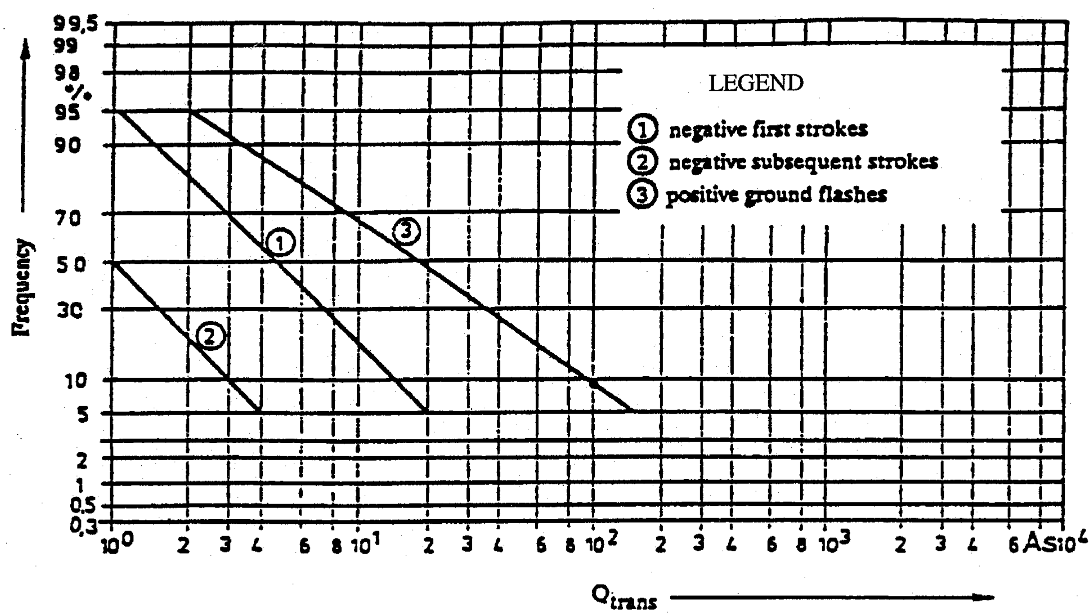


Figure 16—Frequency distribution of the transient lightning charge Q_{trans}

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 (Birkl 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]).

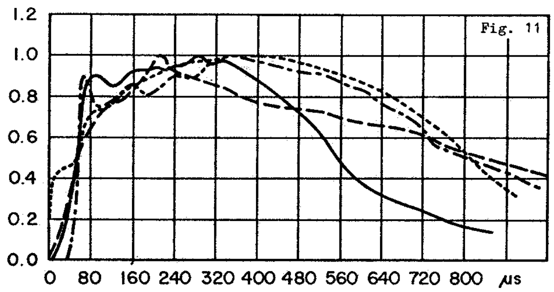


Figure 11
Formes de courant typiques – Impulsions positives
Typical current shapes – positive strokes

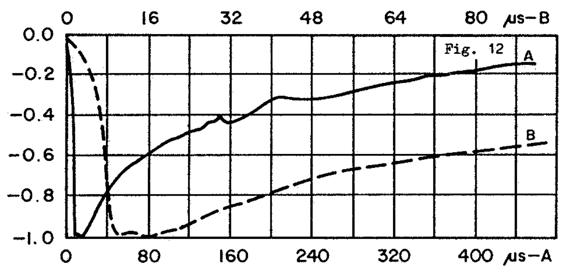


Figure 12

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

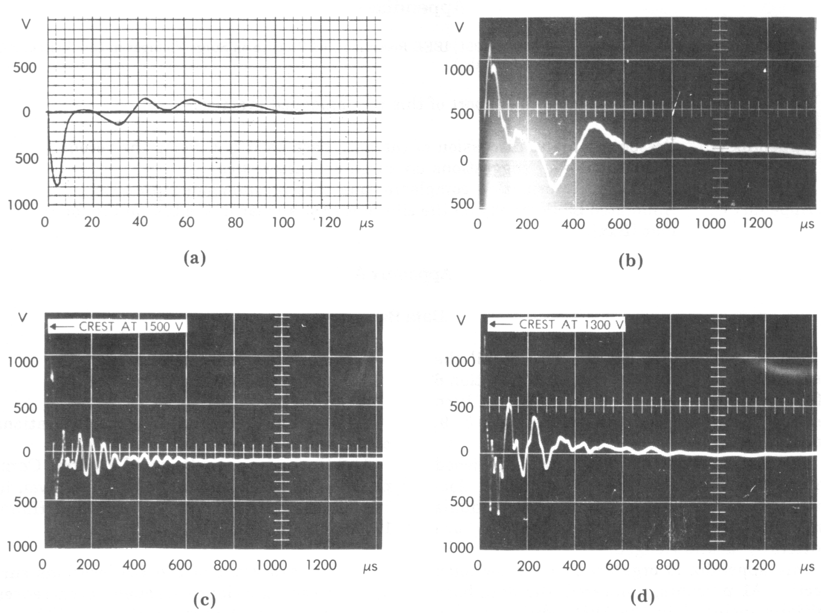
Oscilloscope recordings and surge-counter data were contributed from several sources, in addition to the surge-counter data obtained by members of the working group. Representative oscillograms and summary statistics are reproduced in this subclause in support of the recommended levels and waveforms 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 Laboratories[8]

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



(a) 120 V outlet, laboratory bench
(b) 277/480 V service entrance
(c) 277/480 V service entrance
(d) 277/480 V service entrance

Figure A.1—Typical oscillograms from the Bell data

[8]Data contributed by P. M. Speranza.

A.1.1.2 Recordings by General Electric Company[9]

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

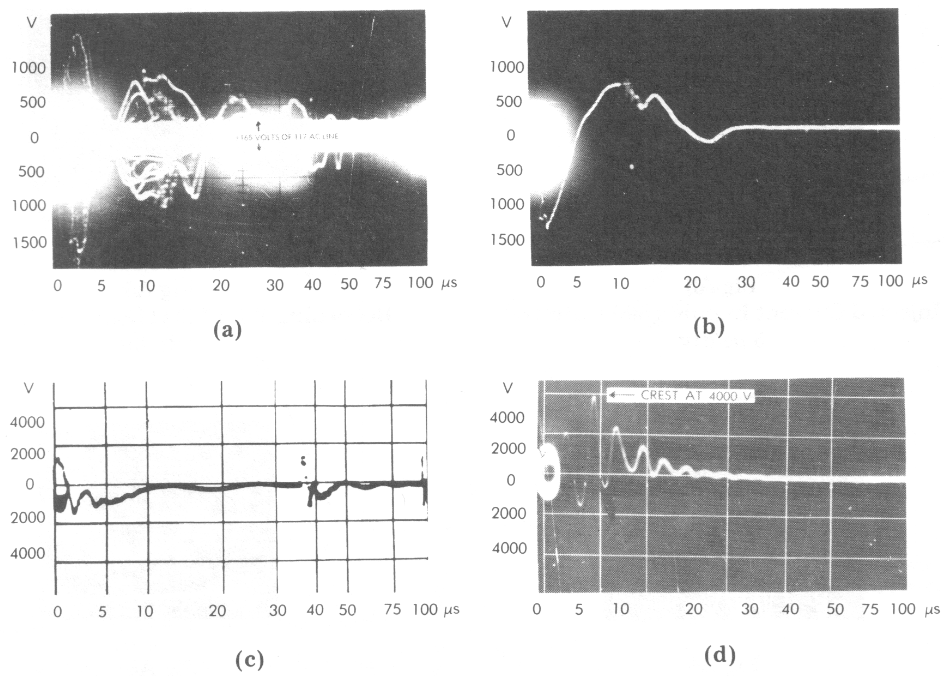
Location	Number of homes surveyed	Recording period (weeks)	Houses with repetitive surges
Providence, RI	4	2–6	None
Cleveland, OH	28	2–4	None
Auburn, NY	12	2–3	None
Lynchburg, VA	3	2–3	None
Syracuse, NY	8	1–2	1
Chicago, IL	23	1–6	None
Ashland, MA	24	1–2	1
Holland, MI	6	2–10	None
Louisville, KY	10	2–6	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.

[9]Data contributed by F. D. Martzloff.



(a) Furnace ignition, 24 h period
(b) Furnace ignition, single recording
(c) Service entrance, lightning storm
(d) Street pole, lightning storm

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

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

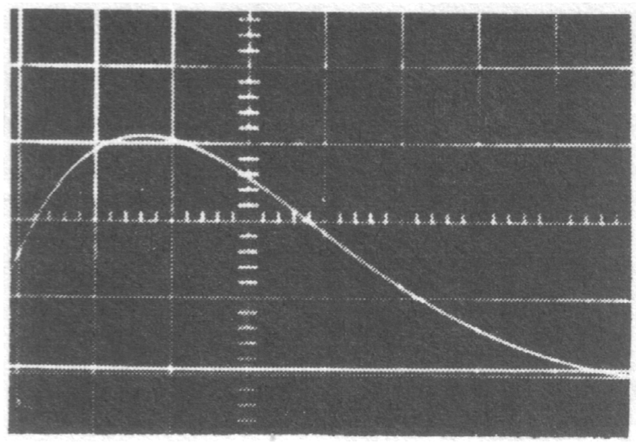


Figure A.3—Injected current: 500 A/div and 5 μs/div

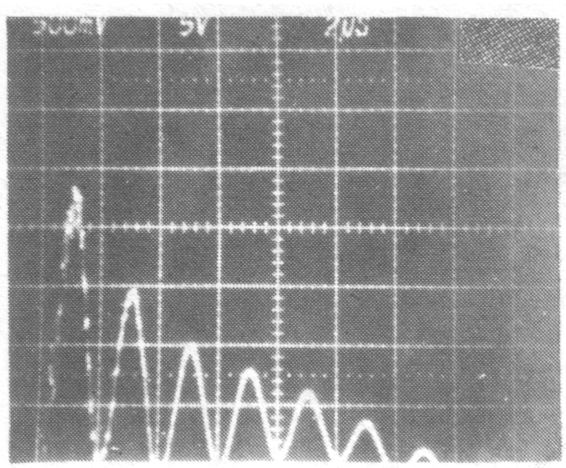


Figure A.4—Open-circuit: 500 V/div and 2 μs/div

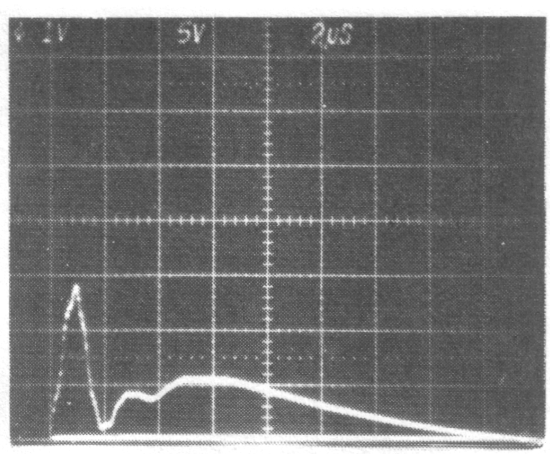


Figure A.5—Recording with 130 Ω load: 500 V/div and 2 μs/div

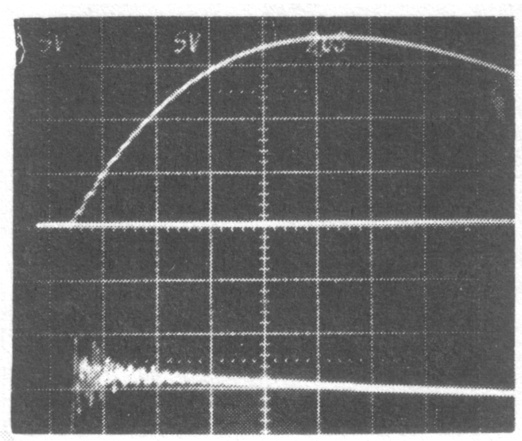


Figure A.6—Top trace: Discharge current at maximum injection 1000 A/div and 2 μs/div

A.1.1.3 Statistics by Landis and Gyr Company[10]

Surge recorders were installed at various locations of 220/380 V system in Switzerland, monitoring the line-to-ground transients. Figure A.7 shows a plot of the frequency of occurrence as a function of voltage level for locations including residential apartments, commercial and industrial buildings, and a rural location served by a long overhead line. These transients recordings represent a composite of switching and lightning transients.

Switching transients measurements and calculations are the basis of the three curves shown in Figure A.8, where the peak voltages reached for circuit interruptions at a light load are plotted as a function of the system voltage. The fast transients (the time to the half-value, T_h, = 5 μs) reach higher peaks than long transients (T_h = 1000 μs), but, in all cases, the peaks increase more slowly than the system voltage.

A.1.1.4 Working group surge-counter statistics

Surge-counters with four threshold levels (350 V, 500 V, 1000 V, and 1500 V) were made available to the working group by Joslyn Electronics Systems for recording surge occurrences at various locations. Members of the working group installed them on 120 V and 240 V systems of various types, including the following: outlets in urban, suburban, and rural residences; outlets in a hospital; secondary circuits on distribution system poles (recloser controls); secondary of pad-mounted distribution transformers; lighting circuits in an industrial plant; life test racks at an appliance manufacturer; and the bench power supply in a laboratory.

Limitations on the availability of personnel and communications made this sampling less than optimum from a statistical point of view. However, by computing weighted averages for each location, one can quote an acceptable overall average; this average has been included when establishing the low-exposure and medium-exposure limits.

[10]Data contributed by L. Regez.

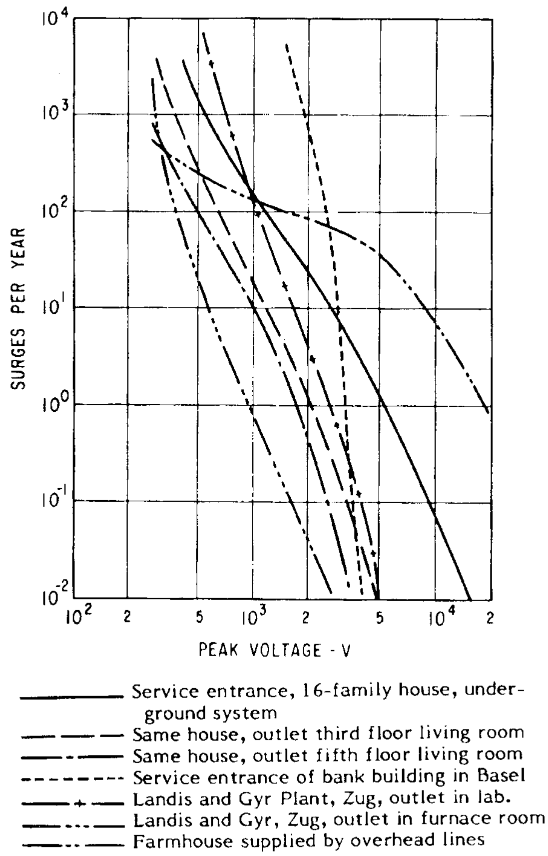


Figure A.7—Rates of surge occurrence recorded in a 220 V system

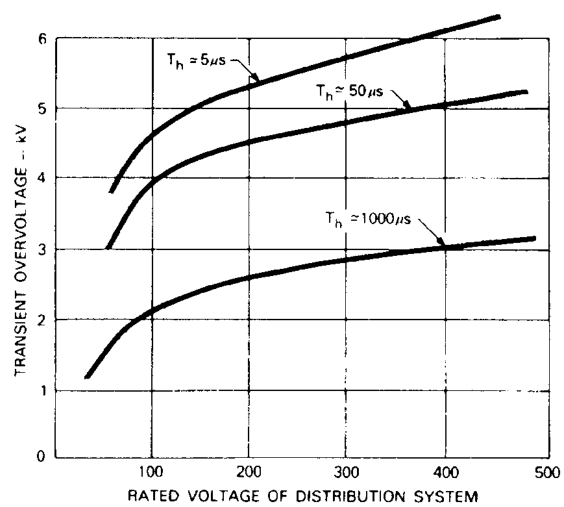
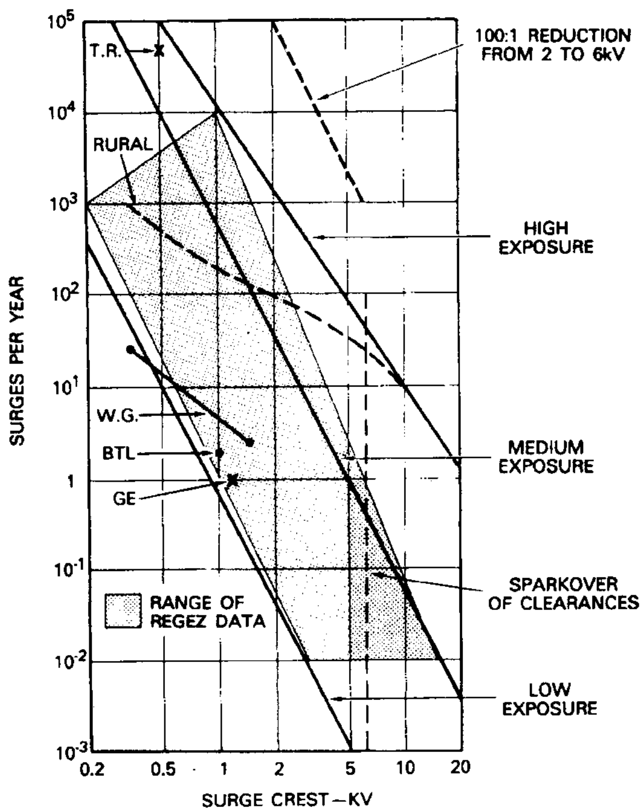


Figure A.8—Effect of system voltage on transient overvoltages for three pulse durations

The statistics of these working group measurements can be summarized as follows:

- The database was collected from 18 locations with a total recording time of 12 years spread over 4 calendar years, using 6 counters.
- The number of occurrences per year (weighted averages) at "average locations" were
  350 V 22 occurrences
  500 V 11 occurrences
  1000 V 7 occurrences
  1500 V 3 occurrences
- The following extremes values were significant:
  - One home experienced a large number of surges caused by washer operation.
  - Four locations out of 18 never experienced a surge, perhaps due to the presence of continuous loads.
  - One home experienced several occurrences above 1500 V, with none below that value.
  - One industrial location (switching of a test rack) produced thousands of surges in the 350 V to 500 V range. This location was left out when compiling the average, but it is shown in the composite plot of Figure A.9.



NOTE—While not formally documented, it is probable that these data were collected from locations with no installed SPDs.

Figure A.9—Combined transient recording data

A.1.1.5 Combined results

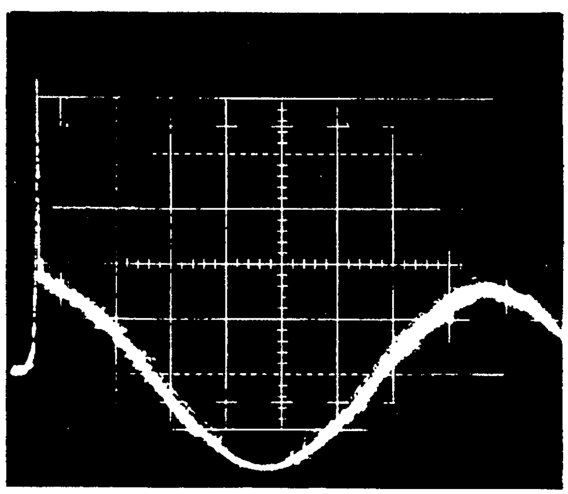
From the data collected from the four preceding examples, Figure A.9 can be drawn together with the following information on voltage versus the frequency (rate) of occurrence at unprotected locations:

1. The Bell Telephone Laboratories (BTL) data yield a point of 1000 V at about two occurrences per year.
2. The General Electrical Company (GE) counter statistics yield a point of 1200 V at about one occurrence per year.
3. The GE clock data indicate a ratio of 100:1 in the rate of occurrence from 2 kV to 6 kV.
4. The Regez data provide a band for the majority of locations, with the exception of the rural location with a long overhead line, which has more occurrences.
5. Working group (WG) statistics indicate a moderate slope, perhaps because of the influence of outdoor locations included in the sample (similar to the rural data of Regez). An extreme case of switching transients was also identified near a test rack (TR).

Three lines have been drawn in Figure A.9: The medium-exposure and the low-exposure lines are parallel to the 100:1 reduction line. The high-exposure line, reflecting isolated cases, corresponds to locations where voltages are not limited by clearance sparkover.

A.1.1.6 Surges created by clearing faults with current-limiting fuses

a) **Residential environment**.[11] The three oscillograms of Figure A.10 through Figure A.12 are excerpted from an unpublished document reporting results of tests made by clearing short circuits at several residences in a 220/380 V residential distribution system. Various makes of fuses were used in the tests. The data show a somewhat inverse relationship between peak voltage and duration of the surges. The reported durations, however, are not as long as those of the Meissen data [B81].

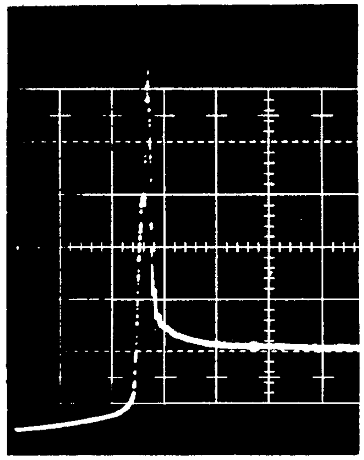


Vert.: 200 V/div   Sweep: 2.5 ms/div

NOTE: Power-system voltage is zero at origin until fuse clears, producing a surge.

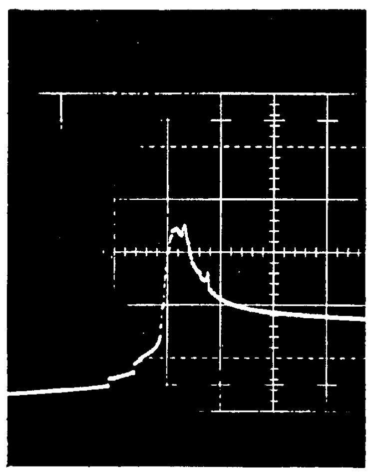
Figure A.10—Voltage pulse accompanying break of current

[11]Data contributed by the Netherlands National Committee of the IEC.



Vert.: 200 V/div Sweep: 250 μs/div

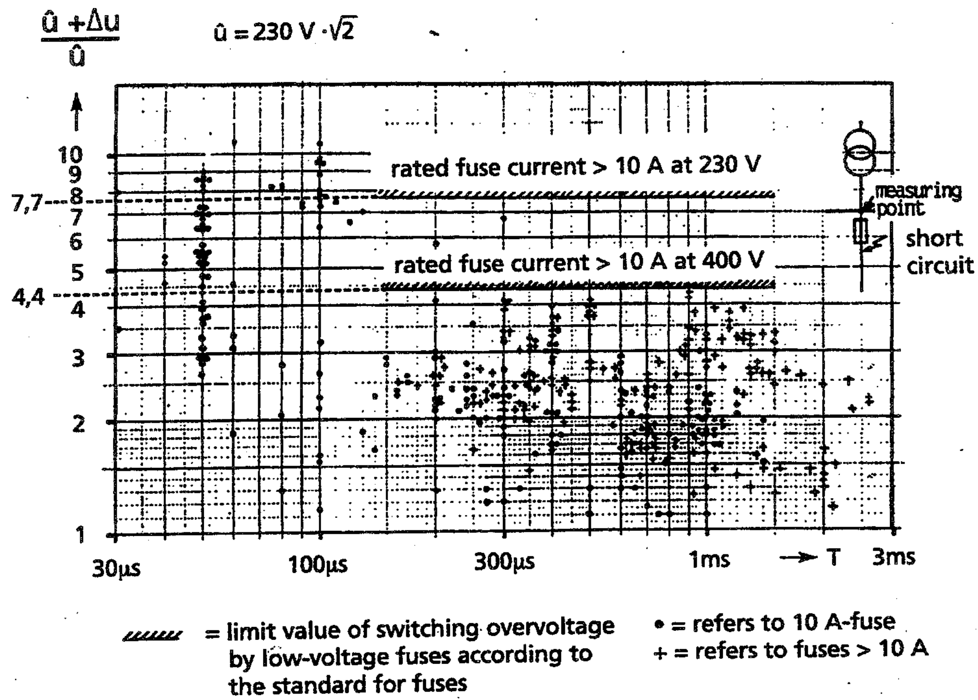
Figure A.11—Surge with high peak (1500 V) but relatively short duration (100 μs)



Vert.: 200 V/div Sweep: 250 μs/div

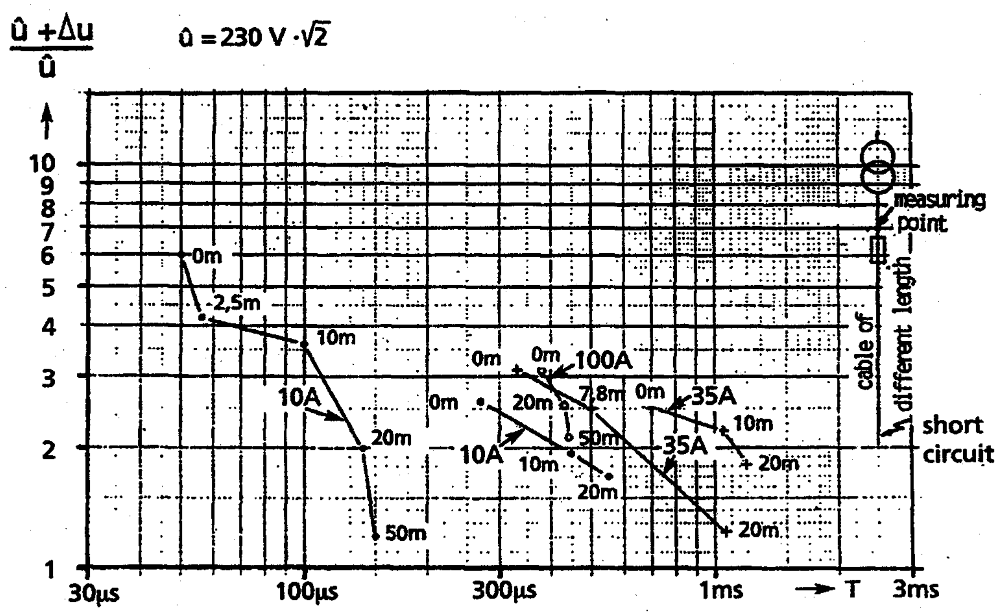
Figure A.12—Surge with long duration but relatively low amplitude

b) **Industrial environment**. The two plots of Figure A.13 and Figure A.14 show results from an investigation of 700 fuse operations in 220/380 V circuits, with various impedance configurations and several rating and types of fuses, as initially reported by Meissen 1983 [B81].



Source: IEC 62066:2002 [B11]

Figure A.13—Measured overvoltage factors for short circuits behind a branch-circuit fuse



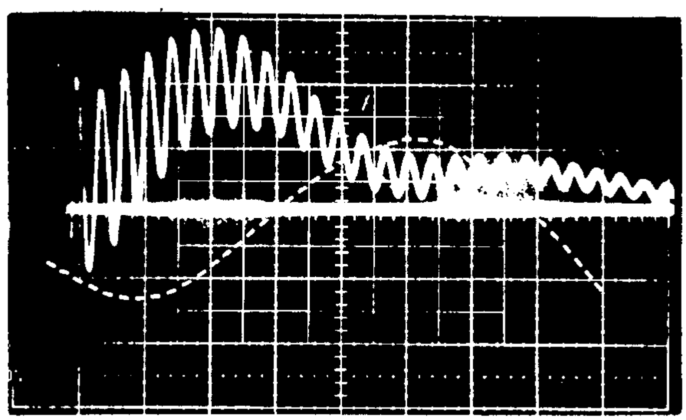
Source: IEC 62066:2002 [B11]

Figure A.14—Influence of cable length on overvoltage at end of cable

A.1.1.7 Surge created by switching of capacitor banks

The oscillograms of Figure A.15 through Figure A.19 were recorded under conditions that were not fully defined, but were identified as associated with capacitor switching by the investigators who provide the information.

a) **Staging the switching of a large capacitor bank**. Figure A.15 and Table A.3 show data collected during an investigation of MOV failures attributed to excessive surge energy (Martzloff 1986 [B218]). The oscillogram of Figure A.15 was recorded at the point of use of the 480 V supply when a 5.4 Mvar bank on the 23 kV side was switched on at the remote utility substation. Table A.3 shows the five highest transients recorded, at the point of use of the 480 V system, during a series of 10 switching-on operations of the capacitor bank.



Vert.: 500 V/div Sweep: 0.5 ms/div

NOTE: Dotted sine wave shows amplitude of the mains voltage but not the same sweep.

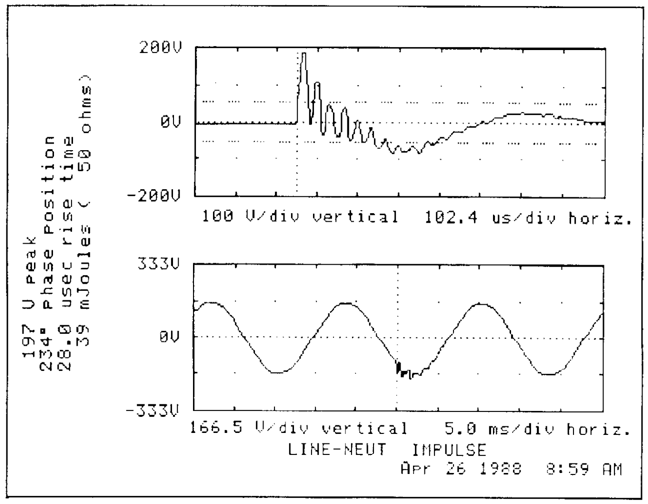
Source: Martzloff 1986 [B218]

Figure A.15—Switching surge recorded in the 480 V system

Table A.3—Capacitor-energizing surges

Without varistors		With varistors
Peak (V)	**Per unit of peak**	**Peak (V)**
1450	2.16	1100
1400	2.00	1100
1300	1.93	1050
1300	1.93	1050
1300	1.95	1050

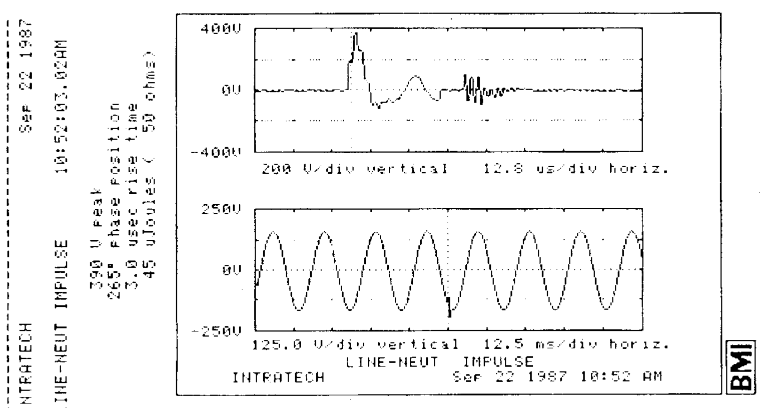
b) **Monitoring typical capacitor-switching transients**



NOTE: This type of waveform has been found in lightly loaded buildings with fairly large step-down transformers. The waveform may be caused by interaction between the initial utility waveform and the resonant characteristics of the service entrance transformer.

Source: Unpublished oscillogram and comment contributed by T. Shaunessy

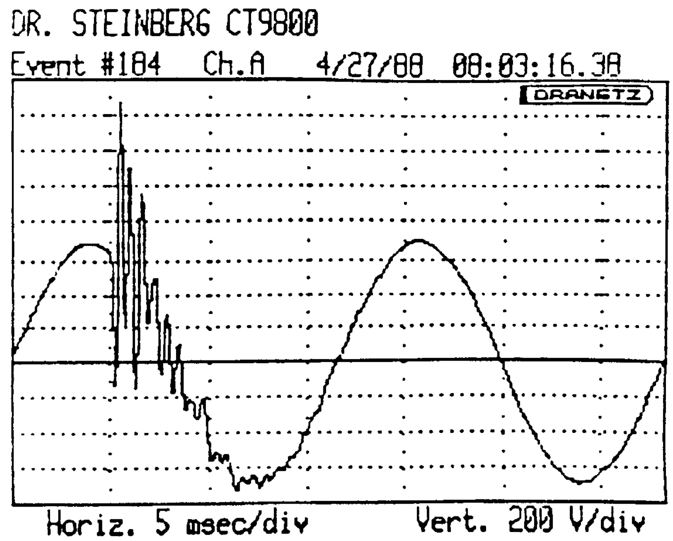
Figure A.16—Typical capacitor-switching transient recorded on a 120 V system



NOTE: This disturbance is caused by switching on a capacitor, thus causing an initial removal of energy from the line (positive initial rise occurring during the negative portion of the mains voltage). The resulting oscillation can be considered as a surge, according to the broad definition of surge.

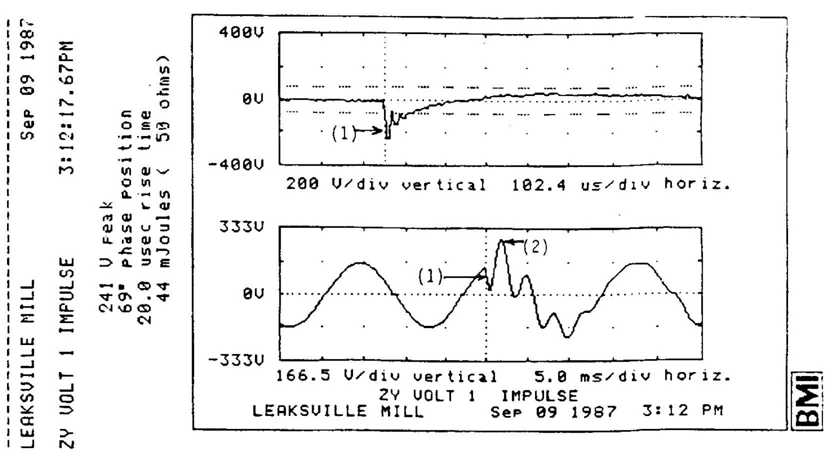
Source: McEachern 1989 [B159]

Figure A.17—Capacitive load switching



Source: Unpublished data contributed by H. Rauworth

Figure A.18—Capacitor-switching transient recorded in a hospital environment



NOTE: This disturbance is caused by energization of a 600 kvar capacitor bank on the secondary side of a delivery transformer feeding an industrial customer. The capacitor is installed for voltage-regulation purposes and may switch several times a week. There are two components in this transient that may cause problems:

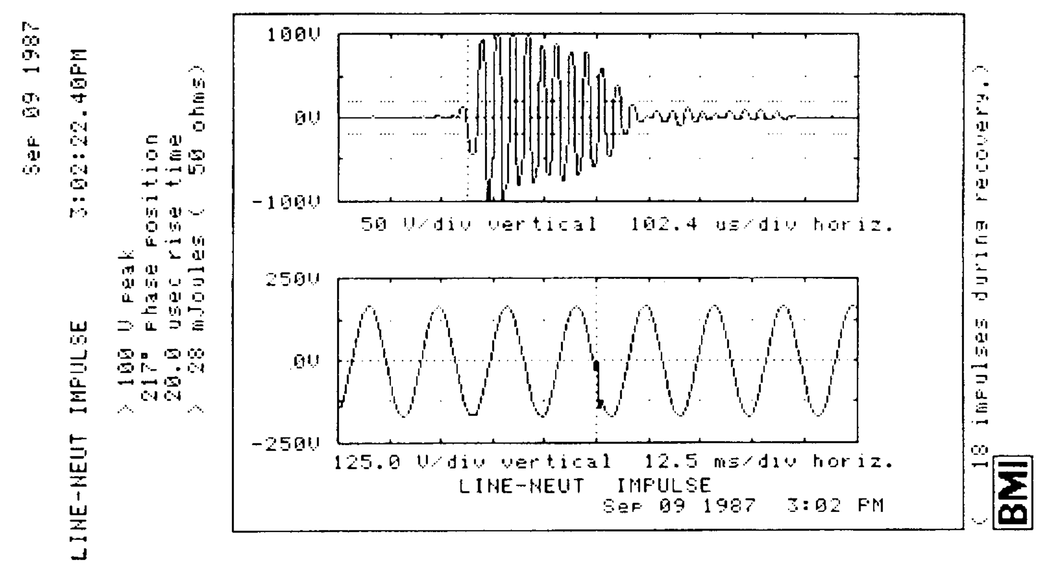
(1) A high dv/dt resulting from the bus voltage suddenly changing to coincide with the uncharged capacitor
(2) The transient overvoltage resulting from the natural frequency oscillation as the system settles to a new operating condition.

Source: Unpublished data and comment contributed by J. G. Dalton

Figure A.19—Typical industrial capacitor-switching transient (low-voltage bank)

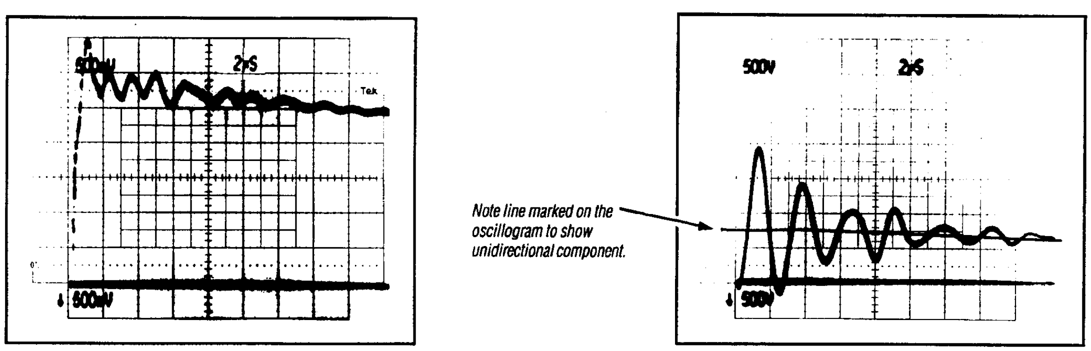
A.1.1.8 Ring Waves

Ring Waves can be produced by unidirectional stimulation of a power system, as shown in Figure A.20 and Figure A.21.



