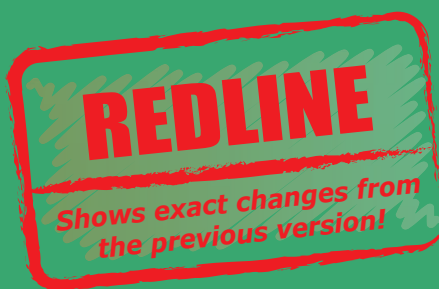




1100™

IEEE Recommended Practice for

**Powering and
Grounding
Electronic
Equipment**



Published by the
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IEEE Std 1100™-2005
(Revision of
IEEE Std 1100-1999)

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IEEE Std 1100™-2005
(Revision of
IEEE Std 1100-1999)

IEEE Recommended Practice for Powering and Grounding Electronic Equipment

Sponsor

Power Systems Engineering Committee
of the
Industrial and Commercial Power Systems Department
of the
IEEE Industry Applications Society

Approved 9 December 2005

IEEE-SA Standards Board

Approved 29 December 2005

American National Standards Institute

Abstract: The *IEEE Emerald Book*™ presents a collection of consensus best practices for the powering and grounding of electronic equipment used in commercial and industrial applications. The main objective is to provide consensus recommended practices in an area where conflicting information and conflicting design philosophies have dominated. The recommended practices described are intended to enhance equipment performance while maintaining a safe installation. A description of the nature and origin of power disturbances is provided, followed by theory on the various parameters that impact power quality. Information on quantifying and resolving power and grounding related concerns using measurement and diagnostic instrumentation and standardized investigative procedures are included. Recommended power protection equipment and wiring and grounding system design practices are presented. Information on telecommunications system power protection as well as grounding, industrial system grounding, and noise control is included. Finally a selection of case studies are presented to support the recommended practices presented throughout the book.

Keywords: commercial applications, electrical power, electronic equipment, grounding, industrial applications, power conditioning, power disturbance, power monitor, power quality

The Institute of Electrical and Electronics Engineers, Inc.
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Print: ISBN 0-7381-4979-9 SH95510
PDF: ISBN 0-7381-4978-0 SS95510

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Liebert Corporation for Figures 7-6, 7-7, 7-8, 7-9, 7-10, 7-11, 7-13, 7-16, 7-17, 7-19, 7-20, 7-21, 7-22, 7-24, 7-25, 7-26, 7-27, 7-28, 7-29, 7-30, 7-31, 9-21, 9-22, 9-24, 9H-1, and 9H-2.

D. R. MacGorman, M. W. Maier, and W. D. Rust, "Lightning Strike Density for the Contiguous United States from Thunderstorm Duration Records," for Figure 3-3.

A. McEachern, *Handbook of Power Signatures*, for Figure 4-42.

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SEMI (Semiconductor Equipment and Materials International, Inc.), SEMI F47-0200, "Specification for Semiconductor Processing Equipment Voltage Sag Immunity," February 2000, for Figure 3-13.

Signals, Power & Grounding Specialists, Inc. (SPGS).

Skyline Marketing Group for Figures 9D-3, 9D-4, 9D-5, and 9D-6.

Ronald B. Standler, *Protection of Electronic Circuits from Overvoltages*, for Figure 4-14.

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Introduction

(This introduction is not part of IEEE Std 1100-2005, IEEE Recommended Practice for Powering and Grounding Electronic Equipment.)

This recommended practice is a publication of the Industry Applications Society (IAS) of the IEEE and is one of the *IEEE Color Books*[®], which relate to industrial and commercial power systems. The recommended practices described are intended to enhance equipment performance from an electric powering and grounding standpoint, while maintaining a safe installation as prescribed by national and local electric code requirements. The purpose of this recommended practice is to provide consensus recommended practices in an area where conflicting information and conflicting design philosophies have dominated.

As the proliferation of digital electronic equipment continues to change the way society utilizes and relies on electric power continuity, the need for standardized practices for power protection and grounding continues to grow. The requirements of the digital society have essentially outgrown the capabilities of the present day electric power supply, and the need for practices that promote system compatibility of both the electric supply and the connected equipment is important from the largest industrial facilities all the way down to home offices. The concept of system compatibility, which is covered extensively in this book, describes the mechanisms of interaction and requirements necessary to ensure that not only does the electrical power equipment connected to its power source operate properly even during moderate power fluctuations, but also that same equipment does not interfere with other equipment connected to the common power system. The responsibility for system compatibility is shared among all parties, including the electric suppliers, the equipment manufacturers, the building designers, the power conditioning equipment manufacturers, and the facility equipment specifiers, and this document supplies methods to ensure that when a system compatibility problem is present, there are adequate means of investigating and resolving the concern. It is also the intent of this document to supply power system design guidelines and recommended practices that would minimize the potential for a system compatibility concern to occur.

To address the topics detailed in the *IEEE Emerald Book*[™], the IEEE Working Group on Powering and Grounding Electronic Equipment was originally formed in 1986 to write a recommended practice. The first *IEEE Emerald Book*[™] was subsequently published in 1992, followed by a revision in 1999. The project was sponsored by the IAS Industrial and Commercial Power Systems Engineering Subcommittee. This recommended practice is intended to complement other recommended practices in the *IEEE Color Books*[®] and has been coordinated with other related codes and standards.

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IEEE Recommended Practice for Powering and Grounding Electronic Equipment

Chapter 1 Overview

1.1 Scope

This ~~recommended practice document~~ presents recommended ~~engineering principles and practices for powering and grounding electronic equipment in commercial and industrial applications. The scope of this document is limited to recommended~~ design, installation, and maintenance practices for electrical power and grounding (including both ~~power-related~~ safety and ~~signal-related~~ noise control) and protection of electronic ~~processing~~ loads such as industrial controllers, computers, and other information technology equipment (ITE) used in commercial and industrial applications.

1.2 Purpose

The main objective is to provide a consensus of recommended practices in an area where conflicting information and confusion, stemming primarily from different viewpoints of the same problem, have dominated. Practices herein address electronic equipment electrical performance and protection issues while maintaining a safe installation, as specified in the National Electrical Code® (NEC®) (NFPA 70-~~1999~~, 2005 Edition) [B1]¹ and recognized testing laboratories' standards. This recommended practice is not intended to replace or to take precedence over any codes or standards adopted by the jurisdiction where the installation resides.

1.3 Background

As electronic loads and ITE proliferate in industrial and commercial power systems, so do problems related to power quality. Powering and grounding electronic equipment continues to be a growing concern for commercial and industrial power system designers. This concern frequently materializes after start-up, when electronic system operating problems begin to occur. Efforts to alleviate these problems have ranged from installing power conditioning equipment to applying special grounding techniques that are not found in conventional safe grounding practice. ~~Grasping for conditioning equipment or "magic" grounding methods is a common response.~~ In some cases this approach has led to unsafe practices and violations of the NEC, without solving operating problems. Many times even after installing power conditioning devices, the protected equipment still fails or does not operate as expected during thunderstorms and power outages. In response to this situation, this recommended practice attempts to provide an understanding of the fundamentals of proper powering and grounding for facilities and electronic equipment as well as examples of the various problems that can arise.

The concept of load and source compatibility is not new. The need to provide power with steady voltage and frequency has been recognized since the inception of the electric utility industry. ~~However, the definition of steady has changed over the years, reflecting the different susceptibility of electronic equipment to the departure from steady conditions~~ Some of the early concerns were flicker of light bulbs due to voltage fluctuations and overheating of motors due to voltage waveform distortion (harmonics). Recognition of these problems led to the development of voluntary standards that contributed significantly to reductions in occurrences.

More recently, transient voltage disturbances associated with lightning and power system switching have emerged as a major concern to manufacturers and users of electronic equipment. The issue of grounding, and particularly how to deal with lightning protection, noise, and safety simultaneously, is complicated by conflicting philosophies advocated by people of different backgrounds. Power-oriented engineers and signal-oriented engineers often differ in their perception of the problem and potential solutions.

¹The numbers in brackets correspond to those of the bibliography in 1.5.

~~Today's~~ Complaints about the quality of power today are not easily resolved because they involve both a multitude of different causes and a variety of specific sensitivities in the affected equipment. A commonly applied solution to power incompatibilities is to install interface equipment such as power conditioners between commercial power and sensitive loads. Difficulties in assessing the need to apply power interface equipment include [the following](#):

~~Since the earliest days of electric power, users have desired that utilities provide electricity without interruptions, surges, or harmonic waveform distortions. Reducing such power line disturbances has always been a concern for utilities. Recently, however, new sources of disturbances have begun to proliferate, just as many loads are becoming more sensitive to these same power disturbances. Some of these disturbances are generated by adjacent equipment and by inadequate wiring and grounding practices. These developments have presented utilities and users with a new set of complex power quality issues that require wide-reaching cooperative efforts in order to be resolved.~~

- a) The inability to quantify precisely how much downtime is power related
- b) The subjective nature of estimating the cost of sensitive load misoperation that is attributable to power line disturbances
- [c\) A reluctance of end users to spend money on equipment they feel is not their responsibility to have to provide when they are already paying for the commercial electric power and for the electronic equipment that is being affected](#)

The cost/benefit aspects of the problem can be addressed from a technical point of view in standards, but detailed economic analysis and specific decisions remain the prerogative of the user. Power system designers, utility companies, and manufacturers of electronic equipment need to cooperate with each other to find effective solutions to reduce the potential sources of interference, reduce the susceptibility of the load equipment, or apply power conditioning equipment.

As in the past, voluntary consensus standards are also needed. Focusing on the technical issues, dispelling misconceptions, and recommending sound practices can assist the user in making informed economic decisions. Two of the goals of this recommended practice are to promote a better understanding of the significant issues and to dispel misconceptions.

Fortunately, powering and grounding an electronic system is fundamentally the same as any electrical system. Estimating the load, matching current and voltage requirements, or planning for future growth involves the same basic information. Similarly, designing an appropriate electrical distribution system, selecting and coordinating overcurrent protection, and assuring voltage regulation makes use of the same engineering practices. Even the principles of grounding for safety can be applied to electronic loads in the same way as to any other load.

The *IEEE Color Books*[®] are an excellent reference library available for designing commercial and industrial power systems of all types. Each *IEEE Color Book*[™] provides recommended practices in a specific subject area. The objective is to assist in the design of safe, reliable, and economical electric power systems by providing the consensus of knowledge and experience of the contributing IEEE members. The *IEEE Emerald Book*[™] is directed specifically at powering and grounding electronic equipment.

