

IEEE Guide for the Application of Surge-Protective Devices for Use on the Load Side of Service Equipment in Low-Voltage (1000 V or Less, 50 Hz or 60 Hz) AC Power Circuits

IEEE Power and Energy Society

Sponsored by the
Surge Protective Devices Committee

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IEEE Guide for the Application of Surge-Protective Devices for Use on the Load Side of Service Equipment in Low-Voltage (1000 V or Less, 50 Hz or 60 Hz) AC Power Circuits

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Abstract: Guidance is provided to specifiers, users and manufacturers of surge-protective devices (SPDs) about the application considerations of SPDs to power distribution systems and associated equipment. This guide applies to SPDs to be connected to the load side of the service equipment (and main over current protective device) of 50 Hz or 60 Hz ac power circuits rated 1000 V ac or less. Information on surge origins, effects of surges, number and magnitude of surge events, location categories, power distribution system (PDS) configurations, grounding and bonding, SPD specifications, SPD ratings, SPD characteristics, SPD lifetime, interactions of SPDs with a PDS, and SPD coordination considerations are provided in the guide.

Keywords: arrester, bonding, grounding, IEEE C62.72™, internally generated surges, lightning, SPD, surge-protective device coordination, surge-protective device, switching, transient, transient voltage surge suppressor

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Introduction

This introduction is not part of IEEE Std C62.72-2016, IEEE Guide for the Application of Surge-Protective Devices for Use on the Load Side of the Service Equipment in Low-Voltage (1000 V or Less, 50 Hz or 60 Hz) AC Power Circuits.

One purpose of this guide is to provide specifiers, users, and manufacturers of surge-protective devices (SPDs) with an understanding of numerous application considerations to be evaluated before SPDs are installed in low-voltage ac power circuits. Given this understanding, specifiers, users and manufacturers can exercise due diligence in applying SPDs, take steps to prevent their misapplications, and act to either prevent or mitigate adverse effects that SPDs may have on a power distribution system (PDS) in an effort to improve the effectiveness and benefit of applying SPDs to the PDS.

The growth of interest in and use of low-voltage power SPDs parallels the increasing number of installations with sensitive, sophisticated, and expensive electronic equipment and components that can be exposed and susceptible to surge voltages. It must be recognized that SPDs are not designed to correct every type of power system disturbance. However, SPDs can be extremely effective at mitigating the impact of transient overvoltages or surges. The functionality of any SPD is directly related to the specific location where it is connected to a low-voltage PDS and the methods used to make the required electrical connections to the PDS. SPDs installed at various locations in the low-voltage PDS, as well as in specific equipment, can interact with each other, with protective relaying systems, and with other components of the PDS. Due to the complex nature of surges and the numerous environments where surges are generated and SPDs exist, the application of SPDs has yet to become an exact science.

This guide is one document in the IEEE C62™ group of standards that deals with power systems surges and surge protection. Other IEEE C62 documents describe performance characteristics of SPDs, recommend standard test protocols for verifying performance, and provide guidance on the interaction between power systems disturbances and SPDs. This application guide is the sister document to IEEE Std C62.62™¹, IEEE Standard Test Specifications for Surge-Protective Devices (SPDs) for Use on the Load Side of the Service Equipment in Low-Voltage (1000 V and Less) AC Power Circuits. The guide was limited in scope to the load side of the service equipment to harmonize with IEEE Std C62.62 and to prevent conflict with another project, PC62.44™, which covers the application of SPDs on the line side of the service equipment.

As part of the ongoing improvement and life cycle of this guide, the following topics and changes were specific work areas focused on by the working group:

- Discussion of internally generated surges due to normal and abnormal system operations
- Expanded explanation of short-circuit current ratings of SPDs including fault current and load-side short circuit interruption capability
- The grounding (earthing) and bonding clause of the guide underwent a major revision while emphasizing the discussion around SPD applications
- Discussion of the surge tests described in IEEE Std C62.62 and how they impact the application of SPDs
- Revisions to the clauses regarding SPD surge current, nominal discharge current ratings and the use of these ratings for specifying SPDs
- Additional guidance on the maximum continuous operating voltage rating

¹ Information on references can be found in Clause 2.

- A clause further dispelling the use of response time as a useful characteristic on an SPD
- A direct statement that energy ratings (Joule ratings) should not be used when characterizing SPDs
- Guidance on the load-side surge withstand capability of two-port SPDs
- An explanation of the UL SPD Types nomenclature from (UL 1449 [B72]²)
- Explanation of SPD enclosure ratings and application considerations
- Application considerations regarding SPD disconnectors
- SPD safety and regulatory considerations
- Expanded discussion of SPD modes of protection
- Discussion of overvoltage failures of SPDs and TOVs
- Extensive additions to the clauses on SPD coordination considerations
- Surge waveforms and durations, ring waves, combination wave generator surges
- SPD conductor connection length
- Distance between SPDs
- Comparison and coordination of SPD terminologies
- SPD maximum continuous operating voltage coordination
- Surge current rating/nominal discharge current rating coordination
- Aging of SPDs
- Coordination of SPDs to the grounding (earthing) and bonding system
- Integral installation of SPDs within electrical distribution and end-use equipment
- SPDs used in conjunction with lightning protection systems
- SPD installation in hazardous locations
- SPD documentation

Suggestions for improvements to this guide are welcome. They should be sent to the Secretary, IEEE Standards Board, The Institute of Electrical and Electronic Engineers, 445 Hoes Lane, Piscataway, NJ 08855-1331, USA.

² The numbers in brackets correspond to those of the bibliography in Annex A.

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1. Overview

1.1 Scope

This guide covers the application of surge-protective devices (SPDs) for installation on the load side of the service equipment for 50 Hz or 60 Hz, ac power circuits rated 1000 V rms or less.

