IEEE Std 1100-1999
(Revision of
IEEE Std 1100-1992)

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 22 March 1999

IEEE-SA Standards Board

Abstract: Recommended design, installation, and maintenance practices for electrical power and grounding (including both power-related and signal-related noise control) of sensitive electronic processing equipment used in commercial and industrial applications are presented. 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 performance issues while maintaining a safe installation. A brief description is given of the nature of power quality problems, possible solutions, and the resources available for assistance in dealing with problems. Fundamental concepts are reviewed. Instrumentation and procedures for conducting a survey of the power distribution system are described. Site surveys and site power analyses are considered. Case histories are given to illustrate typical problems.

Keywords: commercial applications, electrical power, grounding, industrial applications, sensitive equipment

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First Printing
September 1999
SH94741

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

Published 15 September 1999. Printed in the United States of America

Print: ISBN 0-7381-1660-2 SH94741
PDF: ISBN 0-7381-1661-0 SS94741

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Introduction

(This introduction is not a part of IEEE Std 1100-1999, 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 books in the *IEEE Color Book Series*, which relates to industrial and commercial power systems. The purpose of this recommended practice is to provide consensus for installing and providing power to electronic equipment in literally all sectors and power system environments. This has been a growing area of concern as incompatibilities between power system characteristics and equipment tolerances have caused operating problems and loss of productivity in all kinds of power systems.

As load and source compatibility concerns have become more common, the facility engineers and system designers have been in the spotlight to provide solutions. Power and microelectronic equipment designs also have a role in solving the problems. Electronic equipment can be a contributor to, and a victim of, powering and grounding incompatibilities in power systems. A cooperative effort is required among power system designers, equipment manufacturers, and the electric utilities to provide and maintain an acceptable level of load/source compatibility.

To address this multidisciplined area, the Working Group on Powering and Grounding Sensitive Electronic Equipment was formed in 1986 to write a recommended practice, which was first published in 1992 and subsequently revised in accordance with IEEE-SA rules. The project was sponsored by the IAS Industrial and Commercial Power Systems Department, Power Systems Engineering Committee. This practice is intended to complement other recommended practices in the *IEEE Color Book Series* and has been coordinated with other related codes/standards, as well as nationally recognized testing laboratories.

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The final conditions for approval of this recommended practice were met on 22 March 1999. This recommended practice was conditionally approved by the IEEE-SA Standards Board on 18 March 1999, with the following membership:

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IEEE Recommended Practice for Powering and Grounding Electronic Equipment

Chapter 1
Overview

1.1 Scope

This recommended practice 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 and signal-related noise control) of electronic processing equipment 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 performance issues while maintaining a safe installation, as specified in the National Electrical Code® (NEC®) (NFPA 70-1999) [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 proliferate in industrial and commercial power systems, so do problems related to power quality. Powering and grounding electronic equipment has been 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,

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

without solving operating problems. In response to this situation, this recommended practice attempts to provide an understanding of the fundamentals of powering and grounding electronic equipment and the various types of 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 variations, and overheating of electromagnetic loads or interference of communication loads due to voltage waveform distortion. Recognition of these problems led to the development of voluntary standards that contributed significantly to reducing occurrences.

More recently, transient voltage disturbances associated with short circuits, 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 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.

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.

Today’s complaints about the quality of power 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 between commercial power and sensitive loads. Difficulties in assessing the need to apply power interface equipment include

a) The inability to quantify precisely how much downtime is power related; and
b) The subjective nature of estimating the cost of sensitive load misoperation that is attributable to power line disturbance.

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 Book Series* is an excellent reference library available for designing commercial and industrial power systems of all types. Each 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 are included. Also provided 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 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 useful for investigating and diagnosing problems in power systems that serve electronic equipment.

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 with wiring and grounding checks and progress through voltage disturbance measurements to harmonic analysis.

Chapter 7 (formerly Chapter 8) presents the myriad of available power enhancement equipment from the points of view of basic technology, performance, and function. Specification, performance verification, and maintenance are also covered.

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 is 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. The chapter makes extensive use of existing industry standards, such as ANSI T1 standards, and industry specifications, such as those by Bellcore and BICSI.

Chapter 10 (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 illustrate the need to follow specific recommended practices, and indicate potential results when recommended practices are not followed.

1.5 Bibliography

Additional information may be found in the following source:

[B1] NFPA 70-1999, National Electrical Code® (NEC®).[2]

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[2] The NEC is published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA (http://www.nfpa.org/). Copies are also available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.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, 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 new definition that conveys a common understanding for the word as used in the context of this recommended practice.

The remainder of this chapter is divided into three parts. First, an alphabetical listing of definitions is provided in 2.2. The reader is referred to IEEE Std 100-1996 for all words 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 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. This clause 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 bonding: (A) The electrical interconnecting of conductive parts, designed to maintain a common electrical potential [see the National Electrical Code® (NEC®) (NFPA 70-1999)]. **(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. (See the NEC.)

2.2.2 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, cable racks, and bonding conductors. The CBN always has a mesh topology and is connected to the grounding electrode system. *Note:* The CBN may also be known in the public telephone network as an integrated ground plane.

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[1] Information on references can be found in 2.5.

2.2.3 bonding network, isolated (IBN): (A) A bonding network that has a single point of connection (single-point ground) to either the common bonding network (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 (also known in the telephone industry as a *ground window*) to interface the rest of the building metallics (the CBN). The IBN should not be confused with the isolated grounding receptacle (IGR) circuit discussed in Section 250-146(d) of the NEC. *Note:* The IBN may also be known in the public telephone network as an *isolated ground plane.*

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

2.2.5 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 IEEE Std 100-1996 (previously given only for signal cables) to the power conductors supplying electronic equipment.

2.2.6 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.

2.2.7 crest factor (of a periodic function): The ratio of the peak value of a periodic function (y_{peak}) to the rms value (y_{rms}); $cf = y_{\mathrm{peak}}/y_{\mathrm{rms}}$.

2.2.8 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 IEEE Std 100-1996 definition links the device to the quality of its power supply.

2.2.9 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.)

2.2.10 degradation failure: *See:* **failure, degradation.**

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

2.2.12 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.

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

2.2.14 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 *total harmonic distortion*. (See IEEE Std 519-1992.)

2.2.15 dropout: A loss of equipment operation (discrete data signals) due to noise, voltage sags, or interruption. (See IEEE Std 1159-1995.)

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

2.2.19 equipment grounding conductor: 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 Section 100 of the NEC.

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

2.2.22 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 to 60 Hz power systems, and 20 to 25 kHz for 380 to 480 Hz power systems.

2.2.26 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: (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. *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). *See also:* **signal reference structure.**

2.2.28 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.)

2.2.29 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.

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

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 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.

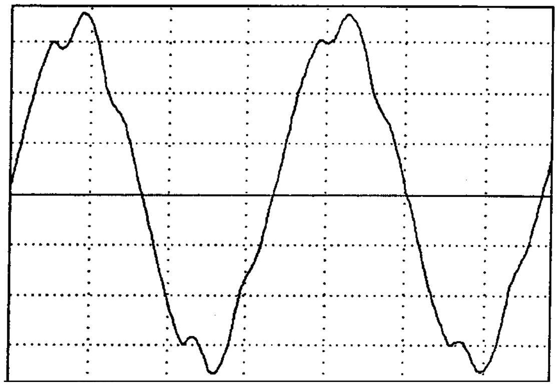
2.2.34 ground potential shift: The difference in voltage between grounding or grounded (earthed) structures such as the opposite corners of a metal building. Generally, ground potential shift increases with distance of separation of ground locations and with the frequency or wave front rise time of the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

2.2.35 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*.

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

2.2.37 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.

2.2.38 harmonic distortion: The mathematical representation of the distortion of the pure sine waveform. *See also:* **distortion factor** and Figure 2-1.[2]



Source: The Dranetz Field Handbook [B3].

Figure 2-1—Distortion example

2.2.39 impulse: *See:* **transient.**

2.2.40 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.**

2.2.41 input voltage range (of a power system): The range of input voltage over which the system can operate properly. (See ANSI C84.1-1995.)

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

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

2.2.43.1 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.)

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

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 isolated equipment ground: An isolated equipment grounding conductor 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 isolated-ground-type 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.

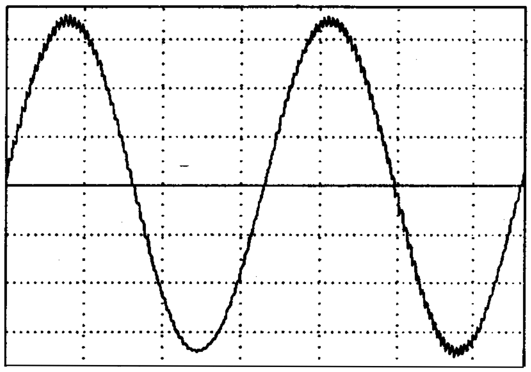
2.2.45 isolation: Separation of one section of a system from undesired influences of other sections.

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

2.2.47 noise, common-mode: *See:* **common-mode noise.**

2.2.48 noise, differential-mode: *See:* **transverse-mode noise.**

2.2.49 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).



Source: The Dranetz Field Handbook [B3].

Figure 2-2—Noise example

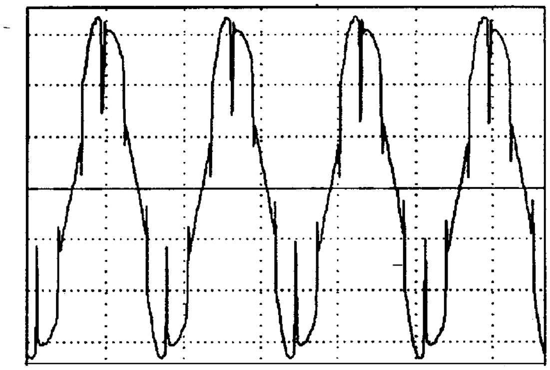
2.2.50 noise, normal-mode: *See:* **transverse-mode noise.**

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

2.2.52 nonlinear load: A load that draws a nonsinusoidal current wave when supplied by a sinusoidal voltage source. (See IEEE Std 519-1992.)

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

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 Figure 2-3.) *See also:* **transient.**



Horizontal 10 milliseconds/division Vertical 200 volts/division

Source: The Dranetz Field Handbook [B3].

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 1.1–1.2 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, and 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.

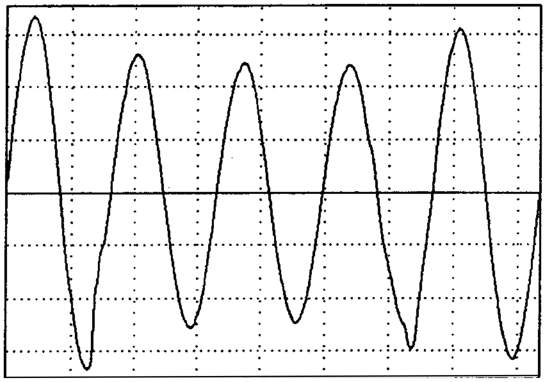
2.2.64 radial ground: *See:* **ground, radial.**

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. (Clarification notes from IEEE Std 100-1996 are excluded.) *Note:* 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 Figure 2-4.) *Note:* The IEC terminology is *dip*. *See also:* **notch; undervoltage.**

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 requirement and material.



Source: The Dranetz Field Handbook [B3].

Figure 2-4—Sag

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

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

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.

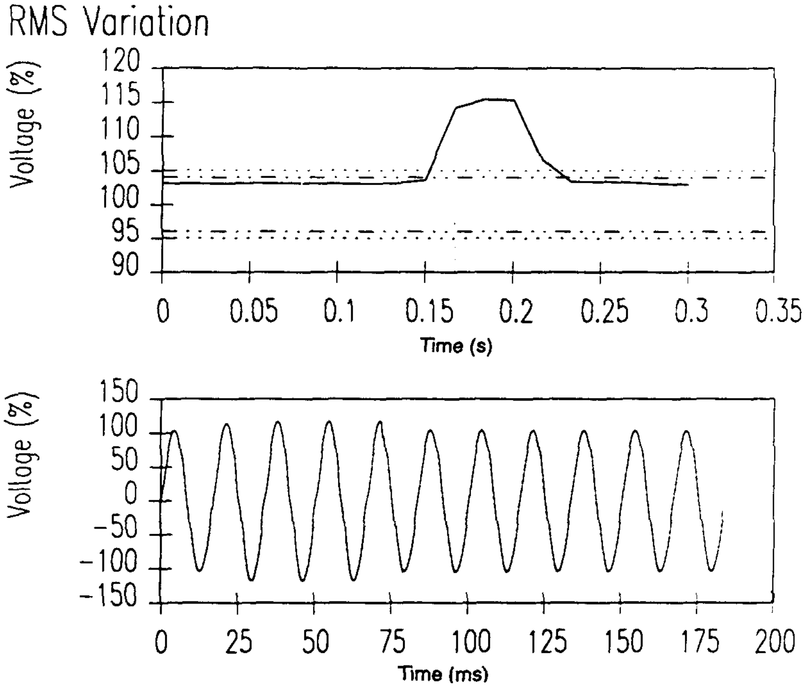
2.2.74 surge: *See:* **transient.**

2.2.75 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 1.1–1.8 pu. (See IEEE Std 1159-1995.) (See also Figure 2-5.)



Source: IEEE Std 1159-1995.

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. (See TIA/EIA 607-1994.)

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

2.2.83 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.**

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

2.2.85 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 equipment grounding conductor or associated signal reference structure 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 0.8–0.9 pu. (See IEEE Std 1159-1995.)

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 Abbreviations and acronyms

The following abbreviations are utilized throughout this recommended practice:

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
CEA	Canadian Electrical Association
CG	cloud to ground
CMR	common-mode rejection
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	direct current equipment grounding conductor (telecommunications)
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
GTO	gate turn-off
HF	high frequency
IBN	isolated bonding network
IEC	International Electrotechnical Commission
IG	isolated/insulated grounding
IGR	isolated grounding receptacle
IMC	intermediate metal conduit
IT	information technology
ITC	Information Technology Industry Council
ITE	information technology equipment

LDC	line drop compensator
MCT	metal cable tray
M-G	motor-alternator/generator
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
OEM	original equipment manufacturer
OSHA	Occupational Safety and Health Administration
PABX	private automatic branch exchange
PC	personal computer
PCC	point of common coupling
PDU	power distribution unit
PQ	power quality
PTN	public telephone network
PWM	pulse-width modulation
RFI	radio-frequency interference
RMC	rigid metal conduit
RMS	root mean square
SCR	silicon-controlled rectifier
ScTP	screened twisted pair
SDS	separately derived ac system

SE	service entrance
SMPS	switched mode power supply
SPD	surge protective device
SPG	single-point ground
SRGG	signal reference ground 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
Telco	telephone company
TER	telecommunications equipment room
THD	total harmonic distortion
TIA	Telecommunications Industry Association
TTE	telephone 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 References

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).[3]

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 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.[4]

IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (*IEEE Green Book*).

IEEE Std 519-1992, IEEE Recommended Practice for Harmonic Control in Electric Power Systems.

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

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

NFPA 70-1999, National Electrical Code® (NEC®).[5]

TIA/EIA 607-1994, Commercial Building Grounding/Bonding/Requirement Standard.[6]

2.6 Bibliography

Additional information may be found in the following sources:

[B1] IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Systems.

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[3] ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA (http://www.ansi.org/).

[4] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).

[5] The NEC is published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA (http://www.nfpa.org/). Copies are also available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).

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

[B2] McEachern, Alexander, *Handbook of Power Signatures*, Foster City, CA: Basic Measuring Instruments, 1989.

[B3] *The Dranetz Field Handbook for Power Quality Analysis*, Edison, NJ: Dranetz Technologies Inc., 1991.

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 why today's complaints about the quality of power 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 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 sensitive 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 sensitive 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.

In the commercial sector 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, VCRs, CD players, and digital clocks abound. In the near future we can expect electronically driven heat pumps, washing machines, and lighting—eventually we will see 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 sensitive 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 that the requirements of the National Electrical Code® (NEC®) (NFPA 70-1999)[1] prevent their

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[1] Information on references can be found in 3.9.

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 (industrial), and a few thousands 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 components 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 sinewave of system voltage. A brief discussion is given below of the need for evaluation of their impact on sensitive loads.

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) Waveform variations occur when nonlinear loads draw a current that is not sinusoidal. One could also describe an amplitude variation as momentary waveform variation, but the intended meaning of the term is a steady variation of the 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 1159-1995.

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).

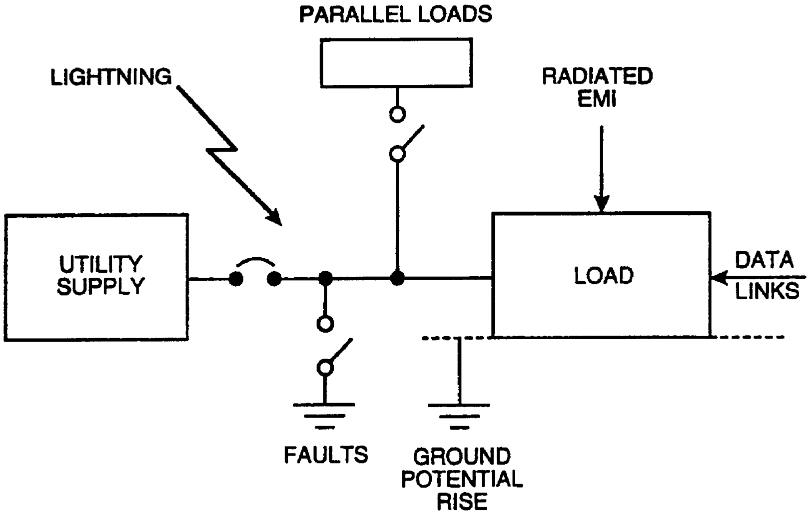

Figure 3-1—Sources of load disturbances (both internal and external)

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 [B12]).[2] Figure 3-2 shows typical number of sag events per year by severity level, from a monitoring study conducted in the U.S.

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: 1–10 seconds
b) Microprocessor-controlled equipment (PLC, PC, TV, VCR, etc.): 1–20 cycles
c) Induction motors: 10 cycle-seconds

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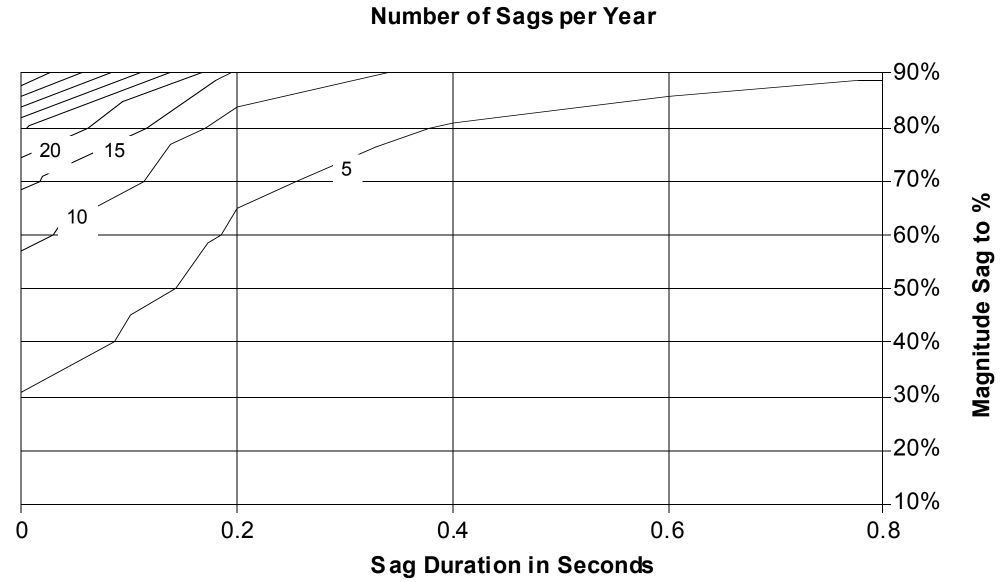
[2] The numbers in brackets correspond to those of the bibliography in 3.10.

d) Motor starters and contactors: 1–2 cycles

e) Adjustable-speed drives: 1 cycle-second (control dependent)



Example data: Not intended to represent typical performance.

Source: EPRI [B5].

Figure 3-2—Sags per year for 222 sites (from 6/1/93 to 6/1/95)

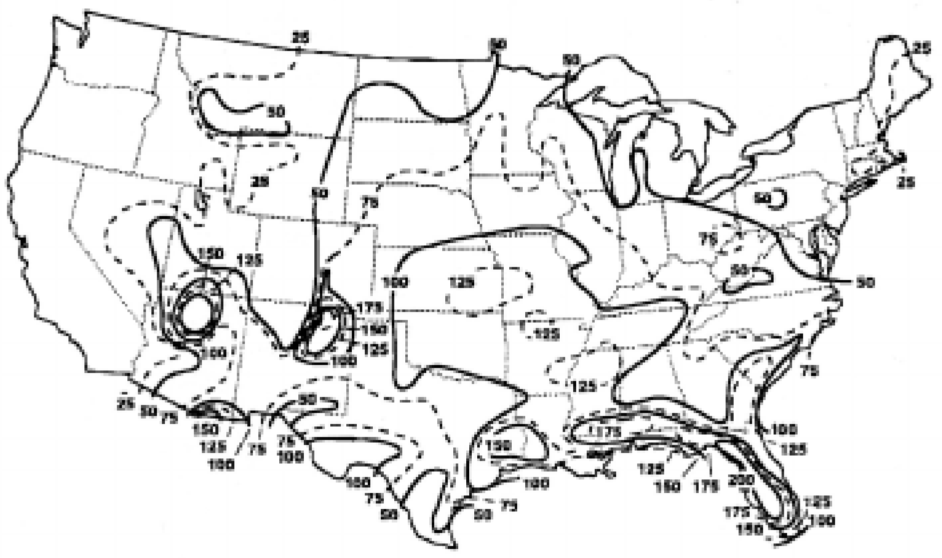
3.2.6 Expectation of surge disturbance

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 C62.41-1991). 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.

