

# IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment

Sponsor

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**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 view points 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 analysis are considered. Case histories are given to illustrate typical problems.

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

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## Foreword

(This foreword is not a part of IEEE Std 1100-1992, IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment.)

This Recommended Practice is a publication of the Industry Applications Society of the IEEE and is one of the IEEE Color Book Series, which relates to industrial and commercial power systems. The purpose of the Recommended Practice is to provide consensus for installing and providing power to sensitive 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 multidisciplinary area, the Working Group on Powering and Grounding Sensitive Electronic Equipment was formed in 1986 to write a Recommended Practice. 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 recognized testing laboratories.

At the time this Recommended Practice was approved, the IEEE Working Group on Powering and Grounding Sensitive Electronic Equipment had the following membership:

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This Recommended Practice was developed by a team involving the Working Group members and other contributors listed in the foreword. This team included specialists from electric utilities, load equipment manufacturers, architects and engineers, independent consultants, facility engineers, academia, power conditioning and monitoring equipment manufacturers, and several IEEE Societies. The work was coordinated by Chapter Chairs as follows:

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#### APPENDIX

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# Chapter 1

## Introduction

**1.1 Scope.** This Recommended Practice presents recommended engineering principles and practices for powering and grounding sensitive electronic equipment.

The scope and purpose of this document are limited to 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.

The main objective is to provide a consensus of recommended practices in an area where conflicting information and confusion, stemming primarily from different view points 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) 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.

**1.2 Background.** As sensitive electronic loads proliferate in industrial and commercial power systems, so do problems related to power quality. Powering and grounding sensitive 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 expensive power conditioning equipment to applying special grounding techniques that are not found in conventional safe grounding practice. Grasping for conditioning equipment or "magic" grounding methods is a common response. In some cases this approach has led to unsafe practices and violations of the NEC, without solving operating problems. In response to this situation, this Recommended Practice attempts to provide a true understanding of the fundamentals of powering and grounding sensitive electronic equipment and the various types of problems that can arise—knowledge that has been lacking in commercial and industrial power systems.

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 greater susceptibility of increasingly sophisticated 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 common problems and solutions.

Since the earliest days of electric power, users have desired that utilities provide electricity without interruptions, surges, and harmonic waveform distortions. Reducing such power line disturbances has always been a critical concern for utilities. Recently, however, new sources of disturbances have begun to proliferate, just as many pieces of equipment 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 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 this need are as follows:

- (1) The quantification of precisely how much downtime is power-related, and
- (2) 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 sensitive electronic equipment, potential sources of interference, and voltage conditioning equipment must cooperate with each other to find effective solutions.

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. One of the goals of this Recommended Practice is 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. There are currently ten Color Books in the series, each of which 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 Emerald Book is a new entry in the series, directed specifically at powering and grounding sensitive electronic equipment.

**1.3 Road Map.** The following provides the reader with a road map of this Recommended Practice.

Chapter 2 provides definitions of the descriptors that pertain specifically to power quality issues and are generally not otherwise available in IEEE standards. Also provided is a list of terms that have been deliberately avoided in this Recommended Practice because they have a wide range of different meanings and no generally accepted single technical definition.

General need guidelines are provided in Chapter 3. 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 performance definition and recommended practices in subsequent chapters.

Chapter 4 introduces the reader to the fundamental concepts necessary for understanding and applying recommended practices. Fundamentals not unique to sensitive electronic and electrical equipment are treated very lightly, or by reference to other standards.

Chapter 5 presents information on available measurement instruments that are needed to investigate and diagnose problems in power systems that serve sensitive electronic equipment.

Site power analysis and site surveys are covered in Chapter 6. This chapter draws from the technical information base established in previous chapters, and presents practical applications of problem identification and diagnosis. Measurement techniques are also discussed. The approach is to start with wiring and grounding checks and progress through voltage amplitude and disturbance measurements to harmonic analysis. Electromagnetic interference (EMI) is covered primarily by reference.

Case histories are presented in Chapter 7. These are intended to provide examples of real-world performance and safety problems that have been encountered in the field. Cases are selected that illustrate the need to follow specific recommended practices and potential results when recommended practices are not followed.

Chapter 8 presents the myriad of available power enhancement equipment from the points of view of basic technology, performance, and function. Performance verification is also covered.

Chapter 9 covers both recommended and nonrecommended design and installation practices. The intent is to present the Working Group's collective engineering experience and judgment of effective practices. The discussion of nonrecommended practices very deliberately attacks "old wives' tales" and raises "warning flags," but does not introduce any new concepts or materials. The discouragement of commonly observed nonrecommended practices is emphasized.

## 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 of this chapter is to define those terms that will aid in the understanding of concepts within this Recommended Practice. Where possible, definitions were obtained from the IEEE Std 100-1988 [4].<sup>1</sup> 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.

This chapter is divided into three parts. First, an alphabetical listing of definitions is provided in 2.2. The reader is referred to the IEEE Std 100-1988 for all words not listed herein. The second subsection (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 ac distribution-related power problems, but tend not to convey significant technical meaning. The third subsection (2.4) lists abbreviations that are employed throughout this Recommended Practice.

**2.2 Alphabetical Listing of Terms Used in This Recommended Practice.** The primary source for the definitions in this section is IEEE Std 100-1988 [4].

This section does not include any device or equipment definitions (e.g., isolation transformers, uninterruptible power systems); the reader is advised to refer to the index. Most pertinent equipment is described in Chapter 8.

**bonding.** (1) The electrical interconnecting of conductive parts, designed to maintain a common electrical potential [2]. (2) The permanent joining of metallic parts to form an electrically conductive path which will assure electrical continuity and the capacity to conduct safely any current likely to be imposed [2].

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

**common-mode noise.** 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 definition expands the existing definition in IEEE Std 100-1988 [4] (previously given only for signal cables) to the power conductors supplying sensitive sensitive electronic equipment.

**coupling.** Circuit element or elements, or network, that may be considered common to the input mesh and the output mesh and through which energy may be transferred from one to the other [4].

**crest factor.** Ratio between the peak value (crest) and rms value of a periodic waveform [4].

---

<sup>1</sup> The numbers in brackets correspond to those of the references in 2.5; when preceded by the letter “B,” they correspond to those in the bibliography in 2.6.

**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.

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

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

**direct-reading ammeters.** Ammeters that are employed with a series shunt and that carry some of the line current through them for measurement purposes. They are part of the circuit being measured.

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

**distortion factor.** The ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity, expressed as a percent of the fundamental [4]. Also referred to as *total harmonic distortion* [6].

**dropout.** A loss of equipment operation (discrete data signals) due to noise, sag, or interruption.

**dropout voltage.** The voltage at which a device will release to its deenergized position (for this Recommended Practice, the voltage at which a device fails to operate).

**efficiency (of a power system).** The relationship between the input power that a power system draws and the corresponding power that it is able to supply to the load (kilowatt out/kilowatt in).

**equipment grounding conductor.** The conductor used to connect the noncurrent 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). (This term is defined more specifically in the NEC [2], Section 100).

**failure, degradation.** Failure that is both gradual and partial.

NOTE: In time, such a failure may develop into a complete failure [4].

**failure mode.** The effect by which a failure is observed [4].

**flicker.** A variation of input voltage sufficient in duration to allow visual observation of a change in electric light source intensity.

**form factor (periodic function).** The ratio of the root-mean-square value to the average absolute value, averaged over a full period of the function [4].

**forward transfer impedance.** An attribute similar to internal impedance, 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 5–60 Hz power systems, and 20–25 kHz for 380–480 Hz power systems.

**frequency deviation.** An increase or decrease in the power frequency. The duration of a frequency deviation can be from several cycles to several hours.

**ground.** 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.

NOTE: It is 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) [4].