1.2 Purpose

The purpose of this guide is to provide users, specifiers, installers and manufacturers with guidance on the use, selection, application and installation of SPDs for installation on the load side of the service equipment for 50 Hz or 60 Hz, ac power circuits rated 1000 V rms or less.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std C62.41.1TM, IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits.^{1,2}

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

IEEE Std C62.62TM, IEEE Standard Test Specifications for Surge-Protective Devices (SPDs) for Use on the Load Side of the Service Equipment in Low Voltage (1000 V and Less) AC Power Circuits.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.³ In this guide, the word “terminal” is used to mean the connection used to attach the surge-protective device (SPD) to the power distribution system (PDS) or load to be protected. This could be a wire, conductor, bus bar, lug or similar connection.

avalanche breakdown diode (ABD): A device to limit transient voltages and divert surge current by P-N junction breakdown

cascade coordination: The planned interaction between two or more surge-protective devices (SPDs) on the same power distribution system.

circuit interrupt device: A device to interrupt the flow of current, usually in response to a fault. (See IEEE Std C62.62-2010)

degradation: Change of original performance parameters as a result of exposure of the SPD to surge, service, or unfavorable environment. (IEC 61643-1[B23])

in-line SPD: A two-port surge-protective device (SPD) connected in series between the power supply and a load where the load current passes through the conductive terminals of the SPD such that the removal of the SPD opens the circuit but has no intended impedance. (See IEEE Std C62.62-2010)

main overcurrent protective device: The first overcurrent device between the secondary terminals of the distribution or power class transformer and the load terminals of the service equipment. Also identified as the service entrance main.

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² IEEE publications are available from The Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

³ IEEE Standards Dictionary Online subscription is available at: <http://ieeexplore.ieee.org/xpls/dictionary.jsp>.

measured limiting voltage (MLV): 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. (IEEE Std C62.34™-1996 [B32])

mode of protection: Surge-protective device (SPD) protective components might be connected line to line, line to earth, line to neutral, or neutral to earth, and any combination thereof. (IEC 61643-11 [B23])

nominal system voltage: A nominal value assigned to designate a system of a given voltage class. (IEEE Std C62.62-2010)

one-port SPD: A surge-protective device (SPD) connected in shunt with the circuit to be protected. (IEEE Std C62.62-2010)

service equipment: The necessary equipment, usually consisting of a circuit breaker(s) or switch(es) and fuse(s) and their accessories, connected to the load end of service entrance conductors to a building or other structure, or an otherwise designated area, and intended to constitute the main control and cutoff of the electrical service supply. (National Electrical Code® (NEC®) (NFPA 70) [B54])

short-circuit current rating (SCCR) of a surge-protective device: The level at which a surge-protective device (SPD) is suitable for use on an ac power circuit that is capable of delivering not more than the declared root-mean-square symmetrical current at a declared voltage during a short-circuit condition.

SPD disconnect: A solid-state or mechanical device that is responsive to thermal overloads or fault currents or both, and has load and fault current interrupting capability

surge-protective device (SPD): A device that is intended to limit transient overvoltages and divert surge current, or both. It contains at least one nonlinear component. (IEEE Std C62.34-1996 [B34])

two-port SPD: SPD with two sets of terminals, input and output. A specific series impedance is inserted between these terminals. (IEC 61643-1[B22])

Type 1 SPD: Permanently connected SPDs intended for installation between the secondary terminal of the supplying transformer and the line side of the service equipment overcurrent device, as well as the load side, including watt-hour meter socket enclosures and intended to be installed without an external overcurrent protective device. (UL 1449 [B72])

Type 2 SPD: Permanently connected SPDs intended for installation on the load side of the service equipment overcurrent device; including SPDs located at the branch panel. (UL 1449 [B72])

Type 3 SPD: Point of utilization SPDs, installed at a minimum conductor length of 10 m (30 ft) from the service equipment to the point of utilization, for example, cord-connected, direct plug-in, receptacle type, and SPDs installed at the utilization equipment being protected. (UL 1449 [B72])

NOTE—The distance (10 m) is exclusive of conductors provided with or used to attach SPDs. If the nominal discharge current test is performed on a Type 3 SPD, the minimum distance from the service equipment does not apply.⁴

Type 1, 2, 3 Component Assemblies: Consists of a Type 4 component assembly with internal or external short circuit protection. (UL 1449 [B72])

⁴ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

Type 4 SPD: Component assembly consisting of one or more Type 5 components together with a disconnect (integral or external) or a means of complying with the limited current tests. (UL 1449 [B72])

Type 5 SPD: Discrete surge-protective components, such as MOVs that may be mounted on a printed wiring board (PWB), connected by its leads or provided within an enclosure with mounting means and wiring terminations. (UL 1449 [B72])

3.2 Acronyms and abbreviations

ABD	avalanche breakdown diode
ACEG	ac equipment grounding conductor
ATS	automatic transfer switch
CBN	common bonding network
EFT	electrical fast transient
EGC	equipment grounding (earthing) conductor
EPR	earth potential rise
EPS	electrical power system
GES	grounding electrode system
GFP	ground-fault protection
GPR	ground-potential rise
GRE	ground-reference equalizer
ICCB	insulated-case circuit breaker
IEC	International Electrotechnical Commission
IP	ingress protection
IT	IEC electricity supply system earthing code, see Table C.1
LPS	lightning-protection system
LVPB	low-voltage power breaker
MCCB	molded-case circuit breaker
MCOV	maximum continuous operating voltage
MLV	measured limiting voltage
MOV	metal-oxide varistor
NEC	National Electrical Code

NRTL	Nationally Recognized Testing Laboratory
OCPD	overcurrent protective device
ONT	optical network terminal
PDS	power distribution system
PE	protective earth
PEN	protective earth neutral
PPE	personal protective equipment
SAD	silicon avalanche diode
SCCR	short-circuit current rating
SPC	surge-protective component
SPD	surge-protective device
SRE	surge-reference equalizer
TN	IEC electricity supply system earthing code, see Table C.1
TOV	temporary overvoltage
TT	IEC electricity supply system earthing code, see Table C.1
VPR	Voltage Protection Rating

4. Introduction to surge protection

Protection of ac power circuits and connected equipment from surges is best achieved through the application of SPDs that are properly installed and rated for the particular application. An understanding of the origin of surges, exposure to the surge environment, location categories, configuration of a power distribution system (PDS), and characteristics of the end-use equipment are essential factors in the successful application of SPDs.

