Recognized as an

American National Standard (ANSI)

IEEE Std 1159-1995(R2001)

IEEE Recommended Practice for Monitoring Electric Power Quality

Sponsor

IEEE Standards Coordinating Committee 22 on Power Quality

Reaffirmed 2 August 2001
Approved 2 February 1996
American National Standards Institute

Reaffirmed 17 March 2001
Approved 14 June 1995
IEEE Standards Board

Abstract: The monitoring of electric power quality of ac power systems, definitions of power quality terminology, impact of poor power quality on utility and customer equipment, and the measurement of electromagnetic phenomena are covered.

Keywords: data interpretation, electric power quality, electromagnetic phenomena, monitoring, power quality definitions

The Institute of Electrical and Electronics Engineers, Inc.

345 East 47th Street, New York, NY 10017-2394, USA

ISBN 1-55937-549-3

IEEE Standards documents are developed within the Technical Committees of the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE that have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason IEEE and the members of its technical committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
445 Hoes Lane
P.O. Box 1331
Piscataway, NJ 08855-1331
USA

IEEE Standards documents may involve the use of patented technology. Their approval by the Institute of Electrical and Electronics Engineers does not mean that using such technology for the purpose of conforming to such standards is authorized by the patent owner. It is the obligation of the user of such technology to obtain all necessary permissions.

Introduction

(This introduction is not part of IEEE Std 1159-1995, IEEE Recommended Practice for Monitoring Electric Power Quality.)

This recommended practice was developed out of an increasing awareness of the difficulty in comparing results obtained by researchers using different instruments when seeking to characterize the quality of low-voltage power systems. One of the initial goals was to promote more uniformity in the basic algorithms and data reduction methods applied by different instrument manufacturers. This proved difficult and was not achieved, given the free market principles under which manufacturers design and market their products. However, consensus was achieved on the contents of this recommended practice, which provides guidance to users of monitoring instruments so that some degree of comparisons might be possible.

An important first step was to compile a list of power quality related definitions to ensure that contributing parties would at least speak the same language, and to provide instrument manufacturers with a common base for identifying power quality phenomena. From that starting point, a review of the objectives of monitoring provides the necessary perspective, leading to a better understanding of the means of monitoring—the instruments. The operating principles and the application techniques of the monitoring instruments are described, together with the concerns about interpretation of the monitoring results. Supporting information is provided in a bibliography, and informative annexes address calibration issues.

The Working Group on Monitoring Electric Power Quality, which undertook the development of this recommended practice, had the following membership:

J. Charles Smith, *Chair* **Gil Hensley,** *Secretary*

Larry Ray, *Technical Editor*

Mark Andresen
Vladi Basch
Roger Bergeron
John Burnett
John Dalton
Andrew Dettloff
Dave Griffith
Thomas Gruzs
Erich Gunther
Mark Kempker

Thomas Key
Jack King
David Kreiss
François Martzloff
Alex McEachern
Bill Moncrief
Allen Morinec
Ram Mukherji
Richard Nailen
David Pileggi
Harry Rauworth

John Roberts
Anthony St. John
Marek Samotyj
Ron Smith
Bill Stuntz
John Sullivan
David Vannoy
Marek Waclawlak
Daniel Ward
Steve Whisenant

In addition to the working group members, the following people contributed their knowledge and experience to this document:

Ed Cantwell
John Curlett

Christy Herig
Allan Ludbrook
Harshad Mehta

Tejindar Singh
Maurice Tetreault

The following persons were on the balloting committee:

James J. Burke
David A. Dini
W. Mack Grady
David P. Hartmann
Michael Higgins
Thomas S. Key
Joseph L. Koepfinger
David Kreiss
Michael Z. Lowenstein
François D. Martzloff
Stephen McCluer
A. McEachern
W. A. Moncrief
P. Richman
John M. Roberts
Jacob A. Roiz
Marek Samotyj
Ralph M. Showers
J. C. Smith
Robert L. Smith
Daniel J. Ward
Charles H. Williams

When the IEEE Standards Board approved this standard on June 14, 1995, it had the following membership:

E. G. "Al" Kiener, *Chair* **Donald C. Loughry,** *Vice Chair*
Andrew G. Salem, *Secretary*

Gilles A. Baril
Clyde R. Camp
Joseph A. Cannatelli
Stephen L. Diamond
Harold E. Epstein
Donald C. Fleckenstein
Jay Forster*
Donald N. Heirman
Richard J. Holleman
Jim Isaak
Ben C. Johnson
Sonny Kasturi
Lorraine C. Kevra
Ivor N. Knight
Joseph L. Koepfinger*
D. N. "Jim" Logothetis
L. Bruce McClung
Marco W. Migliaro
Mary Lou Padgett
John W. Pope
Arthur K. Reilly
Gary S. Robinson
Ingo Rusch
Chee Kiow Tan
Leonard L. Tripp

*Member Emeritus

Also included are the following nonvoting IEEE Standards Board liaisons:

Satish K. Aggarwal
Richard B. Engelman
Robert E. Hebner
Chester C. Taylor

Rochelle L. Stern
IEEE Standards Project Editor

Contents

CLAUSE PAGE

ANNEXES PAGE

IEEE Recommended Practice for Monitoring Electric Power Quality

1. Overview

1.1 Scope

This recommended practice encompasses the monitoring of electric power quality of single-phase and polyphase ac power systems. As such, it includes consistent descriptions of electromagnetic phenomena occurring on power systems. The document also presents definitions of nominal conditions and of deviations from these nominal conditions, which may originate within the source of supply or load equipment, or from interactions between the source and the load.