Source: McEachern 1989 [B159]

Figure A.20—Lightning-induced Ring Wave



SURGE AT BUILDING SERVICE ENTRANCE, RESULTING FROM A COMBINATION WAVE APPLIED AT 480 V TRANSFORMER PRIMARY
Vertical: 500 V/div Sweep: 2 μs/div

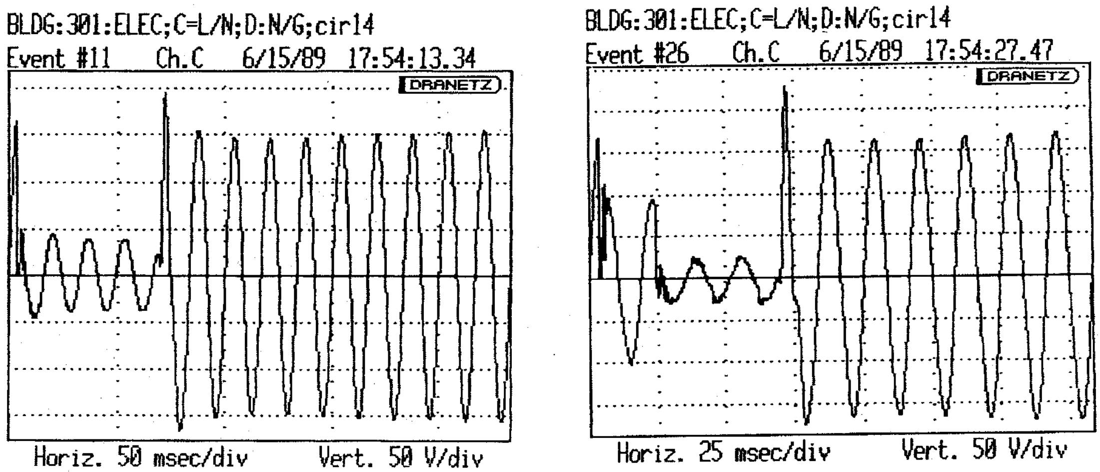
RESULTING SURGE WITHIN BUILDING, ON BRANCH CIRCUITS DOWNSTREAM FROM 120/208 V TRANSFORMER SECONDARY
Vertical: 500 V/div Sweep: 2 μs/div

Source: Martzloff 1990 [B125]

Figure A.21—Conversion of a unidirectional surge into an oscillatory surge

A.1.1.9 Swells

Swells have not been documented because they are generally outside of the area of interest of researchers investigating surges. Anecdotal reports on varistor failure might be explained by assuming the occurrence of a large swell or the cumulative effect of repeated swells (Martzloff and Leedy 1989 [B219]; Lagergren et al. 1992 [B216]). The two oscillograms in Figure A.22 show the momentary overvoltage occurring upon recovery of a power system from a momentary undervoltage ("sag"). These disturbances were identified as occurring during a thunderstorm, with several such disturbances a few seconds apart (note the time stamps on the records). These overvoltages of Figure A.22 are at the boundary between the definition of a surge and the definition of a swell.



Source: Unpublished data contributed by F. D. Martzloff

Figure A.22—Swells occurring upon recovery from a remote system fault

A.1.2 1999 database additions

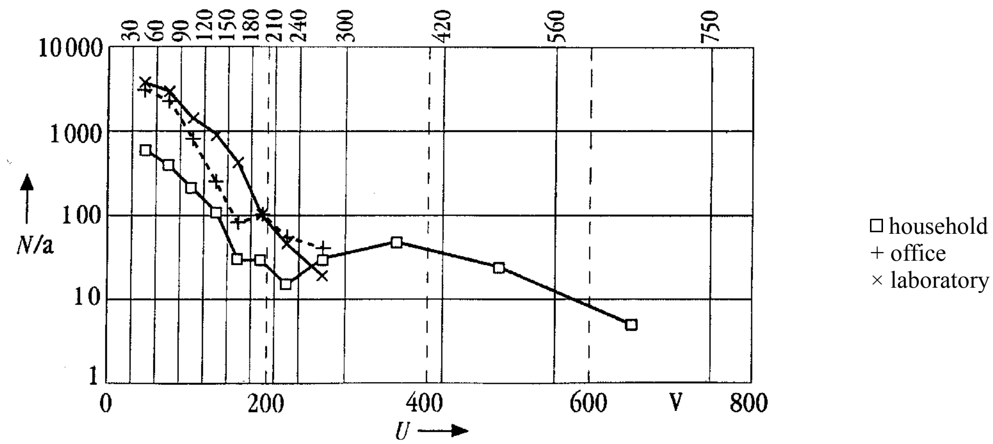
The new data on surge occurrence recordings accumulated during the 1990s are somewhat different from those presented in A.1.1. Significant differences affect these data, as discussed in A.4. As presented here, the data are shown as reported by the respective researchers, unfettered by discussion, but caution is advisable in deriving conclusions without considering the factors discussed in A.4.

A.1.2.1 Surveys in German power systems

Three surveys by different groups of researchers were conducted at various locations in Germany.

In the first survey, domestic, office, and laboratory locations were monitored in the late 1980s, as reported in Pfeiffer and Scheuerer 1992 [B87]. Figure A.23 shows a plot of the results from this survey, as number of recorded occurrences per year versus amplitude.

An industrial location was added later on. The additional measurements were performed over rather long periods of time at each location. Table A.4 shows a summary of these measurements, which are consistent with the previous data reported in Meissen 1983 [B81], especially if the different locations and the limited amplitude measuring range of the earlier ones are taken into account.



Source: Pfeiffer and Scheuerer, in IEC 62066:2002 [B11]

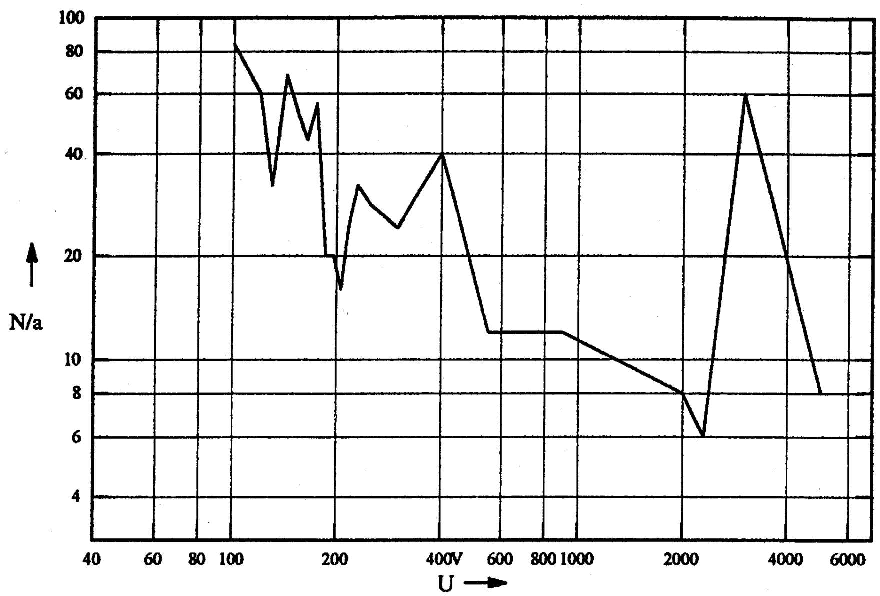
Figure A.23—Example of survey of switching overvoltages in three types of installations

Table A.4—Minimum, maximum, and mean values of the amplitude and rate of rise of the recorded switching surges at different locations

	Household	Office	Laboratory	Industrial
Minimum amplitude, V	35	35	35	50
Maximum amplitude, V	644	294	257	4916
Mean amplitude, V	97	80	86	280
Minimum rate of rise, V/µs	4	1	2	270
Maximum rate of rise, V/µs	1690	1190	1385	10766
Mean rate of rise, V/µs	255	253	216	600

Source: Pfeiffer and Scheuerer 1992, in IEC 62066:2002 [B11]

In an industrial installation, equipment can be located in rather short distances from distribution transformers and the facility grounding bar (called “collecting bar” in the source paper). Under those conditions switching surges of up to 5 kV amplitude have been recorded. As can be seen from the evaluation of the absolute probability of occurrence of switching surges (N/a = events per year) shown in Figure A.24, there seems to be a superposition of the regular distribution according to the third power law with a special event causing switching overvoltages of approximately 5 kV amplitude, such as the switching on and off of a distribution transformer at every weekend.



Source: Pfeiffer and Gräf 1994, in IEC 62066:2002 [B11]

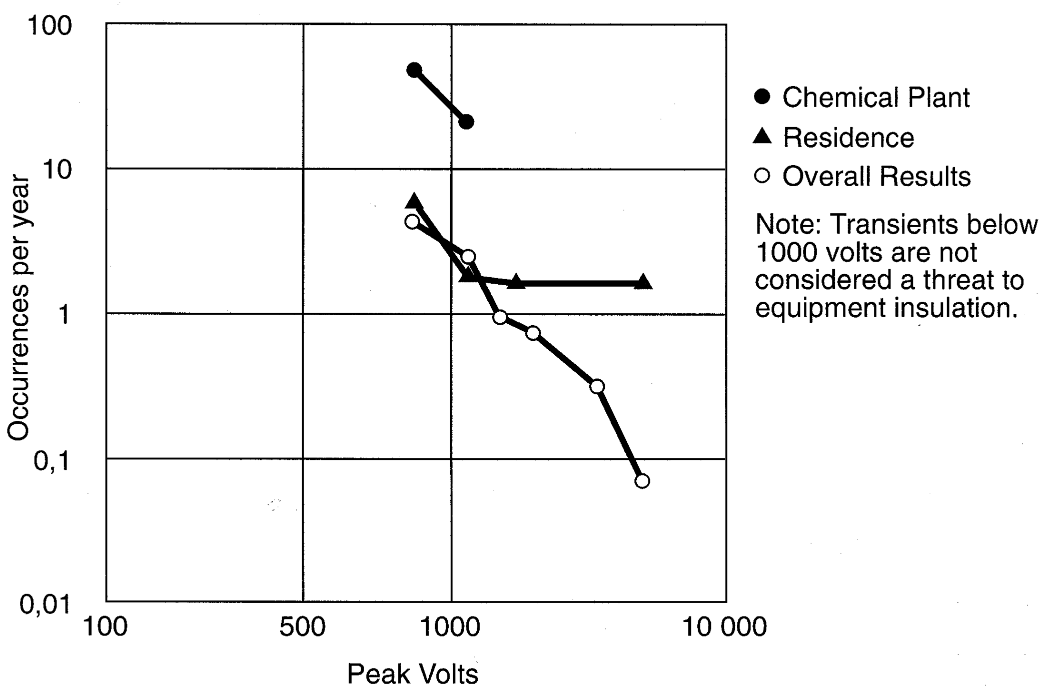
Figure A.24—Switching surges in an industrial plant measured near the collecting (facility grounding) bar

Another investigation, reported by Ackermann et al. covered two stages, one of general characterization and one of high-risk locations. The aim was to monitor maximum overvoltages stressing the insulation of low-voltage equipment.

In the first part of the investigation (Ackermann et al. 1993 [B44]), during a two-year period, 40 measuring points were monitored, covering commercial and industrial locations, as well as office buildings and residential buildings. Figure A.25 shows the frequency of occurrence per year for the recorded events. The source article does not provide information on wave shape, except a statement that a duration of at least 1 μs was required for the instrumentation to register. Because the main objective was to assess the stress on insulation, the wave shape was less important than the peak values.

In the second part of the investigation (Ackermann et al. 1997 [B45]), overvoltages were measured at 25 locations where frequent and severe overvoltages might be expected. The locations selected were in 400 V installations, and the measurements were made from line to protective earth. According to the report of this investigation, all SPDs that were "detected" at the measuring point were removed. Nevertheless, it is difficult to guarantee that all SPDs were disconnected, considering the widespread practice to have built-in SPDs in modern equipment.

Most of the recorded overvoltages were in a range of 500 V to 1000 V, but only those above 1000 V were considered for evaluation. The expectations that frequent and severe overvoltages would be found at the "high-risk" locations were not validated. At some locations, not even the 500 V threshold was exceeded. Table A.5 shows a summary of the findings. For most of the recorded transients, the maximum voltages were much lower than previously expected.



Source: Ackermann et al., in IEC 62066:2002 [B11]

Figure A.25—Frequency of occurrence at selected sites and overall results

Table A.5—Measurement points and results of the long range measurement (second part)

Measurement points	Installation type	Network type	Measurement results					
			0.5 kV	1 kV	1.5 kV	2 kV	4 kV	6 kV
Municipal hall	household	overhead line	X					
Automotive industry	industry	cable						
Producing firm No. 2	industry	overhead line						
SPD factory	industry	cable	X					
Lignite open cast mining	industry	cable						
Chemical factory No. 1	industry	cable	X	X	X			
Chemical factory No. 2	industry	cable						
Fibrous material factory	industry	cable	X					
High-rise warehouse	industry	cable	X					

Table A.5—Measurement points and results of the long range measurement (second part) *(continued)*

Measurement points	Installation type	Network type	Measurement results					
			0.5 kV	1 kV	1.5 kV	2 kV	4 kV	6 kV
Chipboard factory	industry	cable	X					
Producing firm No. 1	industry	cable	X					
University laboratory	university	cable	X					
Surface technique factory	industry	cable	X					
Factory	industry	cable	X					
Switchgear factory	industry	cable	X					
TV transmitter	miscellaneous	cable	X					
Telecom station	miscellaneous	cable	X					
Mains network No. 1	utility network	overhead + cable	X					
Mains network No. 2	utility network	overhead line	X					
Residential building	household	cable	X	X	X	X		X
District office	office	overhead line						
Tower station	utility network	overhead line	X					
Farm	miscellaneous	overhead line	X					
Radio transmitter No. 1	miscellaneous	overhead line	X					
Radio transmitter No. 2	miscellaneous	overhead line	X					

Source: Ackermann et al., in IEC 62066:2002 [B11]

A.1.2.2 Surveys in North America

In a survey reported in Dorr 1995 [B63], the emphasis was more on sags (dips) and interruptions than on surges as the survey was part of an attempt to characterize power quality in low-voltage end-user systems in North America. The results for recorded transients are shown in Table A.6. A significant finding in that survey was the relatively rare occurrence of high-amplitude transients, which Dorr suggests to be the result of the proliferation of SPDs in low-voltage end-user systems.

The Dorr measurements, as were the Martzloff and Hahn 1970 measurements [B78], were made on single-phase or polyphase systems, between line and neutral, for the purpose of assessing the stress applied to electronic components connected between line and neutral. Because the North American practice is to bond the neutral to the local earth at the service entrance, these measurements also represent the line-to-earth stress. In contrast, some of the measurements reported by other researchers cited in this annex were made from line to the local earth, for the purpose of assessing the stress applied to the equipment insulation.

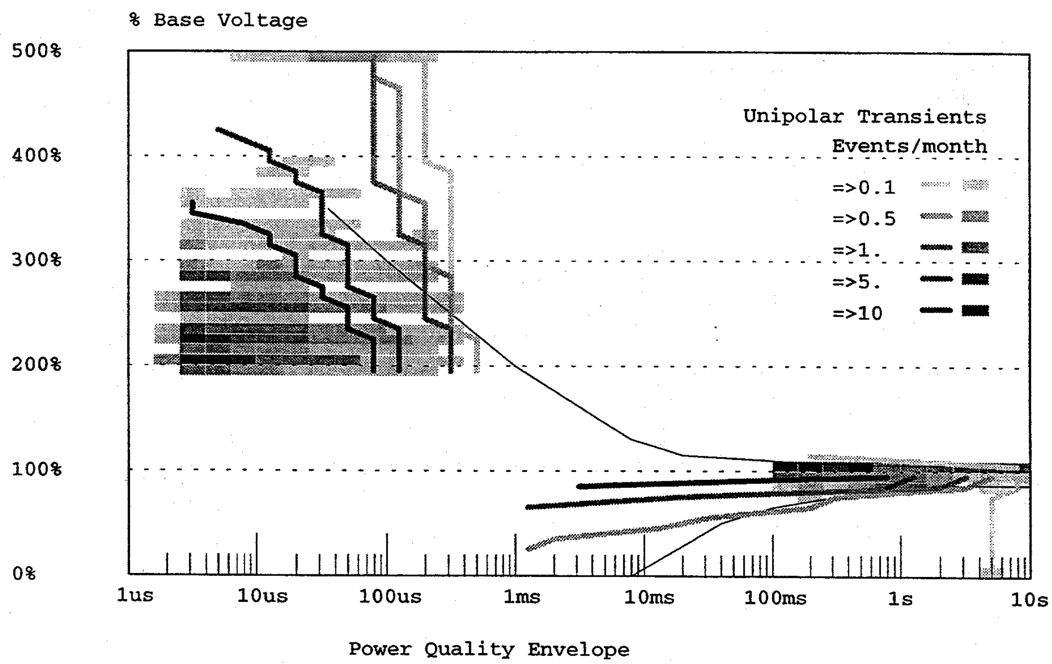
Table A.6—Distribution of recorded transients

	<1	1-2	2-3	3-4	4-5	5-10	10-20	20-30	30-50	50-100	100-150	150-200	200-250	250-300	300-400	400-500
>1000	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
901-1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
801-900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
701-800	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0
601-700	1	2	0	0	0	1	2	1	0	0	0	0	0	0	0	0
501-600	0	0	1	3	0	1	0	1	0	0	0	0	0	0	0	0
451-500	0	1	2	4	0	0	1	1	0	1	1	0	0	4	1	0
401-450	1	2	4	12	0	1	3	1	1	1	10	0	1	16	0	0
351-400	0	6	10	14	3	2	2	2	1	5	10	7	2	11	1	2
301-350	1	10	15	15	4	3	6	3	25	21	23	9	9	19	8	1
251-300	3	5	14	20	6	15	39	6	58	67	79	23	15	31	8	8
200-250	5	25	60	23	13	130	473	78	116	158	210	86	15	58	20	9
150-200	19	89	187	728	687	976	1702	1975	749	832	887	513	214	197	99	36
100-150	140	503	1350	3875	2488	11108	7035	3816	3352	12193	4162	2536	811	393	357	234

Duration of transients, microseconds

Source: Dorr 1995 [B63]

The Canadian Electrical Association commissioned in the early 1990s a survey of power quality parameters, a summary of which is reported in Hughes and Chan 1995 [B74]. A total of 550 customer sites were monitored, each for about one month, and the results combined by categories, from which “profiles” were reported. The four categories were industrial, commercial, residential, and the points of delivery from the distribution systems. The major emphasis of the survey was not on surges (“transients”) but on comparing the complete array of disturbances to an envelope derived from the so-called CBEMA curve, which the authors call “Power Quality Envelope.” This envelope has an aspect similar to the conceptual relationship shown in Figure 1 (in Clause 1) of this guide. The summaries of the recordings show the statistical distribution of events in percent of the base voltage as a function of the duration from 2 μs to 10 s, from which the transient activity can be obtained. Figure A.26 is an example of the graphical representation of the statistics.



Source: Hughes and Chan 1995 [B74]

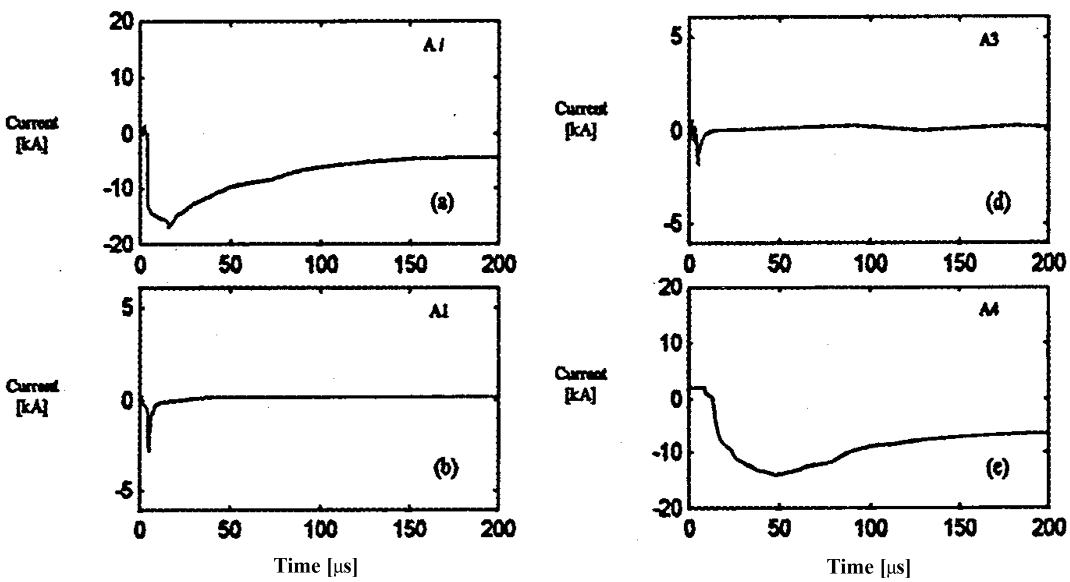
Figure A.26—Residential customer group summary

A.1.2.3 Triggered lightning tests and current dispersion measurements

The University of Florida Lightning Research Group used rocket-triggered lightning to test the lightning protection system of a simulated test house (Fernandez et al. 1998 [B64]; Mata et al. 1998 [B129]; Rakov et al. 2001 [B136]). Triggered lightning strokes are similar to subsequent strokes in natural lightning, although the first stroke of natural lightning is not reproduced by triggered lightning. The electrical circuit of the test house, protected by SPDs mounted at the base of meter and by internal 6 kV spark gaps, was connected to the secondary of a pad-mounted distribution transformer located at a distance of about 50 m from the test house. The transformer primary was connected to a 650 m long unenergized underground power cable, which was open-circuited at the other end. The neutral of the cable was grounded at both ends. The test house had two ground rods, one for the lightning protection system grounding (measured resistance 1550 Ω) and the other for the power supply system grounding (measured resistance 300 Ω). The two rods were about 3 m apart and were connected by a braided conductor. The lightning current was injected into the lightning protection system ground rod, and the currents and voltages at different point in the test system were measured.

The peak values of injected lightning current ranged from 12 kA to 19 kA, comparable to the median current peak of 30 kA for first strokes in natural lightning. Lightning current rise times (10–90%) ranged from 0.5 µs to 1 µs. The ground rods at the test house appeared to filter out the higher frequency components of the lightning current, allowing the lower frequency components to enter the electrical circuits of the house. The authors interpreted this observation as being due to a capacitive rather than the expected resistive behavior of the ground rods. This effect was observed for grounding resistances of the rods (driven in typical sandy Florida soil) ranging from many hundreds of ohms to some tens of ohms. The peak value of the current entering the electrical circuits of the test house was found to be from 65% to over 80% of the total lightning current peak. Typical recordings of the current waveforms at several measuring points are shown in Figure A.27.

From separate triggered-lightning experiments, it has been found that when lightning strikes earth at tens of meters from the system grounds, an appreciable fraction of the total lightning current enters the system from earth (Fernandez et al. 1998 [B64]; [B105]). The observed peak values of current entering the system from earth in percent of the total lightning current peak were (for three different events) 10% at 60 m, 5% at 40 m, and 18% at 19 m from the ground strike point.



(a) Total lightning current
(b) Current into first ground rod
(c) Current into second ground rod
(d) Current entering the house circuits

Source: Rakov et al. 2001 [B136]

Figure A.27—Typical dispersion of lightning current in the Camp Blanding experiments

A.1.2.4 Lightning detection network data

The lightning detection network data can be processed to obtain statistics on the peak amplitude of the strokes detected by the system network. Figure A.28, from Cummins et al. 1998 [B61], shows examples of the statistics obtained for the southeastern United States.

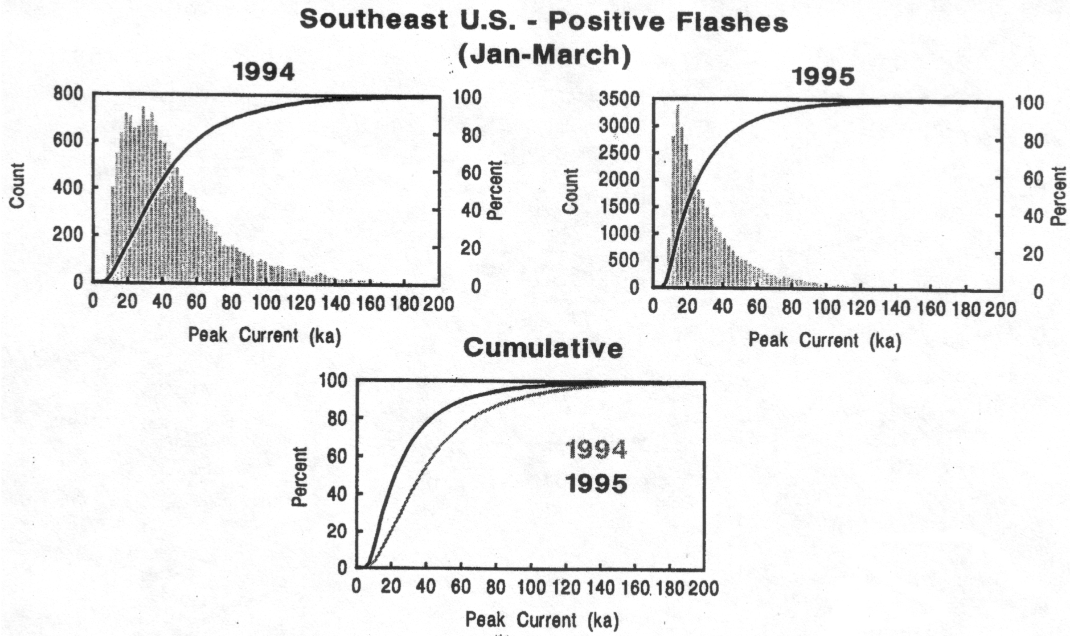


Figure 11. Peak current histograms and cumulative distributions for positive flashes in the southeastern United States during January-March 1994 (before the upgrade was complete) and 1995 (after).

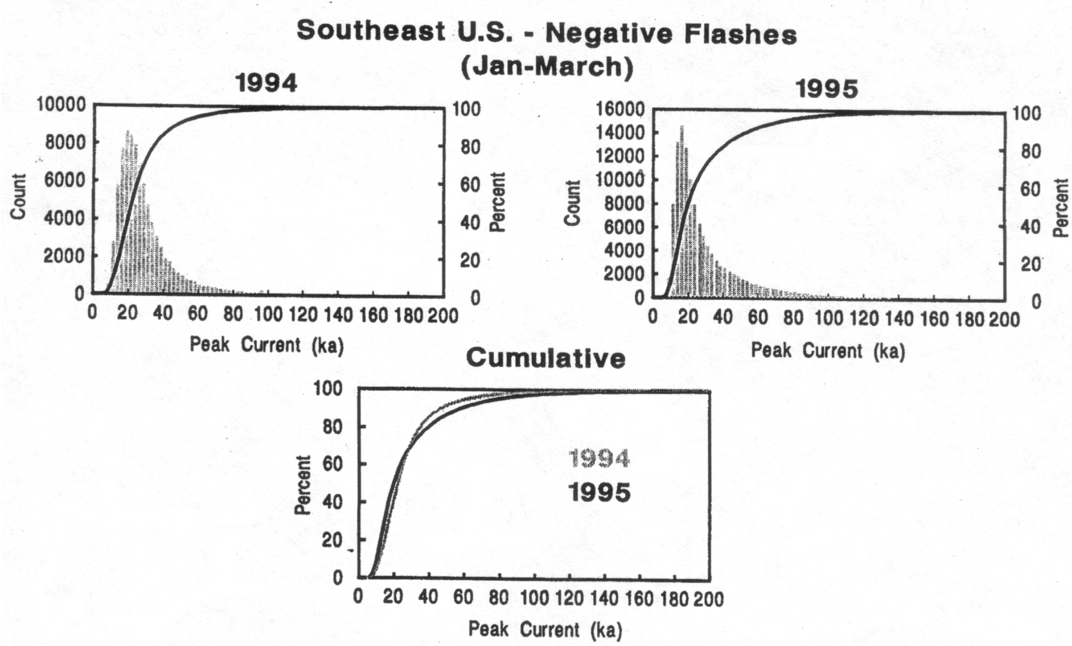


Figure 12. Same as Figure 11, but for negative flashes.

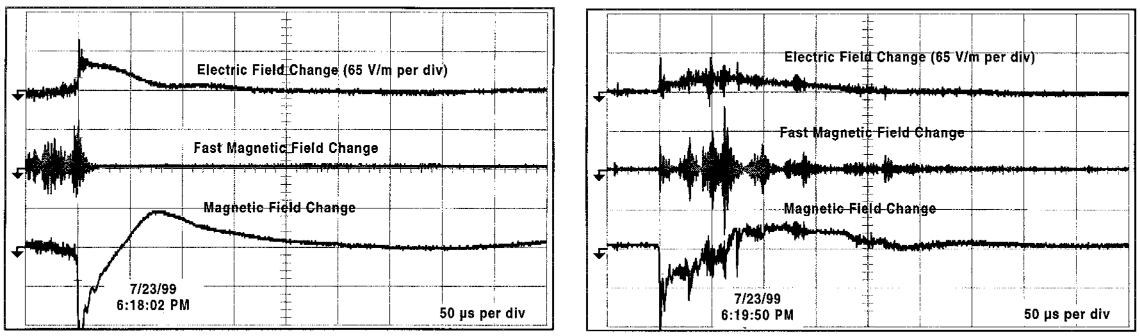
Source: Cummins et al. 1998 [B61]

Figure A.28—Example of data from the lightning detection network

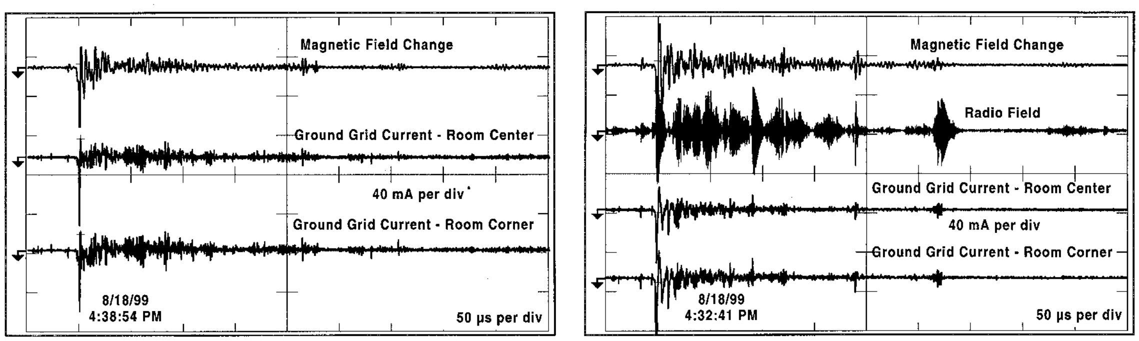
A.1.2.5 Field measurements inside a building during a lightning storm[12]

Figure A.29 shows examples of recordings made in a building during a lightning storm involving flashes within 5 km of the building. The building construction was a three-story steel frame, with masonry walls. The measurements were made in the first-floor computer room, which had a copper grounding grid under the floor.

These recordings have some limitations in that the decay time might be associated with the instrumentation response, but they do illustrate how the rapidly changing field does induce voltages and the resulting currents in the wiring. Anecdotal observations have also been reported that damage to equipment in the building is more severe or more frequent for strokes that were multiple. Two explanations have been proposed: The damage might be caused by the continuing current between the subsequent strokes or might be associated with the higher (up to ten times) rate of current change in subsequent strokes, compared to the first stroke.



(a) Electric field (calibrated) and magnetic field (not calibrated)



(b) Ground-grid current (calibrated), magnetic field change (not calibrated), and radiated field (not calibrated)

Figure A.29—Examples of recordings in a building during a close-by lightning storm

A.1.2.6 Anecdote on interaction between systems[13]

This anecdote illustrates the mechanism discussed in Clause 7 and provides an example of the levels of voltage surges that can occur as a result of interactions between different systems. A wood-structure residence in a rural environment suffered two successive failures of video equipment during lightning storms, a few months apart. The owners allowed engineers to visit the site and acquire the second failed TV receiver for a postmortem.

[12]Unpublished data contributed by M. F. Stringfellow.
[13]Data contributed by K. O. Phipps, from unpublished report.

— ***Site configuration.*** The power service entrance is located at one end of the house, while the cable TV service entrance is located at the opposite end. A visit to the site revealed that the cable TV shield was grounded only by a questionable ground rod next to the house foundation (within the drip line, and thus in dry soil). Furthermore, this grounding connection was not bonded to the grounding connection of the power service entrance, a clear violation of the NEC [B19], according to the current edition as well as several, if not all, earlier editions.
— ***Postmortem and surge tests.*** One of the failed TV receivers was made available for examination. No evidence of damage was found on the power side of the chassis (connected to one of the power cord conductors), but a clear indication of surface flashover was observed between the cable input "ground" termination (connected to the incoming cable shield) and the shielding can of the tuner. After cleaning as best as possible the carbonized path of the flashover, removing the material to a greater depth and covering it with epoxy, the gap was subjected to incremental steps of a 1.2/50 µs impulse. Flashover occurred at 2.5 kV, at another part of the original insulation separating the two "grounds" of the power system and of the cable TV system, thus providing valid information on the original withstand capability.
— ***Conclusion.*** This example illustrates the classic situation of nonadjacent service entrances, compounded with incorrect bonding. The examination and withstand test demonstrate that at least 2.5 kV can be developed across the power port and the cable TV port of that receiver under a condition of distant or nearby lightning strike.

A.2 Experiments and computations

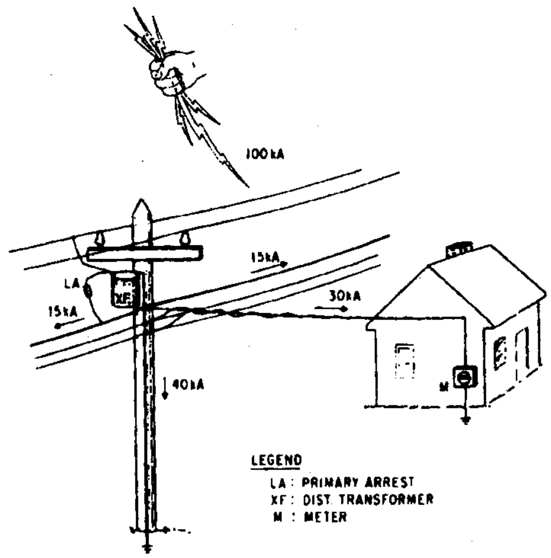
A.2.1 Injection of surges (Scenario I)

A.2.1.1 Injection into a simulated house model

A lightning strike terminating on the conducts of an overhead secondary distribution system will seek a path to ground that involves more than one grounding point of the system. Figure A.30 illustrates this situation, where a lightning strike of 100 kA is assumed to terminate on the primary conductors, with the arrester diverting this current to the multiple-grounded neutral conductor at the utility pole. The lightning current will divide into several paths to earth ground, as shown in the figure, according to the inverse of the impedance of each path of the parallel combination. The relative values shown in the figure are arbitrary and given merely to illustrate the concept; the level of 100 kA chosen for this example is based on the following analysis.

The frequency distribution of peak currents shown in Figure 15 indicates that only 5% of the first negative strokes will exceed a peak current of 100 kA. The frequency of the lightning flashes is dependent upon the geographic location (see the flash density map of Figure 3), and the point of strike, determined by the upward streamer, depends on local structure. A typical expectation of a stroke involving the pole of the utility distribution circuit near a house with no adjacent tall trees or buildings might be in the order of one per 400 years for most of the United States. Thus, at a 5% probability for 100 kA, the likelihood of the Figure A.30 scenario at any pole would be one time in 8000 years—but there are millions of poles in the United States.

Under a real-world scenario, it may be expected that massive flashovers would occur at the pole, involving all conductors. However, in the experiment of the laboratory simulation, the 30 kA current delivered by the laboratory 8/20 µs generator was only in the ground conductors as reported in Martzloff and Crouch 1978 [B117]; Crouch and Martzloff 1978 [B99], from which the data in A.1.1.2 (Figure A.3 through Figure A.6) were extracted. While the current was involving only the grounded (neutral) conductor of the service drop, this test may still be considered a Scenario I event. The results of this test indicated that a unidirectional current in the ground conductor can generate an oscillatory voltage appearing in the line-to-neutral (ground) at the service entrance.



Source: Martzloff and Crouch 1978 [B117]

Figure A.30—Dispersion of lightning current among multiple paths

Connecting a surge arrester at the service entrance of the building in Figure A.30 would allow the two phase conductors of the service drop to share the lightning current being dispersed toward the house. Under such an arrangement, each side of the service-entrance SPD would carry a third of the 30 kA current, so that an arrester rated 10 kA (8/20 µs) would be appropriate. On the other hand, a direct stroke to the service drop—a rare occurrence—might involve higher currents, a situation intermediate between a Scenario I and a Scenario II stress for the service-entrance SPD.

The voltage and current amplitudes described (***but not specified***) in the tables of IEEE Std C62.41.2-2002 attempt to represent typical surges impinging (Scenario I) or exiting (Scenario II) the building, but should not be considered "worst case" because the definition of what constitutes a "worst case" and the corresponding risk assessment involve subjective elements, as discussed in B.23.

