C62.72™

IEEE Guide for the Application of Surge-Protective Devices for Low-Voltage (1000 V or Less) AC Power Circuits

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IEEE Power Engineering Society

Sponsored by the
Surge Protective Devices Committee

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Abstract: Information is provided to specifiers and users of surge-protective devices (SPDs) about the application considerations of SPDs associated with power distribution systems within North America. This guide applies to SPDs to be connected to the load side of the service entrance main over current protective device of 50 Hz or 60 Hz ac power circuits rated at 100 V to 1000 V rms. The effects and side effects on the presence and operation of SPDs in low-voltage power distribution systems are described. The coordination of multiple SPDs on the same circuit is described.

Keywords: lightning protection, surge protection coordination, surge-protective device

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Introduction

This introduction is not part of IEEE Std C62.72-2007, IEEE Guide for the Application of Surge-Protective Devices for Low-Voltage (1000 V or Less) AC Power Circuits.

One purpose of this guide is to provide specifiers and users 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 and users 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.

The growth of interest in low-voltage 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. Specifiers and users of SPDs might be under the impression, or might be led to believe the misconception, that by installing one or more SPDs in their respective facility or within specific equipment, there will be total immunity to any and all power system disturbances. Actually, unanticipated and unexpected events can occur, which makes absolute immunity to the events of surges an unreasonable and unrealistic goal. In addition, there are numerous misconceptions that SPDs are so generic in application and construction that the method employed in their installation and their respective locations within a power distribution system are not variables in their functionality. In reality, SPDs will respond to and have an effect on some power system disturbances but not on others. The functionality of any SPD is also directly related to the specific location where it is connected to a low-voltage power distribution system and the methods used to make the required electrical connections to ac power circuits. The effects that SPDs will have on power system disturbances are often less than desired. SPDs installed at various locations in the low-voltage power distribution system, as well as in specific equipment, can interact with each other, with protective relaying systems, and with other components of the power distribution system. In those scenarios, the effect of a given SPD is often imprecise and can be unpredictable. 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 member of the IEEE C62™ family 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.

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

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IEEE Guide for the Application of Surge-Protective Devices for Low-Voltage (1000 V or Less) AC Power Circuits

1. Overview

1.1 Scope

The transient overvoltages or surge events that are described and discussed in this guide are those that originate outside of a building or facility and impinge on a power distribution system (PDS) through the service entrance conductors. Transient overvoltages or surge events that originate from equipment within a specific facility are not within the scope of this document.

This guide applies to surge-protective devices (SPDs) that are manufactured for connections to 50 Hz or 60 Hz ac power circuits that are rated between 100 V rms and 1000 V rms. This guide applies to SPDs that are specifically identified, labeled, or listed for connections on the load side of the service entrance main overcurrent protective device. This guide does not cover those SPDs identified, labeled, or tested as a secondary surge arrester intended for connections on the line side of the service entrance main overcurrent protective device.

The SPDs covered in this guide are those manufactured for use in an association with electrical power distribution equipment such as load centers, motor control centers, panelboards, switchboards, switchgear, and end-use equipment installed in commercial and industrial facilities. This guide excludes SPDs associated with retail and consumer appliances and components for residential use.

This guide does not specify or set limits on insulation levels of any components associated with power distribution systems or end-use equipment. In addition, it is not the intent of this guide to address individual SPD component specifications associated with any specific manufacturer of surge protection products.

The SPDs discussed in this guide contain at least one nonlinear component for either diverting surge currents and/or dissipating surge energy. Examples of such nonlinear components are metal-oxide varistors (MOVs), silicon avalanche diodes (SADs), spark gap tubes, or thyristors. Ferroresonators, motor-generators, uninterruptible power supplies, and filters containing only inductive or capacitive components are not considered SPDs in the guide.

1.2 Purpose

The primary purpose of an SPD is to provide a desirable level of surge protection by diverting surge currents and by reducing surge voltages to a level that can be tolerated by the PDS and the equipment connected to the system. When specifying and installing any SPD in low-voltage power distribution equipment associated with commercial and industrial installations, numerous application considerations should be reviewed and evaluated before installation. Failure to consider the applications or misapplications of any SPD can directly influence the expected performance of the SPD and can result in undesirable effects on a PDS and/or end-use equipment. It is the intent of this guide to inform specifiers and users of SPDs, such as specifying engineers, electrical inspectors, facilities engineers, or authorities having jurisdiction*,* of application and installation considerations for the purpose of desirable and satisfactory application of SPDs.

2. Normative references

The following referenced documents are indispensable for the application of this standard. 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 C62.41.1™-2002, IEEE Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits.[1, 2]

IEEE Std C62.41.2™-2002, IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits.

3. Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B20][3] should be referenced for terms not defined in this clause.

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

3.2 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 entrance equipment. Also identified as the service entrance main.

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

3.3 service entrance 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 facility, or other structure, or an otherwise designated area, and intended to constitute the main control and cutoff of the electrical service supply.

3.4 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.

4. Beginning the surge-protective device selection

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 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 from outside a facility, originate primarily from two sources. These sources are lightning and switching.

a) *Lightning surges*. Lightning surges are the result of a direct flash to the power system, to the structure of interest and nearby structures, or to the soil. Distant lightning flashes can also induce voltage surges in the circuits of an installation.
b) *Switching surges*. Switching surges are the result of intentional actions on the power system, such as load or capacitor switching. They can also be the result of unintentional events, such as power system faults and the subsequent corrective actions.

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 of interest, but other coupling mechanisms into overhead or buried power circuits can also produce overvoltages and associated surge currents. 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 and magnetic fields penetrating the structure and coupling inductively in the building 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 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 various power system electrical equipment (capacitors, breakers, reclosers, etc.) located throughout a PDS. These operations can occur as a result of normal and abnormal operations or conditions.

5.2.1 Normal operations

Normal operations are those such as switching electric loads ON and OFF, periodic transients caused by power converter switching devices, multiple reignitions or restrikes of power switches when they are opening or closing, and the energization of power factor correction capacitors.

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 may occur.

5.2.2 Abnormal operations

Abnormal operations include the opening and reclosing of circuit protective devices during fault conditions and major power system switching. Another abnormal operation would include capacitor bank switches inadvertently restriking. Abnormal operations can result in transient overvoltages of sufficient magnitude to cause equipment malfunctions and may cause SPD operation.

6. Effects of surges

The effects of a surge on power distribution systems 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 performance 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.

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

Acceptable temporary loss of function but no faulty operation of equipment or processes.

6.2.2 Major

Temporary faulty operation or performance that might be self-recoverable through automatic self-test and restart programming.

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. Ignition of a fire or an explosion could occur. In these cases, facilities operations and equipment functions are dramatically 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 associated with the PDS.

Where an individual evaluation is not possible, such as in 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 [B19]. The effects of increased numbers of SPDs installed within the PDS will also directly effect the distribution of a surge. The repetitive operation of numerous SPDs within a PDS 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 sparkover event. Changes in the environment are a function of one or more combinations of events.

Factors that can contribute to flashover or sparkover events are as follows:

a) Indoor versus outdoor equipment ratings.
b) Air temperatures exceeding the range of equipment.
c) Air temperatures caused by a temporary external heat source near the SPD.
d) Exposure of energized parts to damaging fumes or vapors.
e) Excessive dirt or other contaminates within the electrical equipment and around the SPD.
f) Exposure of energized equipment to salt spray or other current conductive deposits.
g) Exposure of energized equipment to moisture, steam, or water.
h) Exposure of energized equipment to explosive atmospheres.
i) Exposure of energized equipment to abnormal vibrations or shocks.
j) Insufficient clearances between energized parts and nearby conductive objects.
k) 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

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:

a) Loss of neutral ground on normally grounded circuit.
b) Abnormal speed regulation on a station service generator.
c) Resonance conditions during faults.

d) System voltage instability.

e) 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. Data indicate 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 C62.41.1-2002[4] 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 [B35], Lewis and Foust [B38], and Transient Voltage Suppression [B55]). 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 a usually a multiple stroke event, and the subsequent strokes often have less energy than the initial stroke.

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. During a thunderstorm, the separation of charges can occur within a cloud. 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 [B57]). 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 [B41]). 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 [B57], Thottappillili [B53], IEEE PES T&D Committee [B21], and Tominaga et al. [B54]).

In most cases, subsequent strokes have a peak current that is less than the measured value of the initial return stroke current (Uman [B57], Thottappillili [B53], and IEEE PES T&D Committee [B21]). Fifty percent of subsequent return strokes are between 12 kA and 15 kA (Uman [B57] and Thottappillili [B53]). 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 [B53]). In other studies, the maximum current of subsequent return strokes is determined to be 30 kA (Uman [B57] and IEEE PES T&D Committee [B21]).

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[4] Information on references can be found in Clause 2.

The time interval between the initial return stroke and subsequent return strokes range from approximately 7 ms to 500 ms (Uman [B57] and Thottappillili [B53]). However, separation times of 46 µs to 110 µs have been recorded in a minority of lightning flashes in data collected from the Kennedy Space Center (Rakov and Uman [B48]). The amount of current that flows in the lightning channel has a maximum value of 500 A with a typical value of 100 A (Thottappillili [B53]).

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 [B57]). 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.

Table 1—Distribution of negative lightning flashes (Uman [B57])

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

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 [B53]).

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 [B37]). 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 [B57] and Thottappillili [B53]). Several research papers show peak currents greater than 100 kA (McCann [B41], Goto et al. [B8], and Miyake et al. [B42]).

7.5 Exposure levels

As discussed in IEEE Std C62.41.1-2002, the exposure level of a PDS to induced surges is an important consideration. 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 Alaska are significantly different than those found in the coastal regions between

Texas and Florida. 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.

7.5.1 Low exposure

Power distribution systems in geographical areas known for low lightning activity and with little load or capacitor switching activity.

7.5.2 Medium exposure

PDS in geographical areas known for medium-to-high lightning activity or with significant switching transients. One or both of these may be present.

7.5.3 High exposure

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 may be helpful in initial risk assessment analysis, it should be noted that, in general, the sparkover of wiring devices indicates that a 6 kV withstand capability for an SPD may 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 C62.41.1-2002 and its predecessor documents. SPDs are often rated for use in specific location categories.

8. Location categories

When planning for surge immunity for a PDS at a specific geographical location, IEEE Std C62.41.1-2002 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 design the most effective protection match possible. To achieve the match, it is important to first recognize the types and severity of surges in a specific environment, plus the operational characteristics and surge susceptibility of all equipment in that particular environment or location category. 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. These categories represent most locations, from those near the service entrance to locations remote from the service entrance.

For surges impinging on a building and originating in the utility supply, the source impedance may 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 wiring sparkover at the surge source or its point of entry in the service equipment. Any wiring sparkover may limit the duration and possibly the magnitude of a surge before it could travel further into the building.

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

Typical Category B locations are as follows:

- Service entrance equipment located inside a facility, feeder circuits, and short branch circuits.
- Distribution panelboards and devices.
- Busways and feeders in industrial plants.
- Heavy appliance outlets with short connections to the service entrance equipment.
- Lighting systems in large building or facilities.

Typical Category A locations are as follows:

- All outlets at more than about 10 m from Category B.
- All 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 2 provides a suggested list of questions or important issues to consider in an assessment of a PDS. Subclauses 9.1 through 9.5 supply additional detail.

Table 2—Power distribution systems

1. Does the facility where the SPDs are to be installed have a history of reoccurring electrical supply anomalies such as frequent grid switching, 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 C62.41.1-2002.
2. What are the locations at which the SPDs are intended to be installed? Service entrance? Switchgear? Motor control center? Distribution panel? Subpanel? Individual equipment disconnects?
    a. List each location where an SPD may be installed.
    b. Evaluate each of these locations separately.

For each SPD installation location, determine the following:

3. 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) [B44]. An SPD listed for Wye configured system is not permitted for use on a Delta configured system.
4. What is the available short-circuit current at the location where the SPD is to be installed?
    a. The NEC [B44] requires that the short-circuit current rating 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 ensure 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 may increase the available short-circuit current).
5. If at the service entrance 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.
6. 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.
7. What is the insulation level of the wiring and loads connected to the electrical system?
    a. The SPD should be capable of reducing the expected surge amplitudes to levels below the insulation rating or susceptibility level of the electrical system and loads being protected. For more information on the types and levels of surges expected, refer to Clause 7 and to IEEE Std C62.41.1-2002.
    b. This consideration is a critical issue as this function is considered a rudimentary function of the SPD.
8. What types of equipment are connected to the electrical system at the point of installation? What level of surge suppression is actually needed for the end-use equipment?
    a. Loads that are less susceptible to transient voltages may not require the same level of protection as those that are more sensitive to even low-level transient voltages. Inductive loads and electronic loads generally have different susceptibility to transient voltages, although consideration for the insulation level of inductive loads is important when specifying SPDs for these types of loads. The SPD should be capable of reducing the expected surge amplitudes to levels below the insulation rating or the susceptibility level of the load being protected. Repetitive transients, even at a low level, can damage these types of loads over time.

Table 2—Power distribution systems (*continued*)

9. What is the length of the wire connection between the location where the SPD is intended to be installed and the load being protected? Is the wiring to the load being protected exposed to external transient sources (for example, is the wiring routed outdoors, along the roof of a building, up a pole, or in a similar fashion)? a. If the length of wire between the SPD and the load being protected is long (>30 m) and/or the wiring is exposed to another source of transient surges (direct or induced), consideration may be given to installing an additional suppressor at the load being protected. b. If the wiring to the load being protected is routed outdoors, along the roof of a building, up a pole, or in a similar fashion, or the load being protected is located outdoors. then this connection should be considered to have the same exposure or similar lightning activity levels as expected for the area. In this case, strong consideration should be given to install SPDs at either end of the wiring, that is, at the panel and at the load being protected.
10. What level of overvoltage will the SPD withstand? a. In the United States, utilities commonly regulate the system voltage with a ±10% tolerance. If the installation location of the SPD has a history of poor voltage regulation, the maximum voltage withstand or maximum continuous operating voltage (MCOV) of the SPD should be considered. The MCOV of the SPD should be coordinated with the expected voltage regulation level. That is, the MCOV should be higher than the maximum expected voltage that would normally occur on the system. b. Situations could arise that may damage the SPD. A few examples of these situations include, but are not limited to, extended overvoltages that exceed the MCOV of the SPD, a loss of neutral condition, transformer failures, and unintentional contact between utility lines. These situations are considered abnormal and should be considered when evaluating the end-of-service conditions of the SPD. In these situations, the SPD is often intended to reach its end-of-service condition in order to provide a degree of protection to the electrical system. Underwriters Laboratories, Inc. (UL) 1449 [B56] provides several tests that demonstrate the end-of-service condition of an SPD.
11. Does the electrical system use backup power sources such as generators or emergency power supplies? a. In situations where backup or emergency power systems are used, consideration must be given for protecting the electrical system when these systems are in operation and replace the utility feed. Many systems use transfer switches that may switch the SPD out of the system when backup or emergency power is online. In these cases, additional SPDs may be considered for protecting the electrical system, which would be installed near the source when the system is switched to the backup or emergency power source. b. In installation locations that use external backup power sources such as generators or emergency power supplies, the MCOV of the SPDs used should also be coordinated with level of regulation that these backup systems can provide.
12. What level of upset can be tolerated by the end-use equipment at the installation location of the SPD? Minor? Major? Critical? a. When considering the installation of an SPD, the level of disruption should be evaluated. For more information on this topic, refer to Clause 6. b. Installation of an SPD at a location where the level of upset is considered major or critical is often considered essential. One basic function of the SPD would likely be to provide a degree of protection against such upsets.
13. If more than one SPD is installed on a specific PDS, will there be cascade coordination between devices? If so, how will that coordination be achieved? a. The concept of SPD cascade coordination centers on the proper installation and connection of two or more SPDs at different locations within a PDS. For example, one connected to the service entrance equipment and other connected to feeder or branch distribution panels or specific end-use equipment. Cascade coordination is achieved when the SPD closest to the source of the impinging surge diverts the majority of the energy from an impinging surge and a downstream SPD diverts the remaining or residual surge energy. b. Clause 16 covers several major variables affecting successful coordination of SPDs.