**ground electrode.** A conductor or group of conductors in intimate contact with the earth for the purpose of providing a connection with the ground [2].

**ground electrode, concrete-encased.** 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. (This term is defined more specifically in Article 250 of the NEC [2].)

**ground grid.** A system of interconnected bare conductors arranged in a pattern over a specified area and buried below the surface of the earth. (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 which could flow if the circuit being worked became energized for any reason or if an adjacent energized circuit faulted. Metallic surface mats and gratings are sometimes utilized for the same purpose [4].) This term should not be used when referring to a **signal reference structure**, which is defined in this chapter.

**ground, high-frequency reference.** See: **signal reference structure**.

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

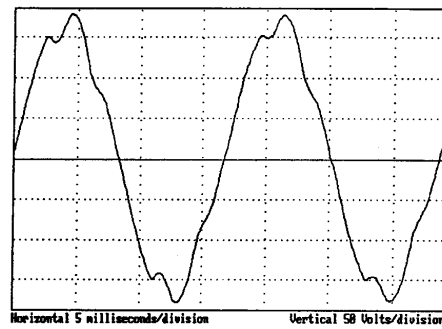
**ground loop.** A potentially detrimental loop formed when two or more points in an electrical system that are nominally at ground potential are connected by a conducting path such that either or both points are not at the same ground potential [4].

**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.

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

**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.

**harmonic distortion.** The mathematical representation of the distortion of the pure sine waveform. See: **distortion factor**. (See Fig 2-1.)



Source: [B2].

**Fig 2-1**  
**Distortion Example**

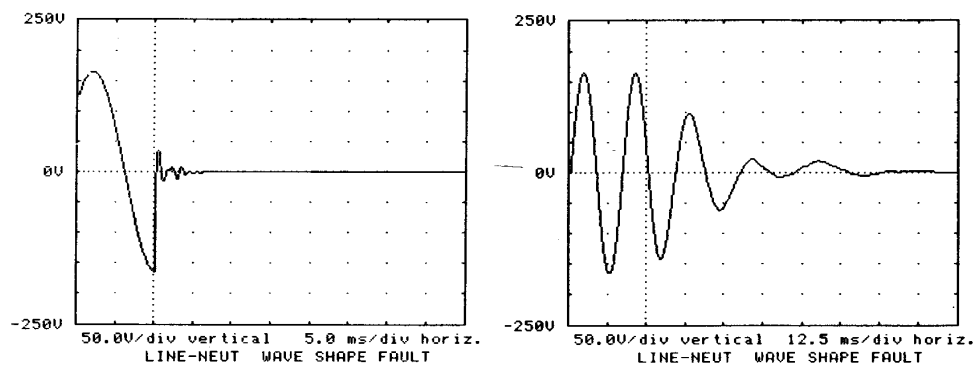
**impulse.** *See:* transient.

**input power factor (of a system).** Specifies the ratio of input kilowatts to input kilovoltamperes at rated or specified voltage and load.

**input voltage range (of a power system).** The range of input voltage that the system can operate over.

**inrush.** The amount of current that a load draws when it is first turned on.

**interruption.** The complete loss of voltage for a time period. (See Fig 2-2.)



Source: [B3].

**(a) Local Power Failure**

**(b) Utility Power Failure**

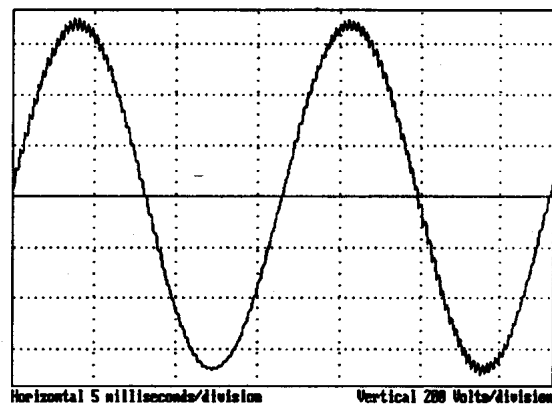
**Fig 2-2**  
**Interruption**

**isolated equipment ground.** An insulated equipment grounding conductor run 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. (This term is defined more specifically in the NEC [2]), Sections 250-74 and 250-75.)

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

**linear load.** An electrical load device which, in steady state operation, presents an essentially constant load impedance to the power source throughout the cycle of applied voltage.

**noise.** Electrical noise is unwanted electrical signals that produce undesirable effects in the circuits of the control systems in which they occur [4]. (For this Recommended Practice, “control systems” is intended to include sensitive electronic equipment in total or in part.) (See Fig 2-3.)



Source: [B2].

**Fig 2-3**  
**Noise Example**

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

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

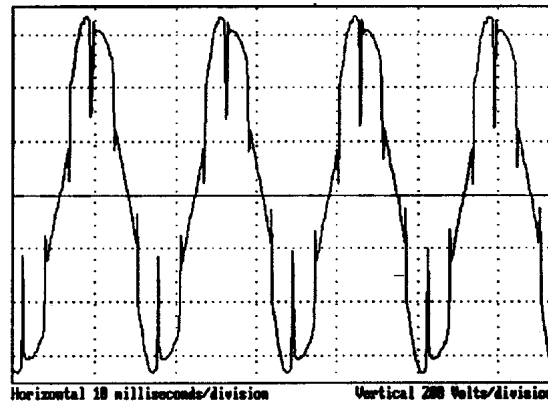
**noise, normal-mode.** *See: transverse-mode noise.*

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

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

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

**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: transient.* (See Fig 2-4.)



Source: [B2].

**Fig 2-4**  
**Notches**

**outage.** *See: interruption.*

**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: forward transfer impedance.*

**overvoltage.** A rms increase in the ac voltage, at the power frequency, for durations greater than a few seconds. *See: swell and surge.*

**phase shift.** The displacement in time of one periodic-waveform relative to other waveform(s).

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

**power disturbance monitor.** Instrumentation developed specifically for the analysis of voltage and current measurements.

**power factor, displacement.** The displacement component of power factor; the ratio of the active power of the fundamental wave, in watts, to the apparent power on the fundamental wave, in volt-amperes [4].

**power factor, total.** The ratio of the total power input in watts to the total volt-ampere input [4].

**power quality.** The concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment.

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

**receptacle circuit tester.** A device that, by a pattern of lights, is intended to indicate wiring errors in receptacles. Receptacle circuit testers have some limitations. They may indicate incorrect wiring, but cannot be relied upon to indicate correct wiring.

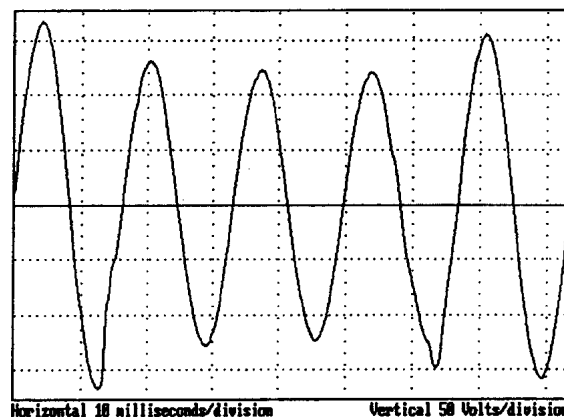
**recovery time.** Time interval needed for the output voltage or current to return to a value within the regulation specification after a step load or line change [2]. Also may indicate the time interval required to bring a system back to its operating condition after an interruption or dropout.

**recovery voltage.** The voltage that occurs across the terminals of a pole of a circuit interrupting device upon interruption of the current [4].

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

**sag.** A rms reduction in the ac voltage, at the power frequency, for durations from a half-cycle to a few seconds. *See: notch, undervoltage.* (See Fig 2-5.)