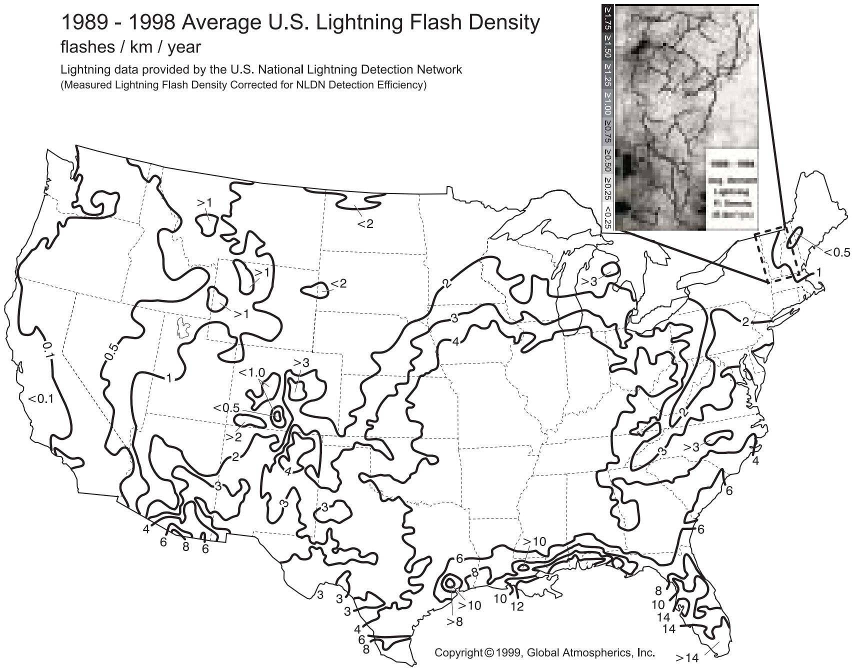
Induction of surges by nearby lightning discharges is a less dramatic but more frequent event. The resulting surge characteristics are influenced not only by the driving force—the electromagnetic field—but also by the response of the power system—its natural oscillations. This dual origin makes a general 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.



Source: Adapted from MacGorman et al. [B20].

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

Thunder heard indicates that a lightning discharge has occurred. It may be either from cloud to ground, or within a thundercloud. Most discharges occur within thunderclouds. Cloud-to-ground (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.



Source: Global Atmospherics, Inc.

Figure 3-4—Average annual cloud-to-ground flashes per km^2 per year in the continental U.S.

Note that most of the continental U.S. experiences at least 2 CG flashes/km^2/y. About one-half of the area will see 4 CG flashes/km^2/y, which is equivalent to about 10 discharges/mi^2/y. The maximum flash densities are found along the southeastern Gulf Coast and the Florida peninsula, where the values approach 20 CG flashes/km^2/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 an average of 4 CG flashes/km^2/y (see Figure 3-4). We also assume that the area of the house is about 10×20 m^2 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 $30 \times 40 = 1200$ m^2, 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 once every 200 years. Another way to think of this hazard is that, in the 4 CG flashes/km^2 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.

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 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, electrostatic discharges 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 by which lightning currents cause damage are still not completely understood. In the human body, the current heats tissue and causes a variety of electrochemical reactions. 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).

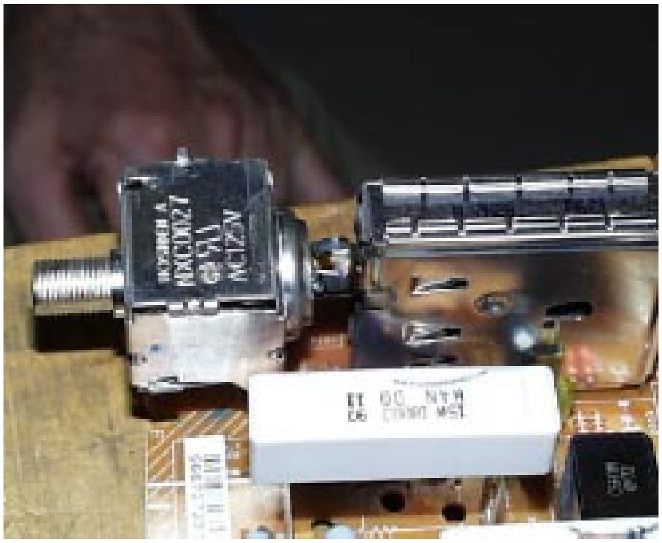


Figure 3-5—Lightning damage to electronic circuits on a circuit board

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, 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 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).

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		X		X		
- Windings		X	X			
- Edges		X	X			
Clamping SPDs						
- Bulk	X	X			X	X
- Boundary layer		X				
Crowbar SPDs	X			X	X	X
Semiconductors						
- Thyristors		X	X			X
- Triacs	X	X	X			X
- IGBTs		X	X			X
Power conversion						
- DC level	X	X		X	X	
- Other			X	X		
Data processing malfunction		X	X		X	

[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.

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*.

a) 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).
b) 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 five to ten percent 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 a surge protective device that is designed to absorb large but short impulses of energy. There is a growing recognition that the horror tales of surge protective device failures are more likely to be caused by swells rather than by large surges.

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, which 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 1159-1995 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 [B14]).

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. [B19]), 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 three-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.

   Residential, commercial, and industrial customer sites were monitored at their 120 V or 347 V service-entrance panels. Monitoring was done at the service-entrance panel because it was considered to offer a blended average of the power quality throughout the customer's premises. CEA decided that monitoring further into the premises could have made the results unduly influenced by electrical loads on an individual branch circuit. Monitoring at the distribution feeder would not have shown disturbances originating within the customer's own premises. Only line-to-neutral voltages were monitored. Neutral-to-ground voltages were not monitored because neutral is bonded to ground at the service-entrance panel.

b) NPL Survey

   In 1990, NPL initiated a five-year survey of single-phase, normal-mode electrical disturbances. The objective of the survey was to provide a large, well-defined database of recorded disturbances that profiles power quality at typical points of power usage. Single-phase, line-to-neutral data was collected at the standard wall receptacle. The disturbances found at this point of utilization are often coupled into computers and other electronic appliances. Data was collected from 130 sites within the continental U.S. and Canada.

The sites included a broad range of building locations, building types, building ages, and population areas. Included were locations where participants felt they had power quality problems and also those where no problems were perceived. The diversity of locations yielded a representative climatic and geographic cross section of the U.S. and Canada as well as a representative cross section of the major types of utility loads (heavy industry, light industry, office and retail stores, residential, and mixed).

c) EPRI Survey

In 1992, EPRI conducted a survey to determine the quality of power on ac distribution feeders in the U.S. This project was intended to monitor and then to simulate the electrical disturbances recorded at the selected feeders. Twenty-four geographically dispersed U.S. utilities participated in the survey. The objective of the monitoring portion of the survey was intended to provide a statistically valid set of data reflecting the number and types of electrical disturbances typically found at ac distribution feeders. The survey includes monitoring at 300 locations. Table 3-2 summarizes the parameters of the three surveys.

Table 3-2—Summary overview of the CEA, NPL, and EPRI power quality surveys

Survey	Monitor period	Quantity of data (monitor months)[a]	Number of sites	Measured parameters
CEA	1991 to 1994	530	550	Voltage
NPL	1990 to 1995	1200	130	Voltage
EPRI	1992 to 1995	5400	300	Voltage and current

[a] One monitor month is 30.4 days of data from one monitor.

3.3 Grounding considerations

3.3.1 Grounding for safety

A lot has been written on grounding for industrial and commercial power systems. Proper grounding is essential to safe and satisfactory performance of a power system. There are generally three requirements for such grounding:

a) Providing a low-impedance path for the return of fault currents, so that an overcurrent protection device can act quickly to clear the circuit;

b) Maintaining a low potential difference between exposed metal parts to avoid personnel hazards;

c) Overvoltage control.

A very comprehensive discussion of these considerations, applicable to any installation, can be found in other books in the *IEEE Color Book Series:* IEEE Std 141-1993, IEEE Std 142-1991, and IEEE Std 446-1995.

3.3.2 Referencing for performance

This aspect of grounding is much less well defined than the safety grounding practice. Electronic equipment and systems vary greatly with respect to noise and transient immunity. Some electronic processing system configurations are very difficult to adequately ground in a typical factory or office building installation.

Three particular system installation scenarios tend to experience more grounding- or referencing-related upsets, surge damage, and undesired processing performance than others. When these difficult installation scenarios are encountered then special attention to grounding details is likely to be required. A summary of what to look for is given in Table 3-3.

Table 3-3—Electrical measures and equipment symptoms of difficult installation scenarios

Difficult installation scenarios	Troublesome electrical condition	Typical electronic equipment symptoms	What and where to measure
1. Separately located and powered components of the same system	*Different signal reference levels* or induced currents on data cables	Temporary or chronic data errors, hangs or lockups, slow transfers, more retries, or I/O damage	Measure for 60 Hz voltage level between equipment chassis
2. Multiple external connections to ports of a single appliance or system	*Transient voltages and currents* at data and signal port connections	Intermittent lock ups, corrupted signals, or damage of exposed I/O circuits and communication ports	Monitor for transient voltages at equipment terminals
3. A single appliance or system sharing a grounding path with other equipment	*Stray currents and common-mode noise* in equipment grounding conductor and on data cables	Random data errors or slow transfer, particularly in analog- rather than digital-based systems	Check for stray currents above 1–2 A in green-wire ground

3.3.3 Difficult installation scenario 1—An electronic processing system with separately located and powered components interconnected by data or control cables

Here the trouble is different system components (e.g., a computer, a printer, a data network, an industrial process control, or a PC-connected security system) interconnected by data cables and powered from different circuits in the building electric system. This arrangement is often vulnerable to differences in ground reference voltage levels between components or induced currents in data lines, which occur by connection of data cable grounds. For example, a long printer cable RS-232 interface, or a network coax cable shield connected between different processing system components experience differences in ground reference voltages.

The ground referencing problem scenario has two critical factors to look for. First, it occurs where one component, such as the printer, is ground referenced to another system component, such as the PC, via data line. Second, the electronic components in this scenario are fed by different branch circuits or from different points in the power system, as shown in Figure 3-6. The data cable link may have either one or both ends of the cables grounded to the equipment chassis. With both ends grounded, transient or steady currents will flow on the link. With only one end connected, transient or steady voltages appear at the open terminal.

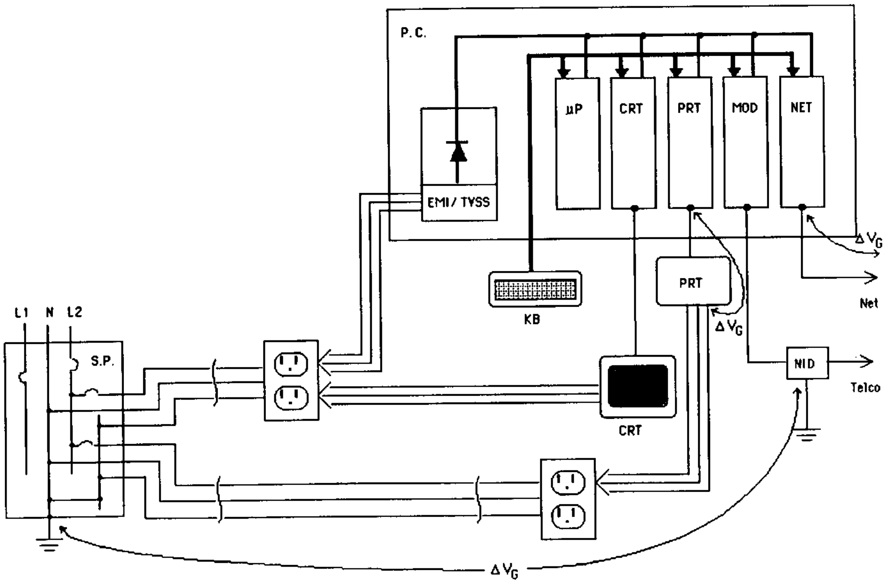


Figure 3-6—CPU and peripheral interfaces with various wiring and circuit reference grounding paths

These conditions sometimes cause data-transfer problems during transient events such as surge currents or voltages in ground conductors. Typical equipment symptoms of a referencing problem are temporary data hangs, slowdown of data transfer, multiple retries and permanent lock ups, or in the worst case, I/O damage. However, sensitivity varies between electronic equipment models and designs because of differences in upset thresholds, dependence on stable ground reference, and degrees of data line isolation.

Site conditions that may lead to ground referencing problems in an electronic processing system are

a) Long data cables, e.g. RS-232 longer than 8 m (25 ft), and coax and twisted pair longer than 30 m (100 ft).

b) Long distances from a common power reference, e.g., when any of the components (servers, printers, or PCs) are on a different branch circuit, different power panel, or in the worst case, a different power service entrance.

c) Exposure to transient currents in nearby conductors (which induce current transients when the cable shield is connected at both ends and voltage transients when the cable shield is connected at only one end).

3.3.4 Difficult installation scenario 2—A single electronic component has connections to more than one external utility system

In this arrangement the trouble is that one electronic component (such as a modem or PC) is referenced to more than one external system, and may experience transient voltages and currents between these systems. Typical external system connections include electric power, telephone, cable TV, and local area networks. These separate utility systems are difficult to maintain at the same voltage level, especially if they are grounded at different locations and enter the building or equipment area from different sides. This condition invites exposure to upsetting or damaging transient voltage problems.

The typical symptoms are slowdown of data transfer, retry, lockup and even damage of exposed I/O components. Key variables that will determine the likelihood of transient overvoltage problems are

a) How far apart the different systems enter the building or area in the building where the processing system is located; and

b) How effectively the different systems' ground references are bonded together.

Figure 3-7 shows the typical example of exposure to transient voltages for a fax machine connected to the telephone system.

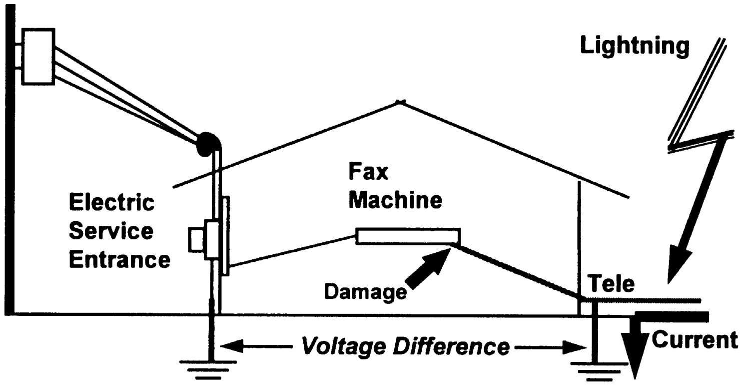


Figure 3-7—Impact of transient voltage surge in the telephone system on a fax machine

If the power line surge momentarily raises the fax machine tip or ring reference level, then the entire surge voltage may appear between the telephone line interface and the power cord of the fax. Signal interference or tuner damage may be expected. An isolated/insulated grounding (IG) circuit is not going to help in this scenario because it does nothing to equalize voltages between different system interfaces with equipment. In fact an IG is likely to exaggerate this problem by eliminating local ground bonds.

Transient upset or damage problems also can occur when a data modem is connected to the local telephone and power systems. The telephone jack input to the modem becomes the point where the two utility systems come together. This interface may experience a large voltage difference between the two utility systems when a surge current is induced in one of the utility systems and not in the other. Such transient potential differences can be equalized by referencing all external conductors to the same ground window.

3.3.5 Difficult installation scenario 3—An electronic processing system with power, data, or control cables exposed to stray currents

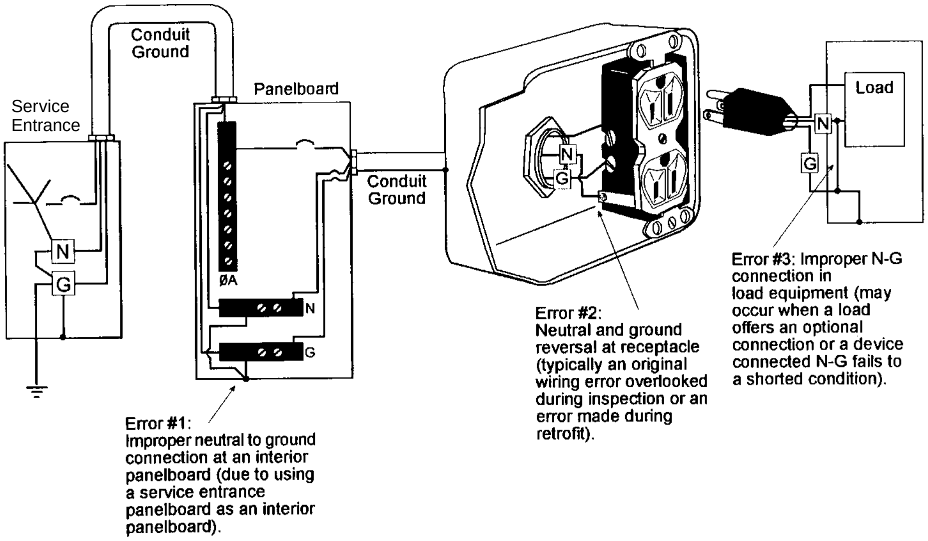
In this scenario the trouble occurs when several different processing system components (i.e., a computer, a printer, a data network, a server, etc.) are physically separated, but interconnected by various data cables, and may be fed by different branch circuits of the same electric power system. This arrangement may be vulnerable to stray currents in power or data lines, which enter via bonding of power grounds or the connection of data cable grounds and cable shields. For example, an RS-232 printer interface cable or the shields of network coax cables are grounded at both ends. Also the grounding conductors of power circuits are bonded to metal enclosures and the building grounding electrode system. Here bonding may promote a stray current problem.

Stray ground currents and common-mode electrical noise between components of the system cause either voltage differences or EMI of data communications. Stray currents are more likely to occur when branch circuits feed a variety of electronic and other equipment, and there is little or no control over the type and condition of the other equipment sharing the circuits. Symptoms that may be observed when these conditions exist are seemingly random electronic process or data transfer upsets, particularly in digital- rather than analog-based systems.

3.3.5.1 Stray currents and voltages related to isolated grounding techniques

To recognize the presence of stray ground currents and related voltages, look for symptoms. Stray ground currents usually exceed the normal mA-level leakage on the ground conductor expected from various connected load equipment. When these currents flow, the normal wiring impedance leads to stray voltages. Conditions that cause stray currents are sometimes transient (as opposed to continuous). For example, stray ground currents come from an electrostatic discharge to a metal enclosure, faults in wiring or equipment, and capacitive-coupling from nearby circuits when equipment is energized or a surge current is in the area. However, miswiring in building electrical circuits or inside connected equipment is probably the most common cause of stray ground currents.

Typical wiring errors that allow stray ground currents. Wiring errors such as neutral-to-ground bonds in subpanels, neutral-ground reversals in receptacles, or miswiring in equipment are a common cause of stray currents. A neutral conductor that is inadvertently grounded downstream of the main disconnect will allow normal currents to stray into the ground system as shown in Error 1 of Figure 3-8. Error 2 describes another source of stray current from a neutral-to-ground reversal wiring error in an electric outlet. Sometimes wiring errors or component breakdown occurs inside individual load equipment, such as an inadvertent neutral-ground connection. This connection, which can cause stray ground currents, is pointed out in Figure 3-8.



Error #1: Improper neutral to ground connection at an interior panelboard (due to using a service entrance panelboard as an interior panelboard).

Error #2: Neutral and ground reversal at receptacle (typically an original wiring error overlooked during inspection or an error made during retrofit).

Error #3: Improper N-G connection in load equipment (may occur when a load offers an optional connection or a device connected N-G fails to a shorted condition).

Figure 3-8—Typical wiring errors on a branch circuit

Stray ground currents are intermittent currents in the green wire that exceed the normal mA leakage current expected from various connected load equipment. These currents are common in virtually every power system and can occur under a variety of conditions, many of which are transient (as opposed to continuous). For example, stray ground currents may come from an electrostatic discharge to enclosures, short circuits in wiring or equipment, and capacitive coupling from nearby circuits when equipment is energized or a surge is produced. However, miswiring in building circuits or in connected equipment is probably the most common cause. A neutral conductor that is inadvertently grounded downstream of the main disconnect will allow normal currents to stray.

These stray currents in the equipment grounding conductor or ground reference path can cause variations in the ground potential levels throughout the equipment grounding system. Inadvertent neutral-to-ground bonds or neutral-ground reversal wiring errors are probably the most common cause of stray currents. Suspect stray ground currents or EMI when you have these wiring conditions exist and symptoms of electronic processing upsets are observed, particularly in digital- rather than analog-based data systems. For example, when random upsets in existing electronic processing systems are occurring, branch circuits feed a variety of electronic and other equipment loads, and there is little or no control over the type and condition of the other loads sharing the circuit.

3.4 Protection of susceptible equipment

3.4.1 General information

The concept of protection implies preventing a hostile environment from affecting susceptible equipment. Protection of the equipment against the hostile environment is the goal of the technology of electromagnetic compatibility (EMC). Discussing the need for protection, therefore, takes on two aspects: characterizing the environment and characterizing the susceptibility of the equipment. Disturbances to the environment have been briefly discussed in the preceding paragraphs. More complete descriptions can be found in other IEEE standards, such as IEEE Std 519-1992 and IEEE Std C62.41-1991.

One aspect that many protection strategies do not address is the significance of the rate of change in voltage disturbances. This rate of change is important in two aspects:

a) A fast rate of change has greater capability of producing a disturbance in adjacent circuits by capacitive and inductive coupling; and

b) A slow rate of change can make ineffective a protective device based on inserting a series inductance in the power line.

Detailed analysis of the rate-of-change issue is beyond the scope of this chapter, but Figure 3-9 takes the concept one step further in identifying the issues.

3.4.2 Noise protection

Noise on the power line is generally understood as a disturbance of low amplitude, a small fraction of the system voltage (and high frequency relative to the power system), while a surge on the power line is generally understood as a disturbance of larger fraction, or a multiple of the system voltage. The boundary between the two phenomena is not clear, and documents prepared by groups of different backgrounds and interest can vary on the definition of this boundary. Noise effects are often lumped under the label of EMI and addressed by frequency-domain-oriented specialists. Surge effects are generally addressed by time-domain-oriented specialists more concerned with damaging effects than upset effects. These different points of view are also reflected in Figure 3-3. IEEE Std 518-1982, Morrison [B17], and Ott [B18] provide comprehensive discussions of noise-reduction practices.