A.2.1.2 Injection into a commercial/industrial building

A rare opportunity was offered to inject surges into an actual, new commercial/industrial building before and after it was populated with its full complement of equipment (Martzloff 1990 [B124]). Several test configurations were investigated, including injection of a 100 kHz Ring Wave at various points within the building and injection of a Combination Wave into the (unpowered) 480 V primary of the transformer feeding the building. The oscillograms of Figure A.21, corresponding to the injection at the transformer primary, illustrate how a unidirectional stimulus can produce oscillatory voltages in the wiring of the building. The tests also demonstrated that voltage surges propagate with very little attenuation (nor reflections) in branch circuits terminating into small loads (high impedance, or open circuit), hence the unbroken horizontal line for the voltage of Figure 9, with same level for the two Location Categories B and A. This fact was also significant for the revision of IEC 664 [B6] in which the earlier concept of installation categories was abandoned.

A.2.1.3 Limitation by clearance flashover

The limitation of voltage surges by flashover of clearances was recognized as early as the 1980 version of this guide and restated in the 1991 version as well as the present update (see Figure 14). As one of the "reality checks" suggested to moderate excessively high proposals for surge amplitudes in low-voltage circuits of a building, a study was conducted to demonstrate the physical impossibility for current surge with high amplitude and short rise time to propagate very far into a building (Mansoor and Martzloff 1997 [B115]). This study—under the epigraph of "More begets less"—included both an actual branch circuit originating from a service panel and a numerical simulation of that circuit. The results were in good agreement, allowing a parametric assessment of the likelihood of a clearance flashover for postulated surge characteristics, clearance withstand, and length of the branch circuit.

Table A.7 shows the results of the parametric assessment as a function of surge characteristics, wiring devices withstand capability, and length of a branch circuit terminating into a 130 V MOV. For all but the short branch circuit length (10 m) and moderate current amplitudes (5 kA at 10 µs rise time), the upstream voltages are clearly in excess of what the wiring device clearances might withstand (shown in shaded cells). Consequently, the varistor at the end of the branch circuit would be relieved from the energy being deposited after the clearance flashover. While it is not suggested that flashover of wiring device clearances is a desirable event, the end-result is still that the varistor would not be exposed to the full stress of a large, steep-front surge. Table A.8 shows the energy that would be deposited in a 130 V MOV for a scenario involving a 6 kV clearance flashover at the service entrance (likely to be performed by internal gaps of the revenue meter) for given values of the surge and of the branch circuit length. The energy levels without flashover (clear cells) are well within the range of typical varistors installed in Location Category A and are negligible when flashover occurs (shaded cells).

Table A.7—Upstream voltage (in kV) necessary to drive a current of the peak value shown and rise time of 10 µs into a branch circuit of length shown terminated with a 130 V MOV

Peak (kA) / Length (m)	2	3	5	7	10
10	2.3	3.3	5.2	7.2	10
30	5.8	8.5	14	20	27
50	9.3	14	23	32	45

Table A.8—Energy deposited in a 130 V varistor as a function of the branch circuit length and injected peak current, with clearance flashover set at 6 kV

Peak (kA) / Length (m)	2	3	5	7	10
10	17 J	27 J	51 J	670 mJ	220 mJ
30	17 J	130 mJ	30 mJ	23 mJ	18 mJ
50	70 mJ	35 mJ	17 mJ	11 mJ	10 mJ

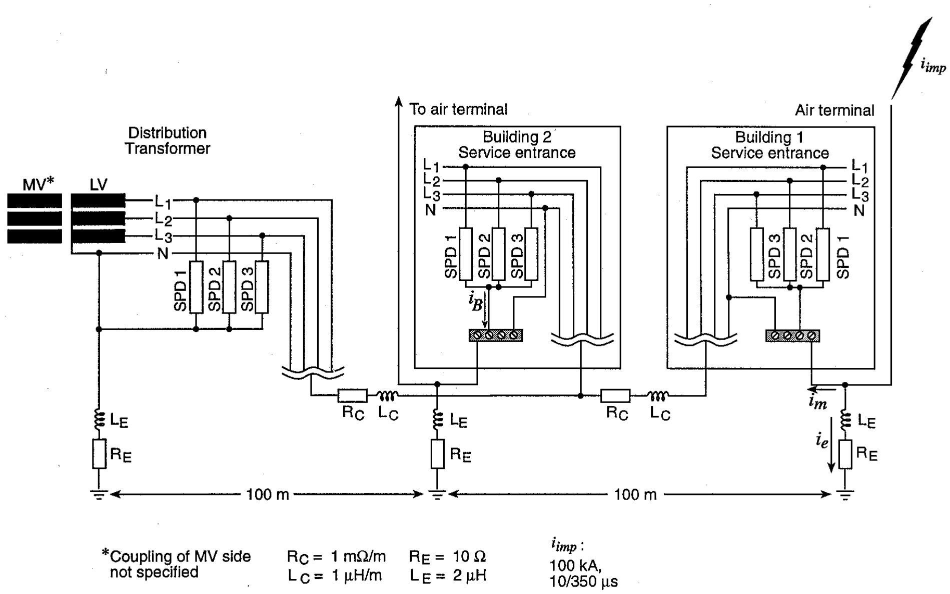
A.2.2 Computations

The literature contains several reports of projects conducted for assessing the dispersion of lightning current for the scenario of a direct flash to the building of interest. Two of these are summarized in this subclause. Another computation is presented in this subclause to illustrate the induction of significant surge voltages in the circuits of a building struck by lightning as the current flows in a down-conductor.

A.2.2.1 IEC 62066:2002 [B11] example

The first example of dispersion computation is given in IEC 62066:2002 [B11]. In this model, two buildings are supplied from a distribution transformer with lightning striking the second building. Table A.9 shows the currents occurring in the available paths for the postulated surge. According to the proposals of IEC 61312-3:2000 [B9], this lightning flash would have a peak of 100 kA and a waveform of 10/350 µs.

At Building 1 of Figure A.31, the injected current i_{imp} flows from the air-termination system of the lightning protection system through the down-conductor to the earth-termination system. At that point, the lightning current divides into two components, i_e flowing into the local earth of the building, and i_m flowing through the power supply cable toward the distant earth. These two currents divide according to the inverse ratio of the impedances. In the initial phase of the impulse current, the current division is determined by the ratio of the inductances. In the later phase of the dispersion, the current division is determined by the ratio of the earthing resistances. It is noteworthy that it is not the absolute values of the earthing resistances that determine the dispersion, but their relative values.



Source: IEC 62066:2002 [B11]

Figure A.31—Model for computing dispersion of lightning current among parallel buildings

With several buildings electrically connected, the effective resistance R_m decreases. In other words, the portion of the lightning current that flows out of the struck building into the low-voltage system will increase when more buildings are connected into the string. For the example of Figure A.31, Table A.9 shows the current amplitudes among the available paths to earth (after the initial inductance-dominated stage) For these computations, no evidence was found of any oscillations caused by reflections, because of the low 10 Ω earthing impedances and no capacitances having been postulated in the model (Birkl et al. 1996 [B97]).

As a general conclusion, the higher the density of buildings in an area, the greater the portion of the lightning current flowing to earth through the incoming low-voltage power system cable. This conclusion has implications for the building being struck as well as for adjacent buildings.

Table A.9—Current dispersion in available paths in the example of Figure A.31 (10/350 µs, 100 kA stroke)

Available path to earth	Approximate current amplitude, kA (beyond initial stage)	Approximate charge, C
Earthing electrode(s) of Building 1($i_{Earthing}$)	33	165
Outgoing from Building 1 toward Building 2 by power supply cable		
Total (i_{mains})	66	33
Direct by Neutral	17	9
Through SPD1	16	8
Through SPD2	16	8
Through SPD3	16	8
Earthing electrode of Building 2		
Total	34	16.5
Direct by Neutral	9	4.7
Through SPD1	8	4
Through SPD2	8	4
Through SPD3	8	4
Outgoing from Building 2 toward transformer station by power supply cable		
Total	33	16
Neutral	9	4.5
Line 1	8	4
Line 2	8	4
Line 3	8	4

A.2.2.2 Effect of neutral grounding practices

Different practices on earthing the neutral are found in different countries, so that some differences can be expected in the way the lightning current will disperse among the available paths. In Mansoor and Martzloff 1998 [B116], the modeling included several types of distribution systems and grounding practices. When the neutral is earthed at every building, as in a TN-C-S system, no SPD is involved in the neutral conductor paths, providing some relief for the other SPDs associated with the line conductors. For instance, Figure A.32 shows a radial configuration with three service drops connected at the secondary terminals of a distribution transformer. One of the buildings is postulated being struck by a 100 kA, 10/350 µs stroke. For the values of earthing impedance shown in the figure, the peaks of the lightning current that exits the building via the three conductors are shown in the figure. (The source paper provides additional details on the waveforms.) As previously mentioned, it is the relative values of the earthing impedances that determine how much of the lightning current exits via the power system connection. Note the significant, but not very large, difference between the current carried by the neutral conductor and the current in the phase conductors that involve the additional voltage drop across the service-entrance SPD. In this model, the postulated earthing resistances were 5 Ω at the transformer and 10 Ω at the two other buildings. If a PDS includes many earthing electrodes on its multiple-grounded neutral, then the relative impedance of this neutral conductor, compared to the impedance of the phase (live) conductors, can be much lower, thus reducing the stress imposed upon the SPDs involved in the exit path.

The literature contains a large number (over 15 000) of lightning-related papers (Martzloff 2000 [B127]) where computations made by other researchers might be found. For the purpose of this annex, the two examples cited are based on the assumption of a fixed value for the earthing resistances, postulated to be a simple linear resistance and an inductance. More sophisticated models might be considered where the earthing impedances vary with the amplitude of the current or where capacitive effects seem to be involved (Fernandez et al. 1998 [B105]; Mata et al. 2000 [B130]).

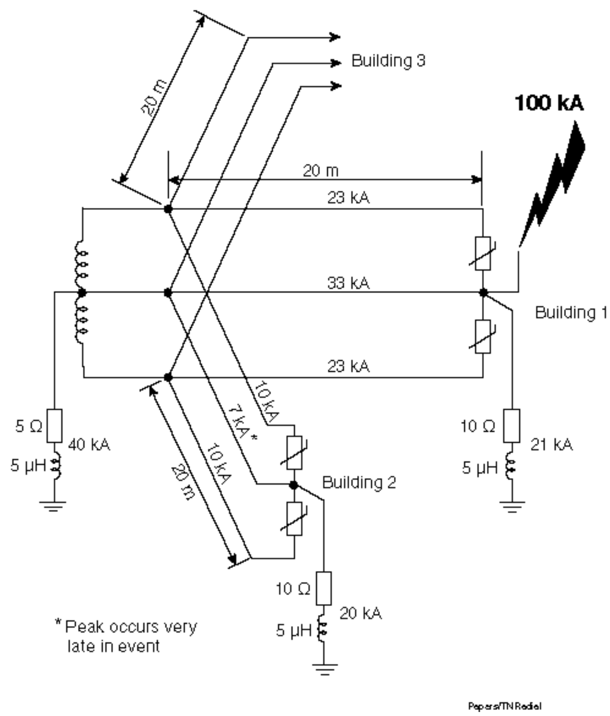


Figure A.32—Dispersion of the lightning current in a radial configuration

A.2.2.3 Voltages induced in cables adjacent to down-conductors

To place some of the Scenario II effects in perspective, computations were performed to quantify the voltages that might be induced during the flow of a lightning current in the down-conductor of a building that received a direct stroke. The voltage induced in a circuit loop by the current with a rate of rise d*i*/d*t* can be determined by the relationship

$$U = M \times \mathrm{d}i/\mathrm{d}t$$

where

U is the induced voltage;
M is the mutual inductance between the loop and the current-carrying path.

As one method of computing the induced voltage,[14] Figure A.33 shows the relative position of the down-conductor and the loops formed by a conductor pair, for a lightning stroke on the air terminal. Two cases are considered: a vertical cable parallel to the down-conductor and a cable perpendicular to the cable. The "loops" are formed by two conductors, bonded at one end and open at the other end, where they would be connected to input terminals of some equipment. The input port of that equipment would then be subjected to the induced voltage, *U*.

[14]Data contributed by W. Zischank.

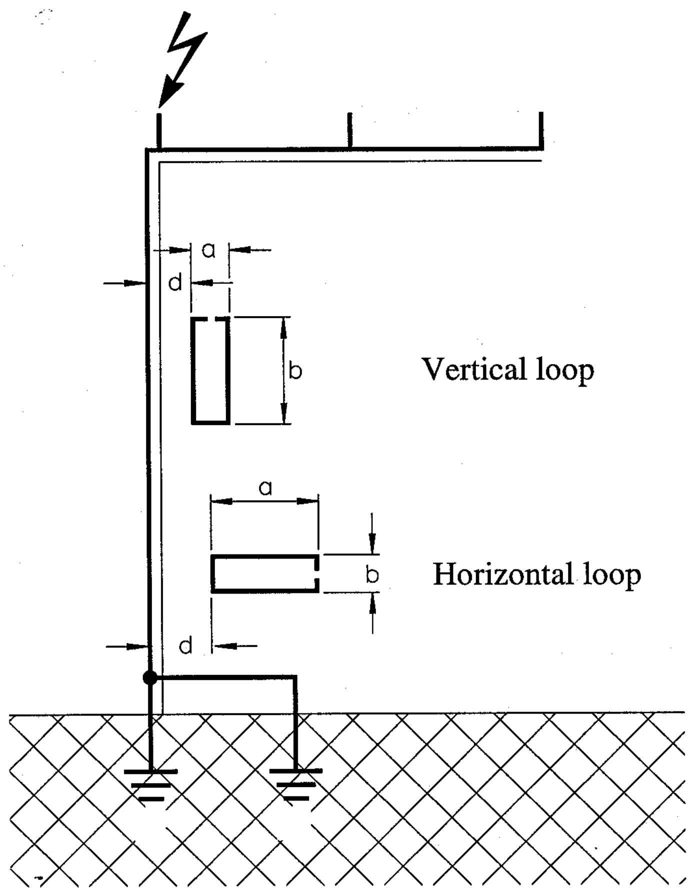
For the geometry defined in Figure A.33, the induced voltage becomes

$$U = 0.2 \times 10^{-6} \times b \ln[(d + a)/d] \times \mathrm{d}i/\mathrm{d}t$$

where

U	is in volts;
$\mathrm{d}i/\mathrm{d}t$	is in amperes per second;
The ratio $[(d + a)/d]$	is dimensionless;
b	is in meters.

Because the waveforms, particularly the rates of rise, are quite different for the first return stroke and subsequent strokes, Table A.10 shows values of the induced voltages for the case of a postulated 100 kA, 10/350 µs waveform (first return stroke) and for the case of a postulated 50 kA, 0.25/100 µs waveform (subsequent stroke). These computations do not include common-mode coupling, should some point of the loop be bonded to the equipotential bar at the base of the building. For the short values of the distance d shown in the table, such a bond would result in a side-flash for a length b of a few meters.



LEGEND

In a plane containing the down-conductor, the cable pair is parallel:

- The two conductors are separated by a.
- The closest side of the pair is at distance d from the down-conductor.
- The length of the cable is b.
- The voltage is computed for the open end.

In a plane containing the down-conductor, the cable pair is horizontal:

- The two conductors are separated by b.
- The closest end of the loop is at distance d from the down-conductor.
- The length of the cable is a.
- The voltage is computed for the open end.

Figure A.33—Relative positions of down-conductor and cables in the building example

Table A.10—Induced voltage in cable loops (*V*) for several configurations and current rate of rise

Rate of rise (kA/µs)	Cable loop	*a* (m)	*b* (m)	*d* (m)	
				1.0	10
27 (first stroke)	Vertical	0.01	1	54	5.4
	Horizontal	1	0.01	37	5.1
270 (subsequent stroke)	Vertical	0.01	1	540	54
	Horizontal	1	0.01	370	51

These values of induced voltages can be sufficient to cause malfunction or damage. Anecdotal observations have shown that damage or upset is most frequently associated with flashes involving subsequent strokes.[15] Note that the maximum rate of rise d*i*/d*t* cannot be directly determined from the rise time and the peak amplitude. Determining the maximum d*i*/d*t* requires the assumption of an underlying equation that fulfills the set of the three parameters i_{max}, T_1 (front time), and T_2 (duration). This assumption has significant influence for two commonly used equations:

Double exponential wave: $$i = \frac{i_{max}}{\eta} \times \left[\exp\left(-\frac{t}{\tau_1}\right) - \exp\left(-\frac{t}{\tau_2}\right)\right]$$

S-shape front wave (IEC): $$i = \frac{i_{max}}{\eta} \times \frac{(t/\tau_1)^{10}}{1+(t/\tau_1)^{10}} \times \exp\left(-\frac{t}{\tau_2}\right)$$

where

η is a correction factor for direct insertion of the desired peak current value into the formula;
t is time.

The values for the parameters in these equations are given in Table A.11, and examples of values are shown in Table A.12.

As a second method, curves for assessing the induced voltages as a function of the configuration, vertical or horizontal cables, have also been developed, incorporating the corresponding mutual inductance (Weisinger and Hasse 1977 [B205]). Figure A.34 and Figure A.35, redrawn with English translation from the German source handbook, give the value of a coefficient k_u from which the induced voltage can be calculated by a simple formula.

Induced voltage in vertical loop: $U_v = k_{U3} \times$ kA/µs (per meter of loop length)

Induced voltage in horizontal loop: $U_h = k_{U4} \times l \times$ kA/µs (l and b in meters)

[15] Observation communicated by M. F. Stringfellow.

Table A.11—Equation parameters for double exponential or S-shape front

Waveform	i_{max} T_1 / T_2	η	τ_1	τ_2
Double exponential	200 kA 10/350 µs	0.951	470.1 µs	4.0641 µs
	50 kA 0.25/100 µs	0.995	143.1 µs	92.4 ns
S-shape front	200 kA 10/350 µs	0.93	19 µs	485 µs
	50 kA 0.25/100 µs	0.993	0.454 µs	143 µs

Table A.12—Maximum d*i*/d*t* for two "10/350 µs" waveforms with same parameters, but different underlying equations

i_{max} (kA)	T_1 (µs)	T_2 (µs)	Maximum d*i*/d*t* (kA/µs)	
			S-shape front	Double exponential
200	10	350	27	50
50	0.25	100	270	540

Example:

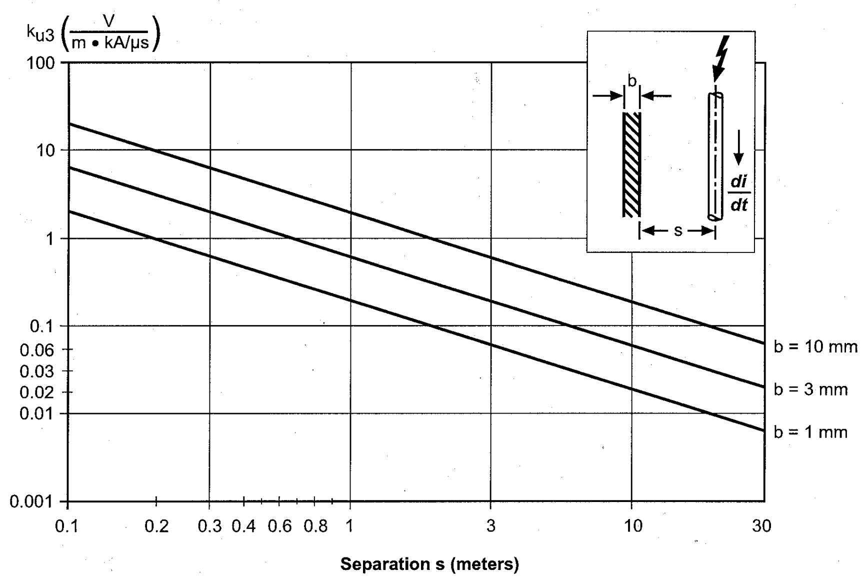
— Vertical cable with 10 mm between conductors, 1 m long, and 1 m from the down-conductor
— Read k_{U3} = 0.2 on upper curve of Figure A.34
— With a 270 kA/µs rate of rise (subsequent stroke):

$U_v = 0.2 \times 270 = 54$ V (same as the value from Table A.10)

For the sake of a complete analysis, some other mechanisms should be mentioned, which would contribute to the voltage stress across the terminals of the loops, such as electric field effects and radiation. Capacitive coupling between the down-conductor and a loop not bonded to earth could produce a common-mode voltage appearing over the whole loop with respect to earth. That effect could be increased if a corona sheath would develop around the down-conductor in extreme cases. However, these additional effects would be small enough, compared to the magnetic induction discussed above, and may be neglected in most cases.

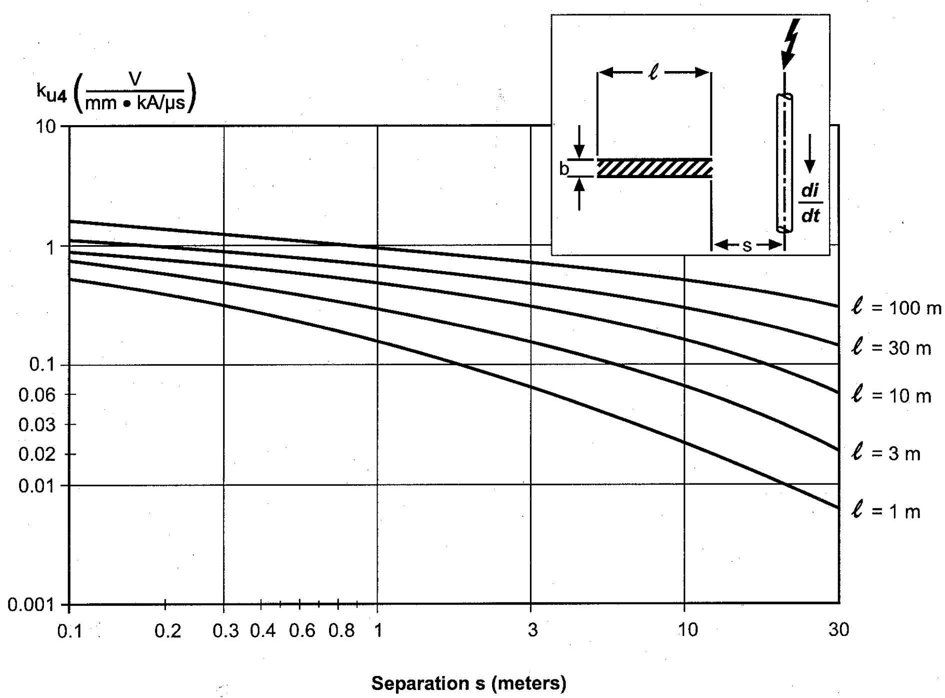
A.3 Inferences from field experience

Documented case histories of equipment failures attributable to surges are a valuable addition to the database. Likewise, documented successful field experience also provides information on the surge environment. In the epoch preceding the proliferation of SPDs, the case history of clock motor failure rates gave a strong confirmation to the recognition of a correlation between the rate of occurrence and the levels of voltage surges. Another observation, applicable to that pre-SPDs epoch but later confirmed by experiments, the failure mode of incandescent light bulbs, provided an input on the frequency of occurrence of surges. In a more recent period, the low failure rate reported by a manufacturer of distribution arresters and low-voltage SPDs also provides a reality check on the occurrence and magnitude of surges. These three examples are briefly summarized in the following paragraphs. It is likely that many similar situations have been observed, but not formally documented.



Source: Weisinger and Hasse 1977 [B205]

Figure A.34—Coefficient for calculating the induced voltage in a vertical cable parallel to the down-conductor



Source: Weisinger and Hasse 1977 [B205]

Figure A.35—Coefficient for calculating the induced voltage in a horizontal cable parallel to the down-conductor

A.3.1 Clock motors

In the early 1960s, long before the proliferation of SPDs and digital clocks, a particular design of the clock motor resulted in an unacceptable failure rate. A posteriori tests to assess the surge withstand capability of that design showed a typical failure level at about 2 kV (1.2/50 µs impulse). Subsequent redesign of the motor for a 6 kV withstand level produced a 100:1 reduction in the failure rate (Martzloff and Hahn 1970 [B78]). From this observation, the conclusion can be drawn with a high level of confidence that 6 kV surges were at that time 100 times less frequent than 2 kV surges. This high degree of confidence is based on the experience of thousands of failures that were reported for clocks of the 2 kV design versus survival of more thousands of clocks after the redesign.

There is some uncertainty about the exact value of these two numbers, 2 kV and 6 kV, because the actual failure level of individual clocks at each of the two test levels, and in the field, undoubtedly followed some statistical distribution. The ratio of the failure rates, however, reflects the rate of occurrence between the two levels. The "surge monitoring" by these 2 kV clocks was performed at tens of thousand locations on a continuous basis, in contrast with the conventional monitoring surveys reported in the literature, involving a much smaller number of units and much shorter durations. The 100:1 reduction provided a highly reliable confirmation of the slope of the frequency distribution, as shown in Figure 14 and Figure A.9 of this guide.

A.3.2 Incandescent lamp failure levels

The data in the 1991 version of this guide included remarks on the failure levels of light bulbs, as observed in laboratory experiments showing that most designs of 120 V light bulbs fail when subjected to surges in the range of 1.1 kV to 1.5 kV. Inferences could be drawn according to the following logic:

a) The common experience of all consumers has been that incandescent lamps typically fail in three modes, although these failures generally do not occur frequently within the expected life of the bulb:
   1) During current inrush associated with turn-on, after some aging of the filament, sometimes with a bright flash.
   2) At some undetermined time, a failure occurring without witness;
   3) During normal operation of the bulb, with a bright flash.
b) Knowing that bulbs typically fail with surges in the range of 1.1 kV to 1.5 kV, if premature failures of the third type are noted to be rare, it means that the occurrences of surges above this range are also rare.

This logic was applied to the observations made before the proliferation of SPDs, which one could now expect to reduce the occurrence of the third mode (triggered by surges above a critical level). Because the mechanisms producing these surges have not been affected by the proliferating SPDs, the conclusions offered in 1991 are still valid.

The third failure mode has sometimes been observed during lightning storms and occasionally without any obvious power disturbance or mechanical shock applied to the lamp. The laboratory tests showed that this failure mode can be precipitated by applying surges to the lamp power supply. This scenario of failure mode can readily explain the anecdotes of more frequent failures of this type in summer cottages (long overhead lines), illustrating the definition of the "high exposure" as mentioned in 6.6.8.

This failure is associated with an internal flashover, triggered by the surge. A test series was also performed, applying surges just short of the flashover to a bank of energized light bulbs, with an identical bank of energized light bulbs but not subjected to the surges. After 50 000 surges over a period of several weeks, no bulb had failed in either bank, an indication that accumulated mechanical fatigue of the filament associated with a surge current was not involved. These results were communicated informally to the working group during the development of the 1991 version of this guide, although not documented in a formal report.

These somewhat anecdotal data resurfaced during the development of the IEC report on surges (IEC 62066:2002 [B11]), leading to a replication of the laboratory tests, this time with published and peer-reviewed documentation (Bachl et al. 1997 [B24]). These tests were performed at a laboratory in the United States and at a laboratory in Austria, using 120 V bulbs and 240 V bulbs at both laboratories. The applied surges were the Ring Wave as well as the Combination Wave. The conclusions reached from this more systematic investigation were

- The surge level necessary to trigger the power-frequency flashover depends on the phase angle of the applied surge and on the energy deposited in the plasma of the initial sparkover by the surge.
- For surges with high energy-delivery capability, such as the Combination Wave, typical 120 V bulbs experience failure with levels as low as 800 V, and 240 V bulbs with levels as low as 1800 V.
- For surges with low energy-delivery capability, such as the Ring Wave, typical 120 V bulbs experience failure with levels as low as 2100 V, and 240 V bulbs with levels as low as 2200 V.

Thus, the inferences made from the 1991 database were confirmed, with additional qualitative information. With the relatively rare occurrence of failures observed by consumers under no-disturbance conditions, the inescapable conclusion is that surges such as those represented by the Combination Wave with levels above about 1000 V are rare, and surges of low energy-delivery capability represented by the 100 kHz Ring Wave with levels above about 2000 V are also rare.

A.3.3 Distribution arresters and low-voltage SPDs

Metal-oxide surge arresters have widely replaced traditional silicon carbide (SiC) arresters for overvoltage protection. When a surge occurs, an SiC arrester will operate and let through the surge current. After the surge disappears, the SiC arrester will continue to carry a follow current of several hundred amperes until a current zero is reached or the arrester gaps deionize. Energy dissipated in SiC arresters is mainly due to the follow current and not to surge impulses. The failure rate of SiC arresters was significant and led to the misconception that higher lightning stroke intensity parameters should be considered.

MOV arresters have non-linear characteristics and do not experience follow current. Modern MOV distribution arresters are designed to satisfy IEEE Std C62.11-1993 [D.1.1] or -1999 [D.1.2], which include 4/10 μs and 2000 μs test waveforms. For secondary arresters, only the 4/10 μs withstand test is required. Surge arresters designed according to that standard are very reliable devices and have very low failure rates (according to one manufacturer only 50 failures in 1 000 000 arresters with almost all attributed to TOVs even when applied in high isokeraunic areas (Goedde et al. 2000 [B27]).

When a lightning flash strikes a distribution line, gapless arresters will operate and share some energy with other nearby arresters that operate so the arrester will see less energy than if operated alone. Under the same conditions, because of the operating characteristics of the gap, only one series-gapped metal-oxide arrester will operate and it will not share energy. Field experience shows that series-gapped metal-oxide arresters are as reliable as gapless arresters and have comparable failure rates. This observation weakens the rationale that energy sharing by multiple nearby arresters on distribution lines would reduce the stress on arresters. This also indicates that the lightning stroke energy seen by arresters is not as high as previously assumed on the basis of the SiC arresters field experience.

The 1998 issue of IEC 61312-3 [B9] specifies some new lightning current parameters for surge arresters, which include 10/350 μs test waveforms with current magnitudes up to 200 kA. This type of waveform has a longer decay time than the impulse test waveforms and larger charge transfer than the rectangular test waveform specified by IEEE Std C62.11-1999 [D.1.2], resulting in higher overall energy deposition or charge transfer.

Current practices in surge arrester application and operation indicate that arrester designs based on IEEE Std C62.11-1999 [D.1.2] test requirements provide reliable overvoltage protection in distribution and low-voltage systems, as documented in Goedde et al. 2000 [B27]. This paper presents a comparison of different surge arrester characteristics, together with a review of the effectiveness of existing overvoltage protection practices in distribution and low-voltage systems. This paper also presents surge arrester failure rates, and a discussion of the surge arrester characteristics required for reliable overvoltage protection.

The logic offered as an axiom in 6.5 of this guide, concerning the validity of environment standards is indeed applicable in this case: ... if arresters designed in accordance with a standard perform well in the field, the chances that the standard be a good standard are pretty good. Thus, it would appear that the requirements of IEEE Std C62.11-1999 [D.1.2] are a valid representation of the stresses typically encountered by distribution and secondary arresters.

A.4 Discussion of the database

A.4.1 Review of published recordings

This review first provides a chronological listing of published papers reporting surge monitoring surveys performed by independent researchers, with a synopsis of each paper. A comparison is then presented on the difference among the reported results, including differences in surge amplitudes, waveforms, and rates of occurrence.

A.4.1.1 Bull and Nethercot

In a 1964 article [B57], Bull and Nethercot report monitoring performed in the mid-1960s on 240 V systems in Great Britain with instruments of their design. Their first instrument used vacuum tubes, leading to the development of a solid-state circuit, which may be considered the forerunner of modern monitors. The instrument had several channels, each with a different threshold. Eventually, the solid-state instrument was made available commercially, and several units of that design were used in some of the monitoring performed in the United States, as cited under A.1.1.1 and A.1.1.4.

The monitoring locations were selected to include a variety of conditions, with data collected for several weeks at each location, over a total period of two years. The results do not mention transients above 600 V. It seems that no channels were provided above that level because the authors were only concerned with the range of 50 V to 600 V.

A.4.1.2 Martzloff and Hahn

In a 1970 paper [B78], Martzloff and Hahn report the highlights of measurements made from 1963 to 1967 on residential, commercial, and industrial circuits, mostly single-phase 120 V. Waveform data were obtained with commercial, custom-modified oscilloscopes fitted with a motor-driven camera. These oscilloscopes were installed a various locations where transient activity was suspected. In addition, a peak counter was developed and 90 units with a 1.2 kV or 2.0 kV threshold were deployed at 300 locations where there was no prior suspicion of unusual transient activity.

The oscilloscope data gave one of the first indications that the traditional unidirectional impulse, long used for dielectric testing, might not be representative of surges occurring in low-voltage circuits. The threshold data indicated locations where surges above 1.2 kV occur frequently (about 3% of the sample), while other locations appeared to be far less exposed to surges. The 100:1 reduction of an alarming failure rate of clock motors, achieved by increasing the surge withstand capability of the motors from 2 kV to 6 kV, is documented in that paper.

A.4.1.3 Cannova

In a 1973 paper [B58], Cannova reports the monitoring of surges on US Navy 120 V and 450 V shipboard power systems performed in the late 1960s. Instrumentation used for the initial phase of the monitoring program consisted of oscilloscopes similar to those used by Martzloff and Hahn 1970 [B78]. Provision was also included for the option of measuring the transients alone (through filters) or superimposed on the ac line voltage. This option reflects the old dichotomy, still unsettled to this day, about whether the transients should be measured as an absolute value or as a deviation from the instantaneous value of the ac sine wave (see Table 2). The results are not reported separately for 120 V and 450 V systems; it is not possible to express them in per-unit terms or as percentage of the nominal system voltage.

Cannova's statistical treatment aims at fitting the recorded transients to a normal distribution and concludes that a log-normal distribution is a better fit. A brief statement is made on the duration of the recorded transients (without a statement on how those durations are defined), citing a majority of durations between 4 µs and 6 µs, with a few at 19 µs. From the database, acknowledged to be a small total number of events, a protection level of 2.5 kV was defined. Two aspects of the conclusions are especially worth noting:

1) There was no information on the source impedance of the surges, and yet the data eventually served to specify requirements for SPDs.
2) A large difference in frequency of occurrence was noted among ships of the same type and class, similar to the observations made on land-based surveys.

A.4.1.4 Allen and Segall

Allen and Segall, in a 1974 paper [B47], report the monitoring of several types of power disturbances at computer sites, performed with oscilloscopes, oscillographs, and digital instruments, from 1969 to 1972. Details of the instrumentation were described in a separate paper (Allen 1971 [B146]). Disturbances are described as overvoltages and undervoltages, oscillatory decaying disturbances, voltage spike disturbances, and outages. The terms *sag* and *swell* had not yet made their appearances in the jargon.

The survey was conducted in two phases. In a first phase, preliminary information was obtained on ranges of disturbances, leading to the development of a second generation of monitors deployed in the next phase. The recorded disturbances are described by plots and histograms.

The highest surge recorded in the first phase is shown as 350 V. In the second phase, the monitors grouped all surges into three categories, the highest having a range of 100% (of line voltage) to infinity, so that no detailed information is provided to describe high peak values. The survey does report in detail the occurrence of undervoltages and overvoltages, providing a basis for the comparisons with the Goldstein-Speranza study described in A.4.1.5.

A.4.1.5 Goldstein and Speranza

In a 1982 paper [B69], Goldstein and Speranza report monitoring several types of disturbances at a variety of locations in the Bell System, with digital multiparameter instruments, from 1977 to 1979. The conditions of the survey are documented, including instrument locations and parameter definitions, as well as the methods of data processing.

The findings are only briefly reported because emphasis is on predictions of disturbances expected at a specific sites. The prediction is obtained by using a statistical model derived for all sites and making adjustments reflecting specific site conditions determined by a limited survey at that site. The authors are emphatic about the point that the lack of correlation between sites prevents a blanket application of the overall findings to any specific site, but that useful predictions are possible by combining the overall data with limited knowledge on specific site data. This concept is echoed in Figure 14, presenting the frequency of occurrence in graphic form.

A Polya distribution is identified by Goldstein and Speranza as the best fit for this type of data on rare events, in contrast to other surveys where their authors attempted to fit a normal distribution or a power or exponential law profile.

A.4.1.6 Meissen

In a 1983 paper [B81], Meissen reports the measurement of surges associated with the clearing of a fault by a current-limiting fuse in various industrial environments. The paper does not include oscillograms that would define the waveforms in detail, but does include several graphs showing the relationship between the peaks and the duration of the surges. Peak values are quantified in terms of x times the crest of the power-frequency voltage, with values of x typically ranging from 1 to 3, and exceptionally from 1 to 10 for some of the lower ampere ratings of the fuses. The durations of the surges [full width at half maximum (FWHM)] range from 0.1 ms to 3 ms. See also the previously unpublished results of measurements in Dutch residential distribution systems cited in A.1.1.6 (Figure A.10 through Figure A.12) that report comparable events.

A.4.1.7 Wernström, Broms, and Boberg

Wernström, Broms, and Boberg, in a 1984 report published in Sweden and circulated in the United States as a draft English translation [B96], report monitoring of industrial 220/380 V systems by digital multithreshold instruments, corroborated by waveform recordings with digital storage oscilloscopes. The parameters to be recorded and reported are defined in an introductory section; however, their description of “common mode” and “differential mode” in the English translation does not correspond to symmetrical and asymmetrical voltages defined by the IEC. In the section discussing transient sources and propagation, they make a significant comment that “common mode voltages are the most interesting and at the same time are the voltages most difficult to defend against.”

The range of surges recorded extends from 0.2 kV to 2 kV. In a summary tabulation, rise times are shown as ranging from 20 ns to 200 ns and duration from 0.2 µs to 2.5 µs. An interesting additional measurement was made by simultaneous recordings at two distant points of the PDS, showing some aspects of the propagation and attenuation of a surge. Simultaneous multiple-point recordings provide important results for individual users considering surge protection in distributed electronic systems, such as local area networks. The survey shows a wide difference of surge activity among sites, but a relatively constant slope of the rate of occurrence versus level.