NOTE: The IEC terminology is *dip*.



Source: [B2].

**Fig 2-5**  
**Sag**

**shield.** As normally applied to instrumentation cables, a conductive sheath (usually metallic) applied over the insulation of a conductor or conductors, for the purpose of providing means to reduce coupling between the conductors so shielded and other conductors that may be

susceptible to, or that may be generating, unwanted electrostatic or electromagnetic fields (noise).

**shielding.** Shielding is the use of a conducting barrier between a potentially disturbing noise source and sensitive circuitry. Shields are used to protect cables (data and power) and electronic circuits. They may be in the form of metal barriers, enclosures, or wrappings around source circuits and receiving circuits.

**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.

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

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

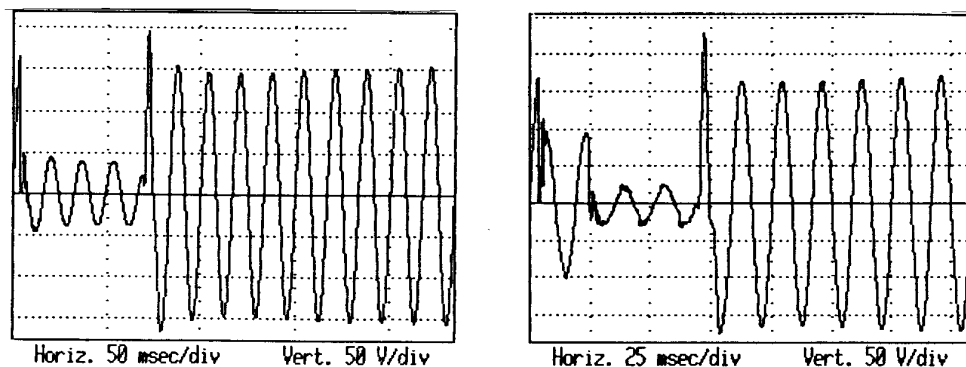
**star-connected circuit.** A polyphase circuit in which all the current paths of the circuit extend from a terminal of entry to a common terminal or conductor (which may be the neutral conductor).

NOTE: In a three-phase system this is sometimes called a Y (or wye) connection [4].

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

**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.

**swell.** An rms increase in the ac voltage, at the power frequency, for durations from a half-cycle to a few seconds. *See: overvoltage and surge.* (See Fig 2-6.)



Source: [B1].

**Fig 2-6**  
**Swells Occurring Upon Recovery From a Remote System Fault**

**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.

**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: **swell**, **notch**, and **overvoltage**.

**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.

**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.

**undervoltage.** A rms decrease in the ac voltage, at the power frequency, for durations greater than a few seconds.

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

**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 Because of No Single Technical Definition.** 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 sensitive electronic equipment:

blackout  
brownout  
clean ground  
clean power  
computer grade ground  
conducting barriers  
counterpoise ground  
dedicated ground  
dirty ground  
dirty power  
equipment safety grounding conductor  
frame ground  
frequency shift  
glitch

## DEFINITIONS

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:

|       |                                                |
|-------|------------------------------------------------|
| AFD   | adjustable frequency drive                     |
| ALVRT | automatic line voltage regulating transformer  |
| ASAI  | average service availability index             |
| CATV  | cable accessed television                      |
| COTC  | central office trunk cable                     |
| CPC   | computer power center                          |
| CPU   | central processing unit                        |
| CRT   | cathode ray tube                               |
| CVT   | constant voltage transformer                   |
| EFT   | electrical fast transient                      |
| EGC   | equipment grounding conductor                  |
| EMC   | electromagnetic compatibility                  |
| EMI   | electromagnetic interference                   |
| EMT   | electrical metallic tubing                     |
| ESD   | electrostatic discharge                        |
| FMC   | flexible metal conduit                         |
| HF    | high frequency                                 |
| IEC   | International Electrotechnical Commission      |
| IG    | isolated/insulated grounding                   |
| IMC   | intermediate metal conduit                     |
| IT    | isolation transformer                          |
| LDC   | line drop compensator                          |
| M-G   | motor-alternator/generator                     |
| MCT   | metal cable tray                               |
| MTBF  | mean time between failures                     |
| NEMP  | nuclear electromagnetic pulse                  |
| NEC   | National Electrical Code                       |
| NIST  | National Institute of Standards and Technology |
| OEM   | original equipment manufacturer                |
| OSHA  | Occupational Safety and Health Administration  |

|      |                                                                                |
|------|--------------------------------------------------------------------------------|
| PC   | personal computer                                                              |
| PDU  | power distribution unit                                                        |
| PLC  | power line conditioner                                                         |
| PWM  | pulse width modulation                                                         |
| RFI  | radio frequency interference                                                   |
| RMC  | rigid metal conduit                                                            |
| SDS  | separately derived ac system                                                   |
| SE   | service entrance                                                               |
| SG   | solidly grounded; solid grounding (See: <b>equipment grounding conductor</b> ) |
| SI   | solidly interconnected                                                         |
| SRG  | signal reference grid                                                          |
| SRP  | signal reference plane                                                         |
| SRS  | signal reference structure                                                     |
| THD  | total harmonic distortion                                                      |
| TVSS | transient voltage surge suppressor                                             |
| UL   | Underwriters Laboratories                                                      |
| UPS  | uninterruptible power supply                                                   |
| VDT  | video display terminal                                                         |

**2.5 References.** This standard shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply:

[1] ANSI C84.1-1989, American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz).<sup>2</sup>

[2] ANSI/NFPA 70-1993, National Electrical Code.<sup>3</sup>

[3] IEEE Std C62-1990, Complete 1990 Edition: Guides and Standards for Surge Protection.<sup>4</sup>

[4] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).

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

[6] IEEE Std 519-1992, IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters (ANSI).

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<sup>2</sup> ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

<sup>3</sup> NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

<sup>4</sup> IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[7] P1159, Recommended Practice on Monitoring Electric Power Quality, D2/June 30, 1992.<sup>5</sup>

## 2.6 Bibliography

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

[B2] *The Dranetz Field Handbook for Power Quality Analysis*, Edison, NJ: Dranetz Technologies Inc., 1991.

[B3] McEachern, Alexander, *Handbook of Power Signatures*, Foster City, CA: Basic Measuring Instruments, 1989.

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<sup>5</sup> This IEEE authorized standards project is available from the Sales Dept., IEEE Service Center, 445 Hoes Lane, Piscataway, NJ 08855-1331.

## 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 delivery can occur during the normal operation of the system as well as during abnormal conditions, resulting in equipment damage or operational upset. This dichotomy may be the source of misunderstandings at best or disputes at worst between suppliers and users of electric power, and between manufacturers and users of sensitive equipment. One of the goals of this book is to promote better understanding of the significant issues and to dispel some misconceptions about how to avoid or correct problems.

This chapter presents a brief description of the nature of power quality problems, of possible solutions, and of the resources available for assistance in dealing with problems. A brief historical review of the resolution of some of the earlier conflicts provides a useful perspective on solving these types of 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 their 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 Disturbing Loads.** 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 major 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 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 The Concept of Power Quality.** Emerging concerns over these issues has resulted in focusing attention on the quality of the power necessary for successful operation of diverse loads, on practical limits to the capability of delivering power of high quality to diverse customers, and on the economics of 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 understood as low level of disturbances; agreement on acceptable levels of disturbances is needed. As one step in that direction, 3.4 presents an overview of the nature of disturbances.

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 book, but the detailed economics are beyond its scope. As generic information, Chapter 8 provides guidance on the selection of line-conditioning equipment.

**3.1.4 Conflicting Design Philosophies and Safety.** The issue of power quality is made more confusing 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)

(ANSI/NFPA 70-1993 [1]<sup>6</sup>) prevent their system from operating in a satisfactory (safe) 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 directives 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 large loads.