Table 2—Power distribution systems (*continued*)

14. What modes of protection are required for the SPD? a. Surges are coupled or transmitted in or through equipment by two modes. The first mode is normal mode, which is either line-to-neutral (L–N) and/or line-to-line (L–L). The second mode is common mode, which is either line-to-ground (L–G) and/or neutral-to-ground (N–G). For normal mode protection, the SPD should provide protection between each current carrying conductor pair (L–L) and L–N). For common mode protection, the SPD should provide protection between the line-to-ground (L–G) and/or neutral-to-ground (N–G) modes. b. Properly applying an SPD is dependent on the configuration of the PDS and equipment connected to the electrical distribution network. The modes of protection of the SPD, i.e., line-to-neutral, line-to-ground, neutral-to-ground, and/or line-to-line, must be in concert with that of the PDS. For example, if the PDS is a three-phase Wye, 4W+G system, then the modes of protection that are available to be protected are line-to-neutral, line-to-ground, neutral-to-ground, and line-to-line. c. Refer to Clause 12 and 16.7 for more discussion on modes of protection.
15. Is the SPD to be installed in parallel to the electrical system or in series with the load to be protected? a. With regard to the topology of the installation, SPDs are available in two forms, parallel connected and series connected. Parallel connected SPDs are widely used and can be installed on nearly any electrical system as the load current does not pass through the device. In contrast, series connected SPD can be used for electrical systems with relatively low load currents. Typically, series connected SPDs are available for systems with load currents up to 30–60 A, although some devices are available for systems with load currents of 200 A or more. b. If the load current allows, consideration should be given to the choice of a parallel connected versus a series connected SPD because the connection lead length of the parallel connected device is variable. The shorter the lead length of the connection from the SPD in parallel to the electrical system, the less impact that the inductive effect of the leads will have on the performance of the SPD. With series connected SPDs, all lead length for any parallel connected SPD components is internal to the SPD and fixed in length; therefore, where feasible, series connected SPDs often offer a benefit of reduced lead length. c. If the SPD is to be connected in series with the load to be protected, consideration must be given to whether the series connected SPD will take the load offline in the event of an SPD failure. The specifier must understand the failure mode of the series connected SPD for this situation. Often, it would be undesirable to remove power to a load in the event of an SPD failure. With parallel connected SPDs that have proper coordination between the SPD and any external overcurrent device that may be required as part of the installation (in series with SPD but in parallel to the electrical system), the load typically remains online even with an SPD failure. d. Furthermore, if the SPD is to be connected in series with the load to be protected, consideration must be given to whether the series connected SPD will withstand the available short-circuit current of the system that might pass through the device. For example, if a series connected SPD is installed on a system with 25 000 A of available short-circuit current but only has a fault current withstand capability of 5000 A, then the series connected SPD might not withstand the current flowing through the SPD and produce an undesirable SPD failure.

9.1 System configuration

The SPD specifier or user should be familiar with the system configuration of the PDS in which any SPD is to be installed. The system configuration of any PDS is based on the configuration of the secondary windings of the distribution or power class transformer that supplies the service entrance equipment and any other transformers within the facility that serve various loads. This includes whether the transformer windings are referenced to earth via a grounding conductor. It also includes whether the transformer is connected as single-phase or three-phase. The system configuration is not based on how any specific load or equipment is connected to a particular PDS. For example, the system configuration can be a three-phase, four-wire, solidly grounded Wye with a specific load connected three-phase, three-wire Delta. In this example, the system configuration is three-phase, four-wire, solidly grounded Wye.

The secondary windings of the three-phase transformers are normally connected in either a “Delta” or “Wye” configuration. Transformers can be selected for use in three-phase, three-wire systems or three-phase, four-wire systems. The electrical system can be referenced to earth, or grounded, by the connection to an intentional grounding conductor at a designated point on the secondary winding of the transformer either solidly or through an intentional impedance to limit ground fault currents (IEEE Std 142™-1991 [B24]). See Figure 1.

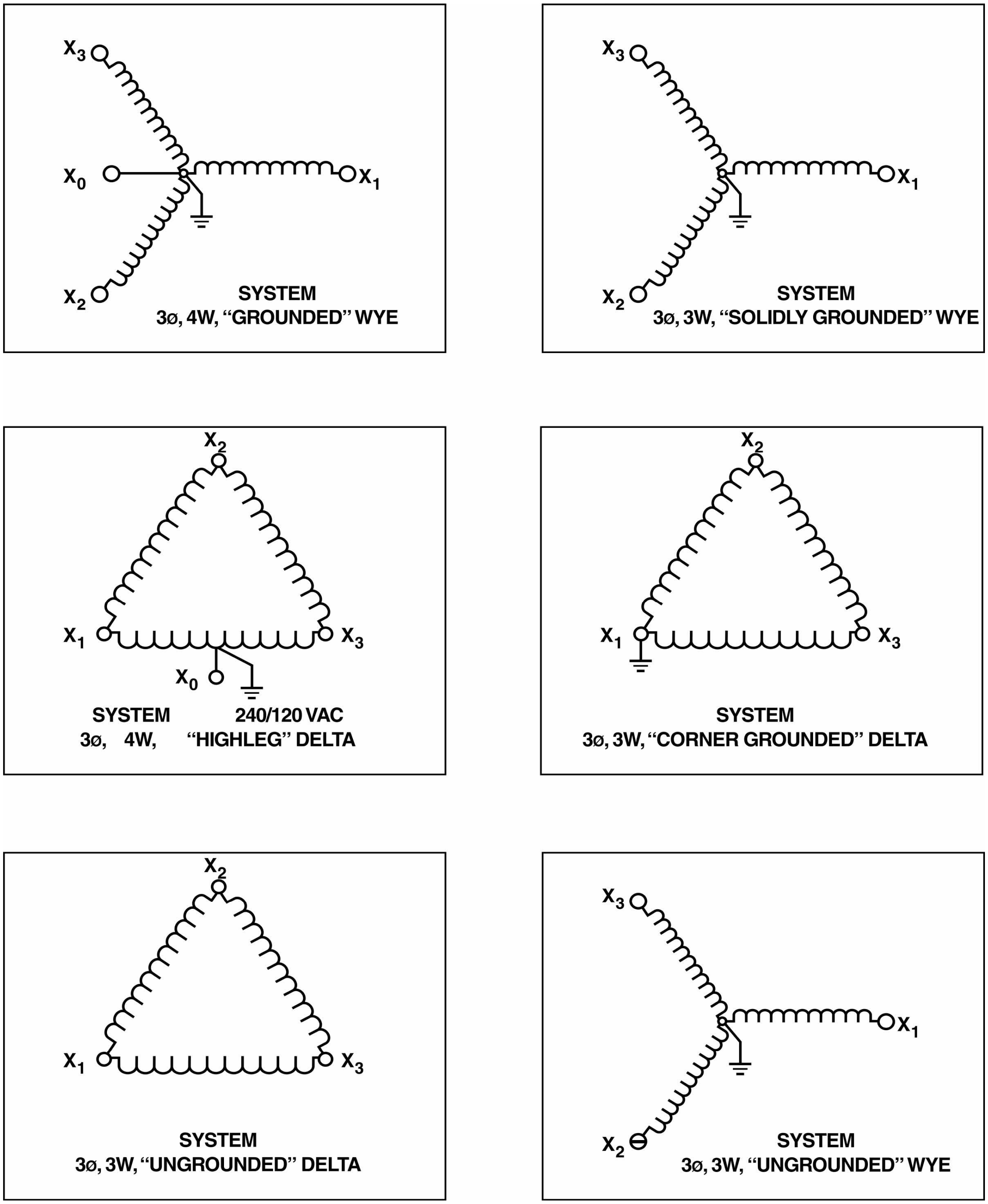


Figure 1—Examples of transformer secondary winding configurations used in North America (impedance grounded systems are also used but are not shown here)

9.2 System arrangement or distribution

The system arrangement or system distribution refers to how power is distributed from a specific distribution or power class transformer to each specific load via feeders and branch circuits. It also includes how specific loads or equipment are connected to the PDS. Examples of system arrangement or distribution would be whether the service entrance is into switchgear, switchboard, motor control centers, panelboards, or load centers.

9.3 Common North American voltages

The selection of system voltages is based on a variety of factors. Some common factors are economic considerations, standard practices, and reliability. This guide does not recommend one system voltage over another. A listing of the common three-phase voltage identifications used in North America for lighting and power is shown in Table 3.

Table 3—Common power system voltages used in North America

Voltage	Phase	Wire	Configuration
120/240	1	3	Solidly grounded single winding
208Y/ 120	3	4	Solidly grounded Wye
220Y/127	3	4	Solidly grounded Wye
240/120	3	4	“High-leg” Delta
480	3	3	Ungrounded Delta
480	3	3	“Corner grounded” Delta
480Y/277	3	4	Solidly grounded Wye
600 and 240	3	3	Ungrounded Delta
600Y/347	3	4	Grounded Wye
480/277 and 600/347	3	4	Impedance grounded Wye

9.4 Available short-circuit current and surge-protective device short-circuit current rating

Listing agencies and electrical codes require that equipment intended to break current at other than fault levels shall have an interrupting rating at nominal circuit voltages sufficient for the current that must be interrupted. The interrupting rating of a component or device is determined under standard test conditions that are designed to equal or exceed the actual installation needs. The term *interrupting rating* is generally understood to refer to fuses and breakers, but the term has a broader interpretation. The ability of an overcurrent device to safely interrupt high levels of fault current does not necessarily mean that equipment connected downstream of the device is capable of withstanding the let-through value of the available short-circuit current.

Merely providing an overcurrent protective device ahead of an SPD with sufficient interrupting rating will not ensure adequate short-circuit protection for the device. When the available short-circuit currents exceeds the short-circuit current rating (SCCR) of an electrical component, then the overcurrent protective device installed ahead of the SPD must limit the let-through energy within the rating of the device. An SPD can be damaged or destroyed if the SCCR of the SPD is exceeded. The subsequent damage can involve surrounding components, including the overcurrent protective device.

The specifier or user should be certain that any SPD selected has a short-circuit current rating equal to or greater than the available short-circuit current at the proposed connection point in the PDS. Furthermore, the specifier or user shall refer to the manufacturer of the SPD for recommendations regarding the appropriate overcurrent protective device to use inline with any SPD.

Often short-circuit current ratings are confused with surge current ratings. The two ratings are not the same. As discussed, short-circuit current ratings are determined at the steady-state frequency of the system, i.e., 50 Hz or

60 Hz. Surge current ratings are determined using an impulse of specified waveshape and amplitude, i.e., using an 8/20 µs current impulse (IEEE Std C62.45™-2003 [B28]). For more information on surge current ratings, refer to 13.3.

Every electrical system has an inherent available short circuit or fault current. That is, the system is capable of delivering a certain amount of current into a short circuit or fault at a given point within the electrical system at its normal, steady-state operating frequency. The terms *short-circuit current* and *fault current* are often used interchangeably. However, short-circuit current refers to the condition that would allow the maximum amount of current to flow in the system—into a short circuit with no impedance. Fault current implies that the condition causing current flow may have impedance; therefore, the current flow would be limited by this impedance. The available short-circuit current is dependent on different factors, including but not limited to, proximity to the electrical utility or power generating system, impedance of the electrical system delivering power to the system, size of the transformers feeding the system, the type and size of circuit interrupt devices used in the electrical system, and the size and length of wiring within the electrical system.

To determine the specific amount of short-circuit current available at a particular location in an electrical system, a short-circuit analysis must be completed. If a facility is newly constructed, this study should be available as part of the design process of the facility. Existing facilities or facilities that have undergone changes to the electrical system (changes in the PDS feeding the facility, replacement of transformers, addition of electrical services, increase to the size of the conductors feeding or within the electrical system, changes to the overcurrent protective devices within the facility, etc.) may require an updated short-circuit analysis. More detail on short-circuit current studies can be found in IEEE Std 141™-1993 (*The Red Book*) [B23] and IEEE Std 242™-2001 (*The Buff Book*) [B25].

All components of the electrical system must be able to withstand or interrupt the amount of available short-circuit current at the point at which they are installed. SPDs are components of the electrical system and must also withstand or interrupt the amount of available short-circuit current at the installation location. Furthermore, listing agencies and electrical codes require that SPDs have a short-circuit current rating (NEC [B44] and NFPA 780-2004 [B45]). The short-circuit current rating of an SPD can be obtained through the utilization of either internal or external overcurrent protective devices, e.g., fuses or circuit breakers. If an SPD has an internal overcurrent protective device, an external overcurrent protective device can still be required to ensure that a short-circuit or fault condition on conductors to the SPD does not create a hazardous condition. For an SPD to be properly applied, the short-circuit current rating of the SPD must be coordinated with the available short-circuit current of the electrical system at the point of installation as determined by a short-circuit current study, or the let-through current of an overcurrent protective device used with the SPD must limit the available short-circuit current to the SPD to a level below the short-circuit current rating of the SPD.

One method to help ensure that the available short-circuit current of the installation location does not exceed the short-circuit current rating of an SPD is to specify SPDs with higher short-circuit current ratings than the available short-circuit current at the serving transformer. This value would be the maximum short-circuit current available to the electrical system, as the connection impedance from the serving transformer to the main service equipment and the impedance of the remainder of the electrical system will further limit the available short-circuit current. If the serving transformer is utility provided, the utility should be able to provide the specifier or user with the short-circuit current available at the output of the serving transformer.

To further illustrate the correct and incorrect application of an SPD with regard to available short-circuit current, two examples are cited from Cole et al. [B4].

Example 1. As an example of a correct application, assume that an SPD is going to be installed on the PDS of a facility at a branch panel location. At this point in the PDS, the available fault current capability is 42 000 A. The available fault current at this location, or any other within the PDS of the facility, must be determined through a fault current analysis by the supervising engineer. Assume that this SPD is placed behind a circuit breaker with an SCCR of 42 000 A, shown as in Figure 2. In addition, the SPD has obtained an SCCR of 65 000 A. In this example, the SCCR of the SPD is coordinated with that of the facility's PDS, resulting in correct and coordinated application. In fact, as long as the SCCR of the SPD is equal to, or exceeds the point of, application within the power distribution and the preceding overcurrent protective device, the SCCR of the SPD is correctly coordinated.