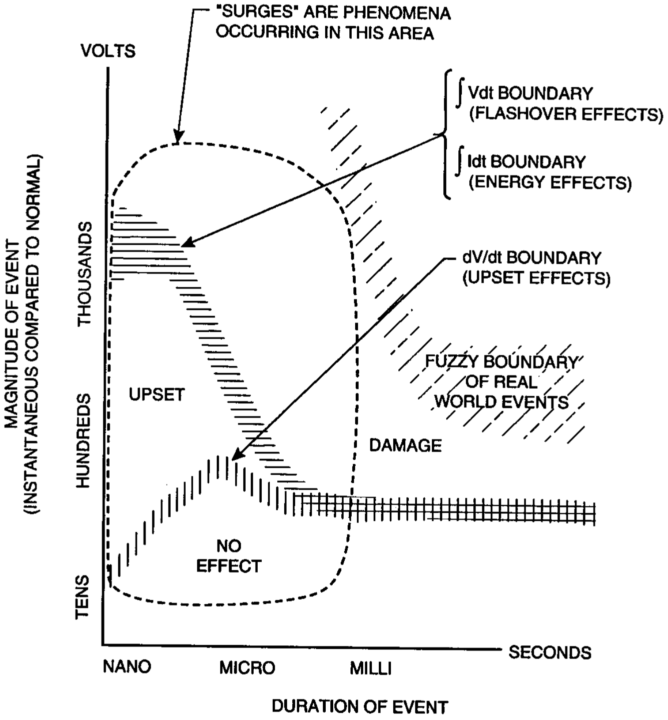


Figure 3-9—Relationship between disturbance characteristics and their effects on equipment

3.4.3 Surge protection

Surges can have many effects on equipment, ranging from no detectable effect to complete destruction. In general, electromechanical devices withstand voltage surges until a dielectric breakdown occurs, while electronic devices can have their operation upset before hard failure occurs. At intermediate levels, progressively more intense upset occurs until breakdown takes place. The semiconductor junctions of electronic devices are particularly susceptible to progressive deterioration. Definitions of the level beyond which a transient overvoltage becomes a threat depend on the type of victim equipment. While electromechanical devices can generally tolerate voltages of several times their rating for short durations, few solid-state devices can tolerate much more than twice their normal rating. Furthermore, data processing equipment can be affected by fast changes in voltage with relatively small amplitude compared to the hardware-damaging overvoltages.

The issue of survival or undisturbed operation of the equipment can be attacked in three ways: eradication of the cause of surges (e.g., the elimination of lightning); building equipment immune to any level of surges, no matter how high; or the obvious choice, finding the best economic tradeoff. Moderate surge-withstand capability is built into equipment, and the worst surges occurring in the environment are reduced, by application of suitable protective devices, to a level that the equipment can tolerate (see IEEE Surge Protection Standards Collection [B10]).

Low-voltage, end-user-type surge protective devices are often described as “transient suppressors,” but their operation is really a diversion of the surge current through a low-impedance path preventing the rise of high voltages across the load terminals. For large surge currents, this diversion is best accomplished in several stages. The first diversion should be performed at the entrance to the building, typically by conventional surge arresters rated for this duty. Then, any residual voltage resulting from the action of the arrester can be dealt with by a second protective device at the power panel of the computer room, or at the terminals of a connected load, or both. In this manner, the wiring inside the building is not required to carry the large surge current to and from the diverter at the end of a branch circuit. Such a long path for the current would produce inductive voltage drops in the branch circuit wires, resulting in a rise of the neutral or grounding conductor terminals with respect to local grounds. A potential problem, however, is associated with the multistage protection scheme; if not properly coordinated, a downstream protective device may attempt to divert all of the impinging surge and fail in the process. Thus, proper attention must be given to coordination of cascaded surge protective devices (see Martzloff [B13]). Additionally, proper attention must be given to insuring that surge protection on the power port is coordinated with the surge protection devices on all other ports of entry to the equipment, such as modems, network cables, and printer cables.

3.4.4 Sag protection

Sag protection consists of providing some source of energy to make up for the momentary loss of input power. Sag protection can vary from short ride-through provided by added capacitance to a full UPS system (see 7.2.8, 7.2.9, IEEE Std 446-1995, and IEEE Std 1346-1998 for more information). A more detailed discussion of sag immunity testing is given in 3.5.1.2.

3.5 Information technology equipment (ITE)

3.5.1 Powering ITE

The powering requirements for common office equipment such as personal computers, fax machines, copiers, alarm systems, as well as a wide assortment of consumer electronics products fall into a range such as ±10%. All of these devices typically have some level of built-in immunity to voltage variations, which can be defined by power quality performance testing to define what is commonly referred to as the CBEMA-type curve or profile for the device under test. A CBEMA curve approach is simply the application of a two-dimensional grid to plot the input voltage vs. time duration performance of any electronic appliance. These plots are a useful way to compare the power quality performance of different electronic products. In effect, this is the input vs. output energy performance for that product (or power supply) because we are comparing the amount of input energy (either high, low, or nominal) to the ability of the power supply to support its output load without interference or upset.

The classic example of this approach is the switch-mode power supply that is found in modern single-phase electronic products. The front end of the power supply is a bridge rectifier with a bulk capacitor for energy storage. The input ac is converted to a dc voltage that is in turn stepped down or converted to the appropriate dc voltages required by the output loads. Monitoring this output load voltage for “out of limits” deviations, while injecting sags, swells, transients, interruptions, and steady-state voltage variations at the input terminals to the power supply yields the input voltage vs. duration performance plot referred to as that product's "CBEMA-type curve."

The susceptibility level of the equipment, however, is a subject that is more difficult to quantify because it requires the disclosure by manufacturers of information that some are reluctant to provide, lest it be misunderstood or misused. Nevertheless, the consensus process has produced a useful graph of typical susceptibility levels—or the converse, tolerance levels for single phase equipment such as personal computers, copiers, fax machines, and other ITE devices. This graph has been widely published, but has been recently revised to more accurately reflect the tolerance capabilities of the aforementioned equipment, and is reproduced here as Figure 3-10. Note that the graph only addresses the magnitude of the voltage, with a corresponding duration.

Part (a) of Figure 3-11 shows an example of power supply ride through a voltage sag, and part (b) of Figure 3-11 shows an example of power supply ride through a voltage interruption. The input voltage drops to zero and several cycles later, the output dc bus begins to drop. For this case, one data point would be plotted at 0 V and 5 cycles, which is the point where the dc bus dropped from 5 to 4.75 V. The arbitrary pass/fail criteria selected here is –5% of nominal or 4.75 V dc for the 5 V dc bus, which is a level specified in many digital logic data books as the lower limit for guaranteed performance of a given logic chip. Similarly, by injecting other high- and low-voltage events at the power supply input terminal, and monitoring a low- or high-output threshold, enough data points may be gathered to fill in or plot the CBEMA-type curve for the example switch-mode power supply.

If the product being tested were an adjustable speed drive (ASD) instead of a PC power supply, some other arbitrary pass/fail criteria would have to be selected. In the ASD case, this could possibly be the speed in RPM of the output motor. Because there is such a wide diversity in pass/fail performance criteria that may be selected for a given product or a given process, it is important to emphasize that the new CBEMA curve shown in Figure 3-10 is intended for single-phase ITE and is not intended to reflect the performance of all electronic-based equipment. There are simply too many variables, such as power supply loading, nominal operating voltage level, and process complexity, to try to apply a "one size fits all" CBEMA curve.

3.5.1.1 History of the CBEMA curve

The origination of the CBEMA curve goes back to 1977 when the Computer and Business Equipment Manufacturers Association's (CBEMA) ESC-3 Working Group was asked to provide their input into an energy performance profile for computer equipment that was proposed for publication in IEEE Std 446-1995 (*IEEE Orange Book*). After some minor modifications to the proposal, the ESC-3 Working Group approved this initial version of the curve, which remained unchanged until early in 1996. Throughout the nearly twenty years that the original version was published, it grew in stature from a simple curve describing the performance of mainframe computer equipment (PCs were not available), to a curve that was used to attempt to define everything from specification criteria for electronic equipment to the basis of power quality performance contracts between electric utilities and large industrial customers. Obviously this is quite an extension from the initial intent of describing the power quality performance of typical mainframe computers.

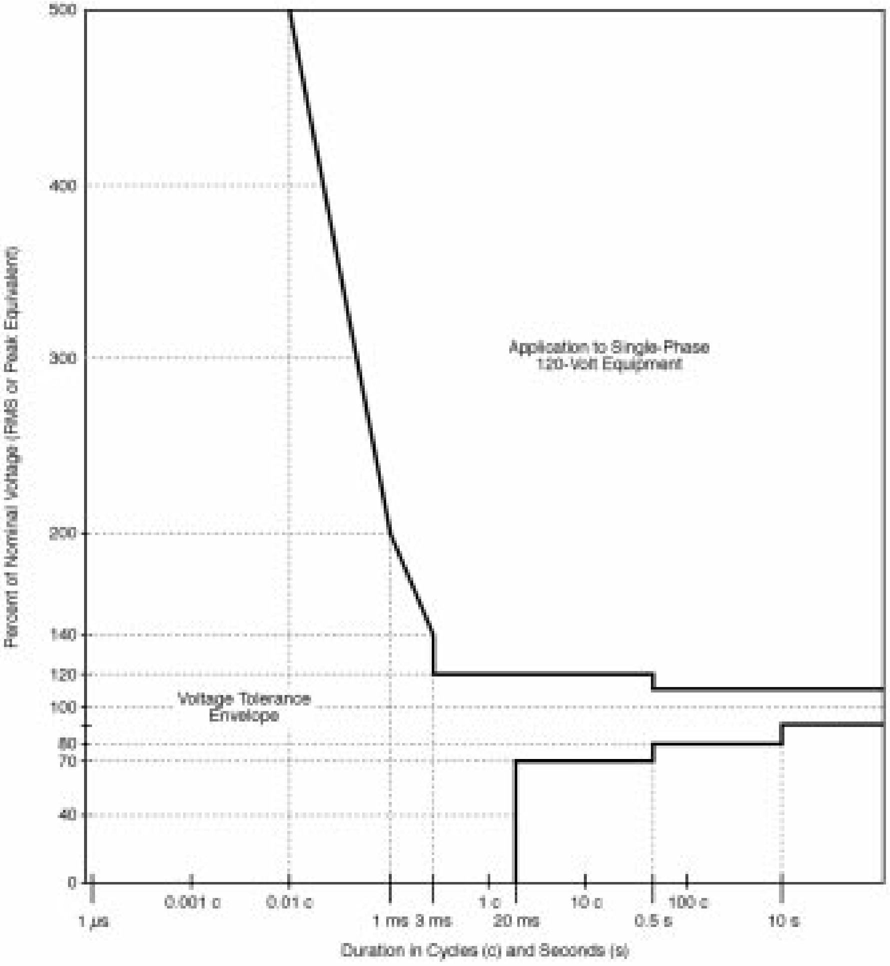
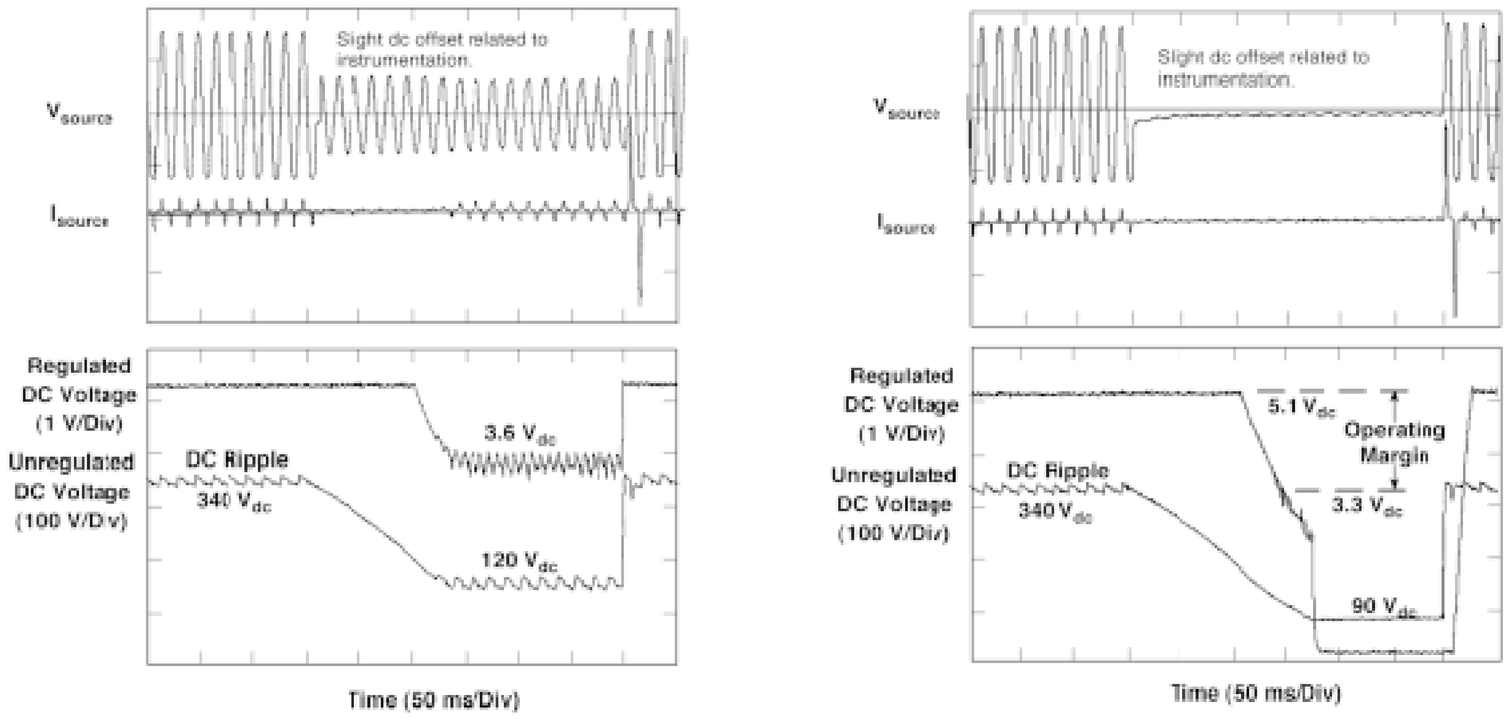


Figure 3-10—New ITIC (CBEMA) curve (1996)



(a)

(b)

Figure 3-11—Example performance of a switch-mode power supply 5 V dc bus during a momentary event

Because of this elevated stature, the ESC-3 Working Group and several sponsors took on the task of developing a curve revision that would be more representative of the power quality performance of modern PCs and other ITE. The basis of this new curve is supported by tests that were conducted on a representative sample of eight PC power supplies supplied by eight different manufacturers. Armed with performance knowledge from the PC power supply test results and some very insightful product performance input from the ESC-3 Working Group, a new curve was defined that was more in line with the expected performance of modern electronic equipment. This new CBEMA curve is shown in Figure 3-10 with an overlay of the old CBEMA curve. There is not much curvature to the new performance envelope, but it will continue to be officially referred to as the "CBEMA curve" with a footnote stating that it was revised in 1996 by the Information Technology Industry Council (ITIC), formerly the CBEMA. The ITIC is the new international representative of the ITE manufacturers.

3.5.1.2 Testing equipment to the new CBEMA limits

Because this new CBEMA curve has some carefully negotiated data points, each of these points may be useful as criteria to test the performance of a given product. The description of how to test to these points has been developed.

In general, testing on the RMS portion of the curve is to be performed with nominal line voltage applied to the power supply. For example, to determine whether a given product can withstand an interruption of 20 ms without upset, power is removed from the unit under test and the output is monitored to determine whether or not that particular unit's output remains unaffected for at least 20 ms. Similarly, the data point at 70%-0.5 s can be evaluated by sagging the input to 70% of nominal for 0.5 s and then bringing the input back to normal. If the output is unaffected, then the product has met the criteria for this data point. It should be noted that the sag to 70% may last longer than 0.5 s, but if the output is not affected until sometime after 0.5 s, then the product has met the limit described by the new CBEMA curve.

On the high-voltage side of the curve, the testing is slightly more difficult because a transient surge generator and an amplifier are required to test for the data points to the left of, and including, the 3 ms duration point. A surge generator is used to inject IEEE C62.41-1991 and IEEE Std C62.45-1992 [B11] defined "combination wave" transients [x] to determine if the product is upset by a transient surge with an amplitude 500% of the nominal peak voltage (850 V_{peak} for a 170 V nominal peak-rated product). The transient is applied at the 90° peak of the nominal waveform or may be applied at other phase angles if desired. For the data point at 200%-1 ms, an amplifier is used to simulate a capacitor-switching transient waveform. The amplitude of this waveform would be 340 V (2 times peak) measured from zero to peak if the unit under test is rated 120 V RMS. The initial ringing frequency (f) for this transient is determined by the equation

$$f = 1/t \tag{1}$$

where t is time (in seconds).

This yields a frequency of 1 kHz when we plug in 1 ms for time. An example of the 200%-1 ms capacitor-switching transient is shown in Figure 3-12.

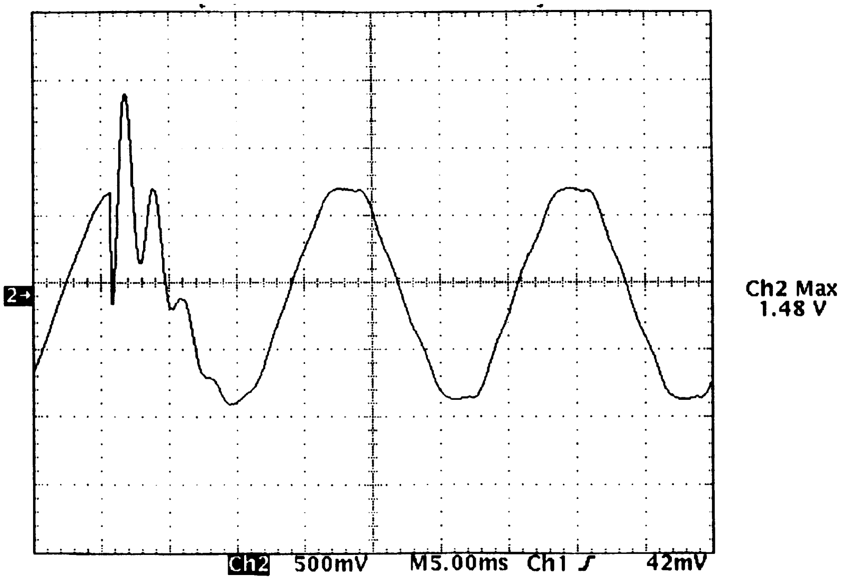


Figure 3-12—Sample capacitor-switching oscillatory transient

Similarly, the data point at 140%-3 ms is tested with a capacitor-switching waveform having a zero to peak magnitude 1.4 times the nominal voltage peak and an initial ring frequency of approximately 330 Hz. All points to the right of the 3 ms mark can be tested in a manner identical to the testing described for the low voltage points, with the exception that a swell or overvoltage is applied for the prescribed duration.

3.5.1.3 Evaluation of what the new CBEMA curve covers

Even with the new look, a CBEMA-type criteria has some important limitations. It is not in itself sufficient criteria for typical office systems. This subclause identifies what should be expected, and what cannot be obtained from a CBEMA-type criteria.

Most modern commercial buildings have a large amount of electronic data processing equipment or ITE. These equipment are usually interconnected to form business-critical IT systems. Often some sort of network links users internally and provides a window for communication with the outside world. For these systems to operate trouble free in their electrical environment, the following three criteria should be met:

a) Power should be provided continuously and with adequate quality;
b) Data links should operate as intended, without noise-related interference;
c) Reference grounds should be at equal potentials and free of transient voltage shifts.

A weak point in any one of these areas of the electrical environment will compromise the IT system's immunity.

The CBEMA curve addresses most of criterion (a), excluding noise immunity. This criterion is referred to as the *energy delivery criterion.* It is the voltage levels and durations at the equipment terminals that represent acceptable energy delivered by the power system. For example, during a short-duration, low-rms event, or sag, the CBEMA curve limit tells us the time available before the ITE has insufficient energy to operate. At zero voltage, or outage, the curve shows the ITE ride-through time, when no energy is delivered. A high voltage for a short period of time, less than 10 ms, gives the ITE peak voltage limit, indicating too much energy. For longer time periods both the overvoltage and undervoltage limits of the curve indicate required RMS voltage regulation, or “criteria for the wrong potential energy.” These energy-related criteria are covered well by the new CBEMA curve.

In contrast, criterion (b) is not related to energy, and here the CBEMA curve has only indirect relevance. This *data transfer criterion* is concerned with the performance of data links and interactions between power and data lines. For example, the CBEMA surge voltage withstand is shown to be quite high at the ITE terminals, perhaps hundreds or even thousands of volts peak. When these same surges are somehow coupled into data lines, a greatly reduced immunity is anticipated. It may be said that the back door, or communication port entry, represents an increased susceptibility not depicted by a power port-oriented CBEMA curve.

Likewise, criterion (c), referred to as *equal references*, may also bring a vulnerability level to the IT system not depicted by the CBEMA. Considering two typical scenarios, a printer may be ground referenced to a different point than the central processing unit (CPU) driving it, or power to a modem may be referenced to a different point than its telephone service input. Criteria for ground referencing or equalizing potential differences between grounds do not show on the energy-related CBEMA curve. Yet a few volts induced by an otherwise harmless power line surge may halt data transfer or damage an I/O interface.

So it can be seen that the latest CBEMA curve is necessary, but is only a partial picture of the required immunity limits in modern office electronic systems. It provides a very useful energy- and power-interface criteria. However more work is needed to define other criteria for the complete system, particularly for multiport ITE and their interconnecting networks.

3.5.2 Grounding ITE

All equipment incorporating at least two ports is classified under IT systems: a data port for input and output of signals, and a power supply port. The data port can be linked to the public telephone network, to a dedicated terminal, or to a communications bus or system. The significant aspect of such equipment is its two-port configuration; in many instances, the power port design and connections are regulated by one set of standards, while the data port is regulated by another set of standards, if any.

Safety aspects of grounding practices are fulfilled with no conflict by power system designers. On the other hand, designers of IT systems may have different criteria or practices from those of the power system designers. Signal circuits are not always grounded by a low (zero) impedance bond to their equipment (chassis, enclosure) ground. Some of these systems use a reference that is grounded. Others use balanced pairs that may or may not carry their own ground reference. However, at the high frequencies associated with disturbances, all circuits are capacitively coupled to ground, and to adjacent circuits. Therefore, noise can be injected in these data circuits by power system ground or fault currents, by EMI from other systems or lightning, and by other sources. Remedies to noise problems proposed by IT specialists are sometimes at variance with the requirements for effective grounding from the point of view of power system faults or lightning current protection.

One especially troublesome problem is that of systems featuring several elements in different locations, powered from different branch circuits, but linked by a data cable that carries its own zero reference—a conductor linking the grounding connections in the different locations. Under moderate conditions, the ground loop thus formed can couple noise into the signal path. Under more severe conditions, such as a power system fault or a surge being diverted through the grounding conductors, substantial differences can exist between the “ground” potential of two distant elements of the system; this difference in potential can cause component failures in the circuits.