1.4 Text organization

The following chapter descriptions provide the reader with a road map of this recommended practice: Chapter 2 provides definitions of the terms that pertain to power quality issues and that are generally not otherwise available in IEEE standards. A description and a definition of power disturbances is included. Also provided [in Chapter 2](#) is a list of terms that have been deliberately avoided in this recommended practice because they have several different meanings and no generally accepted single technical definition.

Chapter 3 provides general needs guidelines. This chapter is intended to identify the relevant codes and standards, as well as [to define](#) the existing electrical environments to which equipment is typically subjected.

These guidelines are established as a basis for the treatment of instrumentation, site surveys, selection of equipment, and recommended practices in subsequent chapters.

Chapter 4 introduces the reader to the fundamental concepts necessary for understanding and applying recommended practices for the design of a compatible and essentially hazard-free interconnection to the power system. Fundamentals not unique to electronic and electrical equipment are treated lightly, or by reference to other standards.

Chapter 5 presents information on available measurement ~~instruments that are~~ [equipment](#) useful for investigating and diagnosing problems in power systems that serve electronic equipment. [Emphasis is on the use of instrumentation that will measure, record, and report power quality related voltage and current fluctuations without error.](#)

Chapter 6 covers site power analyses and site surveys. This chapter presents the fundamentals of how to conduct a site survey for problem identification and diagnosis. The recommended approach ~~is to start~~ [presented suggests getting a clear understanding of the problem and defining all of the survey objectives before starting the audit. Once the key objectives are defined, the approach typically begins](#) with wiring and grounding checks and progresses through voltage disturbance measurements to harmonic analysis [as appropriate vs. the survey objectives.](#)

Chapter 7 ~~(formerly Chapter 8)~~ presents the myriad of available power ~~enhancement~~ [conditioning](#) equipment from the points of view of basic technology, performance, and function. Specification, performance verification, and maintenance are also covered. [The equipment detailed ranges from large scale megawatt sized “whole facility” power conditioners, to small \(less than 100 W\) process control “device level” power conditioners.](#)

Chapter 8 ~~(formerly Chapter 9)~~ covers the recommended design and installation practices for powering and grounding electronic equipment. The intent is to present the Working Group’s collective engineering experience and judgment of effective practices.

[Chapter 9 provides recommendations for powering and grounding telecommunications, information technology, and distributed computing systems \(including Internet equipment\) in commercial and industrial locations.](#) This chapter was a new addition to IEEE Std 1100-1999 ~~and covers the recommended design and installation practices peculiar to the powering and grounding of distributed computer systems and telecommunications equipment and has been considerably expanded in this latest revision.~~ [Recommendations are provided for the building’s grounding and bonding infrastructure for telecommunications; grounding and bonding of electrical and electromagnetic protection devices and apparatus; shielded cabling; premises outside plant telecommunications facilities; and premises tower structures. Recommendations are given for auditing the location for proper powering and grounding of telecommunications.](#) The chapter makes extensive use of existing industry standards, such as ANSI T1 standards, and industry specifications, such as those by ~~Belleore~~ [Telcordia](#) and BICSI.

Chapter 10 is a new addition to the *IEEE Emerald Book*[™]. This chapter describes the grounding and wiring methods to minimize the impact of noise on industrial control systems. It is the intent of the chapter to provide a basic understanding of the principles and recommended practices for the most useful noise prevention techniques. The primary audience for this chapter is the panel builder. The panel builder uses components like programmable logic controllers, servos, sensors, and drives to control a steel rolling mill, a cookie oven, or an amusement park ride. They combine different equipment from many manufacturers often in a one-of-a-kind system. Consequently, the possibility of interference problems is high if proper techniques are not followed.

Chapter 11 (~~formerly Chapter 7~~) presents case histories. These case studies provide examples of real-world performance and safety problems that have been encountered in the field. Cases that are presented have been selected to support the material presented throughout the *IEEE Emerald Book*[™] and to encompass the various power quality concerns, including wiring and grounding related issues, surge protective device (SPD) application, voltage sag concerns, harmonics, transients, use of power quality monitors, and other topics of interest. The case studies illustrate the need to follow specific recommended practices, ~~and indicate potential results~~ and detail specific problems that can be encountered when recommended practices are not followed.

1.5 Bibliography

Additional information may be found in the following source:

[B1] NFPA 70, 2005 Edition, National Electrical Code[®] (NEC[®]).²

²The NEC is published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA (<http://www.nfpa.org>). Copies are also available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

Chapter 2

Definitions

2.1 Introduction

The electronic power community is pervaded by terms that have no scientific definition. One of the purposes of this chapter is to eliminate the use of those words. Another purpose is to define those terms that aid in the understanding of concepts within this recommended practice.

~~Where possible, remainder of~~ This chapter is divided into three parts. First, an alphabetical listing of definitions is provided in 2.2. These definitions were obtained from ~~IEEE Std 100-1996.~~¹ ~~The second choice was to use other~~ appropriate sources, ~~and the final choice was to use a~~ or are new definitions that convey a common understanding for the word as used in the context of this recommended practice.

The reader is referred to *The [Authoritative Dictionary of IEEE Standards Terms \[B1\]](#)*¹ for all terms not listed herein. The second part (2.3) lists those terms that have been deliberately avoided in this document because of no generally accepted single technical definition. These words find common use in discussing distribution-related power problems, but tend not to convey significant technical meaning. The third part (2.4) lists acronyms and abbreviations that are employed throughout this recommended practice.

2.2 Alphabetical listing of terms

~~The primary source for the definitions in this clause is IEEE Std 100-1996.~~ For purposes of this recommended practice, the following terms and definitions apply. *The Authoritative Dictionary* should be referenced for terms not defined in this subclause. This subclause does not include any device or equipment definitions (e.g., *isolation transformers* and *uninterruptible power systems*); the reader is advised to refer to the Index. Most pertinent equipment is described in Chapter 7.

2.2.1 battery return conductor: A conductor that carries dc return current between a dc power source and the loads it serves. Battery return conductors are grounded conductors, usually bonded by one (or more) dc system grounding conductor(s) to proper point(s) of the grounding system. They are usually designated BR or an equivalent acronym, but are sometimes designated by using a “+” or “-” followed by the nominal system voltage (e.g., +48, -130, etc.).

2.2.2 bonding: **(A)** The electrical interconnecting of conductive parts, designed to maintain a common electrical potential. [National Electrical Code (NEC®) (NFPA 70, 2005 Edition)²] **(B)** The permanent joining of metallic parts to form an electrically conductive path that will assure electrical continuity and the capacity to conduct safely any current likely to be imposed. (NEC)

2.2.3 bonding network, common (CBN): **(A)** The principal means for affecting bonding and earthing inside a building. **(B)** The set of metallic components that are intentionally or incidentally interconnected to form the (earthed) bonding network (a mesh) in a building. These components include structural steel or reinforcing rods, metallic plumbing, ac power conduit, equipment grounding conductors (EGCs), cable racks, and bonding conductors. The CBN always has a mesh topology and is connected to a grounding electrode system via one or more grounding conductors. ~~–Note: The CBN may also be known in the public telephone network as an integrated ground plane.~~

2.2.4 bonding network, isolated (IBN): (A) A bonding network that has a single-point connection (single-point ground) to either the CBN or another isolated bonding network. (B) Typically a system-level grounding topology used by the original equipment manufacturer (OEM) to desensitize its equipment to suspected or known site environmental issues such as power fault and surge, lightning, and grounding potential rise. The IBN requires the use of a single-point connection ~~location~~ [window \(SPCW\)](#) (also known in the telephone industry as a *ground window*) to interface the rest of the building metallics (the CBN).

¹The numbers in brackets correspond to those of the bibliography in 2.6.

²Information on references can be found in 2.5.

NOTE—The IBN should not be confused with the insulated grounding receptacle (IGR) circuit discussed in Article 250-146(d) of the NEC. ~~Note: The IBN may also be known in the public telephone network as an isolated ground plane.~~³

2.2.5 commercial power: Power furnished by an electric power utility company.

2.2.6 common bonding network: [See: bonding network, common.](#)

2.2.7 common-mode noise (longitudinal): The noise voltage that appears equally, and in phase, from each current-carrying conductor to ground.

NOTE—For the purposes of this recommended practice, this abbreviated definition extends the existing definition in *The Authoritative Dictionary* (previously given only for signal cables) to the power conductors supplying electronic equipment.

2.2.8 coupling: The association of two or more circuits or systems in such a way that power or signal information may be transferred from one system or circuit to another.

2.2.9 crest factor (of a periodic function): The ratio of the peak value of a periodic function (y_{peak}) to the root mean square (rms) value (y_{rms}); $\text{cf} = y_{\text{peak}}/y_{\text{rms}}$.

2.2.10 critical load: Devices and equipment whose failure to operate satisfactorily jeopardizes the health or safety of personnel, and/or results in loss of function, financial loss, or damage to property deemed critical by the user.

NOTE—This definition refers to function of the device, whereas *The Authoritative Dictionary* definition links the device to the quality of its power supply.

~~2.2.10 degradation failure: See: failure, degradation~~

2.2.11 customer premises equipment (CPE): Any equipment connected by customer premises wiring to the customer side of the demarcation point (network interface). (~~See ANSI T1.318-1994.~~)

2.2.12 dc equipment grounding conductor (DCEG): [The conductor that bonds an equipment frame, cabinet, or other enclosure to the site grounding system. The DCEG may also bond an equipment unit within a frame, cabinet, or enclosure to the site grounding system.](#)

2.2.13 dc system grounding conductor (DCG): [A conductor or conductive path used to provide a connection between one side of a dc source and a point on the site grounding system. The dc source can be a battery plant, a converter plant, or one or more individual dc/dc converters.](#)

2.2.14 differential-mode noise: *See:* **transverse-mode noise.**

2.2.15 direct-reading ammeters: Ammeters that employ a shunt and are connected in series and carry some of the line current through them for measurement purposes. They are part of the circuit being measured.

2.2.16 displacement power factor: *See:* **power factor, displacement.**

2.2.17 distortion factor: The ratio of the root square value of the harmonic content to the root square value of the fundamental quantity, expressed as a percent of the fundamental. ~~Note: Also referred to as~~ See also: **total harmonic distortion.** (~~See~~ IEEE Std 519™)

~~**2.2.16 dropout voltage:** The voltage at which a device will revert to its de-energized position, i.e., the voltage at which a device fails to operate.~~

~~**2.2.17 earth, remote:** The point beyond which further reduction in ground electrode or grid impedance results in negligible effects. (See ANSI T1.318-1994.)~~

2.2.18 dropout: A loss of equipment operation (discrete data signals) due to noise, voltage sags, or interruption. (IEEE Std 1159™)

2.2.19 efficiency: The output real power divided by the input real power.

³Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the recommended practice.

2.2.20 electrical noise: *See:* **noise, electrical.**

~~**2.2.20 failure, degradation:** Failure that is both gradual and partial. Note: In time, such a failure may develop into a complete failure.~~

2.2.21 equipment grounding conductor (EGC): The conductor used to connect the non-current-carrying parts of conduits, raceways, and equipment enclosures to the grounding electrode at the service equipment (main panel) or secondary of a separately derived system (e.g., isolation transformer).

NOTE—This term is defined more specifically in Article 100 of the NEC.

2.2.22 failure mode: The effect by which a failure is observed to occur.

2.2.23 flicker: A variation of input voltage, either magnitude or frequency, sufficient in duration to allow visual observation of a change in electric light source intensity.

~~**2.2.23 foreign potential:** Any voltage and resultant current imposed on telecommunications plant or equipment that is not supplied from the central office or from telecommunications equipment.~~

2.2.24 form factor (periodic function): The ratio of the root square value to the average absolute value, averaged over a full period of the function.

2.2.25 forward transfer impedance: An attribute similar to internal impedance of a power source, but at frequencies other than the nominal (e.g., 60 Hz power frequency). Knowledge of the forward transfer impedance allows the designer to assess the capability of the power source to provide load current (at the harmonic frequencies) needed to preserve a good output voltage waveform. Generally, the frequency range of interest is 60 Hz to 3 kHz for 50 Hz to 60 Hz power systems, and 20 KHz to 25 kHz for 380 Hz to 480 Hz power systems.

2.2.26 ground: (A) A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth or to some conducting body of relatively large extent that serves in place of the earth. (B) High-frequency reference. *See also:* **signal reference structure**.

NOTE—Grounds are used for establishing and maintaining the potential of the earth (or of the conducting body), or approximately that potential, on conductors connected to it and for conducting ground currents to and from earth (or the conducting body).

~~**frequency deviation:** An increase or decrease in the power frequency from nominal. The duration of a frequency deviation can be from several cycles to several hours. *Note:* The IEEE Std 100-1996 definition is “system frequency minus the scheduled frequency.”~~

2.2.27 ground electrode: A conductor or group of conductors in intimate contact with the earth for the purpose of providing a connection with the ground. (~~See the~~ NEC)

2.2.28 ground electrode, concrete-encased: Also known as a *Ufer ground*. A grounding electrode completely encased within concrete, located within, and near the bottom of, a concrete foundation or footing or pad, that is in direct contact with the earth.

NOTE—This term is defined more specifically in Article 250 of the NEC.

~~**2.2.30 ground grid:** A system of interconnected bare conductors arranged in a pattern over a specified area on, or buried below, the surface of the earth. Normally, it is bonded to ground rods driven around and within its perimeter to increase its grounding capabilities and provide convenient connection points for grounding devices. The primary purpose of the ground grid is to provide safety for workmen by limiting potential differences within its perimeter to safe levels in case of high currents that could flow if the circuit being worked on became energized for any reason, or if an adjacent energized circuit faulted. Metallic surface mats and gratings are sometimes utilized for this same purpose. *Note:* This term should not be used when referring to a signal reference structure, which is defined in this clause~~

2.2.29 ground impedance tester: A multifunctional instrument designed to detect certain types of wiring and grounding problems in low-voltage power distribution systems.

2.2.30 ground loop: A potentially detrimental loop formed when two or more points in an electrical system that are nominally at ground potential are connected by a conducting path such that either or both points are not at the same ground potential.

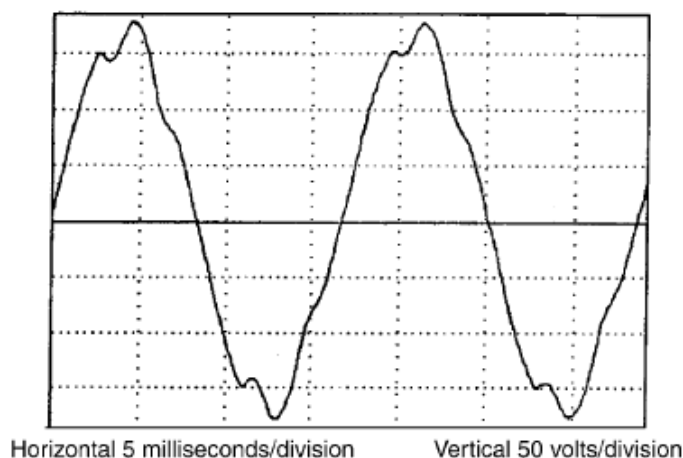
2.2.31 ground, radial: A conductor connection by which separate electrical circuits or equipment are connected to earth at one point. Sometimes referred to as a *star ground*.

2.2.32 ground window: The area through which all grounding conductors, including metallic raceways, enter a specific area. It is often used in communications systems through which the building grounding system is connected to an area that would otherwise have no grounding connection.

~~**2.2.32 grounding conductor (telecommunications), direct current equipment (DCEG):** The conductor used to connect the metal parts of equipment, raceways, and other enclosures to the system grounded conductor (battery return), the conductor providing the system ground reference, or both, at the source of a direct current system (dc power plant)~~

2.2.33 harmonic distortion: The mathematical representation of the distortion of the pure sine waveform.
See also: **distortion factor.**

NOTE—See Figure 2-1.



Reprinted with permission from *The Dranetz Field Handbook for Power Quality Analysis* [B5].

Figure 2-1—Distortion example

2.2.34 impulse: *See:* **transient.**

~~**2.2.34 ground potential shift:** The difference in voltage between grounding or grounded (earthed) structures such as the opposite corners of a metal building. Generally, ground potential shift increases with distance of separation of ground locations and with the frequency or wave front rise time of the resulting current flow. Ground potential shift problems are generally exacerbated by surge events from lightning and utility power sources~~

2.2.35 input power factor (of a system): The ratio at the input of active power (measured in watts or kilowatts) to input apparent power (measured in volt-amperes or kilovolt-amperes) at rated or specified voltage and load. *See also:* **power factor, displacement; power factor, total.**

2.2.36 input voltage range (of a power system): The range of input voltage over which the system can operate properly. (ANSI C84.1)

~~**2.2.36 ground, ufer:** *See:* **ground electrode, concrete-encased.**~~

2.2.37 inrush: The amount of current that a load or device draws when first energized.

2.2.38 insulated equipment ground: An insulated equipment grounding conductor (EGC) runs in the same conduit or raceway as the supply conductors. This conductor is insulated from the metallic raceway and all ground points throughout its length. It originates at an insulated (isolated) grounding receptacle or equipment input terminal block and terminates at the point where neutral and ground are bonded at the power source.

NOTE—This term is defined more specifically ~~in Sections 250.96(b) and 250.146(d) of the NEC, as *isolated equipment ground* in the NEC, but this recommended practice discourages the use of the word *isolated* as this has caused confusion. This equipment ground is not isolated from the grounding system for the electrical distribution system.~~

2.2.39 insulated grounding receptacle (IGR): A receptacle in which the grounding terminal is purposely insulated from the receptacle mounting means, for the reduction of electrical noise (electromagnetic interference) on the grounding circuit. The receptacle grounding terminal shall be grounded by an insulated (isolated) EGC run with the circuit conductors.

NOTE—This term is defined as *isolated ground receptacle* in the NEC, but this recommended practice discourages the use of the word *isolated* as this has caused confusion. This equipment ground is not isolated from the grounding system for the electrical distribution system.

2.2.40 interruption: The complete loss of voltage for a time period.

2.2.41 interruption, momentary (power quality monitoring): (A) A type of short duration variation. (B) The complete loss of voltage (<0.1 pu) on one or more phase conductors for a time period between 0.5 cycles and 3 s. (~~See IEEE Std 1159-1995.~~)

²The numbers in brackets in the source for Figure 2-1 correspond to those of the bibliography in 2.6

2.2.42 isolated bonding network: See: bonding network, isolated.

2.2.43 isolation: Separation of one section of a system from undesired influences of other sections.

~~**2.2.43.2 interruption, sustained (power quality monitoring):** The complete loss of voltage for a time period greater than 1 min.~~

~~**2.2.43.3 interruption, temporary (power quality monitoring):** (A) A type of short duration variation. (B) The complete loss of voltage (<0.1 pu) on one or more phase conductors for a time period between 3 s and 1 min. (See IEEE Std 1159-1995.)~~

2.2.44 linear load: A load that draws a sinusoidal current wave when supplied by a sinusoidal voltage source.

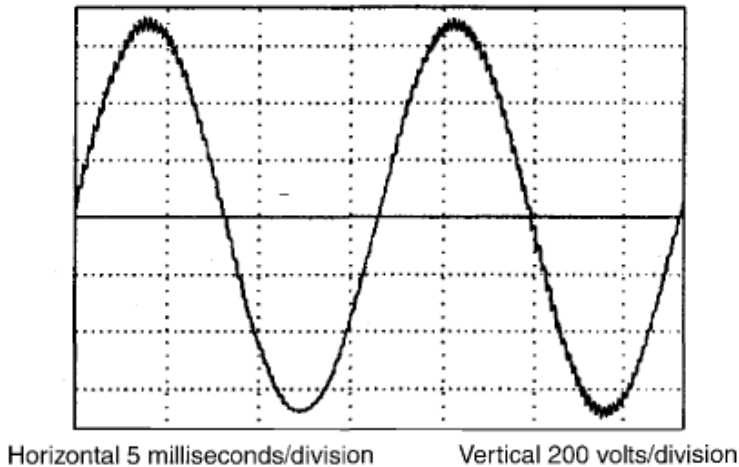
2.2.45 momentary interruption: See: interruption, momentary.

2.2.46 noise, common-mode: See: common-mode noise.

2.2.47 noise, differential-mode: See: transverse-mode noise.

2.2.48 noise, electrical: Unwanted electrical signals that produce undesirable effects in the circuits of the control systems in which they occur.

NOTE—For this recommended practice, *control systems* is intended to include electronic equipment in total or in part (see Figure 2-2).



