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# IEEE Guide on Interactions Between Power System Disturbances and Surge-Protective Devices

## IEEE Power Engineering Society

Sponsored by the
Surge Protectors Device Committee

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# IEEE Guide on Interactions Between Power System Disturbances and Surge-Protective Devices

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**IEEE Power Engineering Society**

Approved 28 October 2005

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**Abstract:** Information is provided to users and manufacturers of surge-protective devices (SPDs) about the interactions that can occur between SPDs and power system disturbances. This guide applies to SPDs manufactured to be connected to 50 Hz or 60 Hz ac power circuits rated at 100–1000 V rms. The effects of the presence and operation of SPDs on the quality of power available to the connected loads are described. The interaction between multiple SPDs on the same circuit is also described.
**Keywords:** harmonics, noise, power system disturbance, surge-protective device (SPD), swell, voltage sag, voltage surge

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# Introduction

This introduction is not part of IEEE Std C62.48-2005, IEEE Guide on Interactions Between Power System Disturbances and Surge-Protective Devices.

The purpose of this guide is to provide users and manufacturers of surge-protective devices (SPDs) with an understanding of the nature of power system disturbances and SPDs, and of the interactions that can occur between them and between SPDs. Given this understanding, users will be able to take steps to either prevent or mitigate adverse effects of such interactions.

The growth of interest in low-voltage SPDs parallels the increasing number of applications of highly sophisticated electronic equipment that can be exposed and susceptible to surge voltages. Users of SPDs can sometimes be under the impression, or can be led to believe, that by installing an SPD in their facility or within their equipment, they will provide total immunity to any and all power system disturbances. In reality, SPDs will respond to and affect some power system disturbances. The effects that SPDs will have on power system disturbances are often less than desired. SPDs installed at various locations in the wiring systems as well as in equipment can interact with those wiring systems and with each other. In this scenario, the effect of any given SPD is imprecise and predictable only within wide limits. Proper application of SPDs will eliminate or reduce the effects of these disturbances for which it was designed. The use of SPDs is covered in other IEEE C62™ family documents.

The SPDs discussed herein are intended to limit transient overvoltages that can appear in low-voltage ac power systems having service voltages of 1000 V or less.

This guide is a member of the IEEE C62 family that deals with power system surges and surge protection. IEEE Std C62.41.2™-2002 characterizes and provides information on surge voltages in low-voltage ac power circuits. Other IEEE C62 documents describe performance characteristics of SPDs, recommend standard test protocols for verifying SPD performance, and provide SPD applications guidance.

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## Participants

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

**James Funke,** *Chair, Technical Editor*
**Ray Hill,** *Vice Chair, Secretary*

Ken Brown
William Bush
Richard Chadwick
Ernie Gallo
Andi Haa
Jim Harrison
Mike Hopkins
Wilhelm Kapp
Joseph L. Koepfinger
François Martzloff
Richard Odenberg
Alan Rebeck
Mike Stringfellow
Tony Surtees
Hans J. Steinhoff
Frank Waterer
Matt Wakeham

Other individuals who have contributed review and comments are as follows:

Richard Bentinger
J. Bonnesen
William Goldbach
David Jackson
Deborah Jennings-Conner
Phillip Jones
Mike Parente
D. Singleton
Edgar Talyor
James Wilson
Don Worden

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

Richard Bentinger
Enrique Betancourt
Thomas Blair
Mark Bushnell
James Case
Tommy Cooper
Ronald Daubert
Randall Dotson
Gary Engmann
Clifford Erven
Marcel Fortin
James Funke
Ernie Gallo
Jerry Goerz
William Goldbach
Randall Groves
Ajit Gwal
Steven Hensley
Raymond Hill
Edward Horgan, Jr.
Joseph Jancauskas
David Jackson
Wilhelm Kapp
Joseph L. Koepfinger
Stephen R. Lambert
Boyd Leuenberger
Jason Lin
Peter Lips
Gary Michel
Lisardo Lourido
Al Maguire
Ahmad Mahin Fallah
William Majeski
John McDaniel
Mark McGranaghan
Abdul Mousa
Fredrick O'Keefe
Joseph Osterhout
Thomas Pekarek
Alan Rebeck
Thomas Rozek
James Ruggieri
Cameron Smallwood
Hans Steinhoff
Keith Stump
Tony Surtees
Donald Turner
Reigh Walling
Daniel Ward
Steven Whisenant
James Wilson
Zhenxue Xu

# Contents

# IEEE Guide on Interactions Between Power System Disturbances and Surge-Protective Devices

## 1. Overview

### 1.1 Scope

This guide applies to surge-protective devices (SPDs) manufactured to be connected to 50 Hz or 60 Hz ac power circuits rated at 100–1000 V rms.

This guide describes the effects on SPDs of power system disturbances occurring in these low-voltage ac power circuits. The disturbances are not limited to surges. The effects of the presence and operation of SPDs on the quality of power available to the connected loads are described. The interaction among multiple SPDs on the same circuit is also described.

This guide discusses both voltage and current surges. The current surges discussed in this guide are the result of voltage surges. Current surges that are solely the result of load changes and do not result in voltage increases, such as a short circuit, are not discussed in this guide.

An SPD's primary purpose is to provide surge protection. Devices discussed in this guide contain at least one nonlinear component for diverting surge current and/or dissipating surge energy, such as a metal oxide varistor (MOV), silicon avalanche diode (SAD), thyristor, or spark gap. Uninterruptible power supplies (UPSs), ferroresonators, motor-generators, and filters containing only inductive and/or capacitive components are not considered SPDs in this guide.

### 1.2 Purpose

The purpose of this guide is to provide information on the interactions between power system disturbances and SPDs that is not readily available in other standards. This guide provides summary information on power system disturbances that affect or can affect SPDs. The description of the interactions is intended to inform the potential user of such SPDs as to what can be expected from such devices.

NOTE—Data used for the preparation of this standard were obtained primarily from low-voltage ac power distribution systems used in North America.[1]

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

## 2. Normative references

The following referenced documents are indispensable for the application of this guide. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C84.1 (R2005), American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz).[2]

IEEE Std C62.41.1™, IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits.[3]

## 3. Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B3][4] should be referenced for terms not defined in this clause.

**3.1 nonlinear load:** An electrical load that draws current discontinuously or whose impedance varies during the cycle of the input ac voltage waveform.

**3.2 nonlinear load current:** Load current that is discontinuous or is not proportional to the ac voltage.

**3.3 power cross:** An event in an electrical distribution system where a higher voltage conductor, such as from a transmission line, falls on a lower voltage conductor, such as a distribution or secondary line.