3.6 Shielded, filtered, enclosed EMI/EMC areas

3.6.1 General information

EMI/EMC requirements are intended to limit the spurious emissions given off by electronic equipment and to ensure that electronic equipment is not adversely affected by such emissions. Typical EMI/EMC requirements are contained in CFR 47 [B2] or in documents promulgated by Technical Committee 77 (Electromagnetic Compatibility) of the International Electrotechnical Commission (IEC). The requirements implied by TEMPEST have different motivations. TEMPEST is a government term referring to the concerns over compromising emanations from any information processing equipment. Many years ago, Department of Defense personnel learned that it is possible to intercept the radio emissions given off by electronic equipment and that, with the aid of computers, classified information could be extracted from these signals by unauthorized parties. As the use of computers has become more commonplace in the office and the “decoding” business, the probability of such interceptions has increased.

TEMPEST requirements are usually achieved by placing a shielded enclosure around the equipment emanating the compromising signal. EMC requirements are achieved the same way. This metal enclosure reflects or absorbs the signals and attenuates them to an undetectable level. In recent years, TEMPEST interest has increased in nongovernment agencies. Some computer manufacturers now offer TEMPEST shielded computers and peripherals for commercial use.

3.6.2 Electrical safety requirements

Shielding hardware and power distribution system designed to meet the objectives of EMI/EMC and TEMPEST must always meet the requirements of the NEC). In particular, the grounding and bonding of shields and associated components must comply with Article 250 of the NEC. Distribution systems and equipment within the shielded area are bonded to the interior of the shield while the outside of the shield is bonded to the facility grounding system (see MIL-HNDBK-419 [B15]). Although this external connection has little or no effect on the equipment within the shield, it is essential to prevent the enclosure from reaching dangerous potentials relative to its surroundings.

3.6.3 Other requirements

A Faraday cage that provides an electromagnetic and radio-frequency shield enveloping the equipment to be protected best describes the basic requirements of EMI/EMC and TEMPEST. This shield isolates the protected circuits from spurious external signals and also attenuates TEMPEST emanations to levels that are too small to be intercepted or analyzed. To be usable, this shield must have penetrations for personnel and equipment access, power lines, control cables, and ventilation. The number of shield penetrations must be held to a minimum since each penetration is a potential leakage source and will require additional maintenance. For those penetrations that cannot be eliminated, proper construction to eliminate leaks is essential. Also, equipment and hardware installed within the shielded area must comply with EMI/EMC requirements in order to tolerate any residual internal electromagnetic fields. Topological grounding methods should also be employed. That is, each shielded region (topological zone) should have a separate grounding system making contact with both the inner and outer shield defining the zone (see Graf and Nanevicz [B8]). For more information on shielded areas, see MIL-HNDBK-419 [B15] and MIL-STD-188/124 [B16].

3.7 Safety systems

Safety systems protect life and property from damage or loss due to accidents. For equipment, the degree of protection should be based on the value and criticality of the facility. Personnel safety is covered rigorously in the NEC and many other standards. Defining this degree requires an in-depth knowledge of the installation and its function. The following questions should be considered when designing these systems:

a) How long will it take to replace the equipment and at what cost?
b) Can the function of the facility be performed elsewhere?
c) Loss of what key component would result in operation interruptions?

Safety systems can be as simple as a manually operated emergency power-off button, or as complex as a fully interlocked system. However, the more complex a fully integrated system becomes, the higher the probability of system confusion or failure. Typical systems include the following functions:

- Smoke and fire protection
- Environmental control
- Smoke exhaust
- Fire extinguishing
- Emergency lighting
- Security

The interfacing of a safety system is generally unique for each installation and requires a logical design approach. Through a well-defined logic matrix and sequence priorities, it is possible to develop a system that can be maintained, modified, or expanded with little confusion and minimum expense.

Generally, safety systems operate from 120 V ac, 24 V ac, or 24 V and 12 V dc. In any case, these systems must remain powered at all times. The quality of the power supplied to these systems is as important as that of the power delivered to the IT system. Disturbances in the power supply of the safety system can cause shutdown of the protected system.

3.8 Coordination with other codes, standards, and agencies

3.8.1 General information

There is a large body of guidelines, standards, and codes that address the issues of power quality, safety, and operational integrity of a power system and its connected equipment. These documents are prepared by diverse organizations, including voluntary consensus standards such as the IEEE documents, national position standards such as the recommendations of the IEC, safety standards such as those of the Underwriters Laboratories (UL), performance standards prepared by users' organizations, interchangeable standards prepared by manufacturers trade organizations, and regulatory standards promulgated by local and national agencies.

While conflicts are not intended among these documents, the wide diversity of needs and points of view unavoidably create ambiguities at best and conflicts at worst. As indicated earlier, however, the safety and legal aspects of any conflict mandate a prevailing role for the NEC.

3.8.2 National Electrical Code (NEC)

The NEC is a document prepared by consensus of a number of panels where national experts develop a set of specific and detailed requirements. These requirements are based on long-established practices, complemented by a permanent review process with a three-year cycle. The NEC is generally adopted by local jurisdictions, either in its entirety or with some modifications, and thus becomes enforceable by local inspection authorities. Conspicuous exceptions exist, however, in the domain of application: the power generation and distribution facilities of electric utilities are not regulated by the NEC, but have their own safety standards; U.S. government facilities are not regulated by the NEC, although installations are generally made in accordance with the NEC; some jurisdictions, notably large cities in the U.S., have their own local codes that are usually based on the NEC with additional requirements.

3.8.3 UL standards

UL is an independent, not-for-profit organization operating in the field of public safety. It operates product safety certification programs to determine that manufactured materials and products produced under these programs are reasonably safeguarded against foreseeable hazards. UL publishes standards, product directories, and other information. Approximately 500 published standards now exist. These standards are generally recognized by inspection authorities in the U.S. Note, however, that there are other competent testing agencies that can conduct certification programs based upon UL standards.

3.8.4 Other laboratories and testing agencies

Other laboratories and testing agencies have also performed tests on equipment, for the purpose of listing or for providing an independent verification of performance. The Occupational Safety and Health Administration (OSHA) requires listing only by a "recognized" testing agency, without defining such agencies.

3.8.5 National Electrical Manufacturers Association (NEMA) standards

NEMA develops product standards, some of which are recognized as Accredited Standards Committee standards. These standards are generally concerned with equipment interchangeability, but also contain documentation on operation and safety features.

3.8.6 National Institute of Standards and Technology (NIST)

NIST (formerly the National Bureau of Standards) is a U.S. government agency established initially for the purpose of maintaining standards of measurements and calibration of instruments, including tractability. Over the years, the role of NIST has expanded to include a broad range of research activities. The staff of NIST is active in many standards-writing groups, through individual contributions of experts in each specific field. However, NIST does not promulgate standards in the meaning of documents such as IEEE, IEC, or ANSI standards.

3.8.7 International standards

International standards are developed by a different process than the typical voluntary standard process used in the U.S., as exemplified by the present book. The prevalent set of standards is developed by the IEC, and covers most of the engineering and application aspects of electromechanical and electronic equipment. Technical Committees involved in the development of documents related to power and grounding include the following:

a) Technical Subcommittee 28A, for insulation coordination concerns. A report prepared by this subcommittee (IEC 60664-1:1992) discusses in detail an approach whereby overvoltage categories would be assigned to various types of equipment. The overvoltage capability of the equipment would become part of the equipment nameplate information, ensuring proper installation in known environments.
b) Technical Committee 64, for fixed (premises) wiring considerations.

c) Technical Committee 65 WG4, for electromagnetic compatibility of industrial process control equipment. This working group has produced and continues to update a family of documents addressing surge immunity, fast transients, and electrostatic discharges (IEC 6100-4-1: 1992).

d) Technical Committee 77, for electromagnetic compatibility. Within the broad scope of all possible disturbances to EMC, this committee is developing documents related to conducted disturbances. These documents are generic descriptions and classifications of the environment, leading to the specification of immunity tests in general. Detailed test specifications for a given equipment are left to the relevant product committee.

3.9 References

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.

IEC 60664-1: 1992, Insulation coordination for equipment within low-voltage systems—Part 1: Principles, requirements and tests.[3]

IEC 61000-4-1: 1992, Electromagnetic compatibility (EMC)—Part 4: Testing and measurement techniques—Section 1: Overview of immunity tests. Basic EMC Publication.

IEEE Std 141-1993, IEEE Recommended Practice for Electrical Power Distribution for Industrial Plants (*IEEE Red Book*).[4]

IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (*IEEE Green Book*).

IEEE Std 446-1995, IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (*IEEE Orange Book*).

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

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

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

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

[4] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).

IEEE Std 1346-1998, IEEE Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment.

IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Systems.

NFPA 70-1999, National Electrical Code® (NEC®).[5]

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[B2] CFR 47, Part 15, Telecommunication.[6]

[B3] Dorr, D. "Point of Utilization Power Quality Study Results," IEEE Transactions on Industry Applications, vol. 31, no. 6, pp. 658–666, July/Aug. 1997.

[B4] Dorr, D. et al., "Interpreting Recent Power Quality Surveys to Define the Electrical Environment," *IEEE Transactions on Industry Applications*, vol. 33, no. 6., Nov/Dec 1997.

[B5] EPRI TR-106294-V2, *An Assessment of Distribution System Power Quality: Volume 2: Statistical Summary Report*, Palo Alto, California, May 1996.

[B6] FIPS 94-1983, Guideline on Electrical Power for ADP Installations.[7]

[B7] Goldstein, M., and Speranza, P. D., "The Quality of U. S. Commercial ac Power," *INTELEC (IEEE International Telecommunications Energy Conference)*, pp. 28–33 [CH1818-4], 1982.

[B8] Graf, W., and Nanevicz, J. E., "Topological Grounding Anomalies," International Aerospace and Ground Conference on Lightning and Static Electricity, June 20–28, 1984.

[B9] Hughes, M. et al., "Distribution Customer Power Quality Experience," *IEEE Transactions on Industry Applications*, vol. 29, no. 6, Nov./Dec. 1993.

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[5] The NEC is published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA (http://www.nfpa.org/). Copies are also available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).

[6] CFR publications are available from the Superintendent of Documents, U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20013-7082, USA.

[7] U.S. Regulatory Guides are available from the Superintendent of Documents, U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20013-7082, USA.

[B10] IEEE Surge Protection Standards Collection (C62), 1995 Edition.

[B11] IEEE Std C62.45-1992 (Reaff 1998), IEEE Guide on Surge Testing for Equipment Connected to Low Voltage AC Power Circuits.

[B12] Key, T. S., “Diagnosing Power Quality Related Computer Problems,” *IEEE Transactions on Industry Applications,* vol. IA-15, no. 4, July/Aug 1979.

[B13] Martzloff, F. D., “Coordination of Surge Protectors in Low-Voltage AC Power Circuits,” *IEEE Transactions on Power Apparatus and Systems,* vol. 99, no. 1, pp. 129–133, Jan/Feb 1980.

[B14] Martzloff, F. D., and Gruzs, T. M., “Power Quality Surveys: Facts, Fictions, and Fallacies,” *IEEE Transactions on Industry Applications*, vol. 24, no. 6, pp. 1005–1018, Nov/Dec 1988.

[B15] MIL-HNDBK-419, Grounding, Bonding, and Shielding for Electronic Equipment and Facilities, vol. 1 (Basic Theory) and vol. 2 (Applications).[8]

[B16] MIL-STD-188/124, Grounding, Bonding and Shielding for Common Long Haul Tactical Communication Systems Including Ground Based Communications—Electronics Facilities and Equipment.

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[B18] Ott, H., *Noise Reduction Techniques in Electronic Systems,* New York: John Wiley & Sons, 1989.

[B19] Sabin, O. O., Grobe, T. C., and Sundrnam, A., “Surveying Power Quality Levers on U.S. Distribution Systems,” *Proceedings of the 13th International Conference on Electricity Distribution (CIREO ‘95)*, Brussels Belgium, May 1995.

[B20] MacGorman, Don et al., Figure 8 from *Lightning Strike Density for the Contiguous United States from Thunderstorm Duration Records.* Norman OK: National Severe Storms Laboratory, Environmental Research Laboratories, NOAA, May 1984.

[B21] *Westinghouse Electrical Transmission and Distribution Reference Book,* 1964.

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[8] MIL publications are available from Customer Service, Defense Printing Service, 700 Robbins Ave., Bldg. 4D, Philadelphia, PA 19111-5094.

Chapter 4
Fundamentals

4.1 Introduction

Successful, reliable operation of electronic equipment requires adherence to the fundamentals of physics. This chapter reviews appropriate fundamental concepts, with the objective of establishing an appreciation of how things work and their related failure modes. This focus on fundamentals prepares the reader for recommended design practices given in Chapter 8.

Rapid changes in the electronics and communications industries make it almost impossible for design engineers to be experts in all related disciplines. Therefore, a further objective of this chapter is to forge a consensus on related design issues and the expression of these issues via a common language.

4.2 Impedance considerations

An understanding of electrical impedance is fundamental to the design of power systems for electronics. The total system impedance can be grouped into four fundamental parts: the power source; the distribution; the load impedances; and very importantly, the grounding/bonding system's impedances (e.g., power/safety and performance parts). It is important to note that the nature and magnitude of these impedances vary with frequency. The impedances and their frequency-related considerations are discussed in this clause.

4.2.1 Frequencies of interest

The most distinguishing characteristic of power systems and the associated grounding/bonding systems for electronic equipment is that they must behave in an orderly fashion from dc to tens of megahertz. This total frequency range can be conceptualized as two distinct frequency ranges: a power/safety range and a performance range.

4.2.1.1 Power/safety range

The power/safety range typically encompasses a frequency range from dc to several tens of harmonics above the power source's nominal frequency (e.g., 60 Hz). Harmonics as high as the 50th are typically of interest, placing the upper frequency limit to about 3 kHz for the power/safety range. Note that this is all well within the audio frequency range. Impedances in this range tend to be dominated by lumped resistance, inductance, and capacitance. Designers of typical industrial and commercial power systems are generally familiar with the needs and design standards of this frequency range, especially in relation to safety issues [see the National Electrical Code® (NEC®) (NFPA 70-1999)[1] and IEEE Std 446-1995].

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[1] Information on references can be found in 4.9.

4.2.1.2 Performance range

The term *performance range* is defined here to be in the frequency range between tens of kHz and tens of MHz. It is within this range that conducted, coupled, and radiated electromagnetic energy in the conducted mode and both the near- and far-field modes can significantly impact the operational performance of most forms of electronic equipment.

The upper portion of this range has historically been the domain of radio-frequency engineers, and in general is identified as a specialty area, distinctly different from power engineering. Accordingly, there is often a need to apply wave and transmission line theory to the conductors and circuits operating in the performance range as the use of circuit theory is not adequate once conductors achieve significant portions of a wavelength at a given frequency, and this occurs with regularity over the performance range.

In general, once a conductor becomes approximately $\geq 1/20\ \lambda$ at some given frequency, circuit theory no longer applies, so wave and transmission line theory must be used to explain the path's conditions of impedance, how the current and voltage distribution occurs on it, and how signals are reflected and propagated across it as functions of time and velocity factor in the transporting medium. Nowhere is this more important than on grounding and bonding conductor systems. Impedances in this range tend to be characterized by distributed resistive, inductive, and capacitive elements, particularly at the higher frequencies (see NFPA 75-1999).

Wiring techniques that are adequate in the power/safety frequency range are typically unsuitable for use over most of the performance frequency range, unless augmented by special design techniques. These are discussed later in this chapter and are presented in recommended practice form in Chapter 8.

4.2.2 Power source dynamic impedance

Knowledge of the power source's dynamic impedance is key to the understanding of critical load-source interactions. Power source dynamic impedance, Z, is the ratio of incremental internal voltage drop within the same source, dE, to the incremental load current supplied by that source, dI; i.e.,

$$Z = \frac{dE}{dI}$$

Impedance of a power source can be further delineated as being a static or dynamic internal impedance, forward transfer impedance, and output impedance. These basic concepts of source impedance can be illustrated by a simplified equivalent diagram of a transformer. Figure 4-1 shows such a diagram where, for purposes of clarity, the magnetizing inductance of the core is neglected, as are other stray coupling paths.

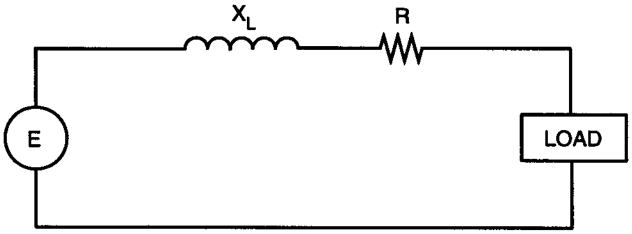

Figure 4-1—First order model of transformer impedances

4.2.2.1 Internal impedance

Internal impedance is the impedance of the power source at its design frequency. In practice it is more convenient to express this as a percentage that can be applied for whatever range of kVA that the subject transformer is available in. For example, the determination of a transformer internal impedance (%*Z*) is typically done at field level per Equation (4-1).

$$\%Z = 100\left(\frac{I_{\text{full-load}}}{I_{\text{short-circuit maximum}}}\right) \tag{4-1}$$

The internal impedance and %*Z* is often provided on transformer nameplates.

Due to the method of testing in a transformer factory or test-stand setting, the calculation of %*Z* requires knowledge of the following:

a) The input voltage necessary to make the current in a short-circuited secondary equal to the rated current;
b) The rated input voltage.

Then, the transformer internal impedance, again expressed as a percent (%*Z*), is the ratio of item (a) to item (b), multiplied by 100.

Typical dry-type power transformers suitable for most types of electronic equipment are identified in IEEE Std C57.110-1998 [B29].[2] These transformers tend to have impedances in the range of 3–6% at their nominal design frequency (e.g., 60 Hz).

Two examples of %*Z* and its use follow:

— A transformer with a 5% internal impedance allows 20 times its rated current to flow during short-circuit conditions [(100/5) = 20], assuming sufficient fault current is available on its primary. This is more than sufficient to ensure swift operating times for overcurrent protective devices clearing faults. Conversely, a 20%*Z* would limit available fault current to no more than 5 times full-load current, and this would not be

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[2] The numbers in brackets correspond to those of the bibliography in 4.10.

sufficient to ensure a prompt operation of a main overcurrent protective device (at least 10 times current is often recommended).

— Although not to be confused with the subject of voltage regulation, the %*Z* of a transformer does have a relationship to load changes and output voltage stability as follows:

A transformer with a 5% internal impedance also allows a 5% voltage variation to occur on its output when a step change from no-load to full-load occurs. With a transformer of 2.5%*Z*, this would be reduced to a 2.5% variation. Conversely, a 20%*Z* rating would allow a 20% voltage variation and this may be too great for most electronic loads to tolerate without malfunction (see FIPS Pub 94-1983).

It is desirable to have a low internal impedance, such that supply voltage variances are small for normal swings in load currents. However, if the source impedance is too low, possible short-circuit current can be excessive to the point that special circuit breakers or supplementary current-limiting fuses are required to interrupt fault current.

Note that to determine the full range of voltage variation from a transformer's output under varying load conditions, the impedance characteristics of the primary circuit supplying it must also be considered. Such series impedance will act in concert with the transformer's %*Z*, and will in almost all cases produce larger voltage variations than indicated above for %*Z* alone.

4.2.2.2 Forward transfer impedance (transformers)

Forward transfer impedance is an attribute similar to internal impedance, but at frequencies other than the nominal power system's fundamental frequency (e.g., 60 Hz). Forward transfer impedance is often an important part of a transformer-based power conditioning device's specification and the related performance claims made by its original equipment manufacturer (OEM). Forward transfer impedance assumes that a signal source exists on the input side of the transformer and the secondary-connected load is the target. Knowledge of the forward transfer impedance allows the designer to assess the capability of the power source to

a) Provide load current at the harmonic frequencies needed to preserve a suitable output voltage waveform. Generally, the highest frequency of interest is 3 kHz for 50–60 Hz power systems ($h = 50$), and 20–25 kHz for nominal 400 Hz power systems (which is also about 50 times the supply frequency).

b) Pass unwanted frequencies, such as transverse-mode noise, between the input and output terminals.

Of the two above parameters, the second is more important in typical cases, such as where transformer-based power conditioning equipment is being considered for an application.

A common method for determining forward transfer impedance of transformers (and filters) is to measure simultaneously an input test signal voltage and short-circuited output current. The ratio is the forward transfer impedance. Testing may be done at a single frequency of interest, or more often it is undertaken over a wide range of frequency to determine the overall bandpass characteristic for forward transfer impedance. This may be done by using a suitably amplified output from a signal generator and plotting the results of several spot-frequency measurements. Alternately, a sweep signal generator with slow sweep-rate and slaved $x - y$ recording indicator may be employed for the dynamic development of bandpass curves.

Generally, the forward transfer impedance will increase with increasing frequency. During testing, points of resonance may be encountered within the test frequency range and very high or low impedances may be noted to occur at these points, depending upon whether the resonance is from series or parallel parasitic elements. These resonances may act to further beneficially attenuate, or to unwantedly accentuate, the transfer of signal across the transformer, again depending upon the type of resonance.

It is desirable to have a minimum forward transfer impedance at the nominal power frequency (this relates to transformer efficiency) and impedance as low as possible for its low-order harmonics (e.g., up to 50th harmonic). At frequencies above the 50th harmonic, a high value of forward transfer impedance is highly desirable to attenuate transient voltages conducted by the power system toward the load. In most cases testing should be undertaken to at least several hundreds of kHz, and should not be stopped when the first or subsequent resonant points are reached. Testing to at least 1 MHz is recommended.

4.2.2.3 Output impedance (transformers)

Output (reverse transfer) impedance of a power source is an attribute similar to forward transfer impedance, but it describes the impedance of the power system as seen from the load looking into the transformer from the secondary side.

If the load generates harmonic currents (e.g., it is a harmonic current source), then these currents circulate on the wiring system between the load and the power source in much the same manner as fundamental currents do. Similar to fundamental currents, these higher-frequency currents produce voltage drops across the distribution wiring system’s impedance and the source’s internal impedance—all of which algebraically add to (or subtract from) the power system voltage. Therefore, the amplitude and waveshape of the line voltage can change significantly, and harmonic voltage waveform distortion results. Accordingly, it is very important that the power source path (and particularly the supply transformer) have low-output impedance to present to both the fundamental and to these harmonic currents.