At all these voltage and power levels, no matter how high, the equipment is dependent upon maintenance of a normal operating voltage because it has only limited capability of withstanding voltages exceeding the normal level. 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, involving 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 disturbances according to their impact on the quality of the available power. A brief discussion is given below of the need for evaluation of their impact on sensitive loads.

*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.

*Amplitude variations* can occur in several forms; their description is inextricably associated with their duration. They range from extremely brief durations 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.

*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.

*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

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<sup>6</sup> The numbers in brackets correspond to those of the references in 3.9; when preceded by the letter "B," they correspond to those in the bibliography in 3.10.

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.

**3.2.3 Origin of Disturbances.** The term “origin of disturbances” can be understood in two different manners. According to one interpretation, the concern is over 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” (external source), or to the “user side of the meter” (internal source).

According to another interpretation, the concern is over the nature of the source; the disturbance 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, 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 disturbance problems to the utility source. Many other sources of disturbances, however, are located within the building and are attributable to operation by the end-user of other equipment. 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, ground potential differences, and operator errors (Fig 3-1).

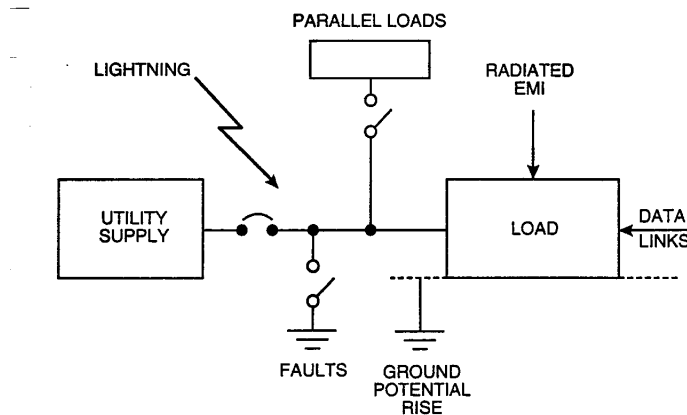
Some disturbances occur at random and are not predictable for a given site and are not repeatable although statistical information may be available on their occurrence (IEEE Std C62.41-1991 [7], IEEE Std 519-1992 [12]). Other disturbances, especially those associated with operation of other equipment, 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.

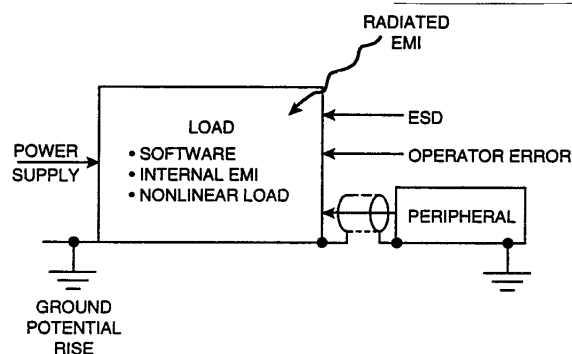
A lightning strike to the power system can activate a surge arrester, producing a severe reduction or a complete loss of the power system voltage for one half-cycle. A flashover of line insulators can trip a breaker, with reclosing delayed by several cycles, causing a momentary power outage. Thus, lightning 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, but nevertheless a consensus exists on representative threats for various environments.



(a) Examples of Interference That Do Not Involve Utility Supply



(b) Example of Source Interference

**Fig 3-1**  
**Sources of Disturbances**

*Load switching* is a major cause of disturbances. 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 of 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 operating 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.

*Power system faults* occur on both sides of the meter, resulting from 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 [B7].

*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 with capacitor-input filter, such as used in most computers, drawing current only at the peaks of the voltage sine wave. This situation 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.

*Other disturbances.* 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 (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.

Another concern is related to nuclear explosions effects, under the acronym of NEMP (nuclear electromagnetic pulse). However, concerns over this type of “disturbance” are beyond the scope of this standard, and are the subject of specialized documents.

**3.2.4 Power Quality Site Surveys.** Power quality site surveys have been performed and reported and 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, a new IEEE Working Group has been chartered and is attempting to provide unique definitions for the disturbances. 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 on 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 ([B2], [B5]); 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 [B9].

**3.3 Grounding Considerations.** Proper grounding is essential to safe and satisfactory performance of a power system. There are three requirements for such grounding:

- (1) Providing a low-impedance path for the return of fault currents, so that an overcurrent protection device can act quickly to clear the circuit,
- (2) Maintaining a low potential difference between exposed metal parts to avoid personnel hazards, and
- (3) 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 141-1986 [8], IEEE Std 142-1991 [9], and IEEE Std 446-1987 [10].

Grounding of sensitive equipment, such as information technology equipment, involves another aspect because this type of equipment, by design, communicates with other equipment by data lines. These data lines often carry their own zero-reference conductors that may or may not be bonded to the equipment safety ground. Thus, there may be a common path between the signal circuits and the power circuits, giving rise to problems of noise coupling. These data lines generally carry high-frequency signals, so that impedance considerations related to the power-frequency safety aspects of a grounding system may not necessarily provide the desirable low impedance at the signal frequencies. Worst yet, conflicts may arise between the perceptions of signal engineers on the goals of their grounding practices and the non-negotiable safety requirements of power system grounding practices.

In the case of computer systems distributed throughout a facility, the situation is different. The local ground at the point where a terminal is connected to the power system is likely to be at a high-frequency potential different from those of the other elements of the system. This concern is briefly addressed in 3.7 of this chapter. A comprehensive discussion of the high-frequency aspects of grounding practices for mainframe computer rooms can be found in [B4].

### 3.4 Protection Against Disturbances

**3.4.1 General.** The concept of protection implies the confrontation of a hostile environment and susceptible equipment. Protection of the equipment against the hostile environment is the goal of the technology of electromagnetic compatibility. 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 (IEEE Std 519-1992) [12], (IEEE Std C62.41-1991) [7].

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. This graph has been widely published, and is reproduced here as Fig 3-2. Note that the graph only addresses the magnitude of the voltage, with a corresponding

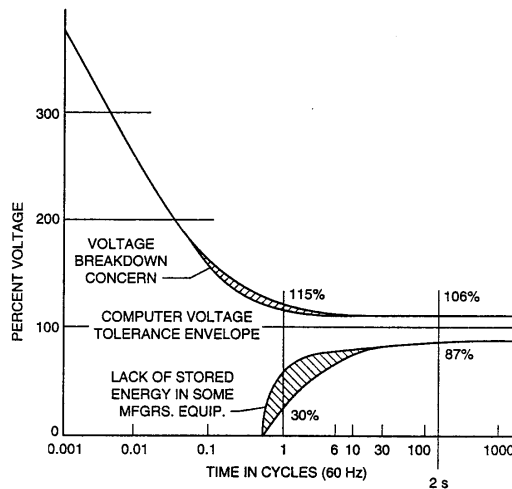


**Fig 3-2**  
**Typical Design Goals of Power-Conscious Computer Manufacturers**

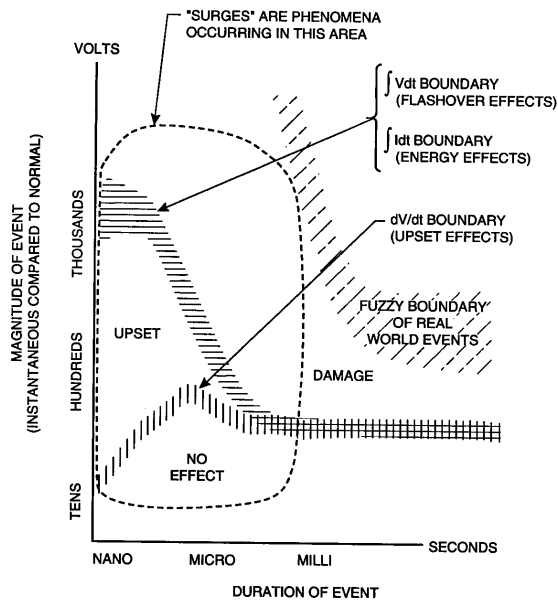


**Fig 3-3**  
**Relationship Between Amplitude, Duration, Rate of Change of Disturbances, and Their Effects on Equipment**

duration of the disturbance. One aspect that it does not address is the significance of the rate of change in voltage disturbances. This rate of change is important in two aspects:

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

- (2) 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 Fig 3-3, inspired from Fig 3-2, 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, while a surge on the power line is generally understood as a disturbance of larger fraction, or 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 electromagnetic interference (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 Fig 3-3. IEEE Std 518-1982 [11] and textbooks [B12] and [B13] provide a comprehensive discussion of noise-reduction practices.