## 4. Power system disturbances

Power system disturbances are increases or decreases in the system voltage or the power frequency beyond what is considered the normal tolerance (e.g., as described by ANSI C84.1[5]). The changes in voltage on the ac mains can range from complete loss (no voltage) for various durations lasting up to seconds, minutes, or even hours to very high-magnitude, short-duration impulses of 50 or more times the normal system voltage lasting for no more than a few millionths of a second. Some of these disturbances can have an undesirable effect on the connected equipment, including SPDs. The SPDs discussed in this guide are connected to the low-voltage mains (100–1000 V ac), though some of the disturbances originate on the high-voltage distribution system. SPDs are intended to reduce the severity of some power system disturbances but can be unable to do anything about others.

Before discussing the interactions between power system disturbances and SPDs in detail, the power system disturbances will be described along with a brief summary of the interactions. Table 1 presents a summary of the interactions.

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[2] 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/).

[3] IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08854-1331, USA (http://standards.ieee.org/).

[4] The numbers in brackets correspond to those of the bibliography in Annex A.

[5] For information on references, see Clause 2.

Table 1—Power system disturbance and SPD interaction

| **Power system disturbances** | **Surges** | **Swells** | **Temporary overvoltages (TOVs)** | **Notches** | **Sags** | **Temporary undervoltages** | **Harmonics** | **Noise** |
|---|---|---|---|---|---|---|---|---|
| Effect on SPD | Some | Possibly adverse | Possibly adverse | None | None | None | Possibly adverse | None |
| SPD effect on disturbances | Reduce | Possibly reduce | None | None | None | None | None | Possibly reduce |

## 4.1 Surges

Surges are described in IEEE Std C62.41.2™-2002. They include short-duration, high-energy surges; bursts of high-frequency transients; and high-energy, lower-voltage, and lower-frequency disturbances due to power-system operations.

Surges can be subdivided into externally generated and internally generated surges. External surges are those surges generated outside a facility and brought into the facility by the utility wires. Internal surges are generated within a facility by the user's own equipment. External surges are typically more severe but less frequent than internal surges.

Externally generated surges can result from lightning, power system switching, and operation of overcurrent protective devices (OCPDs), such as circuit breakers, reclosers, and fuses. Lightning surges can result from a direct strike to the power service or induced by strikes to nearby lines or to earth. Buried power cables are not immune to lightning surges. Lightning currents can flow along the sheath of a buried cable and induce voltages on the conductors within the cable. Wires inside a plastic conduit are also subject to induced voltages that might be capable of damaging vulnerable equipment. Capacitor switching can also generate voltage surges in the secondary supply system.

Internally generated surges typically result from switching inductive or capacitive loads. They can also result from an OCPD opening in an inductive circuit. The operation of an SPD can also result in internal surges.

SPDs are intended to reduce surge voltages by conducting the surge currents to neutral, ground, or to another phase. In the process, there is voltage division with the impedance of the rest of the current path; hence, there is less surge voltage at the point of connection of the SPD than there would be without the SPD. SPDs absorb some surge energy and dissipate it in the form of heat (a gas tube or an air gap would absorb very little energy). They are typically intended to do this for surges ranging in duration from less than 1 μs to 10 ms. Surges outside the specified capability of the SPD might damage or destroy the SPD.

## 4.2 Swells

Swells might result from switching operations in the utility distribution system, power switching from one source to another, intermittent loss of a neutral connection, a phase-to-ground fault, such as a flashover of an insulator on one phase of a multiphase system, or possibly a high-voltage conductor contacting a low-voltage conductor. A phase-to-ground fault on an ungrounded three-phase supply system can result in the voltage of the unfaulted phases increasing to 1.91 times the normal amplitude ($\sqrt{3}$ times the nominal phase-to-neutral voltage plus nominal system tolerance), and in extreme cases, for up to several seconds. In a multiple ground system (typical in North America), it is extremely unlikely that the phase voltage will exceed 1.35 times nominal voltage for overhead systems and 1.45 times nominal voltage for underground distribution [B13].

A swell can result from switching a heavy load quickly from one power source to another. An example of this is a load with motors switched from a standby generator to commercial power. The running motor, disconnected from its power source, will generate a back emf. If this motor, at the peak of its back emf, is connected to another power source at the peak of the line voltage, the resulting voltage might be doubled momentarily. A swell might also result from the loss or disconnection of a high-current load.

If the voltage is high enough, a swell is likely to damage or destroy the SPD. There are indications, although not documented in published papers, that (because of their large energy content) swells can damage heavy-duty SPDs more often than surges.

## 4.3 Temporary overvoltages

Temporary overvoltages (TOVs) are power system disturbances of a longer duration than swells. A TOV might be caused by a fault on one phase of a three-phase system, a short in the primary winding of a transformer, a power cross from a higher-voltage line. Overvoltages can occur when cogeneration units are present on distribution systems. Overvoltages can be caused when a distribution system generator and part of the distribution network are separated from the utility. This condition is called islanding and could be caused by an opening of the substation OCPD or a feeder recloser. The overvoltages can be caused by ungrounded transformer connections, self-excitation, or ferroresonance. When a single phase-to-ground fault occurs and the substation OCPD opens, the system becomes a three-wire, ungrounded system driven by the delta-connected distribution system generator. The phase-to-ground voltage will attempt to rise to the phase-to-phase voltage (√3 times the phase-to-neutral voltage). The 10% tolerance on the nominal voltage can increase this to 1.91 times the nominal phase-to-neutral voltage. Fault-protection schemes used at the cogeneration site would be expected to sense the islanding condition and disconnect from the system in a matter of a few seconds. Ungrounded systems are much more likely to suffer TOV than a multiple grounded wye system.

An intermittent or loose neutral connection on a 120/240 V three-wire single-phase system on the line side of an SPD can put as much as 240 V across the SPD. This occurs primarily when there are unbalanced loads connected to the phase and neutral where the SPD is installed and the other phase has a load on it downstream from the loss of neutral. (See Figure 1.)