Brief, generic descriptions of load susceptibility to deviations from nominal conditions are presented to identify which deviations may be of interest. Also, this document presents recommendations for measurement techniques, application techniques, and interpretation of monitoring results so that comparable results from monitoring surveys performed with different instruments can be correlated.

While there is no implied limitation on the voltage rating of the power system being monitored, signal inputs to the instruments are limited to 1000 Vac rms or less. The frequency ratings of the ac power systems being monitored are in the range of 45–450 Hz.

Although it is recognized that the instruments may also be used for monitoring dc supply systems or data transmission systems, details of application to these special cases are under consideration and are not included in the scope. It is also recognized that the instruments may perform monitoring functions for environmental conditions (temperature, humidity, high frequency electromagnetic radiation); however, the scope of this document is limited to conducted electrical parameters derived from voltage or current measurements, or both.

Finally, the definitions are solely intended to characterize common electromagnetic phenomena to facilitate communication between various sectors of the power quality community. The definitions of electromagnetic phenomena summarized in table 2 are not intended to represent performance standards or equipment tolerances. Suppliers of electricity may utilize different thresholds for voltage supply, for example, than the ± 10% that defines conditions of overvoltage or undervoltage in table 2. Further, sensitive equipment may malfunction due to electromagnetic phenomena not outside the thresholds of the table 2 criteria.

1.2 Purpose

The purpose of this recommended practice is to direct users in the proper monitoring and data interpretation of electromagnetic phenomena that cause power quality problems. It defines power quality phenomena in order to facilitate communication within the power quality community. This document also forms the consensus opinion about safe and acceptable methods for monitoring electric power systems and interpreting the results. It further offers a tutorial on power system disturbances and their common causes.

2. References

This recommended practice shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

IEC 1000-2-1 (1990), Electromagnetic Compatibility (EMC)—Part 2 Environment. Section 1: Description of the environment—electromagnetic environment for low-frequency conducted disturbances and signaling in public power supply systems.[1]

IEC 50(161)(1990), International Electrotechnical Vocabulary—Chapter 161: Electromagnetic Compatibility.

IEEE Std 100-1992, IEEE Standard Dictionary of Electrical and Electronic Terms (ANSI).[2]

IEEE Std 1100-1992, IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment (Emerald Book) (ANSI).

3. Definitions

The purpose of this clause is to present concise definitions of words that convey the basic concepts of power quality monitoring. These terms are listed below and are expanded in clause 4. The power quality community is also pervaded by terms that have no scientific definition. A partial listing of these words is included in 3.2; use of these terms in the power quality community is discouraged. Abbreviations and acronyms that are employed throughout this recommended practice are listed in 3.3.

3.1 Terms used in this recommended practice

The primary sources for terms used are IEEE Std 100-1992[3] indicated by ([a]), and IEC 50 (161)(1990) indicated by ([b]). Secondary sources are IEEE Std 1100-1992 indicated by ([c]), IEC-1000-2-1 (1990) indicated by ([d]) and UIE -DWG-3-92-G [B16][4]. Some referenced definitions have been adapted and modified in order to apply to the context of this recommended practice.

3.1.1 accuracy: The freedom from error of a measurement. Generally expressed (perhaps erroneously) as *percent inaccuracy*. Instrument accuracy is expressed in terms of its uncertainty—the degree of deviation from a known value. An instrument with an uncertainty of 0.1% is 99.9% accurate. At higher accuracy levels, uncertainty is typically expressed in parts per million (ppm) rather than as a percentage.

---

[1] IEC publications are available from IEC Sales Department, Case Postale 131, 3, rue de Varembé, 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.

[2] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[3] Information on references can be found in clause 2.

[4] The numbers in brackets correspond to those bibliographical items listed in annex B.

3.1.2 accuracy ratio: The ratio of an instrument's tolerable error to the uncertainty of the standard used to calibrate it.

3.1.3 calibration: Any process used to verify the integrity of a measurement. The process involves comparing a measuring instrument to a well defined standard of greater accuracy (a calibrator) to detect any variations from specified performance parameters, and making any needed compensations. The results are then recorded and filed to establish the integrity of the calibrated instrument.