If the installation of SPDs is desirable for a specific PDS, then it is recommended that the application be considered during the initial design phase of the construction or when the PDS is to be renovated or updated.

In many cases, however, the installation of SPDs occurs well after the commissioning of a PDS or just after a damaging surge event has occurred.

Regardless of when SPDs are selected or installed, exercising due diligence in the selection and application of the SPDs relative to specific PDS will enable the optimum surge protection for both the system and the connected equipment.

5. Surge origins

Surges that occur in low-voltage ac power systems, and impinge on a PDS or distributed generation feed from outside a facility, originate primarily from two sources. These sources are lightning and switching. Other surges that occur more frequently within facilities, in most cases, originate from internal sources. For this guide, these are referred to as internally generated surges, as follows:

- *Lightning surges.* Lightning surges are the result of direct lightning strokes 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.
- *Switching surges.* Switching surges are the result of intentional actions on the power system (on the line side of the service equipment), 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.
- *Internally generated surges.* Surges produced by sources internal to the power system (on the load side of the service equipment) due to switching activity whether from normal, abnormal, intentional, or unintentional activity.

5.1 Lightning

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 or facility of interest, but other coupling mechanisms into overhead or buried power circuits can also produce overvoltages and associated surge currents. Additional consideration needs to be taken into account when multiple power sources are used. In particular, when secondary power generation systems are used they might include wind, solar, and on-site generation that are connected to the load side of the main utility power. These lightning surges can be described under two distinct scenarios:

- a) *Scenario I.* In the event of a lightning flash not directly involving the structure, two different coupling mechanisms occur:
 - 1) Surges coupled into the power system, either directly or indirectly, and impinging at the service entrance of the building of interest.
 - 2) Electric fields (capacitive) and magnetic fields (inductive) penetrating the structure and coupling to the building or facility wiring.
- b) *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:
 - 1) Surges coupled into the ac power circuits by direct coupling.
 - 2) Surges coupled into the ac power circuits by inductive coupling.
 - 3) Surges associated with local earth potential rise (EPR) causing operation of a service-entrance SPD.

5.2 Switching

Switching transients result from electrical loads turning ON and OFF and the mechanical operation (opening and closing) of power system electrical equipment (breakers, re-closers, etc.) located throughout a PDS. These operations can occur as a result of normal and abnormal operations or conditions.

5.2.1 Externally generated (switching) surges

5.2.1.1 Normal operations

Switching operations are a normal part of any electric power system. Normal operations are those that occur due to any requirement to change steady-state conditions and are usually the result of changing loads or the need to balance voltage levels. Nevertheless, any switching operation that involves a change in capacitive or inductive loading, or as a result of the characteristics of the switching devices, can introduce transient overvoltages on the system.

The effects of normal operations typically result in transients that do not have sufficient amplitude or duration to damage power system wiring or load equipment, although occasional equipment upset might occur.

5.2.1.2 Abnormal operations

Abnormal or unintended operations or conditions in a power system can produce significant transient overvoltages. Examples include the opening and reclosing of circuit breakers, fault clearing by current-limiting fuses, clearing faults on ungrounded systems, and switching of capacitor banks. Abnormal operations can result in transient overvoltages of sufficient magnitude to cause equipment malfunctions and cause SPD operation.

5.2.2 Internally generated (switching) surges

Internally-generated surges that are on the load side of the service equipment can come from a variety of sources. Most often, internally-generated surges are produced during some type of switching activity whether they are considered a normal, abnormal, intentional, or unintentional activity. These occurrences are exaggerated when devices are interrupted under load. From Clause 4.3 of IEEE Std C62.41.1™-2002:

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.

The standard goes on to detail specific information regarding the expected waveform, amplitude, and frequency of oscillation associated with these internally-generated surges. Specific sources and activities that lead to internally-generated surges are described below with examples cited from (Hotchkiss, 2008 [B12]).

5.2.2.1 Normal operations

5.2.2.1.1 Contactor, relay, and breaker operations

Unless inherently or otherwise protected, contactors, relays, and breakers (or other overcurrent circuit protective devices) can often produce switching surges that have complex waveforms and amplitudes that are several times greater than the nominal system voltage. The sudden interruption of current during a switching operation results in an overvoltage spike due to wiring or load inductance. This phenomenon is complicated by arcing that often occurs across the output contacts of the contactor, relay or breaker. In inductive-capacitive circuits the switching arc is often unstable, particularly when interrupted under full current draw. This scenario can cause the current to interrupt and re-strike several times before opening the circuit properly (IEEE Std C62.48 [B39]). The action of the arc forming between the contacts generates a switching surge that has a ringing voltage waveform.

5.2.2.1.2 Switching of capacitor banks

Capacitor banks are commonly used for operations as power factor correction within many electrical systems. Further, these capacitor banks are often switched into and out of the electrical system depending on the characteristics of the loads that are currently connected to the electrical system such as power factor. As a capacitor bank is energized, it causes a momentary short-circuit as it begins to charge resulting in a sudden collapse of the applied voltage. The voltage will try to maintain itself and creates a rebounding effect producing an oscillation. The switching action can create ringing, voltage transients that are as high as two times the nominal voltage. This phenomenon is detailed in IEEE Std C62.41.1™-2002. Figure 1 is an example oscillogram of a capacitor switching transient.