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Figure 2-2—Noise example

2.2.49 noise, normal-mode: *See:* **transverse-mode noise.**

2.2.50 noise, transverse-mode: *See:* **transverse-mode noise.**

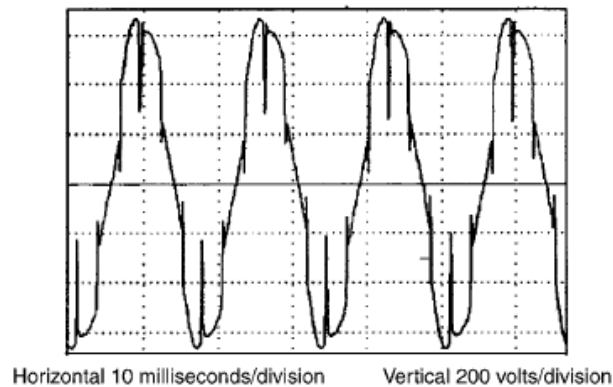
2.2.51 nonlinear load: A load that draws a nonsinusoidal current wave when supplied by a sinusoidal voltage source. (IEEE Std 519)

2.2.52 nonlinear load current: Load current that is associated with a nonlinear load. *See also:* **nonlinear load.**

2.2.53 normal-mode noise: *See:* **transverse-mode noise.**

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

NOTE—See Figure 2-3.



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Figure 2-3—Notches

2.2.55 output (reverse transfer) impedance (of a power source): Similar to forward transfer impedance, but it describes the characteristic impedance of the power source as seen from the load, looking back at the source. *See also:* **forward transfer impedance.**

2.2.56 overvoltage: When used to describe a specific type of long duration variation, refers to an rms increase in the ac voltage, at the power frequency, for a period of time greater than 1 min. Typical values are 1.1 pu to 1.2 pu. *See also:* **swell; transient.** (~~See-IEEE Std 1159-1995.~~)

2.2.57 pathway: A facility for the placement of telecommunications. (~~See-TIA/EIA 607-1994.~~)

2.2.58 phase shift: The displacement between corresponding points on similar wave shapes; it is expressed in degrees leading or lagging.

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

2.2.60 power disturbance monitor: Instrumentation developed specifically to capture power disturbances for the analysis of voltage and current measurements.

2.2.61 power factor, displacement: **(A)** The displacement component of power factor. **(B)** The ratio of the active power of the fundamental wave, in watts, to the apparent power of the fundamental wave, in volt-amperes.

2.2.62 power factor, total: The ratio of the total power input, in watts, to the total volt-ampere input.

NOTE—This definition includes the effect of harmonic components of current and voltage and the effect of phase displacement between current and voltage.

2.2.63 power quality: The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment.

2.2.64 radial ground: *See: ground, radial.*

2.2.65 recovery time: Specifies the time needed for the output voltage or current to return to a value within the regulation specification after a step load or line change.

NOTE 1—Clarification notes from *The Authoritative Dictionary* are excluded.

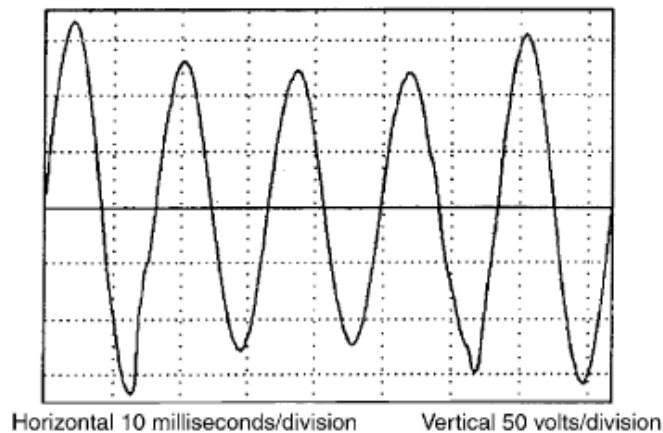
NOTE 2—For this recommended practice, recovery time may also indicate the time interval required to bring a system back to its operating condition after an interruption or dropout.

2.2.66 safety ground: *See: equipment grounding conductor.*

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

NOTE 1—The IEC terminology is *dip*.

NOTE 2—See Figure 2-4.



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Figure 2-4—Sag

2.2.68 shield: Braid copper, metallic sheath, or metallic-coated polyester tape (usually copper or aluminum) applied over the insulation of a conductor or conductors for the purpose of reducing electrostatic coupling between the shielded conductors and others that may be either susceptible to, or generators of, electrostatic fields (noise). When electromagnetic shielding is intended, the term *electromagnetic* is usually included to indicate the difference in shielding requirements and material.

2.2.69 shielding: The process of applying a conducting barrier between a potentially disturbing noise source and electronic circuitry. Shielding is used to protect cables (data and power) and electronic circuits. Shielding may be accomplished by the use of metal barriers, enclosures, or wrappings around source circuits and receiving circuits.

2.2.70 signal reference structure (SRS): A system of conductive paths among interconnected equipment that reduces noise-induced voltages to levels that minimize improper operation. Common configurations include grids and planes.

2.2.71 single-point connection bar: A copper bus bar located entirely within the single-point connection window (SPCW) and serving as a means for bonding the metallic conductors associated with the isolated (insulated) bonding network (IBN) to ground. After passing through the SPCW, these conductors must remain insulated from the common bonding network (CBN); no additional paths to ground, intentional or unintentional, are permitted inside the IBN.

2.2.72 single-point connection window (SPCW): The interface or transition region between an IBN and CBN, typically envisaged as a sphere with a diameter of 2 m (6 ft).

~~2.2.72 star ground: See: ground, radial.~~

2.2.73 single-point connection (SPC): Unique location where an IBN is connected to the CBN, usually to the grounding electrode system or its extension.

~~2.2.73 star connected circuit: A polyphase circuit in which all the current paths of the circuit extend from a terminal of entry to a common terminal or conductor (which may be the neutral conductor). Note: In a three-phase system this is sometimes called a Y (or wye) connection.~~

2.2.74 slew rate: Rate of change of (ac voltage) frequency.

2.2.75 surge: See: transient.

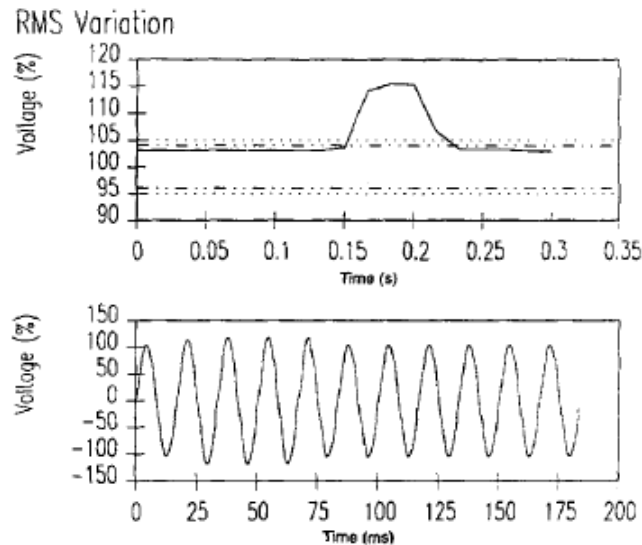
2.2.76 surge protective device (SPD): A device that is intended to limit transient overvoltages and divert surge currents. It contains at least one nonlinear component.

~~2.2.76 surge reference equalizer: A surge protective device used for connecting equipment to external systems whereby all conductors connected to the protected load are routed, physically and electrically, through a single enclosure with a shared reference point between the input and output ports of each system.~~

2.2.77 surge suppressor: A device operated in conformance with the rate of change of current, voltage, power, etc., to prevent the rise of such quantity above a predetermined value.

2.2.78 swell: An increase in rms voltage or current at the power frequency for durations from 0.5 cycle to 1.0 min. Typical values are 1.1 pu to 1.8 pu. (IEEE Std 1159)

NOTE—See Figure 2-5.



Source: IEEE Std 1159.

Figure 2-5—Swells occurring upon recovery from a remote system fault

2.2.79 telecommunications: Any transmission, emission, and reception of signs, signals, writings, images, and sounds, i.e., information of any nature by cable, radio, optical, or other electromagnetic systems. (TIA/ EIA 607)

2.2.80 telecommunications equipment room (TER): A centralized space for telecommunications equipment that serves the occupants of the building.

2.2.81 total harmonic distortion (THD): *See:* **distortion factor.**

2.2.82 total power factor: *See:* **power factor, total.**

2.2.83 transfer time (uninterruptible power supply): The time that it takes an uninterruptible power supply (UPS) to transfer the critical load from the output of the inverter to the alternate source, or back again.

2.2.84 transient: A subcycle disturbance in the ac waveform that is evidenced by a sharp, brief discontinuity of the waveform. May be of either polarity and may be additive to, or subtractive from, the nominal waveform. *See also:* **notch; overvoltage; swell.**

2.2.85 transient voltage surge suppressor (TVSS): A device that functions as an SPD or surge suppressor.

2.2.86 transverse-mode noise (with reference to load device input ac power): Noise signals measurable between or among active circuit conductors feeding the subject load, but not between the EGC or associated SRS and the active circuit conductors.

~~**2.2.86 unbalanced load regulation:** A specification that defines the maximum voltage difference between the three output phases that will occur when the loads on the three are of different levels.~~

2.2.87 undervoltage: When used to describe a specific type of long duration variation, refers to an rms decrease in the ac voltage, at the power frequency, for a period of time greater than 1 min. Typical values are 0.8 pu to 0.9 pu. (IEEE Std 1159)

2.2.88 voltage distortion: Any deviation from the nominal sine waveform of the ac line voltage.

2.2.89 voltage regulation: The degree of control or stability of the rms voltage at the load. Often specified in relation to other parameters, such as input voltage changes, load changes, or temperature changes.