A.4.1.8 Aspnes, Evans, and Merritt

In a 1985 paper [B49], Aspnes, Evans, and Merritt report a survey of the power quality in rural Alaska at isolated power generation facilities. The monitoring instruments are identified as one of the contemporary commercial digitizing monitors. A comprehensive summary of the recordings is presented, including “sags” and “surges” (the latter would be called “swells” according to the definitions of this document), “impulses” (i.e., surges), and outages.

Some ambiguity surfaced in connection with the possibility that built-in surge protection in the monitors might have attenuated the surges being recorded. Knowing the source impedance of the surges (not the impedance at power frequency) would have settled the issue. This case history points out, again, the desirability of including surge current monitoring in future surveys, as a method of characterizing the source impedance of the surges.

A.4.1.9 Odenberg and Braskich

In a 1985 paper [B84], Odenberg and Braskich report monitoring computer and industrial environments with a digital instrument capable of the simultaneous recording of voltage surges and current surges. This new capability for relating voltage and current shows a growing awareness of the need to monitor current surges—an improvement over previous surveys that were limited to the measurement of voltages. However, the reported surge currents are those of a current toward undefined loads downstream from the instrument; they do not include any measurement of the current through a shunt-connected surge diverter, a measurement that would have provided new information on the source impedance of the surges.

The digital processing applied by the instrument yields two points of the surge: the peak value with the time to reach peak, and the time elapsed until decay to 50% of the peak value (see Figure A.36). From these two points, a "waveform" description is proposed, without any other information on the actual waveform. From a large number of recorded surges (over 250 000 events), a startling finding is cited, that 90% of the recorded surges have their 50% point in a narrow window of only 900 µs to 1100 µs. Attempts to reconcile this singular finding with the observations reported by other surveys have not been successful.

A.4.1.10 Goedbloed

In a 1987 paper [B67], Goedbloed describes in detail a custom-built automated measurement system used to monitor 220/380 V networks in Europe. By combining two commercial recorders with a custom interface, the system developers obtained recordings with a 10 ns sampling interval and 20 µs window on the first recorder and a 1 µs sampling interval with 2 ms window for the second recorder.

The system included provisions for automated data reduction, yielding raw data as well as statistical information on amplitude, rate of rise, energy measure, spectral density, and conversions from time domain to frequency domain. With a relatively low threshold of 100 V above the line voltage, the distribution of occurrences is weighted toward low amplitudes; nevertheless, some occurrences are reported above 3 kV.

The Goedbloed paper also addresses indirectly the question of normal-mode versus common-mode surges by discussing "symmetrical voltage" and "asymmetrical voltage" as defined in the IEC *Multilingual Dictionary of Electricity* [B3]. An indirect definition is proposed for a third type used in the survey and identified in the paper as "the so-called non-symmetrical voltage" (line to grounding conductor, called "protective earth" in Europe).

Looking for guidance in IEC definitions does not help much: the IEC definition addresses delta networks, but the Goedbloed paper states that nearly all networks monitored were of the TN type (phase, neutral, and protective-earth conductors). The paper clearly states the mode of connection, so that there is no ambiguity, but this instance serves again to illustrate the need to harmonize definitions.

A.4.1.11 Standler

Standler, in a 1989 paper [B94], describes the wave shapes of transients measured between line and grounding conductors and between the neutral and grounding conductors in a residence. Statistical analysis showed that the common-mode voltage is usually much larger than the differential-mode voltage. The paper also showed that about half of the observed events during monitoring had maximum values of dV/dt greater than 0.7 kV/µs, and about 10% had maximum values greater than 1.3 kV/µs. By comparing rates of events when the home was occupied to when it was not occupied, it was concluded that 60% of the transients observed in an occupied residence had an origin inside the building.

A.4.1.12 Dorr

The Dorr measurements [B63], as were the Martzloff and Hahn measurements [B78], were made on single-phase or polyphase systems, between line and neutral, for the purpose of assessing the stress applied to electronic components connected between line and neutral. Because the North American practice is to bond the neutral to the local earth at the service entrance, these measurements also represent the line-to-earth stress. In contrast, some of the measurements reported by other researchers cited in this annex were made from line to the local earth (not the grounded neutral as in North America), for the purpose of assessing the stress applied to the equipment insulation. A noteworthy finding is the small number of surges reported in this survey, most likely the result of the proliferation of SPDs in the monitored locations.

A.4.1.13 Hughes and Chan

The Canadian Electrical Association commissioned in the 1990s a survey of power quality parameters, a summary of which is reported in Hughes and Chan 1995 [B74]. A total of 550 customer sites were monitored, each for about one month, and the results combined by categories, from which "profiles" were reported. The four categories were industrial, commercial, residential, and the points of delivery from the distribution systems. The emphasis of the survey was not on surges ("transients") but on comparing the complete array of disturbances to an envelope derived from the so-called CBEMA curve, which the authors call "Power Quality Envelope." This envelope has an aspect similar to the conceptual relationship shown in Figure 1 (in Clause 1) of this guide. The summaries of the recordings show the statistical distribution of events in percent of the base voltage as a function of the duration from 2 μs to 10 s, from which the transient activity can be obtained. Figure A.26 is an example of the graphical representation of the statistics.

A.4.1.14 Sabin

In a 1996 report [B92], Sabin presents a statistical analysis of a comprehensive power quality survey performed on distribution systems. However, the major emphasis of the survey was to characterize low-frequency disturbances (harmonics, sags, interruptions, and primary-side capacitor-switching transients). The monitoring instrument did not have the band-pass for recording microsecond-type events.

A.4.1.15 Ackermann et al.

In two successive papers ([B44]; [B45]), Ackermann and co-workers report the results of surge monitoring performed in Germany. In the first part of the investigation 40 measuring points were monitored, covering commercial and industrial locations, as well as office buildings and residential buildings The source article reports peak voltages but does not provide information on wave shape because the main objective was to assess the stress on insulation. In the second part of the investigation, overvoltages were measured at 25 locations where frequent and severe overvoltages might be expected. The locations selected were in 400 V installations, and the measurements were made from line to protective earth.

The authors state expectations that frequent and severe overvoltages would be found at the "high-risk" locations, but report that these expectations were not validated. At some locations, not even the 500 V threshold was exceeded. With hindsight, it would seem that in spite of the statement that all SPDs that were "detected" at the measuring point were removed, it is likely that some SPDs remained in the circuits. It is difficult to guarantee that all SPDs were disconnected, considering the widespread practice to have built-in SPDs in modern equipment.

A.4.2 Explaining differences in the results

Apparently significant differences can be found in the results reported by the researchers in the period extending from the 1960s to the 1990s. These differences involve the amplitudes (and their distribution) as well as the waveforms of the surges (when reported).

A.4.2.1 Differences in reported amplitudes and rates of occurrence

The amplitudes of the surges reported in the surveys vary over a wide range, and comparisons are difficult because the data are not presented in a uniform format. An attempt was made to get a quantitative comparison of the amplitude distributions reported in these surveys. However, the exercise was found to be futile, because of the following two main reasons (Martzloff and Gruzs 1988 [B192]):

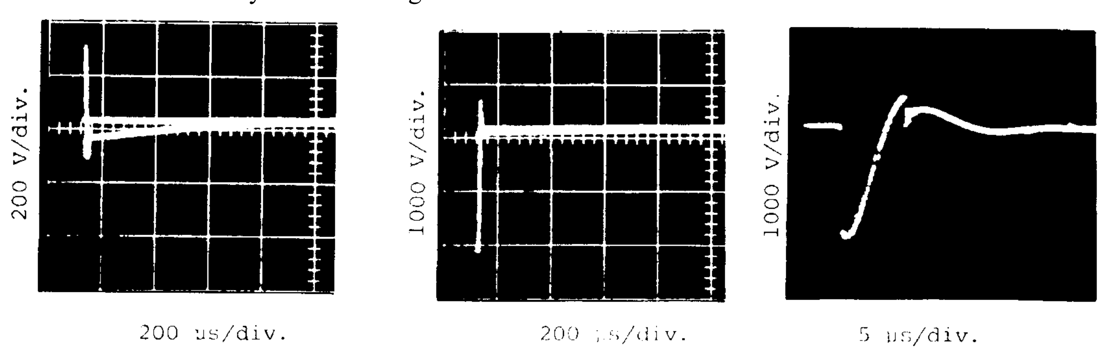
— Looking at the "maximum values," one finds that in some surveys the quoted maximum is actually a value in excess of the range of the instrumentation while for others it is the measured value. There are too few points and insufficient information to attempt a statistical treatment of this truncated database (censored data in statistical terms). Furthermore, the quoted value in some surveys is the total voltage (instantaneous value of the ac sine wave plus surge), while in others the sine wave has been filtered out. When surges are in the range of several thousand volts (the concern being damages), the difference between the two definitions is not significant; however, when the surges are in the range of a few hundred volts (the concern being malfunctions), the difference is significant.

— Because the lower threshold setting of the recording instrument varies among surveys and the frequency of occurrences increases dramatically with lower threshold settings, the labels of average, median, most frequent, typical, etc., are not meaningful (and might be misleading) for comparing amplitudes.

For these two reasons, any comparison at the present stage of inconsistency in report format can only be qualitative. Conjecture or speculation, rather than hard fact, might explain the differences as illustrated by the following three examples.

1) Two of the surveys listed in A.4 have been widely cited, one performed in the early 1970s by Allen and Segall [B47], the other in the early 1980s by Goldstein and Speranza [B69]. Their findings do not at first appear to be in agreement; a difference seems to exist between the relative occurrence of different types of disturbances (sags versus surges). However, a detailed comparison of these two surveys shows that the difference is attributable to the different thresholds set by each researcher. Thus, comparison provides a good illustration of the pitfalls of superficial interpretation of survey results.
2) The relatively small number of high-amplitude surges reported by Allen and Segall [B47] compared to other surveys (this before the proliferation of SPDs) might be explained by a limitation of their instrument, as discussed in Martzloff and Gruzs 1988 [B192]. Briefly stated, the storage oscilloscopes used by Allen and Segall had the limited writing speed of contemporary technology. Furthermore, the small amplitude set for full-scale was such that a high-amplitude transient would have its peak off-screen, and the steep rise would not be recorded on the phosphor.

   Figure A.36 shows oscillograms recorded by Martzloff in preparation of a discussion of the Allen and Segall conference paper [B47],[16] subsequently included in Martzloff and Gruzs 1988 [B192]. The storage oscilloscope used by Martzloff in the experiment was the same model as those used by Allen and Segall.



(a) (b) (c)

Figure A.36—Possible explanation for the low values reported by Allen and Segall

Oscillogram (a) show the transient as generated in the experiment, appearing on the screen as a benign 400 V transient when the oscilloscope is set in anticipation of relatively low-amplitude transients and relatively low sweep speed, as was the case in the monitoring performed by Allen and Segall.

[16]Discussions of conference papers, even when submitted in writing, were not printed and published by the IEEE.

Oscillogram (b) shows what the same oscilloscope displays, still at slow sweep speed, but with a vertical sensitivity set for larger anticipated signals.

Oscillogram (c) shows the transient as correctly recorded with an oscilloscope having a higher writing speed and set to display signals of higher amplitude than in oscillogram (a).

3) Another difference in the observed amplitudes is found in the results of the Alaska power survey (Aspnes et al. 1985 [B49]). An explanation for the relatively low surge level observed was suggested in the discussion of that IEEE Transactions paper: the built-in surge protection of the power supply for the internal electronics of the monitoring instrument might have reduced the levels of the surges observed by the monitors, which had their power cord and monitoring probe connected to the same duplex receptacle. This example was a forewarning of the profound effect that the proliferation of SPDs and PCs would have on the results of surveys limited to recording of voltage surges (Mansoor et al. 1999 [B155]). As mentioned in the synopsis of the surveys, this effect is most likely the reason why Ackermann et al., Hughes et al., and Dorr found only a few high values.

A further explanation of some differences in the amplitudes found in the various surveys might be the fact, observed and reported by some of the authors, of the lack of correlation between sites. Finally, some surveys included sites where equipment failures were experienced or expected (clearly a biased sample), while other surveys were made at sites not singled out for particular problems (but not necessarily a random selection).

A.4.2.2 Differences in waveforms

The "typical" waveforms suggested by each author of the surveys made with waveform-recording capability have been collected in Figure A.37. The finding of ring waves, as opposed to the traditional unidirectional impulses, seems general in these low-voltage circuits.

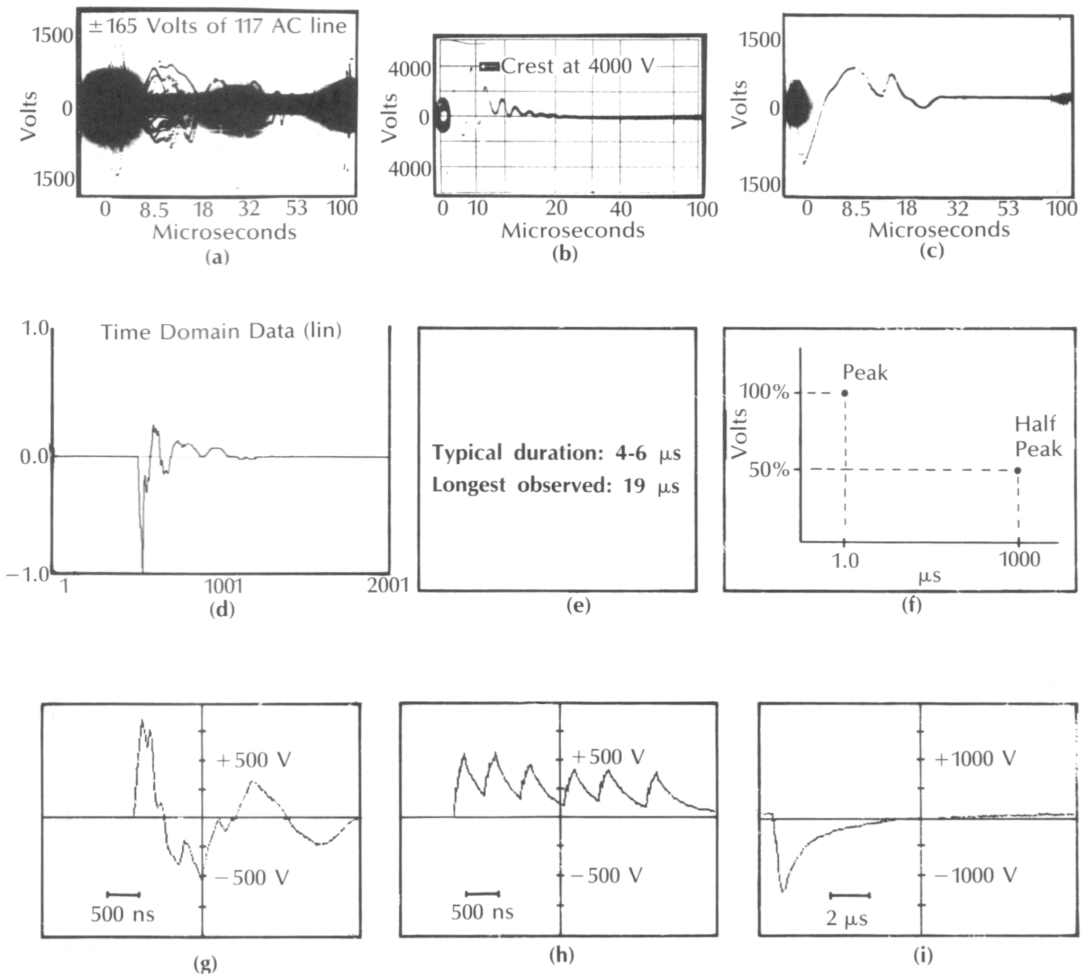
Martzloff and Hahn [B78] were among the first to report ring waves. Their reported measurements were incorporated in the data that resulted in the definition of the 0.5 µs–100 kHz Ring Wave.

Cannova [B58] did not report detailed description of the waveforms, but his statements of "4 µs to 9 µs" and "up to 19 µs" could be interpreted either as a time at half maximum or time between the initial rise and the first zero crossing of a ring wave. Interestingly, that database led to the specification of a unidirectional, longer impulse, the classical 1.2/50 µs voltage impulse for the shipboard environment.

Wernström et al. [B96] gave three examples of their recordings. The first is a ring wave with a rise time of 0.2 µs and frequency of about 500 kHz, the second is a burst of nanosecond-duration transients, similar to the IEC EFT, and the third is a short unidirectional impulse.

Odenberg and Braskich [B84] reported data different from the other authors in that only two points of the waveform were recorded: peak and 50% of peak amplitude. As such, this description is not a complete waveform; furthermore, the report that 90% of their 250 000 recordings show the 50% point occurring between 900 µs and 1100 µs is unique among all surveys.

Goedbloed [B67] reported data collected with the objective of characterizing interference rather than damage. Hence, the emphasis was given to amplitude, rate of rise, and "energy" rather than waveform. An oscillogram with a frequency of about 800 kHz, characterized as "typical" by Goedbloed, is included in Figure A.37. In the data processing by conversion of the recorded events to a standardized trapezoidal pulse, the median of the time to half-value is found to be about 2 µs, which is an indirect measure of the relatively short duration of the observed surges.



"Typical" waveforms reported in the site surveys:

(a) (b) (c) Three examples of surges recorded by Martzloff
(d) Typical waveform according to Goedbloed
(e) Description of waveform by Cannova
(f) Description of waveform by Odenberg and Braskich
(g)–(i) Three examples of surges recorded by Wernström et al.

Figure A.37—Comparison of waveforms reported in the literature

McEachern [B80] presents a general discussion of the many types of waveforms recorded by instruments with built-in graphics capabilities. The data presented in his handbook are described as generic types, culled from a collection of 20 000 records collected over a period of two years. Figure A.17 and Figure A.20 show typical surges selected by McEachern as typical surge signatures. In addition to presenting data in the form of recordings, the handbook provides guidance on conducting and interpreting the results of measurements, thus avoiding some of the interpretation and comparison problems discussed in this informative annex.

A.4.2.3 New data collected in the 1990s

The data collected in the 1990s were collected, sometimes with novel equipment, under the conditions of an evolving surge environment. These two new factors are briefly discussed below:

1) ***Limitation of frequency response of the instrumentation.*** Systematic monitoring of power quality characteristics in distribution and end-user power systems became possible in the 1990s as a result of both the availability of a new generation of power quality monitoring instruments and the growing interest in the issues of power quality in general, not only surges. Because of this wide interest, a greater emphasis was given to issues related to harmonics, sags, and interruptions rather than to surges in the microsecond range. Some of the instruments used in a broad survey (Sabin 1996 [B92]) had a cut-off in their frequency response that limited their ability to record surges other than capacitor switching, compared with the more cumbersome, but with broader frequency response instrumentation deployed in the 1970s and 1980s.
2) ***Proliferation of "surge-mitigating" devices.*** The term *surge-mitigating* rather than *surge protective* is deliberately used here because an emerging factor is contributing to the proliferation of such devices: the new electronic appliances that include an internal power supply of the switch-mode type, where the capacitor of the intermediate dc link is effectively connected across the ac mains through a full-wave rectifier. The result is that surge impinging on the service entrance of an installation can be mitigated not only by the many SPDs being installed by end-users or incorporated in the equipment, but additionally by all these capacitors (Mansoor et al. 1999 [B33]).

Consequently, the data included in recently published summaries have to be scrutinized, lest oversimplification would mask the continuing transient (surge) activity in low-voltage ac power circuits.

Annex B

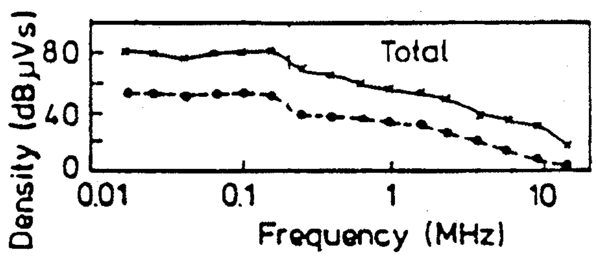
(informative)

Complementary information

B.1 Amplitude spectral density

Immunity of the electronic equipment will depend on the energy spectral density of the surge. At relatively low frequencies, there can be large transfer coupling losses between the surge and the disturbed circuits, but at higher frequencies these transfer losses become smaller. Thus, it may be important to suppress surges of small amplitude but large rate of change.

This class of surges is often characterized in the frequency domain. By the use of the Fourier transform, the amplitude spectral density can be found, as shown in Figure B.1.



Source: Goedbloed [B67]

Figure B.1—Amplitude spectral density for total Goedbloed data

Note that the spectrum is nearly flat up to 160 kHz and then decreases at 20 dB/decade. Furthermore, there is almost no significant component in the spectrum above 20 MHZ. The use of this figure may be helpful in the design of power mains filters. Individual surges at individual sites having a specific ring frequency produce a peaked distribution of amplitude spectral density (Standler 1989 [B203]). When many surges and sites are combined in a plot, the result is a broad and declining distribution. Thus, a distinction must be made between single events as they impact specific equipment having a specific frequency response and the composite result.

B.2 Capacitor-switching transients

B.2.1 General

The application of utility capacitor banks has long been accepted as a necessary step in the efficient design of utility power systems. Also, capacitor switching is generally considered a normal operation for a utility system, and the transients associated with these operations are generally not a problem for utility equipment. These low-frequency transients, however, can be magnified in a customer facility (if the customer has low-voltage power-factor correction capacitors) or can result in the nuisance tripping of power electronics-based devices, such as adjustable-speed drives. Capacitor energizing is just one of the many switching events that can cause transients on a utility system. However, due to their regularity and impact on power system equipment, they quite often receive special attention.

Transient overvoltages and overcurrents related to capacitor switching are classified by peak magnitude, frequency, and duration. These parameters are useful indices for evaluating potential impacts of these transients on power system equipment. The absolute peak voltage depends on the transient magnitude and the point on the fundamental frequency voltage waveform at which the event occurs. This peak voltage is important for dielectric breakdown evaluation. Some equipment and types of insulation, however, can also be sensitive to rates of change in voltage or current. The transient frequency, combined with the peak magnitude, can be used to estimate the rate of change.

There are a number of transient-related concerns that are generally evaluated when transmission and distribution shunt capacitor banks are applied to the power system. These concerns include insulation withstand level, switchgear ratings and capabilities, energy duties of protective devices, and system harmonics. In addition, these system concerns need to be extended to include customer facilities due to the increased use of power electronics-based end-user equipment. Application concerns often include

- Overvoltages associated with normal capacitor energizing
- Open line/cable end transient overvoltages
- Phase-to-phase transients at transformer terminations
- Voltage magnification at lower voltage capacitor banks
- Arrester duties during restrike events
- Current-limiting reactor requirements
- System frequency response and harmonic injection
- Impact on sensitive power electronics loads at customer facilities
- Ferroresonance and dynamic overvoltage conditions

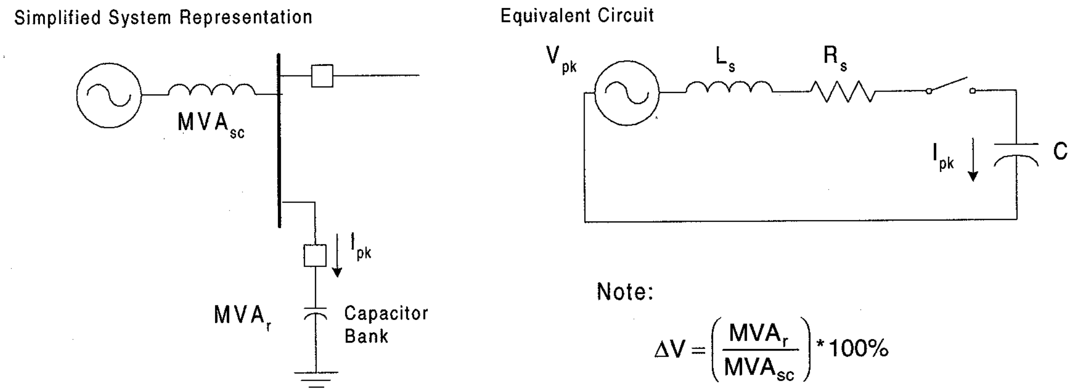
Power quality symptoms related to utility capacitor switching include customer equipment damage or failure, nuisance tripping of adjustable-speed drive or other process equipment, SPD failure, and computer network problems.

B.2.2 Characteristics of energizing an isolated capacitor bank

Transient characteristics depend on the combination of the initiating mechanism and the electric circuit characteristics at the source of the transient. Circuit inductances and capacitances are responsible for the oscillatory nature of transients. These inductances and capacitances can be discrete components, such as shunt capacitance of power-factor capacitor banks or inductance in transformer winding. They can also result from stray inductance or capacitance because of proximity to other current-carrying conductors or voltages. Natural frequencies within the power system depend on the system voltage level, line lengths, cable lengths, system short-circuit capacity, and the application of shunt capacitors.

Energizing a shunt capacitor bank from a predominantly inductive source results in an oscillatory transient that can approach twice the normal system peak voltage (V_{pk}). Figure B.2 illustrates the simplified equivalent system for the energizing transient. The characteristic frequency (f_s) of this transient is given by Equation [1] in Figure B.2.

Relating the characteristic frequency of the capacitor energizing transient (f_s) to a steady-state voltage rise (ΔV) design range provides a simple way to quickly determine the expected frequency range for utility capacitor switching. For example, a 60 Hz system with a design range of 1.0% to 2.5% would correspond to a characteristic frequency range of 380 Hz to 600 Hz. For a shunt capacitor bank on a high-voltage bus, transmission line capacitance and other nearby capacitor banks cause the energizing transient to have more than one natural frequency. However, for the first order approximation, Equation [1] in Figure B.2 can still be used to determine the dominant frequency.



$$\Delta V = \left(\frac{MVA_r}{MVA_{sc}}\right) * 100\%$$

$$f_s = \frac{1}{2\pi\sqrt{L_s C}} \approx f_{system} * \sqrt{\left(\frac{X_c}{X_s}\right)} \approx f_{system} * \sqrt{\left(\frac{MVA_{sc}}{MVA_r}\right)} \approx f_{system} * \sqrt{\left(\frac{1}{\Delta V}\right)} \qquad [1]$$

and the peak inrush current (I_{pk}) is determined using

$$I_{pk} = \frac{V_{pk}}{Z_s} \qquad Z_s = \sqrt{\left(\frac{L_s}{C}\right)} \qquad [2]$$

	[example]
where: f_s = characteristic frequency (Hz)	[379 Hz]
L_s = positive sequence source inductance (H)	[17.53mH]
C = capacitance of bank (F)	[10.03μF]
f_{system} = system frequency (50 or 60 Hz)	[60 Hz]
X_s = positive sequence source impedance (Ω)	[6.61 Ω]
X_c = capacitive reactance of bank (Ω)	[264.50 Ω]
MVA_{sc} = three-phase short circuit capacity (MVA)	[2000 MVA]
MVA_r = three-phase capacitor bank rating (MVAr)	[50 MVAr]
ΔV = steady-state voltage rise (per-unit)	[2.5%]
V_{pk} = peak line-to-ground bus voltage (V)	[93897.11 V]
Z_s = surge impedance (Ω)	[39.35 Ω]

Figure B.2—Equivalent circuit for capacitor energizing

Because capacitor voltage cannot change instantaneously, energizing a capacitor bank results in an immediate drop in system voltage toward zero, followed by an oscillating transient voltage superimposed on the fundamental power frequency waveform. The peak voltage magnitude depends on the instantaneous system voltage at the instant of energization and can reach 2.0 times the normal system voltage (V_{pk} in per unit, or p.u.) under worst-case conditions. The voltage surge is at the same frequency as the inrush current (I_{pk}) and rapidly decays to the system voltage.

For a practical capacitor energization without trapped charge, system losses, loads, and other system capacitances cause the transient magnitude to be less than the theoretical 2.0 p.u. Typical magnitude levels range from 1.2 p.u. to 1.8 p.u., and typical transient frequencies generally fall in the range from 300 Hz to 1000 Hz. Figure B.3 illustrates an example, recorded in the field, of a distribution capacitor energizing transient.

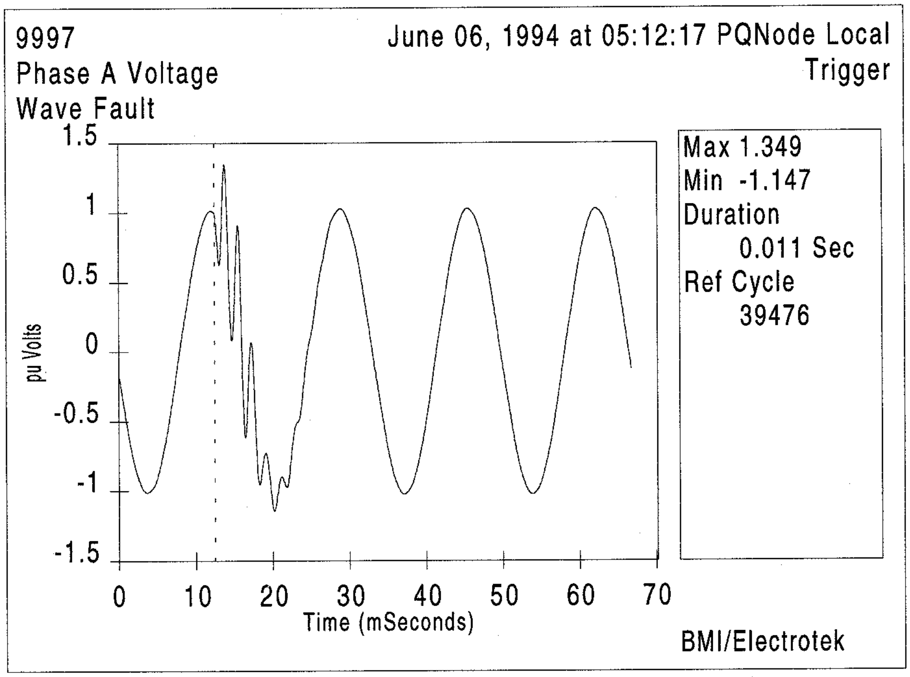


Figure B.3—Typical distribution bus voltage during capacitor energizing

B.2.3 Characteristics of resulting secondary voltages

Transient overvoltages caused by capacitor switching are generally not of significant concern to a utility because their peak magnitudes are often just below the level at which utility SPDs begin to operate. However, because of the relatively low frequencies involved, these transients will often be coupled through step-down transformers to customer loads. In addition, the frequent switching of transmission and distribution capacitor banks, in the context of power quality concerns for sensitive customer equipment, has led to a heightened awareness of resulting secondary voltages.

Secondary capacitor-switching transients, as illustrated in Figure B.4, are often a function of the turns ratio of the step-down transformer. However, if the customer uses capacitors for the correction of power factor on the low-voltage side, higher per-unit overvoltages can occur. Such an event is often referred to as “voltage magnification.” Voltage magnification occurs when a transient oscillation, initiated by the energization of a utility capacitor bank (transmission or distribution), excites a series resonance in the low-voltage system circuit (inductance of the step-down transformer and capacitance of the low-voltage power-factor correction). The result is a higher per-unit overvoltage at the lower voltage bus. The worst magnification occurs (Hensley et al. 1992 [B110]) when the following conditions exist:

a) The size of the switched capacitor bank is significantly larger (more than 10 times) than that of the lower voltage customer bank.
b) The characteristic energizing frequency is close to the series resonant frequency of the circuit formed by the step-down transformer and the power-factor correction capacitor bank.
c) There is relatively little damping (resistive) provided by the low-voltage load (typical of industrial plant configurations, which are primarily motor load).

Distribution system overvoltages resulting from the energization of transmission system capacitor banks can be sufficient to sparkover gapped arresters—typically SiC design. Gapless arresters—typically MOV design—should be capable of withstanding this event. However, this should be verified using computer simulation or transient network analysis. Low-voltage systems can be exposed to transient overvoltages between 2.0 p.u. and 4.0 p.u. These overvoltages can occur over a wide range of low-voltage capacitor sizes (note that the low-voltage capacitor must be present for magnification to occur). Typically, these transient switching overvoltages might simply damage low-energy SPDs or cause a nuisance trip of power electronics-based equipment. Nevertheless, case histories have been reported of complete failure of end-user equipment.

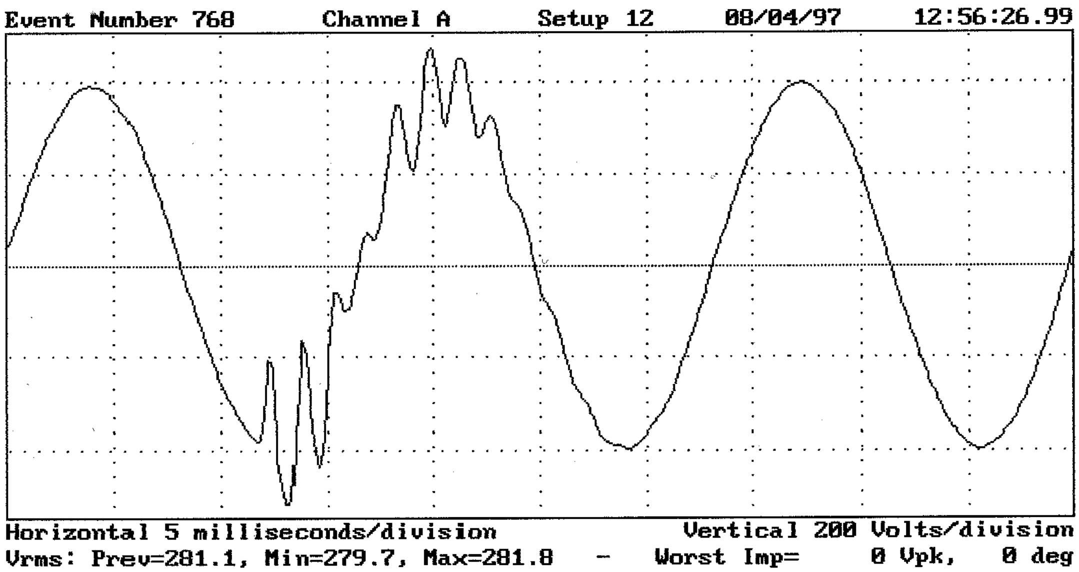


Figure B.4—Example of secondary bus voltage during utility capacitor switching

B.2.4 Characteristics of energizing back-to-back capacitor banks

Energizing a shunt capacitor bank with an adjacent capacitor bank already in service is known as “back-to-back switching.” High-magnitude and high-frequency currents, as illustrated in Figure B.5, will flow between the banks when the second bank is energized. This current must be limited to acceptable levels for switching devices and current transformer burdens. Generally, series reactors are used with each bank to limit the current magnitude and frequency, although pre-insertion resistors/inductors can be used with some types of switches.

The frequency and magnitude of the inrush current during back-to-back switching depends on the size of the discharging capacitor bank, the impedance of the discharging loop, and the instantaneous voltage at the terminals of the capacitor bank at the time of contact closure. The impedance of the discharging loop is much lower than the system impedance. Therefore, the inrush current is much higher than that of energization of an isolated bank. Typically, the inrush current lasts for only a fraction of a power-frequency cycle.

The high-frequency inrush current might exceed the momentary transient-frequency capability of the switching device as well as the I^2t withstand of the capacitor fuses. It can also cause false operation of protective relays and excessive voltages for current transformers in the neutral or phases of grounded-wye capacitor banks.

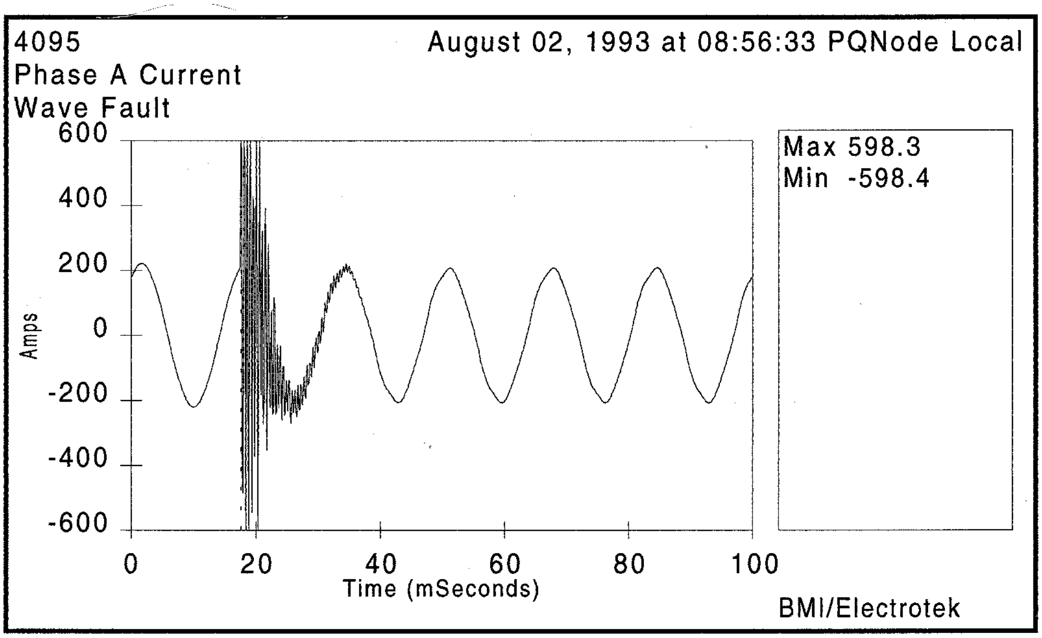


Figure B.5—Example of distribution-feeder current during back-to-back switching

B.2.5 Characteristics of capacitor bank restrike events

Figure B.6 illustrates the sequence of a restrike event following an attempt to disconnect a capacitor bank. The capacitor-switching device will de-energize at current zero; because the current is capacitive, the voltage at the time of current interruption is at a system peak. Successful interruption depends on whether the switch can develop sufficient dielectric strength to withstand the rate of rise and the peak recovery voltage. For a grounded-wye capacitor bank, twice the system peak voltage (2 p.u.) will appear across the switch contacts one half-cycle after interruption. If the switch cannot withstand this recovery voltage, the switch will restrike.