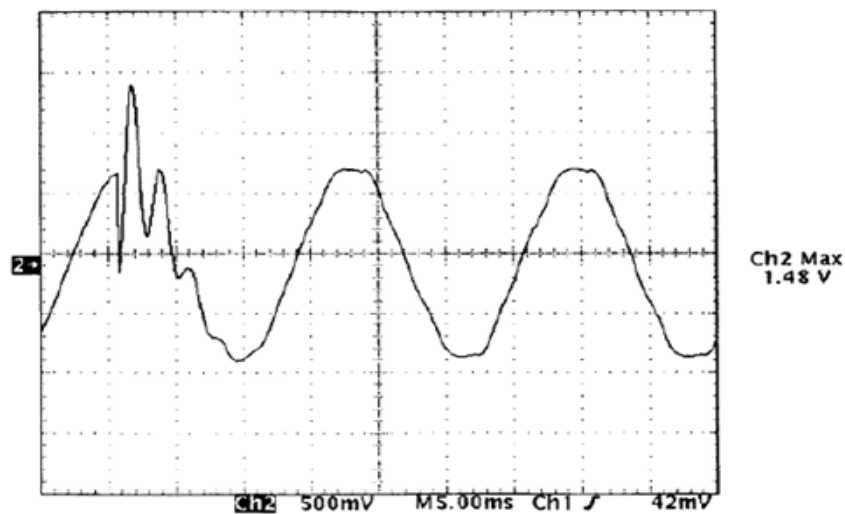


Figure courtesy of IEEE Std 1100™-2005 [B31]

Figure 1—Example of a capacitor switching transient

5.2.2.1.3 Discharge of inductive devices

Another common source of switching transients is the discharge of inductive devices. This can include the discharge of energy stored in fault current limiters, transformers, reactors and motors (IEEE Std C62.48) [B39]. These devices store energy while completing their action. When this type of load is switched off the energy stored in the device can be released into the electrical system. The signature of the switching transient is formed by the inductance and capacitance of the circuit and the system. The waveform will typically be a damped oscillation—the peak voltage being related to the rate of change of current and the inductance of the supply cable (IEEE Std 1100-2005 [B31]). An example of this is shown in Figure 2.

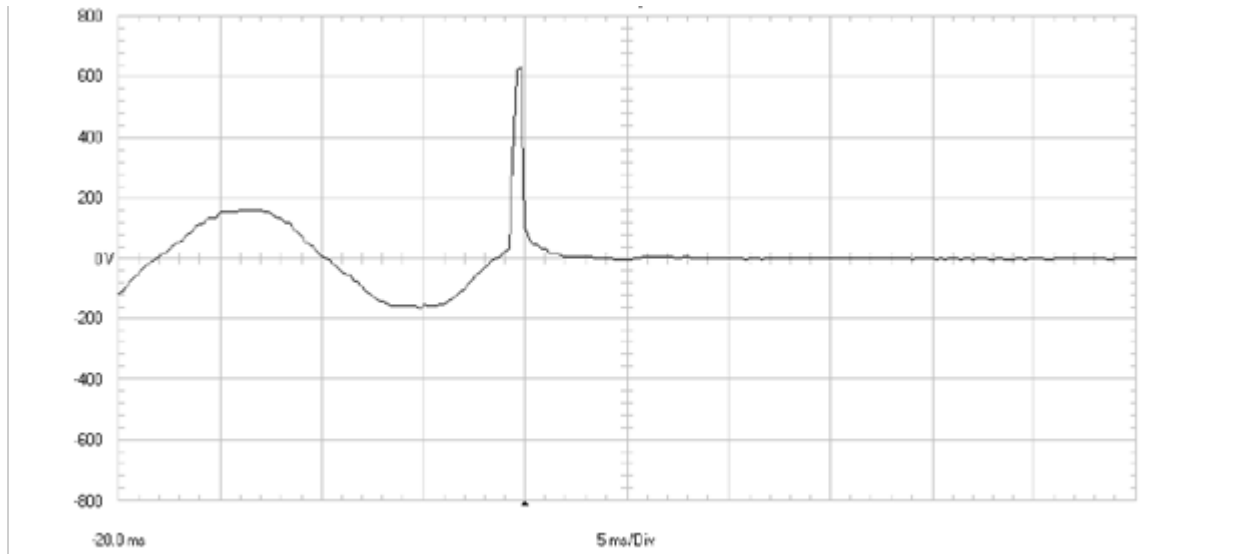


Figure courtesy of IEEE Std 1100-2005 [B31])

Figure 2—Inductive transient across a relay coil

5.2.2.1.4 Starting and stopping of loads

In a similar fashion to that described above in the discharge of inductive devices, starting and stopping loads often creates a voltage transient (IEEE Std C62.48-2005 [B39]). Further, the higher the operating current involved, the more severe the transient tends to be. Switching large loads on or off can produce long-duration voltage changes beyond the immediate transient response of the circuit (IEEE Std 1100-2005 [B31]). As an example, this happens frequently when voltage fluctuates at the startup of a motor producing a voltage surge.

5.2.2.1.5 Arc and fault initiation

Another common source of switching transients that are from normal and intended sources includes devices that create an intentional fault or arc as part of their operation. A prime example of this type of source is an arc welder (IEEE Std C62.48-2005 [B39]).

5.2.2.2 Abnormal operations

In contrast, other sources of internally generated surges are created by abnormal operations. These sources are sometimes intentionally activated but typically are due to an undesired or unintended event, such as a fault. Fault currents represent an extreme case of transient current flow and thus ac line-voltage disturbance. Depending on the power system impedance, several orders of magnitude of normal full-load current may be available (IEEE Std 1100-2005 [B31]). Other sources grouped with abnormal operations include actions from faulty equipment or wiring. As stated in IEEE Std C62.41.1™, the intended or corrective reaction of the electrical system to abnormal events can also produce surges.