Example 2. As an example of an incorrect application, assume that the SPD has an SCCR of 25 000 A (from UL 1449). Assume that this particular SPD was placed behind a circuit breaker with an SCCR of 65 000 A, as shown in Figure 2. Additionally, assume that the maximum SCCR available at this particular location on the PDS is 42 000 A. As with the previous example, the supervising engineer is responsible for determining the available fault current at this particular point within the PDS of the facility. In this particular example, the SPD is incorrectly applied. Because the SPD has obtained an SCCR rating of only 25 000 A, it might not be capable of withstanding an interrupt current of 42 000 A.

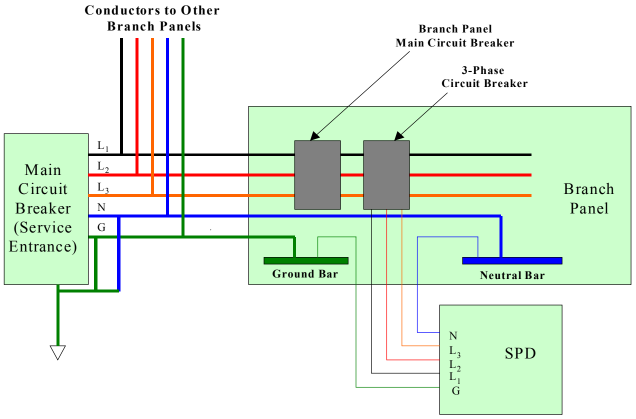


Figure 2—Connection of the SPD with a dedicated circuit breaker

A few different approaches can be considered to rectify this particular example so that the SPD has been installed in accordance with the NEC [B44] and the UL 1449 conditions of acceptability. The first approach would be to apply an SPD with an SCCR of 42 000 A or greater. Even though the circuit breaker preceding the SPD is greater than the SPD, the maximum short-circuit current available at the panel is 42 000 A. Therefore, the SPD has an SCCR equal to the PDS at that point.

The second approach is to use a current-limiting circuit breaker that will limit the SCCR to the SPD to a value of 25 000 A or less. This option presents some complications. In accordance with the NEC, the device must be applied in compliance with its safety agency listing requirements. The SPD must have been tested with a specified circuit breaker at a specified current rating. Using a circuit breaker produced by a different manufacturer, at a different SCCR, or even a different part number is not acceptable and is outside the scope of its safety agency listing. If the SPD is installed with an untested or improperly tested current limiting circuit breaker, then it is the same as not using a product evaluated by an independent safety agency, such as the UL.

The third approach would be to install a finite amount of impedance in the line prior to the panel. The amount of impedance would have to be high enough to limit the amount of SCCR to 25 000 A or less. One possible method to reach this amount is by installing a transformer in the PDS to lower the overall SCCR rating at that particular point. This option can be very expensive and might require additional space, but it has some advantages in mitigating other power quality problems that might need to be addressed.

Figure 3 represents an SPD that includes the overcurrent protection within the device itself. In this case, the SPD may not require that the device be preceded with a circuit breaker. However, the same rules apply. The SPD has a specified SCCR, which has been evaluated by the UL; it is marked either on the product or in the accompanying installation instructions and must be connected appropriately.

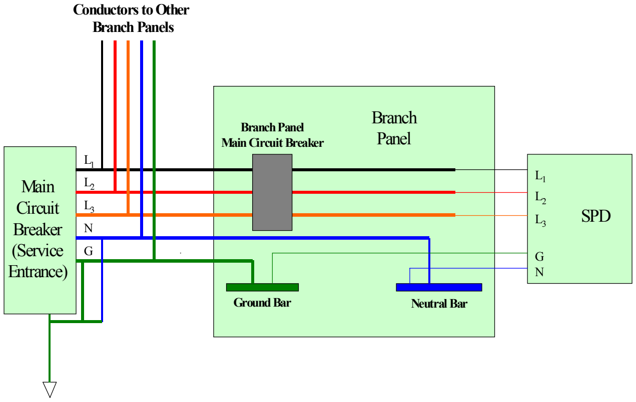


Figure 3—Connection of the SPD with the main circuit breaker of the panel

9.5 Voltage ratings of surge-protective devices

As part of a PDS evaluation, it is important to know where and how the specific facility under review is connected to the medium-voltage PDS supplying the transformers of the facilities. Utility companies routinely incorporate the use of line voltage regulators and transformer tap changers to regulate service entrance voltages for their customers. Power class transformers have tap changers associated with their primary windings. Often these tap changers are automatic load tap changers and are part of the transformer construction. The voltages on a medium-voltage distribution line routinely fluctuate because of changing loads.

Electric service providers usually set voltage regulators and tap changers to maintain an average voltage near the center of the distribution line. Changing loads on the medium-voltage distribution line and the location of service entrance equipment near a utility substation can subject the end user to higher than normal line voltages. Most utilities only guarantee a service entrance voltage of plus or minus 10% of the system nominal. It is recommended that specifiers and users of SPDs be aware of potential fluctuations in the service entrance line voltage and select SPDs with a MCOV above any expected higher than normal line voltages. Sustained over voltage conditions can shorten the operational life of SPDs.

10. Grounded and ungrounded systems

Grounded or ungrounded power distribution systems are determined by the intentional grounding conductor placed on the secondary windings of the distribution or power class transformer providing service entrance power. The selection of a grounded or ungrounded PDS is strictly dependent on the purpose and intended use of the electrical system. There are advantages and disadvantages to each system. For more extensive detail on the subject matter, refer to IEEE Std 142-1991 (*The Green Book*) [B24].

10.1 Grounded systems

Application of SPDs for grounded-neutral service requires that the system be effectively grounded. Most grounded systems employ some method of grounding the system neutral at one or more points. These methods can be divided into two general categories: solid grounding and impedance grounding. The solidly grounded, three-phase systems provide a voltage stability that minimizes certain transient overvoltage conditions. In solidly grounded "Wye" systems, there is the advantage of operating both single-phase lighting loads and three-phase motor loads without the installation cost of additional transformers. To ensure the benefits of solid grounding, it is necessary to determine the degree of grounding provided in the system.

A good guide in answering this question is the magnitude of ground-fault current as compared with the system three-phase fault current. The higher the ground-fault current in relation to the three-phase fault current, the greater the degree of grounding in the system. Effectively grounded systems will have a line-to-ground short-circuit current of at least 60% of the three-phase short-circuit value. In terms of resistance and reactance, effective grounding of a system is accomplished only when $R_0 \leq X_1$ and $X_0 \leq 3X_1$, and such relationships exist at any point in the system (IEEE Std 142-1991 (*The Green Book*) [B24]). The X_1 component used in the above relation is the Thevenin equivalent positive-sequence reactance of the complete system, including the subtransient reactance of all rotating machines.

10.1.1 Ground-fault conditions

In grounded systems, phase-to-ground faults are easily located, and during such faults, the voltage does not rise above the phase-to-ground potential. A potential disadvantage is the higher probability of phase-to-ground faults combined with high short-circuit levels.

10.2 Impedance grounded systems

In resistance grounding, the neutral is connected to ground through one or more resistors. In this method, with the resistor values normally used, and except for transient overvoltages, the line-to-ground voltages that exist during a line-to-ground fault are nearly the same as those for an ungrounded system (IEEE Std 142-1991 (*The Green Book*) [B24]).

10.3 Ungrounded systems

The traditional benefit of three-phase, ungrounded systems was the ability to continue the operations of three-phase motor loads if a phase-to-ground fault occurred during normal production or equipment operations. Historically this system design allowed operators to schedule the shutdown of equipment. However, ungrounded systems are not completely ungrounded, and voltages can become dynamically unstable. Although there may be no intentional grounding conductor on the secondary winding of the supply transformer of a specific PDS, in ungrounded, three-phase, power distribution systems, a capacitive coupling exists between the systems conductors and the earth. Ungrounded systems are susceptible to higher transient overvoltages during switching operations and sustained overvoltages during phase-to-ground faults.

10.3.1 Ground-fault conditions

During a phase-to-ground fault, the current flow is usually quite low and typically only ranges from 1 A to 20 A. If an unintentional solidly connected bond were to occur between one phase conductor and ground, the potential rise on the remaining ungrounded phase conductor can rise to a value 173% of the nominal phase-to-ground voltage (IEEE PES T&D Committee [B21]). However, if the phase-to-ground fault is an arcing fault, and the supply transformer is a three-phase, three-wire, ungrounded Delta transformer, the repetitive induction of voltage or the charging and discharging of the distributed system capacitance can raise the phase-to-phase voltage on the unfaulted phases by a value of six to eight times the nominal, phase-to-phase voltage (IEEE Std 142-1991 (*The Green Book*) [B24]). In power distribution systems supplied by a transformer with the secondary winding connected in a Wye configuration with an isolated or floating neutral, some relatively high voltages well above the insulation rating of the conductors can occur when not protected with SPDs (Norinder and Dahle [B46]).

The overstressing of the insulation system on the unfaulted phases often causes a second phase-to-ground fault to develop. The second fault creates a phase-to-phase short circuit. In addition to the disadvantage of potential overvoltage conditions, phase-to-ground faults on ungrounded systems are difficult to locate. Between the time the first phase-to-ground fault occurs and the time the affected equipment is identified and isolated from the system, serious insulation damage might have occurred.

10.4 Ferroresonance

Another serious concern is the electrical phenomenon known as ferroresonance. This condition can exist on some solidly grounded power systems and on ungrounded systems, but it tends to be more prevalent on the ungrounded systems. The condition occurs when an alternating voltage of sufficient magnitude is applied to a circuit consisting of capacitance and ferromagnetic inductance. It has both transient and steady-state mode characteristics, including overvoltages and very irregular waveshapes. Ferroresonance is associated with the excitation of one or more saturable inductors through capacitance in series with the inductor. Such resonant circuits can distort the normal phase-to-ground impedance so that the voltage on one or more of the phases of a three-phase circuit can rise to a destructive level.

The phenomenon has been well documented to occur in specific types of power, control, and metering circuits for many decades (Boyajian and McCarty [B1], Gleason [B7], IEEE Std 242-1986 (*The Buff Book*) [B25], Peterson [B47], and Weller 0). Three configurations or conditions that can create a ferroresonance phenomenon include:

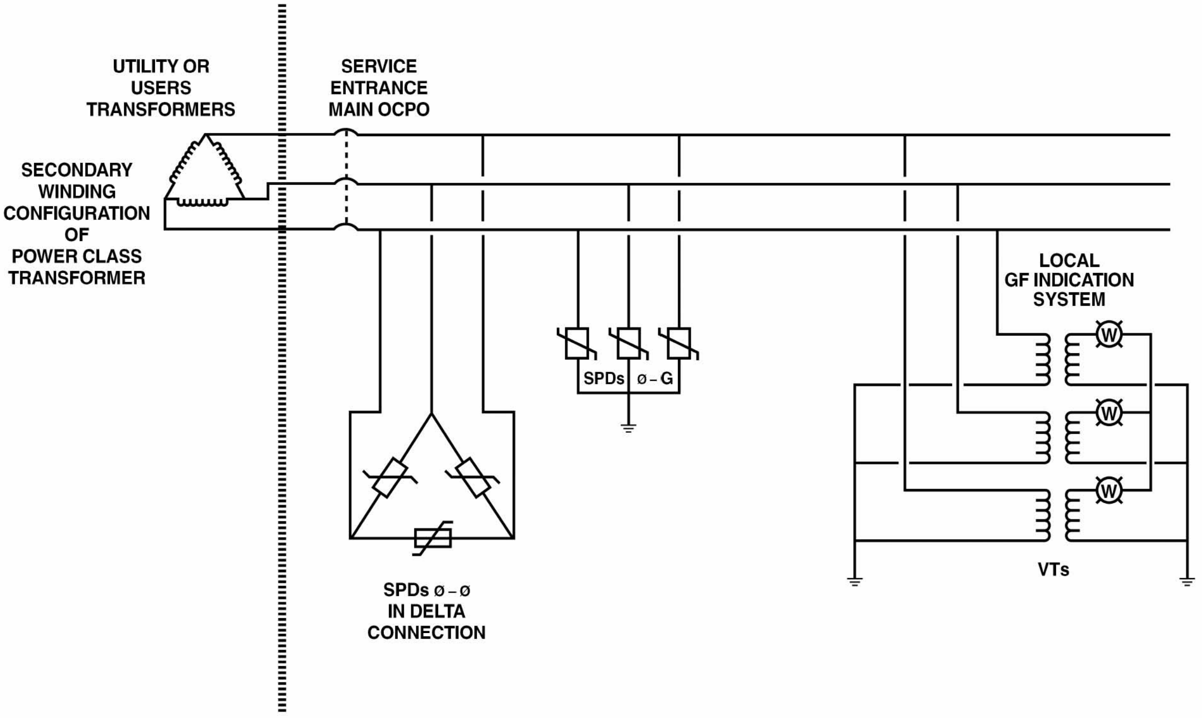
a) A facility supplied by a set of power class transformers with the secondary windings connected in a three-phase, three-wire, ungrounded "Delta" configuration.

b) The existence of a set of ground-fault indication lights supplied by voltage transformers connected in a "Wye–Wye" configuration. The voltage transformers provide line-to-ground connections on an ungrounded system through the primary winding of the voltage transformers. (The intent of these lights is to provide ground-fault indication by creating a "phase-to-ground" circuit for the lights associated with the "unfaulted phases" when a single ground-fault condition occurs.) The grounding of the primary winding presents the concern. See Figure 4 and Figure 5.

c) The capacitive reactance from the power cable being nearly equal to the exciting reactance of the facility supply transformer. Capacitive reactance is a normal and expected electrical phenomenon that occurs whenever any two conductors are separated by an insulator. Power cables in a metallic conduit have multiple capacitances, between phases and between phases and ground.

In such combination, the exciting reactance of the voltage transformers is equal to, or nearly equal to, the total capacitive reactance in the PDS. A parallel resonant circuit of very high impedance is formed, and as a result, a high "line-to-ground" and "line-to-line" voltage is created. The PDS must be initially designed to avoid Ferroresonance conditions. The avoidance of ferroresonance conditions should also be kept in mind when any power system is modified or changed during the operational life of the system.