**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. 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.

Survival or undisturbed operation of the equipment can be achieved in three manners: eradication of the cause of surges (for instance, the elimination of lightning . . .), building equipment immune to any level of surges, no matter how high, or, the obvious choice, finding the best economic trade-off. 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 [B1].

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 two 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. 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 conductors terminals with respect to local grounds. A potential problem, however, is associated with the two-stage protection scheme: if not properly coordinated, the second 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 [B8].

**3.4.4 Sag Protection.** Sag protection is not addressed here. See 8.2.8 and 8.2.9, and IEEE Std 446-1987 [10] for more information.

**3.5 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, of course, is not dependent on these criteria. Defining this degree requires an in-depth knowledge of the installation and its function. The following questions should be considered when designing these systems:

- (1) How long will it take to replace the equipment and at what cost?
- (2) Can the function of the facility be performed elsewhere?
- (3) Is the loss that of a key component, resulting in operation interruption?

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:

- (1) Smoke and fire protection
- (2) Environmental control
- (3) Smoke exhaust
- (4) Fire extinguishing
- (5) Emergency lighting
- (6) 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 information technology system. Disturbances in the power supply of the safety system can cause shutdown of the protected system.

**3.6 Information Technology Systems.** Under the name of information technology systems we classify all equipment incorporating at least two ports: 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 information technology 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 inductively coupled to adjacent circuits. Therefore, noise can be injected in these data circuits by power system ground or fault currents, by electromagnetic interference from other systems or lightning, and by other sources. Remedies to noise problems proposed by information technology 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, therefore 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 of potential can cause component failures in the circuits.

### 3.7 Shielded, Enclosed EMI/EMC Areas (TEMPEST)

**3.7.1 General.** Electromagnetic interference and electromagnetic compatibility (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 [B3] 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.

**3.7.2 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 [1]). 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 [B10]. 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.

**3.7.3 Basic 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 [B6]. For more information on shielded areas, see [B10] and [B11].

### 3.8 Coordination with Other Codes, Standards, and Agencies

**3.8.1 General.** 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, interchangeability 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 creates 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 [1].

**3.8.2 National Electrical Code (NEC).** The NEC [1] 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; United States 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 United States, have their own local codes usually based on the NEC with additional requirements.

**3.8.3 Underwriters Laboratories (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 United States. 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 performances. 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 United States Government agency established initially for the purpose of maintaining standards of measurements and calibration of instruments, including traceability. 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 standard-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. A notable exception is a developing series of standards under the category of Federal Information Processing Standards Publications, such as [B4].

**3.8.7 International Standards.** International standards are developed by a different process than the typical voluntary standard process used in the United States, 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:

- *Technical Subcommittee 28A*, for insulation coordination concerns. A report prepared by this subcommittee (IEC Publication 664-1980 [2]) 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.
- *Technical Committee 64*, for fixed (premises) wiring considerations.
- *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 Publications 801-1 (1984) [3], 801-2 (1984) [4], 801-3 (1984) [5], 801-4 (1988) [6]).
- *Technical Committee 77*, for electromagnetic compatibility. Within the broad scope of all possible disturbances to electromagnetic compatibility, 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 standard shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply:

[1] ANSI/NFPA 70-1993, National Electrical Code.<sup>7</sup>

[2] IEC Publication 664-1980, Insulation co-ordination within low-voltage systems including clearances and creepage distances for equipment.<sup>8</sup>

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<sup>7</sup> NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

<sup>8</sup> IEC publications are available from IEC Sales Department, Case Postale 131, 3 rue de Varembe, CH 1211, Genève 20, Switzerland/Suisse. 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.

- [3] IEC Publication 801-1 (1984), Electromagnetic compatibility for industrial-process measurement and control equipment, Part 1: General introduction.
- [4] IEC Publication 801-2 (1984), Electromagnetic compatibility for industrial-process measurement and control equipment, Part 2: Electrostatic discharge requirements.
- [5] IEC Publication 801-3 (1984), Electromagnetic compatibility for industrial-process measurement and control equipment, Part 3: Radiated electromagnetic field requirements.
- [6] IEC Publication 801-4 (1988), Electromagnetic compatibility for industrial-process measurement and control equipment, Part 4: Electrical fast transient/burst requirements.
- [7] IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits (ANSI).<sup>9</sup>
- [8] IEEE Std 141-1986, IEEE Recommended Practice for Electrical Power Distribution for Industrial Plants (IEEE Red Book) (ANSI).
- [9] IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book) (ANSI).
- [10] IEEE Std 446-1987, IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (IEEE Orange Book) (ANSI).
- [11] IEEE Std 518-1982 (Reaff 1980), IEEE Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources (ANSI).
- [12] IEEE Std 519-1992, IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters (ANSI).

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- [B3] CFR (Code of Federal Regulations), Title 47, Part 15, published by the Office of the Federal Register.
- [B4] Federal Information Processing Standards Publication 94: *Guideline on Electrical Power for ADP Installations*, National Technical Information Service, 1983.

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<sup>9</sup> IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

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- [B9] Martzloff, F. D. and T. M. Gruz, "Power Quality Surveys: Facts, Fictions, and Fallacies," *IEEE Transactions on Industry Applications*, Vol. 24, No. 6, Nov/Dec 1988, pp. 1005–18.
- [B10] MIL-HNDBK-419, Grounding, Bonding, and Shielding for Electronic Equipments and Facilities, Vol. 1 (Basic Theory), Vol. 2 (Applications).
- [B11] MIL-STD-188/124, Grounding, Bonding and Shielding for Common Long Haul Tactical Communication Systems Including Ground Based Communications—Electronics Facilities and Equipments.
- [B12] Morrison, R. *Grounding and Shielding in Instrumentation*, New York: John Wiley & Sons, 1977.
- [B13] Ott, H. *Noise Reduction Techniques in Electronic Systems*, New York: John Wiley & Sons, 1989.

## Chapter 4

### Fundamentals

**4.1 Introduction.** Successful, reliable operation of sensitive 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 9.

Rapid changes in the electronics and communications industries make it almost impossible for design engineers to be expert 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 sensitive electronics. The total system impedance can be grouped into three fundamental parts: the power source, the distribution, and the load impedances. It is important to note that the nature and magnitude of these impedances vary with frequency. They and their frequency related considerations are discussed in this section.

**4.2.1 Frequencies of Interest.** The most distinguishing characteristic of power systems, for sensitive 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). 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 (National Electrical Code (NEC) (ANSI/NFPA 70-1993 [2]),<sup>10</sup> IEEE Std 446-1987 [10]).

**4.2.1.2 Performance Range.** The performance range extends from dc to tens of megahertz. 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. The term performance range is defined here to denote that the conducted and radiated electromagnetic energy (in the frequency range between tens of kilohertz and tens of megahertz) can significantly impact the operational performance of sensitive electronic equipment. Impedances in this range tend to be characterized by distributed resistive, inductive, and capacitive elements, particularly at the higher frequencies (FIPS PUB 94 [11]).