2.3 Words avoided

The following words have a varied history of usage, and some may have specific definitions for other applications. It is an objective of this recommended practice that the following ambiguous words not be used to generally describe problem areas nor solutions associated with the powering and grounding of electronic equipment:

Blackout

Brownout Clean

ground Clean

power

Computer grade ground

Conducting barriers

Dedicated ground

Dirty ground

Dirty power

Equipment safety grounding conductor

Frame ground Frequency shift Glitch

Natural electrodes

Power surge

Raw power

Raw utility power

Shared circuits

Shared ground

Spike

Subcycle outages

Type I, II, III power disturbances

2.4 Acronyms and abbreviations

The following [acronyms and abbreviations](#) are utilized throughout this recommended practice:

ACEG	ac equipment grounding conductor
ALVRT	automatic line voltage regulating transformer
ASAI	average service availability index
ASD	adjustable-speed drive
CAD	computer-aided design
CATV	cable accessed television
CBEMA	Computer and Business Equipment Manufacturers Association
CBN	common bonding network
CDCPS	centralized dc power system
CEA	Canadian Electrical Association
CG	cloud-to-ground
CMR	common-mode rejection
CO-OSP	customer-owned outside the plant
COTC	central office trunk cable
CPC	computer power center
CPE	customer premises equipment
CPU	central processing unit
CRT	cathode-ray tube
CT	current transformer
CVT	constant voltage transformer
DCEG	dc equipment grounding conductor (~~telecommunications~~)
DCG	dc system grounding conductor
DVR	dynamic voltage restorer
EFT	electrical fast transient
EGC	equipment grounding conductor
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EMT	electrical metallic tubing
EPRI	Electric Power Research Institute
ESD	electrostatic discharge
FCC	Federal Communication Commission
FFT	fast Fourier transform
FMC	flexible metal conduit
GPR	ground potential rise
GTO	gate turn-off
~~HF~~	~~high frequency~~
IBA	inside building area
IBN	isolated (insulated) bonding network
IEC	International Electrotechnical Commission
IG	~~isolated~~ /insulated ground or grounding
IGR	insulated grounding receptacle
IMC	intermediate metal conduit
IT	information technology
~~ITC~~	~~Information Technology Industry Council~~
ITE	information technology equipment
ITI	Information Technology Industry Council (also known as ITIC)
LAN	local area network
LDC	line drop compensator
LPS	lightning protection system
LVD	low-voltage disconnect
MCBN	mesh common bonding network
MCT	metal cable tray

M-G	motor-alternator/generator
MIBN	mesh isolated (insulated) bonding network
MOV	metal-oxide varistor
MPG	multipoint grounding
MTBF	mean time between failures
NEC	National Electrical Code
NEMA	National Electrical Manufacturers Association
NEMP	nuclear electromagnetic pulse
NIST	National Institute of Standards and Technology
NPL	National Power Laboratory
NRTL	nationally recognized testing laboratory
OBA	outside building area
OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
OSP	outside plant
PABX	private automatic branch exchange
PC	personal computer
PCC	point of common coupling
PDU	power distribution unit
PoE	Power over Ethernet
~~PQ~~	~~power quality~~
POUTS	point-of-use transfer switch
PTN	public telephone network
PWM	pulse-width modulation
RAA	restricted access area
RFI	radio-frequency interference
RMC	rigid metal conduit
rms	root mean square
SCBN	sparse common bonding network
SCR	silicon-controlled rectifier
ScTP	screened twisted pair
SDS	separately derived ac system
~~SE~~	~~service entrance~~
SIBN	star isolated (insulated) bonding network
S-MIBN	sparse-mesh isolated (insulated) bonding network
SMPS	switched-mode power supply
SPC	single-point connection
~~SRGG~~	~~signal reference ground grid~~
SPCW	single-point connection window
SPD	surge protective device
SPG	single-point ground or grounding
SRE	surge reference equalizer
SRG	signal reference grid
SRGP	signal reference ground plane
SRP	signal reference plane
SRS	signal reference structure
SSB	solid-state circuit breaker
SSTS	solid-state transfer switch
STATCON	static condenser
STS	static transfer switch
Telco	telecommunications company
TER	telecommunications equipment room
TGB	telecommunications grounding bus bar
THD	total harmonic distortion

TIA	Telecommunications Industry Association
<u>TMGB</u>	<u>telecommunications main grounding bus bar</u>
<u>TSP</u>	<u>telecommunications service provider</u>
TTE	telecommunications terminal equipment
TVSS	transient voltage surge suppressor
UL	Underwriters Laboratories
UPS	uninterruptible power supply
UTP	unshielded twisted pair
VDT	video display terminal
VFD	variable-frequency speed drive

2.5 Normative references

The following referenced documents are indispensable for the application of this recommended practice. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies. ~~This recommended practice shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.~~

ANSI C84.1-~~1995~~, American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz).⁴

ANSI T1.318-~~1994, American National Standard for Telecommunications—~~, Electrical Protection Applied to Telecommunications Network Plant at Entrances to Customer Structures or Buildings.

IEEE Std 142-~~1991~~TM, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (*IEEE Green Book*).^{5,6}

IEEE Std 519-~~1992~~TM, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.

IEEE Std 1159-~~1995~~TM, IEEE Recommended Practice for Monitoring Electric Power Quality.

NFPA 70, 2005 Edition, National Electrical Code® (NEC®).⁷

TIA/EIA 607, Commercial Building Grounding/Bonding/Requirement Standard.⁸

⁴ANSI publications are available from the Sales Department, American National Standards Institute, ~~11~~ 25 West ~~42nd~~ 43rd Street, ~~13th~~ 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

⁵IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

⁶The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

2.6 Bibliography

Additional information may be found in the following sources.

[B1] IEEE 100 ~~1996~~, [The Authoritative Dictionary of IEEE Standards Electrical and Electronics Terms](#).

[B2] IEEE Std C62.41TM-1991, IEEE Recommended Practice for Surge Voltages in Low-Voltage AC Power ~~Systems~~, [Circuits](#).

[B3] IEEE Surge Protection Standards Collection (C62), 1995 Edition.

[B4] McEachern, A., *Handbook of Power Signatures*. Foster City, CA: Basic Measuring Instruments, 1988.

[B5] *The Dranetz Field Handbook for Power Quality Analysis*. Edison, NJ: Dranetz Technologies, Inc., 1991.

⁷The NEC is published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA (<http://www.nfpa.org>). Copies are also available from the Institute of Electrical and Electronics Engineers, [Inc.](#), 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

⁸~~TIA~~/EIA publications are available from Global Engineering [Documents](#), 15 Inverness Way East, Englewood, CO 80112-~~5704~~, [USA](#), ~~tel. (303) 792-2181~~ (<http://global.ihs.com/>).

Chapter 3

General needs guidelines

3.1 Introduction

The need to provide reliable power with a steady voltage and frequency has been recognized since the inception of the electric utility industry. However, the engineering reality of a large power system is that disturbances are unavoidable. These disturbances in the quality of power delivered can occur during the normal operation of the electric power system, like switching of a power factor correction device, or during abnormal events, like clearing a feeder short circuit. Depending on end-user equipment or process immunity, damage, operational upset, or no effect may be the result. An incompatibility may be corrected at the utility, at the equipment, or by adding some power conditioning in between, and blame is difficult to place. This dichotomy may be a source of misunderstandings, at best, or a source of disputes, at worst, between suppliers and users of electric power, and between manufacturers and users of susceptible, sensitive equipment. One of the goals of this recommended practice is to promote better understanding of the significant compatibility issues and to dispel some misconceptions about how to avoid or correct problems of incompatibility.

This chapter presents a brief description of the nature of power quality problems, of possible solutions, and of the resources available for dealing with these problems. A brief historical review of the evolution of interest in power quality and resolution of some of the earlier conflicts provides a perspective on solving today's problems.

3.1.1 Historical perspective

As public expectations of uniform lighting intensity grew and as more manufacturers began to use electric motors to drive production lines, utilities adopted stricter standards for voltage regulation. During the 1930s, utilities also found that they had to pay increasing attention to voltage disturbances caused by customer equipment on their distribution lines. Research showed that flicker in incandescent lamps caused by voltage fluctuations could be perceived even if the pulsation on the power line was only a third of a volt on a 120 V system. This type of problem led to an increasing number of industry standards for end-use equipment aimed at reducing voltage fluctuations sent back along a power line.

A somewhat different problem arose during the 1950s as air conditioners rapidly became popular. When early models were switched on, so much energy was used to get their compressors started that the incoming line voltage was temporarily reduced and the motors often could not reach operating speed, ran poorly, or stalled. Fortunately, in this case, a remedy was readily available—adding power-factor correction capacitors in the system.

The reason complaints about the quality of power today cannot be handled so simply is that they seem to reflect both a multitude of different causes and a variety of specific sensitivities in the customer equipment most affected. Just as the air conditioner problems were eventually solved by a coordinated effort among affected parties, so too can new standards on equipment and on levels of permissible voltage distortions help guide the design and application of both sensitive electronic equipment and heavy-duty apparatus. Such standards will have to be applied much more selectively than in the past, however, and address a much more complex set of issues.

3.1.2 Proliferation of power electronic equipment

The advent of electronic power conversion has been widely applauded by users, but the drawbacks from the point of view of power quality have not always been recognized. The very advantages of solid-state devices that made possible modern switching power supplies, inverter-rectifiers, high-frequency induction heating, and adjustable-speed drives also make these power converters into generators of harmonic currents and additional sources of line-voltage drops. Thus, in addition to the disturbances generated by the normal operation of the familiar power delivery and load equipment, the disturbances resulting from the new electronic loads must be taken into consideration.

Harmonic currents caused by many types of customer load and utility equipment provide an example of this complexity. For many years, harmonic currents originated mainly from a few large-scale sources, such as arc furnaces and high-voltage dc transmission terminals. In these cases, they could be removed ~~with relative ease~~ by placing a large (and expensive) filter between the source and the main power line. Today, however, significant power line harmonics are being caused by many small, widely dispersed customer loads, such as rectifiers and solid-state controls for adjustable-speed motors. At the same time, an increasing number of other customers are using ~~sensitive~~ susceptible equipment, such as computers, the operation of which may be adversely affected by harmonics.

It would not be economically feasible to detect and filter each small source of harmonics or to isolate each susceptible load from all power line disturbances. A more practical approach is to control harmonics by agreement on limits for emission levels with filters installed on major offending loads, while defining an acceptable susceptibility level for equipment. Unusually susceptible electronic equipment may be supplied by special power conditioning interfaces, external to, or incorporated with, the equipment. Such an approach will require collaboration among utilities, equipment manufacturers, users, regulatory agencies, and standards-setting bodies.

3.1.3 Proliferation of microelectronic equipment

Increased use of microelectronics in equipment, controls, and processes has also increased the need to consider the quality of powering and grounding systems in the industrial sector. Many tools and equipment are electronic-processor based as factories become more automated and process intensive. Programmable logic systems control electronic adjustable-speed drives and servos based on inputs from electronic sensors and resolvers. Often the mechanical aspects of these processes, such as web tensioning, spindle acceleration, conveyor speed, extruder flow, or spray pressure, cannot tolerate variations caused by momentary ~~power dips~~ voltage fluctuations.