Even though some of these scenarios are undesired or unintended, they are also common. Examples of sources of internally generated surges include the following.

5.2.2.2.1 Arcing faults and arcing ground faults

Often, arcing faults or arcing ground faults occur due to an instance of insulation breakdown, either in electrical system wiring or in motor winding insulation, for example. Much like the action of a contactor or relay as described previously, the arc associated with an arcing fault can generate surges that interact with the inductance and capacitance of the system. Further, in ungrounded systems, where many arcing ground faults occur, the stray capacitance of the system allows the surge amplitude to rise to 2 or 3 times the peak voltage. During conditions of resonance, the amplitudes can be much greater (IEEE Std C62.48-2005 [B39]).

5.2.2.2.2 Fault clearing

The reaction of the electrical system to a fault is typically to clear the fault through the opening of a fuse or circuit breaker. Current-limiting fuses or fast-acting circuit breakers can leave inductive energy trapped in the circuit upstream. If no low-impedance path is offered to lessen the stored energy, high voltages are generated. The resultant voltage surge appears in parallel with the loads where the fault is being cleared (IEEE Std C62.48-2005 [B39]). This is particularly evident when one phase of a three phase system short-circuits, the other phases can see a rise in voltage. At the point where the device clears, a transient can result.

5.2.2.2.3 Power system recovery

As part of the action of trying to clear a fault from the electrical system, the system might be re-closed. This re-closing of the electrical system can produce voltage surges of amplitudes that approach twice the nominal voltage and are of longer durations (IEEE Std C62.41.1™). Although, these occurrences are often considered outside the scope of a “surge” [often considered a swell] (IEEE Std C62.48-2005 [B39]), they are noteworthy nonetheless.

5.2.2.2.4 Loose connections

Another unintended source of internally generated surges is loose connections – more specifically, the arcing that can occur due to loose connections (IEEE Std C62.48-2005 [B39]). The switching surges generated by this condition can be similar to that described above for contactor and relay operations and arcing faults. Further, this situation is not only a source of switching surges but also a concern with heat buildup and intermittent or incorrect operation of connected equipment.

6. Effects of surges

The effects of a surge on PDSs or end-use equipment can range from no observable effect to obvious and severe damage.

6.1 No observed change

The absence of visible changes could seem to demonstrate that the equipment was immune to the surge level in question, and in some cases, it may be. However, the equipment can continue normal operation within specified limits and thus appear to meet the criterion of no loss of function or performance. Yet significant consequences are possible such as degradation of performance still within specification but foreboding larger degradation, latent failure of a component, or an unforeseen consequence elsewhere in the equipment environment. The long-term operation of the equipment might be impacted and shortened.

6.2 Upset

This consequence can be a self-recoverable upset by the planned design of the controls, components, or software and therefore not immediately apparent or permanent. Such upsets often require operator intervention or the programming of automatic actions that occur after some time delay. These upsets are identified in the following three categories:

- Minor
- Major
- Critical

6.2.1 Minor

A temporary loss of functionality of the equipment or a process does occur. The equipment or processes are capable of operating throughout the complete interaction of the surge event on the PDS, but there is a degradation of performance of the equipment, an observed deviation of electrical power, or a deviation in the process.

6.2.2 Major

A temporary loss of functionality of the equipment or a process does occur. The equipment or process is interrupted as a result of the surge event on the PDS, but the equipment, power or process is recoverable automatically (without human interaction) through the interaction of the control system after the event. After the automatic reset of the equipment, power or process, there is no degradation in the performance.

6.2.3 Critical

A loss of functionality of the equipment or a process does occur. The equipment or process is interrupted as a result of the surge event on the PDS. The equipment, power, or process must be reset through manual interaction. After the manual reset of the equipment, power or process has occurred, there is no degradation in the performance.

6.3 Damage

This consequence includes the subtle as well as the obvious. Subtle damage (for example, insulation breakdown) can occur without being detected unless special assessment of the equipment condition is performed. Obvious damage would be burned circuit board traces or evidence of a flashover at a panel or at an equipment location.

6.4 Consequential damage

This consequence includes the possibility that equipment subjected to a surge could cause damage to its surroundings well beyond the importance of the damage or upset itself. In extreme cases, fire or explosion could occur. In these cases, facilities operations and equipment functions might be disrupted.

Damage can result from unseen hardware upset, during which data become corrupted. The corruption can subtly degrade other elements in the database, automated controllers, or programmable logic controllers while the user is left unaware of the situation.

7. Number and magnitude of surge events

The magnitude of a surge and its effect on equipment varies, depending on the design and construction of the PDS and its specific geographical location. The prediction of the level or magnitude of a surge event at any point within a specific PDS is always difficult (and frequently impossible), based on current technology and the lack of understanding of all variables associated with surge events. Many variables can contribute to the rate and magnitude of surge events. Examples of some of these variables are the level and distribution of surges, changes in the environment, changes in the loads connected to the PDS, and changes in the medium voltage distribution system of a utility.

7.1 General

Low-level (low-magnitude) surges are more prevalent than high-magnitude surges. A surge voltage level observed in a PDS can be a function of one or more components of the original surge, the remnant energy available after a sparkover or flashover event, or the operation of an overcurrent protective device (OCPD) associated with the PDS.

Where an individual evaluation is not possible, such as is the case of a direct lightning strike, it might be assumed that 50% of the total lightning current enters the ground termination of the lightning protection system of the structure considered. The other 50% of the current is then assumed to be distributed among the services entering the facility. This distribution of lightning current is also noted in (IEC 61643-12 [B24]). The effects of increased numbers of SPDs installed within the PDS will also directly affect the distribution of a surge. The repetitive operation of numerous SPDs can significantly affect the voltage stability of the system.