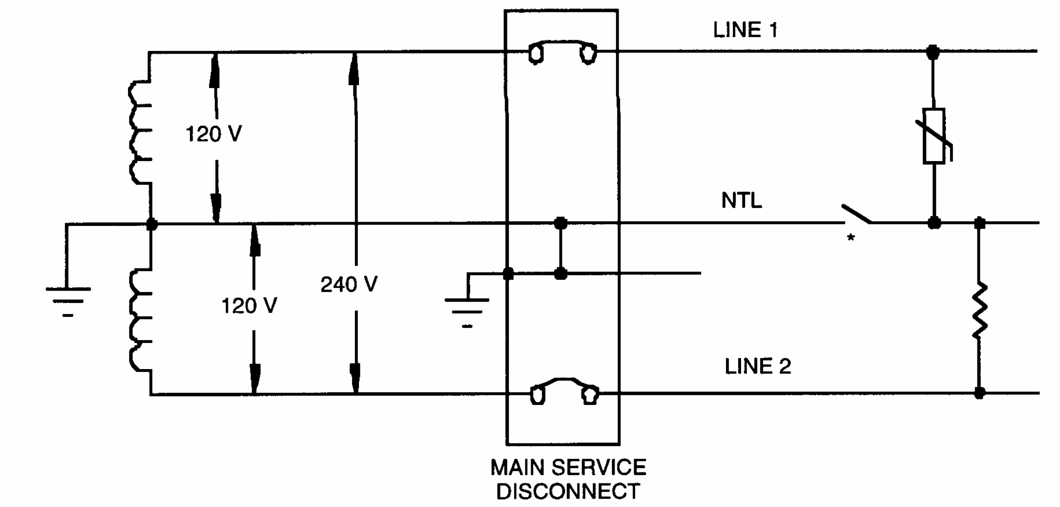

Figure 1—Example of loose connection causing overvoltage

TOV beyond the rating of the SPD will most likely damage or destroy the SPD. Alternatively, a device that is very tolerant of TOV might not protect the equipment from voltage surges due to high let-through voltages.

## 4.4 Notches

Notches in the ac voltage wave are frequently caused by the action of electronic switches, such as semiconductor controlled rectifiers (SCRs) or switch mode power supplies (nonlinear power supplies) that draw a heavy load current during a small portion of the sine wave. Notches might be noted in a heavy industrial environment that has loads controlled by SCRs. Notches might also be seen on the line side of some UPSs.

Notches have no effect on most SPDs, and SPDs have no significant effect on notches. However, if a filter circuit has been incorporated in the SPD, it could have an effect on the notch.

## 4.5 Sags

Sags (also called “dips” in the IEC vocabulary) result from normal load changes and various types of power system disturbances on the system. The most frequent cause of a severe sag is a fault on an adjacent feeder. For this type of sag, the duration is equal to the clearing time of devices such as fuses, circuit breakers, etc., involved in the faulted feeder—typically, a few cycles. Sags can be caused by a fault on distant feeders, faults within connected transmission networks, or by inrush current into a nearby load. Their duration is determined by the clearing time of the distant fault (a few cycles), or by the inrush characteristics of the nearby load (from a few to tens of cycles).

For most SPDs, sags will not involve a significant interaction—neither sags on SPDs nor SPDs on sags. There exist rare cases where some interactions might be involved. The operation of a voltage-switching SPD might act as a virtual short circuit and thus cause a sag in a connected or adjacent circuit.

## 4.6 Temporary undervoltages

Temporary undervoltages can be the result of power system faults that are of longer duration than those causing sags. These power system faults might include the case of a fault on one phase of a three-phase system in an area of high ground resistance, resulting in a relative long delay before the fault is isolated. Temporary undervoltages might also result from a temporary load on the power system that exceeds its capacity.

For most SPDs, temporary undervoltages will have no effect on the SPD, and the SPD will have no effect on the temporary undervoltage.

## 4.7 Harmonics

Harmonic distortion is the misshaping of the sinusoidal waveform resulting from the algebraic addition to the fundamental waveshape of higher frequency sine waves that are integer multiples of the fundamental frequency and known as harmonics. Typically, the slope of the resulting waveshape is steeper and the peak is flatter than the fundamental waveshape. In an ac distribution system, even harmonics are not present when the positive and negative half-cycles are symmetrical about the *x*-axis (i.e., they have the same shape and amplitude). Odd triplen harmonic currents (odd multiples of three, namely the 3rd, 9th, 15th, 21st, etc., harmonic) of a three-phase, four-wire power system, being zero sequence components, are additive in the neutral conductor. Abnormal levels of the odd triplen harmonic currents can cause overheating of the neutral conductor and other neutral components. Abnormal levels of harmonic currents, in general, can cause overheating of power sources (transformers, generators, etc.), nuisance tripping of protective devices, and failure of power factor correction capacitors. Abnormal levels of harmonic voltage can cause overheating of magnetic devices (motors, transformers, coils, etc.) and misoperation of sensitive electronic equipment, including those that rely on zero crossings for timing.

SPDs containing large capacitors might contribute to any or all of the above-cited problems. The allowable voltage *total harmonic distortion* (THD) typically cited by electronic and computer manufacturers is 5% or less. Voltage THD inherent in a utility feed to a facility normally ranges from less than 1% to 3%. THD in a facility in excess of 5% is not uncommon. Switch mode power supplies utilized in many computers are nonlinear loads (the current waveform does not conform to the waveform of the impressed voltage). Since current is drawn in short bursts of high amplitude, a high impedance in the power delivery system or series-connected SPD (see Figure 2) can result in current starvation and flattening of the top of the voltage sine wave. Harmonic current distortion up to 20% can occur and, in some situations, exceed 100%.

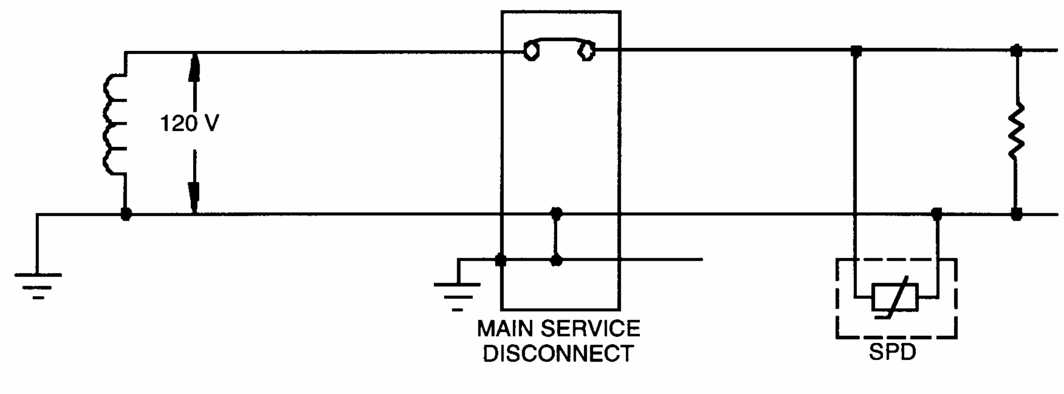

**Figure 2—Example of shunt-connected SPD**

Most SPDs will have no effect on harmonics. SPDs with inductive and capacitive components might be prone to failure caused by harmonics prevalent on the distribution system.

## 4.8 Noise

A variety of asynchronous interference in addition to the surges and other transients covered under 4.1 can appear on the ac mains. The most prevalent of these is random bursts of noise, with dominant frequency spectra ranging from 100 kHz to 10 MHz, caused by corona or partial discharge. The source is usually inside of equipment operating within a facility, but it can also lie outside the facility, in which case spectra will usually be limited to some hundreds of kilohertz.