At higher frequencies than those produced by the harmonics, a high-output impedance provides some beneficial filtering of high-frequency transients as generated from the load(s) (e.g., due to $-e = L\,di/dt$ switching), and which can attenuate them before they can be unwantedly impressed onto the transformer’s input supply circuit. Once this occurs, they are unwantedly propagated upstream to other parts of the distribution system. Transformer output impedances generally rise with frequency, but parasitic reactances within the transformer can allow series resonances that may lower output impedance at specific frequencies and unwantedly allow these frequencies to easily pass across the transformer from the output to the input.

4.2.2.4 Interwinding electrostatic shielding (transformers)

A solidly grounded bypass capacitor that creates a capacitive voltage divider and current shunt can be introduced into the interwinding capacitance between the primary and secondary in the typical isolation transformer by adding a metal foil between the windings, and then by suitably bonding it in low-inductance fashion to equipment ground within the isolation transformer (see Figure 4-2 and Lewis [B34]). This has three major effects:

a) Interwinding short circuits are largely prevented due to the introduction of a solidly grounded fault-current path as provided by the electrostatic shield (see Figure 4-2).

b) High-frequency currents in the common mode (CM) are capacitively shunted into the grounding system in bidirectional fashion from either the primary or the secondary circuits (see Figure 4-3).

c) The capacitive voltage divider action reduces the available noise voltage to be coupled capacitively between the two windings (see Figure 4-3).

The benefits from effect (a) are obvious, but the conditions in effects (b) and (c) produce mixed results. For example, the capacitive shunting action beneficially reduces the amount of CM current coupled across the transformer from either direction, but also increases the CM current flow in the grounding system the transformer and its shield are referenced to. With a suitably designed signal reference structure (SRS) grounding system, per Chapter 8, this is not normally a problem. However, if nonrecommended grounding system designs are employed this can be a significant problem—especially with single-point ground (SPG) designs and most variations of them (see Chapter 8).

Also, if the shield’s grounding/bonding conductor is not installed as a low-inductance pathway, then per Figure 4-3 it can be seen that it will act to defeat the shunt and voltage divider action provided by the electrostatic shield since it is an inductance added in conjugate with the capacitance provided between the electrostatic shield and the associated faces of the windings. Bypass capacitors must be grounded via low-inductance means if they are to be fully effective, and if the exhibition of unwanted resonances is to be avoided.

Electrostatic shielding can produce practical reductions in CM noise transfer across the transformer in ranges from approximately –20 dB to –40 dB and sometimes to –60 dB across some reasonably defined range of frequencies. This will be strongly influenced by specific product design, number of phases, input and output voltage, kVA rating, and the physical size of the transformer involved. Practical attenuation values above this are generally not realizable in real-world installations of the transformer—particularly when the installation conforms to the requirements of the NEC. Typical industry-favored performance attenuation tests based upon the MIL-STD-T-27(d) method, and which involve factory-specified and artificial capacitive voltage divider actions, are generally not a valid means of determining the performance of the electrostatic shielding system in practical cases (see Lewis [B34]).

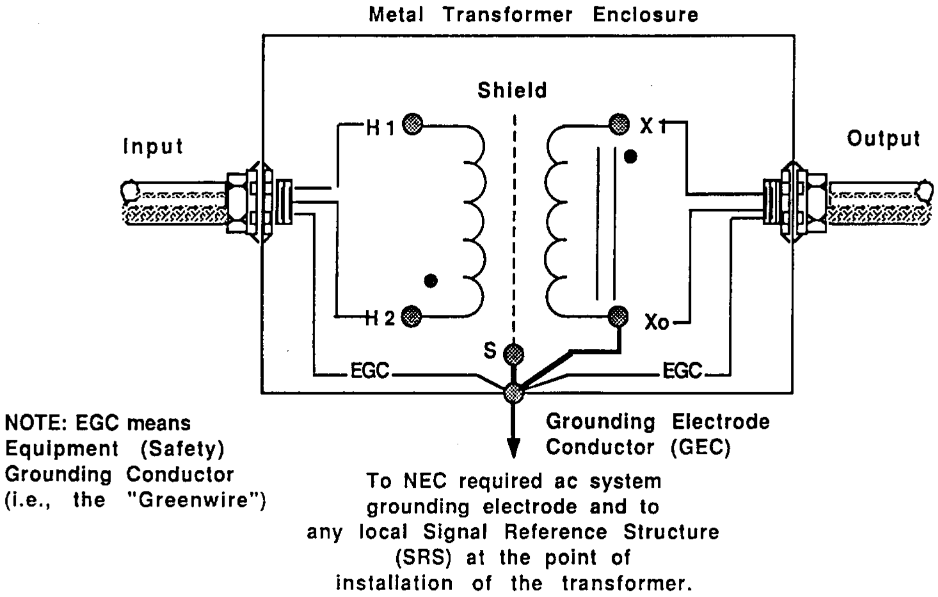


Figure 4-2—Typical electrostatically shielded isolation transformer (single-layer shield shown)

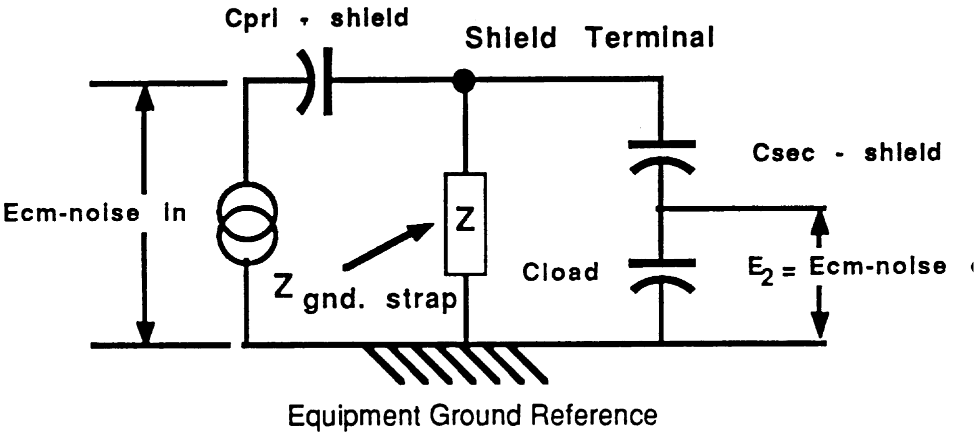


Figure 4-3—Electrostatic shield in transformer that forms a capacitive voltage divider within the isolation transformer for CM noise currents

Adding more (ungrounded) shields to the primary and secondary windings and operating them at their associated winding's line-voltage potential permits a beneficial reduction in common-mode to transverse-mode noise conversion across the transformer. Several tens of decibels of attenuation across a wide range of frequencies can be realized by this simple method of additional shielding.

At higher frequencies, where wave and transmission line theory must be used, the interwinding shield appears as a point of impedance mismatch from which transient currents (and voltages) can be reflected and re-reflected. This produces attenuation on the downstream side of the point of impedance mismatch. Also, reflections initiated by travelling waves on the ac power wiring to and from the shield, are also found on the grounding conductor(s) and grounding system to which the shield has been connected for reference purposes. This latter point is very important and underscores the reason that specialized broad-band SRS grounding techniques, as discussed in Chapter 8, must be used when avoiding noise problems in the grounding system, as opposed to SPG and related hybrid designs.

4.2.2.5 Add-on filter components (transformers)

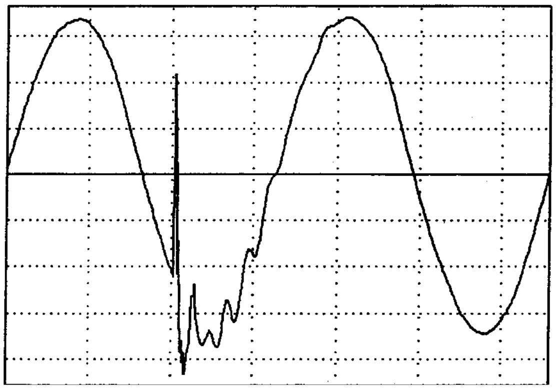
Transformers can be enhanced by using additional capacitors and inductors to create low-pass filter arrangements that use the reactances of the transformer as an integral part of the filter's design. If this is carefully done, the resulting low-pass filter will usefully attenuate high-frequency transients above the filter's –3 dB cutoff point and within the energy handling capability of the add-on reactances used in the construction of the final product. However, as noted in 4.2.2.4, any noise current that is shunted into the grounding system (e.g., via an electrostatic shield or any shunt-connected capacitors to ground) can cause problems depending upon the design of the grounding system (see 8.5 and Lewis [B34]).

Transients with rise time in microseconds and ring frequencies in the kilohertz range, such as the ring wave defined in IEEE Std C62.41-1991, are not attenuated rapidly by typical power transformers or building wiring (see IEEE Std 141-1993 [B27] and Martzloff [B35]). Switching of reactive loads, such as transformers and capacitors, create transients in the kilohertz range. Figure 4-4 and Figure 4-5 illustrate waveforms that are not unusual. It is on these and similar types of transients that add-on filter components may be highly useful.

Electromechanical switching devices also interact with the distributed inductance and capacitance in ac distribution and loads to create electrical fast transients (EFTs), as shown in Figure 4-6. EFTs are associated with a broad band of frequencies.

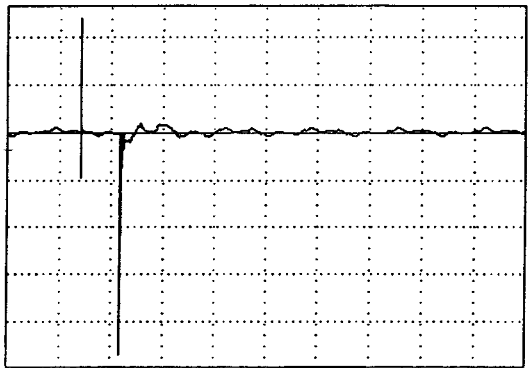
4.2.3 Building ac distribution system impedance

The impedance of local electrical distribution systems is mostly resistive and inductive at power frequencies of most interest (60 Hz to 3 kHz, $h = 50$) and mostly inductive and capacitive at higher frequencies, especially above 1 MHz (see Table 4-1). Therefore, local ac distribution wiring can be used to significant advantage in attenuating unwanted high-frequency noise voltages and short first-transition time surges. This is made clear in IEEE Std C62.41-1991 where reference is made to the attenuation provided on long feeders and branch circuits as opposed to short ones, and to the test waveforms used, which are designed to simulate the effects of lightning (see Lee [B32]).



Source: The Dranetz Field Handbook [B54].

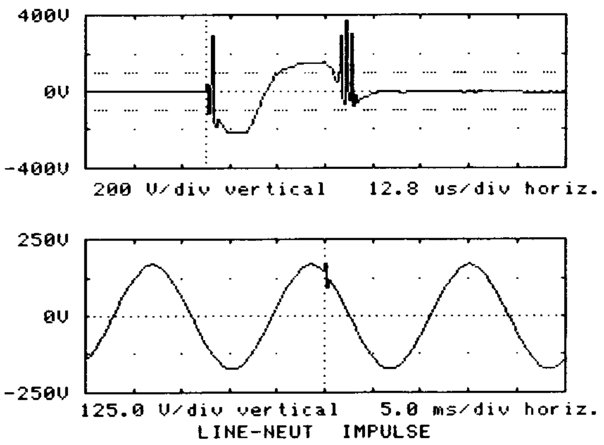
Figure 4-4—Phase-neutral transient resulting from addition of capacitive load to the electrical system



Source: The Dranetz Field Handbook [B54].

NOTE—Neutral-ground transients must typically be measured at a panelboard that is remote from the involved ac system's neutral-to-ground/chassis bond for ac system grounding. Otherwise, the only voltage to be observed will be that developed across the N-G bond jumper itself, and this is likely to be close to zero.

Figure 4-5—Neutral-ground transient resulting from addition of inductive load from the electrical system



Source: McEachern [B40].

Figure 4-6—Phase-neutral transient resulting from arcing and bouncing contactor

Actual impedances of ac feeders and branch circuits vary considerably, due both to their configurations and loads. For purposes of analysis and modeling, equivalent circuits of ac branch circuits have been identified (see Golde [B15] and Sunde [B52]). Figure 4-7 depicts the resulting ac branch circuit impedance for such a model as reported in Golde [B15]. The general behavior of impedance with frequency, shown in Figure 4-7, is typical for most ac feeder and branch circuits; but actual impedances can vary considerably and resonances above 1 MHz can greatly alter the impedance behavior. It should also be noted that the commonly, but incorrectly, assumed fixed characteristic impedance of 50 Ω for ac distribution circuits can contribute to significant errors if used to calculate surge energy levels (see 4.6.6).

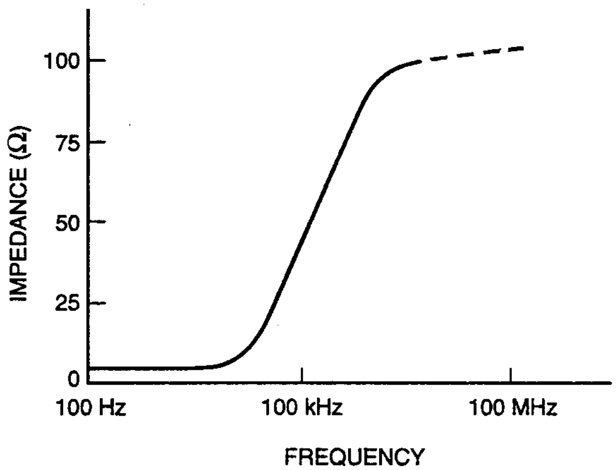


Figure 4-7—Typical ac distribution branch circuit impedance vs. frequency (no load connection)

Table 4-1—Example cable impedances at high frequencies (copper cable suspended in free air)

(a) #4 AWG building wire (25 mm^2)

Length in ft (m)	L (μH) (>1 MHz)	@ 1 MHz		@ 10 MHz		@ 100 MHz	
		Rf (Ω)	ω*L* = *Z* (Ω)	Rf (Ω)	ω*L* = *Z* (Ω)	Rf (Ω)	ω*L* = *Z* (kΩ)
10 (3)	4	0.05	26	0.15	260	0.5	2.6
20 (6.1)	9	0.1	57	0.3	570	1.0	5.7
40 (12.2)	20	0.2	125	0.6	1250	2.0	12.5
60 (18.3)	31	0.3	197	0.9	1970	3.0	19.7
100 (30.5)	55	0.5	350	1.5	3500	5.0	35.0

(b) #4/0 AWG building wire (107 mm^2)

Length in ft (m)	L (μH) (>1 MHz)	@ 1 MHz		@ 10 MHz		@ 100 MHz	
		Rf (Ω)	ω*L* = *Z* (Ω)	Rf (Ω)	ω*L* = *Z* (Ω)	Rf (Ω)	ω*L* = *Z* (kΩ)
10 (3)	3.6	0.022	23	0.07	230	0.22	2.30
20 (6.1)	8	0.044	51	0.14	510	0.44	5.10
40 (12.2)	18	0.088	113	0.28	1130	0.88	11.3
60 (18.3)	28	0.132	176	0.42	1760	1.32	17.6
100 (30.5)	50	0.220	314	0.70	3140	2.20	31.4

In the higher-frequency ranges where wave and transmission line theory predominates over circuit theory, the typical feeder and branch circuit assumes the character of a lossy transmission line of unevenly distributed impedance. It also presents itself with impedance mismatched terminations at each end (and at any midpoint taps or other connections), which produce reflections and re-reflections of transient currents (or voltages) being propagated on the path.

4.2.4 Load impedance

Electronic equipment typically contains motors, transformers, and rectifiers. Outputs of these transformers and rectifiers are typically electronically regulated to provide constant voltage to load circuits. Insight can be gained as to the nature and operation of these loads by analyzing their basic components.

The basic components of (passive) load impedance each have a distinct variation with frequency. Resistance, R, ideally does not change with frequency. Therefore, its curve is simply a straight horizontal line, with a magnitude of R ohms above the frequency axis [see Figure 4-8].

Inductive reactance, X_L, linearly increases with frequency (of the form $y = mx + b$). Inductive reactance vs. frequency is plotted in Figure 4-9, with a slope equal to the inductance, L, of the inductor and intercepting at the origin ($X_L = \omega L + 0$).

Capacitive reactance, X_C, is a hyperbolic function of frequency of the form $yx = k$, where the frequency, ω, is the independent variable and $-1/C$ is the constant. Capacitive reactance vs. frequency [$X_c = -1/(\omega C)$] is plotted in Figure 4-10. From Figure 4-9 and Figure 4-10 it can be seen that, as frequency increases, inductive reactance becomes the dominant factor.

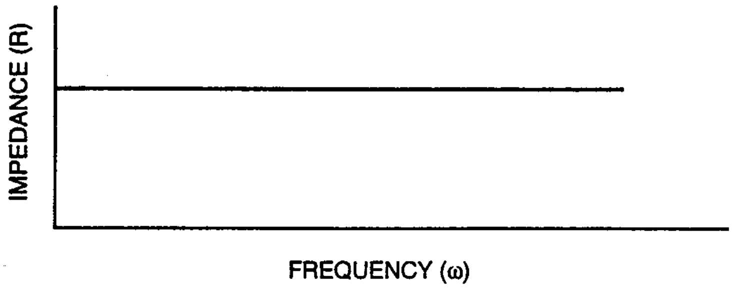


Figure 4-8—Passive load resistance vs. frequency

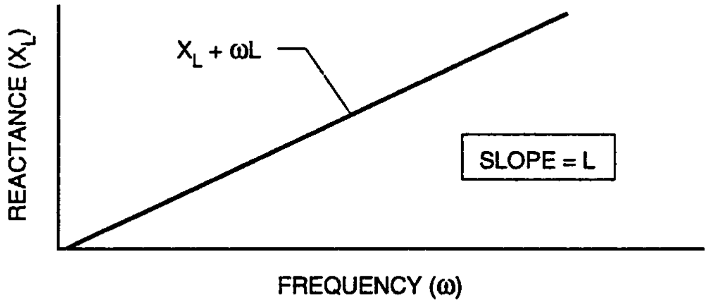


Figure 4-9—Passive load inductive reactance vs. frequency

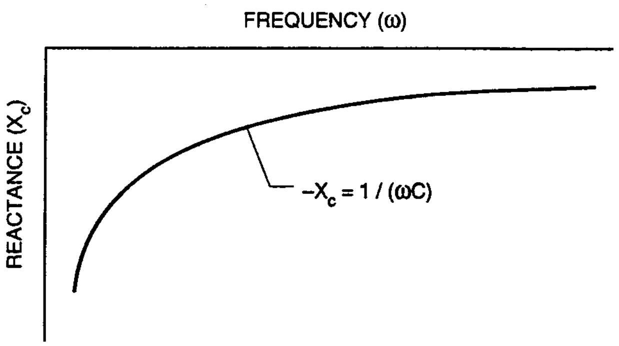


Figure 4-10—Passive load capacitive reactance vs. frequency

4.2.5 AC system resonance considerations

AC circuits characteristically have

a) Capacitive and inductive elements; and

b) The means to transfer oscillatory energy between these elements.

At frequencies where the inductive and capacitive reactances are equal, resonance occurs and the resulting effective impedance can be very high (parallel resonance) or very low (series resonance).

If an ac current source exists at or near the circuit resonant frequency, the circuit voltage at that resonant frequency can rise significantly, especially with little or no resistive load to provide damping {e.g., reduction of “Q” where Q is the quality factor [$Q = (1/R)(L/C)^{1/2}$]}. The voltage or the current will be seen to dramatically rise depending upon where the measurement is being taken in the circuit and whether the circuit undergoing resonance is of the parallel or series type.

It is important to analyze the power system’s frequency response, with the object of avoiding resonance problems. Most unwanted resonance conditions occur on power system wiring due to the presence of power factor correction capacitors interacting with the inductance present on the circuit. To a lesser degree, but still of concern, is the contribution of the shunt capacitors provided with LC low-pass filters on ac power entry ports of some types of electronic load equipment. An example of power system resonance is shown in Figure 4-11. These resonances tend to occur at harmonically related frequencies to the power system’s fundamental. However, resonance conditions in the performance frequency range, as defined in 4.2.1, are not unknown and can occur when the electrical system’s higher resonant frequencies are excited by transient current events such as lightning, switching, and fault clearing. The result is a high-frequency oscillatory, decaying current flowing in the resonant circuit’s path.

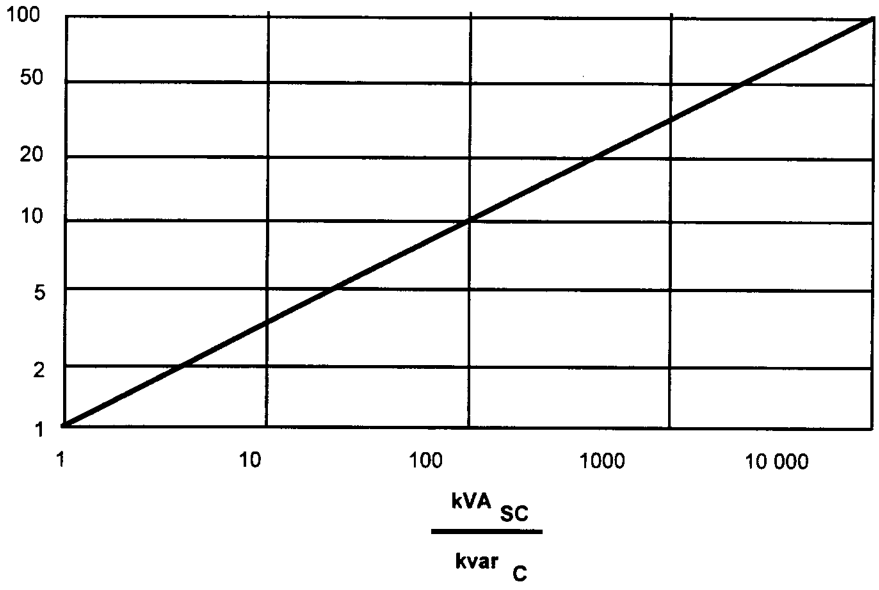


Figure 4-11—Harmonic resonance conditions on typical ac distribution systems

4.2.5.1 Series resonance

Series resonance on ac power systems results from the series combination of line/transformer inductances and capacitor banks on the ac power system. Figure 4-12 shows all three reactance elements superimposed on the same impedance vs. frequency graph. Series resonance occurs at the frequency, ω_0, where $|X_L| = |X_C|$. The minimum circuit impedance also occurs at the resonant frequency, ω_0, and is equal to the resistance, R, of the circuit. Series resonance acts as a low-impedance path for harmonic currents at the tuned frequency of the circuit. Series resonant currents on the ac power system flow (or oscillate) through the series resonant circuit's elements, from their source of excitation (e.g., the power source, the load(s), or both), and the intervening wiring and power transport components (e.g., transformers and overcurrent protective devices). In particular, nonlinear loads acting as current sources at the resonant frequency, provide current to the upstream circuits into which they are connected for ac power.