7.2 Environmental factors

Variations in surge magnitudes and surge events can be related to changes in the environment. Environmental changes can alter the conductive path of a surge current or can facilitate a premature flashover or spark-over event. Changes in the environment are a function of one or more combinations of events.

Factors that can contribute to flashover or spark-over events are as follows:

- Indoor versus outdoor equipment ratings.
- Temperatures exceeding the range of equipment.
- Temperatures caused by a temporary external heat source near the SPD.
- Exposure of energized parts to damaging fumes or vapors.
- Excessive dirt or other contaminants within the electrical equipment and around the SPD.
- Exposure of energized equipment to salt spray or other current conductive deposits.
- Exposure of energized equipment to moisture, steam, or water.
- Exposure of energized equipment to explosive atmospheres.
- Exposure of energized equipment to abnormal vibrations or shocks.
- Insufficient clearances between energized parts and nearby conductive objects.
- Increase of voltage on conductive parts that are greater than the rating of the component, equipment, or part.

7.3 Changes in the power distribution system (PDS)

The desired function of an SPD can be affected by changes in a PDS. Changes in the system can be a function of one or more combinations of events as a change in the nominal frequency of a PDS or operating conditions whereby the ratings of an SPD might be temporarily exceeded. The conditions listed below can cause conditions that exceed the listing voltage ratings of a specific SPD.

Abnormal changes that occur in PDS as follows:

- Loss of neutral ground on normally grounded circuit.
- Abnormal speed regulation on a station service generator.
- Resonance conditions during faults.
- System voltage instability.
- Persistent single line-to-ground fault on an ungrounded three-phase, three-wire PDS.

7.4 Rate of occurrence (versus) current level

Data collected from many sources show a decreasing number of occurrences for high crest surges with a slope that is independent from the site of data collection. The absolute number of occurrences varies from site to site. The data collected indicates that low-amplitude surges occur more frequently than high-amplitude surges. The events of higher amplitudes can be extrapolated or estimated from the general slope of occurrences.

IEEE Std C62.41.1 provides a large database with regard to the rate of occurrence of surges. A large number of studies are cited and the reader is referred to that document for further information regarding the rate of occurrence.

The data collected indicate that the peak current levels of most lightning strikes are in the range of 10 kA to 40 kA. The median value of the peak current reported was in the range of 15 kA to 20 kA. Only 6% of the currents were above 60 kA, and less than 2% of the currents were above 100 kA (Key and Martzloff [B45]), (Lewis and Foust [B48]), and Transient Voltage Suppression [B68]). The rate and peak current levels of surge events will also vary depending on the geographical location. In addition, the research data indicate the value of the initial stroke. Lightning is usually a multiple stroke event, and the subsequent strokes often have less energy than the initial stroke. Further, it should be understood that the peak current values detailed above are that of the lightning stroke only and not the peak current value entering the PDS.

7.4.1 Lightning characteristics and current level

Lightning is an environmental condition caused during the attempted equalization of charges between planetary locations of different polarity. The separation of charges can occur between clouds, between different parts of a cloud and between cloud and ground. As the separation of charges continues over a period of time, a dielectric breakdown will occur. When dielectric breakdown occurs between two points, the result is the neutralization of charges through a flow of current, which is defined as lightning. There are three types of lightning flashes: negative, positive, and bipolar. It is estimated that 90% of the lightning discharges are negative and that less than 10% are positive (Uman [B73]). Bipolar lightning discharges are rare, and they make up the remaining percentage of the lightning discharges from cloud to earth.

7.4.1.1 Negative lightning flashes

Research examining the peak current associated with lightning flashes occurred as far back as 1944 (McCann [B52]). Similar to the differences in the rate of rise of the stroke current between initial strokes and subsequent strokes, there are differences in the peak current between initial strokes and subsequent strokes. For negative flashes, 50% of the initial return strokes exceeds 30 kA, and only 5% of the initial peak return stroke currents measured exceeds 80 kA (Uman [B73], Thottappillili [B66], IEEE PES T&D Committee [B26]), and Tominaga et al. [B67]).

In most cases, subsequent strokes have a peak current that is less than the measured value of the initial return stroke current (Uman [B73], Thottappillili [B66], and IEEE PES T&D Committee [B25]). Fifty percent of subsequent return strokes are between 12 kA and 15 kA (Uman [B73] and Thottappillili [B65]). Disagreement exists in the literature about the peak current of subsequent return strokes. Thottappillili indicates that the maximum current of a subsequent return strokes approach 75 kA (Thottappillili [B65]). In other studies, the maximum current of subsequent return strokes is determined to be 30 kA (Uman [B73] and IEEE PES T&D Committee [B26]).

The time interval between the initial return stroke and subsequent return strokes range from approximately 7 ms to 500 ms (Uman [B73] and Thottappillili [B65]). However, separation times of 46 μ s to 110 μ s have been recorded in a minority of lightning flashes in data collected from the Kennedy Space Center (Rakov and Uman [B73]). The amount of (average) current that flows in the lightning channel has a maximum value of 500 A with a typical value of 100 A (Thottappillili [B65]).

Several research studies have been published on the number of strokes per lightning flash. Analysis by Uman from studies conducted with 1800 lightning flashes in South Africa and 105 flashes in Florida is depicted in Table 1 (Uman [B73]). Approximately 25% of the negative lightning flashes are single stroke, whereas approximately 75% of the lightning flashes are multiple stroke events. Variations in the number of strokes can be noted between the two geographical areas, but 50% of the lightning flashes in both geographical areas have between two and five strokes.

The mean number of strokes per lightning flash is 4.0 for data obtained from South Africa and 4.1 from data obtained from Florida. A small number of lightning flashes contain 10 or more strokes. The maximum number of strokes recorded in a single lightning flash was 26, which were recorded in New Mexico (Thottappillili [B65]).