In the commercial sector we find personal computers (PCs), fax machines, copiers, ~~and printers that are now combining with~~ electronic fluorescent lighting, adjustable-speed heat pumps, and various electronic communications, ~~will likely lead to an all-electronic and paperless office~~. Even in the residential sector, we find electronics in every room from toys and tools to microwave ovens. Personal computers connected to the Internet, home entertainment systems, VCRs, CD and DVD players, and digital clocks abound. ~~In the near future~~ We can expect proliferation of electronically driven heat pumps, washing machines, and lighting—~~eventually we will see as well as~~ microwave clothes drying, electric vehicle battery charging, and the “all electronic kitchen.”

Many of these electronic-based appliances are sensitive to voltage variations that were not noticed in the past. We now have more electronics in the power system than ever before and the forecast is for increasing levels. The bottom line is that our equipment has changed radically and a key question is, “Can the power supply as designed handle it?” Disturbance mitigation and power conditioning equipment, and associated costs, are well known but there is no clear assignment of financial responsibility.

3.1.4 The need for quality of power standards

Emerging concerns about electronic equipment upset and related issues have resulted in more attention to the quality of the power necessary for successful operation. Along with the need for quality power is the need for practical compatibility levels of end-user equipment, and for definition of economic responsibility in the producer-user partnership. The term *power quality* is now widely used, but objective criteria for measuring the quality of power—a prerequisite for quantifying this quality—need better definition. A high level of power quality is generally understood as a low level of power disturbances, however a high level of equipment tolerance may also be an effective solution. Agreement on acceptable levels of disturbances and of tolerance to these disturbances is needed.

Another difficulty in assessing the need for an interface between the utility power and susceptible loads is the subjective nature of estimating the cost of equipment misoperation attributable to power disturbances. This particular aspect is addressed from the technical point of view in this recommended practice, but the detailed economics are beyond its scope.

3.1.5 Conflicting design philosophies for performance and safety

The issue of power quality is made more difficult by conflicting philosophies advocated by people of different technical backgrounds and commercial interests. An example of this problem is found in the apparent conflicts resulting from interpretations of grounding requirements. The general requirement of a safe configuration and a safe operation for a power system is endorsed by all parties (utilities, users, regulatory bodies, voluntary standards organizations, etc.), but in some instances these requirements translate into wiring practices alleged to interfere with smooth operation of electronic systems.

Many anecdotal case histories have been encountered where system designers complain the requirements of the National Electrical Code® (NEC®) (NFPA 70, 2005 Edition)¹ prevent their system from performing in a satisfactory manner. This apparent conflict of philosophy can only be settled by giving safety the prevailing directive. That prevailing directive is precisely the purpose of the NEC, and correct application of the NEC articles does not prevent satisfactory operation of properly wired and grounded installations. If any adaptations have to be made for the system to operate satisfactorily, the equipment manufacturer must incorporate them in the equipment design, rather than ask for deviations from the NEC.

3.2 Power quality considerations

3.2.1 General discussion

Power systems operate with a constant line voltage, supplying power to a wide variety of load equipment. Power levels range from a few watts to megawatts, and the voltages at which the energy is generated, transported, and distributed range from hundreds of volts to hundreds of kilovolts. Transmission and primary distribution of this power are made at high voltages, tens to hundreds of kilovolts, in order to provide efficient and economic transportation of the energy over long distances. Final utilization is generally in the range of 120 V (typical residential) to less than one thousand [volts](#) (industrial), and a few thousands of volts for larger loads.

At all these voltage and power levels, no matter how high, the equipment is dependent upon maintenance of a normal operating voltage range. At higher than normal levels, there is limited capability for component voltage withstand. At lower than normal levels, the equipment performance is generally unsatisfactory or there is a risk of equipment damage. These two disturbances, excessive voltage and insufficient voltage, are described with different names depending on their duration. There are also types of disturbances, as described in 3.2.2, that involve waveform distortion and other deviations from the expected sine wave.

3.2.2 Classification of disturbances

Four power system parameters—frequency, amplitude, waveform, and symmetry—can serve as frames of reference to classify the voltage and power disturbances according to their impact on the quality of the normal sine wave of system voltage. A brief discussion of the need for evaluation of their impact on sensitive loads follows.

¹Information on references can be found in 3.9.

- a) Frequency variations are rare on utility-connected systems, but engine-generator-based distribution systems can experience frequency variations due to load variations and equipment malfunctions.
- b) Amplitude variations can occur in several forms; their description is inextricably associated with their duration. They range from extremely brief duration to steady-state conditions, making the description and definition difficult, even controversial at times. Their causes and effects need close examination to understand the mechanisms and to define an appropriate solution.
- c) Voltage waveform variations occur when nonlinear loads draw a current that is not sinusoidal. One could also describe an amplitude variation as momentary voltage waveform variation, but the intended meaning of the term is a steady variation of the voltage waveform or lasting at least over several cycles. This type of disturbance may be described as harmonic distortion because it is easy to analyze as the superposition of harmonics to the nominal frequency of the power system.
- d) Dissymmetry, also called *unbalance*, occurs when unequal single-phase loads are connected to a three-phase system and cause a loss of symmetry. This type of disturbance primarily concerns rotating machines and three-phase rectifiers and, as such, is not receiving broad attention. It is important, however, for machine designers and users. The percentage by which one-phase voltage differs from the average of all three is the usual description of this type of disturbance. A detailed definition of various measures of voltage and power quality by magnitude, duration, and spectral content is provided in IEEE Std 1159™.

3.2.3 Origin of disturbances

The term *origin of disturbances* can be understood in at least two different contexts or interpretations. According to one interpretation, the concern is for the source of the disturbance and whether it is external or internal to the particular power system. Typically, the boundary of a power system is defined as the watt hour meter, and reference is made to the “utility side” of the meter (utility source side) or to the “user side” of the meter (user load side). According to another interpretation, the concern is for the nature of the disturbance source and is then described in technical terms, such as lightning, load switching, power system fault, and nonlinear loads. Depending on local conditions, one can be more important than the others, but all need to be recognized. The mechanism involved in generating the disturbance also determines whether the occurrence will be random or permanent, and unpredictable or easy to define.

The first interpretation is motivated by the goal of assigning responsibility for the problem and possibly liability for a remedy. The second interpretation is motivated by the goal of understanding the problem and developing a technically sound remedy. When discussing the problem among the parties involved, the different points of view must be recognized, lest misunderstandings occur. In the following paragraphs, the second interpretation leads to a description of mechanisms producing the disturbances.

The general tendency of users is to attribute most of their equipment upset problems to the utility source. Many other sources of disturbances, however, are located within the building and are attributable to operation of other equipment by the end user. Finally, there are sources of disturbances—or system errors—not associated with the power input of the equipment, such as electrostatic discharges to the equipment enclosure or cables, radiated electromagnetic interference (EMI), ground potential differences, and operator errors (see Figure 3-1).

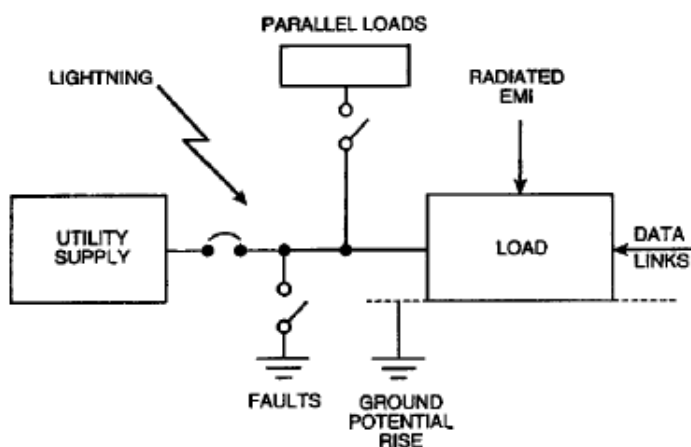
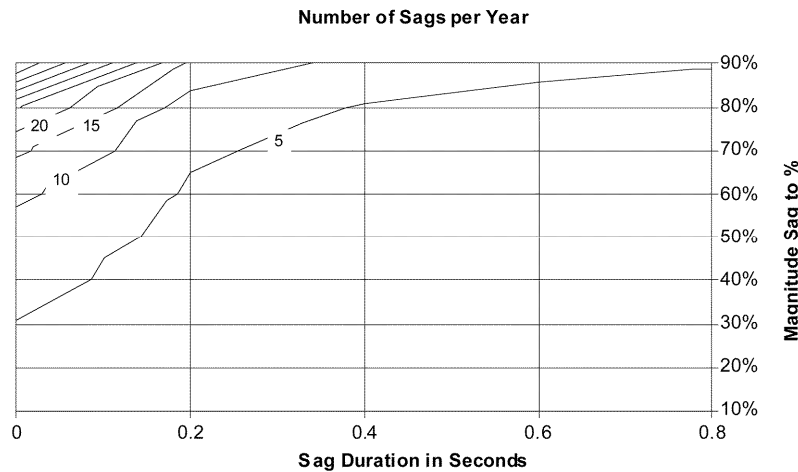


Figure 3-1—Sources of load disturbances (both internal and external)

3.2.4 Expectation of voltage sag disturbance

Power system faults occur on both sides of the meter, resulting from power system equipment failure or external causes (vehicle collisions, storms, human errors). These disturbances can range from a momentary voltage reduction to a complete loss of power lasting for minutes, hours, or days. Their accidental origin makes them unpredictable, although the configuration of a power system and its environment can make it more or less prone to this type of disturbance (see Key [12]).² Figure 3-2 shows the typical number of sag events per year by severity level, from a monitoring study conducted in the U.S.



Reprinted with permission from EPRI [B5].

Figure 3-2—Sags per year for 222 sites (from 6/1/93 to 6/1/95). Example data: Not intended to represent typical performance.

²The numbers in brackets correspond to those of the bibliography in 3.10.

3.2.5 Prediction of sag-related upset and damage

Low-voltage conditions are primarily upsetting to the equipment that cannot ride through periods of reduced available voltage. However, some automated processes may be disturbed at a critical time where either the processing equipment or the end product may be damaged. For example, a data processing system or network communication loss can corrupt the information, while low-voltage trip of an automobile glass processing line may leave overheated windows sized to rollers or rough finished windows with blemishes or scars.