Conducted *electromagnetic interference* (EMI) (or noise) is a high-frequency, low-current, low-energy waveform superimposed on the sine wave of the ac mains. The frequency of the conducted EMI can range from the low kilohertz into the megahertz region. This low-level interference is typically characterized by a voltage of less than 50 V and an associated current of less than 1 A. Noise is not a component-damaging anomaly, but can be very costly in the form of data errors, lost data, or down time.

Potential noise sources in electrical distribution systems include motors, transformers, capacitors, generators, lighting systems, power conditioning equipment, and SPDs. Harmonics produced from nonlinear loads on the distribution system (switch mode power supplies, SCRs in lighting systems, ac line regulators, voltage-switching surge protectors) can produce noise frequencies from the audio into the radio frequency range. Electrostatic discharge (ESD) induced onto the electrical distribution contains a great deal of high-frequency noise. Resonance to radio frequency interference (RFI) occurs when wire lengths match interfering signal wavelengths and are the strongest at multiples of one-quarter wavelength.

Interaction between voltage-switching surge protectors, employing a gas tube or SCR, and capacitors can result in high-frequency voltage oscillations on a distribution system. The voltage oscillation occurs when the notch created by the firing of the gas tube, or switching of the SCR, appears on the system as a high amplitude square wave pulse. This pulse causes the distribution system to ring at its natural frequency. The inverters in some uninterruptible and standby power supplies operate at frequencies of 20 kHz and above and can result in noise frequencies being reflected back onto the input distribution system from the UPS or standby power supply.

Properly applied shunt-connected SPDs will have negligible effects on noise. Series-connected SPDs are often designed to include series-connected inductors together with shunt-connected capacitors that are capable of reducing some noise.

### 4.9 Voltage magnification

A combination of high-voltage and low-voltage capacitors could result in high overvoltages on the low-voltage circuit when switching the high-voltage capacitor [B11]. Voltage magnification arises from a resonance condition between the two capacitor banks. The response of SPDs to voltage magnification is similar to that of swells and TOVs. If the magnitude and duration are high enough, the SPD could be damaged. In general the SPD would have no effect on the voltage magnification itself.

## 5. Interactions of power system disturbances on SPDs

### 5.1 Response to voltage surges

The response of SPDs to voltage surges depends, first of all, on their design, or more specifically, on the SPD components used. SPD components typically respond to overvoltages by changing from a high impedance state to a low impedance state. Voltage-switching (crowbar) devices change from a high impedance state to a low impedance state when the breakdown voltage is exceeded. The voltage across the voltage-switching SPD typically drops to a few tens of volts. Voltage-limiting (previously known as voltage clamping) devices attempt to maintain the voltage at a relatively low level above the conduction voltage. As the voltage across the voltage-limiting device increases, the impedance continues to decrease, permitting more surge current flow. In the process of responding to the surge voltage, the SPD diverts the surge currents to the grounded power conductor, or to a grounding conductor or another power conductor. The current conducted by the nonlinear SPD components increases very rapidly when a specified voltage is exceeded. Hence, the response of SPDs to surges consists of the following three key features:

- SPDs limit the peak voltage passed to downstream equipment by dropping some of the incident overvoltage across the impedance of the power-frequency mains.
- SPDs divert the surge current.
- Part of the energy of the surge is converted into heat in the nonlinear element.

An example of a typical shunt-connected SPD with the nonlinear element connected across the power line is shown in Figure 3. Some SPDs contain components connected in series with the input and output terminals of the SPD as well as the nonlinear element connected across the power line as shown in Figure 2. The series element also acts as a coordination element within the SPD. Internal linear elements—typically, inductances—impede the flow of surge current while nonlinear elements divert it. Hence, series-connected SPDs limit the peak voltage passed to downstream equipment by dropping some of the incident overvoltage inside the SPD and dropping some of it outside of the SPD across the impedance of the ac mains.

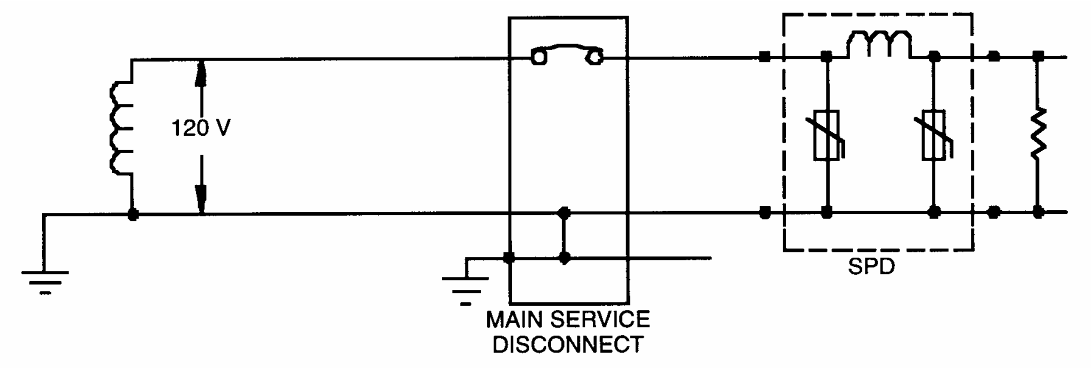

**Figure 3—Example of series-connected SPD**

The basic surge response voltage characteristic of SPDs depends on the type of nonlinear component used, which can be of a voltage-limiting or voltage-switching type, or a combination of the two types. For voltage-limiting devices, the surge response voltage tends to be lowest at low current and to increase somewhat at higher currents. For voltage-switching devices, the current conducted tends to switch abruptly from very low to very high values when a device turns on, and the voltage across the SPD can drop when current flows.

Voltage-switching components are sometimes used in series with voltage-limiting components. Voltage-switching components are also used in parallel with voltage-limiting components. SPDs using voltage-switching and voltage-limiting components in series or in parallel are called combination-type SPDs. For combination-type SPDs the surge response can be a combination of the voltage-switching and voltage-limiting action.

The response of SPDs to surges, including the surge response voltage, can also depend on the characteristic of the surge itself. The surge response voltage can be a function of the peak voltage and current amplitude, the rate of rise of current, and the rate of rise of voltage. Additionally, the functional characteristic of SPDs can be affected by parasitic inductance in the leads connecting the SPD to the ac mains. Response time is sometimes thought to be an important consideration in the performance of an SPD. In actuality, the response time of voltage-limiting SPD components are similar and within the nanosecond range. However, voltage-switching devices have a volt time characteristic that has the effect of introducing a response time delay that depends on the surge voltage rate of rise. In this time frame, lead length has a greater effect on the response of the device than does any sub-nanosecond component response time. Spark gaps, which are voltage-switching devices, require a finite time to turn on. Therefore, their let-through voltage at higher voltage rate of rise is higher than that at a lower voltage rate of rise.