From another study published by Schneider Electric [B65], for 31 266 negative strokes recorded during one time period, 82% were less than 30 kA and 98% were less than 60 kA.

Table 1—Distribution of negative lightning flashes (Uman [B73])

Number of strokes per flash	Frequency of occurrence South Africa (%)	Frequency of occurrence Florida (%)
1	27	26
2	14	15
3	9	12
4	11	17
5	16	6
6	6	5
7	4	4
8	5	8
9	5	1
10 or more	6	6

7.4.1.2 Positive lightning flashes

A positive cloud to earth lightning flash occurs when the charge of earth is negative and the charge of the thunderstorm cloud is positive (Lai and Martzloff [B47]). Unlike negative lightning flashes, positive lightning flashes are rarely multiple stroke events. Positively charged lightning typically occurs during the winter months and in the higher earth latitudes. With only approximately 10% of the lightning flashes having a positive polarity, they are rare in nature. However, with a number of the world's major cities located in higher latitudes, positive lightning flashes have received significant research attention recently.

The peak current associated with positive lightning flashes ranges from a few kiloamperes to hundreds of kiloamperes. Ninety-five percent of the peak currents exceed 4.6 kA, 50% exceed 35 kA, and 5% will exceed 250 kA (Uman [B73] and Thottappillili [B65]). Several research papers show peak currents greater than 100 kA (McCann [B52], Goto et al. [B9], and Miyake, et al. [B53]).

From another study (Surge Protection [B65]), for 2597 positive lightning strokes 95% were less than 30 kA and 98% were less than 60 kA. The study claims that the unprecedented 33 863 data points provide supportable evidence of representative currents within lightning events. In aggregate, the data reveals that less than 2% of the positive or negative strokes had a current magnitude greater than 60 kA. The vast majority of strokes were less than 30 kA.

7.5 Exposure levels

IEEE Std C62.41.1 provides the expected surge environment for a PDS. The needs and requirements for surge protection along with the rating of an SPD will vary greatly relative to the geographical areas where SPDs are installed. For example, the lightning activity and power system switching in regions such as extreme northwest of the United States are significantly different than those found along the coastline of the Gulf of Mexico in the southeastern United States. The dense urban and industrial areas along the gulf coast region of the United States plus the extremely active atmospheric disturbances of that region combine to make one of the extreme environments for lightning surges and switching transients on the planet. It is

recommended that specifiers or users of SPDs refer to this standard as a guide for understanding and classifying their suspected exposure level before making a selection.

Exposure levels have historically been related to the risk assessment of the exposure of a circuit reflecting regional characteristics, specifically lightning flash density as well as power system conditions. As a result of this work, three main exposure levels have been accepted as follows:

- *Low exposure:* Power distribution systems in geographical areas known for low lightning activity and with little load or capacitor switching activity.
- *Medium exposure:* Power distribution systems located in geographical areas known for medium-to-high lightning activity or with significant switching transients. One or both of these might be present.
- *High exposure:* This category includes those rare installations that have greater surge exposures than those defined by low exposure or medium exposure. The more severe conditions result from extensive exposure to lightning or unusually severe surges.

Although this information can be helpful in initial risk assessment analysis, it should be noted that, in general, the spark-over of wiring devices indicates that a 6-kV withstand capability for an SPD can be adequate for indoor installations. A withstand capability of 10 kV and above would be more suitable for outdoor and Category C locations.

Clause 8 of this standard provides guidance on the location categories that have been developed in IEEE Std C62.41.1 and its predecessor documents.

7.6 Risk assessments

Determining an adequate strategy to mitigate the adverse effects of surges on the PDS, equipment or process can be a difficult endeavor. The use of a Lightning Risk Assessment is one method to identify a strategy. Lightning Risk Assessments can be conducted using existing standards or general Risk Assessment procedures. There are many factors to be considered in the risk assessment. Lightning risk assessments are described in US and international standards (NFPA 780 [B56] and IEC 62305-2 [B25]). A simple risk assessment to determine if a lightning protection system (LPS) is required is described in this document.

Performing a lightning-risk assessment allows the specifier or user to utilize information related to facility and surrounding environment to determine whether a lightning protection system is needed. The lightning-risk assessment should take into account parameters associated with the structure and its surrounds, the lightning flash density of the location, and the importance of the facility and its processes to the business, the community, and the environment.

A lightning-risk assessment compares environmental factors to tolerable risk factors for a given facility or structure. If the environmental factors exceed the tolerable risk factors, then a lightning protection system is recommended to aid in the protection of the facility, processes, equipment, and personnel within the facility.

The components to determine the environmental factors (N_d) are:

- The collective area of the facility (A_e)
- A coefficient to describe the surrounding environment (C_1)
- The lightning flash density of the area (N_g)

The environmental factors are described mathematically by:

$$N_d = N_g A_e C_1 (10^{-6})$$

The components to determine the tolerable risk (N_c) are:

- A coefficient to describe the type of structure (C_2)
- A coefficient to describe the contents of the structure (C_3)
- A coefficient to describe the structure occupancy (C_4)
- A coefficient to describe the consequence of loss of operation of the structure (C_5)

The tolerable risk is described mathematically by:

$$N_c = (1.5 \times 10^{-3}) / (C_2 C_3 C_4 C_5)$$

If the numerical value of the environmental factors exceeds the numerical value obtained from calculating the tolerable risk, then a lightning protection system is recommended.

Sample Lightning Risk Assessment Example (Cole [B4]):

This example shows how to conduct a lightning risk assessment based on the following parameters:

- a) Structure size: 100-m long, 60-m wide, 15-m tall (approximately 325-ft long, 200-ft wide, 50-ft tall)
- b) The structure is the tallest structure in the vicinity
- c) The location of the facility is in St. Petersburg, Florida
- d) The structure is metal with a metallic roof
- e) The structure contains a data center for a regional bank (exceptional value)
- f) The structure is normally occupied with more than 300 people (continuity of service required)

Based on these conditions, the values and coefficients have been determined and are reported in Table 2.