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<sup>10</sup> The numbers in brackets correspond to those of the references in 4.9; when preceded by the letter "B," they correspond to those in the bibliography in 4.10.

**4.2.2 Power Source Impedance.** Knowledge of the power source impedance is critical to the understanding of critical load-source interactions. Power source impedance is the ratio of incremental internal voltage drop within the same source,  $dE$ , to the incremental load current supplied by that source,  $dI$ . That is, the impedance is  $Z = dE/dI$ . Impedance of a power source can be further delineated as internal, forward-transfer, and output impedance. These basic concepts of source impedance can be illustrated by a simplified equivalent diagram of a transformer. Fig 4-1 shows such a diagram where the magnetizing inductance of the core is neglected.

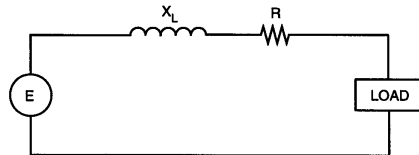


**Fig 4-1**  
**First Order Model of Transformer Impedances**

**4.2.2.1 Internal Impedance.** Internal impedance is the impedance of the power source at its design frequency. For example, the determination of a transformer percent internal impedance (%Z) requires a knowledge of the following:

- (1) The input voltage necessary to make the current in a short-circuited secondary equal to the rated current.
- (2) The rated input voltage.

The transformer internal impedance, expressed as a percent, is the ratio of (1) above divided by (2), then multiplied by 100. The internal impedance is often provided on transformer nameplates.

A transformer with a 5% internal impedance allows 20 times its rated current to flow during short-circuit conditions, assuming sufficient fault current is available on its primary. Typical power transformers suitable for electronic equipment are identified in [B25]. These transformers tend to have impedances in the range of 3–6% at their nominal design frequency (e.g., 60 Hz).

It is desirable to have a low-internal impedance, such that supply voltage variances are small for normal swings in load currents. 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. A suitable internal impedance range for transformers, which serve nonlinear load currents for sensitive electronic equipment, is 3–6%.

**4.2.2.2 Forward Transfer Impedance.** Forward transfer impedance is an attribute similar to internal impedance, but at frequencies other than the nominal power system frequency (e.g., 60 Hz). 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 suitable output voltage waveform. Generally, the highest frequency of interest is 3 kHz for 50–60 Hz power systems, and 20–25 kHz for nominal 400 Hz power systems (which is about 50 times the supply frequency).

A common method for determining forward transfer impedance of transformers and filters is to measure simultaneously the input signal voltage and short-circuited output current. The ratio is the forward transfer impedance.

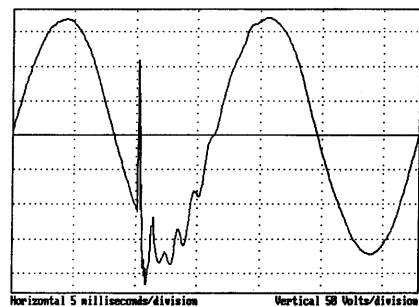
Generally, the forward transfer impedance will increase with increasing frequency. It is desirable to have a low forward transfer impedance at the nominal power frequency and its low-order harmonics (e.g., up to 50th harmonic). At frequencies above the 50th harmonic, a high value of forward transfer impedance is desirable to attenuate transient voltages conducted by the power system.

**4.2.2.3 Output Impedance.** 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.

If the load generates harmonic currents, then these currents flow back towards the source of power. These currents produce voltage drops across the source impedance which add to (or subtract from) the power system voltage. The amplitude and waveshape of the line voltage can change significantly. Therefore, it is very important that the power source have low-output impedance to these harmonic currents. At higher frequencies than those produced by harmonics, a high-output impedance provides some filtering of high-frequency transients before these reach the load. Output impedances generally rise with frequency but distributed capacitances can allow resonance that may lower output impedance at specific frequencies.

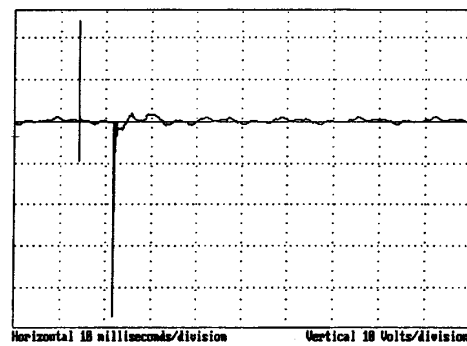
Distributed primary to secondary capacitance in transformers can act to accentuate higher frequency transients on the load side relative to the power frequency. Adding shields within the transformer can reduce the primary to secondary capacitance. Using additional capacitors and filters to attenuate these higher frequency transients can have unexpected and undesirable consequences if shunt capacitors (which are usually involved) elevate the voltage of the signal reference (see 9.20). These additional components must be used with great care.

Transients with microsecond rise time and ring frequencies in the kilohertz range, such as the Ring Wave defined by IEEE Std C62.41-1991 [8], are not attenuated rapidly by typical power transformers or building wiring [B31]. Switching of reactive loads, such as transformers and capacitors, create transients in the kilohertz range. Figs 4-2(a) and 4-2(b) illustrate waveforms that are not unusual.



Source: [B10].

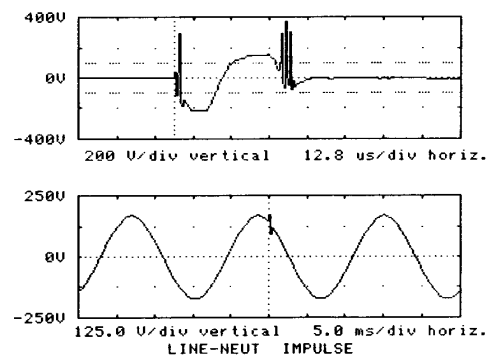
**Fig 4-2 (a)**  
**Phase-Neutral Transient Resulting From Addition of Capacitive Load**



Source: [B10].

**Fig 4-2 (b)**  
**Neutral-Ground Transient Resulting From Addition of Inductive Load**

Electromechanical switching devices interact with the distributed inductance and capacitance in ac distribution and loads to create electrical fast transients (EFTs), as shown in Fig 4-3. EFTs are associated with a broad band of frequencies.



Source: [B36].

**Fig 4-3**  
**Phase-Neutral Transient Resulting From Arcing and Bouncing Contactor**

**4.2.3 Building AC Distribution System Impedance.** The impedance of local electrical distribution systems is mostly resistive and inductive at power-frequencies of interest (60 Hz to 3 kHz) and mostly inductive and capacitive at higher frequencies (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 rise-time surges.

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 [B14], [B47]. Fig 4-4 depicts the resulting ac branch circuit impedance for such a model reported in [B14]. The general behavior of impedance with frequency, shown in Fig 4-4, is typical for most ac feeder and branch circuits; but actual impedances can vary considerably and resonances above 1 MHz can alter the impedance

behavior. It should also be noted that the commonly, but incorrectly, assumed characteristic impedance of 50  $\Omega$  for ac distribution circuits can contribute to significant errors, if used to calculate surge energy levels (see 4.5.6).