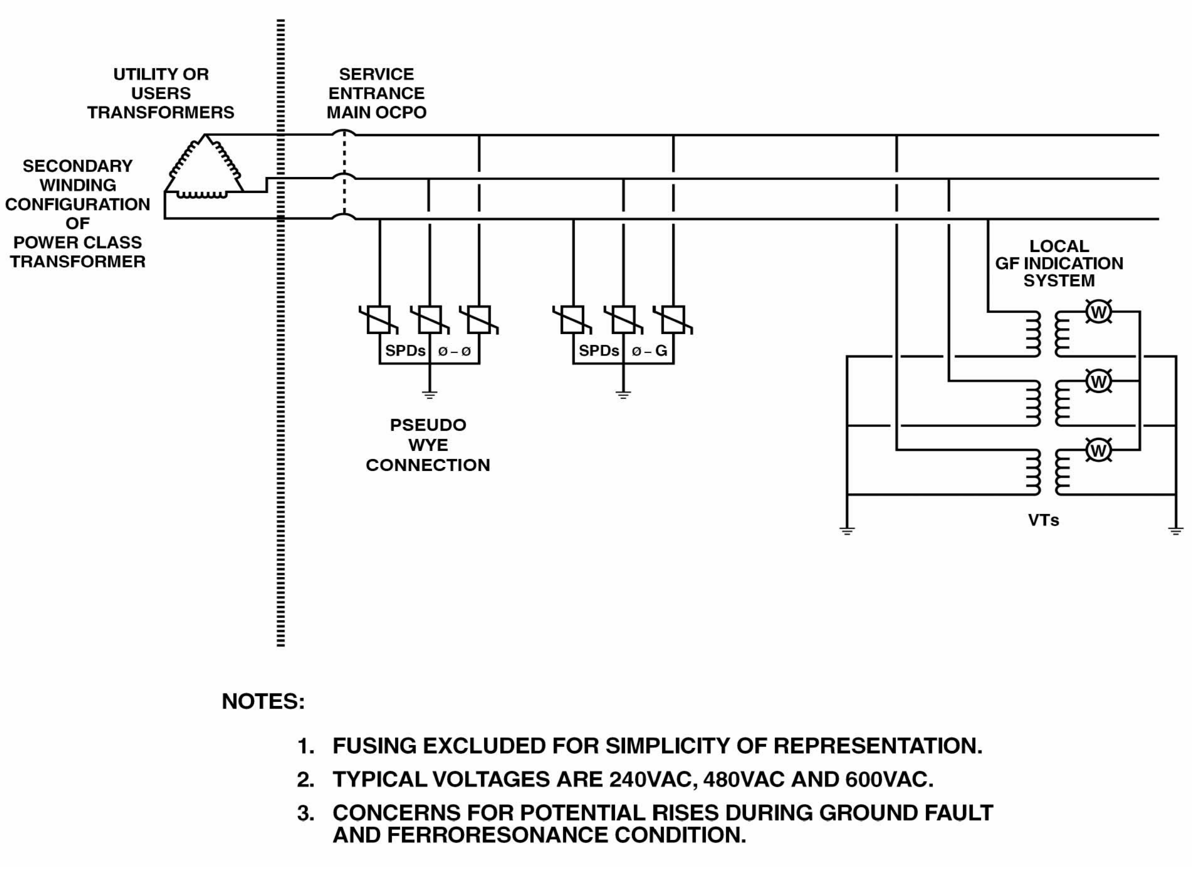
If SPDs are selected for use in an ungrounded PDS, care should be taken to ensure that all SPDs are rated and designed for the specific applications. In addition to seriously overstressing the insulation of equipment connected to the system, high voltages from a ferroresonance condition can cause an SPD to immediately and continuously conduct to the point of self-destruction.



NOTES:

1. FUSING EXCLUDED FOR SIMPLICITY OF REPRESENTATION.
2. TYPICAL VOLTAGES ARE 240VAC, 480VAC AND 600VAC.
3. CONCERNS FOR POTENTIAL RISES DURING GROUND FAULT AND FERRORESONANCE CONDITION.

Figure 4—Ground fault indicating lights with Delta connected SPD



NOTES:

1. **FUSING EXCLUDED FOR SIMPLICITY OF REPRESENTATION.**
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Figure 5—Ground fault indicating lights with pseudo-Wye connected SPD

11. Grounding and bonding

For the purposes of optimizing the lighting protection performance of any installed SPDs, the concept of minimizing the earthing impedance is the important parameter, and this is best achieved through proper bonding and grounding (earthing) at both low and high frequency. IEEE Std C62.41.1-2002 provides detailed discussion of earthing impedance and how this relates to the dispersion of lightning currents and the subsequent protection of the electronic equipment of a facility.

This clause describes the two major aspects in promoting a low-impedance path for the dispersion of lighting currents when SPDs are involved. The first aspect is the physical bonding of all metallic infrastructure, equipment cases, and grounding conductors within the building perimeter in order to create one low-impedance common bonding network. The second aspect is the grounding or connection to earth of this common bonding network in a manner that maintains the low-impedance objective.

11.1 Bonding

Without bonding, a facility would have several different systems that would not be connected together, including the ac power system, alternative power systems, telecommunications systems, lightning protection systems, and the mechanical structure of the facility (NEC [B44] and NFPA 780-2004 [B45]). Effective bonding consists of a set of interconnections and terminations that, taken together, form a common bonding network that is a usefully low-impedance path at all frequencies of interest, for the flow of current through them. If done properly, this arrangement then can be used to successfully limit the development of unwanted potentials across the ends of the bonding connection. The objective is that each termination (bond) be such that the electrical properties of the total path are a function of all connected elements, and not just the interconnections.

Relative to the installation of SPDs, the condition of the facility bonding network should be inspected to ensure compliance to local electric codes and optimized low-impedance bonding techniques. The best bond occurs when there is a metal-to-metal connection. The connection can be achieved by either a mechanical connection or a welded connection. Whether the connection is a mechanical one or a welded one, all efforts should be made to eliminate paint and adhesives from the immediate vicinity of the connection. Solder and gaskets can deteriorate over time from environmental and physical stress that can be put on the connection and should not be used for bonding connections.

A welded connection is more stable than a mechanical connection. Welding creates a better bond between two objects because it changes two conductors into one solid connection. This process produces a higher contact area and a consistence connection. When making a welded connection, only materials of the same metallic makeup should be welded. When using a mechanical connection, scheduled maintenance should be instituted to check the integrity of the connections. Mechanical connections can loosen over time, and the resistance of the connection can increase.

11.2 Grounding

The importance of ensuring that the grounding system provides a low earth impedance, and not simply a low earth resistance, must be understood. A spectral study of the typical waveforms associated with transient impulses, such as those characteristic of lightning and switching surges, reveals both high-frequency and low-frequency components. The high-frequency component is associated with the extremely fast rising “front” of the transient (typically less than 10 μs to peak current), whereas the low-frequency component resides in the long “tail” or follow-on current of the decaying impulse. High-frequency components are significant for inductive effects (induced voltages in the circuits), whereas low-frequency components are significant for energy effects (deposited energy in resistive elements).

A ground system designed to promote optimal operation of SPDs should exhibit a low impedance, rather than simply a low resistance, thereby ensuring it maximizes the dissipation of both the high-frequency and low-frequency components characteristic of surges and fault transients. A grounding system appears to such transient events as an impedance rather than simply as a resistance. Correct interpretation of the effectiveness of this ground system requires an understanding of transmission line theory. A low-impedance grounding system is only achieved by considering the roles played by each of resistance, capacitance, and inductance within the system. For more extensive theory on each of these parameters, Chapter 4 of IEEE Std 1100™-2005 (*The Emerald Book*) [B26] provides additional discussion on the roles of each electrical parameter as well as on the recommended practices and physical descriptions for the most appropriate grounding and bonding hardware.

The *capacitance* of the ground system dominates during the steep rising front of the impulse by providing a path-to-ground for these high-frequency components. To assist this process, the capacitance of the ground system should be maximized. In practice, this means that the surface area of contact made with the ground, must be as large as possible. The use of flat instead of round conductors, buried metal plates, meshes, and ground enhancing materials (which effectively increase the surface contact of driven rods) are all ways of increasing the capacitance of the coupling to true earth of the ground system.

The *inductance* of the ground system dominates during the rapid change of current with time as the current is injected into the earth. The voltage developed from the inductive term is given by $V = L\, di/dt$. This level may become very large, creating the risk of a flashover, if attention is not paid to ensuring that inductance is minimized in the system. Sharp bends in lighting protection system (LPS) down conductors and bonding conductors should be avoided, and the use of flat conductors, instead of round ones, can provide some small level of improvement.

Finally, the *resistance* of the contact to the earth medium is particularly important during the decaying "tail" of the surge as this is where the large energy content of the charge deposition (Joules) resides. A low-resistance contact ensures the safe dissipation of this excess energy into the ground. In practice, this can be achieved by using longer driven rods, multiple rods, and larger diameter rods or by encasing the rods with conductive ground-enhancing materials.

Measurement of earth resistance with conventional low-frequency instruments may not provide results that are indicative of the ground response to a lightning discharge. In complex installations, many "grounds" can be interconnected to form a ground "system." If simple dc and low-frequency measurement techniques are now performed on this system, a false level of confidence might be obtained if the reading is considered "low enough." What is not being appreciated is that this low-frequency measurement is correctly evaluating the presence of both near and distance "grounds" and that, under normal lightning transients, the distance grounds can be too far away to have any impact on limiting the peak voltage that will develop at the point of current being injected into the ground system. Here is an explanation. It is well known that approximately 75% of cloud-to-ground lightning discharges exhibit a primary stroke (return stroke) followed by several successive re-strikes. These re-strikes can number as many as 10 per event, and typically they occur some 50 ms to 100 ms apart. The current rise time for the first stroke is typically between 1 μs and 10 μs, whereas the rise time of the subsequent re-strikes may be as short as 0.2 μs because of the presence of the preionized conductive channel from cloud to earth. If one now assumes that the propagation velocity of this current discharge into the ground is approximately that of the speed of light (300 m/μs), it is not hard to see that the local earth mass at the point of charge deposition is subject to the peak value of the discharge current before the wavefront has traveled 60 m in dispersing into the surrounding earth mass. This travel distance is even less if one allows for the effects of distributed inductance and capacitance of the connecting conductors to the "ground system." Hence, the contribution of such distant ground connections to the overall "system" is limited because the discharge wavefront has not even reached such points for their benefit as part of the total system to be felt. Put another way, the voltage at the point of injection (to which the equipment is connected) has reached the highest potential it will experience as the crest of the current wave passes through it, before the distance ground points in the system even start to carry a contribution of the initial impulse current!

With lightning protection systems, it is only the "grounding" within a fairly small radius of the point of injection (typically less than 30 m) that has any significant influence on the performance of the system. Because of the short rise times associated with lightning-induced transients, parallel paths of more than a few tens of meters will present enough impedance to self-limit their ability to divert a significant portion of the total surge current to ground. Hence, any measurement of the lightning protection earth that includes the effect of more distant earths, such as is the case with dc resistance measurements, may not provide an accurate indication of its true performance under lightning conditions. This gives rise to a practical "rule of thumb," namely, "the 30 meter rule." It is the first 30 m of "grounding" that will have the greatest effect under transient conditions. For example, to achieve a desired resistance target, it might be required to bury a straight length of 100 m of copper cable. This process will achieve the resistance target as measured by a simple resistance meter and for 50/60 Hz power faults. It would not provide an effective ground for dissipation of lightning transients because of its length. A more effective method would be to use five radials in a star pattern, each approximately 20 m long!

To summarize, optimum performance of SPDs is achieved in the presence of a low-impedance grounding system. When a combination of both low-frequency and high-frequency system testing is not feasible, the following recommendations should be considered:

- To increase capacitance and promote the dissipation to remote earth of high-frequency surge components, the surface area of contact made with the ground should be as large as possible. The use of flat instead of round conductors, buried metal plates, meshes, and ground-enhancing materials (which effectively increase the surface contact of driven rods) are all ways of increasing the capacitance of the coupling to true earth of the ground system.
- To minimize the voltage developed from the interaction of the system inductance and the fast rise times during lightning events, sharp bends in LPS down conductors and bonding conductors should be avoided, and the use of flat conductors, instead of round ones, can provide some small level of improvement.

- A low-resistance contact ensures the safe dissipation of excess energy during surge conditions into the ground. In practice, this can be achieved by using longer driven rods, multiple rods, and larger diameter rods or by encasing the rods with concrete or conductive ground-enhancing materials.
- For more effective lightning protection systems, consider grounding configurations that optimize the use of the first 30 m surrounding the protection system.
- Keep in mind that the common bonding objectives and recommendation found in the NEC [B44] and supplementary standards, such as IEEE Std 142-1991 (*The Green Book*) [B24] and IEEE Std 1100-2005 (*The Emerald Book*) [B26], promote the concepts of lowering impedance and resistance, which are both desirable objectives for optimal performance of SPDs.

12. Modes of operation

Surges are coupled or transmitted in or through equipment by two modes. The first mode is *normal mode*, which is line-to-neutral (L–N) and/or line-to-line (L–L). The second mode is *common mode*, which is line-to-ground (L–G) and/or neutral-to-ground (N–G).

For normal mode protection, the SPD should provide protection between each current carrying conductor pair (L–L and L–N).

For common mode protection, the SPD should provide protection between the line-to-ground (L–G) and/or neutral-to-ground (N–G) modes.

12.1 Considerations for neutral-to-ground surge-protective device application

For N–G common mode protection, the greatest benefit is obtained when the SPD is some distance from the main bonding jumper. Most electrical codes require that a main bonding jumper be connected in service entrance equipment between the neutral and ground. Similar requirements also exist for separately derived power sources such as generators. With few exceptions, the main bonding jumper within service entrance equipment is a relatively large, permanently installed conductor or piece of bus work. When an SPD with an N–G connected device is installed in close proximity to the main bonding jumper, the N–G mode of protection performs no function because neutral and ground of the power system are essentially shunted at a single point. In addition, the local utility or customer will also bond the X_0 terminal of the distribution or power class transformer to ground.

The purchase of an N–G mode of surge protection might seem unnecessary for new installations where the SPD will be installed in close proximity to the service entrance and the main bonding jumper. However, as time elapses and environmental conditions vary, connections to the main bonding jumper can loosen resulting in high impedances at lightning frequencies. If maintenance procedures are not instituted to check the all conductor connections on a routine basis, lightning-induced currents can create N–G potentials that are hazardous to adjacent equipment. For service entrance locations, N–G mode protection is not a mandated requirement, but the utilization of the facility, the anticipated maintenance procedures, and cost differential of adding the N–G mode of protection should all be considered by the design engineer.

The same is true for panelboards, switchboards, and switchgear containing the first system disconnecting means or overcurrent protective device of a separately derived power source. Any surge condition conducting through an N–G mode in the service entrance equipment would most likely be a direct lightning strike with very high energy. Such direct lightning strikes to service entrance equipment are extremely rare.

13. Surge-protective device specifications

Specifiers and users of SPDs can often become confused by the numerous, and sometimes conflicting, SPD specifications. It is important that specifiers and users of SPDs review and understand the relevance of some of these specifications relative to SPD operation.

13.1 Measured limiting voltage

The measured limiting voltage is determined during the application of a predetermined impulse with specified waveshapes and amplitudes. The measured limiting voltage is the residual let-through voltage, under the stated test condition. The measured limiting voltage magnitude is often measured with a combination wave generator set to produce a 6 kV/1.2/50 µs open circuit voltage/3 kA, 8/20 µs short-circuit current–combination wave, but also it applies to other test waveforms, surge amplitudes, and generator setups (IEEE Std C62.45-2003 [B28]). As SPDs are intended for the protection of utilization equipment, different measured limiting voltages can be found dependent on the intended voltage application. Furthermore, the characteristics of the SPD can modify the peak current value and the waveshape of the current used for determining the measured limiting voltage (IEEE Std C62.45-2003 [B28]).

The performance of any SPD connected to the PDS is affected by the rise time (di/dt) of the transient and the means of interconnect. Whether internally or externally mounted to the PDS, the conductor configuration used for the interconnection means can add to the residual let-through voltage of an SPD. This configuration includes not only the conductor length but also the conductor characteristics. Conductor characteristics, such as insulation, stranded versus solid, and whether the conductors are twisted, can also affect the residual let-through voltage.