When SPDs divert surge current, some of the energy of the surge is dissipated not only in the SPD, which can include its linear and nonlinear components, but also in the impedance of the ac mains and their loads.

SPDs can reflect surge energy back toward the source. Voltage-switching devices, which breakover to a low voltage, reflect more surge energy than voltage-limiting devices. On the other hand, when voltage-switching and combination-type SPDs divert surge current, they can also continue to conduct follow current from the ac mains for a half-cycle or more, depending on the current interrupting capability of the voltage-switching SPD component. This can affect the mains voltage and the connected equipment. SPDs that contain a voltage-switching and a voltage-limiting SPD device in series do not conduct follow current if the voltage-limiting SPD is limiting to a higher value than the mains voltage.

Voltage side effects can be created as SPDs divert surge currents. See 6.3 for a discussion of these effects.

The effects of surges on SPDs partially depend on the type of components used in the SPD. Components might have limitations as to the number of surges of a certain amplitude and waveform that they can survive. On some SPDs the voltage at a particular current increases with repetitive surges, on some it decreases, and some show very little change. Some SPD components might exhibit a trend toward failure while others remain well within specification until they fail.

## 5.2 Response to swells

The response of an SPD to a swell is dependent on the amplitude and duration of the swell and on the protective characteristics of the device. If the peak of the voltage during the swell does not exceed the level where the SPD starts to conduct current, the SPD will have no effect on the swell. If the voltage of the swell is high enough to cause the SPD to start conducting current, the SPD will try to suppress the swell. In the case of a voltage-limiting-type SPD, the effect on the SPD can be minimal because the SPD can still be operating in the high resistance region. In the case of a voltage-switching-type SPD, the swell can be reduced significantly during each half-cycle, if the sparkover voltage or limiting voltage of the SPD is exceeded.

If the amplitude and duration of the swell is such that the energy-handling capability of the SPD components is exceeded, the SPD can be damaged or destroyed. Swells generally cause more SPD failures than lightning or other surges.

During a swell, an SPD can change into a low impedance state and conduct significant current. Although during the swell this can be beneficial, it is generally damaging to the SPD that lacks the heat dissipation needed. If the SPD has been damaged during the swell, it can remain in this low impedance state. That would lead to high current draw by the SPD and associated sags on the rest of the system. These sags can result in disruption of equipment on the local power system. Not all swells will cause this possible damage, however, it would be more common as the swell voltage increases or the duration increases or both.

## 5.3 Response to TOVs

The response of SPDs to TOV is similar to that of voltage swells. Where swells are defined to last from more than one cycle to less than a few seconds, TOVs can last from less than a few seconds to several hours. If the TOV exceeds the turn-on voltage of the SPD, the SPD will suppress the overvoltage within its associated design parameters. The TOV, being of a longer duration than a voltage swell, can have a more destructive effect on the SPD than most surges or swells.

SPDs can be designed with TOV protection incorporated, which will protect an SPD from the damage that can result from a TOV or swell condition. However, there are still limits to this TOV protection and damage can still occur if their voltage or time ratings are exceeded.

## 5.4 Response to notches

SPDs employing only nonlinear elements will be unresponsive to notches in the ac voltage waveshape. SPDs employing capacitors might have some effect on the notches, depending on the size of the capacitor, the kilovolt ampere rating of the power system, and the degree of notching. In general, an SPD cannot be relied on to fill notches in a power system.

## 5.5 Response to sags

Shunt-connected SPDs will be unresponsive to undervoltage conditions if they contain only nonlinear components. More complex series-connected SPDs can employ both shunt and series linear components. An example in which the SPD can be affected could occur when a series-connected SPD is used to protect a constant power load. In this case, when the voltage is reduced, the current will be increased. This could result in a load current through the SPD that exceeds its current rating.

## 5.6 Response to temporary undervoltages

The response of SPDs to temporary undervoltages is the same as their response to sags, discussed in 5.5. Due to the longer duration, a temporary undervoltage can cause significantly more heating of a series component in a series-connected SPD than a sag. Appropriate overcurrent protection is required to prevent damage to the SPD.

## 5.7 Response to harmonics

It is mostly the harmonic current that causes problems in installations. Shunt-connected SPDs not containing capacitors do not react to harmonic currents. These devices will react to harmonic voltages in the same manner that they react to any voltage. If the amplitude of the harmonic voltage exceeds the threshold voltage of the device, the device will go into conduction and try to reduce the voltage level. Currents in some SPDs can increase with the presence of harmonic voltages. The increased current might shorten the life of the SPD. SPDs with capacitors, under some conditions, might react to the harmonics in a manner that could damage the capacitors. The flattening of the ac sine wave might reduce possible stress on some SPDs.

Capacitor failure can result from high harmonic content in the electrical distribution system. The impedance $X_c = 1/(2\pi fC)$ of a capacitor decreases as the frequency of the applied voltage increases. At high frequencies, the impedance of capacitors added in an SPD for filtering can be so low as to constitute a virtual short circuit. If the current available at these frequencies is high enough, capacitor failure or failure of a nonlinear load can occur. Unusually high currents can develop if harmonics establish a parallel resonant condition in the capacitor circuit. The resonant circuit amplifies the harmonic current resulting in an OCPD operation or nonlinear load failure. Harmonic current flowing through the system will have no effect on a shunt-connected SPD. However, these currents flowing through a series-connected SPD can contribute additional heating that might be damaging to the SPD.

## 5.8 Response to noise

The response of an SPD to noise will depend on the design of the SPD and the amplitude and frequency of the noise pulses. An SPD employing only nonlinear elements will show little response to noise whose amplitude does not exceed the switching or limiting voltage of the device. SPDs employing MOVs and/or SADs might demonstrate some attenuation of the noise pulses because of their capacitance. This incidental noise attenuation might be less effective on shunt-connected SPDs because of the inductance of the connecting leads. Noise might have an adverse effect on the monitoring section of an SPD resulting in false indication.

## 5.9 Response to voltage magnification

The use of shunt capacitors in low-voltage circuits, when switching high-voltage shunt capacitors, can lead to failures in the low-voltage circuits. Studies of this problem have shown that voltages occurring in 480 V circuits have exceeded five times the nominal voltage. The energy content of these waves has caused failures of SPDs used for overvoltage protection of low-voltage control circuits.

The problem is basically caused by resonance phenomena between electrically coupled circuits. The frequency and magnitude of the resonance depends on the complex impedance of the various circuits involved. In most cases, it can be simplified by only reviewing the largest nearby capacitor banks involved on the high and low-voltage networks. Otherwise, a computer simulation would be necessary to more accurately understand the interactions of the system.