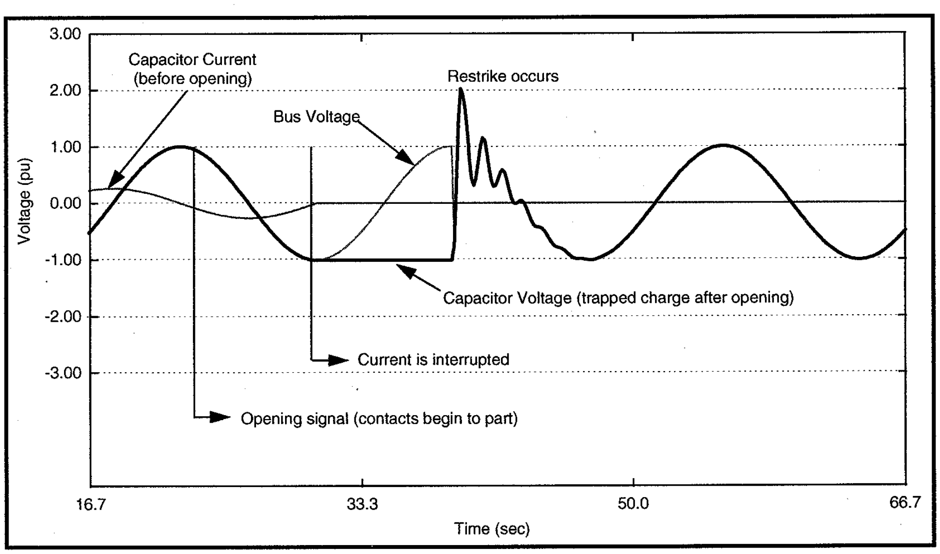


Figure B.6—Illustration of capacitor bank restrike event

During normal de-energization of a grounded-wye capacitor bank, the capacitor current is interrupted at the peak system voltage, thus leaving a 1.0 p.u. trapped charge on the capacitor. This trapped charge results in an offset in the transient recovery voltage that reaches a magnitude of 2.0 p.u. one half-cycle after opening. Substantial transient voltages can occur if the switch restrikes during the opening sequence. The worst case occurs when twice the system peak voltage appears across the switch contacts. In this case, the magnitude of the transient voltage approaches theoretically 3.0 p.u.

Ungrounded-wye capacitor banks can expose the capacitor switch to recovery voltages greater than 2.0 p.u. Recovery voltages can reach 2.5 p.u. on the first phase to open when the other phases open at the next current zero. If the two phases delay opening, the recovery voltage can reach 3.0 p.u. on the first phase to open. Finally, if one of the other phases delays, the transient recovery voltage would be 4.1 p.u. Should a restrike occur on the first phase to open at 2.5 p.u., a recovery voltage of 6.4 p.u. can occur on one of the two other phases because of the voltage that builds up across the neutral capacitance. The high recovery voltage on another phase can cause a second restrike, resulting in a two-phase restrike.

Capacitor switch restrike events can produce high-voltage surges that result in severe energy-duty for adjacent arresters or damage on unprotected equipment. Therefore, it is recommended to select a switching device that will minimize the possibility of a restrike event. In addition, it is advisable to protect adjacent equipment with surge arresters of appropriate size.

B.3 Changes in the environment

Prior to the proliferation of SPDs in low-voltage systems, a limitation had already been recognized for peak voltages: the flashover of clearances, typically between 2 kV and 8 kV for low-voltage wiring devices.

Literally millions of SPDs, varistors in particular, have been installed in low-voltage ac power circuits since their introduction in 1972 (Martzloff 1980 [B235]; Mansoor et al. 1999 [B155]). Therefore, a new limitation exists in surges that occur in this changing environment. Monitoring instruments are routinely installed to record the occurrence of surges at a site where a sensitive load is to be connected. The recording of the surges will be affected by the presence of a nearby SPD. Close proximity of an SPD to a recording instrument may impact present and future measurements in several ways, as contrasted to previous measurement campaigns. Four of these are outlined below.

a) Locations where voltage surges were previously identified—assuming no change in the source of the surges—are now likely to experience lower voltage surges, while current surges will occur in the newly installed protective devices.
b) Not only will the peaks of observed voltages be changed, but also their waveforms will be affected by the presence of nearby protective devices.
    1) If an SPD is located between the source of the surge and the recording instrument, the instrument will record the limiting voltage of the protective device. This voltage will have lower peaks, but longer time to half-peak, than the original surge.
    2) If the instrument is located between the source of the surge and an SPD or if such a device is installed in a parallel branch circuit, the instrument will record the limiting voltage of the device, preceded by a fast transient corresponding to the inductive drop in the line feeding the surge current to the protective device.
    3) If an SPD is connected between line conductor and neutral conductor and a surge impinges between line and neutral at the service entrance, a new situation is created. The line-to-neutral voltage is indeed clamped as intended; however, the inductive drop in the neutral conductor returning the surge current to the service entrance creates a fast transient voltage between the neutral and the grounding conductors at the point of connection of the SPD and downstream points supplied by the same neutral. Because this transient will have a short duration, it may be enhanced by the transmission line effect between the neutral and grounding conductors if there is a high impedance between these two conductors at the line end.

c) The surge-voltage limitation function previously performed by flashover of clearances is now more likely to be assumed by the new SPDs that are constantly being added to the systems.
d) These three situations (item a through item c) produce a significant reduction in the mean of surge recordings of the total population of different locations as more SPDs are installed. The upper limit, however, will still be the same for the locations where no SPD has been installed. Focusing on the mean of voltage surges can create a false sense of security and incorrect description of the environment. Furthermore, the need for adequate surge-current handling capability of a proposed new SPD might be underestimated if partial surge diversion is already being performed by a nearby device.

Another case of changing environment is that of large sensitive loads, for which a growing practice is to supply them with dedicated mains from the service entrance. This practice has two implications:

— While the load is being separated from internally generated surges, it is also separated from the beneficial effects of the proliferating SPDs on other branch circuits.
— A dedicated branch circuit provides a closer coupling to the Location Category B environment than would a distributed wiring system that would result in a Location Category A.

Furthermore, the monitoring device might contain SPDs within its circuitry for self-protection. This arrangement may give incorrect data on the environment and the effect of the device.

B.4 Description versus specification

Published documentation of fast transients is scarce; for instance, a 1964 paper by Hayter ("High Voltage Nanosecond Duration Power Line Transients," presented at the Tenth Tri-Service Conference on EMC) is not retrievable in the open literature. IEEE Std 518-1982 [B16] cites one example of a "showering arc," but does not derive from this example a recommendation for a conducted fast transient test, unlike the revised surge withstand capability test in IEEE Std C37.90.1™-1989 [B13]. Thus, as discussed in B.7, it is the recommendation of the IEC to apply the EFT Burst test to the equipment covered by the scope of IEC 61000-4-4:1995 [B8] that provides the basis for adoption of that additional waveform in the present guide.

The justification for this adoption is that equipment that passes the EFT Burst test appears to perform with fewer occurrences of upset than equipment that does not pass the EFT Burst test. This situation illustrates the basic approach to specifying surge tests: A test wave is applied to a device, not to demonstrate that it can survive any of the waves that it will encounter in nature, but only to demonstrate for the benefit of both manufacturer and purchaser that the device can survive an agreed-upon, simple, clean surge. By surviving the test surge, the inference is made, subject to confirmation by field experience, that the device has the capability to survive the wide variety of surges that it will encounter during its life in the real world. Test waves should not be misconstrued as representing the actual natural phenomena (Martzloff 1983 [B119]); Martzloff and Leedy 1990 [B123]).

B.5 Differential mode and common mode

The terms *differential mode* (also *normal mode*) and *common mode* have been avoided in this document because they could create confusion if applied to ac systems consisting of phase, neutral, and grounding conductors. Rather, the specific and unambiguous use of L-N, L-L, L-G, N-G, LL-G, and LN-G is recommended.

It is important to note the existence of two different practices in bonding the neutral and grounding conductors, resulting in different levels of surges involving the grounding conductor. In typical US practice, the neutral conductor is bonded to the grounding conductor at the service entrance, and both are bonded to the local building ground. Local building grounds can be the structural steel, metal piping, earth electrodes, etc., in a sequence of priorities defined by Section 250-81 of the NEC [B19].

In typical European practice, the grounding conductor, generally called “protective earth,” is bonded to the neutral and to an earth electrode only at the distribution transformer. This protective-earth conductor is then brought into the building without further bonding to the local grounds.

Thus, in the US practice, there cannot be any N-G surges at the service entrance. External N-G surges cannot propagate into the building. Conversion of L-N surges within the building, however, can produce N-G surges at the end of branch circuits (Martzloff and Gauper 1986 [B120]). Internal load switching can also produce N-G surges (Standler 1989 [B94]; Forti and Millanta 1990 [B106]).

In some European practices with no neutral-ground bonding at the service entrance, external N-G surges can propagate into the building. This situation justifies the requirement of demonstrating higher surge-withstand capability in the “common mode” than in the “normal mode” specified by many IEC documents.

B.6 Dispersion of the lightning current in Scenario II

Most of the published models for the dispersion of the lightning current in a Scenario II event postulate a current source applied to the lightning protection system of the building. From that point, the current travels along the down-conductor(s) to the bonding bar or equipotential connection of the building, where it divides according to the impedances of each available path toward a symbolic “ground” or “earth” where the return path is not explicitly shown on the circuit diagrams. These impedances have generally been postulated as relatively low (Lin et al. 1980 [B114]; Rakotomala et al. 1994 [B135]; Birkl et al. 1996 [B97]; Mansoor and Martzloff 1998 [B116]; Mata et al. 1998 [B130]; Rousseau et al. 2000 [B138]). However, some reports of triggered lightning experiments (Fernandez et al. 1998 [B64] and [B105]; Rakov et al. 2001 [B136]) indicate higher resistances than those postulated in the numerical models. However, the long-term (after the initial rise) dispersion is controlled by the ***relative*** impedance (mostly resistance) of the available paths to ground, not by their absolute value.

This relative impedance consideration is an important factor in assessing a stress level to the SPDs involved in the exit path. These SPDs, in addition to the neutral conductor, offer to the lightning current a path toward the remote earthing electrodes of the power system. Such remote earthing electrodes include not only the many earthing electrodes at the poles or vaults in the case of a multiple-grounded neutral typical of North American practice, but also the earthing electrodes of adjacent buildings. The service entrance of these adjacent buildings is then subjected to an impinging current surge that can be a significant stress although these buildings were not the point of strike of a direct flash (Mansoor and Martzloff 1998 [B116]).

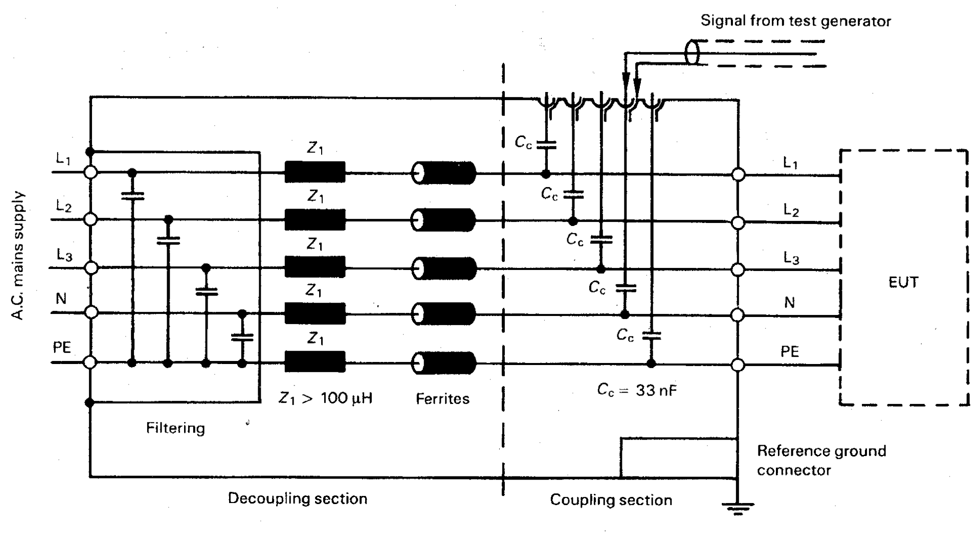
There is some irony in the Scenario II: one might expect that the inherent earthing electrodes (made electrodes, utilities, building steel, rebars) of a building struck by lightning might carry the bulk of the flash current, leaving only a portion to exit via the power supply connection (IEC publications suggest postulating a 50% level in the absence of specific information). But if there are many adjacent buildings, an attractive (low impedance) path is offered to the dispersion of the lightning current via the power supply connection, including the SPDs involved in the exit path. To the building being struck, having many neighbors is bad news for its exit-path SPDs as more current will flow through these than in the case of an isolated building where the exit path is ***relatively*** less attractive. On the other hand, if the PDS includes many earthing electrodes on its multiple-grounded neutral, then the relative impedance of this neutral conductor, compared to the impedance of the phase (live) conductors can be much lower, thus reducing the stress imposed upon the SPDs involved in the exit path.

B.7 EFT Burst

The EFT Burst test requirements of IEC 61000-4-4:1995 [B8] apply to all lines connected to the equipment under test (EUT) (“ ... either supply, signal, or control ...”). In the present context of the Trilogy, only the “supply lines”—the mains connection in the language of the Trilogy—are of interest. For these lines, according to the IEC procedure, the pulses can be injected into the equipment via a coupling/decoupling network (Figure B.7) or by a coupling clamp (Figure B.8) if the coupling/decoupling network cannot be used. Note in Figure B.7 the use of a coaxial cable for the connection to the test generator and the inference that the pulses are applied on one line at a time.

When using a coupling clamp, and if the ac mains connection includes a shield, the pulses are essentially applied to the shield and very little will be coupled to the conductors within the shield. The coupling circuit acts as a capacitive divider, the "high side" of which is the capacitance between the coupling clamp and the cable shield, and the "low side" of which is the capacitance between the conductors contained within the shield and the grounded enclosure of the EUT (Figure B.9).

This brief discussion of the EFT Burst test procedures offers another opportunity to emphasize the fact that this waveform, well accepted as a test method, is not suggested as a representation of the environment. There is no inference that the high voltage levels proposed for the test (up to 4 kV) imply that such pulses actually occur on the ac mains. It is only a method for assessing the immunity of equipment to induced interferences.

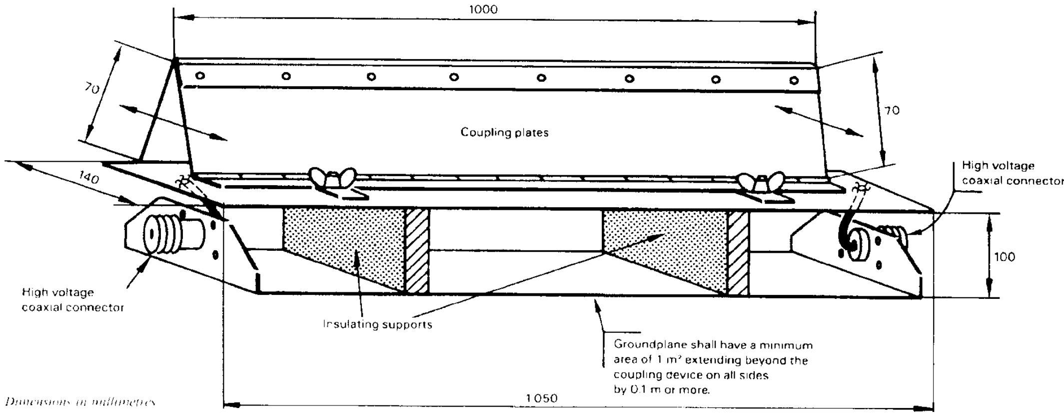


Source: IEC 61000-4-4:1995 [B8]

Figure B.7—Direct coupling of EFT pulses into the ac mains connection of the EUT

IEC 61000-4-4:1995 [B8] also contains a clause suggesting that the more severe test condition produced by the direct capacitor coupling to the ac line conductors, rather than by the coupling clamp, can justify the negotiation of lower levels of severity than the 1 kV to 4 kV values specified for the open-circuit voltage of the generator when using the coupling clamp.

This situation makes even more important the distinction to be maintained between the general concept of describing the ac surge environment and the adoption of a test procedure. Once again, the severity levels prescribed by IEC 61000-4-4:1995 [B8] when using the coupling clamp should not be construed as implying that these levels of transients can be expected in the ac mains. In other words, the EFT Burst does not represent the environment but is a test justified by the possible impact of the environment on installed equipment.



Source: IEC 61000-4-4:1995 [B8]

Figure B.8—Coupling clamp for EFT Burst test

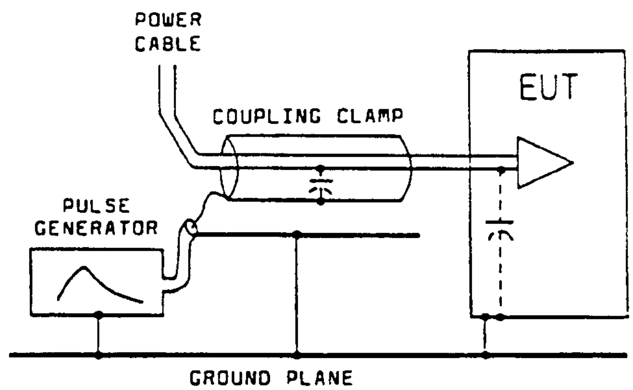


Figure B.9—Capacitive divider effect in the EFT Burst test

B.8 Energy-delivery capability

Recent surveys have addressed the issue of energy-delivery capability in various manners. A distinction must be made between two aspects of the energy involved in a surge event: the energy available from the surge source and the energy delivered to the equipment (protective device or load equipment). The energy, *W*, delivered by the source for a surge having time boundaries of t_1 and t_2 is given by

$$W = \int_{t_2}^{t_1} i(t) \times v(t) \mathrm{d}t$$
$$= \int_{t_2}^{t_1} \frac{v^2(t)}{z(t)} \mathrm{d}t$$

where

- i is the current from the source;
- t is time;
- v is the voltage across the source;
- z is the impedance, v/i, of the system connected to the source.

The energy delivered to the equipment is determined by the source voltage and the impedance divider effect between the source and the equipment. Both the source impedance and the equipment impedance are a function of frequency.

The impedance of a voltage-limiting SPD is, by its very nature, a strong function of the surge current. In recognition of this fact, Goedbloed, in his 1987 paper [B67], gave only

$$S = \int_{t_2}^{t_1} v^2(t)\mathrm{d}t$$

where

S is the “energy measure.”

At low frequencies (surges having a low rate of change of voltage) or for nonlinear SPDs, the use of a constant, resistive source impedance is not justifiable (Standler 1989 [B41]). Furthermore, the “energy in the surge” would be different from the energy deposited in an SPD or a particular load. Thus, the concept of recording the “energy measure” could promote the arbitrary reporting of “surge energy” by assuming a value for the impedance and then quoting the results in joules (Lindes et al. 1997 [B154]).

While there is definite merit in an attempt to describe the capability of a surge for delivering energy to circuit components, readers of monitoring survey reports should realize that “energy” reports should be evaluated with a clear understanding of the underlying assumptions. As progress continues in the development of power system disturbance monitors, the database should be expanded by making appropriate measurements of the surge current diverted by SPDs installed at the point of monitoring (Standler 1989 [B41]). This SPD could be selected to have the lowest limiting voltage among the other SPDs installed in the facility, thus attracting the largest part of the impinging surge (Martzloff 1996 [B157]).

One should not confuse this energy database issue with that of the energy stored in a test generator. A surge generator can test the energy-absorbing abilities of the equipment and the effects of the deposition of energy in the equipment. Furthermore, a distinction has to be made between surges of high amplitude, but short duration, and surges of high or moderate amplitude, but longer duration. The former have the potential of upsetting equipment operation, but can transfer little energy, while the latter can transfer a large amount of energy to the SPD or to the vulnerable equipment.

Exclusive or excessive reliance on energy considerations can also lead to misconceptions. Evidence has been reported (Bartkowiak et al. 1999 [B25]) that the rate at which a surge is depositing energy into a MOV—the current waveform—has a significant effect on the amount of energy that results in failure of the varistor.

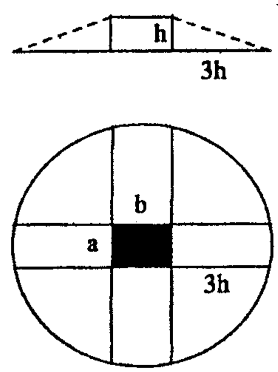
B.9 Expected occurrence of a direct strike

Consideration for protection against a Scenario II (direct flash to the structure) involves a determination of the likelihood of such an event. With the emerging availability of flash density information for many regions of the world, it becomes possible to make such a determination. As discussed in 4.2, this new development has replaced the former reliance on isokeraunic maps.

The expected average annual frequency N_d of direct flashes to a structure (located in a region for which flash density is available) can be assessed by the product of the annual ground flash density N_g (flashes per square kilometer) for the region and the equivalent collection area of the structure A_e (in square meters) is given by the following equation:

$$N_d = N_g \times A_e \times 10^{-6} \text{ per year}$$

The equivalent collection area of the structure is defined as an area of ground surface that has the same annual frequency of direct flashes as the structure. For isolated structures the equivalent collection area is the area enclosed within the border line obtained from the intersection between the ground surface and a straight line with a 1:3 slope that passes from the upper parts of the structure and rotates around it. Figure B.10 gives an example of the equivalent collection area A_e for the case of a building in flat country.



$$A_e = ab + 6h(a + b) + 9\pi h^2$$

Figure B.10—Equivalent collection area for flat country site

B.10 IEC earthing (grounding) practices

Network systems are classified by the IEC Publication 364 series according to the type of grounding, or earthing, practices used in the PDS and the methods used for protection against electrical shock in the installation. Although all of the IEC network systems are not presently used within the United States, some of the classifications can be applied.

An important note is the difference in language, between the IEC usage and that of North America, for terms having the same meaning. In this guide, the terms *earthed* and *unearthed* have the same meaning as *grounded* and *ungrounded*. For clarity to the readers, this document will substitute for the IEC term *earthed* the common North American term *grounded*, and for the IEC term *unearthed* the common North American term *ungrounded*.

PDSs are divided into grounded and ungrounded systems. IEC Publication 364 classifies network systems according to the configuration of current-carrying conductors (including the neutral) and the type of grounding system used. As part of the classification, the following nomenclature is used. The first letter, I or T, shows the relationship between the current-carrying conductors and the grounding system. The second letter, T or N, shows the relationship of the accessible conductive parts, including a metallic frame, of the component or equipment in the installation with respect to the grounding system.

B.10.1 First letter (I or T)

The first letter "I" represents isolation. The letter "I" signifies that all live parts are isolated from ground or earth or that points of the network are connected to earth through some impedance such as a surge arrester or air gap. The first letter "T" represents earth by using the Latin word, terra, meaning earth. The "T" signifies a direct connection of at least one point in the network to earth. Special grounding requirements or practices might be necessary depending on the type of network system used. See Figure B.11, Figure B.12, Figure B.13, and Figure B.19.

B.10.2 Second letter (T or N)

The second letter designates the type of connection between the protective equipment-grounding conductor used in the installation and earth. The second letter "T" signifies a direct connection between accessible conductive parts of connected equipment and ground (terra), which is independent of the grounding system that might or might not exist on current-carrying conductors of the system (see Figure B.17). The second letter "N" signifies a direct connection of accessible conductive parts to the ground points of the PDS by means of a protected earth neutral (PEN) or protected earth (PE) conductor. The PDS is then connected to ground. See Figure B.14 through Figure B.16.

In IEC network systems, the grounding of the PDS and the means of protection against electric shock are independent considerations. Current-carrying conductors are grounded to limit the voltage rise that can develop from lightning, transient overvoltages, connect with higher voltage conductors, or ground fault that can occur in a PDS. PDSs can be intentionally ungrounded to avoid service interruption when a single ground fault occurs. See Table B.1

Table B.1—IEC systems and equipment grounding

System designation	System grounding	Equipment grounding
IT	No direct system grounding. May be connected to earth through impedance or gap.	Independently and directly connected to ground
TT	Connected to earth at one or more points in the PDS outside of the premises wiring	Independently and directly connected to earth.
TN	Connected to earth at one or more points in the PDS and at one or more points in the premises wiring.	Connected to the PDS via a PEN- or PE-conductor.

B.10.3 Third letter (C or S)

In TN systems a third letter designates the possible configuration of the neutral conductor, the PE-conductor, and the PEN-conductor, as well as the relationship among these conductors.

In a "TN-C" PDS, the suffix "C" represents a common function. The PEN-conductor is used to serve the common function of a grounding or protective-earthing conductor as well as the neutral conductor for the PDS. In a "TN-C" PDS, ground-fault current and neutral current use the same return path to the source. In such installations the neutral conductor is bonded to the frame of the equipment or apparatus at each utilization point. In a "TN-C" PDS, the application and installation of ground-fault protective devices are not indicated or recommended because such devices would never reliably function as intended. (In North America, a single-phase circuit in a "TN-C" system is represented by older low-voltage appliances with metallic frames and residential two-prong receptacle circuits where a separate grounding conductor is not utilized.) See Figure B.14.

In a “TN-S” PDS, the suffix “S” represents a separate grounding or protective-earthing conductor. There is no PEN-conductor. The PE-conductor is only bonded once to the neutral conductor and only at the neutral terminal of the supply transformer for the PDS. In a “TN-S” PDS, ground-fault current and neutral current use separate conductive paths. In such installations, a separate grounding conductor is bonded to the frame of the equipment or apparatus at each utilization point for the conduction of ground-fault current. In a “TN-S” PDS, the separation of the PE-conductor and the neutral conductor allows for the successful application and utilization of a ground-fault protection system. See Figure B.15.

B.10.4 TN-C-S systems

A “TN-C-S” PDS is a combination of a “TN-C” and a “TN-S” system. The “TN-C-S” PDS is the most commonly used grounding system. In a “TN-C-S” PDS, there are a PEN-conductor, a separate PE-conductor, and a separate neutral conductor. The PEN-conductor is utilized only between the supply transformer and the service-entrance equipment. The actual connections to earth of the PEN-conductor are commonly made at the neutral terminal of the supply transformer and on the neutral conductor in the service-entrance equipment. Beyond the service-entrance equipment, only separate neutral conductors and PE-conductors are utilized. In a “TN-C-S” PDS, the separation of the PE-conductor and the neutral conductor allows for the successful application and utilization of a ground-fault protection system as those used in a “TN-S” type system. However, a ground-fault protection system can be utilized only downstream or on the load side of the PEN-conductor. In addition, any electrical connections between, or bonding of, a PE-conductor and a neutral conductor downstream of the PEN-conductor could cause dysfunction in a ground-fault protection system installed in the “TN-C-S” system. See Figure B.16, Figure B.18, and Figure B.20.

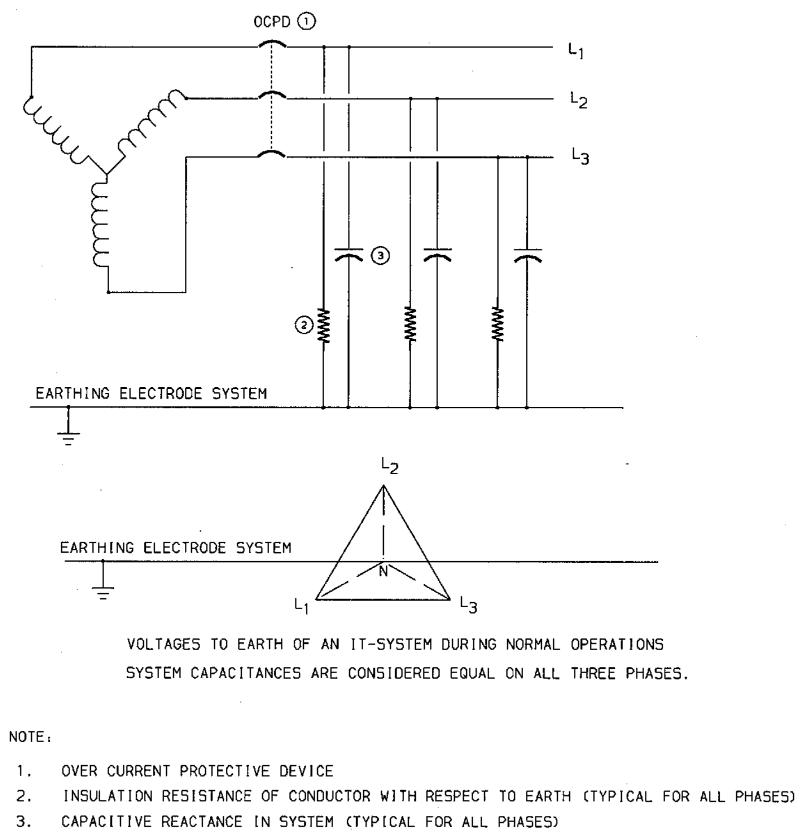


Figure B.11—Voltages to earth during normal conditions on IT system

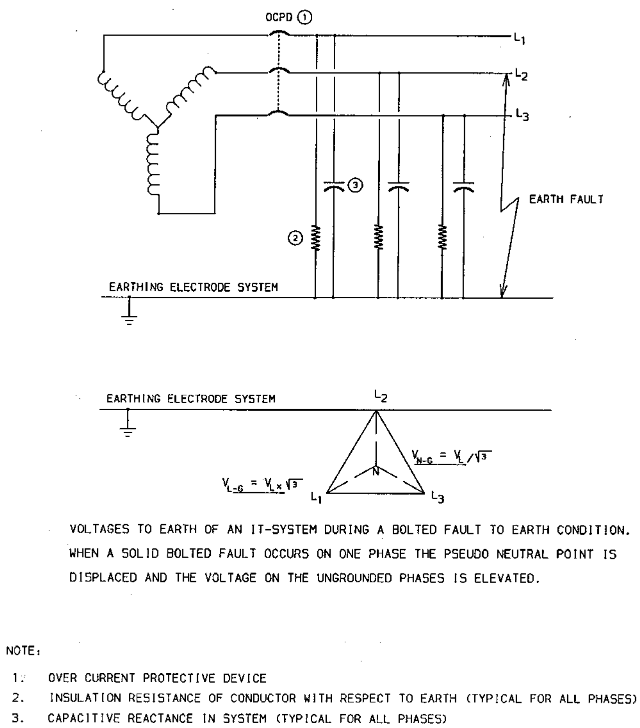


Figure B.12—Voltages to earth during bolted fault to earth on IT system

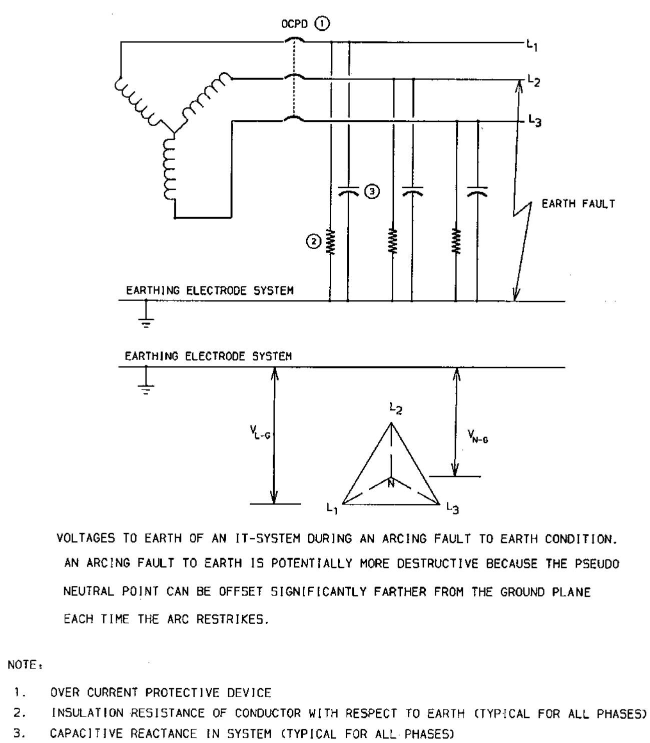
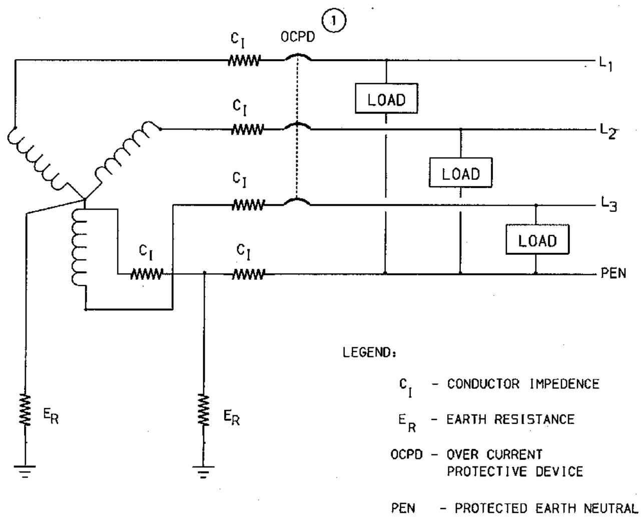


Figure B.13—Voltages to earth during arcing fault on IT system

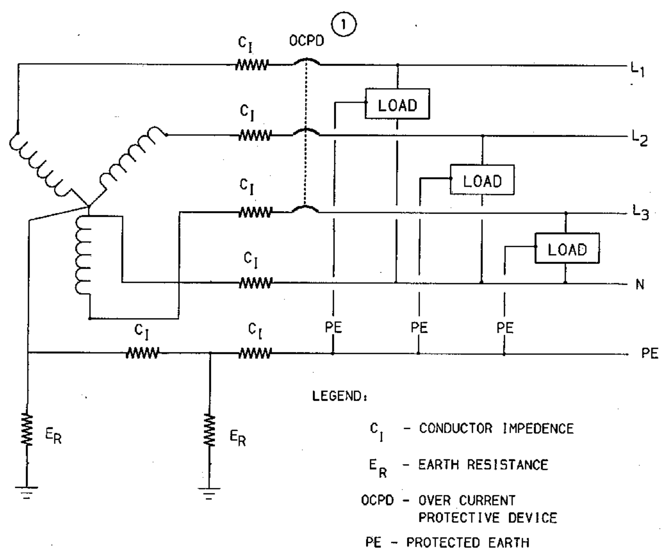


TYPICAL EXAMPLE OF A TN-C SYSTEM

NOTE:

1. MAIN OVERCURRENT PROTECTIVE DEVICE SHOULD NOT HAVE GROUND FAULT PROTECTION

Figure B.14—Typical example of TN-C system



TYPICAL EXAMPLE OF A TN-S SYSTEM

NOTE:

1. OCPD CAN INCLUDE, OR NOT INCLUDE, GROUND FAULT PROTECTION

Figure B.15—Typical example of TN-S system

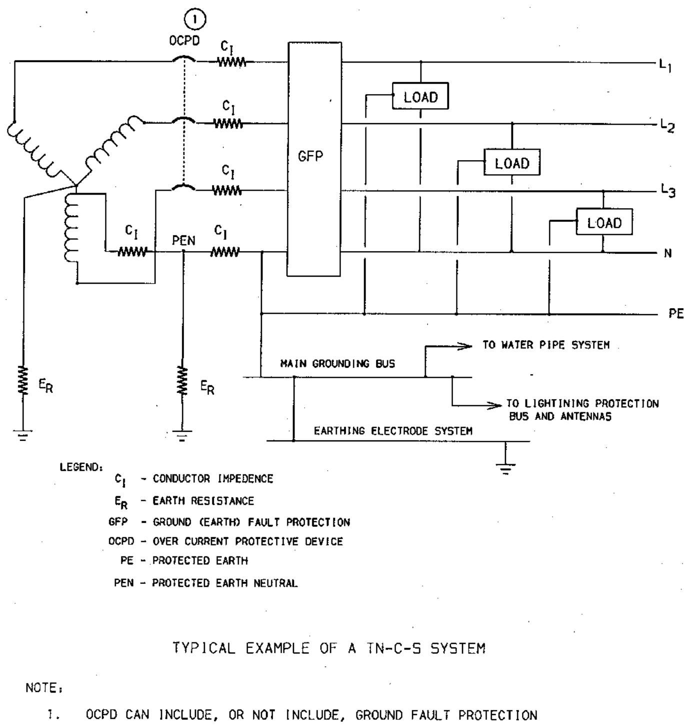


Figure B.16—Typical example of a TN-C-S system

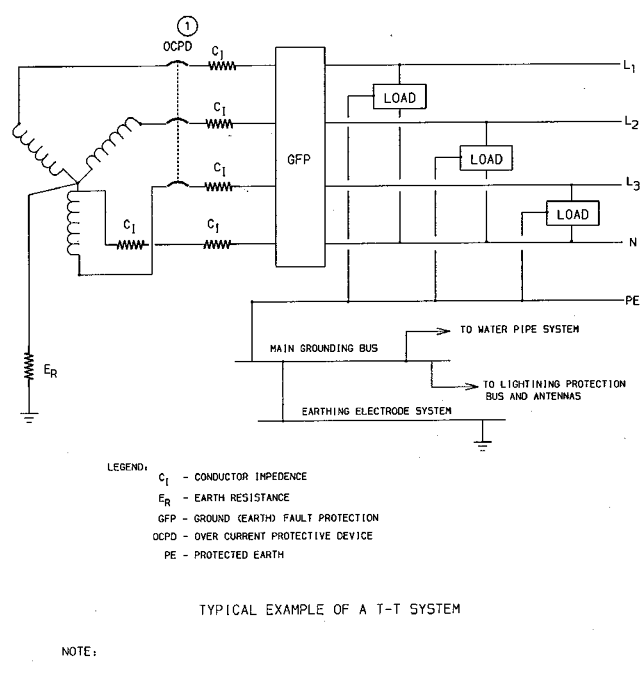


Figure B.17—Typical example of a T-T system

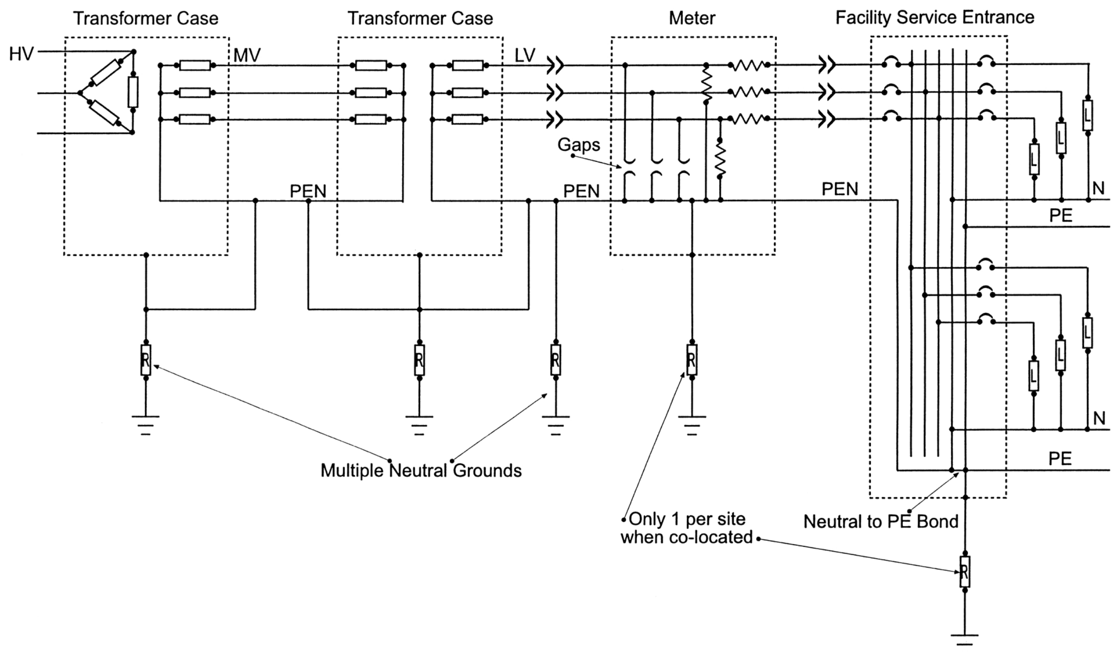


Figure B.18—Typical example of grounding practice for wye service entrance served by wye multiple-grounded medium-voltage system in North American systems