The environmental factor for the structure (N_d) is calculated as 0.42819. The tolerable risk factor (N_c) is calculated as 0.00017. Dividing the environmental factor by the tolerable risk factor returns a value of 2569. Any number of 1.0 or greater indicates that a lightning protection system should be installed, whereas a number less than 1.0 indicates that lightning protection system is not required.

A lightning protection system is an important component in protecting a structure, electrical systems and critical business processes. Surge-protective devices (SPDs) are an important component of a lightning protection system and are required by US and international standards to be installed if a lightning protection system is installed.

Table 2—Risk assessment example

Parameters	Coefficient
Collective area (A_e)	26 762 m ²
Surrounding environment (C_1)	0.5
Lightning flash density (N_g)	16 flashes/yr/km
Structure type (C_2)	0.5
Structure contents (C_3)	3.0
Structure occupancy (C_4)	3.0
Structure operations (C_5)	2.0

8. Location categories

When planning for surge mitigation for a PDS at a specific geographical location, IEEE Std C62.41.1 can also provide guidance to a specifier or user of an SPD in recognizing the relationship of equipment susceptibility, environmental hostility, and degree of reliability required for equipment. Reconciling equipment susceptibility and environmental hostility to surge requires investigation and analysis. A goal should be to establish the most effective equipment protection possible. To achieve this, it is important to first recognize the types and severity of surges in a specific environment. Further, the operational characteristics and surge susceptibility of all equipment in that particular environment or location category should be considered. Because of the wide range of possible source impedances and the difficulty of selecting a specific value, three broad categories of circuit locations have been defined (see Figure 15). These categories represent most locations, from those near the service entrance to locations remote from the service entrance.

For surges impinging on a building or facility and originating in the utility supply, the source impedance might not be constant. However, the increasing impedance between the service entrance and the point of connection for a piece of equipment will have an effect on the surge current. This impedance places a limit on the maximum rate of current change that can occur in the wiring because rapid changes of current require a driving voltage that would result in insulation flashover at the surge source or its point of entry in the service equipment. Any insulation flashover can limit the duration and possibly the magnitude of a surge before it could travel further into the building or facility.

As a result, the surge current at the service entrance (Category C or Category B) would not be the same as the surge current at a branch circuit outlet (Category A).

Typical Category C locations are as follows:

- Outside and including the service equipment.
- Service drop from pole or transformer to a building or facility.
- Conductors between the utility's revenue meter and service equipment.
- Overhead line to detached buildings or facilities.
- Underground line to a well pump or other outdoor electrical equipment.

Typical Category B locations are as follows:

- Service equipment located inside a facility, feeder circuits, and short branch circuits.
- Distribution panelboards, switchboards, switchgear, motor control centers and devices.

- Busways and feeders in industrial plants.
- Heavy appliance (convenience) outlets with short connections to the service equipment.
- Lighting systems in large building or facilities.

Typical Category A locations are as follows:

- All appliance (convenience) outlets at more than about 10-m from Category B.
- All appliance (convenience) outlets at more than about 20-m from Category C.

9. Power distribution systems

Before selecting and installing an SPD, it is recommended that a specifier or user make an assessment of the PDS where SPDs could be installed and connected. Table 3 provides a suggested list of questions or important issues to consider in an assessment of a PDS. Subclause supply additional detail can be found in 9.1 through 9.5.

Table 3—Assessment of the use of SPDs for power distribution systems (PDSs)

Does the facility where the SPDs are to be installed have a history of reoccurring electrical supply anomalies (e.g., frequent load switching, fault initiation, fault interruption, and power service interruptions)?
a) These issues and related ones are often associated with high occurrences of externally generated switching surges. For more information on this topic refer, to Clause 5 and IEEE Std C62.41.1.
What are the locations at which the SPDs are intended to be installed? Service equipment? Switchgear? Motor control center? Distribution panel? Subpanel? Individual equipment disconnects?
a) List each location where an SPD might be installed.
b) Evaluate each of these locations separately.
For each SPD installation location, determine the following:
What is the nominal system voltage and configuration of electrical system at the installation location? For example, three-phase Wye at 208Y/120 V versus three-phase Delta at 480 V versus single-phase at 120 V.
a) This information is used to select the voltage configuration of the SPD so that it will work properly at the installation location.
b) It should be verified that the SPD is listed for use on a particular system. For example, only SPDs listed for use on Delta configured systems are permitted to be installed on such systems according to the National Electrical Code® (NEC®) (NFPA 70) [B54]. An SPD listed for Wye configured system is not permitted for use on a Delta configured system.
What is the available short-circuit current at the location where the SPD is to be installed?
a) The NEC [B54] requires that the short-circuit current rating (SCCR) of the SPD be equal to or greater than the available short-circuit current at the point of installation.
b) The coordination of the available short-circuit current of the system at the point of installation and the short-circuit current rating of the SPD is a critical factor when selecting an SPD. For more information on this topic, refer to 9.4.
c) Any existing short-circuit current study should be verified to determine that it is reflective of the current state of the electrical system. Changes to the electrical system will affect the amount of short-circuit current available within the system (for example, changes to the transformer feeding the facility can increase the available short-circuit current).
If at the service equipment or on the load side of a transformer and when the system has a neutral, is the neutral ground bond present? Is the neutral connection in good condition?
a) A loss of neutral or loss of the neutral to ground bond can be detrimental to an SPD.
b) For a system where the neutral and ground are intended to be bonded or a neutral is intended to exist, the presence of these conditions should be verified.
What is the condition of the grounding and bonding system used at the facility?
a) The grounding and bonding system of the facility can impact the effectiveness of the SPD.
b) Refer to Clause 11 for more information on grounding and bonding.

Table continues