The solution or avoidance of the problem can therefore be a joint effort of the electric utility and the customer, both of whom can have shunt capacitor banks that are located electrically close. The user should always be judicious in the choice of shunt capacitors in low-voltage circuits, and the utility should want to investigate how their capacitors can be switched.

# 6. Interactions of SPDs on power system disturbances

## 6.1 Benefits for downstream and upstream loads

The purpose of SPDs is to limit surge voltages by diverting surge currents and dissipating surge energy in the form of heat. The greatest benefits will be for loads downstream of the SPD if the surge entered the systems upstream of the SPD. There can be some benefit to upstream loads, depending on the proximity of the load to the SPD and the impedance presented to the surge by the wiring between the load and the SPD.

An SPD at the service entrance can reduce the incoming lightning and switching surges to tolerable voltages and energies if an adequate device is selected and is properly installed. Proper installation includes a low impedance connection of the SPD. These voltages can again increase in amplitude as the surge remnant travels through the wiring system, if there is no additional SPD close to the load. This can occur due to a surge being reflected at an effectively open termination, and if the travel time is longer than the rise time. For this reason, additional SPDs are recommended to be installed downstream from the main SPD at the service entrance. These devices should be placed as close as possible to the sensitive loads.

The interaction between two or more SPDs on the same power system is an important consideration. The planned interaction between SPDs is sometimes termed cascade coordination. Two or more SPDs can be required to protect some equipment because the equipment might be installed too far from the service entrance for the service entrance SPD to protect it against internally generated surges. The length of the leads required to connect an SPD to a large service cabinet might result in the surge response voltage being greater than can be tolerated by the equipment to be protected, thus requiring another SPD at the equipment. The SPD at the service entrance should be capable of handling lightning surges, but the second SPD at the equipment needs to handle only the surge response voltage of the first SPD and part of any surges introduced into the system between the two SPDs.

Cascaded SPDs are capable of having undesirable interactions if they are not properly coordinated. The downstream SPD might be subjected to more energy than it was designed for if its operating voltage is not coordinated with the surge response voltage of the upstream SPD. This applies also to the coordination between the SPD at the service entrance and at the utility transformer.

## 6.2 Partial loss of power with voltage-switching devices

Side effects of the use of SPDs can result both from the type of devices used and from the method of installation of such devices. A voltage-switching device, such as an air gap or a gas tube, can reflect surges back toward the source because of the rapid change in voltage from the firing voltage of the device, which is hundreds of volts, to the arc voltage, which is typically tens of volts. The voltage across the voltage-switching device will remain at the low arc voltage until the device clears (which is typically near the next zero crossing of the ac line current). This low voltage across the voltage-switching component can produce a reduction of the mains voltage for a significant portion of the half-cycle, to a level where relays can drop out and some loads can suffer from a power interruption.

## 6.3 Surge current introduction into a facility

Side effects from the installation of SPDs include high surge currents introduced into facility wiring if SPDs are installed at or within loads but not at the service entrance. This situation is a common occurrence because their manufacturers equip many types of electronic devices with voltage-limiting SPDs (such as

MOVs). These devices include TVs, VCRs, microwave ovens, washers, dryers, etc. Many users of personal computers also purchase plug-in or cord-connected SPDs.

In the case where an SPD is installed at the service entrance and also at (or within) the load equipment, undesirable side effects can still occur. The SPD at the load can have a lower surge response voltage than the SPD at the service entrance. This situation can occur because some voltage-limiting SPDs used in equipment or plug-in protectors are selected on the basis of their low limiting voltage (such as 130 V ac rated MOVs for 120 V mains). The SPD at the service entrance might use voltage-limiting SPDs rated for 175 V ac (secondary arrester rating) or even higher for 120 V mains. Many other SPDs installed at the service entrance use 150 V ac rated voltage-limiting SPDs. This combination of a higher voltage SPD followed by a lower voltage SPD can result in a significant amount of surge current flowing toward the lower voltage SPD at the equipment. This surge current in the building wiring can induce undesirable or harmful voltages in nearby communications or signal wiring. On the other hand, this scenario depends upon the impedance of both devices and the interconnecting wiring at the current in question. For example, a device with more or larger suppression components at the service entrance, even with a higher conduction voltage, can actually present a lower impedance at significant currents than a smaller downstream device with a lower conduction voltage.

Wires connecting the SPD will increase the voltage response due to the high-frequency impedance of the conductor. This impedance is dependant on the type of wire used, the wiring methods, and the length of the wires. This causes a concern if the only SPD in a facility is located downstream of the equipment bonding conductor as all the building wiring to this point becomes effectively the SPD connecting wires. The presence of an SPD between phase or neutral and the equipment grounding conductor at the protected equipment could result in a significant instantaneous voltage on the frame of the protected equipment with respect to other surrounding equipment. The surge current appearing in the equipment grounding conductor of the protected equipment causes a transient voltage ($e = -L\, di/dt$) across the equipment grounding conductor and the frame of the protected equipment during current discharge of the SPD. The issue comes out of the difference in voltage between grounds. This will be lessened if there are multiple SPDs throughout the facility due to current splitting and similar ground voltages during the surge. Further, an SPD at the service entrance will eliminate this issue as the grounding of the facility is all referenced here.

## 6.4 Voltage oscillations caused by SPDs

Studies have shown that voltage oscillations occur downstream from an operating SPD. The amplitude of this oscillation depends on the circuit parameters as well as on the incoming surge voltage and waveshape. In special cases, the maximum voltage can be more than twice the surge response voltage. This ringing transient will be at low current and is due to the voltage reflection as described in 6.1.

## 6.5 Effects of inductance between SPDs

The inductance between cascaded SPDs might have different effects on the surge response voltage at the location where the SPDs are connected to the mains. For example, during the front of the surge, while the current is rising, the first SPD will see the voltage of the second SPD plus the voltage across the inductance. During the tail of the surge, the first SPD will also see the voltage across the second SPD and across the inductance, but since the voltage across the inductance is now negative, the voltage across the first SPD will now be less than the voltage across the second SPD. Thus, the second SPD is influencing the voltage across the first SPD. The second SPD can therefore be subjected to much more energy than was intended.

## 6.6 SPD failure-mode effects on power systems

An SPD can fail as an open circuit, a high impedance condition, or a low impedance short circuit condition. These failures can result from excessive or repetitive surge voltages or currents, from prolonged TOVs, or from random component failures. These failures can cause both surge voltages and undervoltages on power systems as well as short circuit faults, follow current, and loss of power to part or all of the power system.

An open circuit failure (for shunt-connected devices only) causes no effect on the power system other than an immediate loss of surge protection from that component. With proper overcurrent protection, an SPD that fails as a short circuit will result in an open circuit condition once the overcurrent device has operated and cleared the short circuit. However, considerable line disturbances can be caused until the failed SPD is disconnected from the power system.