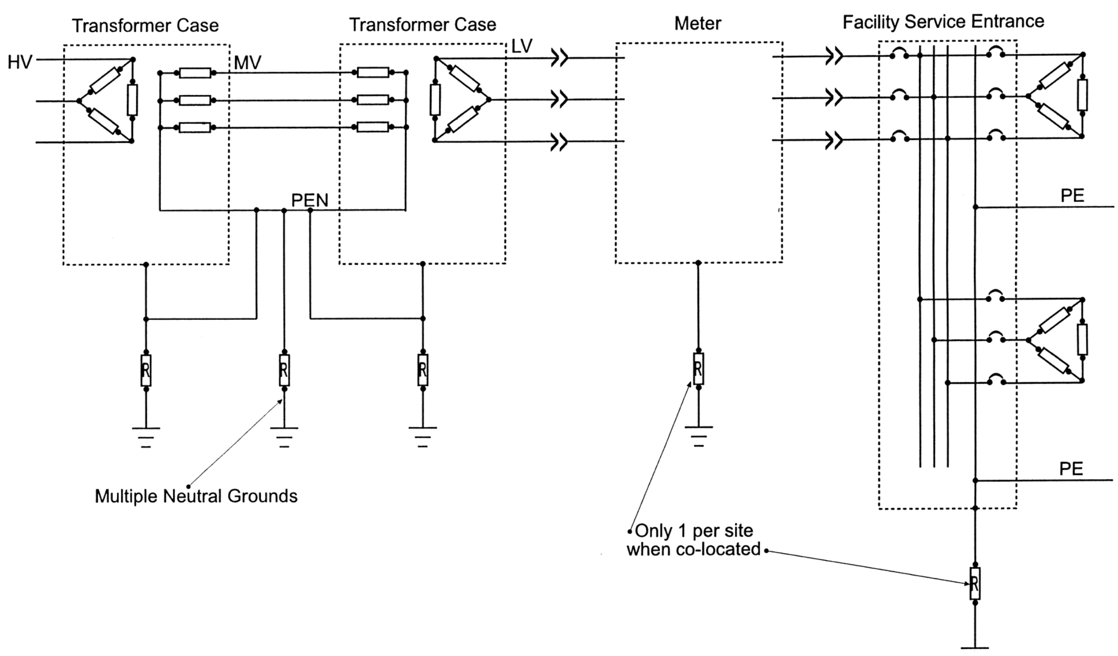


Figure B.19—Typical example of grounding practice for delta service entrance served by wye multiple-grounded medium-voltage system in North American systems

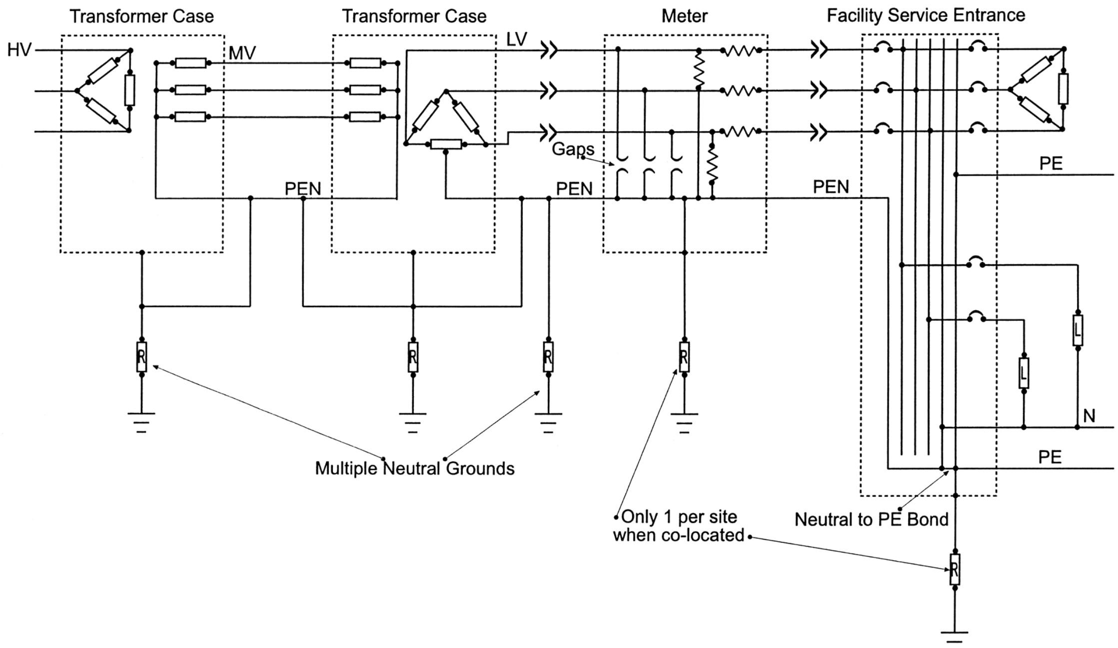


Figure B.20—Typical example of grounding practice for center-tapped delta service entrance served by wye multiple-grounded medium-voltage system in North American systems

B.11 Interface devices

The user of the the Trilogy is primarily concerned with understanding the environment of the equipment at the location where it is intended to be used. This location is normally the attachment point of the equipment to the permanent premises wiring. With the proliferation of interface devices installed for surge protection, isolation, voltage regulation, and power continuity, the description of the environment at the end of the premises wiring (Location Category A or B) might not correspond to the conditions prevailing at the power port of the equipment. Nevertheless, surge events associated with local system operations (switching, fault clearing) can still introduce surges between an interface device and the equipment at the end of the wiring premises.

Commonly used isolation transformers provide decoupling or cancellation of neutral-to-ground surges if properly installed. However, they do not isolate or decouple line-to-line or line-to-neutral surges (Martzloff 1983 [B119]). These surges will be passed unattenuated through isolation transformers. Surge events can also appear on the output of these interface devices through inductive coupling between conductors or flexible cords commonly used for connecting the devices. Wiring errors involving the neutral and equipment grounding conductors, or the improper attachment of premises-wiring neutral conductors to the outputs of these devices, are other mechanism by which these surges can be injected.

B.12 Low-voltage system oscillatory surges during lightning

For the evaluation of power system equipment against lightning surges encompassing a wide spectrum of waveforms, two standard test waves have evolved over the years: a 1.2/50 µs voltage wave and an 8/20 µs current wave for discharge-voltage tests of surge arresters. Other unidirectional waveforms that have been used or are being proposed are a 4/10 µs and a 10/350 µs waveform. The significance of voltages being induced in circuits not struck directly by lightning, but close to intended or unintended lightning down-conductors, has also been recognized. To that effect rates of changes have been proposed to represent the first stroke and the subsequent strokes, respectively. Subclause A.2.2.3 offers some examples of such rates of change and their effects in nearby circuits.

The database on recorded events (A.1) includes some observations of oscillatory surges associated with lightning events. Such information does not contradict the Scenario II for which the currents flowing in the power circuits inside the building are the result of resistive coupling and ground potential rise.

For instance, Lenz reports the recording of 50 surges associated with lightning events in two locations. Figure A.2(d) (in Informative Annex A) shows such a recording, with a peak amplitude of 5.6 kV at the pole of a 120/240 V system (Lenz 1964 [B76]). The frequency of these surges ranged from 100 kHz to 500 kHz. Martzloff reports oscillatory lightning-related surges in a house during a multiple-stroke flash (Martzloff and Hahn 1970 [B78]). Injection of an 8/20 µs current surge of only 1.5 kA amplitude injected in the grounded neutral of the service drop resulted in a 2.2 kV, 500 kHz oscillation at the end of the branch circuits of the model house, as shown in A.2.1.1. Another experiment of injecting unidirectional Combination Wave surges into the wiring of an empty building produced a 150 kHz oscillation superimposed to the unidirectional surge, as shown in A.2.1.2. Other researchers have also reported oscillations at high frequencies (Wernström et al. 1984 [B96]; Goedbloed 1987 [B67]).

B.13 Open-circuit voltages and wiring sparkover

Voltage surges propagate with very little attenuation in a low-voltage power system when there are no substantial connected loads. Measurements made in a residential system as well as in a laboratory simulation (Martzloff and Crouch 1978 [B117]) have shown that the most significant limitations are produced by sparkover of the wiring devices, not by attenuation along the wires (Martzloff 1983 [B119]; Mansoor and Martzloff 1997 [B115]). Ironically, a carefully insulated installation (in the absence of SPDs) is likely to experience higher surge voltages than an installation where sparkover of wiring devices occurs at lower levels.

Therefore, the open-circuit voltage specified at the origin of an end-use power system—say the service entrance—should be assumed to propagate unattenuated far into the system. This lack of attenuation is the reason for maintaining the 6 kV level when going from Location Category B to Location Category A. This situation was recognized in the revision of the 1980 edition of IEC 664 into IEC 60664:1992 [B6], in which the concept of the “voltage staircase” was abandoned.

B.14 Per unit

The amplitude of disturbances, including transient overvoltages, is often expressed in normalized form, which is called “per unit” in power engineering (*The Authoritative Dictionary of IEEE Standards Terms* [B12]). If the amplitude of a disturbance is V volts, then the per-unit value is V/U_n, where U_n is the peak of the amplitude of the nominal mains voltage. For example, consider a disturbance with an amplitude of 250 V occurring on single-phase mains with a nominal mains voltage of 120 V rms: the per-unit value is then $250/(120\sqrt{2})$ or 1.5 p.u.

While the concept of per unit is simple, there is a source of ambiguity. Does the “amplitude of the disturbance” include the instantaneous value of the mains voltage? Consider the two disturbances labeled A and B in Figure B.21. The amplitude of the transient part is 70 V, which can be expressed as 0.41 p.u. However, the peak value of A is 126 V (0.74 p.u.), whereas the peak value of B is 240 V (1.41 p.u.). This example shows that there can be different per-unit values associated with the amplitude of the transient disturbance, depending on the convention for reporting total (peak) or only the deviation from the sine wave, as discussed in 6.3.

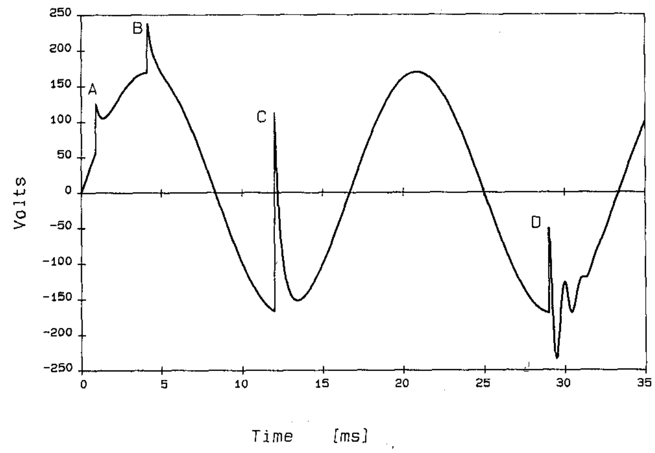


Figure B.21—Effect of relative polarity of surges and mains voltage on interpretation of "per unit"

Consider the disturbance labeled C in Figure B.21. The amplitude of the transient part is 280 V or 1.65 p.u. However the peak value of C is 113 V or 0.67 p.u. Yet another problem arises in the event labeled D in Figure B.21. The amplitude of the transient part is 120 V, the first peak occurs at –49 V, the second peak occurs at –233 V.

In these examples, one could cite per-unit values of 0.71, 0.29, or 1.37. Here the largest magnitude of the voltage, 233 V, does not indicate the amplitude of the disturbance.

There is no easy resolution of the issue of whether to report the level of the transient disturbance independently from the normal mains waveform. Both practices are justifiable. However, the two practices give different values for the amplitude of the disturbance, and thus the meaning should be explicitly stated in reporting results of measurements (Martzloff and Gruzs 1988 [B192]).

For large values of surges, such as thousands of volts on a 120 V system, and for the application of SPDs of the voltage-limiting type having limiting-voltage values on the order of two to three times the peak of the power-frequency voltage, the distinction is not very important. However, concern has increased about possible adverse effects on equipment from surges with lower amplitudes, leading to a wish for tighter limiting voltages. In the case of low limiting voltages, the distinction becomes quite significant. The distinction is also important for the application of filters or SPDs known as "tracking suppressors."

B.15 Power system source impedance

Voltage surges have been recorded by most researchers equipped with what is essentially a voltmeter, but no possibility to determine the impedance between the point of measurement and the point of origin of the surge being recorded. Other unrelated measurements have been reported on the impedance of the power system at the high frequencies involved with the propagation of the surges.

Bull reports that the impedance of a power system, seen from the outlets, exhibits the characteristics of a 50 Ω resistor with 50 μH in parallel (Bull 1975 [B147]). At first, attempts were made to combine the observed 6 kV open-circuit voltage (maximum expected value) with the assumption of a 50 Ω, 50 μH impedance. This combination resulted in a low energy-deposition capability, which was contradicted by field experience of SPD performance. This apparent contradiction led, in the initial 1980 edition of this guide, to the proposed definition of a 100 kHz oscillatory wave, as well as "high-energy" unidirectional waves—now both identified as the two "standard waveforms." In this manner, the effects of both an oscillatory wave and the high energy-deposition capability of the Combination Wave could be provided. This consideration also led to a deeper understanding of the significance of clearance flashover in limiting the observed voltages that result from current-source surges.

B.16 Sparkover of clearances

Sparkover, as defined in *The Authoritative Dictionary of IEEE Standards Terms* [B12], has both a general meaning and a meaning that pertains to surge arresters. In the context of this guide, sparkover is to be understood as a controlled, desirable function, as well as the unplanned arcing between live parts that is not intended, but that performs a voltage-limiting function when it does occur. When sparkover of a clearance occurs, there are three possible results:

1) A follow current occurs, with destructive effects on the components.
2) A follow current occurs, but overcurrent protection (circuit breaker or fuse) limits the damage. The system can be restored to operation after a mere nuisance interruption.
3) No follow current takes place, and the overvoltage protective function of the system can be considered as accomplished.

B.17 Surge impedance and source impedance

To prevent confusion or misunderstanding, a distinction between "source impedance" and "surge impedance" needs to be made. Surge impedance, also called "characteristic impedance," is a concept relating the parameters of a line to the propagation of traveling waves. For the wiring practices of the ac power circuits discussed in this guide, this characteristic impedance would be in the range of 100 Ω to 300 Ω, but because the durations of the waves being discussed—on the order of microseconds—are much longer than the travel times in the wiring systems being considered, traveling wave analyzes are not useful here.

Source impedance, defined as "the impedance presented by a source of energy to the input terminals of a device or network" (*The Authoritative Dictionary of IEEE Standards Terms* [B12]), is a more useful concept here. In the conventional Thévenin's description, the open-circuit voltage (at the terminals of the network or test generator) and the source impedance (of the surge source or test generator) are sufficient to calculate the short-circuit current.

The 1980 edition of this document (IEEE Std 587) defined Location Category A as being branch circuits with wire gauge between AWG 14 and AWG 10 (diameter between 1.6 mm and 2.6 mm) and having a length placing them at least 10 m away from Location Category B and at least 20 m away from Location Category C. Later editions of this document (1991 and the present) do not recognize any relationship between diameter of wire and amplitude of surges. The reason is that the wire diameter has a minor effect, compared to length (Martzloff and Gauper 1986 [B120]).

When a surge current, i, travels down a conductor, a voltage drop, $L(\mathrm{d}i/\mathrm{d}t)$, is produced by the inductance, L, of the wire, decreasing the value of the surge current that can be driven by a voltage applied at the sending end of the conductor. While larger diameter wires will have less inductance per unit length (the relationship is logarithmic), it is difficult to readily estimate the relative values of $L(\mathrm{d}i/\mathrm{d}t)$, since the smaller inductance will allow a larger value of i and $(\mathrm{d}i/\mathrm{d}t)$.

B.18 Surge voltage

Definitions of terms used in the Trilogy are generally consistent with *The Authoritative Dictionary of IEEE Standards Terms* [B12]. However, some differences exist. For instance, [B12] defines a surge as “a transient wave of current, potential, or power in an electric circuit”—a definition broader than the meaning used here. “Transient overvoltage” is defined in [B12] as “a short-duration, highly damped, oscillatory or nonoscillatory overvoltage, having a duration of few milliseconds or less” classified in categories of lightning, switching, and very fast front, short duration. That definition is more appropriate than the somewhat vague definition in [B12] of “surge” for the surges discussed in the Trilogy.

B.19 Switching surges

The switching surges represented by the additional waveforms can occur under a wide range of conditions, which makes it difficult to assign universally applicable severity levels for test purposes. Hence, the levels suggested in IEEE Std C62.41.2-2002 are an attempt at striking a balance between a wish to provide conservative ratings on the one hand and, on the other hand, countless instances of successful operation observed for equipment that do not have the capability of withstanding the severity of the maximum suggested levels of stress.

A 5 kHz waveform had been suggested in 1991 for capacitor-switching transients; however, frequencies can be much lower, as low as 350 Hz. The current levels associated with a capacitor-switching surge can vary significantly and depend on a number of factors, including the type of switching device (and corresponding probability of prestrikes, restrikes, or reignitions), the grounding situation, the system inductance, the kilovar size of the bank, and how often the bank is switched. Any nearby capacitor bank should be analyzed on a case-by-case basis. Subclause B.2 provides more information on the mechanisms leading to capacitor-switching surges.

B.20 Timing of surges with respect to power frequency

Lightning surges are completely random with respect to the power frequency. Switching surges are likely to occur at or near current zero, but variations in the power factors of the loads will produce a quasi-random distribution.

Some semiconductors exhibit failure levels that depend on the timing of the surge with respect to the conduction of power frequency current. Gaps in an SPD or other devices that produce follow current might or might not be capable of withstanding this follow current, depending on the fraction of the half-cycle remaining after the surge, before the power-frequency current zero (Bachl et al. 1997 [B24]).

Therefore, it is important to consider the timing of the surge with respect to the power frequency. In performing tests, either complete randomization or controlled timing should be specified, with a sufficient number of timing conditions to reveal the most critical timing.

B.21 Transitions

The concept of a ***transition that connects***, rather than a ***boundary that separates***, location categories is one of the innovations of the Trilogy, aimed at avoiding unrealistic perceptions or interpretations that the environment can change drastically and suddenly from one location category to the next. The debate was particularly significant for the transition from Location Category C to Location Category B.

In the 1991 version of this guide (IEEE Std C62.41), a dotted-line boundary was shown on the figure illustrating the concept of location categories. Additional words were also included in the legend, indicating that the Location Category C would include the service entrance. The line intersected a link shown between the revenue meter—typically on the outside wall in residential environments—and a panel labeled "Service Entrance." On the basis of this diagram, SPDs intended for connection within or next to the service-entrance panel ("service equipment" in NEC language), but on the load side of the mains disconnect, could be considered as being in a Location Category B environment—a 3 kA 8/20 µs stress level, or possibly a Location Category C with a 10 kA 8/20 µs stress level, depending on the interpretation of the figure or of the text. The 3 kA interpretation was reinforced by the scope of UL Std 1449-1996 [B22] where the demarcation of the "transient voltage surge suppressor (TVSS)" was cited as the load side of the mains disconnect, with a 3 kA level in the 1985 first edition. However, this level was changed to 10 kA in the 1996 second edition.

To harmonize with the approval in 1996 of a new IEEE guide on secondary arresters (IEEE Std C62.34™-1996 [D.1.2]), the demarcation for this guide should be moved from the service disconnect to an undefined point downstream from the service equipment enclosure. A narrow interpretation of that demarcation might have an impact on SPD ratings, an effect that the Trilogy is carefully avoiding in an environment-oriented document. It is to reconcile the 20 yr use of the now fuzzy boundary with the new demarcation that the concept of transitions has been proposed. This concept, illustrated in Figure B.22, makes the selection of a particular SPD rating for a particular installation a matter of application engineering, which is the domain of manufacturers and users, not the scope of the Trilogy. Compounded with the emergence of the possible higher stress requirements for exit-path SPDs in Scenario II, the case for specific application engineering guided by an appropriate risk analysis becomes even stronger.

Figure B.22 shows some distance between the revenue meter and the service equipment in that example. It should be noted that the NEC [B19] specifies that *"The service disconnecting means shall be installed at a readily accessible location either outside of the building or structure or inside nearest point of entrance of the service conductors."* Nevertheless, installations can be found where there is a significant distance between the revenue meter and the service equipment.

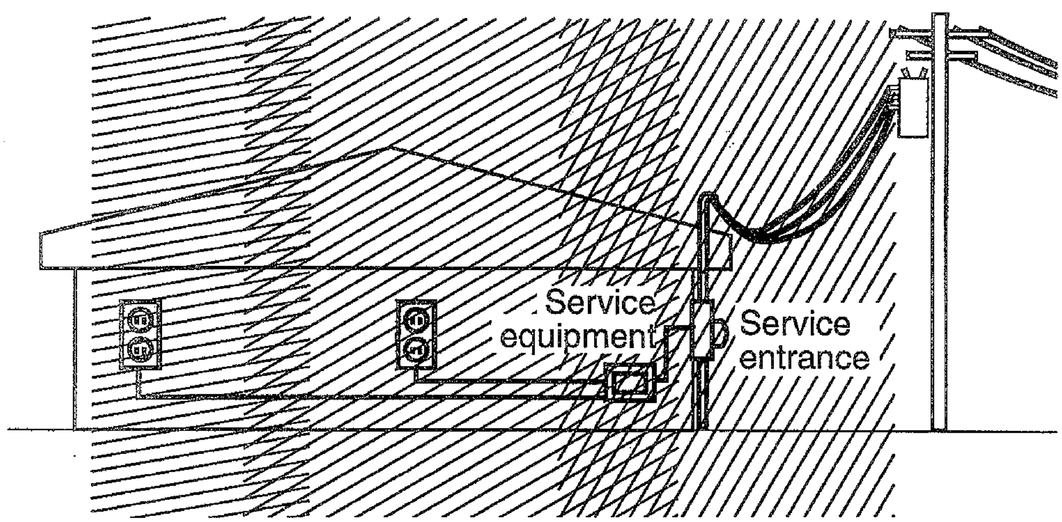


Figure B.22—The concept of transitions connecting location categories

B.22 Utilities interconnections and interactions

Limiting the scope of the surge-environment description to ac power circuits can leave unrecognized a surge-producing mechanism that involves interactions between the mains and data-carrying conductors, the latter being excluded from the scope of this guide. For this reason, it is important to consider the proximity of the conductors of the mains and of the data systems (a telephone, a computer network, a cable TV) within a building.

Ground connection practices for the SPDs provided in these separate systems can result in unexpected voltage differences between the systems during surge events on one system. These voltage differences can occur even though each utility would be observing its mandated practices. Furthermore, these various systems and their functional elements might contain built-in surge protection that can result in side effects (Martzloff 1990 [B124]).

To illustrate these important considerations, Figure B.23 shows in a schematic manner a typical building with an electric utility connection and a telephone utility connection in an attempt to depict the real-life complex wiring that can exist at a typical residence or business. Note that the drawing depicts primary and secondary electric-power wiring circuitry, including feeder and branch circuits within the premises. The drawing also depicts telephone utility wiring facilities outside the premises and the drop wiring arrangements to provide communications service within the premises. The drawing could be made much busier by adding circuits from cable TV systems, premises satellite TV systems, local area communications networks, lightning protection systems, or other similar types of wiring.

The drawing also shows the relative vicinity of Location Categories A, B, and C in this example. Equipment connected to wiring within the boundaries of Category A could conceivably be placed in close proximity (the distance between printed circuit-board traces) with wiring from either Category B or C. An example would be a computer that is connected to its ac power source deep within the premises (relative to the service entrance), but with its telephone modem connected to an aerial telephone circuit located a short distance away on the other side of the premises wall.

The grounding provisions of the different wiring systems are of special note because they are expected to handle surges and are often designated paths for surge diverters. Grounding provisions of separate wiring systems might conduct surges of opposite polarity and thus bring together extreme surge voltages within the confines of electronic equipment cabinets.

Therefore, in making decisions on how to design electronic equipment, the designer needs to recognize the real-world possibilities of bringing together in extremely close proximity two or more wiring systems (from possibly different wiring categories). Designs should include separations and/or surge-withstand capability appropriate for the convergence of such diverse multiple wiring systems. When making decisions on how and where to install electronic equipment and to provide for the most effective protection from the expected surge environment, the decision maker must have a clear concept of actual wiring and the relative proximity and inter-mixing of wiring category types.

The overall protection scheme decided upon should also include some type of ongoing program to ensure that the conditions existing at the installation stage are maintained and not otherwise allowed to deteriorate outside design parameters. A review of accepted practices is summarized in B.22.1 and B.22.2.

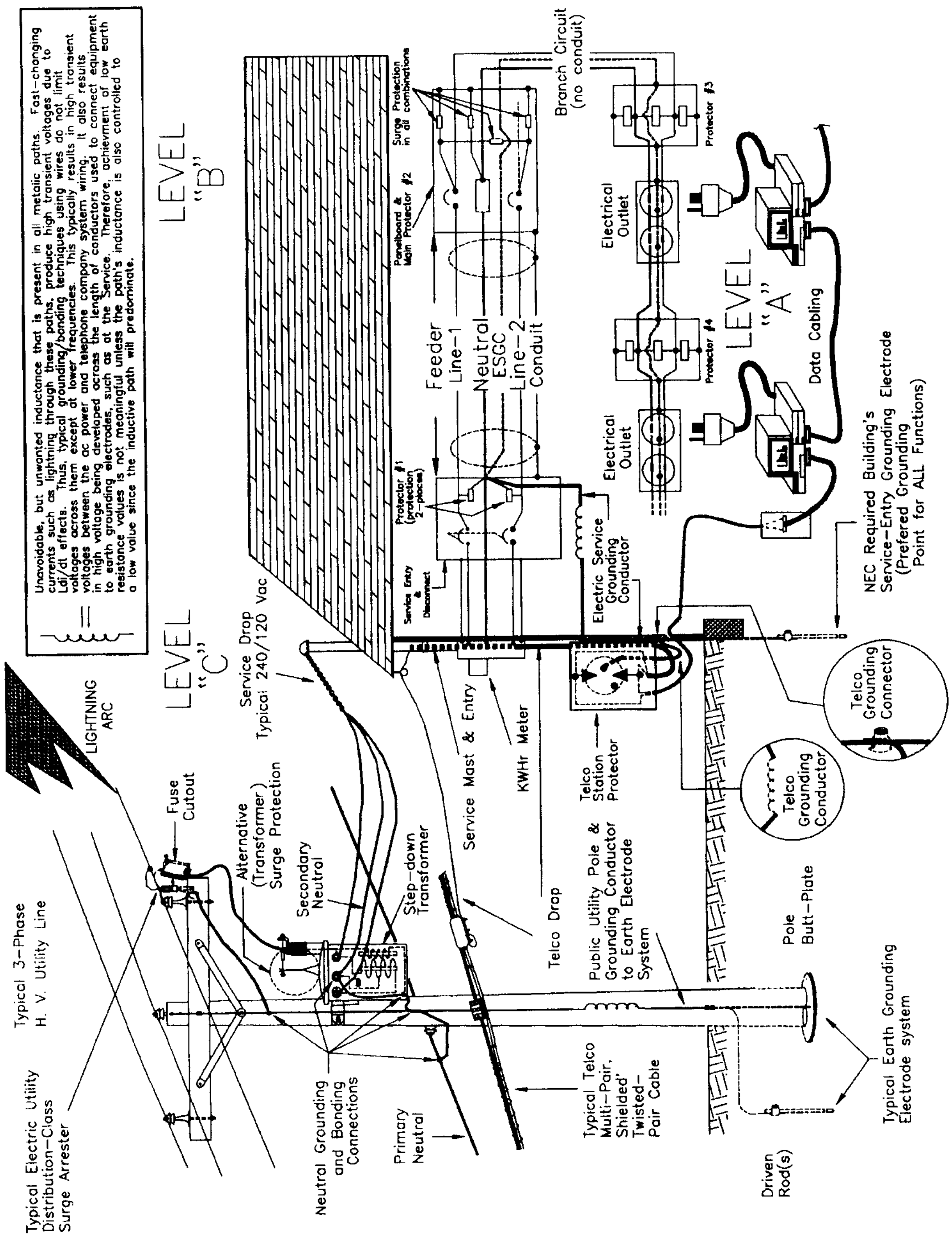


Figure B.23—Example of interconnection and interaction of utilities for typical US practice

B.22.1 AC power service

The surge protection for this service may include an overall protection at the service entrance and/or individual protection for branch circuits. There is also the protection typically provided by surge arresters on the primary of the distribution transformer. This arrester is beyond the control of the end user, but does provide protection of the distribution transformer and, to some degree, for the user on the secondary side, against the surges occurring in the utility system.

Overall protection at the service entrance may be provided at the weather head, at the watthour meter, or on the load side of the main service disconnect. In the United States, the NEC [B19] requires that, where used at a point of a circuit, a surge arrester shall be connected to each ungrounded conductor, and on circuits of less than 1000 V the rating of the surge arrester must be equal to or greater than the maximum continuous phase-to-ground power-frequency voltage available at the point of application.

The user may provide supplemental transient-voltage surge suppression as deemed necessary to protect equipment against disturbances originating from user-owned equipment within the premises or from elsewhere. This type of additional ac power-line protection may be installed in any or all of the following locations:

- Load side of entrance distribution panel
- Branch system distribution panel supplied from a feeder
- Individual branch receptacles (incorporated to the receptacle)
- Plugged in the receptacle, as a removable device

Appropriate coordination of branch-outlet protective devices with service-entrance protection could provide optimal protection from externally generated surges. Unfortunately, little information is available to the purchasers of these devices to assist them in obtaining such a coordination.

B.22.2 Telephone station protector

Telephone companies install telephone surge protection as required by the NEC [B19] at the premises of the customer to limit abnormal voltages between telephone conductors and ground. This protection is required by the NEC where the serving telephone circuits (aerial or underground) are located within the block containing the building served and are exposed to accidental contact with electric light or power conductors operating over 300 V to ground or where serving telephone circuits are partly or entirely aerial and are not confined within a “block.” A block is defined by the NEC as a square or portion or section of a town, city, or village that is enclosed by streets and including the alleys so enclosed but not any street.

The communications circuit protectors may be carbon blocks, gas tubes or solid-state devices. They offer the protection that is required by the NEC. These devices may be mounted inside or outside the premises of the customer.

Many equipment manufacturers and vendors incorporate additional protection in their system designs to limit undesired voltages. The NEC has classified the arrester equipment providing such additional surge protection as “secondary protectors.” The NEC requires secondary protectors (Section 800-32) to limit currents safely to less than the current-carrying capacity of the listed indoor communications wire and cable, the listed telephone set line-cords, and the listed communications terminal equipment having ports for external wire-line communications circuits. This current-limiting requirement was established because of the lower surge-arresting threshold available with secondary protectors and their likelihood of responding before, or at voltages below that of, the protector provided by the telephone utility and their initiation of current flow into the premises via the telephone circuit wiring.

Telephone utility-type station protectors and secondary protectors (whether separate, self-enclosed, add-on pieces of equipment, or secondary protection incorporated within other products users may connect to the telephone network) must be "listed" in accordance with NEC requirements. "Listed" means that the product is included in a document published by an organization acceptable to the authority (state, county, etc.) that mandates NEC compliance. The "listing organization" has to be concerned with product evaluation and must maintain periodic inspection of production of the listed equipment.

B.23 Worst case

Voltage and current amplitude appearing in the tables of Clause 6 and Clause 7 of IEEE Std C62.41.2-2002 are given in an attempt to describe typical occurrences at various levels of severity. In the case of a lightning stroke, one should think in terms of the statistical distribution of strikes, accepting a reasonable upper limit for most cases. Where the consequences of a failure are not catastrophic, but merely represent an economic loss, it may be appropriate to make a tradeoff on the cost of protection against the likelihood of a failure caused by a high but rare surge. For instance, a manufacturer could be concerned with nationwide failure rates at high surge levels, those at the upper limits of the distribution curve, while the user of a specific system could be concerned with a single failure occurring at a specific location under "worst-case conditions." Rates of occurrence can be estimated for average systems, however; and even if imprecise, they provide manufacturers and users with guidance. In the case of capacitor-switching surges, there is a wide range of possibilities from benign to potentially destructive surges. In the case of surges caused by the operation of fuses, the situation is similar, leaving the definition of "worst case" open to debate, depending on the assumptions made for the circuit parameters.

The recommended practice IEEE Std C62.41.2-2002 repeatedly emphasizes that setting specific surge withstand levels remains the prerogative and responsibility of manufacturers in response to the needs of specific applications or user requirements. The temptation to seek assurance of high reliability by requiring "worst-case" capability (with the pitfall of testing only at that level, missing the issue of blind spots) must be tempered by economic realities, which depend on the nature of the equipment and its use.

One approach might be to select a level (and only one) of withstand capability for a type of equipment. That level would cover a high percentage of the applications. The addition of some add-on interface device would provide for the small percentage of the cases of extreme ("worst-case") environments. This approach is reflected in the exposure bands of Figure 14 of this guide, where the exposure bands have imprecise limits. Another approach might be to design the equipment after selecting a level of withstand capability below which it will not be allowed to malfunction. A second, higher level would then be selected, below which the equipment may be allowed to malfunction or even fail, but up to which it will not be allowed to cause personnel hazard or consequential damage.

Annex C

(informative)

Glossary

This glossary is provided in an attempt to foster more consistent usage of terms among utilities, end-users, suppliers, and consultants. Entries include a definition, followed by explanatory comments as necessary, appearing in *small italics*. The definitions cited here have been drawn from several sources, identified by code numbers after the term, corresponding to the following items:

[1] Complementary meaning of the term, for the purposes of the Trilogy
[2] *The Authoritative Dictionary of IEEE Standards Terms* [B12]
[3] IEEE C62 standards, not yet incorporated in [2]
[4] Proposed or published definitions from the IEC Surge-Protective Devices Committee
[5] The NEC [B19]

arrester disconnector [2]. A means for disconnecting an arrester in anticipation of, or after, a failure in order to prevent a permanent fault on the circuit and to give indication of a failed arrester. NOTE: Clearing of the fault current through the arrester during disconnection is generally done by the nearest source-side overcurrent-protective device.

Comment: *Two types of devices are found on the market: One type includes a internal fuse or thermal cut-off that opens, disconnecting the failed SPD component while leaving the load energized (protection is lost for the next surge, but operation of the load is maintained). The second type includes a internal fuse or thermal cut-off that opens, disconnecting the failed SPD component* ***and*** *the load (protection is maintained, but operation of the load is interrupted).*

back filter [2]. A filter inserted in the power line feeding an equipment to be surge tested; this filter has a dual purpose: (1) of preventing the applied surge from being fed back to the power source where it might cause damage. (2) of eliminating loading effects of the power source on the surge generator.

back flashover (lightning) [2]. A flashover of insulation resulting from a lightning stroke to part of a network or electric installation that is normally at ground potential.