Typical low-voltage trip times based on lab testing for several different types of equipment are as follows:

- a) Digital clocks: 1 s to 10 s
- b) Microprocessor-controlled equipment (PLC, PC, TV, VCR, etc.): 1 to 20 cycles
- c) Induction motors: 10 cycles to seconds
- d) Motor starters and contactors: 1 to 2 cycles
- e) Adjustable-speed drives: 1 cycle to seconds (control dependent)

3.2.6 Expectation of surge disturbance

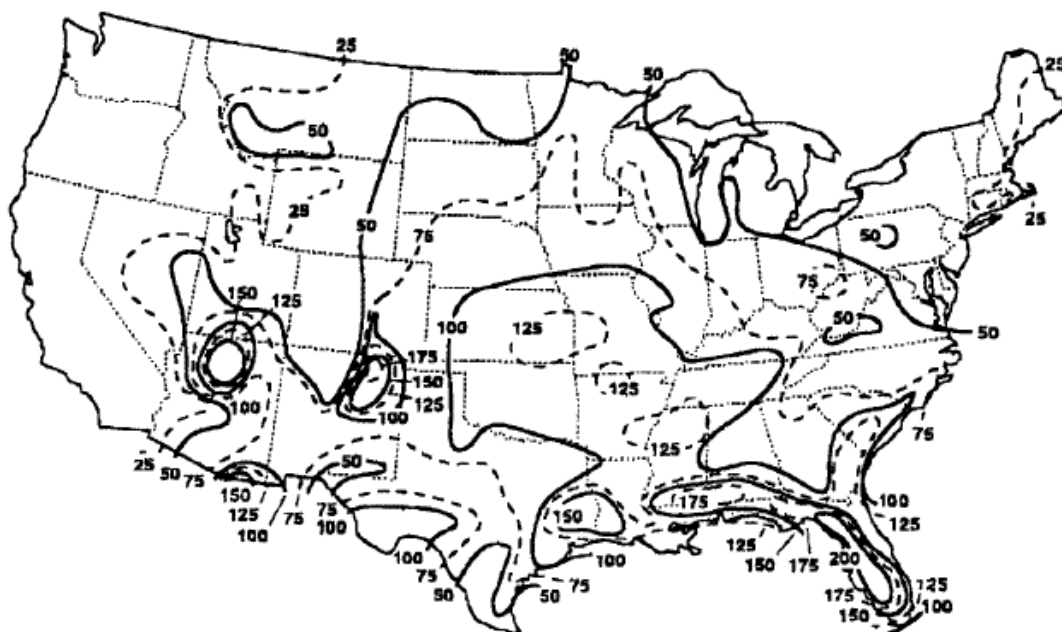
Some disturbances occur at random and are not repeatable or predictable for a given site although statistical information may be available on their occurrence (see IEEE Std C62.41TM). Other disturbances, especially those associated with the operation of other equipment, can be predicted, are repeatable, and can be observed by performing the operating cycle of that equipment.

Lightning surges are the result of direct strikes to the power system conductors as well as the result of indirect effects. Direct strikes inject the total lightning current into the system. The current amplitudes range from a few thousand amperes to a few hundred thousand amperes. However, the rapid change of current through the impedance of the conductors produces a high voltage that causes secondary flashover to ground, diverting some current even in the absence of an intentional diverter. As a result, equipment connected at the end of overhead conductors are rarely exposed to the full lightning discharge current. Indirect effects include induction of overvoltages in loops formed by conductors and ground-potential rises resulting from lightning current in grounding grids or the earth.

A lightning strike to the power system can activate a surge arrester, producing a severe reduction or a complete loss of the power system voltage for one half-cycle. A flashover of line insulators can trip a breaker, with reclosing delayed by several cycles, causing a momentary power outage. Thus, lightning can be the obvious cause of overvoltages near its point of impact, but also a less obvious cause of voltage loss at a considerable distance from its point of impact. Clearly, the occurrence of this type of disturbance is unpredictable at the microscopic level (e.g., specific site). At the macroscopic level (e.g., general area), it is related to geography, seasons, and local system configuration.

Induction of surges by nearby lightning discharges is a less dramatic but more frequent event. The resulting surge characteristics are influenced not only by the driving force—the electromagnetic field—but also by the response of the power system—its natural oscillations. This dual origin makes a general description of the occurrence impractical; nevertheless a consensus exists on representative threats for various environments. Figure 3-3, the classic isokeraunic map of the U.S., shows the average number of days that thunder is heard.

Thunder heard indicates that a lightning discharge has occurred. It may be either from cloud to ground (CG) or within a thundercloud. Most discharges occur within thunderclouds. CG lightning occurs less frequently than lightning within clouds, but the CG is the primary hazard to people or objects on the ground. Figure 3-4 shows a map of the average annual ground flashes per square kilometer in the U.S. between 1989 and 1995.



Reprinted with permission from MacGorman, Maier, and Rust [B13].

Figure 3-3—Isokeraunic map showing number of thunderstorm days

Note that most of the continental U.S. experiences at least 2 CG flashes/km²/y. About one-half of the area will see 4 CG flashes/km²/y, which is equivalent to about 10 discharges/mi²/y. The maximum flash densities are found along the southeastern Gulf Coast and the Florida peninsula, where the values approach 20 CG flashes/km²/y. Overall, about 20 million CG flashes strike the U.S. each year, and lightning is clearly among the nation's most severe weather hazards.

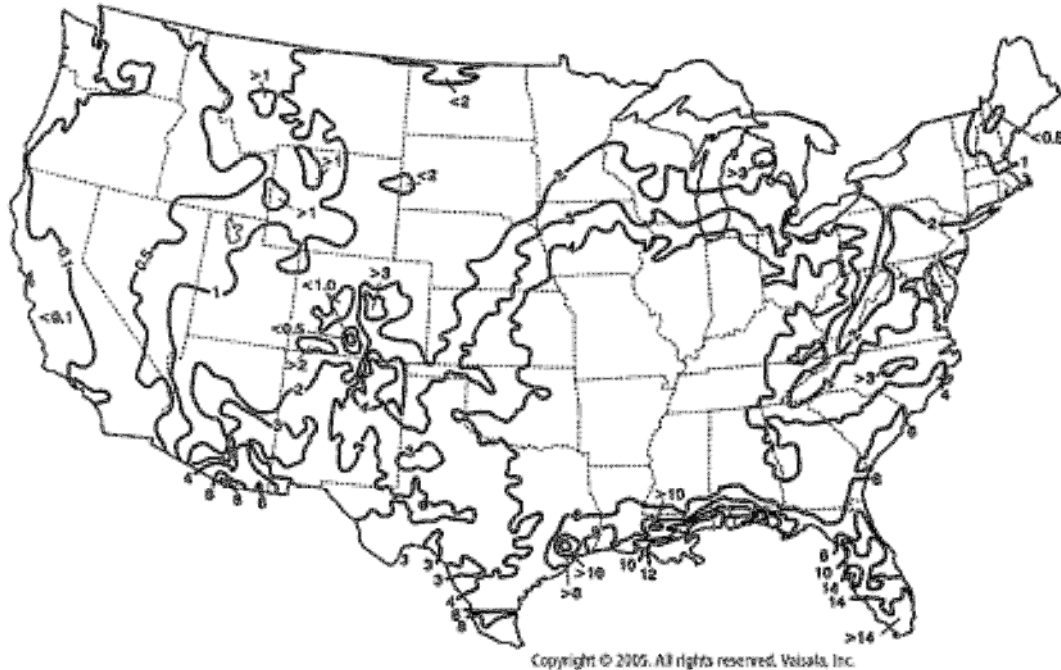
It is useful to estimate how often a normal-sized structure, such as a house, will be struck by lightning. For this, case data from the national lightning detection network are used to identify the typical number of CG flashes. We assume that the house is located in a geographic region ~~that has~~ with an average of 4 CG flashes/km²/y (see Figure 3-4). We also assume that the area of the house is about 10 × 20 m² and that there will be a direct strike any time a stepped leader comes within about 10 m of this area. In this case, the effective area of the house is about 30 × 40 = 1200 m², and the house is predicted to be struck, on average, $(1200 \times 4) / 1\,000\,000 = 4.8 \times 10^{-3}$ times a year, or ~~about~~ approximately once every 200 years. Another way to think of this hazard is that, in the 4 CG flashes/km² region, 1 of 200 houses is predicted to be struck each year, on average.

Load switching is a common cause of surges in power wiring. Whenever a circuit containing capacitance and inductance is being switched on or off, a transient disturbance occurs because the currents and voltages do not reach their final value instantaneously. This type of disturbance is inescapable and its severity depends on the relative power level of the load being switched and on the short-circuit current of the power system in which the switching takes place. Switching large loads on or off can produce long-duration voltage changes beyond the immediate transient response of the circuit. Whether the switching is done by the utility or by the user is immaterial from a technical point of view, although the responsibility may be the subject of a contractual dispute.

1989 - 1998 Average U.S. Lightning Flash Density

flashes / km / year

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



Reprinted with permission from Vaisala, Inc.

Figure 3-4—Average annual CG flashes per km² per year

More complex circuit phenomena, such as current chopping, prestrikes, and restrikes, can produce surge voltages reaching ten times the normal circuit voltages, involving energy levels determined by the power rating of the elements being switched. These complex surges can have very destructive effects, even on rugged equipment, and must be controlled at the source as well as mitigated at the loads.

The occurrence of load switching disturbances is somewhat predictable, but not necessarily under controlled conditions. The introduction of power conversion equipment and voltage regulators that operate by switching on and off at high frequency has created a new type of load switching disturbance. These disturbances occur steadily, although their amplitude and harmonic content will vary for a given regulator as the load conditions vary.

Electrostatic discharge (ESD) is a well-known phenomenon, responsible for interference and damage to electronic components and circuit boards when handled in a careless manner. However, from the point of view of a power system engineer, ESDs do not represent a significant threat because the high frequencies involved, just like in the case of the fast transient bursts, quickly attenuate the surge with distance. The discharge of electrostatic charges built upon the human body or objects, can also inject unwanted voltages or currents into the circuits. This phenomenon is associated with operator contact with the equipment (e.g., keyboards, panel switches, connectors) rather than with the quality of the incoming power. Thus, it is not included in the scope, but should of course not be ignored when troubleshooting equipment problems.

3.2.6.1 Nature of lightning strike damage

Most lightning strikes cause damage as a result of the large current that flows ~~in the return stroke~~ or the heat that is generated by this and the continuing current. If lightning strikes a person, for example, the current can damage the central nervous system, heart, lungs, and other vital organs. Also, many types of electronic circuits can be damaged or destroyed when exposed to an excess current or to an excess voltage produced by that current.