In an actual installation, the protective voltage impressed on the equipment will be the voltage established by the limiting action of the SPD, which is augmented by the voltage induced in the loop area formed by the connecting leads. For practical situations, it is often postulated that connecting leads can be represented by an inductance in the order of 1 µH/m, whereas the resistance of the leads can be neglected. Twisting the leads (minimizing the loop area) helps to reduce the inductive effects.

All SPDs must be connected to the PDS to be protected. Installations that require the connecting leads of the SPD to be excessively long can easily increase the residual let-through voltage of the SPD by several hundred or several thousand volts. Unless the SPD is closely coupled or integrated (with lead length minimized) to the PDS requiring protection, the measured limiting voltage of the SPD can quickly become superfluous.

13.1.1 Suppressed voltage rating

The suppressed voltage rating (SVR) is a specific and special case of the measured limiting voltage, which has its origins within UL 1449, Second edition [B56]. The test is performed using a 6 kV 1.2/50 µs open-circuit voltage/500 A, 8/20 µs short-circuit current–combination wave applied to the device under test, with 15 cm of lead length protruding outside of the enclosure. The measured limiting voltage at the ends of these leads is recorded and rounded up to the nearest of 330 V, 400 V, 500 V, 600 V, 700 V, 800 V, 900 V, 1000 V, 1200 V, 1500 V, 1800 V, 2000 V, 2500 V, 3000 V, 4000 V, 5000 V, 6000 V. This rating is designated as the SPD SVR. The characteristics of the SPD can modify the peak current value and the waveshape of the current used for determining the SVR.

Because this test is standardized and intended to be performed the same way on all products, it does to some extent allow the comparison in clamping performance of different SPDs. However, these rating are often used with little understanding of the intended function of the SPD. Selection of the wrong type of SPD for a specific application can result in inadequate protection of the end-use equipment or the expensive overprotection of the insulation of the PDS.

One common misconception is that SPDs with merely lower suppressed voltage ratings are superior devices. Although low values of suppressed voltage relative to the power system nominal voltage are desirable, this must be balanced against power system variations such as temporary overvoltages that might reduce the life of an SPD. Other operating characteristics and specifications such as MCOV (9.5) should be considered as well when specifying SPDs as part of an overall PDS protection strategy.

SVRs, as well as measured limiting voltages, are useful to the specifier and user because they provide insight to the specifier as to what level the SPD will limit a surge that is expected in a given environment (IEEE Std C62.41.2-2002). This information, in conjunction with the susceptibility of the equipment connected to an electrical distribution system, allows for proper coordination of the SPD with the protection level needed.

13.2 Product response time

The literature associated with SPDs often indicates a value or speed within which an SPD will respond to clamp or divert surge voltage or surge current. Such values of speed are often referred to as the products (response time). SPD manufacturers state response times of their products in microseconds, nanoseconds, or picoseconds; however, none of the recognized SPD standards currently address methods for repeatable measurements of such short times to corroborate such claims. Response time is not solely a reliable means of assessing SPD operation for clamping or L-C filter devices.

A microsecond (µs) is one millionth (1/1 000 000 or 10^{-6}) of a second. A nanosecond (ns) is one billionth (1/1 000 000 000 or 10^{-9}) of a second. A picosecond (ps) is one trillionth (1/1 000 000 000 000 or 10^{-12}) of a second.

The response time in picoseconds is extremely difficult to measure and requires very expensive and precise instrumentation. Response times specified in picoseconds are typically the theoretical response time at the surface of unidirectional silicon chips. These theoretical response times ignore the effects of the connections of the chips to the circuit and the fact that more than unidirectional chips are required for ac power circuits. The circuit connections and the required bidirectional chips, or use of chips with opposite polarities, will slow the response time to the nanosecond range.

The speed of light is approximately 0.3 mm/pc, and electrical signals generally propagate through conductors at between 50% and 80% of the speed of light. Measurements of response characteristics in the picosecond range, although possible, are extremely dependent on the test setup, instrumentation, and experimental methods employed. The propagation time of signals in instrument test lead alone could seriously affect the accuracy of such measurements.

SPDs only employing only spark gap tube voltage switching devices are less responsive than thyristor voltage switching devices or voltage limiting components because of the delay required to ionize the gas or air located between electrodes. A proper engineering evaluation is important when comparing different components. The evaluation should be based on the measured limiting voltage or surge remnant and not on response time.

13.3 Surge current ratings

It is important for specifiers and users of SPDs to understand the term *surge current*. Surge current ratings or the surge current capability of an SPD is one of the most common specification parameters of an SPD. The surge current rating of an SPD refers to the amount of current that the device can divert without the current causing damage or degradation to the SPD.

The surge current rating of an SPD is often confused with the short-circuit current rating. These two parameters are not the same. For more information on short-circuit current rating, refer to 9.4.

When an SPD operates to limit a transient overvoltage the SPD diverts the energy contained in the overvoltage surge by conducting current. Surge current ratings are obtained by testing an SPD on its ability to limit overvoltage transients by diverting surge current. As defined by IEEE C62.62™-2000 [B30], SPDs are subjected to an 8/20 µs current waveform to determine the surge current rating. However, depending on the particular electrical system, grounding system, configuration, environment, and location, other standards, such as IEC 61643-1 [B18], use additional waveforms for determining surge current ratings.

The surge current rating of any specific SPD should be evaluated and reviewed relative to the surge current environment of the specific PDS in which it is connected. The parameters of lightning detailed in 7.4 are actual, measured return stroke parameters from lightning research. These data are not directly transferable to the performance requirements of an SPD.

Most surge current ratings are obtained by testing with 8/20 µs generated current wave, whereas a direct lightning strike might be in the order of tens to hundreds of microseconds. Users and specifiers are encouraged to request documentation from the SPD manufacturer that substantiates how the surge current ratings were obtained.

Testing of the SPD to a standard to determine the surge current rating is paramount. The ability of an SPD to limit overvoltages on the electrical distribution network by diverting surge currents is a function of the surge-protective components, the mechanical structure of the SPD, and the connection to the electrical distribution network. A few common surge-protective components used in manufacturing SPDs are MOVs, SADs, and gas discharge tubes, with MOVs having the largest usage. The surge current rating of an MOV is related to the cross-sectional area and its composition. In general, the larger the cross-sectional area, the higher the surge current rating of the device (Standler [B50] and *Transient Voltage Suppression* [B55]). MOVs generally are of round geometry but come in a plethora of standard diameters ranging from 7 mm (0.28 in) to 80 mm (3.15 in). The surge current ratings of these devices vary widely and are dependent on the manufacturer. By connecting the MOVs in a parallel array, a theoretical current surge rating could be calculated by simply adding the current ratings of the individual MOVs together to obtain the surge current rating of the array.

There are many hypotheses on what component, what topology, and the deployment of specific technology produces the best SPD for diverting surge current. Instead of presenting all of these arguments and letting the reader decipher these topics, it is best that the discussion of surge current rating or surge current capabilities revolve around performance test data. Regardless of the components used in the design, or the specific mechanical structure deployed, what matters is that the SPD has a surge current rating that is suitable for the application.

Finally, laboratory testing of an SPD is not directly transferable to the application of the SPD. Although benchmarking of several SPDs to a multitude of parameters can show how one SPD compares with another, the impedance created by the connection of the SPD to the electrical distribution network, and the bonding of all equipment connected to that network, will determine the overall installed performance of the SPD. A high-quality, high-performing SPD with high surge current capability may fail repeatedly in the application as a direct result of poor connections, e.g., long lead length, and poor equipment bonding. Subsequently, a lower quality, low-performing SPD with low surge current ratings may be successful in protecting the application from lightning-induced transients because of improvements made in connecting the SPD to the electrical distribution network and the utilization of equipotential bonding. Users and those who specify SPDs need to understand that the protection capability of the SPD is directly related to how it is applied.

13.4 Labeling

SPDs are evaluated and tested by following the procedures within documents produced by the manufacturer, various testing laboratories, and listing and electrical standard organizations. Specifiers and users of SPDs may wish to become aware of the evaluations and testing performed on a specific SPD they have selected for installation. Any selected SPD should satisfy the requirements for use in the specific PDS and surge environment. It is important to note that the specific listings and recognitions associated with original equipment manufacturers of electrical distribution equipment and end-use equipment generally exclude the installation of components that are not described in the associated listing and recognition documentation. Although a specific SPD could have listings and recognitions for the component, it should not be inferred that a specific SPD could be installed in every piece of electrical distribution equipment or end-use equipment.

13.5 Joule ratings

The joule rating should not be a method for specifying SPDs**.** Published joule ratings on SPD components are likely not comparable because some manufacturers of SPDs publish data based on waveforms that are not standardized. In addition, a higher joule rating associated with a specific SPD does not correlate with the performance of the device. The opposite can be true. For example, a component with a high joule rating could provide a high let-through voltage. Generally, this characteristic for SPDs is undesirable. A voltage limiting component rated for a lower operating voltage (maximum continuous operating voltage) would have less joules but be a more effective unit. It is also impossible to compare joule ratings for voltage limiting components with joule ratings for voltage switching components. For these reasons, joule ratings are not accepted as a method for comparing SPDs.

14. Surge-protective device lifetime

All SPDs have a limited effective operational life. Components within SPDs will reach an end-of-life condition. Commonly this is a result of exceeding the maximum voltage or current ratings. No SPD has an infinite lifetime or is completely unaffected by surge events. Ideally, an SPD has the same effective operational life as the facility or PDS where intended to be installed. Specifically, MOVs have an effective operational life that is directly related to the number and magnitude of surge events. Increasing the number, or the size, or both MOVs within a specific SPD will increase the life expectancy of an SPD. As the number of MOVs within a specific SPD determines the surge current rating of the device, a longer effective operational life can be expected. A longer effective operational life can extend well beyond the designed life expectancy of a specific facility or PDS.

SPDs are available on the marketplace with very high single-pulse surge current ratings that exceed the highest surge currents observed in power distribution systems. As there is a nonlinear life expectancy versus surge current for MOVs, high single pulse ratings are specified in the hope of increasing the life expectancy of the SPD for the lower level, real-world surge currents. However, because of many factors, similar single pulse ratings do not equate to the same life expectancy for lower surge current events. NEMA LS-1-1992 [B43]] includes specifications and testing to determine the repetitive surge current rating for SPDs, which provide a better representation of the SPD life expectancy rather than specifying high single-pulse ratings in the hope of achieving longer life.

It is important to choose a surge current rating of an SPD that will provide the expected level of protection over the specified effective operational life of the equipment to be protected. A cost–benefit analysis is suggested when selecting an SPD that is rated for hundreds of years when the application clearly may not warrant such a device.

Variables affecting the effective operational life of SPDs are as follows:

a) The magnitude and duration of the surge current to which an SPD has been subjected.
b) The number of times that an SPD has conducted surge currents.
c) The magnitude and duration of overvoltage conditions to which an SPD has been exposed (Karlicek and Taylor [B34]).
d) Improper electrical connection or jobsite installation of the SPDs.
e) Environmental conditions such as excessive heat and moisture.
f) Any combination of the above.

14.1 Overvoltage failures of surge-protective devices

When MOVs reach an end-of-life condition, they lose their ability to block normal system voltage and begin to conduct current continuously. The continuous current condition creates heat. The MOV initiates a conductive condition identified as thermal runaway that inevitably results in the destruction of the MOV. The resulting destruction of the MOV might expel hot metal fragments, conductive ionized gases, and dense conductive smoke and soot. In addition to immediate hazards, the introduction of such materials into the interior of electrical distribution equipment can damage or compromise an insulation system and result in a cascading effect and serious equipment damage.

Resulting damage from cascading effects can be substantial when the electrical equipment, affected by the damaged MOV, is the service entrance equipment. Thermal runaway conditions are extremely destructive, and SPD manufacturers attempt to mitigate these conditions by using a variety of means. Common methods employed to reduce the effect of SPD thermal runaway conditions are as follows:

a) Enclosure of SPD within a suitable enclosure.
b) Encasement of the MOV arrays within appropriate sealing compound or sand, or both.
c) The use of integral or external overcurrent protective device.
d) The use of integral thermal, cut-off devices as fuse links, solder wire, or thermal squibs.
e) Avoid or limit the use of flammable materials in the enclosure.
f) Any combination of any or all of the above.

Voltage limiting and voltage switching devices are susceptible to failure from overvoltage (swell) disturbances above the rated maximum continuous operating voltage of their components. Each SPD can exhibit a different failure mode. Where MOVs can reach an end-of-life condition caused by thermal runaway, avalanche diodes can reach an end-of-life condition caused by the P–N junction overheating and shorting. Gas tubes can reach an end-of-life condition caused by the electrodes melting.

15. Interactions of surge-protective device operations in a power distribution system

An important consideration in the application of SPDs is their potential interaction with other components or systems in a PDS. Power distribution systems are dynamic in nature. When creating or modifying a PDS, the characteristics of each component that make up a PDS should be evaluated and considered as well as how each component will function and interact with all other components or systems. Protective relaying systems and specifically ground-fault protection systems are sensitive to SPD operations.

15.1 Interactions with ground-fault protection systems

As most SPDs contain MOVs that usually become “shorted” at the end of their useful life, it is important to understand the effects that shorted MOVs can have on a system with ground-fault protection installed. SPDs can either use external or internal overcurrent protective devices to disconnect shorted MOVs from introducing objectionable currents onto the grounding system. When external overcurrent protective devices are used, no overcurrent protective device is installed in the N–G mode, which creates a violation of requirements detailed in the NEC [B44] and can affect the proper operation of the ground-fault protection devices. SPDs that rely on internal overcurrent protective devices have to eliminate the adverse interaction with the ground-fault protective devices as the SPDs internal overcurrent protective devices will activate, disconnecting the shorted MOVs from the circuit.

The objectionable currents can also cause the GFP system to become dysfunctional when ground faults are present. In essence, a true ground fault may not be detected if enough of the fault current returns via the N–G shorted neutral path.

Regular inspections and maintenance of power distribution systems are recommended to ensure that SPDs containing N–G connected components have not become shorted to allow for objectionable current flow that is likely to affect any GFP system. One method of performing these inspections can be obtained using the information contained in Chapter 5 and Chapter 6 of IEEE Std 1100-2005 (*The Emerald Book*) [B26].

15.2 Interaction of surge-protective device operation on other protective relaying systems

Another important factor in the selection of an SPD is its coordination with the control and other protective relays intended to be installed or already installed within a PDS. SPDs containing voltage switching type components provide a crowbar effect when activated. This device diverts the high energy by short-circuiting a high voltage to ground. The short circuit will continue until the current is brought to a low level. The voltage switching device will momentarily reduce the voltage below its steady-state value while it is conducting. The momentary voltage drop can cause certain control and protective relays to deenergize, change states, or “drop out” of the normal operating state. Protective relays often initiate a “trip” function in control schemes that can cause main or feeder circuit breakers to open unexpectedly. The nuisance operation of control and protective relays can cause as much disruption to electrical service and facility operations as the destructive effect of a surge or transient on unprotected equipment. It is recommended that specifiers and users review and compare the operational speed of any applicable protective relays with the functional characteristics of an SPD per its data sheet. The settings of the protective relays may require adjustment.