Comment*: The typical example of such an event occurs when a lightning flash strikes the pole or shield wire of a transmission or distribution line, resulting in a flashover of the line insulators.*

clamping (suppression) voltage [2]. The peak voltage across the varistor measured under conditions of a specified peak pulse current and specified waveform. NOTE: Peak voltage and peak current are not necessarily coincident in time.

Comment: *According to more recent documents, the term should be replaced by "measured limiting voltage." See also the IEC definition of "measured limiting voltage."*

combination wave [2]. The combination wave is delivered by a generator that applies a 1.2/50 µs voltage impulse across an open circuit and an 8/20 µs impulse current into a short circuit. The voltage and current and waveforms that are delivered to the surge protective device (SPD) are determined by the generator and the impedance of the SPD to which the surge is applied. The ratio of open-circuit voltage to peak short-circuit current is 2 Ω

Comment: This definition is compatible with a proposed IEC definition, with the voltage-to-current ratio called "fictive impedance" in the IEC documents and "effective impedance" in the IEEE. In many standards, the waveform numbers such as 1.2/50 and 8/20 are not followed by the time unit µs because such time untes are implied by explicit or tacit *convention. In the context of the Trilogy, however, other waveforms are cited, such as 5/50 ns; therefore, showing the units avoids confusion.*

damage [1]. The term *damage* can take on different meanings and degrees of severity depending on the context and the circumstances. For instance, the IEC publications on immunity tests (61000-4 series) list outcomes of the test, with the last (and most severe) defined as follows:

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

This description indicates that “damage” includes not only physical damage to the equipment under test (EUT), but also an irreversible and unacceptable change in software or database.

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

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

Depending on the extent and time expended for the intervention, a conservative view might be that, for practical purposes, the equipment under test (EUT) has been “damaged.” *See also:* **upset**.

device failure [1]. An irreversible change in characteristic, resulting in an inability to perform as intended.

Comment: *In the context of SPDs, the following examples of “device failure” are given in various IEEE C62 documents:*
- *Shorting or opening of any component;*
- *Failure of a component in any one stage of a multistage unit;*
- *Changes of nominal varistor voltage exceeding 10% between pre- and post-tests in the 1 mA dc test;*
- *Overheating, which results in a hazardous condition;*
- *Irreversible change in characteristics of any component beyond the specifications limits.*

Two types of SPDs are found on the market: One type includes a internal fuse or thermal cut-off, or both, disconnecting the failed SPD component while leaving the load energized (protection is lost for the next surge, but operation of the load is maintained). The second type includes a internal fuse or thermal cut-off, or both, disconnecting a failed SPD component ***and*** *the load (protection is maintained, but operation of the load is interrupted).*

electrical environment [1]. The totality of conducted electrical phenomena existing at a given location. NOTE: These phenomena become disturbances only if they degrade the performance of equipment.

energy deposition [1]. The time integral of the power dissipated in a clamping-type surge protective device (SPD) during a current surge of a specified waveform.

Comment: *The energy deposition is commonly used as a measure of the stress imposed on an SPD. Most varistor manufacturers quote the energy ratings of their devices for a specific waveform, typically 10/1000 µs rather than the 8/20 µs, and as a maximum single pulse-rating. This rating is generally conservative. Nevertheless, energy computations during evaluation tests should yield results that are well below the ratings, to make provision for a long life with multiple strokes (see “pulse life” in this glossary and Darveniza 1997 [B209]). There are other parameters for defining the capability of an SPD to handle current surges (with steep front, with very long duration, etc.). The “joule rating” of an SPD, however, should not be used as sole criterion to compare devices.*

failure mode. See ***device failure.***

fail-safe. Use of this term is not recommended. See ***device failure***.

fault current [2]. The current from the connected power system that flows in a short circuit.

Comment: *The amplitude, phase angle, and rate of rise of a fault current resulting from an SPD failure (which might not necessarily be a complete short circuit) have a significant effect on the failure mode. It has been observed that more objectionable failure modes can result from a relatively low available fault current because overcurrent protection in an actual installation takes longer to clear the fault, increasing the length of exposure of surrounding materials to the high-temperature arc. In the lost neutral scenario, where the current through the failed SPD is limited, the branch circuit overcurrent device will not provide the disconnect function.*

follow current (power). Two definitions can be found:

[2] The current from the connected power source that flows through an arrester during and following the passage of discharge current.

[4] Current supplied by the electrical power system and flowing through the SPD after a discharge current impulse and significantly different from the continuous operating current (I_c)

Comment: *The IEEE definition was first developed for arresters using a series combination of gap and SiC varistor, where significant power-frequency current flows after the surge current. Some of the durability (endurance) test concepts with varying phase angles for the surge application were derived from this situation, because the angle of application of the surge affects the duration of the follow current. In SPDs based on MOVs, the follow current is negligible (it is the standby current at the temperature resulting from the surge) unless the surge was large and presents a risk of launching a thermal runaway. The proposed IEC definition (note that it applies only to the current <u>after</u> the discharge, in contrast with the IEEE definition which applies <u>during and after</u> the discharge) seems more appropriate to MOV-based SPDs.*

immunity (to a disturbance) [2]. The ability of a device, equipment, or system to perform without degradation in the presence of an electromagnetic disturbance.

Comment: *This definition was generated within the context of EMC, but can readily be expanded to the context of surge immunity, including the absence of degradations and the ultimate degradation—device failure. See also:* ***damage*** *and* ***upset****.*

made electrode.

Comment: *Without stating a terse definition of this term, Article 250-52 the NEC [B19] provides a list of what objects may be, or shall not be, used as grounding electrodes in association with the grounding system of a structure. The list also provides specific descriptions of metal, dimensions, number, and spacing of such electrodes.*

mains [2]. The ac power source available at the point of use in a facility. It consists of the set of electrical conductors (referred to by terms including "service entrance," "feeder," or "branch circuit") for delivering power to connected loads at the utilization voltage level.

maximum continuous operating voltage (MCOV) [2]. The maximum designated root-mean-square (rms) value of power-frequency voltage that may be applied continuously between the terminals of the arrester.

measured limiting voltage [2]. The maximum magnitude of voltage that is measured across the terminals of the surge protective device (SPD) during the application of a series of impulses of specified wave shape and amplitude.

Comment*: Without the qualifier "measured" appearing in this definition, the shorter term "limiting voltage" is gaining favor as a generic parameter of performance, without reference to a specified waveform, and is used in this guide instead of the earlier term "clamping voltage," which is now deprecated in IEC documents, but still widely used in the industry.*

nominal system voltage [2]. A nominal value assigned to designate a system of a given voltage class.

open-circuit voltage (OCV) [1]. The voltage available from the complete test set-up as configured (surge generator, coupling circuit, back filter, connecting leads), prior to connecting the equipment under test (EUT), at the terminals where the surge protective device (SPD) under test will be connected.

oscillatory surge [2]. A surge that includes both positive and negative polarity values.

prospective overvoltage [1]. The theoretical voltage that a lightning event might couple or induce into a power system if it were not truncated by flashover of insulation or action of an surge protective device (SPD).

pulse life [3]. The number of surges of specified voltage, current amplitudes, and wave shapes that may be applied to a device without causing degradation beyond specified limits. The pulse life applies to a device connected to an ac line of specified characteristics and for pulses sufficiently spaced in time to preclude the effects of cumulative heating.

rated peak single-pulse transient current [2]. Maximum peak current that may be applied for a single 8/20 µs impulse, with rated line voltage also applied, without causing device failure.

rated single-pulse transient energy [2]. Energy that may be dissipated for a single impulse of maximum rated current at a specified wave shape, with rated root-mean-square (rms) voltage or rated dc voltage also applied, without causing device failure.

rated standby power dissipation [3]. The power dissipated in a protective device while connected to an ac line having a voltage and frequency equal to the rating of the device and with no load current flowing and no surges applied.

rated voltage [2]. The designated maximum permissible root-mean-square (rms) value of power-frequency voltage between its line and earth terminals at which it is designed to operate correctly.

rating [2]. The designation of an operating limit for a device.

recovery voltage [2]. The voltage that occurs across the terminals of a pole of a circuit-interrupting device upon interruption of the current. NOTE: For an arrester, this occurs as a result of interruption of the follow current.

repetitive surge and follow-current withstand [3]. The number of surges of specified voltage and current amplitudes and wave shapes that may be applied to a device without causing degradation beyond specified limits. The repetitive surge and follow-current withstand applies to a device connected to an ac line of specified characteristics and for pulses applied at specified rates and phase angles. The effects of any cumulative heating that may occur are included.

Comment*: This definition does not address any differentiation between a test procedure, as seems implied here, and the real-world issue of multiple lightning strokes within a lightning flash (see Darveniza 1997 [B209]). There is a trend on the market toward offering SPDs with higher and higher current-handling capability. This trend might be a simple competitive auction or an attempt to provide, with a single impulse test, the capability of withstanding multiple lightning surges.*

ring wave [3]. An open-circuit voltage wave characterized by a rapid rise to a defined peak value, followed by a damped oscillation in which every successive peak has an amplitude of about 60% of the value of the peak that preceded it. For the 100 kHz Ring Wave, the rise time is nominally 0.5 µs and the ringing frequency is approximately 100 kHz. No short-circuit current waveform is defined; the exact wave that is delivered is determined by the instantaneous impedance to which the Ring Wave is applied.

routine tests [2]. Tests made by the manufacturer on every device or representative samples, or on parts or materials, as required, to verify that the product meets the design specifications.

series gap [2]. An intentional gap between spaced electrodes: It is in series with the valve or expulsion element of the arrester, substantially isolating the element from line or ground, or both, under normal line-voltage conditions.

service equipment [5]. The necessary equipment, usually consisting of a circuit breaker(s) or switch(es) and fuses and their accessories, connected to the load end of service conductors to a building or other structure, or an otherwise designated area, and intended to constitute the main control or cutoff of the supply.

Comment: *According to the concept of transitions proposed in the Trilogy, service equipment is considered to serve as transition between Location Category C and Location Category B.*

service voltage [2]. The voltage at the point where the electric system of the supplier and the electric system of the user are connected.

short-circuit current (SCC) [1]. The current that the test set-up (surge generator, coupling circuit, back filter, connecting leads) can deliver at the terminals where the surge protective device (SPD) under test will be connected, with the SPD replaced by bonding the two lead terminals. (Sometimes abbreviated as "SCI.")

surge [2]. A transient wave of current, potential, or power in an electric circuit. NOTE: The use of this term to describe a momentary overvoltage consisting of a mere increase of the mains voltage for several cycles is deprecated. *See also:* **swell**.

Comment: *This is a generalized definition of surge. For power systems, surge (also called a transient) is a subcycle overvoltage with a duration of less than a half-cycle of the normal voltage waveform. A surge can be of either polarity, can be additive to or subtractive from the normal voltage waveform, and is often oscillatory-decaying.*

surge let-through [2]. The part of the surge that passes by a surge protective device (SPD) with little or no alteration. *See also:* **surge remnant**.

Comment*: There is a subtle difference between this term and surge remnant. Surge remnant is whatever appears downstream of the SPD, attenuated or not. "Surge let-through" explicitly means little or no attenuation, in particular in the initial phase of a surge. Unfortunately, there seems to be lingering confusions between the two terms.*

surge protective device (SPD). Several definitions have been developed in the IEEE C62 series and the IEC TC37 documents concerning SPDs:

a) A device intended either to limit transient overvoltages or divert surge currents, or both. It contains at least one nonlinear component. *(IEEE Std C62.34-1996 [D.1.2])*
b) An assembly of one or more components intended to limit or divert surges. The device contains at least one nonlinear component. *(IEEE Std C62.48™-1995 [D.1.2])*
c) A device that is intended to limit transient overvoltages and divert surge currents. It contains at least one nonlinear component. *(IEC 61643-Ed 1.1:2002 [B10])*

surge remnant [2]. The part of an applied surge that remains downstream of one or several protective devices. *See also:* **surge let-through**.

Comment: *There is a subtle difference between this term and surge let-through. A surge remnant can have lower amplitude than a surge let-through. Obtaining a surge remnant lower than the impinging surge is the very function of an SPD. "Surge let-through" explicitly means little or no attenuation. Unfortunately, there seems to be lingering confusions between the two terms.*

surge response voltage [2]. The voltage profile appearing at the output terminals of a surge protective device (SPD) and applied to downstream loads, during and after a specified impinging surge, until normal, stable conditions are reached.

swell [2]. A momentary increase in the power-frequency voltage delivered by the mains, outside of the normal tolerances, with a duration of more than one cycle and less than a few seconds. *See also:* **surge**.

Comment: *This term has been introduced to avoid the confusion between surge, as defined in IEEE documents, and the popular meaning of surge, a power-frequency increase in rms voltage.*

system (circuit) voltage [2]. The root-mean-square (rms) power-frequency voltage from line to line as distinguished from the voltage from line to neutral.

upset [3]. Malfunction of a system because of electrical disturbances.

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

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

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

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

utilization voltage [2]. The root-mean-square (rms) phase-to-phase or phase-to-neutral voltage at the line terminals of utilization equipment.

voltage rating [2]. The designated maximum permissible operating voltage between its terminals at which an arrester is designed to perform its duty cycle. It is the voltage rating specified on the nameplate.

Annex D

(informative)

Annotated bibliography

This bibliography is provided to give the interested reader a source of reference material with a few lines of comments on content or on the significance of the cited document. The compilation is divided into eight categories, as listed below. Each citation is followed by terse statements on the contents and number of further references. The listing includes citations made in the text as well as additional entries not specifically called for in the text, but still noteworthy. The papers cited in the text and containing topics relevant to more then one category are listed in each category of interest. The listing is arranged by alphabetical order of the lead author in each category. The following are the categories for the listing:

D.1 Published standards related to surges
D.2 Development of standards—reality checks
D.3 Recorded surge occurrences—surveys and staging
D.4 Propagation and coupling of surges—experiments and numerical simulations
D.5 Monitoring instruments, laboratory measurements and test methods
D.6 Textbooks and tutorial reviews
D.7 Mitigation techniques
D.8 Coordination of cascaded SPDs

The volume of this bibliography is testimony to the contributions from all the listed authors to a database that made the Trilogy development possible. The working group acknowledges these contributions, along with those of former members and contributors of the working group who developed the seminal 1980 document (IEEE Std 587) and its 1991 revision (IEEE Std C62.41):

G. J. Bagnall
D. A. Bell
D. W. Bodle
D. W. Boehm
H. A. Buschke
C. E. Chamney
E. J. Cohen
R. A. Combellack
D. R. Covington
M. J. Coyle
J. G. Dalton
R. J. Davidson
E. P. Dick
B. Dillon-Malone
F. Esparza
L. Fish
F. A. Fisher
R. M. Henry
J. I. Herrera
H. A. Gauper
P. Jedlicka
C. J. Kawiecki
K. Lerstrup
W. H. Lewis
C. E. Luebke
E. H. Marrow
L. McAfee
A. McEachern
C. M. Meier
K. A. Meindorfer
R. C. Mierendorf
W. Milwitt
J. J. Napiorkowski
M. Parente
J. A. Plumer
H. Rauworth
L. Regez
P. Richman
W. Roehr
L. Schulman
T. Shaughnessy
P. D. Speranza
R. B. Standler
L. D. Sweeney
D. P. Symanski
M. X. Tetreault
C. R. Wetter
L. Williams

D.1 Published standards related to surges

D.1.1 The IEEE C62 series

A bound-book collection of all ANSI and IEEE C62 standards, compiled periodically by the IEEE, includes all published IEEE standards applicable to low-voltage SPDs at the time of the edition. More recent updates of individual standards are listed after the following contents of the 1995 edition:

IEEE Std C62.1™-1989 (Reaff 1994), IEEE Standard for Gapped Silicon-Carbide Surge Arresters for AC Power Circuits.[17, 18]

IEEE Std C62.2™-1987 (Reaff 1994), IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for AC Systems.

IEEE Std C62.11-1993, IEEE Standard for Metal-Oxide Arresters for AC Power Circuits.

IEEE Std C62.22™-1991, IEEE Guide for the Application of Metal Oxide Surge Arresters for AC Systems.

IEEE Std C62-31™-1987 (Reaff 1993), IEEE Standard Test Specifications for Gas-Tube Surge Protective Devices.

IEEE Std C62.32™-1981 (Reaff 1993), IEEE Standard Test Specifications for Low-Voltage Air Gap Surge-Protective Devices (Excluding Valve and Expulsion Type Devices).

IEEE Std C62.33™-1982 (Reaff 1994), IEEE Standard Test Specifications for Varistor Surge-Protective Devices.

IEEE Std C62.35™-1987 (Reaff 1993), IEEE Standard Test Specifications for Avalanche Junction Semiconductor Surge Protective Devices.

IEEE Std C62.36™-1994, IEEE Standard Test Methods for Surge Protectors Used in Low-Voltage Data, Communications, and Signaling Circuits.

IEEE Std C62.38™-1994, IEEE Guide on Electrostatic Discharge (ESD): ESD Withstand Capability Evaluation Methods (for Electronic Equipment Subassemblies).

IEEE Std C62.41-1991 (Reaff 1995), IEEE Recommended Practice for Surge Voltages in Low-Voltage AC Power Circuits.

IEEE Std C62.42™-1992, IEEE Guide for the Application of Gas Tube and Air Gap Arrester Low-Voltage (Equal to or Less than 1000 V rms or 1200 V dc) Surge-Protective Devices.

IEEE Std C62.45-1992, IEEE Guide on Surge Testing for Equipment Connected to Low-Voltage AC Power Circuits.

IEEE Std C62.47™-1992 (Reaff 1997), IEEE Guide on Electrostatic Discharge: Characterization of the ESD Environment.

IEEE PC62.92.x (A series of guides on neutral grounding practices).

D.1.2 Additional C62 standards

Additional C62 standards published since the 1995 collection include

IEEE Std C62.11-1999, IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits (> 1 kV) (major revision of the 1993 edition).

[17]The IEEE standards or products referred to in Annex D are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.

[18]IEEE 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/).

IEEE Std C62.22™-1997, IEEE Guide for the Application of Metal Oxide Surge Arresters for Alternating-Current Systems.

IEEE Std C62.34-1996, IEEE Standard for Performance of Low-Voltage Surge Protective Devices (Secondary Arresters).

IEEE Std C62.36™-2000, IEEE Standard Test Methods for Surge Protectors Used in Low-Voltage Data, Communications, and Signaling Circuits.

IEEE Std C62.37™-1996, IEEE Standard Test Specifications for Thyristor Diode Surge Protective Devices.

IEEE Std C62.37.1™-2000, IEEE Guide for the Application of Thyristor Surge Protection Devices.

IEEE Std C62.43™-1999, IEEE Guide for the Application of Surge Protectors Used in Low-Voltage (Equal to or Less Than 1000 V rms or 1200 V dc) Data, Communications, and Signaling Circuits.

IEEE Std C62.48-1995, IEEE Guide on Interactions Between Power System Disturbances and Surge-Protective Devices.

IEEE Std C62.62™-2000, IEEE Standard Test Specifications for Surge Protective Devices for Low Voltage AC Power Circuits.

IEEE Std C62.64™-1997, IEEE Standard Specifications for Surge Protectors Used in Low-Voltage Data, Communications, and Signaling Circuits.

D.1.3 Other standards

[B1] Accredited Standards Committee C2-2000, National Electrical Safety Code® (NESC®).[19, 20]

- Rules for the protection of persons during installation, operation and maintenance of power and communications lines and equipment for utilities and for systems under the control of qualified persons.
- For building utilization wiring, refer to the NEC [B19].
- 257 pages, 77 reference documents

[B2] ANSI C84.1-1989, American National Standard for Electric Power Systems and Equipment Voltage Ratings (60 Hz). (Reaffirmed 1995).[21]

- Defines steady-state limits of system voltages for the United States.
- Addresses only steady-state voltages or short-term departures from nominal conditions.
- Provides list of related standards.

[B3] IEC *Multilingual Dictionary of Electricity.* The Institute of Electrical and Electronics Engineers, 1983.

- A conversion of the IEC International Electrotechnical Vocabulary (IEV) into a dictionary.[22]

[B4] IEC 60060-2:1994, High-voltage test techniques—Part 2: Measuring systems.

- Defines parameters of impulse waveforms.

[19]National Electrical Safety Code® and NESC® are both registered trademarks and service marks owned by the Institute of Electrical and Electronics Engineers, Inc.

[20]The NESC is 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/).

[21]ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

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

[B5] IEC 60364-4-442:1999, Electrical installations of buildings—Part 4: Protection for safety—Chapter 44: Protection against overvoltages—Section 442: Protection of low-voltage installations against faults between high-voltage systems and earth.

— Earthing systems and arrangements in transformer substations.
— Earthing arrangements and earthing systems in low-voltage installations.
— Stress voltages in cases of lost neutral (TN and TT), accidental earthing (IT), and line-to-neutral short.

[B6] IEC 664, Insulation coordination within low-voltage systems including clearances and creepage distances for equipment.

1980 edition:

— Superseded, but significant historical document.
— Introduced the staircase concept of surge voltage reduction.

1992 edition (now numbered 60664-1):

— No longer shows a descending staircase of voltages.
— Does not discuss surge source impedance considerations as it is concerned with insulation withstand.

[B7] IEC 61000-2-5:1995, Electromagnetic Compatibility—Part 2: Environment—Section 5: Classification of electromagnetic environments.

— Basic EMC publication (technical report).
— Not a test or performance specification, but a guide to what levels of disturbances might be expected.
— Proposes an arrangement with five classes of locations and correspondingly characterized by levels.

[B8] IEC 61000-4-4:1995, Electromagnetic Compatibility (EMC)—Part 4: Testing and measurement techniques—Section 4: Electrical fast transient/burst immunity tests.

— Specifies interference immunity test with bursts of fast-transient pulses applied to EUT in "common mode" by a coupling clamp or in "selective mode" by capacitor coupling.

[B9] IEC 61312-3:2000, Protection against lightning electromagnetic impulse (LEMP)—Part 3: Requirements of surge protective devices (SPDs).

— Presents the IEC TC81 perception of "requirements" for service-entrance SPDs.
— Approved according to the IEC operating procedures, but with only 68% of the votes.

[B10] IEC 61643 Ed 1.1:2002, Surge protective devices connected to low-voltage power distribution systems—Part 1: Performance requirements and testing methods.

— Defines three classes of tests, I, II, and III, with specific stress levels.
— Does not relate the test levels to the location of application.

[B11] IEC 62066:2002, General basic information regarding surge overvoltages and surge protection in low-voltage a.c. power circuits.

— A tutorial technical report describing the origins, propagation, and mitigation of surges.
— Bibliography with 58 citations, similar to this bibliography.

[B12] IEEE 100™, *The Authoritative Dictionary of IEEE Standards Terms,* Seventh edition.

[B13] IEEE Std C37.90.1-1989, IEEE Standard Surge Withstand Capability (SWC) Tests for Relays and Relays Systems Associated with Electric Power Apparatus.

- A document developed for the environment of high-voltage substation equipment. Its fast transient requirement, with a rise time of less than 10 ns, is similar to the IEC EFT Burst requirement.
- Calls for a 1 MHz to 1.5 MHz ring wave and a 4 kV to 5 kV peak impulse, < 10 ns rise time.
- 14 references

[B14] IEEE Std 4™-1995, IEEE Standard Techniques for High-Voltage Testing.

- Defines impulse parameters.

[B15] IEEE Std 446-1995, IEEE Recommended Practice for Emergency and Standard Power Systems for Industrial and Commercial Applications (Orange Book).

- The earliest publication of the “CBEMA Curve” occurred in the 1980 edition of this standard.

[B16] IEEE Std 518-1982 (Reaff 1996), IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources.

- Discusses the sources of electrical noise; provides an example of the “showering arc” leading to the EFT concept.
- Provides guidance on noise reduction (not suppression) and installation practices.

[B17] IEEE Std 1100-1999, IEEE Recommended Practice for Powering and Grounding Electronic Equipment (Emerald Book).

- Recommended engineering principles and practices for powering and grounding electronic equipment in commercial and industrial applications.
- 400 pages, 120 bibliographic citations

[B18] IEEE Std 1159-1995, IEEE Recommended Practice for Monitoring Electrical Power Quality.

- Provides definitions of power systems disturbances.
- Makes recommendations on deployment of surge-monitoring instruments.
- Makes recommendations on interpretation of power quality surveys.

[B19] NFPA 70-2002, National Electrical Code® (NEC®).[23]

- A fundamental document providing minimum requirements for safe installation practices (United States).
- A companion handbook provides explanations for application of the code.
- Specifies minimum requirements for safety, not necessarily optimum surge protection.
- Allows connection of SPDs between any pair of conductors.
- Updated every three years.

[B20] NFPA 780-2000, Standard for the Installation of Lightning Protection Systems.[24]

- Provides for the practical safeguarding of persons and property from hazards arising from exposure to lightning.
- Describes the rolling sphere concept in predicting likely points of strike.
- Describes bonding techniques and down-conductors.
- 22 references to NFPA, IEC, IEEE, military, and UL publications

[23]The NEC® is published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA (http://www.nfpa.org/). Copies are also 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/).

[24]NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA (http://www.nfpa.org/).

[B21] UL Std 93-1975, Standard for Safety—Ground Fault Circuit Interrupters.[25]

- First proposal to industry of what became the 100 kHz Ring Wave.

[B22] UL Std 1449-1996, Standard for Safety—Transient Voltage Surge Suppressors.

- First edition: 1985; second edition, 1996
- The second edition, which became effective in 1998, features a new set of failure mode tests.
- Specifies safety aspects of suppressor design, with some performance implications.
- Requires citation of limiting voltage levels, from a tabulation of values starting at 330 V.

D.2 Development of standards—reality checks

[B23] Anderson, L. M., and Bowes, K. B., "The effects of power-line disturbances on consumer electronic equipment," *IEEE Transactions PWRD-5*, no. 2, Apr. 1990.

- Experimental study of the immunity of typical electronic equipment to sags and surges.
- Surges applied were not the ANSI C62.41, but a 100 μs or 300 μs pulse, presumably open-circuit voltage.
- Surges of 1000 V did not cause any failure of PCs. (NOTE: The authors did not define whether this value of 1000 V was the open-circuit voltage setting of their generator or the measured value when applied at the power port of the PC.)

[B24] Bachl, H., Martzloff, F. D., and Nastasi, D., "Using Incandescent Lamp Failure Levels for Assessment of the Surge Environment," *Proceedings, International Zurich Symposium on EMC*, 1997.

- Shows failure mechanisms and levels, by electrical measurements, and with high-speed video recording.
- 120 V lamps can fail in the range of 800 V to 1200 V, depending on wave shape and phase angle.
- Makes the point that surges are unlikely to occur frequently at levels above the failure level of lamps.
- 5 references

[B25] Bartkowiak, M., Comber, M. G., and Mahan, G. D., "Failure Modes and Energy Absorption Capability of ZnO Varistors," *IEEE Transactions PWRD-14*, Jan. 1999.

- Simulation of varistor behavior under current pulses of various magnitudes and duration.
- Comparison with experimental results.
- Demonstrates that the energy-handling capability is not a constant, but depends on intensity and duration.
- 14 references, 1 discussion

[B26] Fenimore, C., and Martzloff, F. D., "Validating Surge Test Standards by Field Experience: High-Energy Tests and Varistor Performance," *IEEE Transactions IA-28*, no. 6, Dec. 1992.

- Computer modeling of the resulting current and energy deposition into typical varistors subjected to the proposed 10/1300 μs waveform.
- Yields a prediction of failure for the small varistors and survival for the larger varistors.
- Because small varistors do not fail in the field at the rate that is predicted by the model, the conclusion is that this proposed waveform is unrealistic.
- 15 references

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

[B27] Goedde, G. L., Kojovic, Lj. A., and Woodworth, J. J., "Surge Arrester Characteristics that Provide Reliable Overvoltage Protection in Distribution and Low-Voltage Systems," *Proceedings, IEEE/PES Summer Meeting*, Seattle, WA, July 2000.

— Describes field experience of arresters designed in accordance with IEEE Std C62.11-1999.
— Concludes that tests with a 10/350 µs waveform are not necessary.
— 11 references

[B28] Key, T. S., Martzloff, F. D., Witt, R., May, J., and Black, S., "Developing a Consumer-Oriented Guide on Surge Protection," *Proceedings, PQA'97 North America*, 1997.

— Progress report on the development of a tutorial on surge protection.
— Presents the need for "intersystem bonding" at the entrance of power and communications utilities.
— Brief discussion of the need for surge reference equalizers.
— 6 references

[B29] Maciela, F., "Energetic design and EDF distribution network experience of MV metal oxide surge arresters," *CIGRE SC33.95* (1995 Colloquium).

— Field experience of EDF on 700 000 arresters.
— Failure rate lower (1/4) than calculated in Rousseau 1989 [B38].
— No references

[B30] Mansoor, A., Martzloff, F. D., and Nastasi, D., "Applying Reality Checks to Standards on the Surge Environment," *Proceedings, 23rd International Conference on Lightning Protection*, Florence, 1996.

— Shrinking surge recordings versus proliferation of SPDs.
— Applying equipment failure rates to assess the surge environment.
— Limits to pushing surges into branch circuits.
— 19 references

[B31] Mansoor, A., and Martzloff, F. D., "Driving High Surge Currents into Long Cables: More Begets Less," *IEEE Transactions PWRD-12*, no. 3, July 1997.

— Measurements and modeling, validating each other, show the physical impossibility for large surge currents to propagate very far into the branch circuits of a building, because flashover will occur at the service entrance.
— Demonstrates the importance of considering the maximum rate of rise (early in the surge) rather than the peak value and overall rise time.
— 13 references

[B32] Mansoor, A., and Martzloff, F. D., "The Effect of Neutral Earthing Practices on Lightning Current Dispersion in a Low-Voltage Installation," *IEEE Transactions PWRD-13*, July 1998.

— Compares the TN and TT for dispersion of lightning current in several scenarios.
— Shows the need for careful review of grounding practices in effect at service entrances.
— Questions the applicability of high-amplitude, long-duration requirement for service-entrance SPDs.
— 20 references

[B33] Mansoor, A., Martzloff, F. D., and Phipps, K., "The Fallacy of Monitoring Surge Voltages: SPDs and PCs Galore!" *Proceedings, EPRI PQA'99 Conference*, May 1999.

— Experimental measurements of effective mitigation by multiple SPDs.
— Numerical simulation of the effect of proliferating SPDs and PCs.
— Calls for an industrywide reassessment of surge-monitoring parameters.
— 20 references

[B34] Martzloff, F. D., “Varistor Versus Environment: Winning the Rematch,” *IEEE Transactions PWRD-1*, no. 2, Apr. 1986.

— Staged test of capacitor switching on remote medium-voltage side produces ring waves on low-voltage load.
— Coordination between 3 kV and 480 V varistor-based SPDs.
— 5 references, 1 discussion

[B35] Martzloff, F. D., and Fenimore, C., “Validating Surge Test Standards by Field Experience: High-Energy Tests and Varistor Performance,” *Conference Record, IEEE/IAS Annual Meeting*, Oct. 1990.

— Computer modeling of the current and energy deposition into typical varistors subjected to the 100/1300 µs waveform proposed by German Standard DIN 0160.
— Predictions of failure for the small varistors and survival for the larger varistors agree with anecdotal field experience.
— 15 references

[B36] Meissen, W., “Überspannungen in Niederspannungsnetzen” [Overvoltages in low-voltage networks], *ETZ Bd. 104,* 1983.

— The seminal paper proposing a long waveform with extremely high energy-deposition capability, leading to the development of German Standard DIN 0160.

[B37] Richman, P., “New Fast-Transient Test Standards Inadvertently Permit overstressing by as much as 600 percent,” *EMC Test and Design*, vol. 2, no. 5, Sept./Oct. 1991.

— Points out ambiguities in the test procedures.

[B38] Rousseau, A., *Requirements for rating of MV zinc oxide surge arresters on EDF distribution networks*. CIRED, 1989.

— Design of ZnO medium-voltage arresters based on statistics of lightning current magnitude and tail.
— Sharing of current between many arresters as well as number of lightning strikes per year and per kilometer of overhead line are used in calculations.
— Design based on an energy requirement converted in lab into a 4/10 standard wave shape.
— 13 references

[B39] Smith, S. B., and Standler, R. B., “The Effects of Surges on Electronic Appliances,” *IEEE Transactions PWRD-7*, no. 3, July 1992.

— Clocks, TV receivers, and switching power supplies were subjected to surges with amplitude of 0.5 kV to 6 kV.
— The switching power supplies and TV receivers were damaged with surges between 4 kV and 6 kV.
— Three of five models of digital clocks were upset with surges between 1.6 kV and 6 kV.
— The conventional wisdom that electronic appliances are easily damaged by surges with a peak voltage of a few kilovolts greatly exaggerates the effect of surges on modern consumer appliances.
— 13 references

[B40] Standler, R. B., “Development of a performance standard for surge arresters and suppressors,” *Proceedings, IEEE International Symposium on Electromagnetic Compatibility*, 1991.

— Some critical issues in the development of a performance standard for surge arresters and suppressors for use on low-voltage mains are discussed.
— A series of electrical tests to determine the safety and adequacy of SPDs is described.
— 4 references

[B41] Standler, R. B., “Calculation of Energy in Transient Overvoltages,” *Proceedings, IEEE EMC Symposium*, 1989.

- Shows that using the integral of $V^2/50\Omega dt$ to compute energy in a surge is invalid.
- A quantitative error analysis is presented that uses an artificial ac line network to simulate a long branch circuit and to give the impedance of the ac line as a function of frequency.
- A method for measuring energy dissipated in a varistor is advocated for use in future experiments.
- 18 references

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- — 38 references

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- — 13 references

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- — 7 references

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- — 11 references

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- — Describes a test bed for studying the propagation of surges in low-voltage installations.
- — Test and computer modeling on appliances connected to different systems show reference voltage shifts.
- — 4 references

[B127] Martzloff, F. D., “On the dispersion of lightning current for a direct flash to a building,” *Proceedings, 25th International Conference on Lightning Protection*, Rhodes, 2000.

- — A review of simulation examples and anecdotal case history.
- — 9 references

[B128] Master, M. J., Uman, M.A., Lin, Y. T., and Standler, R. B., “Calculations of lightning return stroke electric and magnetic fields above ground,” *Journal of Geophysical Research*, vol. 86, no. C12, Dec. 1981.

- — Detailed calculations of lightning return stroke electric and magnetic fields above ground are presented.
- — 16 references

[B129] Mata, C. T., Fernandez, M. I., Rakov, V. A., Uman, M. A., Bejleri, M., Rambo, K. J., and Stapleton, M. V., “Overvoltages in underground systems, phase 2 results,” *Technical Report, EPRI TR-109669-P2*, 1998.

— Presents results of triggered-lightning experiments conducted at Camp Blanding including responses (currents and voltages) of a test PDS to direct and nearby lightning strokes.
— For lightning strokes near underground cables up to 50% of the total lightning current can be injected into the underground cable system.
— 43 references

[B130] Mata, C. T., Fernandez, M. I., Rakov, V. A., and Uman, M. A., “EMTP Modeling of a Triggered-lightning Strike to the Phase Conductor of an Overhead Distribution Line,” *IEEE Transactions PWRD-15*, vol. 4, 2000.

— Modeling of the Camp Blanding overhead distribution line subjected to injection of lightning current.
— Model elements include transmission line, MOV arresters, grounding leads, and ground rods.
— 9 references

[B131] Mikhail, S., and Mcgranaghan, M, “Evaluation of Switching Concerns Associated with 345 kV Shunt Capacitor Applications,” *IEEE Transactions PAS-106*, no. 4, Apr. 1986.

— Results of Transient Network Analyzer study evaluating switched capacitor banks.
— Includes normal energizing, voltage magnification, phase-to-phase transients, inrush and outrush, and restrikes.
— 14 references, 2 discussions

[B132] Niggli, M. R., Yturralde, W. E., Niebuhr, W. D., Rocamora, R. G., and Madzarevic, V., “Fault Clearing Overvoltages on Long Transformer Terminated Lines,” *IEEE Transactions PAS-98*, no. 2, Mar./Apr. 1979.

— Transient Network Analyzer study.
— 9 references, 4 discussions

[B133] Paul, C. R., and Hardin, K. B., “Diagnosis and Reduction of Conducted Noise Emissions,” *IEEE Transactions on EMC*, Nov. 1988.

— Method for determination of relative value of common-mode and normal-mode noise, with modeling of candidate mitigation methods.
— 5 references

[B134] Pfeiffer, W., and Gräf, T., “Ausbreitung und Dämpfung von Überspannungen in Niederspannungs-Installationen” [Propagation and damping of overvoltages in low-voltage installations], *Elektrie Bd. 48,* 1994.

— A review of the propagation of surge voltages (in German).

[B135] Rakotomalala, A., Rousseau, A., and Auriol, P., “Lightning distribution through earthing systems,” Proceedings, *IEEE International Symposium on EMC*, 1994.

— Model of electrical installation including power and telecom lines, water pipe, lightning rod and SPDs.
— Sharing of current between various paths, including SPDs, showing that neutral is more stressed in case of strike on lightning rod. Opposite in case of strike on power lines.
— In general 30% of lightning current is shared between all power conductors.
— 8 references

[B136] Rakov, V. A., Uman M. A., Fernandez, M. I., Mata, C. T., Rambo, K. T., Stapleton, M. V., and Sutil, R. R., “Direct Lightning Strikes to the Lightning Protection System of a Residential Building: Triggered-lightning Experiments,” *IEEE Transactions PE-032 PRD* (11-2001).

— Injection of triggered lightning into a house replica at Camp Blanding.

— Measured data on dispersion of the lightning current among available paths to ground.
— Examples of current waveforms.
— 2 references

[B137] Rochereau, H., Xemard, A., Michaud, J., Zeddam, A., and Boutet, F., "ANASTASIA : Un outil de simulation de l'effet de la foudre sur les réseaux aériens de distribution à basse tension" [ANASTASIA: A simulation tool for lightning effects on overhead low-voltage distribution lines], Proceedings, *CIGRE Conference "Power system electromagnetic compatibility,"* Foz do Iguaçu, May 1995.
— Reports an investigation conducted by the French utility (in French).