A high impedance short circuit failure might draw a few amperes and therefore might persist unnoticed for some time. The current will cause localized heating and can damage nearby components. Depending on the damage, this condition can remain for an extended period or can change into a different type of failure.

**WARNING**

This high impedance condition can produce potential smoke or fire hazards unless appropriate overcurrent devices or thermal disconnects are employed.

A low impedance short circuit failure might resemble any other short circuit or fault on the power system. A voltage sag occurs until the overcurrent device clears the short circuit. A voltage surge can occur following fault clearing.

Substantial follow current can occur in gap-type SPDs. The ability of a spark gap to extinguish power system follow current is dependent on both the system voltage and the available fault current at the point of application. Spark gaps designed for use on ac power systems have specific ratings for both maximum nominal system voltage and maximum available fault current, and may not extinguish above these ratings. The time that the spark gap conducts follow current varies substantially between designs. Although some spark gaps are designed to actively extinguish within the first half-cycle, many spark gaps do not extinguish the flow of power system current until a zero crossing of the current is reached. In some cases, the current can continue to flow for one or more additional cycles, until either the spark gap interrupts or an overcurrent device opens the circuit. The flow of power follow current can result in reduced system voltage that, for some spark gaps, is low enough to cause relays to drop out or interruption of operation of other loads connected to the circuit.

A loss of power occurs to loads downstream if a failed SPD causes the OCPD to open. A current-limiting OCPD built into the SPD can prevent loss of power to the protected system.

**WARNING**

In the absence of proper upstream overcurrent protection, the SPD must be capable of withstanding or interrupting the available fault current, or a violent rupture can occur within the SPD.

Issues can exist with components connected neutral to ground. Normally the voltage associated with this mode is low, and the energy content is insufficient to damage components connected neutral to ground. Under unusual conditions, it is possible to damage these components. Due to the low energy associated with this mode, OCPDs on this mode might not open and thus allow an undesired low impedance connection between neutral and ground.

## 6.7 Effects of SPD peripheral components on power systems

Power systems are sometimes used for purposes other than just delivering power. A power system can be used incidentally for transmitting signals or data within a facility. This transmission is done by adding a high-frequency signal on the mains. This use of high-frequency signals is possible only if there are no devices with significant shunt capacitance or series inductance connected to the mains. Some SPDs contain capacitors for attenuation of noise. The value of this added capacitance, which could be large, might not be stated in the specifications for the SPD, so that the possible interference of such a capacitor with signal transmission would not be recognized until it occurs.

## 6.8 Effect of added filter on neutral-ground voltage

When series filtering elements are added to the design of an SPD, steady-state voltage drops can occur across affected phase and neutral conductors, dependent upon the amplitude of the associated current. In the case of the neutral conductor, a significant neutral-to-ground voltage can be created by the SPD that can exceed requirements for maximum phase-to-neutral voltage drop or a protected equipment manufacturer’s maximum neutral-to-ground voltage specifications. Any additional measured neutral-to-ground voltage will be the result of impedance in the neutral conductor and added impedance in the SPD at the power line frequency.

# Annex A

(informative)

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# Annex B

(informative)

# Description of environment

## B.1 The steady-state environment

Utility systems are designed to provide a stable supply of electric power. The steady-state voltage is typically maintained within specified limits. The steady-state service voltage limits for the United States, for instance, are described in ANSI C84.1-1989 and have a tolerance, under certain conditions, of +10%. This means that the steady-state voltage of the nominal 120 V ac system, for instance, could be as high as 132 V rms.

### B.1.1 Power system impedance

Maximum power system impedance at the utilization level can be estimated on the basis that at 80% of rating, which is the maximum recommended by the National Electrical Code® (NEC®) (NFPA 70), the maximum voltage drop allowed by the NEC is 3% for a feeder and 3% for a branch circuit, but the total drop cannot exceed 5%, of the utilization voltage. For a 120 V phase, for example, a 20 A circuit should therefore lose no more than 6 V at 16 A. This implies a single source impedance at line frequency of 6 V/16 A or about 0.38 Ω. For short branch circuits, the figure can be as low as 20% of this figure, or 0.07 Ω.

The minimum phase inductance likely to exist in any typical facility is 50 µH, while for long branch circuits the figure can reach several hundred microhenries. A reasonable upper limit of 200 µH corresponds with an inductive impedance of 75 mΩ at 60 Hz, which corresponds fairly well with the 0.1 Ω calculated from a 2 V drop in a 120 V circuit at 16 A.

### B.1.2 Available rms fault current

For within-building locations, close to a service entrance that happens to be supplied from a nearby transformer rated at 300 kVA or greater, rms fault currents even at the 120 V utilization level can range as high as 26 kA.

For more usual situations, typical within-building rms fault currents at the 120 V utilization level range from 200 A to over 1 kA. Fault currents at higher voltage utilization levels (with corresponding higher kilovolt ampere ratings) are proportionately higher.

### B.1.3 Available peak inrush current

Available peak inrush current is the peak value of the available rms fault current. However, since it is typically measured by simulating an electronic load drawing power from the mains, its actual measured value can be lower. While this is not a characteristic of the mains, it is a characteristic of measurements made on the mains, in context with the applications of mains power to electronic equipment.

Available peak inrush current is measured by monitoring the peak current that flows into a fully discharged, high-value electrolytic capacitor, which is connected to the power mains via a full-wave rectifier bridge, at the peak of the voltage wave. Thus, the measurement can include the effect of the impedance of the electronics, including the equivalent series resistance of the capacitor, which can range from 50 mΩ to 150 mΩ. As a result, the measured value of the available peak inrush current can be lower than the peak of the available rms fault current, by an amount typically ranging from 20% to 50% for long branch circuits, and by even greater amounts for short branch circuits.

## B.2 Sources of power system disturbances

Many disturbances are generated at the user's facility by equipment; others result from an event on the utility system, such as lightning and equipment switching; others can be generated by other user-owned equipment on adjacent circuits (neighbor's circuits).