4.2.5.2 Parallel resonance

Parallel resonance results from "tank" (LC) circuits in the ac distribution system. A parallel resonant circuit may be thought of as being a series-resonant circuit that has been short-circuited back onto itself. Hence, at the resonant point where $X_L = X_C$, there will be a very low impedance and high levels of current being circulated in the resulting tank. There will also be an appropriately high voltage being developed across each of the reactances due to the voltage drop that the high current flowing through them at resonance creates. The terminals of the tank circuit generally appear as points of nearly infinite impedance and maximum circuit voltage at the resonant frequency. Internally, the tank circuit appears as a near short-circuit to the circulating current, which is limited only by the resistive components *R* and *Rac*, present in the path.

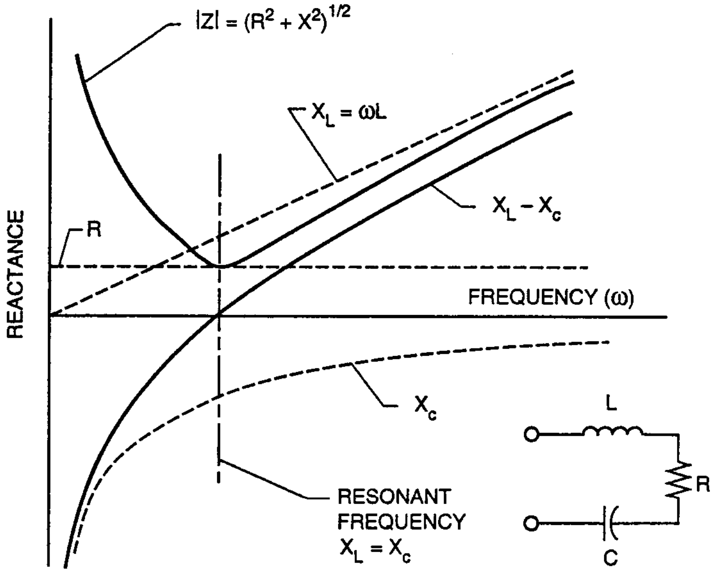


Figure 4-12—Series R-L-C circuit impedance vs. frequency

Due to the fact that parallel resonant paths represent very high impedances for currents at their resonant frequency, they can create voltage-breakdown conditions on conductors and components within, or connected to, the circuit. Harmonic currents at the resonant frequency also may create conditions of high-harmonic voltage across the circuit's terminals, which are also connected to the ac source and its load(s). Thus, the resonant tank circuit appears as a voltage source at the resonant frequency. The resonant tank circuit feeds the distribution system in parallel with the fundamental voltage source. As a result, this frequency-dependent harmonic voltage adds algebraically to the fundamental frequency voltage and to any other harmonic voltage waveforms on the circuit, to produce harmonic distortion of the fundamental voltage waveform.

Parallel resonant circuits behave inversely to the series resonant circuit. They exhibit very high impedance at resonance, whereas the series resonant circuit exhibits a very high admittance (low impedance). A diagram of parallel resonance, Figure 4-13, appears similar to the series resonance diagram, Figure 4-12, when voltages are replaced by currents, currents replaced by voltages, and associated parameters are interchanged with their "inverse equivalents" (see Greason [B18]). The total set of terms utilized in Figure 4-13 and their equivalent series resonance terms are as follows:

Terms	Equivalent series resonance terms
Current (*I*)	Voltage (*V*)
Admittance (*V*)	Impedance (*Z*)
Conductance (*G*)	Resistance (*R*)
Susceptance (*B*)	Reactance (*X*)
Capacitance (*C*)	Inductance (*L*)

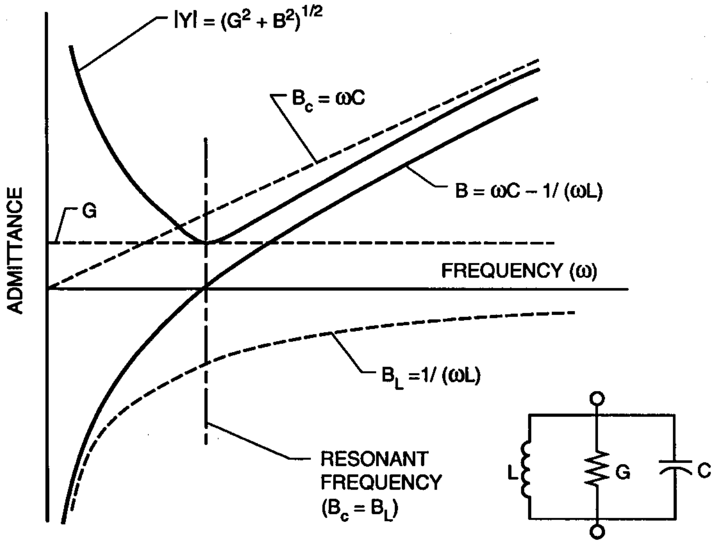


Figure 4-13—Parallel R-L-C circuit impedance vs. frequency

Considerable current can oscillate between the inductive and capacitive storage elements of the circuit when nonlinear loads, with a characteristic harmonic near the parallel resonant frequency, exist in the circuit. Voltage distortion results from these high oscillating current levels. Under certain conditions the oscillating currents can also emit electromagnetic energy, which can interfere with adjacent signal circuits.

In summary, and by comparison, series-resonant circuit currents oscillate through the ac supply system paths and their source, while parallel-resonant circuits confine such current to the parallel circuit's own loop. Therefore, series resonant circuits involve the supply, load, and intervening wiring (and all power transport components in the wiring path), with current at the resonant frequency; and parallel resonant circuits impress voltages (at the resonant frequency) on their source, load, and on the wiring system. These two conditions represent the underlying mechanism for the production of the most common forms of harmonic voltage waveform distortion on the ac wiring system.

4.2.5.3 Resonance on feeders and branch circuits

The conductors used to form feeders and branch circuits possess both distributed self-inductance and distributed capacitance. These are called stray or parasitic reactances. The self-inductance portion is series distributed in longitudinal fashion along the length of the feeder, branch circuit, or both, while the capacitance portion is shunt distributed between all conductors as well as to equipment ground along the same path. Equipment ground is defined as any enclosing metallic raceway, a “greenwire” [e.g., an equipment grounding conductor (EGC)], or nearby grounded metal if the raceway is nonmetallic. This arrangement forms into a transmission line with reactive circuit elements connected across the ends in the form of the ac power source and load. Both series and parallel resonant conditions are thus capable of occurring under proper conditions of excitement. Exciting current is generally provided by switching in the load-source current path, although an exciting current can also be introduced from the equipment ground path via the shunt capacitance.

Loads, such as variable-frequency speed drives (VFDs) for motors, are known to be capable of producing high-frequency currents sufficient to excite the resonant circuit in the feeder, branch circuit, or both. Reflected waves from the motor and power source that oscillate through the intervening wiring path are also associated with this action. This is particularly true for the modern IGBT (or bipolar) drive used with pulse width modulation (PWM) techniques since very fast transition times can be involved during the transistor’s switching between on and off states (on the order of between 50 ns and 200 ns), with switching frequencies of between 2 kHz and 20 kHz. The natural resonant frequency of the typical long-branch or feeder circuit between 15 m and 1000 m (49.2 ft and 3280 ft) and the involved ac source-VFD combination is typically on the order of from 1 MHz to 10 MHz (see von Jouanne et al. [B60]).

The only real damping or limit on the “Q” of the resonant circuit in the feeder or branch circuit is generally provided by the path’s resistance, which is in series with the oscillating current, and this is typically not sufficient by itself to provide rapid damping. As a result, voltage impulses (e.g., transients) on the order of from 1.3 kV to 1.55 kV can appear across the tank circuit and hence the VFD load terminals (see von Jouanne et al. [B60]). This is highly detrimental to the motor insulation life span and can have similar detrimental or disruptive effects to any electronic loads connected into the same circuit.

The foregoing condition can generally be ameliorated by the application of a three-phase, E-core, series-connected choke of commercial design that provides some additional series resistance and acts as a low-pass filter in the path of interest. The low-pass characteristic of the arrangement ensures that only the unwanted high-frequency components of the current are attenuated and not the lower-frequency ones involved with the efficient transmission of electrical power between the source and load.

Lightning, and in some cases ground faults, can similarly excite the long feeder or branch circuit resonances via the shunt capacitance path from ground. Near-field coupling in the H field from nearby sources of high-frequency noise sources can also induce excitation current into the self-inductance of the resonant circuit of the feeder or branch circuit.

4.3 High- and low-frequency regimes defined

Throughout this book and in typical discussions about the control of electrical “noise,” surges, and lightning impulses, the terms *low frequency* (LF) and *high-frequency* (HF) will be used—typically without any useful definition being rendered at the point of usage. Accordingly, this important subject is addressed in the following paragraphs, which must be understood before going further into the material presented in this and some subsequent chapters of this book.

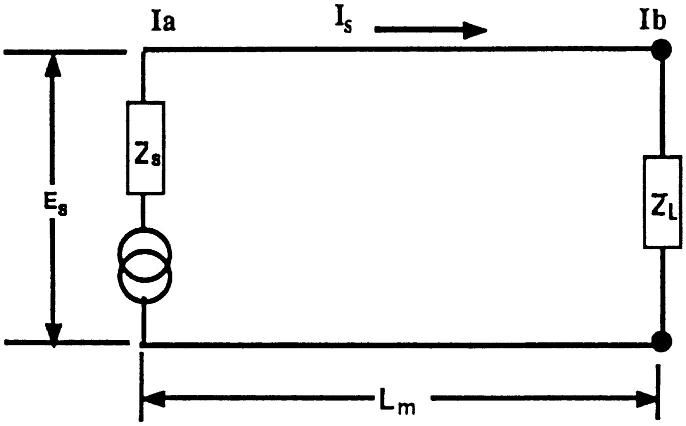
This subject is important since techniques and explanations of things that are useful at a frequency of 20 kHz or less are often totally unsuitable for use at higher frequencies. In similar fashion, the electrical size of the circuit under discussion will have to be specified in order to know how to discuss the circuit and what techniques need to be applied to control interference of all types within it (see Goedbloed [B17]). Hence, we begin by defining the basic current loop.

4.3.1 Definition of the basic current loop

A typical basic current loop is shown in Figure 4-14. Using circuit theory it can be seen that if a sinusoidal voltage E_S is used to drive a current I_a in the closed loop to the load Z_L, along path length L_m, all current and voltage events around the loop will be considered as occurring instantaneously and in continuous fashion for the duration for which E_S is applied. This is a low-frequency view of this circuit appropriate for dc and steady-state conditions, but does not explain what happens at the moment of power application or removal, and at generally higher frequencies, as will be explained.

However, it is the electrical length of the current loop, defined by L_m as the distance between points I_a and I_b, that determines the point at which circuit theory, as discussed above, or transmission line (wave) theory, as discussed below, is applied. This demarcation point between the two regimes is called the boundary point.

Above the boundary point it is seen that not all things happen simultaneously in the current loop—it takes time for things to occur and when they do, they occur sequentially with a true time lag for currents and voltages to travel around in the current loop. Here is where transmission line or wave theory must be used in order to explain what happens in the circuit since circuit theory does not allow for things that do not occur simultaneously. Note that the time it takes a wave to move from point a to point b in a physical medium (e.g., a wire) as opposed to a vacuum, is significantly longer than the speed of light.



NOTE—This is a *small circuit* in relation to the involved current’s highest frequency wavelength if the electrical distance between a and b is ≤ 1/20λ.

Figure 4-14—Typical basic current loop in low-frequency regime suitable for circuit analysis

4.3.2 Velocity of propagation

The time lag for currents and voltages to travel around in the current loop, as discussed in 4.3.1, is properly defined as the *velocity of propagation*. This time lag is determined from the time it takes the first transition point (e.g., the leading edge) on the current waveform to make the trip from point I_a to point I_b in the basic current loop (see Figure 4-14). This time is strongly influenced by the relative permittivity, ε_r, and relative permeability, μ_r, of the path so that the velocity, V, of the current’s propagation through the conductive medium is then found using Equation (4-2).

$$v = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \tag{4-2}$$

where

v is the propagation velocity in m/s,

c is the propagation velocity of an electromagnetic wave in a vacuum (3×10^8 m/s).

NOTE—Units of ε and μ must be the same and cancel.

With the velocity of propagation known, the classification of the subject circuit into the large or small category may proceed, with circuit theory typically applying to small circuits and wave or transmission line theory to large circuits.

4.3.3 Small and large circuits defined

For the most part, a small circuit, where circuit theory may be used with some confidence, occurs when the amount of current change between I_a and I_b is small and the change occurs in the time determined using Equation (4-3):

$$t = \frac{l}{v} \tag{4-3}$$

where

t is time,

l is the length of the path,

v is the propagation velocity.

Further illustration of the foregoing occurs when the period of a given sinusoidal current is compared to the propagation time in the current loop as determined using Equation (4-3). Therefore, using Equation (4-4),

$$t << T \tag{4-4}$$

where

t is the time in seconds from Equation (4-3),

T is equal to $1/f_{\mathrm{Hz}}$ (the period of the waveform).

If, for some reason, it is not desired that the propagation time t be measured in order to determine if a large or small current loop is under consideration, the longest (e.g., worst case) propagation path length (l) can be compared to the wavelength (λ) of the sinusoidal current being considered. This is done per Equation (4-5).

$$v = \lambda f \tag{4-5}$$

where

v is the propagation velocity from Equation (4-2),

λ is the wavelength of the sinusoidal wave,

f is the frequency in Hertz.

From an overall standpoint, the foregoing represents the view that the current loop under consideration is considered to be a small circuit suitable for analysis using circuit theory, only when the length of the current loop is much less than the wavelength of the highest frequency sinusoidal wave comprising the waveform on the path. This is represented in Equation (4-6).

$$l << \lambda \qquad (4\text{-}6)$$

where

l	is the length of the current loop’s path,
λ	is the wavelength of the highest frequency sinusoid in the given waveform.

The approximate ratio of the current in the loop between point I_a and I_b may be determined via Equation (4-7).

$$\left|\frac{I_a}{I_b}\right| = \sqrt{\cos^2 kl + \left[\frac{Z_L}{Z_0}\sin kl\right]} \qquad (4\text{-}7)$$

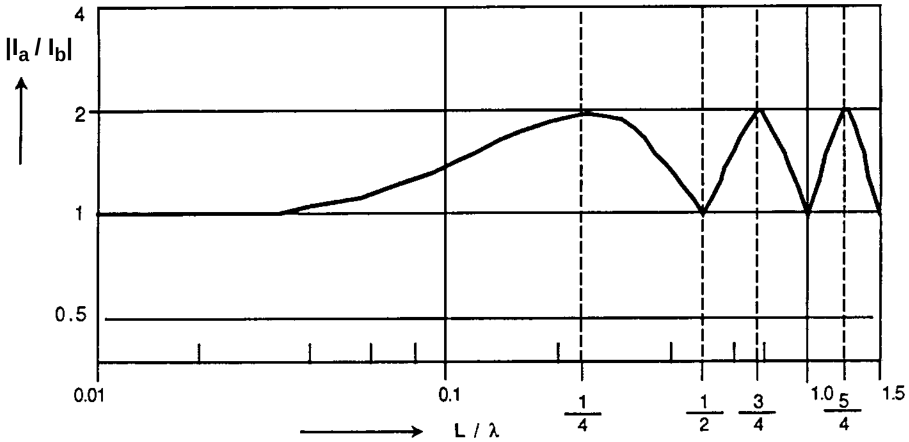
where

I_a	is the current at input of the loop,
I_b	is the current at the end of the loop,
k	is equal to $2\pi/\lambda$, i.e., the wavelength number,
l	is the length of the loop in meters,
Z_L	is the loop’s output-load impedance,
Z_0	is the loop’s input-source impedance.

Equation (4-7) may be presented in graphical form as shown in Figure 4-15. From this graph it can be seen that up to approximately 0.1 λ, the ratio of current for I_a and I_b is not great and so circuit theory can be used on the assumption that the current is flowing at all points in the current loop at the same time. In general, a 0.05 λ value is recommended to be used as a limit in this area, and this coincides with the recommendations in this chapter and in Chapter 8 on limiting the electrical length of a grounding/bonding conductor to no more than (1/20)λ (i.e., 0.05 λ), if it is to be effective as a means of equalizing potential across its length. Note that at 0.1 λ the ratio of 1.4:1 for I_a and I_b exists, and that this is a point of –3dB. Such a point is usually suitable for estimation purposes and relatively non-critical or low-susceptibility equipment, but for most reliable operation of typical digital logic-based equipment, the current ratio established at the (1/20)λ point, as recommended herein by FIPS Pub 94-1983, EPRI [B13], and by Ott [B44], is viewed as a limit.

4.3.3.1 Selecting circuit analysis or wave-transmission line theory

As explained previously in 4.3.3, in order to successfully apply circuit theory to the current loop under consideration, the closed loop path, as measured in meters, must be much smaller than the wavelength in meters of the highest frequency sinusoid comprising the waveform under consideration. Thus, it can be assumed that after the leading edge of the impinging waveform has arrived at the end of the current loop, its main body and trailing edge have not yet cleared the input point of the loop—current is flowing simultaneously in all parts of the circuit from the same waveform event and the use of circuit analysis is valid.



NOTE—Normalized to the wavelength λ of the applied signal, for $Z_L = 2Z_0$ for a 2:1 mismatch.

Figure 4-15—Ratio of current between I_a and I_b per Equation (4-7) as a function of the current loop's length

In the case where the leading edge of the impinging waveform under consideration has not yet arrived at the end of the current loop, wave or transmission line theory must be used to determine the response of the circuit during the time period it takes for the leading edge to arrive. The reverse is also true when the trailing edge of the waveform departs the input end of the current loop and when there is still current flowing in the remainder of the loop. In the former case we deal with a strictly limited period of time for a turn-on event, and in the latter case a turn-off event.

Hence, even with a small circuit, both circuit analysis and wave-transmission line theory must be used to predict the performance of the circuit if a full explanation of its performance is desired. Sometimes however, the concern can be limited to only the effects of the leading edge or the period of time where current is simultaneously flowing in all parts of the circuit. In this case, one analysis method or the other is applied depending upon what information is needed, and the other is discarded.

In the typical event where an impulse is being considered and where it is fully contained on the current loop (e.g., it is travelling down the current loop and its trailing edge has departed, but its leading edge has not yet arrived), only wave-transmission line theory can be used to explain the action and to predict performance.

The foregoing is best appreciated when it is noted that the typical "noise" impulse that undesirably affects digital logic-based equipment is of relatively short duration and contains rapid transitions. Thus, it is almost always necessary to use wave-transmission line theory to explain and predict events on typical wiring paths, such as grounding and bonding conductors in buildings that are used to interconnect items of electrical or electronic equipment. Since these conductors are lengthy in respect to the impulse's duration, there is no hope that circuit theory can be used to explain what is happening or is going to happen—so it must not be used.

Nowhere is the above more important to understand than when the connection leads for typical LC filters or surge protective device (SPD) networks are being considered and where grounding/bonding conductors are used in conjunction with ac-dc power, signal level (all types), and telecommunications circuits that are associated with digital logic-based equipment. Or, when specialized building grounding conductor systems that are many tens of feet in length are being considered, such as typical SPG and related TREE designs, or "daisy-chain" connections.

The foregoing grounding system philosophies are typically, but undesirably, associated with some forms of process-control equipment, computer systems, and especially dedicated telecommunications grounding conductor systems such as are installed in relation to the dc power plant, but in almost all such cases are being misused for HF and surge-current control grounding purposes. These are classic examples of large circuits that require HF wave-transmission line theory approaches, but which are typically mistreated as if they are small circuits that can be analyzed via circuit theory, or as if they only operate at LF.

In summary, if best performance is required the current loop is kept within the recommended limit of less than 1/20 λ—especially where grounding/bonding conductors are concerned. Then, it may be assumed that the circuit has simultaneous current flow to all of its parts and it may then be treated with circuit analysis, which is much simpler to work with than wave-transmission line theory.

4.4 Electric power supplier's distribution system voltage disturbances

Electric power suppliers (which may or may not be regulated utilities) in the U.S. generally adhere to ANSI C84.1-1995 for the delivery of electrical power. This ANSI document provides guidelines for steady-state voltage tolerances, as shown in Table 4-2.

Reasonable continuity (e.g., continuous availability) of electrical power to the service at a given site can generally be obtained from a connection to the electric power supplier's distribution system, however power quality cannot often be assured to the same degree as continuity. Most electric power suppliers have available standard power reliability indices such as the average service availability index (ASAI) (see Edison Electric Institute [B11]).

The typical indices (such as the ASAI) do not take into direct account the very short duration interruptions (momentary interruptions) of power. Momentary interruptions, as defined in these cases by the electric power supplier, generally are considered to be less than 2 min.