15.3 Interaction of surge-protective device operation on other protective devices

The SPDs covered in this guide are connected on the load side of the main overcurrent protective device in the service entrance equipment. The device is typically a circuit breaker. The SPDs could be connected via an additional circuit breaker downstream from the main overcurrent protective device. The surge current carrying capacity of the circuit breaker selected for use with an SPD should be considered in the application of the SPD. The suitability of a specific overcurrent protective device for use with a specific SPD, as it relates to surge current carrying capacity, can be determined by either the manufacturer of the overcurrent protective device or the manufacturer of the SPD.

16. Surge-protective device coordination

The need for coordination of overvoltage protective devices, such as SPDs, can best be compared with the understanding and requirements necessary for the coordination of overcurrent devices as fuses and circuit breakers. The developments in overcurrent protection within the electrical industry and their applications have become a fine art; however, the evolution of overcurrent protective devices and their coordination did not occur overnight.

The concept of SPD cascade coordination centers on the proper installation and connection of two or more SPDs at different locations within a PDS. For example, one is connected to the service entrance equipment, and the other is connected in feeder or branch distribution panels or specific end-use equipment. Cascade coordination is achieved when the SPD closest to the source of the impinging surge diverts most of the energy from an impinging surge and a downstream SPD diverts the remaining or residual surge energy. The successful coordination of SPDs requires a thorough understanding of the specific PDS where SPDs are to be connected and a thorough understanding of numerous variables that can affect the functionality of SPDs. Major variables affecting successful coordination of SPDs are as follows:

a) Waveshape and duration of an impinging surge.
b) Distances between the SPDs and the PDS.
c) Distance between the origin of a surge and the sensitive end-use equipment requiring protection.
d) Measured limiting voltage of the SPDs.
e) Surge current capacity of the SPDs.
f) Age of the SPDs.
g) Connections to, and integrity of, the grounding system of the PDS.
h) Modes of protection selected for each SPD in the PDS.
i) Configuration of a PDS.
j) SPDs integrally connected within end-use equipment.

16.1 Waveshapes and durations

Any SPD selected by a specifier or user should be rated for the surge waveshape and duration that is most probable to be experienced at the specific location. No specific models are representative of all surge environments. The complexity of the surge environment is such that no set of test waveforms will ever completely simulate the real-world environment. However, the SPDs are designed and evaluated relative to simulated waveforms that are considered representative for any given location. They are ring waves, high-energy surges, and fast-transients. (Note, however, that fast transients described as "EFT" in IEEE Std C62.41.2-2002 are more an equipment disturbance issue than an SPD stress or performance consideration.) The SPD should be tested with appropriate waveforms per the installation location categories discussed in Clause 8.

16.1.1 Ring waves

Oscillatory surges of relatively high frequency are labeled "ring waves." Ring waves at the higher end of the frequency range have limited energy deposition capability, but can have high peak voltages. Ring waves at the lower end of the frequency range tend to have higher energy deposition capability but lower peak voltages. Most surge voltages propagating throughout indoor low-voltage systems have oscillatory waveforms. Surges impinging on a PDS excite the natural resonance frequencies of the system. These frequencies result in surges that oscillate and create different amplitudes and waveforms at different places in the system. The frequency of oscillation of these surges ranges from less than 1 kHz to more than 500 kHz. For testing purposes, a ring wave was defined with a 0.5 µs rise time and decaying oscillation at 100 kHz, with each subsequent peak being 60% of the amplitude of the preceding peak of opposite polarity.

The fast rate of change of the front of the ring wave can produce the effects associated with nonlinear voltage distribution in transformer and motor windings. Some semiconductors are also sensitive to dv/dt effects, in particular when forced into and out of conducting states or when a transient occurs during a particular phase angle of the supply cycle.

16.1.2 High-energy surges

High-energy surges usually involve a voltage surge or a current surge, or both, depending on the circuit conditions. For test purposes, a combination wave is represented by a 1.2/50 µs voltage surge and a 8/20 µs current surge, with one or the other, but not both, delivered to the test specimen according to impedance. Another type of high-energy test surge described in IEEE Std C62.41.2-2002 is the 10/1000 μs long wave.

The types of high-energy surge events that can deliver enough energy to cause significant damage are as follows:

a) Lightning surges on overhead distribution.

b) Lightning surges originating in overhead lines and traveling in underground cabling systems.

c) Surges generated by fuse operation involving trapped energy in the power system inductance.

d) Surges generated by power-factor correction capacitor switching.

16.1.3 Fast transients

Circuit opening by air-gap switches (relays and contactors) or circuit breakers produce a succession of clearings and reignitions that generate bursts of “fast-ringing” surges in the circuits being switched open and closed. However, these are not likely to be relevant to SPD applications, except perhaps a spurious operation of a voltage-switching SPD with rate-sensitive trigger circuits.

16.2 Lead length

Connecting conductors of SPDs should be as short as possible to achieve optimal SPD performance. Long lead lengths will add to the measured limiting voltage of the SPDs, and it could be necessary to select an SPD with a lower measured limiting voltage for use in that location. The voltage transferred to the equipment will be the sum of the voltage caused by an SPD and that caused by the inductive voltage of the connecting leads. The two voltages will not peak exactly at the same instant but will add together. In general, the lead inductance is assumed as 1 μH/m. The inductive voltage drop caused by an impulse with a rate of rise of 1 kA/μs will be approximately 1 kV/m of lead length. If the steepness of di/dt is greater, this value will increase.

16.3 Distance between the origin of a surge and the end-use equipment

If the distance between an SPD and the equipment to be protected is exceedingly long, some oscillations or reflections could lead to a voltage increase at the equipment terminals of up to two times higher than the limiting voltage, or even more. Despite the presence of an SPD**,** this could cause failure of the equipment intended to be protected. Such voltage increases the influence of the reflection phenomena on the protecting distance because of the oscillatory decaying waveshape relative to the natural frequency of the PDS.

Acceptable distances depend on the type of SPD selected and installed, the configuration of the PDS, the steepness and waveform of the incoming surge, and the connected loads. In particular, this doubling is only possible if the equipment is a high impedance load, or if the equipment is internally disconnected. In general, oscillations may be disregarded for distances less than 10 m. However, such oscillations can occur at less than 10 m for pure capacitive loads. Sometimes equipment has internal protective components (e.g., varistors) that will significantly reduce the amplitude of the oscillatory wave also at longer distances. Care is necessary in this last case to avoid coordination problems between the SPD and the protective component inside the equipment.

16.4 Voltage-limiting surge-protective devices

Specifiers and users of an SPD should know the values and understand the functional characteristics of the voltage-limiting level of each SPD selected for installation. For example, the voltage attenuation and suppression components within a specific device can respond or conduct at different voltage levels particularly if the SPDs selected originate from different manufacturers. SPDs used in conjunction with other SPDs with different voltage-limiting levels can compound the probability of unreliable coordination. Even different SPD models from the same manufacturer can have very different voltage-limiting levels.

16.5 Surge current capacity of the surge-protective devices

The selection of a surge current rating for an SPD should be matched to the expected surge environment and the expected or desired useful life of the device. As discussed in 13.3, the surge current rating of an SPD with MOVs is relative to the diameter of each MOV and the number of MOVs within an SPD. Underrated SPDs, relative to the expected surge current environment, can cause premature aging of the protective device and reduce or eliminate any coordinated surge protection that may have existed after initial installation.

16.6 Grounding of surge-protective devices

As discussed in Clause 11, the existence of a low-impedance grounding system, and the connections of SPDs to the ground system, will have a direct effect on the SPD operation and coordination. Deteriorated grounding systems or improper connections of SPDs to the grounding system can eliminate any possibility of coordination.

16.7 Modes of protection

Properly applying an SPD is dependent on the configuration of the PDS and on equipment connected to the electrical distribution network. The modes of protection of the SPD, i.e., line-to-neutral, line-to-ground, neutral-to-ground, or line-to-line, must be in concert with that of the PDS. For example, if the PDS is a three-phase Wye, 4W+G system, then the modes of protection that could be applicable are line-to-neutral, line-to-ground, neutral-to-ground, and line-to-line. If the PDS is an ungrounded three-phase Delta three wire system, then the modes of protection that are applicable are line-to-line only. Providing line-to-ground protection requires that the SPD be designed and listed for this application (see the NEC [B44]). The installer should use caution in applying SPDs to ungrounded systems. Ungrounded power systems can produce excessively high line-to-ground voltages during certain fault conditions exposing electrical equipment, including SPDs, to voltages that exceed the designed ratings of that equipment.

The modes of protection of the SPD are also dependent on the equipment connected to the electrical distribution network and on the sensitivity of that equipment to overvoltage surges. This is more complicated than merely specifying the proper modes of protection as one is trying to coordinate the SPD with the electrical equipment to ensure protection. As detailed in 9.4, for proper protection, perform a study to determine the potential overvoltage and surge current requirements at the point of interest on the electrical distribution network, consult with the equipment manufacturer to determine if any overvoltage protection has been installed in the equipment, and consult the SPD manufacturer to ensure that the SPD is capable of being applied to that location.

16.8 Power distribution system configuration

It is important that SPDs be specified and installed consistent with the configuration of the PDS. Although all loads connected to a three-phase, four-wire PDS could be connected as three-phase, three-wire, the system voltage has a “line-to-ground” and “line-to-neutral” reference. As such, the system is three-phase, four-wire and not three-phase, three-wire. Electrical codes require that the neutral conductor from a supplying transformer be installed and bonded in the service entrance section of power distribution equipment. Although a neutral conductor may not be required as part of a distribution circuit for loads connected as three-phase, three-wire, an SPD installed in the service entrance equipment may require a “line-to-neutral” mode of protection.

An SPD providing a “line-to-line” and “line-to-neutral” mode protection in the service entrance equipment might not coordinate with SPDs in distribution equipment or with end-use equipment that provides “line-to-line” and “line-to-ground” surge protection. The limiting voltage level for each installation location within the same PDS could inadvertently be different. In such cases, coordination will be impossible.

16.9 Surge-protective devices within end-use equipment

With the intent to provide the best protection for sensitive end-use equipment, there is a perception that surge suppression is best achieved by installing SPDs with low limiting voltages. One method employed by end-use equipment manufacturers is to incorporate MOVs with the end-use equipment that have a maximum continuous overvoltage rating close to, or only slightly above, the rated system voltage of the PDS. Specifiers and users of SPDs, hoping to provide the better protection, also select and install SPDs in a PDS with low limiting voltages.

The perception might be valid if the impedances and voltages in all power distribution systems were static; however, power distribution systems are dynamic in nature and are rarely constant for any significant period. Changing loads within a specific PDS and voltage fluctuations from utilities, including voltage swells, are normal occurrences and should be expected. SPDs with lower limiting voltage ratings cause frequent interventions of the protective devices and accelerate their aging. The best approach or product is not necessarily the one claiming to suppress surges to the lowest levels (Martzloff and Leedy [B40]).

In addition, specifiers and users might not be aware that end-use equipment has MOVs or other SPDs incorporated within their design or construction. Depending on where such end-use equipment is installed in a PDS, the MOVs or SPDs within the equipment could attempt to divert energy for which they were not rated to conduct. Attempting to coordinate SPDs within power distribution equipment with those MOVs or SPDs installed within end-use equipment creates one of the greatest challenges for PDS designers and operators.

16.10 Coordination methodologies

Numerous technical publications seem at first to be conflicting in their respective conclusion on the best methods for successful SPD coordination. The publications suggest variations in the limiting voltage level, surge current rating, and response time for SPDs in service entrance equipment relative to SPDs in downstream power distribution equipment and end-use equipment.

If there is a ringing of an oscillatory voltage throughout the length of a PDS, some publications suggest that coordination is best achieved by installing SPDs at the service entrance equipment with lower voltage limiting levels than an SPD within the distribution equipment or end-use equipment (Hasse et al. [B9], Hostfet et al. [B10], and Standler [B50], [B51]).

If impinging surges are relatively short in duration, some publications suggest that coordination is best achieved by installing SPDs at the service entrance equipment and within the distribution equipment or end-use equipment with the same voltage clamping levels (Lai and Martzloff [B37] and Martzloff and Lai [B39]).

Some publications suggest that coordination is best achieved by installing an SPD at the distribution equipment or end-use equipment with the lower voltage limiting levels than an SPD at the service entrance equipment because an SPD at the service entrance diverts most of the surge current away from the building wiring (Stringfellow and Stonely [B52]).

A closer evaluation seems to indicate that the results of the research and testing were only valid relative to a specific waveform with specific duration, a specific magnitude of current with a specific waveform, a specific response time, or a specific type of suppression component. In summary, there cannot be a single best means of coordination that is applicable for every PDS regardless of its geographic location or utility supplier. Each specifier and user of SPDs will need to understand and evaluate the numerous variables outlined within this document and decide on what protection is actually and clearly needed relative to the specific geographical environment and PDS in which the SPDs will be installed. The application and coordination of SPDs has been intentionally or unintentionally confounded by a plethora of conflicting advertisements, documents, letters, and specification sheets. However, when a specifier and user is clear on the protection actually needed and on the actual or expected conditions associated with the specific environment where a specific SPD is to be installed, then the process of selecting an appropriate SPD is much easier Standler [B50].

17. Summary

Although much of this guide has been dedicated to revealing the risks associated with the selection and application of SPDs, it must be clearly understood that the use of surge-protective devices has indeed proven to be beneficial.

Several key factors to remember when selecting and applying SPDs include the following:

- Match the surge-protective devices to the environment and the operational requirements of the end-use equipment as presented in Clause 4.
- Consider surge origins, the effects, and the magnitude of surges as discussed in Clause 5 through Clause 7.
- Take advantage of the information provided in IEEE Std C62.41.1-2002 and Clause 8 of this standard to be mindful of the typical Category A, B, or C locations when installing surge protection devices.
- Conduct a thorough power distribution assessment as described in Clause 9 when applying surge-protective devices in a given facility.
- Be cognizant of grounded and ungrounded system requirements (as discussed in Clause 10) as they pertain to the selection and installation of surge-protective devices.
- Pay attention to grounding and bonding considerations as discussed in Clause 11.
- Carefully review SPD modes of protection and specifications as discussed in Clause 12 and Clause 13.
- Be mindful of SPD lifetime considerations as well as the interaction of SPD operations in a power system and SPD coordination, as discussed in Clause 14 through Clause 16, when determining the SPD needed for a given application.

Annex A

(informative)

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Annex B

(informative)

Glossary

For the purposes of this document, the following terms and definitions apply. These and other terms within IEEE standards are found in *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B20].

common-mode: The instantaneous algebraic average of two signals applied to a balanced circuit, both signals referred to a common reference.

fault current: A current that flows from one conductor to ground or to another conductor due to an abnormal connection (including an arc) between the two. A fault current flowing to ground may be called a ground fault current.

ferroresonance: A phenomenon usually characterized by overvoltages and very irregular wave shapes and associated with the excitation of one or more saturable inductors through capacitance in series with the inductor.

lightning: An electric discharge that occurs in the atmosphere between clouds or between clouds and ground.

lightning surge: A transient electric disturbance in an electric circuit caused by lightning.

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.

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

normal-mode: The voltage that appears differentially between two signal wires and that acts on the circuit in the same manner as the desired signal.

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: An assembly of one or more components intended to limit or divert surges. The device contains as least one nonlinear component.

system voltage: The rms power-frequency voltage from line-to-line as distinguished from the voltage from line-to-neutral.

transient voltage surge suppressor (TVSS): A device that functions as a surge-protective device (SPD) or surge suppressor.