### B.2.1 Lightning

Lightning-related surges in the low-voltage distribution system can be introduced as follows in several different ways, either separately or in combination:

- Direct strokes to the low-voltage lines serving the building
- Direct strokes to the high-voltage lines serving the step down transformers and magnetically induced in the secondary winding
- Direct strokes to the high-voltage lines and capacitively coupled to unshielded secondary windings of the power transformer
- Surges that cause the arrester on the transformer primary to operate placing a surge on the ground and neutral wire that is common with the low-voltage secondary
- Strokes to the earth near the transformer that create common mode voltages in the secondaries
- Strokes near the service entrance creating common mode surges
- Strokes to the building housing the equipment creating common mode surges in the chassis ground with respect to the power supply

In addition to the surges (transients of less than half a —cycle) listed above, lightning can be the cause of power-frequency (60 Hz) overvoltages and undervoltages. When lightning causes a flashover on one phase of a three-phase line, the voltage at the flashover location and beyond (away from the source) is essentially zero, but toward the source the voltage increases as a function of the circuit impedance and the fault current. The 60 Hz voltage on the other two phases is highest at the flashover and beyond (the magnitude depending upon zero sequence impedance of the circuit) but approaches normal as one progresses toward the substation. These abnormal 60 Hz voltages exist until the flashover clears. Whether a sag or swell occurs at the affected location depends upon which of the three phases the service is connected to. The magnitude of the sag or swell is determined by the location of the flashover relative to the service transformer, and the duration of the sag or swell is a function of clearing time of the fault. Generally, flashovers require an OCPD to clear the fault and deionize the air, which results in a total loss of voltage until the OCPD resets. Many OCPDs automatically reset and restore power. Other types cannot be reset or faults on automatic resets may leave the line completely shut down.

### B.2.2 Faults (short circuits)

Faults on the utility system are classified as either temporary or permanent. The normal utility overcurrent protective practice is based on the assumption that most faults (on overhead systems) are temporary or can be selectively isolated in order to restore the remainder of the system.

A temporary fault can be due to a flashover from a lightning stroke, an animal contact, wind, etc. When a fault occurs, the line must be de-energized to stop the flow of fault current and to allow enough time to deionize the faulted path. To do this, an OCPD opens to clear the fault, and then automatically recloses after some time delay. This reclosing can occur several times in an effort to reestablish continuity of service following a temporary fault.

The opening and reclosing times of an OCPD is usually short enough that the operation of most lighting and motor-operated equipment will not be seriously affected. A computer or other sensitive load, however, can experience a total system shutdown unless preventive steps are taken, such as the application of a UPS, to maintain service to the load and allow for orderly shutdown. Temporary faults can be a serious problem for some industrial motor-operated equipment.

Permanent faults can be due to equipment failure, accidents with vehicles, a tree limb falling onto the line, etc. They result in service interruptions, which last from minutes to hours. Upon occurrence of a permanent fault condition, the OCPD is usually programmed to operate three or four times in an attempt to reestablish power before it locks open. The fault must then be located and repaired before service is restored to all customers.

Most conductor-related faults on overhead distribution lines are of a temporary nature. By contrast, most faults on underground systems are permanent and take much longer to locate and repair.

### B.2.3 Switching

Most switching operations, both by the utility and the user, result in transient disturbances. These operations include fault clearing, load transfer, fault closing, etc. For example, rapid clearing and current chopping produce voltage spikes generated by energy stored in inductive loads.

Although most users of sensitive equipment are aware that their equipment can be subjected to surges, many are not aware of the magnitude or source of the transients or the specific sensitivities of their equipment. Transients from within the customer's premises occur with load switching or fault clearing. The transient voltage results from the rapid rate of change of current through the inductance of the wiring. The magnitudes of these transients can be quite high.

Information from actual recorded data indicate that internally generated surges (impulses) caused by load switching are likely to be repetitive and can generally be associated with a specific device piece or equipment. Surges can be repeated several times a day.

### B.2.4 Capacitor switching

In addition to voltage regulators and load tap-changers, most utilities and many industrial commercial users employ shunt capacitor banks to help control the power factor or voltage profile by supplying reactive power to inductive loads, such as motors. Placed strategically on the circuit, shunt capacitors also reduce the losses associated with the primary circuit while improving the power factor.

To accommodate widely varying load conditions, most capacitor banks are switched automatically. When a capacitor bank is energized, it can produce peak transient overvoltages of about two times normal at frequencies within the range of 300 Hz to 600 Hz and which are usually attenuated within one cycle of the power frequency. Certain sensitive loads cannot be able to tolerate the normal switching transients associated with routine capacitor switching. A common problem is that the dc capacitor (which has a low impedance at high frequency) within a variable frequency drive (VFD) responds to the capacitor switch event (which is high frequency) and draws more than normal current. The VFD’s electronics records this higher current and shuts the VFD down to prevent damage.

### B.2.5 Motor starting

The starting of large motors is accompanied by a voltage sag resulting from the inrush current flowing through the system impedances. The maximum voltage sag occurs at the motor terminals and can have a noticeable or even objectionable effect on other customers in the area or on nearby loads sensitive to sags.

### B.2.6 Partial discharge

Partial discharge occurs inside insulation. Partial discharge and corona can cause noise on the ac mains.

# Annex C

(informative)

# Glossary

**combination-type SPD:** An SPD that incorporates both voltage-switching-type components and voltage-limiting-type components that can exhibit voltage switching, voltage limiting, or both voltage-switching and voltage-limiting behavior, depending upon the characteristics of the applied voltage.

**commercial power:** Electrical power furnished by the electric power utility company.

**harmonic:** A sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency.

**harmonic distortion:** The mathematical representation of the distortion of the pure sine waveform.

**mains:** 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.

**noise:** Unwanted electrical signals that produce undesirable effects in the circuits of the control systems in which they occur. (For this guide, control system is intended to include sensitive electronic equipment in total or in part.)

**nominal voltage:** A nominal value assigned to a circuit or system for the purpose of conveniently designating its voltage class (as 120/240 V, 480Y/277, 600, etc.).

**notch:** A switching (or other) disturbance of the normal power voltage waveform, lasting less than a half-cycle, which is initially of opposite polarity than the waveform, and is thus subtractive from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to a half-cycle.

**overvoltage:** An rms increase in the ac voltage, at the power frequency, for durations greater than a few seconds.

**power disturbance:** Any deviation from the nominal value (or from some selected thresholds based on load tolerance) of the input ac power characteristics.

**sag:** An rms reduction in the ac voltage, at the power frequency, for durations from a half-cycle to a few seconds.

**surge:** A transient wave of voltage or current. The duration of the surge is not tightly specified but is usually less than a few milliseconds.

**surge-protective device (SPD):** An assembly of one or more components intended to limit or divert surges. The device contains at least one nonlinear component.

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

**swell:** A momentary increase in the power-frequency voltage delivered by the mains, outside of the normal tolerance, with a duration of more than one cycle and less than a few seconds.

**voltage-limiting-type SPD:** An SPD that has a high impedance when no surge is present but reduces it continuously with increased surge current and voltage. Common examples of components used as nonlinear devices are MOVs and suppressor diodes.

**voltage-switching-type SPD:** An SPD that has a high impedance when no surge is present, but can have a sudden change in impedance to a low value in response to a voltage surge. Common examples of components used as nonlinear devices are spark gaps, gas tube thyristors, and silicon-controlled rectifiers. These SPDs are sometimes called “crowbar-type” SPDs.