Table 4-2—Standard nominal system voltages and voltage ranges[a]

VOLTAGE CLASS	NOMINAL SYSTEM VOLTAGE			Nominal utilization voltage (Note 1)	VOLTAGE RANGE A			VOLTAGE RANGE B		
					Maximum	Minimum		Maximum	Minimum	
	Two-wire	Three-wire	Four-wire	Two-wire Three-wire Four-wire	Utilization and service voltage	Service voltage	Utilization voltage	Utilization and service voltage	Service voltage	Utilization voltage
Low voltage (Note 1)	Single-phase systems									
	120			**115**	126	114	110	127	110	106
		120/240		**115/230**	**126/252**	**114/228**	**110/220**	**127/254**	**110/220**	**106/212**
	Three-phase systems									
			208 Y/120	**200**	**218 Y/126**	**197 Y/114**	**191 Y/110**	**220 Y/127**	**191 Y/110** (Note 2)	**184 Y/106** (Note 2)
			240/120	**230/115**	**252/126**	**228/114**	**220/110**	**254/127**	**220/110**	**212/106**
		240		**230**	252	228	220	254	220	212
			480 Y/277	**460**	**504 Y/291**	**456 Y/263**	**440 Y/254**	**508 Y/293**	**440 Y/254**	**424 Y/245**
		480		**460**	**504**	**456**	**440**	**508**	**440**	**424**
		600		**575**	630	570	550	635	550	530
Medium voltage		2 400			2 520	2 340	2 160	2 540	2 280	2 080
			4 160 Y/2 400		4 370 Y/2 520	4 050 Y/2 340	3 740 Y/2 160	4 400 Y/2 540	3 950 Y/2 280	3 600/2 080
		4 160			**4 370**	**4 050**	**3 740**	**4 400**	**3 950**	**3 600**
		4 800			5 040	4 680	4 320	5 080	4 560	4 160
		6 900			7 240	6 730	6 210	7 260	6 560	5 940
			8 320 Y/4 800		8 730 Y/5 040	8 110 Y/4 680	—	8 800 Y/5 080	7 900 Y/4 560	—
			12 000 Y/6 930		12 600 Y/7 270	11 700 Y/6 760	—	12 700 Y/7 330	11 400 Y/6 580	—
			12 470 Y/7 200		**13 090 Y/7 560**	**12 160 Y/7 020**	—	**13 200 Y/7 620**	**11 850 Y/6 840**	—
			13 200 Y/7 620		**13 860 Y/8 000**	**12 870 Y/7 430**	—	**13 970 Y/8 070**	**12 504 Y/7 240**	—
			13 800 Y/7 970		14 490 Y/8 370	13 460 Y/7 770	—	14 520 Y/8 380	13 110 Y/7 570	—
		13 800			**14 490**	**13 460**	**12 420**	**14 520**	**13 110**	**11 880**
			20 780 Y/12 000		21 820 Y/12 600	20 260 Y/11 700	—	22 000 Y/12 700	19 740 Y/11 400	—
			22 860 Y/13 200		24 000 Y/13 860	22 290 Y/12 870	—	24 200 Y/13 970	21 720 Y/12 540	—
		23 000			24 150	22 430	—	24 340	21 850	—
			24 940 Y/14 400		**26 190 Y/15 120**	**24 320 Y/14 040**	—	**26 400 Y/15 240**	**23 690 Y/13 680**	—
			34 500 Y/19 920		**36 230 Y/20 920**	**33 640 Y/19 420**	—	**36 510 Y/21 080**	**32 780 Y/18 930**	—
		34 500			36 230	33 640	—	36 510	32 780	—
					Maximum voltage					
		46 000			48 300					
		69 000			**72 500**					
High voltage		**115 000**			**121 000**					
		138 000			**145 000**					
		161 000			169 000					
		230 000			**242 000**					
Extra-high voltage		**345 000**			**362 000**					
		500 000			**550 000**					
		765 000			**800 000**					
		1 100 000			**1 200 000**					

NOTES:

(1) Minimum utilization voltages for 120–600 V circuits not supplying lighting loads are as follows:

Nominal system voltage	Range A	Range B
120	108	104
120/240	**108/216**	**104/208**
(Note 2) **208 Y/120**	**187 Y/108**	**180 Y/104**
240/120	**216/108**	**208/104**
240	216	208
480 Y/277	**432 Y/249**	**416 Y/240**

(2) Many 220 V motors were applied on existing 208 V systems on the assumption that the utilization voltage would not be less than 187 V. Caution should be exercised in applying the Range B minimum voltages of this table and Note 1 to existing 208 V systems supplying such motors.

Source: ANSI C84.1-1995.

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[a] Preferred system voltages in bold-face type.

Typically, momentary interruptions are the result of a variety of normal and abnormal operations in the electric power supplier's distribution system (see IEEE Std 446-1995 and Allen and Segall [B1]). Due to the definition of a power interruption generally used by electric power suppliers vs. the capabilities of electronic load equipment, distribution circuits that the electric power supplier might consider to be reliable may be totally inadequate to the user of electronic load equipment. It is advisable that users of electronic equipment work with their local electric power supplier to determine operating characteristics of the particular distribution circuits in question, considering both the frequency of momentary interruptions and other pertinent reliability indices—including power quality.

Voltage waveform disturbances at the electric power supplier's feeder level have been monitored (see Allen and Segall [B1], Edison Electric Institute [B11], and Golde [B15]), and compared and contrasted (see Martzloff and Gruzs [B37]). The general conclusion is that line voltage sags are most frequent, and thus most likely to contribute to electronic load disruptions. They are followed by surges, interruptions, and swells, in lesser probabilities. The actual percentage of each type of voltage disturbance varies with time, location, the response characteristics, and the threshold settings of the particular power quality monitoring instrument being used. All things being otherwise equal, these variances are most highly influenced by the particular threshold settings utilized on the monitoring equipment.

User equipment residing near locations where lightning enters the electric power supplier's distribution system will experience high-energy surge conditions via the building's service entry wiring since it provides the interface to the electric power supplier's ac distribution system. But user equipment located at sites further away from the strike location most likely will experience momentary sag conditions as opposed to surges. This typically occurs when one or more lightning "arrestors" located on the electrical supply system's distribution wiring go into operation, and are located between the strike point and the service entry of the user's site. The momentary sags correctly result from deliberate current-shunting actions of the electric power supplier's lightning-protection equipment, which locally load down the ac distribution system during its operation. To a degree this action can also be randomly duplicated by arcing to ground from the conductors, or from insulator flashovers on the distribution system's wiring.

4.5 Load and power source interactions

Interactions of interest between electronic load equipment and their power sources (and sometimes their grounding systems) primarily result in transient disturbances or nearly continuous distortions to the system voltage waveform. Under the heading of "Voltage parameter affecting loads," Table 4-3 summarizes these sources of voltage waveform disturbances, distortions, and their general characteristics (see The Dranetz Field Handbook [B54] and McEachern [B40]). When ameliorating these variances, it is often helpful to know their related current waveforms. For example, certain source/load interactions (e.g., switching) result in short first-transition-time voltage transients (surges). The reader is referred to 4.6 for a discussion of surges.

Table 4-3—Matching sensitive load and power source requirements with expected environments

Voltage parameter affecting loads	Typical range of power sources	Typical immunity of electronic loads		
		Normal	**Critical**	**Units affected and comments**
Over and undervoltage	+6%, –13.3%	+10%, –15%	±5%	Power supplies, capacitors, motors. Component overheating and data upset.
Swells/sags	+10%, –15%	+20%, –30%	±5%	Same as above.
Transients, impulsive and oscillatory, power lines	Varies: 100–6000 V	Varies: 500–1500 V	Varies: 200–500 V	Dielectric breakdown, voltage overstress. Component failure and data upset.
Transients, impulsive and oscillatory, signal lines	Varies: 100–6000 V	Varies: 50–300 V	Varies: 15–50 V	Same as above.
ESD	< 45 kV 1000–1500 V	Varies widely: 200–500 V	Varies widely: 15–50 V	Signal circuits. Dielectric breakdown, voltage overstress. Component failure and data upset. Rapid changes in signal reference voltage.
RFI/EMI (conducted) (normal and common mode)	10 V up to 200 kHz less at higher frequency	Varies widely: 3 V typical	Varies widely: 0.3 V typical	Signal circuits. Data upset, rapid changes in signal reference voltage.
RFI/EMI (radiated)	< 50 kV/m, < 200 kHz < 1.5 kV/m, > 200 kHz	Varies widely with shielding	Varies widely with shielding	Same as above.
Voltage distortion (from sine wave)	5–50% THD	5–10%	3–5%	Voltage regulators, signal circuits, capacitor filters, capacitor banks. Overheating, undercharging.
Phase imbalance	2–10%	5% max	3% max	Polyphase rectifiers, motors. Overheating.

Current parameter affecting sources	Typical range of load current	Typical susceptibility of power sources		
		Normal	**Critical**	**Units affected and comments**
Power factor	0.85–0.6 lagging	0.8 lagging	< 0.6 lagging or < 0.9 lagging	Power source derating or greater capacity source with reduced overall efficiency.
Crest factor	1.4–2.5	1.0–2.5	> 2.5	1.414 normal; impact function of impedances at 3rd and higher harmonics (3–6% *Z*). Voltage shape distortion.
Current distortion	0–10% total rms	5–10% total 0–5% largest	5% max total 3% largest	Regulators, power circuits. Overheating.
DC current	Negligible to 5% or more	< 1%	As low as 0.5%	Half-wave rectifier loads can saturate some power sources, trip circuit breakers.
Ground current	0–10 A rms + noise and surge currents	> 0.5 A	< 0.1 A	Can trip GFI devices, violate code, cause rapid signal reference voltage changes.

Frequency parameter affecting loads	Typical range of power sources	Typical immunity of electronic loads		
		Normal	**Critical**	**Units affected and comments**
Line frequency	±1%	±1%	±0.5%	Zero-crossing counters.
Rate of frequency change	1.5 Hz/s	1.5 Hz/s	0.3 Hz/s	Phase synchronization circuits.

Source: Based on FIPS Pub 94-1983.

4.5.1 Transient voltage disturbance sources/characteristics

In this subclause, *voltage waveform disturbances* are considered to be that set of voltage variances on the power circuits of interest that are

a) Nonsinusoidal at the nominal frequency of the power source; and
b) The result of power-source and load characteristics, which interact with the intervening impedances present in the associated ac building distribution system.

These disturbances in system voltage waveform tend to decay rapidly with time.

Load-related changes and switching events cause almost all voltage disturbances that occur between equipment and their power sources. Several common load-derived sources of voltage waveform disturbances and their relative characteristics are presented below.

4.5.1.1 Step loads

Step load changes are one of the most common sources of voltage disturbance. The basic cause of the voltage disturbance is simply a change in voltage drop caused by the sudden application or removal of load current and the power system impedance. Simply stated, when load current abruptly changes, the voltage drop in the path also abruptly changes. Properly applied ac voltage regulators tend to correct voltage drops within the power distribution system, but only after a time delay that is an inherent characteristic of the feedback system used in the regulator being utilized. All ac voltage regulators have a characteristic time-delay from the sensing of a voltage variation on their output to the time of correction on their output, and this is mainly dependent upon the type of regulator technology chosen in each case.

4.5.1.2 Inrush currents (motors, LC line filters, and power supplies)

Inrush currents are associated with the initial energizing of motors, low-pass type LC line filters (e.g., with shunt capacitors connected on the supply side of the filter), and various ac-dc power supplies (e.g., via the initial magnetizing current for an input transformer if one is used, the initial filter capacitor after the rectifier, or both) are typically found in electronic equipment.

AC motor starting (inrush) currents are about equal to the locked-rotor currents, which are typically 5 to 7 times their rated full-load current. These inrush currents can require around 0.3 to 3.0 s to decay to steady-state values, depending on motor acceleration time and motor load. DC motor-starting currents appear as rectifier loads on the ac power distribution system.

The initial energizing of transformers often create magnetizing current transients (e.g., “premag” currents). Inrush currents 10 to 20 times their normal full-load current can exist, decaying in several cycles under worst-case conditions. Actual inrush currents will depend on the phase angle of the initial voltage waveforms and the state of residual magnetic (core) flux from prior transformer energizing.

Unless the typical ac-dc power supply is equipped with a current-inrush limiting feature (e.g., "soft-start"), the initial capacitor charging current at power-on time can cause fairly high levels of current inrush, especially when the capacitor is fully discharged and the initially applied voltage is at its peak value. For example, typical ac-dc switch mode power supply (SMPS) units often have no input transformer, but instead connect a full-wave, bridge rectifier directly across the ac line, which then directly feeds a large filter capacitor bank that is used for bulk energy storage for the HF inverter stage that follows. This arrangement causes the capacitor bank to be charged as much as possible on the first half-cycle of the applied current, with the current only limited by upstream circuit impedances.

4.5.1.3 Fault currents

Fault currents represent an extreme case of transient current flow and thus ac line-voltage disturbance. Depending on the power system impedance, several orders of magnitude of normal full load current may be available. Severe voltage reductions to adjacent equipment usually result until the fault is cleared. Motors that are running during the fault may act as regeneration current sources and will dump additional current into the fault for up to several cycles in worst case conditions.

Some fault conditions do not result in high currents and may not cause overcurrent protective devices to operate (e.g., arcing ground faults, under certain conditions). These faults often create significant high-frequency transient voltages of large amplitude. Solidly grounded power sources tend to minimize this type of fault and rapidly clear them when they do occur.

Fault currents entering and flowing on externally attached EGCs of all types (e.g., supplementary grounding conductors) can pose a transient voltage problem to connected electronic load equipment that, in turn, is interconnected between units by low-voltage logic, data, or signaling cables. This occurs because the equipment grounding system often presents itself as a source of high transient voltage during ground faults due to the effects of $-e = L\, di/dt$ (neglecting the effects of any distributed capacitance). Transients developed across the inductance of the involved grounding conductors can then destroy interface electronics at the ends of the interconnecting cables, telecommunications cables, and on occasion, related ac-dc logic power supply components.

4.5.1.4 Voltage regulator interactions

Voltage regulators present themselves to the ac supply line as inverse loads, e.g., they increase input current as input voltage decreases. For example, on a typical 1Ø input ac-dc SMPS contained in an electronic load unit, an approximate 25% decrease in input line voltage generally results in a corresponding 25% increase in rms input line current at the lower input voltage. This rms increase of input current with decreased input voltage would also occur on an ac-ac line-voltage regulator that is interposed between a load and an upstream ac power source. This is independent of the primary to secondary winding ratio as long as percent is the means of measurement. The shift in power factor that also accompanies this process will affect the amount of rms current increase that will be seen for the corresponding voltage decrease, etc.

Hence, a very low input ac line voltage to a singular voltage regulator may create conditions of excessive current and additional unwanted line-voltage drop on the upstream branch circuit (which worsens the situation even further). This may cause problems ranging from overcurrent protective device operation to conductor and connection overheating. Small, load-dedicated isolation transformers in the path may also experience overheating due to overload and increased harmonic current effects when this occurs.

When a single, large voltage regulator or groups of smaller ones are involved and their currents are combined at some point on the ac supply system, the increased current associated with a low line voltage can become quite large. This poses overcurrent problems at points such as panelboards, feeders, and upstream supply sources (e.g., transformers or alternators). Additionally, this increased current causes additional voltage drop, and therefore even poorer voltage regulation conditions, to occur on these paths.

Due to overloading on supply circuits, as described previously, any downstream circuits may experience even lower rms line voltage to nonregulated loads (e.g., motors). Additionally, all downstream loads will experience generally increased voltage sag problems. This latter condition occurs since the already low ac line means that the involved voltage regulators are now operating below nominal and closer to their input's low-voltage limit. Hence, a small sag that could otherwise be neglected, can cause a regulator to go out of its regulation band with unexpected effects to its served load(s).

Note that a low line voltage due to increased input current to a voltage regulator's action is compensated for by that regulator demanding a further increase in input current to again create a stabilized output. Thus, a positive feedback (e.g., circular) condition exists and, under certain conditions, can cause a system-wide overcurrent condition that leads to a power loss due to the operation of an upstream main overcurrent protection device. This is especially possible with very wide input range voltage regulators that are operated at very low input voltage (e.g., such as when an emergency or back-up ac power supply is in use and, due to loading effects, is producing a low output voltage). It is also an expected condition when a 3Ø voltage regulator is used and is of the type that can be operated under a 1Ø input line condition and still produce a nearly proper 3Ø output. Under this set of conditions, the $\sqrt{3}$ factor is no longer operative on the input current equation and the full 3Ø load output of the regulator is converted to 1Ø current on the remaining pair of phases.

Note also that a line voltage regulator being operated under conditions of excessively low input voltage may then produce a lower output voltage than nominal. Thus the SMPS loads attached to the regulator see a lower than nominal line voltage on their inputs and then demand increased current as a means of compensation. This effect then causes the line voltage regulator to have to supply even more output current with the usual effect that its output voltage is again reduced, and so on. The final effect occurs when the system no longer can stay in regulation or an overcurrent protective device is opened and the whole involved system shuts down.

Finally, if poorly applied, any voltage regulator may negatively interact in the ac distribution path. The result can range from a tendency to amplify ac line voltage disturbances to uncontrolled oscillations between an upstream (supply) and downstream (load) voltage regulator.

This typically occurs due to sympathetic regulation time-constant problems between the upstream voltage regulator and the regulator contained in the electronic load (see FIPS Pub 94-1983). For example, closely matched ferroresonant transformers (FRT) operated in series have been seen to act like magnetic “flip-flops.” For example, this can occur when an item of electronic equipment has an internal FRT and in an attempt to solve some perceived power quality problem, someone plugs the equipment into an externally installed FRT.

4.5.2 Potential impacts of transient voltage disturbances

Disturbances of the ac voltage waveform and their attendant current harmonics have been shown to significantly impact both the ac distribution system and the electronic loads (see FIPS Pub 94-1983 and Key [B31]). The most significant of these are discussed in 4.5.2.1 through 4.5.2.7.

4.5.2.1 Complete loss of ac power to electronic loads

Excessive motor and transformer inrush currents can exceed the time-current trip curves of upstream overcurrent protective devices, causing an open circuit to electronic loads.

4.5.2.2 Short-term voltage variances

Temporary reductions in the ac distribution voltage can be caused by significant step changes in load current. This is particularly true for transformer and motor inrush currents, and large load systems that dynamically switch on/off their subsystems (FIPS Pub 94-1983). The time duration of these low ac voltages cause stored-energy problems in power ac-dc power supply filter circuits that can exceed their holdup (e.g. ridethrough) time. This acts as the equivalent of an extreme ac line-voltage sag or longer duration interruption.

For example, the inrush current time is minimized when the motor is connected to an ac supply of low impedance since the motor’s current demands can be met by this kind of ac supply without a significant concurrent low-input voltage condition occurring. However, if an ac supply is used with significant impedance present within it, the resulting low line voltage due to inrush current demands will cause the motor to take longer to reach its operating RPM and thus its nominal current input. As a result of this, it can be fairly concluded that using a voltage regulator to serve both motors and other loads that are affected by short-term voltage variances is not a recommended practice without very careful engineering that correctly accounts for these dynamic effects.

4.5.2.3 Transient phase shift due to reactive load changes

This effect is primarily the result of dynamic switching (on/off) of inductive and capacitive load elements (e.g., ac motors and shunt capacitors). These large dynamic changes in load current, fed by reactive ac circuits, result in voltage and current time-shifts on the ac circuits.

Due to the connection or disconnection of large reactive loads, a phase-shift condition rapidly occurs between the circuit’s voltage and current on the involved circuit until the new point of equilibrium is reached. During this period of rapid power factor phase-shift transition any connected dynamic loads such as voltage regulators, ac-dc power supplies, and motors will act to readjust their output to compensate for whatever change in energy demand they require at that moment. This produces momentary electrical disturbances on the upstream ac supply circuits from these dynamic loads, which can be directly related to the "slew rate" (e.g., rate-of-change of time) between peaks or zero-crossings on the voltage, current, or both waveforms as they seek to readjust to the new cycle-by-cycle timing conditions imposed by the reactive load changes.

An additional problem can occur when a typical 3Ø dry-type transformer is under consideration and a variation in the time between zero-crossings of the ac voltage waveform can be seen to occur due to phase-shift phenomena related to load changes on the secondary circuit. In general the number of zero-crossings in a time period will still average out to 60 Hz, but a variation in time can be seen on individual and several related cycles during the period of interest. This can affect equipment that uses zero-crossings of the voltage waveform for timing or triggering considerations where an operating window exists every 8.33 ms that is too narrowly defined to allow a phase-shifted voltage waveform to be acceptable under all conditions.

4.5.2.4 SMPS input voltage selector

Certain SMPS designs have evolved for world-trade purposes where the ac line input to the SMPS may be either 120 V ac (typically North America) or 240 V ac (typically European), with the only difference being the type of input line cord assembly being used. This is generally accomplished by an electronic circuit in the SMPS that automatically connects its input according to the ac voltage that is sensed on the line terminals. A momentarily high ac line voltage can sometimes trigger this circuit into changing the connection from 120 V ac to 240 V ac while operating on a 120 V ac line. Unless the SMPS is equipped with a time-delay or other form of protective circuit to prevent this, the problem can occur. The end result of this unwanted switching action is a malfunction of the SMPS, which will affect its connected load. This is not a problem on SMPS designs that have the input voltage set by manual means.

4.5.2.5 DC bus voltage detectors

A wide range of equipment that is dc operated, but powered from a rectifier system that feeds a dc bus, contains monitoring circuitry to detect when the dc bus voltage goes out of tolerance. Upon such detection a protective shutdown of the dc load is generally effected. Typical equipment of this type is the variable-speed drive (VSD) in which a dc bus is used to power an inverter, which in turn powers an ac motor.

The usual problem with the foregoing arrangement occurs when a surge or oscillatory voltage is applied to the ac line input to the rectifier and which, after passing through the rectifier, then results in a corresponding momentary and oscillating increase-decrease in the dc bus voltage. A common cause of this is when power factor capacitors are switched on-line by the serving electrical power supplier, or when customer-owned capacitor banks are connected.

Some unnecessarily sensitive solid-state uninterruptible power supply (UPS) equipment may also be affected by this phenomena, but the usual result in these cases is not a shutdown of the UPS and its loads. Instead, a momentary no-break transfer to the synchronized bypass line occurs so that operation of the connected loads goes on in unaffected fashion. However, such unnecessary transfer switching is generally undesirable with a UPS and is therefore a potential problem.

4.5.2.6 Digital circuit data upset

Many of the aforementioned disturbances may occur with no other effect on the connected electronic load equipment except to create data transfer or storage errors in digital logic circuits. Since digital logic is also used within equipment for various control purposes, these disturbances may also be seen to unwantedly activate power quality checking circuits, and to trigger them into alarm or error status—often on an electronic system-wide basis. In addition to error and alarm reporting, such circuits may also be connected to cause the associated equipment to be placed into a self-restoring standby state (e.g., temporarily off-line as part of a power “fail-safe” operation) or to be placed into a full power-off state that can only be recovered from by manual, and often complex, operator intervention.

4.5.2.7 Frequency variations and slew rate

When an on-site generating system, such as an engine-alternator, is used as the ac power source for electronic load equipment and is closely matched in size to the load, almost any variations in loading (particularly step-loading) can cause related variations in rotational speed, which in turn produce a temporary change in the ac supply frequency until the engine-alternator’s speed governor makes its correction. Increased loading lowers shaft RPM while decreased loading increases it. The amount of shaft speed change during loading changes is closely related to both the size/mass of the generating set in relation to the amount of the loading step change and to the type of speed-control governor employed on the generating equipment. Typically, a well-controlled correction occurs over several cycles when the recommended isochronous type of speed governor is used on the engine. Other forms of speed governors are generally not effective in minimizing this condition in comparison to the isochronous type.