[B138] Rousseau, A., Roy, D., and Warsmann, P., "What is a lightning earth?" *ERA Earthing*, 2000.
— Mathematical model of high frequency lightning earth/ground.
— High frequency is just useful for overvoltages not for energy sharing between various paths.
— Equipment exist for measuring high-frequency ground impedance, and examples of good "lightning" ground are given based on real measurements.
— 5 references

[B139] Standler, R. B., "Equations for Some Transient Overvoltage Test Waveforms," *IEEE Transactions EMC-30*, Feb. 1988.
— Provides mathematical equations for the 100 kHz Ring Wave and the Combination Wave.

[B140] Standler, R. B., "Calculation of Lightning Surge Currents Inside Buildings," *Proceedings, IEEE EMC Symposium*, Aug. 1992.
— Makes computations with SPICE for a 10/350 µs, 20 kA impinging current.
— MOV arrester at the service entrance and varistors at the end of branch circuits of various lengths.
— Neglects inductance and considers only the wire resistance, justified by the long tail of the surge.
— Concludes that the ANSI C62.41 currents do not stress varistors as much as the 10/350 µs surge.
— 11 references

[B141] Standler, R. B., "Transmission Line Models for Coordination of Surge-protective Devices," *Proceedings, IEEE International Symposium on EMC*, 1993.
— The distribution of surge currents between an arrester and suppressor that are separated by a transmission line is described for six different models of transmission lines.
— Two different surge waveforms are used in the simulation: the 1.2/50 µs wave, and the 10/350 µs wave that simulates the current in a direct lightning stroke.
— Conclusions on the relative accuracy of the various models of transmission lines in this application.
— 14 references

[B142] Standler, R. B., "Neutral-Earth Surge Voltages on Low-voltage AC Mains," *Proceedings, 10th International Zurich Symposium on EMC*, 1993.
— Computer simulations of surge suppressor circuits and propagation of surges on transmission lines show surge voltage wave shapes between the neutral and protective-earth conductors inside buildings.
— A theoretical discussion is included about the common error of approximating a transmission line as a single inductor during calculations of the propagation of surge current.
— Skin effect is critical in calculating the propagation of transient overvoltages on transmission lines.
— 13 references

[B143] Stringfellow, M. F., and Stonely, B. T., “Coordination of Surge Suppressors in Low-Voltage AC Power Circuits,” *Proceedings, Forum on Surge Protection Application, NISTIR-4657*, Aug. 1991.

— Experiments showing the effect of line length and impinging surge waveform on sharing energy between service-entrance arrester and surge suppressor inside building.
— MOVs were applied at three points: service entrance, distribution panel, and load.
— Removal of protection at either load or distribution panel resulted in unacceptably large oscillatory voltages. Best load protection was achieved with MOVs in all three locations.
— 4 references

[B144] Vines, R. M., Trussell, H. G., Gale, L. J., and Oæneal, B., “Noise on Residential Power Distribution Circuits,” *IEEE Transactions on EMC*, Nov. 1984.

— Reports conducted noise measurements from typical residential loads.
— 14 references

[B145] Wiitanen, D. O., Morgan, J. D., and Gaibrois, G. L., “Station Capacitor Switching Transients—Analytical and Experimental Results,” *IEEE Transactions PAS-90*, no. 4, Apr. 1971.

— Switching transients at the 41 kV level.
— 10 references, 2 discussions

D.5 Monitoring instruments, laboratory measurements, and test methods

[B146] Allen, G. W, “Design of Power-Line Monitoring Equipment,” *IEEE Transactions PAS-90,* May 1971.

— Description of the instrumentation used by Allen and Segall [B47].
— 5 references

[B147] Bull, J. H., “Impedance of the Supply Mains at Radio Frequencies,” *Proceedings, 2nd Symposium on EMC*, Montreux, May 1975.

— Reports measurements and 50 Ω/50 µH equivalent circuit.
— 6 references

[B148] Buschke, H. A., “A Practical Approach to Testing Electronic Equipment for Susceptibility to AC Line Transients,” *IEEE Transactions on Reliability*, vol. 37, no. 4, Oct. 1988.

— Describes test methods and test circuits developed independently from standard approaches.
— 3 references

[B149] Cummins, K. L., Krider, E. P., and Malone, M. D., “The U.S. National Lightning Detection Network™ and Applications of Cloud-to-Ground Lightning Data by Electric Power Utilities,” *IEEE Transactions EM-40*, no. 4, Nov. 1998.

— Discusses the principle of lightning detection.
— Provides guidelines on the uncertainties of lightning parameters that are acceptable in the industry.
— 75 references

[B150] Hasse, P., and Birkl, J., “EMV-Testverfahren zur Ableiterkoordination” [EMC Test procedures for coordination of surge protective devices], *EMC Kompendium*, 1998, pp. 112–115.

— Proposes to define a “steepness factor” to characterize the initial rate of rise of current impulses.

[B151] Key, T., and Martzloff, F. D., “Surging the Upside-Down House: Looking into upsetting reference voltages,” *Proceedings, EPRI-PQA’94 Conference*, Amsterdam, Oct. 1994.

— Describes a test bed for the propagation and mitigation of surges.
— Illustrates the differences of voltage references developed across multiple ports of appliances.
— 8 references

[B152] Key, T. S., Mansoor, A., and Martzloff, F. D., "No Joules for Surges: Relevant and Realistic Assessment of Surge Stress Threats," *Proceedings, IEEE International Conference on Harmonics and Power Quality*, Las Vegas, NV, Oct. 1996.

- Challenges the erroneous concept of characterizing "energy in the surge" from a simple voltage measurement.
- Lists surge parameters leading to failure of specific equipment.
- 15 references

[B153] Kreiss, D. G., *The Dranetz Field Handbook for Power Quality Analysis*. Edison, NJ: Dranetz Technologies, Inc., 1991

- One chapter on planning and performing a power quality survey includes the topic of "impulses" (i.e., surges).
- One chapter on waveforms shows examples of recorded surges.

[B154] Lindes, G., Mansoor, A., Martzloff, F. D., and Vannoy, D., "Surge Recordings That Make Sense: Joules Deposition: Yes! Joule Content: Never!," *Proceedings, PQA'97 USA*, 1997.

- Challenges the erroneous concept of characterizing "energy in the surge" from a simple voltage measurement.
- Lists surge parameters leading to failure of specific equipment.
- Proposes the approach for using existing power quality monitors to record available surge currents.
- 24 references

[B155] Mansoor, A., Martzloff, F. D., and Phipps, K., "The Fallacy of Monitoring Surge Voltages: SPDs and PCs Galore!," *Proceedings, EPRI PQA'99 Conference*, May 1999.

- Experimental measurements of effective mitigation by multiple SPDs.
- Numerical simulation of the effect of proliferating SPDs and PCs.
- Calls for an industrywide reassessment of surge monitoring parameters.
- 18 references

[B156] Markel, L. C., Melhorn, C. J., Williams, S. R., Mehta, H., "Design of a Measurement Program to Characterize Distribution System Power Quality," *CIRED 12th International Conference on Electricity Distribution*, 1993.

- Simplification of a systemwide survey through stratified random sampling.

[B157] Martzloff, F. D., "Surge Recordings that make sense: Shifting focus from voltage to current measurements," *Proceedings, EMC ROMA'96 Symposium*, 1996.

- Makes the case that the proliferation of SPDs makes monitoring surge voltages debatable.
- Proposes an approach for using existing power quality monitors to record available surge currents.
- 18 references

[B158] Martzloff, F. D., and Fisher, F. A., "Transient Control Level Philosophy and Implementation: The Reasoning Behind the Philosophy," *Proceedings, 2nd Symposium on EMC,* Montreux, June 1977.

- Techniques and equipment for making transient control level tests.
- 10 references

[B159] McEachern, A., *Handbook of Power Signatures*. Foster City, CA: Basic Measuring Instruments Publisher, 1989.

- Reports generic types of disturbances with nonstandard terminology.
- Calls a surge as defined by IEEE an "impulse." Calls a swell as defined by IEEE a "surge."
- Describes procedures on conducting a site survey.
- 267 pages

[B160] Millanta, L. M., and Forti, M. M., "A Notch-Filter Network for Wide-Band Measurements of Transient Voltages on the Power Line," *IEEE Transactions on EMC,* Aug. 1988.

- Describes the design and characteristics of a probe that filters out the power-frequency component.
- 20 references

[B161] Millanta, L. M., Forti, M. M., and Maci, S. S., "A Broad-Band Network for Power-Line Disturbance Voltage Measurements," *IEEE Transactions EMC-30*, no. 3, Aug. 1988.

- Filter network removing the power-frequency voltage from the record.
- 5 references

[B162] Millanta, L. M., and Forti, M. M., "A Classification of the Power-Line Voltage Disturbances for an Exhaustive Description and Measurement," *Proceedings, IEEE EMC Symposium*, 1989.

- Proposal for systematic classification of disturbances.
- 17 references

[B163] Nave, M. J., "A Novel Differential Mode Rejection Network for Conducted Emissions Diagnostics," *Proceedings, IEEE EMC Symposium*, 1989.

- Discussion of common mode and differential mode from the point of view of frequency domain measurements.
- 5 references

[B164] Richman, P., "Diagnostic Surge Testing, Parts I & II," *Power Conversion*, Sept./Oct. 1979, Nov./Dec. 1979.

[B165] Richman, P., "Single-Output, Voltage and Current Generation for Testing Electronic Systems," *Proceedings, IEEE EMC Symposium,* 1983.

- Presents the case for the Combination Wave rather than separate 1.2/50 µs and 8/20 µs impulses.
- 4 references

[B166] Richman, P., "Changes to Classic Surge-Test Waves Required by Back-Filters Used for Testing Powered Equipment," *Proceedings, Zurich Symposium on EMC*, 1985.

- Powered equipment testing considerations.
- Undershoot effects on unidirectional waves, the case for oscillatory waves.
- 5 references

[B167] Richman, P., "Precision Coil Impulse Testing with 0.3 A, Micro-Breakdown Sensitivity," *Power Conversion International*, vol. 8, no. 5, May 1982.

- General review of surge generator technology.
- Detection of breakdown by monitoring both voltage and current waveforms in EUT.
- 11 references

[B168] Senko, G., "Probes and Techniques for Measuring Surge Voltage Waves with Fronts from 10 ns to 1.2 µs and Peaks to 10 kV," *Proceedings, International Zurich Symposium on EMC*, 1987.

- Describes a differential probe with 10 kΩ input impedance, 2 ns rise time, 10 kV rating.
- 5 references

[B169] Shakarjian, D. R., and Standler, R. B., "AC power disturbance detector circuit," *IEEE Transactions PWRD-6*, no. 2, Apr. 1991.

- Design, construction, and performance of a circuit that detects transients on low-voltage ac mains.

— The disturbance detector circuit can be used to trigger a digital waveform recorder or to operate a counter circuit to simply record the occurrence of a disturbance.
— 7 references

[B170] Standler, R. B., "An Experiment to Monitor Disturbances on the Mains," *Proceedings, IEEE IAS Annual Meeting,* Oct. 1987.
— Describes experiment to collect waveforms of mains disturbances and determine the energy deposited in varistors.
— 16 references

[B171] Standler, R. B., "An experiment to monitor disturbances on the mains," *Conference Record, IEEE Industry Applications Society Annual Meeting*, 1987.
— Describes the design of an experiment to characterize disturbances on the mains, including the trigger criteria for waveform recorders.
— Definitions of some disturbances are provided.
— 16 references

[B172] Standler, R. B., "Equations for some transient overvoltage test waveforms," *IEEE Transactions EMC-30*, no. 1, Feb. 1988.
— Simple equations are provided that satisfy the definitions of five of the most common transient overvoltage test waveforms: the Ring Wave specified in IEEE Std C62.41-1980; the fast transient specified in IEC 801 (now IEC 61000-4-4:1994 [B8]); and the 8/20 µs, 1.2/50 µs, and 10/1000 µs waveforms.
— 7 references

[B173] Standler, R. B., "Standard Waveforms for Surge Testing: Experimental Evaluation and Proposed New Criteria for Tolerances," *Proceedings, 8th International Zurich Symposium on EMC*, 1989.
— Evaluates several commercial surge generators and proposes using equations to define nominal waveforms and tolerances of unipolar waves.
— 11 references

[B174] Standler, R. B., "Calculation of Energy in Transient Overvoltages," *Proceedings, IEEE EMC Symposium*, 1989.
— Shows that using the integral of $V^2/50\Omega dt$ to compute energy in a surge is invalid.
— An artificial ac line network simulates a long branch circuit to give line impedance as a function of frequency.
— A method for measuring energy dissipated in a varistor is advocated for use in future experiments.
— 18 references

[B175] Standler, R. B., "American surge test methods for equipment connected to the low-voltage AC supply mains," *Proceedings, Lightning Protection 92—Buildings, Structures and Electronic Equipment Conference and Exhibition*, 1992.
— Describes how electronic equipment and SPDs are surge tested in the United States, with emphasis on differences between the American and European practices.
— 11 references

[B176] Uman, M. A., Rakov, V. A., Rambo, K. J., Vaught, T. W., Fernandez, M. I., Bernstein, R., and Golden, C., "Triggered-lightning facility for studying lightning effects on power systems," *Proceedings, 23th International Conference on Lightning Protection*, Florence, Italy, 1996.
— Description of rocket-triggered lightning at Camp Blanding, with examples of recordings.
— 6 references

[B177] Wiesinger, J., “Hybrid-Generator für die Isolationskoordination” [Hybrid Generators for the Coordination of Insulation], *ETZ-104*, no. 21, 1983.

— Endorses the concept of the Combination Wave in the European context.

D.6 Textbooks and tutorial reviews

[B178] Bodle, D. W., Ghazi, A. J., Syed, M., and Woodside, R. L., *Characterization of the Electrical Environment*. Toronto and Buffalo, NY: University of Toronto Press, 1976.

— Book initially written from the communications point of view, but applicable to ac power circuits.

— 124 references, 320 pages

[B179] CIGRE Working Group 33.10, “Temporary overvoltages: causes, effects and evaluation,” *Paper 33-210, CIGRE Conference*, Paris, 1990.

— Overview on causes of TOV on high-voltage networks.

— Effect of TOV on insulation coordination and impact on surge arresters.

— Equipment withstand capability and methods of TOV control.

— 23 references

[B180] Davies, D. W., and Standler, R. B., “Ball lightning,” *Nature*, vol. 240, no. 5377, Nov. 1972, p. 144.

— A well-published photograph purportedly of ball lightning has been critically examined.

— It is concluded that the evidence is stronger for interpreting the photograph as that of a street lamp than as that of a lightning ball.

— 7 references

[B181] de la Rosa, F., Nucci, C. A., and Rakov. V. A., “Lightning and Its Impact on Power Systems,” CIGRE *Paper P.34*, *International Conference on Insulation Coordination for Electricity Development in Central European Countries*, Zagreb, Croatia, Sept. 9–12, 1998.

— Comprehensive (44 pages) review of the subject.

— 102 references

[B182] Fernandez, M. I., Rambo, K. J., Rakov, V. A., and Uman, M. A., “Performance of MOV arresters during very close, direct lightning strikes to a power distribution system,” *IEEE Transactions PWRD-14*, no. 2, 1999.

— Injection of triggered lightning current into an overhead distribution line with MOV arresters at Camp Blanding.

— Measurements of the response of the arresters to the lightning current.

— 8 references, one discussion

[B183] Fisher, F. A., and Martzloff, F. D., “Transient Control Levels: A Proposal for Insulation Coordination in Low-Voltage Systems,” *IEEE Transactions PAS-95*, no. 1, Jan./Feb. 1976.

— Proposes parallel with the BIL concept for high-voltage system.

— First published version of a test circuit for 100 kHz Ring Wave.

— 12 references, 3 discussions

[B184] Golde, R. H., ed. *Lightning*. New York: Academic Press, 1977.

— Vol 1: Physics of lightning

— Vol 2: Lightning protection

— Several hundred references

[B185] Greenwood, A., *Electrical Transients in Power Systems*. New York: Wiley-Interscience, 1971.

— Comprehensive textbook.

— Cites 2.1 p.u. overvoltage during ground-fault clearing.

— 210 references, 540 pages

[B186] Gruzs, T. M., “Power Disturbances and Computer Systems: A Comparison of the Allen-Segall and the Goldstein-Speranza Power Line Monitoring Studies,” *Proceedings, Electrical Overstress Exposition*, Nelson Pub., 1986.

— The effect of arbitrary threshold selection on statistics.
— 2 references

[B187] Hasse, P., *Overvoltage Protection of Low-Voltage Systems*. IEEE Power Series. London: Peter Peregrinus Ltd., 1992. (Original German edition in 1987) Available in the United States from IEEE.

— Examples of causes of overvoltages and damage to electrical systems with electronic devices.
— The operation and application of proven overvoltage protection devices are considered.
— Discusses coordination with a “quenching gap” as the upstream SPD.
— 244 pages, 83 references (mostly in German)

[B188] IEEE Committee Report. “Bibliography on Surge Voltages in AC Power Circuits Rated 600 Volts or Less,” *IEEE Transactions PAS-89*, no. 6, July/Aug. 1970.

— Bibliography compiled by the original IEEE Working Group 3.6.4.
— 73 references

[B189] Key, T. S., “Diagnosing Power Quality-Related Computer Problems,” *IEEE Transactions IA-15*, no. 4, July/Aug. 1979.

— Records of disturbances and general discussion.
— The seminal proposal of the computer susceptibility curve, now known as the “CBEMA Curve.”
— 10 references

[B190] Key, T. S., and Martzloff, F. D., “A Consensus on Powering and Grounding Sensitive Electronic Equipment,” *Conference Record, IEEE-IAS Annual Meeting*, Oct. 1986.

— General tutorial discussion of the subject.
— Proposed computer susceptibility curve.
— 19 references

[B191] Martzloff, F. D., Discussion of IEEE paper by Aspnes, J. D., Evans, B. W., and Merritt, R. P., “Rural Alaska power quality,” *IEEE Transactions PAS-104*, no. 4, Mar. 1985.

— Signals the fallacy of surge recordings obtained with a monitoring instrument that included an internal SPD to protect its power supply, inadvertently mitigating surges on the receptacle also used as point of connection for monitoring.

[B192] Martzloff, F. D., and Gruzs, T. M., “Power Quality Site Surveys: Facts, Fiction, and Fallacies,” *IEEE Transactions IA-24*, no. 6, Nov./Dec. 1988.

— Review of instrumentation development, definition deficiencies, and past survey results.
— First proposal of the term *swell*.
— 33 references

[B193] Martzloff, F. D., “Power Quality Measurements: Bringing Order Out of Chaos,” *Proceedings, Energy Technology Conference*, Feb. 1988.

— Condensation of Martzloff and Gruzs paper [B192] for power-quality context.
— 16 references

[B194] Podgorski, A. S., “A Case for a Unified Lightning Threat,” *Proceedings, International Aerospace and Ground Conference on Lightning and Static Electricity*, Oklahoma City, 1988.

— Measurements of lightning currents on tall towers and aircraft.
— Reports current rise times in the 50 ns to 100 ns range.
— 14 references

[B195] Rakov, V. A., “Lightning electromagnetic fields: Modeling and measurements,” *Proceedings, International Zurich Symposium on EMC*, 1997.

— Review of various models proposed to simulate lightning stroke events.
— Comparison of model predictions and measurements of electromagnetic fields.
— 34 references

[B196] Rakov., V. A., “Lightning electric and magnetic fields,” *Proceedings, International Zurich Symposium on EMC*, 1999.

— Review of measured characteristics of the electric and magnetic fields.
— Examples of different types of field waveforms are given.
— 12 references

[B197] Rhoades, W. T., “Designing Commercial Equipment for Conducted Susceptibility,” *Proceedings, IEEE EMC Symposium*, 1979.

— Discusses unprotected product input impedances, transient propagation modes and models, measured transient occurrences, and typical susceptibility.
— 9 references

[B198] Rhoades, W. T., “Development of Power Main Transient Protection for Commercial Equipment,” *Proceedings, IEEE EMC Symposium*, 1980.

— Class distinction of the various wide-range transients from arc to motor turn-on.
— Low product immunity to common-mode transients is caused by high energy-density spectrum.
— 18 references

[B199] Rhoades, W. T., “The Ratiocination of a Commercial Power Main Conducted Susceptibility Standard,” *Proceedings, IEEE EMC Symposium*, 1981.

— Review of transient types, standards, definitions, and cost considerations.
— 18 references

[B200] Rhoades, W. T., “Critical Analysis of Commercial Power Main Transient Designs,” *Proceedings, IEEE EMC Symposium*, 1987.

— Review of environment, statistics, measurements, and standards.
— 38 references

[B201] Rhoades, W. T., “Congruence of Low Voltage Main Transient Designs,” *Proceedings*, *IEEE EMC Symposium*, 1989.

— Survey of the literature on surge occurrence, equipment design, and surge standards.
— 4 references

[B202] Rousseau, A. and Gumley, R., *Surge Protection.* Wiley Encyclopedia of Electrical and Electronics Engineering, 1999.

— Complete review of SPD specifications and characteristics for both telecom and power SPDs including important parameters for selection and comparison.
— Installation rules for SPDs including special case of TN-C-S systems.
— 23 references

[B203] Standler, R. B., *Protection of Electronic Circuits from Overvoltages.* New York: Wiley-Interscience, 1989.

— Comprehensive review of the origin and propagation of surges, SPDs and applications in circuits, and high-voltage laboratory testing techniques.
— 260 references, 434 pages

[B204] Uman, M. A., Rakov, V. A., Rambo, K. J., Vaught, T. W., Fernandez, M. I., Bernstein, R., and Golden, C., "Triggered-lightning facility for studying lightning effects on power systems," *Proceedings, 23th International Conference on Lightning Protection*, Florence, Italy, 1996.
— Description of rocket-triggered lightning at Camp Blanding.
— Examples of recordings.
— 6 references

[B205] Wiesinger, J., and Hasse, P., *Handbuch für Blitzschutz und Erdung* [Handbook for lightning protection and grounding]. Pflaum-Verlag, München; VDE-Verlag, Berlin; 1. Auflage, 1977.
— Handbook addressing types of lightning and their parameters and electric and magnetic fields.
— Protected volume by intercepting devices, overvoltage protection, earthing systems.
— 154 pages, 83 references (German and English)

D.7 Mitigation techniques

[B206] Benda, S., *Interference-free electronics*. Bromley, UK: Chartwell Bratt Ltd.
— The design and use of interference-free systems and printed circuit boards.
— The emphasis of the book is on equipment design.

[B207] Bird, A. O., "The Effects of Installation Practice on the Performance of Transient Voltage Surge Suppressors," *Proceedings, Open Forum on Surge Protection Application,* NISTIR 4657, 1991.
— Review of issues such as length of connecting leads and provision of SPD disconnectors (fuses).
— Cascade coordination.
— 11 references

[B208] Birrell, D., and Standler, R. B., "Failure of surge arresters on low-voltage mains," *IEEE Transactions PWRD-8*, no. 1, Apr. 1991.
— Use of a secondary arrester on low-voltage ac supply mains to prevent damage to electronic equipment is addressed.
— Some failure mechanisms of a secondary arrester are described, and ways to minimize risks from possible failure of the arrester are suggested.
— 36 references

[B209] Darveniza, M., "Multipulse Lightning Currents and Metal-Oxide Arresters," *IEEE Transactions PWRD-12*, July 1997.
— Reports differences noted between tests with single standard pulses and multiple closely spaced pulses.
— Suggests that mechanisms other than mere total energy deposition might be involved.
— Proposes such a multiple test sequence in assessing SPD performance.
— 9 references

[B210] Davidson, R., "Suppression Voltage Ratings on UL Listed Transient Voltage Suppressors," *Proceedings, Forum on Surge Protection Application, NISTIR-4657*, Aug. 1991.
— Some advertising statements claim that the minimum 330 V suppression rating in UL Std 1449-1996 [B22] is "the best UL rating" or that 330 V affords "the most protection possible."
— The ability of a TVSS to protect connected equipment from both upset and damage may depend on a number of factors including knowledge of both the susceptibility and vulnerability of the particular equipment. When these factors are not known, claims that one TVSS provides better protection than another, solely on the basis of the UL Std 1449-1996 [B22] suppression voltage rating, may be misleading.

[B211] Goedde, G. L., Knabe, E. S., and Kojovic, L. A., "Overvoltage Protection of Distribution and Low-Voltage Equipment Experiencing Sustained Overvoltages," *IEEE Winter Meeting*, 1999.

- Describes the overvoltages involved in commingling incidents of medium-voltage lines dropping on low-voltage lines.
- Reports laboratory tests on distribution arresters.
- 4 references

[B212] Grebe, T. E., and Deam, D. R., "Evaluation of Distribution Capacitor Switching Concerns, Final Report," *EPRI TR-107332,* Oct. 1997.

- Provides the results of a joint EPRI/NRECA effort to evaluate the state-of-the-art in distribution system capacitor-switching transient overvoltage mitigation.
- 28 references

[B213] Grebe, T. E., "Technologies for transient voltage control during switching of transmission and distribution capacitor banks," *Proceedings, International Conference on Power Systems Transients*, Lisbon, Portugal, 1995.

- Presents a summary of transient overvoltage mitigation techniques for transmission and distribution banks.
- 7 references

[B214] Hasse, P., *Overvoltage Protection of Low-Voltage Systems*. IEEE Power Series. London: Peter Peregrinus Ltd., 1992. (Original German edition in 1987) Available in the United States from IEEE.

- Examples of causes of overvoltages and damage to electrical systems with electronic devices.
- The operation and application of proven overvoltage protection devices are considered.
- Discusses coordination with a "quenching gap" as the upstream SPD.
- 244 pages, 83 references (mostly in German)

[B215] Key, T. S., Martzloff, F. D., Nastasi, D., and Phipps, K. O., "Some enlightening case histories on lightning damage," *Proceedings, 25th International Conference on Lightning Protection*, Rhodes, 2000.

- Case history on system interaction.
- Case history on damage to communications port, not power port.
- Case history on improper grounding practices.
- 6 references

[B216] Lagergren, E. S., Martzloff, F. D., Parker, M. E., and Schiller, S. B., "The Effect of Repetitive Swells on Metal-Oxide Varistors," *Proceedings, PQA'92 Conference*, Sept. 1992.

- Effects of amplitude, duration, and number of swells, using change in varistor nominal voltage as criterion.
- A relatively small (less than 3%) change in varistor nominal voltage for limited cumulative stresses.
- Failure caused by gradual aging (the 10% limit quoted by industry) was not reached in this experiment.
- Failure by overheating occurs for stresses of long-duration (seconds) TOVs.
- 8 references

[B217] Mansoor, A., Martzloff, F. D., and Phipps, K, "Gapped Arresters Revisited: A solution to Cascade Coordination," *IEEE Transactions PWRD-13*, no. 4, Dec. 1998.

- Demonstrates the principle of a coordination scheme compatible with downstream SPDs having lower limiting voltage than the SPD at the service entrance.
- 23 references

[B218] Martzloff, F. D., “Varistor Versus Environment: Winning the Rematch,” *IEEE Transactions PWRD-1*, no. 2, Apr. 1986.

— Staged test of capacitor switching on remote medium-voltage side produces ring waves on low-voltage load.
— Coordination between 3 kV and 480 V varistor-based SPDs.
— 5 references, 1 discussion

[B219] Martzloff, F. D., and Leedy, T. F., “Selecting Varistor Clamping Voltage: Lower is Not Better!” *Proceedings, International Zurich Symposium on EMC*, 1989.

— Experimental and computed evaluation of heating effects from repetitive swells applied to MOVs.
— Four mechanisms are describe that can lead to premature failure.
— 11 references

[B220] McGranaghan, M., Reid, W. E., Law, S., and Gresham, D., “Overvoltage Protection of Shunt Capacitor Banks Using MOV Arresters,” *IEEE Transactions PAS-104*, no. 8, Aug. 1984.

— Evaluation of MOV surge arresters for the overvoltage protection of shunt capacitor banks, including impact of lightning and switching transients.
— 10 references, 4 discussions

[B221] McGranaghan, M. F., Zavadil, R. M., Hensley, G., Singh, T., and Samotyj, M., “Impact of utility switched capacitors on customer systems—Magnification at low-voltage capacitors,” *IEEE Transactions PWRD-7*, no. 2, Apr. 1992.

— Parametric analysis of the effects of capacitor switching.
— Shows high stresses on SPDs.
— Mitigation at the switched capacitor.
— 5 references

[B222] Mikhail, S., and McGranaghan, M., “Evaluation of Switching Concerns Associated with 345 kV Shunt Capacitor Applications,” *IEEE Transactions PAS-106*, no. 4, 1986.

— Results of a Transient Network Analyzer study of switching 2500 Mvar 345 kV capacitor banks.
— Normal energizing, voltage magnification, phase-to-phase transients, inrush and outrush, and restrike events.
— 14 references, 2 discussions

[B223] Smith, S. B., and Standler, R. B., “The effects of surges on electronic appliances,” *IEEE Transactions PWRD-7*, no. 3, July 1992.

— A total of 16 different clocks, TV receivers, microwave ovens, and dc power supplies were subjected to three different surge waveforms with amplitudes between 0.5 kV and 6 kV.
— Switching power supplies and TV receivers were damaged with surges between 4 kV and 6 kV.
— Three of five models of digital locks were upset (temporary malfunction) with surges between 1.5 kV and 6 kV.
— 19 references

[B224] Standler, R. B., “Protection of small computers from disturbances on the mains,” *Conference Record, Industry Applications Society Annual Meeting*, 1988.

— Simple rules for the protection of small computer system from disturbances on the mains.
— Provides historical data on author’s computer protection experience.
— 12 references

[B225] Standler, R. B., "Use of low-pass filters to protect equipment from transient overvoltages on the mains," *Conference Record, Industrial and Commercial Power Systems Technical Conference*, 1988.

— Review of the design of commercial low-pass filter modules for equipment connected to the low-voltage mains.
— Discusses problems of using these filters to protect electronic equipment from damage or upset by high-voltage transients on the mains.
— 12 references

[B226] Standler, R. B., "Use of a metal-oxide varistor with a series spark gap across the mains," *Proceedings, International Symposium on EMC*, 1990.

— Discusses the use of a series spark gap with a MOV to achieve both a small clamping voltage and a long life time for the surge-protective circuit.
— Extinguishing follow current in the gap and attenuating the remnant that propagates downstream prior to the conduction of the spark gap are discussed in detail.
— 5 references

[B227] Standler, R. B., "Design and performance of surge suppressors," *Proceedings, IEEE International Symposium on EMC*, 1993.

— Tests on more than two dozen different models of commercially available surge suppressors during 1987–1990 showed that some types of suppressors perform much better than others.
— The manufacturer's specifications and UL clamping voltage rating are often not consistent with laboratory measurements.
— 25 references

[B228] Stringfellow, M. F., "Fire Hazard of Surge Suppressors," *Proceedings, Power Quality Conference*, Anaheim, CA, Sept. 1992.

— From suppressors removed from service throughout the United States and Canada, contrary to popular myth, field data show that surge suppressors containing MOVs do not degrade in service.
— All suppressors are, however, exposed to rare incidents of severe power-frequency overvoltage caused by power-line accidents, such as broken neutral conductors that can cause overheating internally.
— Products equipped with overcurrent fuses or magnetic circuit breakers might catch fire in rare cases. This is true for those having both plastic and metal housings and components rated for both 130 V and 150 V.
— 3 references

D.8 Coordination of cascaded SPDs

[B229] Goedde, G. L., Marz, M. B., and Henry, D. C., "Coordinating Lightning Stroke Protection From the Utility System to Load Devices," *Proceedings, 2nd International Power Quality/ESD Conference*, Oct. 1990.

— Describes secondary surge phenomena and the importance of transformer secondary circuit protection coordination to both utilities and end users.
— An effective MOV protection coordination scheme is described and recommended.
— Multiple grounds at different potentials, especially under lightning surge conditions, prevent distribution transformer primary arresters from protecting secondary circuits.
— 13 references

[B230] Hasse, P., Zahlmann, P., Wiesinger, J., and Zischank, W., "Principle for an advanced coordination of surge-protective devices in low-voltage systems," *Proceedings, 22nd International Conference on Lightning Protection*, Budapest, 1994.

— Proposes a scheme where the performance of SPDs for any waveform is converted to an equivalent configuration compared to the performance under the Combination Wave.
— 7 references

[B231] Hostfet, O. T., Hervland, T., Nansen, B., and Huse, J., "Coordination of surge protective devices in power supply systems: Needs for secondary protection," *Proceedings, International Conference on Lightning Protection*, Berlin, Sept. 1992.

— On the basis of observed failures on secondary SPDs, theoretical and experimental investigations are performed in order to clarify the need for such protection, including the sharing of energy stresses in relation to the primary surge protection system.
— The higher energy stresses will generally occur on the device with the lowest limiting voltage. Therefore, the protection level for the secondary protection should be selected somewhat higher than for the primary protection independent of the location.
— 5 references

[B232] Lai, J. S., "Performance Criteria for Cascading Surge-Protective Devices," *Proceedings, Open Forum on Surge Protection Application, NISTIR-4654*, Aug. 1991.

— Voltage limiting level of cascaded devices, their separation distance, and surge waveform are used as parameters to compute the energy deposited in the devices.
— Experimental verification shows reasonable agreement between simulation and experiment.
— Contains details of the database used for Lai and Martzloff 1993 [B233].
— 10 references

[B233] Lai, J. S., and Martzloff, F. D., "Coordinating Cascaded Surge-Protection Devices: High-Low versus Low- High," *IEEE Transactions IA-24,* no. 4, July/Aug. 1993.

— Computations and experiments showing the effect of line length and impinging surge waveform on sharing energy between service-entrance arrester and SPD inside building.
— While the 8/20 μs waveform can still result in a contribution from both devices to sharing the energy, the 10/1000 μs waveform does not produce any inductive separation of the devices past the rise time, so that energy is equally shared between devices of equal rating.
— 11 references

[B234] Mansoor, A., Martzloff, F. D., and Phipps, K., "Gapped Arresters Revisited: A solution to Cascade Coordination," *IEEE Transactions PWRD-13*, no. 4, Dec. 1998.

— Demonstrates the principle of a coordination scheme compatible with downstream SPDs having lower limiting voltage than the SPD at the service entrance.
— 23 references

[B235] Martzloff, F. D., "Coordination of SPDs in Low-Voltage AC Power Circuits," *IEEE Transactions PAS-99*, no. 1, Jan./Feb. 1980.

— Coordination between voltage-switching and voltage-limiting SPDs.
— Where an unidirectional current is injected into the ground system only, the response of the system is an oscillating voltage involving the phase conductors.
— Without substantial connected loads in the system, the open-circuit surges appearing at the service entrance propagate along the branch circuits with very little attenuation.
— 7 references

[B236] Martzloff, F. D., and Lai, J. S., "Cascading Surge-Protective Devices: Coordination versus the IEC 664 Staircase," *Proceedings, PQA'91 Conference*, 1991.

— Coordination of cascaded devices can be achieved under various combinations of parameters, but some combinations might leave the smaller device subjected to the highest stress.

— Significant parameters in achieving successful coordination involve three factors: the relative limiting voltages of the two devices, their separation distance, and the prevailing waveforms for impinging surges.
— 13 references

[B237] Martzloff, F. D., and Lai, J. S., "Cascading surge-protective devices: Options for effective implementations," *Proceedings, PQA'92 Conference*, Sept. 1992.
— Implications of the situation resulting from the present uncoordinated application of devices with low limiting voltage at the end of branch circuits and devices with higher limiting voltage at the service entrance.
— The reality of having many millions of 130 V rated varistors installed on 120 V systems makes the ideal scenario of a well-coordinated cascade difficult or perhaps unattainable in the near future.
— As a compromise, a cascade with equal voltage ratings for the arrester and the suppressor can offer successful coordination, if the impinging surges are presumed to be relatively short.
— ToleranceS on device characteristics might make the compromise ineffective.
— Bibliography with 32 citations

[B238] Marz, M. B., and Mendis, S. R., "Protecting Load Devices from the Effects of Low-Side Surges," *Proceedings, IEEE/ICPS Conference*, May 1992.
— Utilities are becoming aware of the low-side surge phenomenon and are applying secondary arresters to protect their distribution transformers. This practice can increase the voltage stress at the customer service entrance.
— If any ground paths exist on the customer side of the service entrance, these surges can penetrate further into the customer's system.
— Damage caused by low-side surges can be avoided if properly coordinated arresters are installed at the transformer secondary, service entrance, and load device.
— 15 references

[B239] Standler, R. B., "Coordination of Surge Arresters and Suppressors for Use on Low-Voltage Mains," *Proceedings, International Zurich Symposium on EMC*, 1991.
— Results of both a theoretical analysis and laboratory experiments are reported on sharing of current between an arrester at the service entrance and a suppressor at receptacles during surges.
— Shows that it is better to design the arrester with a smaller conduction voltage than the suppressor, in order to obtain better coordination, better EMC, and lower cost.
— Computations were made with only resistance of wire between cascaded devices, no inductance.
— 9 references

[B240] Stringfellow, M. F., and Stonely, B. T., "Coordination of Surge Suppressors in Low-Voltage AC Power Circuits," *Proceedings, Forum on Surge Protection Application, NISTIR-4657*, Aug. 1991.
— Experiments showing the effect of line length and impinging surge waveform on sharing energy between service entrance arrester and surge suppressor inside building.
— Removal of protection at either load or distribution panel resulted in unacceptably large oscillatory voltages. Best load protection was achieved with MOVs in all three locations.
— 4 references

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