**4.2.4 Load Impedance.** Sensitive electronic equipment typically contains motors, transformers, and rectifiers. Outputs of these transformers and rectifiers are typically regulated to provide constant voltage to sensitive load circuits. Insight can be gained as to the nature and operation of these sensitive

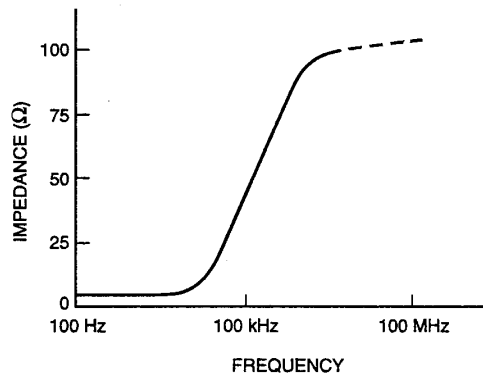


Fig 4-4

**Typical AC Distribution Branch Circuit Impedance Versus Frequency  
(no load connected)**

**Table 4-1  
Example Cable Impedances at High Frequencies  
(copper cable suspended in free air)**

(a) #4 AWG Building Wire (25 mm<sup>2</sup>)

| LENGTH | L<br>(>1 MHz) | @ 1 MHz        |                | @ 10 MHz       |                 | @ 100 MHz      |                 |
|--------|---------------|----------------|----------------|----------------|-----------------|----------------|-----------------|
|        |               | R <sub>f</sub> | $\omega L = Z$ | R <sub>f</sub> | $\omega L = Z$  | R <sub>f</sub> | $\omega L = Z$  |
| 10 ft  | 4 $\mu$ H     | 0.05 $\Omega$  | 26 $\Omega$    | 0.15 $\Omega$  | 260 $\Omega$    | 0.5 $\Omega$   | 2.6 k $\Omega$  |
| 20 ft  | 9 $\mu$ H     | 0.1 $\Omega$   | 57 $\Omega$    | 0.3 $\Omega$   | 570 $\Omega$    | 1.0 $\Omega$   | 5.7 k $\Omega$  |
| 40 ft  | 20 $\mu$ H    | 0.2 $\Omega$   | 125 $\Omega$   | 0.6 $\Omega$   | 1.25 k $\Omega$ | 2.0 $\Omega$   | 12.5 k $\Omega$ |
| 60 ft  | 31 $\mu$ H    | 0.3 $\Omega$   | 197 $\Omega$   | 0.9 $\Omega$   | 1.97 k $\Omega$ | 3.0 $\Omega$   | 19.7 k $\Omega$ |
| 100 ft | 55 $\mu$ H    | 0.5 $\Omega$   | 350 $\Omega$   | 1.5 $\Omega$   | 3.5 k $\Omega$  | 5.0 $\Omega$   | 35.0 k $\Omega$ |

(b) #4/0 AWG Building Wire (107 mm<sup>2</sup>)

| LENGTH | L<br>(>1 MHz) | @ 1 MHz        |                | @ 10 MHz       |                 | @ 100 MHz      |                 |
|--------|---------------|----------------|----------------|----------------|-----------------|----------------|-----------------|
|        |               | R <sub>f</sub> | $\omega L = Z$ | R <sub>f</sub> | $\omega L = Z$  | R <sub>f</sub> | $\omega L = Z$  |
| 10 ft  | 3.6 $\mu$ H   | 0.022 $\Omega$ | 23 $\Omega$    | 0.07 $\Omega$  | 230 $\Omega$    | 0.22 $\Omega$  | 2.30 k $\Omega$ |
| 20 ft  | 8 $\mu$ H     | 0.044 $\Omega$ | 51 $\Omega$    | 0.14 $\Omega$  | 510 $\Omega$    | 0.44 $\Omega$  | 5.10 k $\Omega$ |
| 40 ft  | 18 $\mu$ H    | 0.088 $\Omega$ | 113 $\Omega$   | 0.28 $\Omega$  | 1.13 k $\Omega$ | 0.88 $\Omega$  | 11.3 k $\Omega$ |
| 60 ft  | 28 $\mu$ H    | 0.132 $\Omega$ | 176 $\Omega$   | 0.42 $\Omega$  | 1.76 k $\Omega$ | 1.32 $\Omega$  | 17.6 k $\Omega$ |
| 100 ft | 50 $\mu$ H    | 0.220 $\Omega$ | 314 $\Omega$   | 0.70 $\Omega$  | 3.14 k $\Omega$ | 2.20 $\Omega$  | 31.4 k $\Omega$ |

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  $R$  above the frequency axis (see Fig 4-5(a)).

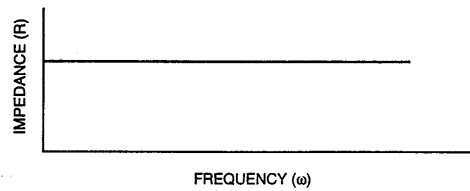


**Fig 4-5(a)**  
**Passive Load Resistance Versus Frequency**

Inductive reactance,  $X_L$ , linearly increases with increasing frequency (of the form  $y = mx + b$ ). Inductive reactance is plotted in Fig 4-5(b), versus frequency, with a slope equal to the inductance,  $L$ , of the inductor and intercepting at the origin ( $X_L = L\omega + 0$ ).

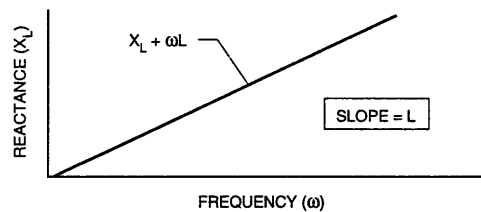


**Fig 4-5(b)**  
**Passive Load Inductive Reactance Versus Frequency**

Capacitive reactance,  $X_C$ , is a hyperbolic function of frequency (of the form  $yk = k$ ), where the frequency,  $\omega$ , is the independent variable and  $1/C$  is the constant. Capacitive reactance versus frequency ( $X_C = -1/(\omega C)$ ) is plotted in Fig 4-5(c). From the above figures it can be seen that, as frequency increases, inductive reactance becomes the dominant factor.

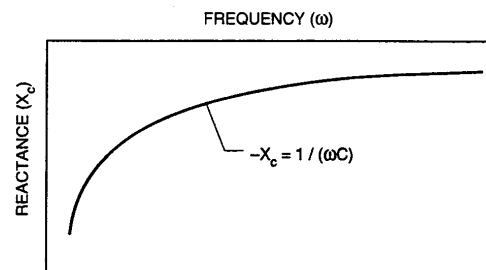


Fig 4-5(c)

**Passive Load Capacitive Reactance Versus Frequency**

**4.2.5 Resonance Considerations.** AC circuits characteristically have (1) capacitive and inductive elements, and (2) the means to transfer oscillatory energy between these elements. At frequencies where the inductive and capacitive impedances 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. If the circuit is a grounding conductor, it will be effectively open-circuited (not grounded) at the resonant frequencies. It is also possible for current to rise. The voltage and/or current rise is dependent upon the type of resonant circuit and where in the circuit these parameters are being measured.

It is important to analyze the power system frequency response, with the objective of avoiding resonance problems. Resonant frequencies of typical (sensitive electronic equipment) power systems tend to occur in the performance frequency range as defined by 4.2.1.

**4.2.5.1 Series Resonance.** Series resonance results from the series combination of line/transformer inductances, resistance, and capacitor banks on the ac power distribution system. Fig 4-6(a) shows all three reactance elements superimposed on the same impedance *versus* frequency graph. Series resonance occurs at the frequency,  $\omega_0$ , where  $X_L = -X_C$ . The minimum circuit impedance also occurs at the resonant frequency,  $\omega_0$ , 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.