Annex C

(informative)

IEC earthing (grounding) practices

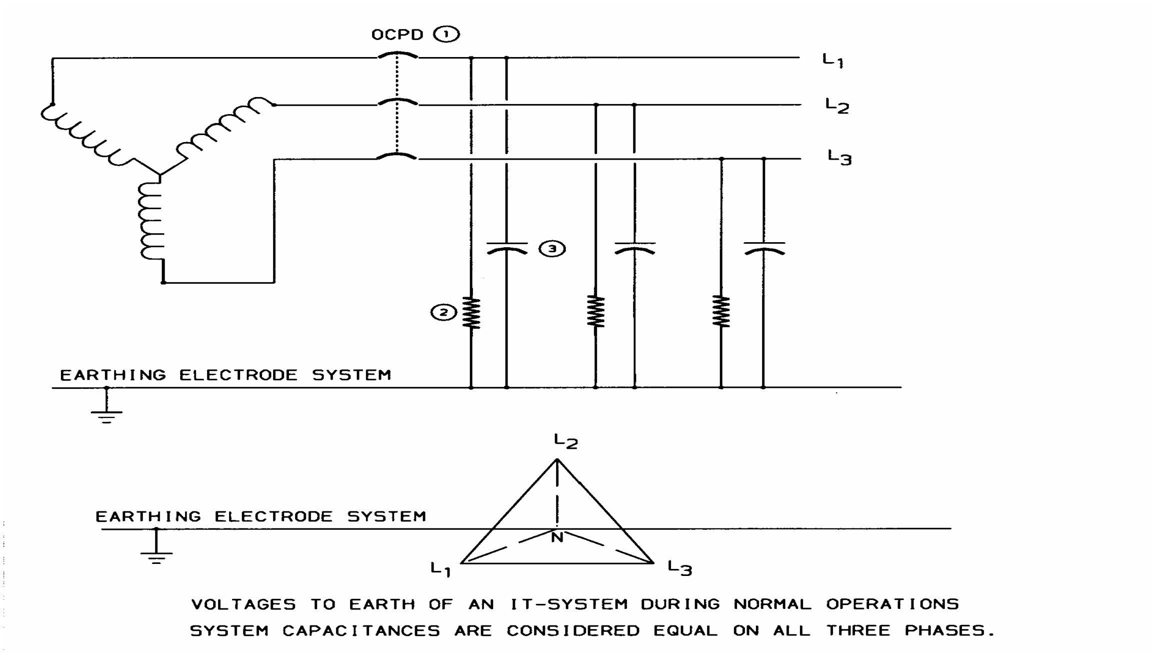
Network systems are classified by the International Electrotechnical Commission (IEC) in IEC 60364-1 [B17] according to the type of grounding, or *earthing*, practices used in the PDS and the methods used for protection against electrical shock in the installation. Although all IEC network systems are not currently used within the United States, some classifications can be applied.

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

The PDS is divided into grounded and ungrounded systems. IEC 60364-1 [B17] classifies network systems according to the configuration of live conductors (including the neutral) and the type of grounding system used. As part of the classification, the following nomenclature is used. The first letter, I or T, shows the relationship between the current carrying conductors and the grounding system. The second letter, T or N, shows the relationship of the accessible conductive parts, including a metallic frame, of the component or equipment in the installation with respect to the grounding system.

First letter (I or T)

The first letter “I” represents *isolation*. The letter “I” signifies that all live parts are isolated from ground or earth, or that points of the network are connected to earth through some impedance as a surge arrester or air gap. The first letter “T” represents earth by using the Latin word, *terra*, meaning earth. The “T” signifies a direct connection of at least one point in the network to earth. Special grounding requirements or practices may be necessary depending on the type of network system used. See Figure C.1 through Figure C.3.

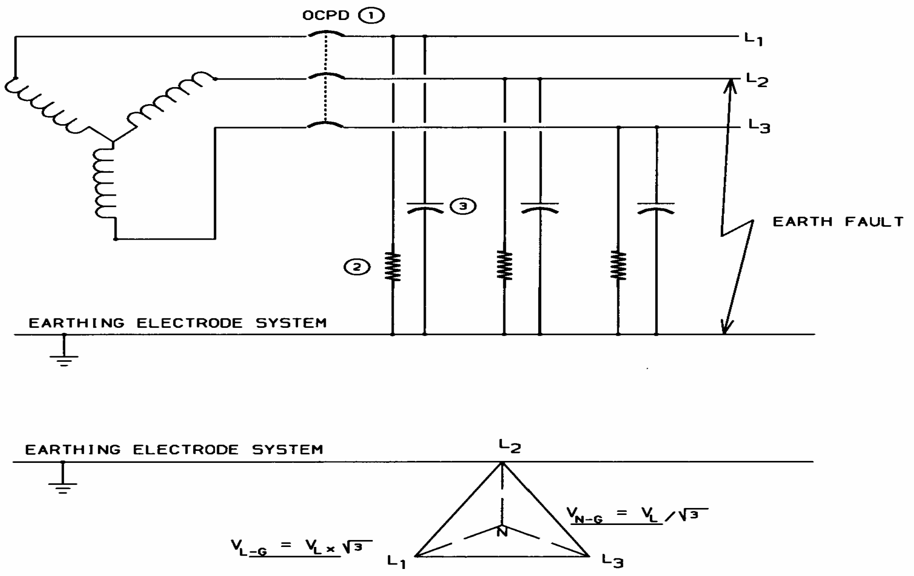


VOLTAGES TO EARTH OF AN IT-SYSTEM DURING NORMAL OPERATIONS
SYSTEM CAPACITANCES ARE CONSIDERED EQUAL ON ALL THREE PHASES.

NOTE:

1. OVER CURRENT PROTECTIVE DEVICE
2. INSULATION RESISTANCE OF CONDUCTOR WITH RESPECT TO EARTH (TYPICAL FOR ALL PHASES)
3. CAPACITIVE REACTANCE IN SYSTEM (TYPICAL FOR ALL PHASES)

Figure C.1— Typical IT system during operation

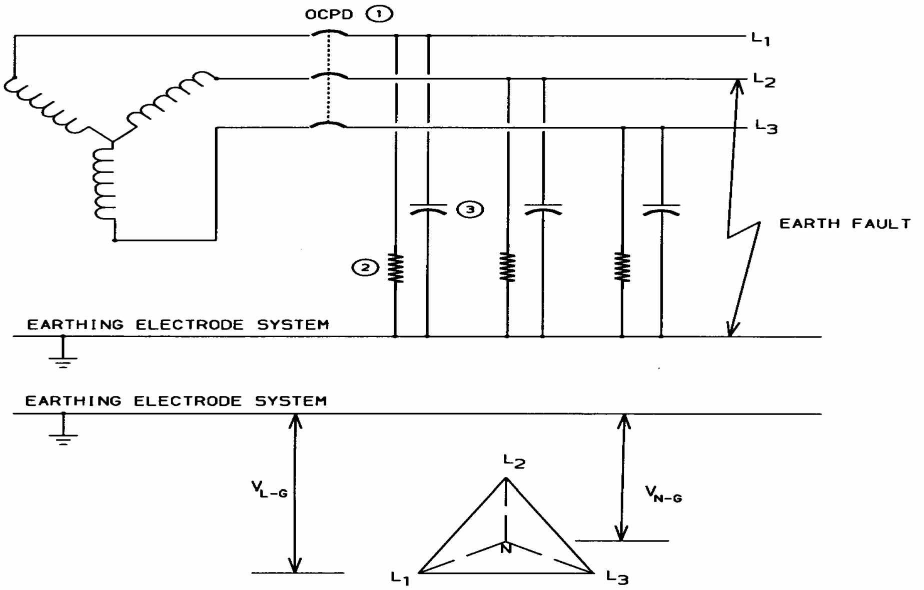


VOLTAGES TO EARTH OF AN IT-SYSTEM DURING A BOLTED FAULT TO EARTH CONDITION. WHEN A SOLID BOLTED FAULT OCCURS ON ONE PHASE THE PSEUDO NEUTRAL POINT IS DISPLACED AND THE VOLTAGE ON THE UNGROUNDED PHASES IS ELEVATED.

NOTE:

1. OVER CURRENT PROTECTIVE DEVICE
2. INSULATION RESISTANCE OF CONDUCTOR WITH RESPECT TO EARTH (TYPICAL FOR ALL PHASES)
3. CAPACITIVE REACTANCE IN SYSTEM (TYPICAL FOR ALL PHASES)

Figure C.2—IT system with a bolted fault



VOLTAGES TO EARTH OF AN IT-SYSTEM DURING AN ARCING FAULT TO EARTH CONDITION.
AN ARCING FAULT TO EARTH IS POTENTIALLY MORE DESTRUCTIVE BECAUSE THE PSEUDO
NEUTRAL POINT CAN BE OFFSET SIGNIFICANTLY FARTHER FROM THE GROUND PLAIN
EACH TIME THE ARC RESTRIKES.

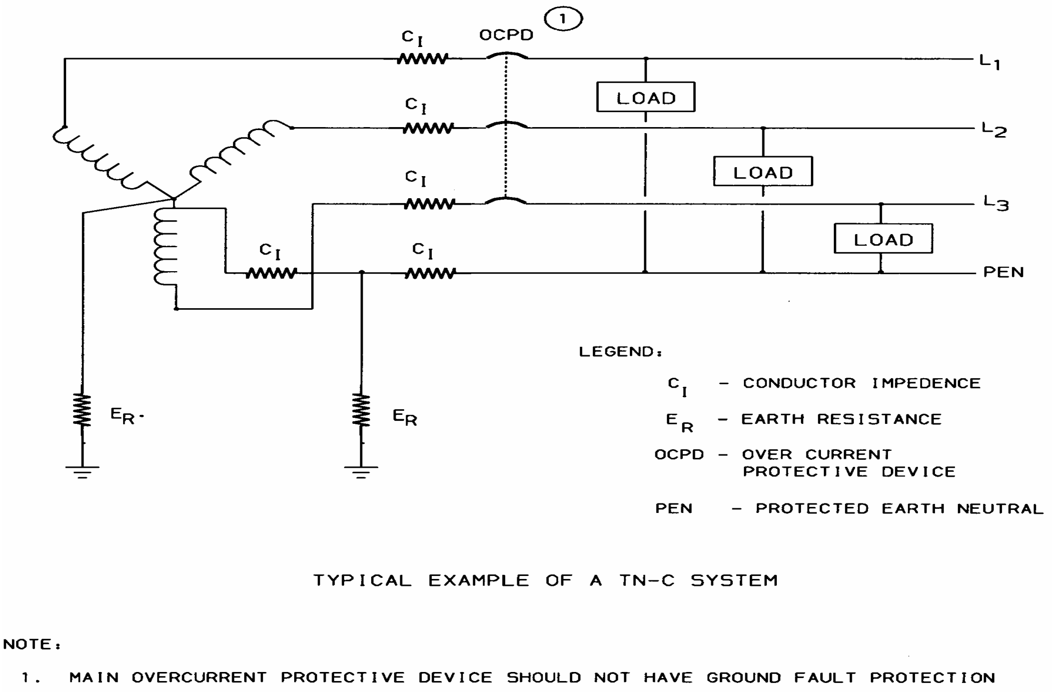
NOTE:

1. OVER CURRENT PROTECTIVE DEVICE
2. INSULATION RESISTANCE OF CONDUCTOR WITH RESPECT TO EARTH (TYPICAL FOR ALL PHASES)
3. CAPACITIVE REACTANCE IN SYSTEM (TYPICAL FOR ALL PHASES)

Figure C.3—IT system with an arcing fault

Second letter (T or N)

The second letter designates the type of connection between the protective equipment–grounding conductor used in the installation and earth. The second letter "T" signifies a direct connection between accessible conductive parts of connected equipment and ground (terra), which is independent of the grounding system that may or may not exist on current carrying conductors of the system. The second letter "N" signifies a direct connection of accessible conductive parts to the ground points of the PDS by means of a PEN (protected earth neutral) or PE (protected earth) conductor. The PDS is then connected to ground. See Figure C.4 through Figure C.7.



LEGEND:

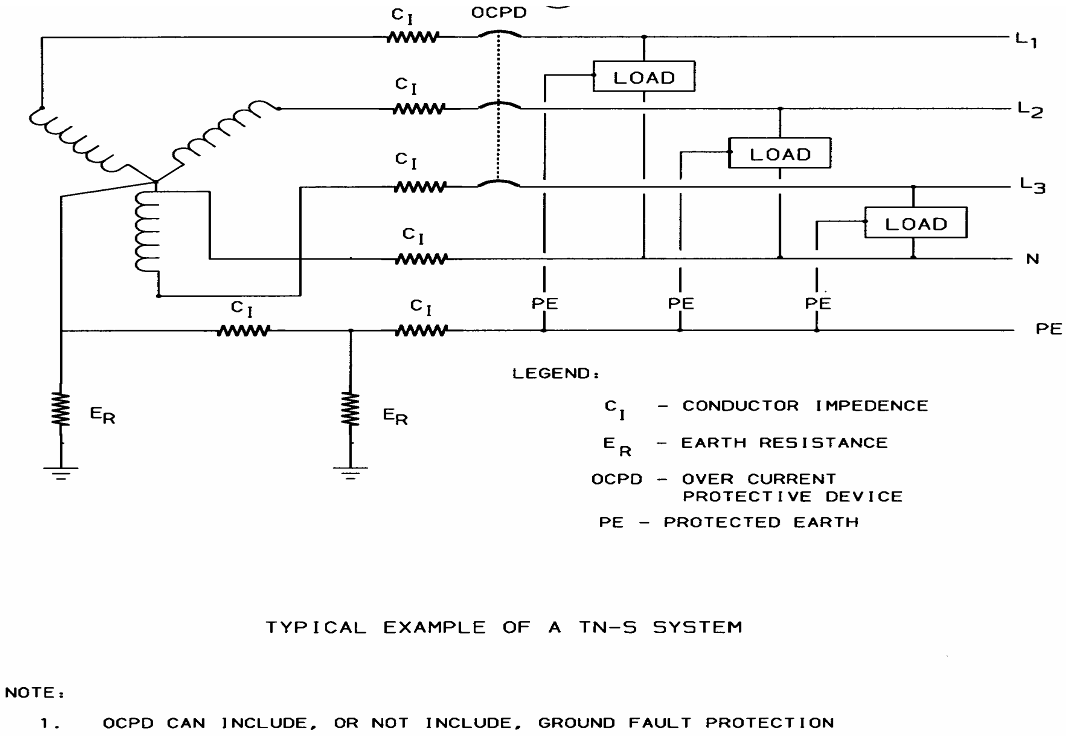
C_I - CONDUCTOR IMPEDENCE
E_R - EARTH RESISTANCE
OCPD - OVER CURRENT PROTECTIVE DEVICE
PEN - PROTECTED EARTH NEUTRAL

TYPICAL EXAMPLE OF A TN-C SYSTEM

NOTE:

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

Figure C.4—Typical TN-C system



LEGEND:

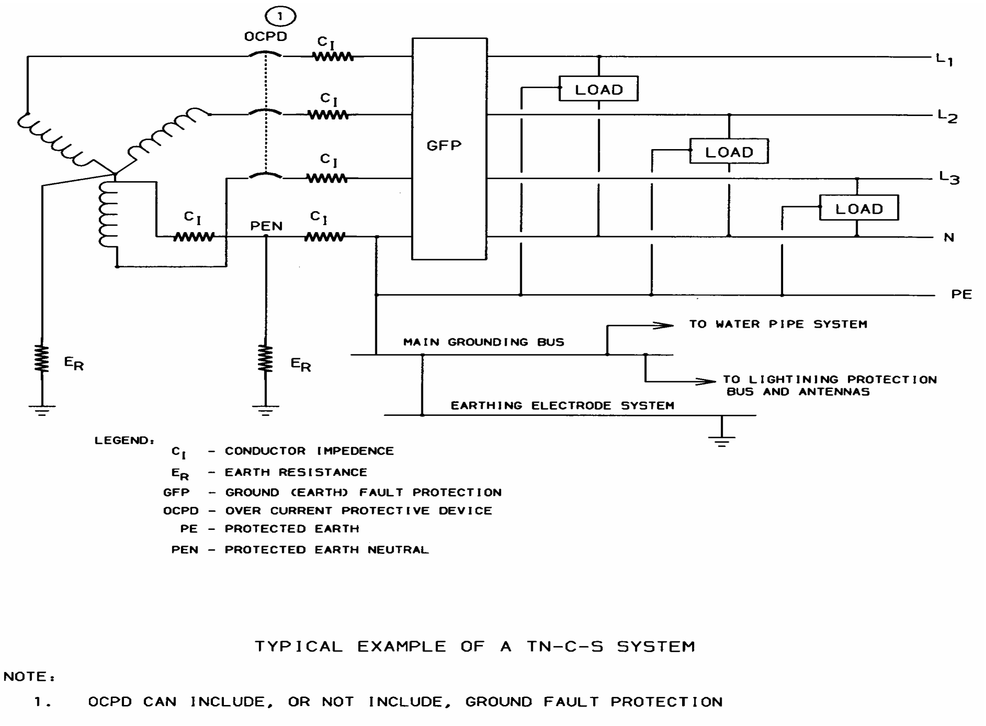
C_I - CONDUCTOR IMPEDENCE
E_R - EARTH RESISTANCE
OCPD - OVER CURRENT PROTECTIVE DEVICE
PE - PROTECTED EARTH

TYPICAL EXAMPLE OF A TN-S SYSTEM

NOTE:

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

Figure C.5—Typical TN-S system

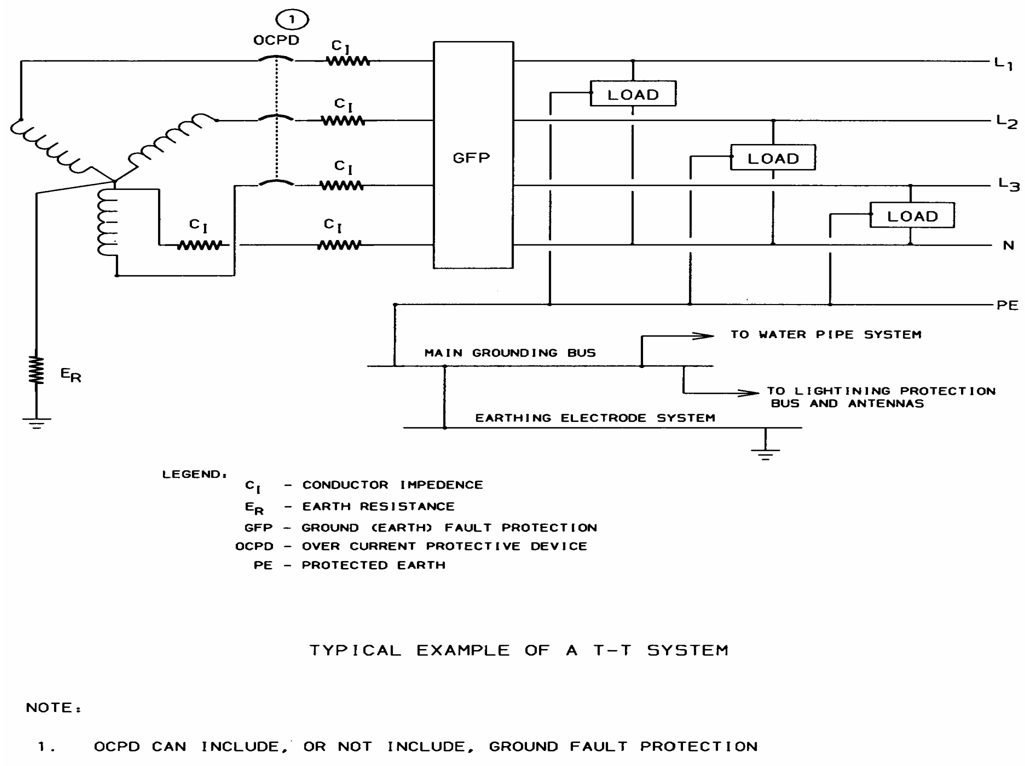


LEGEND:
C_I - CONDUCTOR IMPEDENCE
E_R - EARTH RESISTANCE
GFP - GROUND (EARTH) FAULT PROTECTION
OCPD - OVER CURRENT PROTECTIVE DEVICE
PE - PROTECTED EARTH
PEN - PROTECTED EARTH NEUTRAL

TYPICAL EXAMPLE OF A TN-C-S SYSTEM

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

Figure C.6—Typical TN-C-S system



LEGEND:
C_I - CONDUCTOR IMPEDENCE
E_R - EARTH RESISTANCE
GFP - GROUND (EARTH) FAULT PROTECTION
OCPD - OVER CURRENT PROTECTIVE DEVICE
PE - PROTECTED EARTH

TYPICAL EXAMPLE OF A T-T SYSTEM

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

Figure C.7—Typical T-T system

In IEC network systems, the grounding of the PDS and the means of protection against electric shock are independent considerations. Distribution systems are grounded to limit the voltage rise that can develop from lightning, transient overvoltages, contact with higher voltage conductors, or ground faults that may occur in a PDS. The PDS can be intentionally ungrounded to avoid service interruption when a single ground fault occurs.

See Table C.1.

Table C.1—IEC systems and equipment grounding

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

Third letter (C or S)

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

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

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

TN-C-S Systems

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

Annex D

(informative)

Methods of transient mitigation

Two major methods are used to counter surge events and provide for transient mitigation. These methods are by attenuating or by diverting a transient surge event, or both. Attenuation circuits are sometimes used in SPDs to assist the diverting components in reducing a transient. Note, however, that a filter or attenuation circuit alone is not an SPD by definition of the term *SPD*. Attenuating circuits and "diverting" components will be covered separately and briefly in this annex.

D.1 "Attenuating" devices

Attenuation is provided by inserting filter components in parallel or in series within a circuit. The filter is generally a "low-pass" type. The filter attenuates the transient (high frequency) and allows the power flow (low frequency) to continue undisturbed. As the frequency components of transients are usually several orders of magnitude above the frequency of an ac circuit, an early and simple solution was to install a low-pass filter between the source of the transients and the sensitive loads.

D.1.1 Parallel connected circuits

The simplest form of filter is a capacitor placed across the line. The impedance of the capacitor forms a voltage divider with the source impedance, which results in attenuation of transients at high frequencies. This simple approach, however, has undesirable side effects:

a) Unwanted resonances with inductive components located elsewhere in the circuit leading to high peak voltages. (ferroresonance).

b) High inrush currents during switching.

c) Excessive reactive load on the power system voltage.

Selecting and installing a suitable resistor in series with the capacitor can reduce these undesirable conditions. This is called an "RC" circuit. Being a linear circuit, this type of circuit is only effective for surge mitigation of low-amplitude surges and will not function as desired when subjected to large amplitude surge events, nor to surge of long duration.

A filter circuit is installed within an SPD in parallel between the supply and return conductors. A filter circuit can also consist of a combination of inductors, capacitors, and resistors. Possible modes of connection to an ac power circuit are "line-to-neutral," "line-to-ground," "line-to-line," "neutral-to-ground," or any combination. The impedance of the filter circuit creates a frequency-dependent, voltage divider with the source and load impedances. However, capacitors placed in ground-connected modes can produce leakage currents that could be unacceptable to a specifier or user. Certain applications also have their leakage current restricted by approval or listing agencies.

D.1.2 Series connected circuits

Inductors and capacitors are also used to provide interference mitigation as well as transient protection. These circuits are commonly referred to as "low-pass filters." A low-pass filter is a series-type device containing components in either or both the supply and the return conductors. The low-pass filter can consist of any combination of inductors, capacitors, or resistors. The two most usual configurations of low-pass filters are the L–C and the Pi filters. The L–C, low-pass filter uses inductors in series with the load and a combination of capacitors, inductors, and resistors in parallel. The Pi filter is a balanced-type configuration with capacitors placed in parallel before and after the series inductors.

The limitations to this type of technology for transient protection include:

- The withstand-capacity of the L–C components to the high currents and voltages associated with transients.
- The circuit is linear. The let-through grows with the amplitude of the input transient, in contrast with nonlinear SPDs.
- The relative size and quality of components in L–C circuits for transient protection can limit their use.

D.1.3 “Diverting” devices

D.1.3.1 Voltage-switching types (crowbar)

Voltage-switching type devices involve a switching “ON” action. This action is accomplished by the breakdown of a gas or air between two electrodes or the “turn-on” of a thyristor or other semiconductor device. After switching ON, the voltage-switching type device offers a very low impedance path that diverts the transient away from the parallel connected loads. A voltage-switching device short-circuits a high voltage source to ground. The short circuit will continue until the current is brought to a low level. This device can momentarily reduce the voltage below the steady-state value of the PDS while it is conducting. These devices have two limitations, as presented below.

First, the device will not switch ON until a specific voltage level or rate of rise for some solid-state schemes has occurred. The transition to a switched ON mode or an arc mode takes place by the avalanche breakdown of the gas or air to an ionized state between two electrodes. No significant conduction takes place until the gas or air is ionized. The time delay to switch ON might not be acceptable for sensitive equipment to be protected. The time delay required for the ionization of the medium to occur can result in a significant portion of the overvoltage transient to propagate to the load that is to be protected.

Second, a power current from the steady-state voltage source will follow the discharge. This current is called “follow current.” Depending on the characteristics of the transient currents, the “follow current” might not always be cleared at a natural current zero. Excessive “follow currents” can damage the device. Proper selection of the device is required.

D.1.3.2 Voltage-limiting types (clamping)

A voltage-limiting device is a component having variable impedance depending on the current flowing through the device, or on the voltage across its terminals. These devices exhibit a nonlinear impedance characteristic. Ohm’s Law is applicable, but the equation has a variable resistance (R). A linear impedance is expressed as $I = \mathrm{V}/R$. A nonlinear impedance is expressed as $I = \mathrm{kV}^{\alpha}$, where, α (alpha) represents the degree of nonlinearity of the conduction process.

The variation of the impedance is monotonic. It does not contain discontinuities in contrast to a voltage-switching device, which exhibits a “turn-on” action. The volt-ampere characteristic of these voltage-clamping devices is somewhat time dependent, but they do not involve the same time delay as do spark gap tubes or the triggering of thyristors. The steady-state voltage in the power circuit is not affected by the presence of the device before and after the transient event. The voltage-limiting action results from the nonlinear increase of the current drawn through the device as the voltage increases. The apparent clamping of the voltage results from the increased voltage drop (IZ) in the source impedance caused by the increased current.

These types of devices are dependent on the source impedance to produce the voltage limiting. The voltage-limiting device functions as part of a voltage divider, where the ratio of the divider is not constant but changes as the current changes. If the source impedance is low, then the ratio of the division between the source and the voltage-limiting device will also be low. A voltage-limiting device cannot be effective if the source impedance is at or near zero. When source impedance is near or at zero, there cannot be any voltage dividing action.

D.1.3.3 Silicon avalanche suppressor diodes

Silicon avalanche suppressor diodes (SASDs) function much like regulator-type Zener diodes but have two major differences. The characteristic impedance of an SASD is much lower than that of a Zener diode and the junction size of the SASD is much larger. SASDs have two operating modes: OFF (high impedance) and ON (low impedance). The transition from the OFF state to the ON state is called the avalanche region. The major advantages of SASD technology are extremely fast response time because of low doping of the semiconductor material and effective voltage limiting approaching that of an ideal constant voltage clamp. The original disadvantage of an individual SASD component was energy dissipation capability. Some manufacturers have developed large surface-area SASDs with the intent to create diodes that have an energy rating equivalent to some MOVs.

D.1.3.4 Selenium cells

Early applications of SPDs in low-voltage ac power distribution systems incorporated the use of selenium cells. Selenium-based SPDs apply the technology of selenium rectifiers in conjunction with a process allowing reverse breakdown current at high energy without damaging its internal polycrystalline structures. The cells are built by configuring the rectifier elements on the surface of a metal plate substrate. The metal substrate provides a durable platform with good thermal mass and energy dissipation performances.

Some selenium cell constructions have self-healing characteristics that allow the device to survive energy discharges above its rated values for a limited number of operations. Selenium has a low alpha and poor clamping characteristic, which typically make it less desirable than other technologies except in some hybrid designs. With the introduction of avalanche diodes and MOVs, the application of selenium has been greatly reduced.

D.1.3.5 Varistors

The word *varistor* is a contraction for variable resistor. A varistor functions as a nonlinear, variable impedance as explained above.

D.1.3.6 Silicon carbide varistors

Until the introduction of the MOV, the most common type of varistor was made from specially processed silicon carbide. Silicon carbide varistors have low *alpha values.* Nevertheless, this material has been very successfully applied in high-power, high-voltage surge arresters in conjunction with series gaps. The silicon carbide varistors have been used as a current-limiting resistor to assist some spark gaps in clearing “follow currents.” Low *alpha* values have disadvantages over more recent MOVs offering higher alpha values.

- The protective level is too high relative to the withstand voltage for a device or equipment to be protected.
- For a silicon carbide varistor device operating level to provide a protective level against surges, an excessive standby current would be drawn at normal line voltage.

Silicon carbide varistors were not widely used in low-voltage circuits because of the need to use spark gaps in series with the varistors.

D.1.3.7 Metal-oxide varistors

The MOV was introduced in the early 1970s and is the most commonly used component to mitigate transients. An MOV is composed primarily of zinc oxide with small additions of bismuth, cobalt, manganese, and other metal-oxide trace elements. The structure of the sintered material consists of a matrix of conductive zinc oxide grains separated by grain boundaries providing P–N junction semiconductor characteristics. It is the grain boundaries that are the source of the nonlinear electrical conduction.

A fundamental property of the zinc oxide in the varistor is that the voltage drop across a single interface "junction" between grains is nearly constant. The near-constant or fixed voltage drop allows for predictability of voltage drop across grain boundary, and the voltage drop does not vary for grains of different sizes.

The grain boundaries can be gradually deteriorated with each surge or transient in excess of a certain threshold. MOVs are very sensitive to energy levels beyond specified ratings and are consequently vulnerable to overvoltage conditions lasting more than a few cycles. If the MOV or any SPD component is subjected to energy or voltages beyond its specified rating, the casing or body of the MOV may rupture or explode if the design and installation of the SPD does not address this condition.