If lightning strikes on or near an overhead electric power or telephone line, a large current will be injected into or induced in the wires, and the current can do considerable damage both to the power and telecommunications equipment and to anything else that is connected to the system. If a lightning surge enters an unprotected residence by way of a power circuit, the voltages may be large enough to cause sparks in the house wiring or appliances. When such flashovers occur, they short-circuit the power system, and the resulting ac power arc can sometimes start a fire. In these cases, the lightning does not start the fire directly but causes a power fault; the power system itself does the damage.

When a building or power line is struck by lightning, or is exposed to the intense electromagnetic fields of a nearby flash, the currents and voltages that appear on the structure are determined by the currents and fields in the discharge and by the electrical response of the object that is struck. The grounding system of the structure is a critical part of the equation in determining what the response to the transient will be. For example, the voltages that appear on the electronics inside a grounded metal building are frequently produced by the fastest rising part of the return stroke current. This fast current excites resonant oscillations on the exterior of the building (like the resonance of a bell) that then couple into the structure via apertures in the metal, such as doors and windows.

The ~~exact mechanisms damage caused by which lightning currents cause damage are still not completely understood. In the human body, the current heats tissue is wide and causes a variety of electrochemical reactions varied.~~ In the case of metals, large currents heat the surface of the conductor by interactions between the air arc and the surface, and the interior of the conductor by electron collisions with the metal lattice. If this heat is large enough, the metal melts or evaporates (see Figure 3-5).

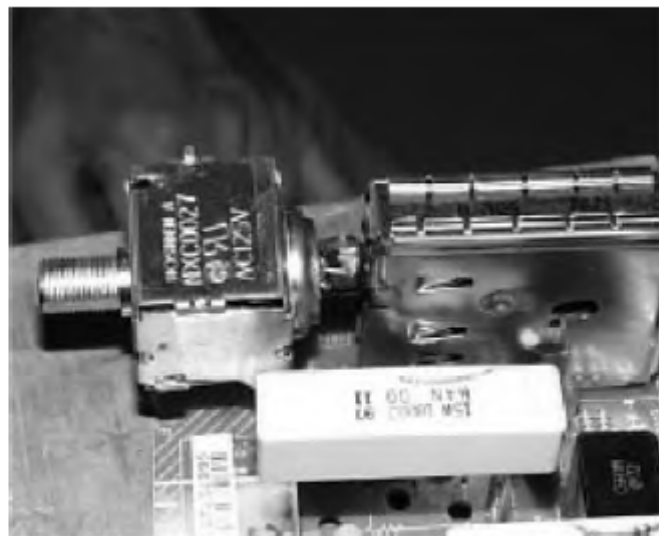


Figure 3-5—Lightning damage to electronic circuits on a circuit board

3.2.6.2 Nature of surge effects in power and communication systems

Power line surges, whether caused by lightning, circuit switching, or other events, typically represent the biggest threat because of larger exposure areas than, for example, a lightning strike. Although damage in the electrical wiring may occur, interactions between power line surges and victim equipment is the main concern. Consider the devices and equipment that may become the victims of a surge and their failure mechanisms. After-the-fact investigations and experimental data show a wide range of surge-related upset and failure mechanisms. These include insulation breakdown, flashover, fracture, thermal and instantaneous peak power overloads, and dV/dt and dI/dt limits being exceeded. The following list gives some generic types of surge victims and the typical failure or upset mechanisms:

a) Electrical insulation breakdown or sparkover

The failure mechanism (breakdown or sparkover) is principally a function of the surge voltage, and rise time of the leading edge. Failure rate increases as surge magnitude and/or rise time increases. *Insulation* is to be taken in the broadest sense of solid or liquid material separating energized conductors in equipment, clearances on a printed circuit board (PCB), edges of semiconductor layers, etc. A distinction must be made between the initial breakdown of insulation, related to voltage only, and the final appearance of the damaged insulation, related to the total energy dissipated in the breakdown path. In another situation, the insulation of the first turns of a winding may be subjected to higher stress than the others as the result of the uneven voltage distribution resulting from a steep front rather than only the peak value of the surge.

b) Surge protective device (SPD) failure

Normally, the voltage across the device is essentially constant, and the energy is a function of the surge current level and duration. One failure mode of such a device will occur when the energy dissipated in the bulk material raises the temperature above some critical level. Failure modes associated with the current level, such as flashover on the sides of a varistor disc, failure at the boundary layers of the varistor grains, or fracture of large discs, have also been identified and may not be related to energy.

c) Semiconductor device damage

Inadvertently, devices such as thyristors responding to the rate of voltage change can be turned on by a surge, resulting in failure of the device or hazardous energizing of the load they control. In a similar way, a triac may be turned on by a voltage surge without damage, but still fail by exceeding the peak power limit during a surge-induced turn-on with slow transition time.

d) Power conversion equipment nuisance trip

An example of this is a front-end dc link where the filter-capacitor voltage can be boosted by a surge, resulting in premature or unnecessary tripping of the downstream inverter by on-board overvoltage or overcurrent protection schemes.

e) Data-processing equipment malfunction

In this case, the malfunction (data errors), not damage, may be caused by fast rate of voltage changes (capacitive coupling) or fast rate of current changes (inductive coupling) that reflect the initial characteristic of the surge event. ~~This response is insensitive to the "tail" of the surge, where all the "energy" would be contained according to the misleading energy-related concept.~~

f) Light bulbs fail prematurely

Lamps may withstand the short burst of additional heating caused by a few microseconds of surge-caused overcurrent. However, they also fail under surge conditions when a flashover occurs within the bulb, triggering a power frequency arc that melts the filament at its point of attachment. This is another failure mechanism originating with insulation breakdown.

Table 3-1 presents a matrix of surge parameters and types of equipment, showing for each type of victim which surge parameter is significant or insignificant. The authors have sought to identify all types of potential victims (and invite additions to this list).

3.2.7 Measurement of power quality

There has been a tendency to attribute disturbances and failures to *power surges*, a term often used by the media but rather ill defined. The ambiguity results in part from an unfortunate dual definition of the word *surge*.

- To some people, a surge is indeed the phenomenon being discussed here, that is, a transient voltage or current lasting from microseconds to at most a few milliseconds, involving voltages much higher than the normal (two to ten times).
- To other people, a surge is a momentary overvoltage, at the frequency of the power system, and lasting for a few cycles, with voltage levels slightly exceeding the 5% to 10% excursions that are considered normal occurrences.

The term *swell* has been adopted by this recommended practice to describe this second type of overvoltage; perhaps one day it will supplant the usage of surge for that meaning. It would be a mistake to attempt protection against these long-duration power frequency swells with an SPD that is designed to absorb large but short impulses of energy. There is a growing recognition that the horror tales of SPD failures are more likely to be caused by swells rather than by large surges.

Table 3-1—Surge parameters affecting equipment failure modes

Type of equipment	Surge parameters					
	Source impedance	Peak amplitude	Maximum rate of rise	Tail duration	Repetition rate	I^2t in device ^a
Insulation —Bulk —Windings —Edges		X X X	X X	X		
Clamping SPDs —Bulk —Boundary layer Crowbar SPDs	X X	X X		X	X X	X X
Semiconductors —Thyristors —Triacs —IGBTs	X	X X X	X X X			X X X
Power conversion —DC level —Other	X	X	X	X X	X	

Data processing malfunction		X	X		X	
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^a The I^2t in the device is actually the result of the combination of surge parameters and device response to the surge. Like other power- and energy-related equipment stress, I^2t is not an independent parameter of the surge.

Nonlinear loads draw nonsinusoidal currents from the power system, even if the power system voltage is a perfect sine wave. These currents produce nonsinusoidal voltage drops through the system source impedance that distort the sine wave produced by the power plant generator. A typical nonlinear load is a dc power supply consisting of rectifiers and a capacitor-input filter, such as used in most computers, drawing current only at the peaks of the voltage sine wave. This current has a high third harmonic content that has also created a new concern, that of insufficient ampacity of the neutral conductor in a three-phase system feeding power supplies (see Chapter 4 for a discussion of this problem).

3.2.8 Power quality survey data

Power quality site surveys have been performed and reported by a number of investigators. However, the reports are difficult to compare because the names of the disturbances and their thresholds vary among the reports. Manufacturers of disturbance recorders have defined the events reported by their instruments at some variance with other sources of definitions. To help resolve the confusion, IEEE Std 1159 provides unique definitions for each type of disturbance. The results of this effort, however, will take some time to be generally recognized and accepted. In the meantime, terms used by different authors might have different meanings, leaving on authors the burden of defining their terms and leaving for readers the burden of being alert for possible ambiguities.

One example of such ambiguities occurs when attempting to summarize data from different surveys. For instance, two surveys have been widely cited (Allen and Segall [B1] and Goldstein and Speranza [B7]); each was aimed at defining the quality of power available for the equipment of concern to the authors. As a result, each author categorized the disturbances according to the criteria significant to that equipment, including the threshold below which disturbances are not recorded by the instrument. With hindsight, it is not surprising that the criteria were different; when comparing the data from the two surveys expressed in percentages (leading to pie chart representations by some authors of application papers), a puzzling difference was found. By analyzing the detail of the survey premises and definitions, the differences can be reconciled to some extent (see Martzloff and Gruzs [B15]).

Advancements in power line monitoring technologies enable sophisticated analyses of the electrical environment. Among the developments that cleared the way for comprehensive, geographically dispersed power line surveys are automated data-acquisition software and remote programming capability of multiple monitoring units. Three of the most recent comprehensive power quality surveys include those conducted by the Canadian Electrical Association (CEA) (see Hughes et al. [B9]), the National Power Laboratory (NPL) (see Dorr [B3]), and the Electric Power Research Institute (EPRI) (see Sabin et al. [B20]), all conducted in North America. The information collected during these three surveys provides a detailed picture of the expected electrical environment in which end-use appliances are intended to be used. The scope of each survey is described in the following paragraphs. (For a detailed description of how the results of these surveys are being presented, see Dorr et al. [B4].)

a) CEA Survey

In 1991, the CEA began a 3-year survey of power quality. The objective of the survey was to determine the general levels of power quality in Canada. The results would serve as a baseline against which future surveys could be compared to determine trends. The results would also familiarize utilities with making power quality measurements and interpreting the data gathered. Twenty-two utilities throughout Canada participated in the survey, with a total of 550 sites monitored for 25 days each.