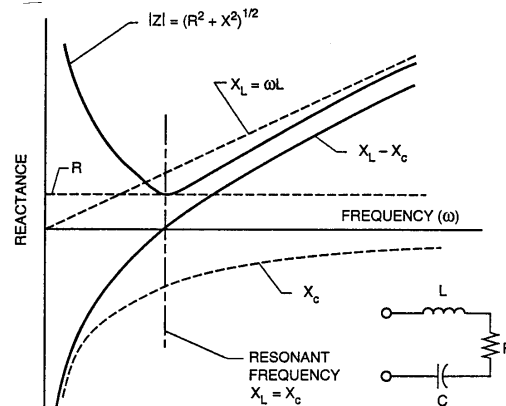


Fig 4-6(a)

**Series R-L-C Circuit Impedance Versus Frequency**

**4.2.5.2 Parallel Resonance.** Parallel resonance results from “tank” (LC) circuits in the ac distribution system being excited at frequencies where their inductive and capacitive impedances are equal. Such parallel resonant paths represent very high impedances for currents at their resonant frequency, and can create voltage-breakdown conditions on conductors and components within, or connected to, the circuit. Harmonic currents at the resonant frequency create conditions of high-harmonic voltage across the circuit’s terminals, which are also connected to the ac source and its load(s). This frequency-dependent

harmonic voltage adds algebraically to the fundamental frequency voltage and to other harmonic voltage waveforms on the circuit, to produce a harmonic distortion of the 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, Fig 4-6(b), appears similar to the series resonance diagram, Fig 4-6(a), when voltages are replaced by currents, currents replaced by voltages, and associated parameters are interchanged with their “inverse equivalents” [B16]. The total set of terms utilized in Fig 4-6(b) and their equivalent series resonance terms are as follows:

- (1) Current ( $I$ )  $\Leftrightarrow$  Voltage ( $V$ )
- (2) Admittance ( $Y$ )  $\Leftrightarrow$  Impedance ( $Z$ )
- (3) Conductance ( $G$ )  $\Leftrightarrow$  Resistance ( $R$ )
- (4) Susceptance ( $B$ )  $\Leftrightarrow$  Reactance ( $X$ )
- (5) Capacitance ( $C$ )  $\Leftrightarrow$  Inductance ( $L$ )

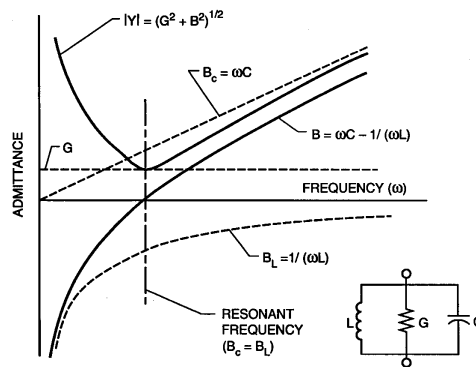


**Fig 4-6(b)**  
**Series R-L-C Circuit Impedance Versus Frequency**

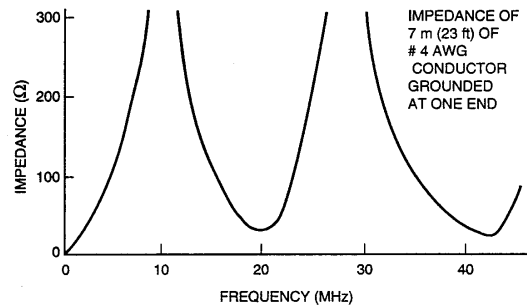
Considerable current can oscillate between the inductive and capacitive storage elements of the circuit when nonlinear loads, with a characteristic harmonic near the parallel resonant frequency, exist in the circuit. Voltage distortion results from these high oscillating current levels. Under certain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

Series-resonant circuit currents oscillate through the load and the source, while parallel-resonant circuits confine such current to the parallel circuit's own loop. Therefore, series resonant circuits involve the supply and load with current at the resonant frequency, and parallel resonant circuits impress voltages (at the resonant frequency) on their source and load. This is the underlying mechanism for the production of harmonic voltage waveform distortion.

**4.2.5.3 Conductor Self-Resonance Effects.** Resonance occurs in conductors, primarily due to their lack of lumped capacitive and lumped inductive elements. Therefore, the conductors of ac electrical distribution systems, which exhibit only distributed capacitance and inductance, oscillate when excited by certain voltage waveforms. They, in essence, act as inadvertent antenna. This type of problem is not often observed in conductors that make up a crude transmission line, such as an ac system feeder or branch circuit; but is a major concern

on externally installed grounding/bonding conductors and data cables that form open-loop areas.

Conductor self-resonance occurs when a conductor's length equals an odd multiple of 1/4-wavelength of an impressed voltage waveform. The conductor ceases to conduct current at its particular resonant frequency. Current conductance at other frequencies, sufficiently different than resonant frequencies, are not affected ANSI/NFPA 75-1992 [3]. Fig 4-7 depicts this relationship.



Source: Based on FIPS PUB 94 [11].

**Fig 4-7**  
**Resonance Characteristics of Conductors**

The relationship between the resonant conductor length and frequency is as follows:

$$L_{\text{resonance}} = (cn)/(4f_{\text{resonance}}) \quad (\text{Eq 4-1})$$

where

$L_{\text{resonance}}$  = resonant conductor length (m)

$n$  = any odd integer (1, 3, 5, . . .)

$c$  = speed of light in free space ( $3 \cdot 10^8$  m/s)

$f_{\text{resonance}}$  = frequency of excitation in conductor (Hz)

In practice, designers must be concerned with the lowest frequency at which a given grounding/bonding conductor length will resonate ( $n = 1$ ). Therefore, grounding/bonding conductors should always be chosen so as to not have physical lengths approaching resonant conditions of near quarter-wavelength and odd-multiples thereof for any electrical noise frequencies which might be imposed on the conductor. One hedge against this is to employ multiple grounding/bonding conductors between the same points, each of a different length than the other. Thus, while one path may be undergoing resonance conditions, one or more of the others will not. Usually a difference of 20% in conductor lengths will suffice (FIPS PUB 94 [11]).

**4.3 Utility Level Distribution Voltage Disturbances.** Electrical utilities in the United States adhere to ANSI C84.1-1989 [1] for the delivery of electrical power. This ANSI document provides guidelines for steady-state tolerances, as shown in Table 4-2.

Continuity of power service at a given site can generally be obtained from utilities. Most utilities have available standard power reliability indices such as ASAI (average service availability index) [B11].

These indices do not include the very short duration interruptions (momentary interruptions). Momentary interruptions generally are considered to be less than a few minutes. They are the result of a variety of normal and abnormal operations in the utility distribution system. Due to the definition of a power interruption generally used by utilities versus the capabilities of sensitive electronic equipment, distribution circuits that the electric utility might consider to be reliable may be totally inadequate to the user of sensitive electronic load equipment. It is advisable that users of sensitive electronic equipment work with their local utility to determine operating characteristics of the particular distribution circuits in question, considering both the frequency of momentary interruptions and pertinent reliability indices.

Voltage waveform disturbances at the utility feeder level have been monitored ([B1], [B11]), and compared and contrasted [B45]. The general conclusion is that line voltage sags are most frequent, and thus most likely to contribute to sensitive 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, and the threshold settings of the monitoring instrument. These variances are highly influenced by the particular threshold settings utilized on the monitoring equipment. Appendix A provides an expanded discussion of utility feeder level power quality.

User equipment residing near locations where lightning enters the utility distribution system, will experience high-energy surge conditions via its building ac distribution system. But user equipment located at sites far away from the strike location often experience momentary sag conditions. The momentary sags result from insulator flashover or current shunting actions of the utility's lightning protection equipment which load down the utility's ac distribution system during operation.

**4.4 Load and Power Source Interactions.** Interactions of interest between sensitive electronic equipment, their power sources, and their environment, primarily result in transient disturbances or steady-state distortions to the system voltage waveform. Table 4-3 summarizes these sources of voltage waveform disturbances and waveform distortions, and their characteristics. When ameliorating these variances, it is often helpful to know their related current waveforms. Certain source/load interactions, e.g., switching, result in short rise-time voltage transients (surges). The reader is referred to 4.5 for a discussion of surges.