Step-load changes cause the generating unit’s shaft speed to change at a faster rate than will occur due to normal corrections controlled by the engine’s speed governor. This is as the speed governor is normally set up to limit the maximum rate-of-change of shaft RPM that results from its feedback input. Hence, the output frequency’s rate-of-change under governor control is limited as well. However, shaft RPM changes and related output frequency rate-of-change caused by step-loading variations are not controlled, except by the maximum rate-of-change in RPM that the equipment’s rotating mechanical mass will allow. Therefore, unacceptably high rates-of-change in output frequency can be experienced due to step-loading changes. This is called a frequency “slew-rate” problem, and it can be a severe problem affecting the operation of some types of electronic load equipment.

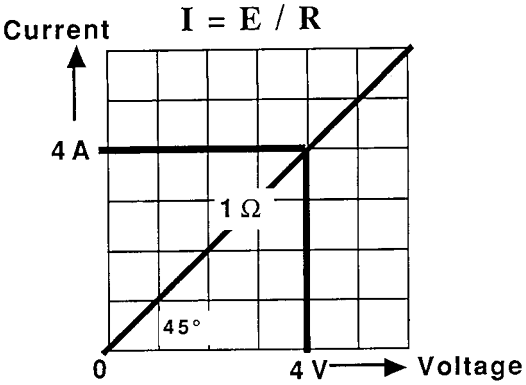
An example of the above is load equipment that establishes a clock timing or other synchronizing state based upon zero-crossings of the voltage waveform. This requirement is particularly susceptible to frequency slew-rate conditions. Typical limits on frequency slew rate are in the range of 1.5 Hz/s for most electronic loads, and 0.3 Hz/s for critical electronic loads (see FIPS Pub 94-1983).

Electronically controlled ac power sources that are derived from crystal-clock or phase-lock governed solid-state inverters, such as in modern solid-state UPS equipment, are virtually immune to loading-related frequency slew-rate problems. In addition, they are designed to limit the frequency slew rate of the inverter, as when it is phase-matching its output to the bypass source in order to permit its output to be transferred between the inverter and bypass source in closely synchronized, no-break fashion via a synchronous static-switch. However, incompatible frequency slew rates between an inverter and an engine-alternator set arrangement can cause synchronous static-switch transfer problems between the inverter's output and the bypass circuit provided by the engine-alternator set(s). For example, oscillation between the two sources via the synchronous static-switch is known to occur and the result is generally an inability to make a reliable, on-demand, at-any-time transfer from one ac power source to the other.

4.5.3 Steady-state voltage distortion sources/characteristics

4.5.3.1 Linear and nonlinear loads

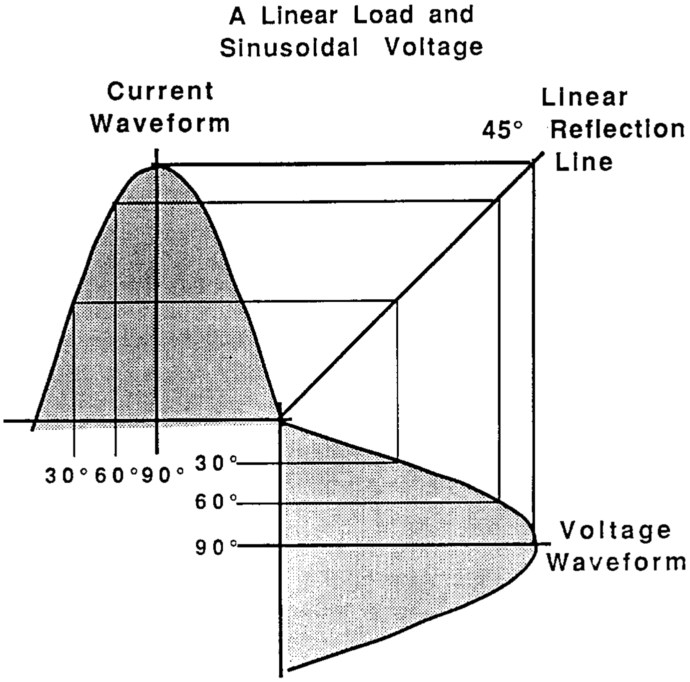
Assuming an undistorted voltage waveform, a linear load is one that proportionally draws current at only the fundamental frequency across the entire period of the applied sinusoidal voltage waveform, as shown in Figure 4-16, where a resistance is shown. A reactance or impedance could be substituted for the resistance and the load would still be linear since the ohmic value of the load remains constant over the entire range of the applied voltage.



NOTE—Produces a proportional result for $I = E/R$ over the entire curve for a linear load.

Figure 4-16—Graph of voltage vs. current at a constant load impedance

When the foregoing linear load's current or voltage is translated across a 45° line of reflection, as shown in Figure 4-17, the resultant waveshape for the voltage or current is exactly the same as for the wave being used as the input model. No harmonic distortion of the wave occurs in this case using a linear load and sinusoidal voltage waveform.

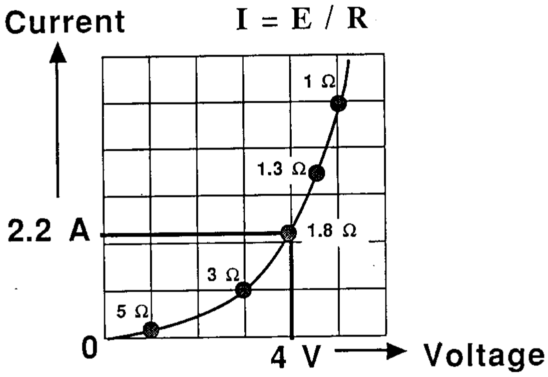


NOTE—Developed across a straight 45° (i.e., linear) load impedance reflection line to a sinusoidal voltage waveform source.

Figure 4-17—Sinusoidal current waveform shape resulting from a linear load

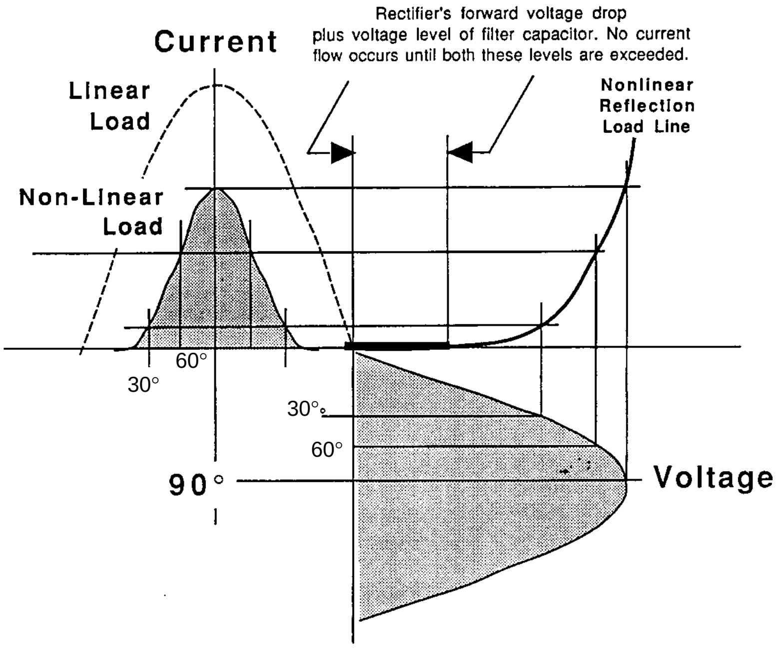
However, when the load does not proportionally draw current in relation to the applied voltage over the entire period of the sinusoidal voltage waveform, as does a rectifier or SCR controlled load for example, and as generally shown in Figure 4-18, it is termed nonlinear. In this case the ohmic value of the load does not remain constant over the entire range of the applied voltage waveform, but changes according to a uniquely characteristic curve that relates to the particular nonlinear load in each case.

The nonlinear load therefore draws current at different rates over the period of the applied sinusoidal voltage waveform, and it does so only at harmonically related frequencies to the power system's fundamental frequency. This results in a harmonically distorted current waveform for that current being drawn from the supply source by the nonlinear load. An example of this is shown in Figure 4-19 where a nonlinear load's characteristic impedance is plotted as a curved (e.g., nonlinear) reflection line across which the applied sinusoidal voltage and resultant harmonically distorted load current waveform's shape can be determined. This is contrasted to the equivalent diagram for a linear load as shown in Figure 4-17 where it can be seen that an applied sinusoidal voltage waveform results in a sinusoidal current waveform for the current flowing through the linear load.



NOTE—Produces a nonproportional result for $I = E/R$ over the entire curve for a nonlinear load. *However,* $I = E/R$ is always valid on an instantaneous basis.

Figure 4-18—Graph of voltage vs. current at a variable load impedance

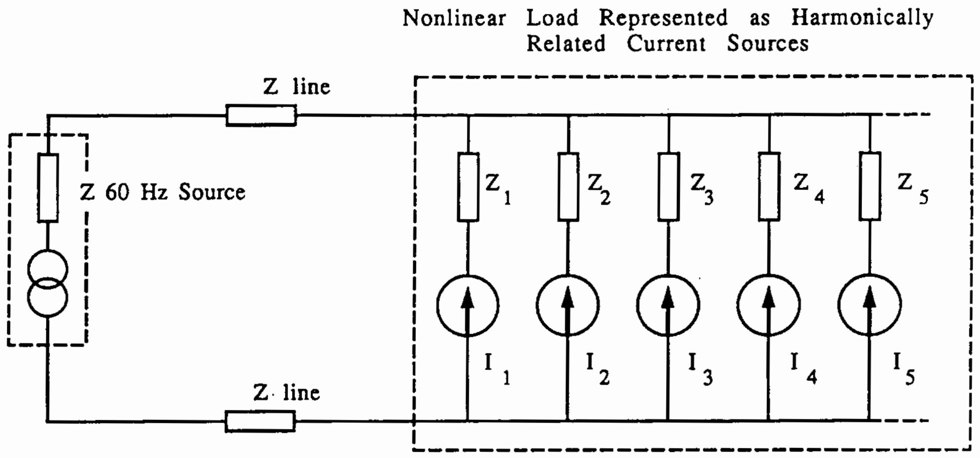


NOTE—Developed across a curved (i.e., nonlinear) load impedance reflection line to a sinusoidal voltage waveform source.

Figure 4-19—Resulting distorted current wafeform shape resulting from nonlinear load

If a harmonically distorted voltage waveform is applied to the linear load, it will result in an identical amount and type of harmonic distortion for the load current's waveform. However, this is not a function of the load's linearity (or lack of), it is a function of the waveshape of the applied voltage across a constant impedance load. But, if a nonlinear load is used with an already harmonically distorted voltage waveform, the resultant distorted current caused by the distorted voltage waveform will simply be algebraically added to the waveform from the current that is related to the load's intrinsic nonlinearity. Therefore, a new, composite current waveform with more (or possibly less) harmonic distortion will be the result.

The effect of nonlinear loading is equivalent to adding one or more current sources to the electrical system that produce characteristic harmonic current flow on and within the supply system wiring between the source (e.g., the nonlinear load) and the ac power supply itself (Figure 4-20).



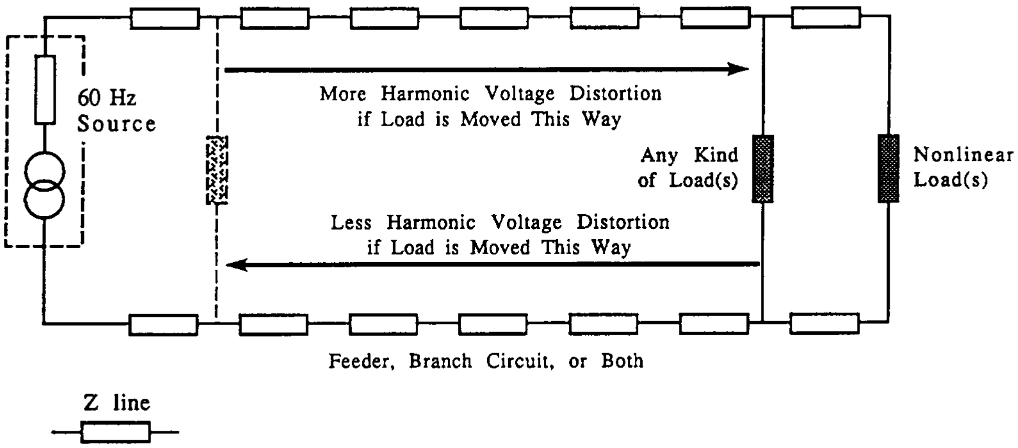
Each Current Source is Defined as Having
a Magnitude (*A*) and Phase Angle (Ø) As $I_n = A\angle Ø°$

Figure 4-20—Nonlinear load modeled as a group of harmonically related current sources connected in parallel across the supply source of fundamental frequency

When harmonic currents from nonlinear loads flow through the internal impedance of the ac supply itself, a voltage drop (e.g., $E = IZ$) is produced across the supply's internal impedance for each harmonic current, in addition to that occurring from fundamental current. The amount of voltage drop in the internal impedance is proportional to the impedance presented by the internal reactance of the supply's windings at each harmonic frequency, and in relation to the amount of current flow at each frequency. Therefore, on a per-ampere basis, 1 A of 3rd harmonic will produce approximately three times the voltage drop that 1 A of fundamental current will, and so on. Also, since the reactance in the power source's windings presented to each harmonic current is different as a function of frequency, the produced IZ drops are normally not in phase with the fundamental voltage and current waveforms, and a phase shift results that is unique to each harmonic. In other words, each harmonic will have its own displacement power factor, as will the fundamental.

The resulting voltage drop occurring within the ac power source from the harmonic currents flowing through it is algebraically added to the intended fundamental voltage being produced in the same winding. This produces a harmonically distorted voltage waveform from the power source, which is then applied to all connected loads—linear and nonlinear alike. Hence, the need for a low-impedance power source used in conjunction with nonlinear loads is somewhat self-evident if the propagation of nonlinear voltage waveforms on the entire downstream wiring system from the power source is to be minimized.

In addition to the harmonic currents producing voltage drops within the ac power source's internal impedance, the same effect occurs on the impedance of all the intervening wiring between the power source and the nonlinear load(s) connected to it. Hence, with the nonlinear load viewed as a harmonic current source, the amount of harmonic voltage distortion produced by it on the wiring system will be seen to increase as connections are made closer to the nonlinear load, and to diminish as the connection moves upstream to the ac power source (see Figure 4-21). The ac power source will then be the point on the wiring system at which minimum harmonic voltage distortion will be seen to exist.



NOTE—The load experiences the least amount of voltage waveform distortion when connected close to the source of power and the most distortion when connected near the nonlinear load(s).

Figure 4-21—Load connected across a power system serving nonlinear loads

The harmonic currents discussed previously are also known to interact with any reactances that exist on the power system, and so excite power system resonances, which produce excessive voltages and currents on the system and which then stress various power system components connected on the same ac distribution system. In particular, power factor correction capacitor banks are of the most concern in these cases and they may be both the culprit and victim at the same time. Harmonic disturbances and proposed limits on them are discussed in detail in IEEE Std 519-1992 [B28].

Most electronic loads exhibit nonlinear characteristics. AC/DC power supplies using simple across-the-line, full-wave diode-input rectifiers and large dc filter capacitors are common examples of this type of load (e.g., the SMPS). More sophisticated ac/dc power supplies now exist with improved input power factor and greatly reduced harmonic current demands. The ac/dc power supplies are becoming available primarily as a result of industry interest and the harmonic current limits suggested by IEC 60555-1: 1982 [B23], IEC 60555-2: 1982 [B24], and IEC 60555-3: 1982 [B25], but the cost per watt is more than for unimproved types. This latter fact is slowing the introduction of these newer designs into the market, and there is still a very large number of the older types of supplies still in use and which will be in use for the foreseeable future—especially where initial cost is of most importance to the purchaser.

Exact analysis of ac/dc power supply input current vs. applied voltage is complex, but it can be said that a load current flows nonlinearly during the ac cycle (see NFPA 75-1999 and Arrillaga et al. [B3]). For example, there is no appreciable input current flow until the rectifier begins to conduct current at the point where the applied input voltage exceeds the existing voltage in the filter capacitor plus the forward voltage drop of the rectifier(s). Hence, charging current flows in pulse fashion with the peak current being drawn at approximately the 90° and 270° points on the applied voltage waveform, as shown in Figure 4-22. The duration of current flow (each half-cycle on each phase) can be described in terms of the conduction angle for switch-mode power supplies and is 30–60°. Typical current crest factors range from 2 to 3 (vs. 1.4 for a linear load fed by sinusoidal ac power).

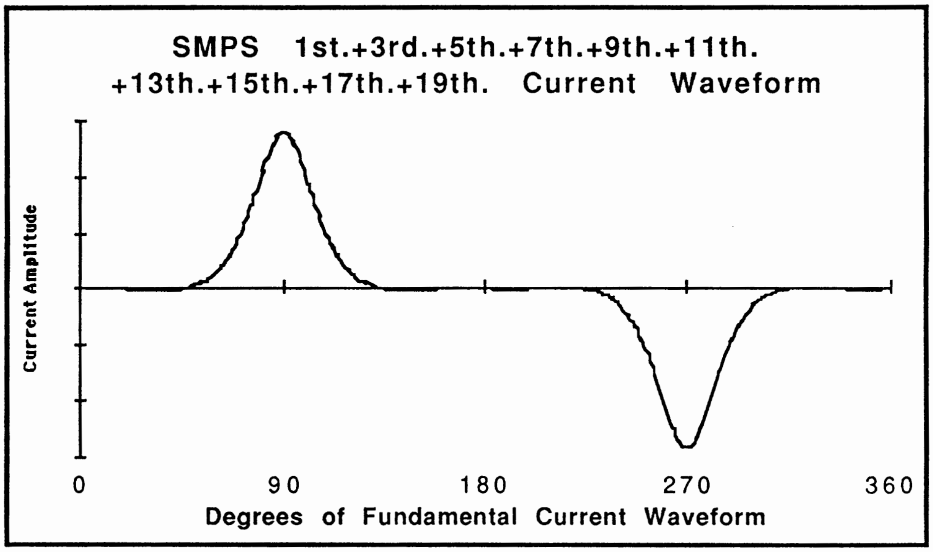


Figure 4-22—Nonsinusoidal ac input current to a typical SMPS with peaks occurring at 90° and 270°

Figure 4-23 illustrates the harmonic content for the ac input to a typical SMPS along with amplitude and phase-angle for each of the currents, which algebraically add together to produce the resultant current waveform shown in Figure 4-22.

Table 4-4 shows an example of the harmonic current content of a balanced line-to-line and line-to-neutral rectifier diode-capacitor power supply in a three-phase power system. In three-phase circuits, the triplen harmonic neutral currents (e.g., odd-order multiples of three such as the 3rd, 9th, and 15th) add together on the neutral instead of cancelling, so unexpectedly high neutral currents may exist where line-to-neutral connected nonlinear loads are in use on a four-wire, wye-connected supply system (see 4.5.4.2 and Gruzs [B20]).

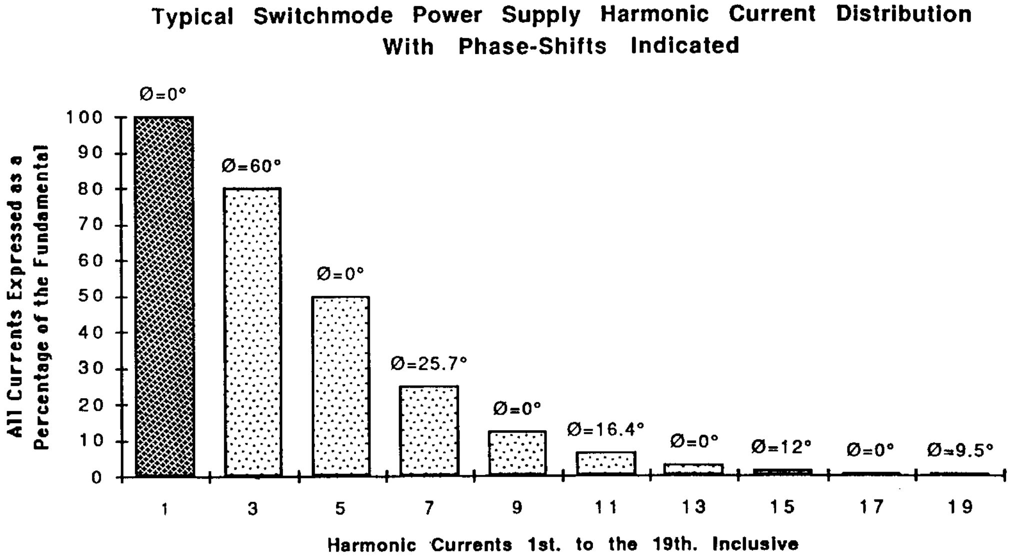


Figure 4-23—Frequency domain display of input current to typical SMPS, both amplitude shown at each harmonic and phase angle

4.5.3.2 Power factor, linear and nonlinear loads

Reactive loads that are linear or mostly so, such as ac motors, low-pass LC power filters, and other reactive components within loads, normally cause nonunity total power factor to occur per Equation (4-8). When nonlinear loads are being considered, the following equation is only valid when true-RMS instrumentation is used to make the necessary measurements, as frequencies other than the fundamental are present in both the voltage and current waveforms at the same time:

$$PF_t = \cos\theta = \frac{P}{P_s} = \frac{\text{Active power}_{\text{kW}}}{\text{Apparent power}_{\text{kVA}}} \tag{4-8}$$

where

PF_t is the total power factor where unity PF occurs when $PF_t = 1.0$,

θ is the phase angle between current and voltage,

P is the active power in (kilo)watts,

P_s is the apparent power in (kilo)volt-amperes.

Table 4-4—Example input harmonic current distortion in balanced three-phase circuits due to rectifier-capacitor power supply

Harmonic number	Line-to-line harmonic current[a]	Line-to-neutral harmonic current[a]
1	0.82	0.65
3	—	0.52
5	0.49	0.42
7	0.29	0.29
9	—	0.13
11	0.074	0.12
13	0.033	0.098
Total phase current	1.00	1.00
Neutral current	0.0	1.61

[a] Normalized to phase current

4.5.4 Potential impacts of steady-state current distortions

4.5.4.1 Transformer heating due to harmonic currents

Transformers serving linear loads have no unusual heat losses related to their operation at the power system's fundamental frequency. There are the typically expected power losses due to I^2R in all of the current paths, and hysteresis plus eddy-current losses within the windings, the core, and any metallic items that stray flux can engage. However, the same linear-load-rated transformer serving nonlinear (typically electronic) loads will generally exhibit