3.1.4 common mode voltage: A voltage that appears between current-carrying conductors and ground.[b] The noise voltage that appears equally and in phase from each current-carrying conductor to ground.[c]

3.1.5 commercial power: Electrical power furnished by the electric power utility company.[c]

3.1.6 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.[a]

3.1.7 current transformer (CT): An instrument transformer intended to have its primary winding connected in series with the conductor carrying the current to be measured or controlled.[a]

3.1.8 dip: *See:* **sag.**

3.1.9 dropout: A loss of equipment operation (discrete data signals) due to noise, sag, or interruption.[c]

3.1.10 dropout voltage: The voltage at which a device fails to operate.[c]

3.1.11 electromagnetic compatibility: The ability of a device, equipment, or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.[b]

3.1.12 electromagnetic disturbance: Any electromagnetic phenomena that may degrade the performance of a device, equipment, or system, or adversely affect living or inert matter.[b]

3.1.13 electromagnetic environment: The totality of electromagnetic phenomena existing at a given location.[b]

3.1.14 electromagnetic susceptibility: The inability of a device, equipment, or system to perform without degradation in the presence of an electromagnetic disturbance.

NOTE—Susceptibility is a lack of immunity.[b]

3.1.15 equipment grounding conductor: The conductor used to connect the noncurrent-carrying parts of conduits, raceways, and equipment enclosures to the grounded conductor (neutral) and the grounding electrode at the service equipment (main panel) or secondary of a separately derived system (e.g., isolation transformer). See Section 100 in ANSI/NFPA 70-1993 [B2].

3.1.16 failure mode: The effect by which failure is observed.[a]

3.1.17 flicker: Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.[b]

3.1.18 frequency deviation: An increase or decrease in the power frequency. The duration of a frequency deviation can be from several cycles to several hours.[c] *Syn.:* power frequency variation.

3.1.19 fundamental (component): The component of an order 1 (50 or 60 Hz) of the Fourier series of a periodic quantity.[b]

3.1.20 ground: A conducting connection, whether intentional or accidental, by which an electric circuit or piece of 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).[a]

3.1.21 ground loop: In a radial grounding system, an undesired conducting path between two conductive bodies that are already connected to a common (single-point) ground.

3.1.22 harmonic (component): A component of order greater than one of the Fourier series of a periodic quantity.[b]

3.1.23 harmonic content: The quantity obtained by subtracting the *fundamental component* from an alternating quantity.[a]

3.1.24 immunity (to a disturbance): The ability of a device, equipment, or system to perform without degradation in the presence of an electromagnetic disturbance.[b]

3.1.25 impulse: A *pulse* that, for a given application, approximates a unit pulse.[b] When used in relation to the monitoring of power quality, it is preferred to use the term *impulsive transient* in place of *impulse*.

3.1.26 impulsive transient: A sudden nonpower frequency change in the steady-state condition of voltage or current that is unidirectional in polarity (primarily either positive or negative).

3.1.27 instantaneous: A time range from 0.5–30 cycles of the power frequency when used to quantify the duration of a short duration variation as a modifier.

3.1.28 interharmonic (component): A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is designed to operate operating (e.g., 50 Hz or 60 Hz).

3.1.29 interruption, momentary (power quality monitoring): A type of *short duration variation*. The complete loss of voltage (< 0.1 pu) on one or more phase conductors for a time period between 0.5 cycles and 3 s.

3.1.30 interruption, sustained (electric power systems): Any interruption not classified as a momentary interruption.

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

3.1.32 isolated ground: An insulated equipment grounding conductor run in the same conduit or raceway as the supply conductors. This conductor may be 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. See Section 250-74, Exception #4 and Exception in Section 250-75 in ANSI/NFPA 70-1993 [B2].

3.1.33 isolation: Separation of one section of a system from undesired influences of other sections.[c]

3.1.34 long duration voltage variation: *See:* **voltage variation, long duration.**

3.1.35 momentary (power quality monitoring): A time range at the power frequency from 30 cycles to 3 s when used to quantify the duration of a *short duration variation* as a modifier.

3.1.36 momentary interruption: *See*: **interruption, momentary.**

3.1.37 noise: Unwanted electrical signals which produce undesirable effects in the circuits of the control systems in which they occur.[a] (For this document, control systems is intended to include sensitive electronic equipment in total or in part.)

3.1.38 nominal voltage (Vn): A nominal value assigned to a circuit or system for the purpose of conveniently designating its voltage class (as 120/208208/120, 480/277, 600).[d]

3.1.39 nonlinear load: Steady-state electrical load that draws current discontinuously or whose impedance varies throughout the cycle of the input ac voltage waveform.[c]

3.1.40 normal mode voltage: A voltage that appears between or among active circuit conductors, but not between the grounding conductor and the active circuit conductors.

3.1.41 notch: A switching (or other) disturbance of the normal power voltage waveform, lasting less than 0.5 cycles, which is initially of opposite polarity than the waveform and is thus subtracted from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to 0.5 cycles [B13].

3.1.42 oscillatory transient: A sudden, nonpower frequency change in the steady-state condition of voltage or current that includes both positive or negative polarity value.

3.1.43 overvoltage: When used to describe a specific type of *long duration variation*, refers to a measured voltage having a value greater than the *nominal voltage* for a period of time greater than 1 min. Typical values are 1.1–1.2 pu.

3.1.44 phase shift: The displacement in time of one waveform relative to another of the same frequency and harmonic content.[c]

3.1.45 potential transformer (PT): An instrument transformer intended to have its primary winding connected in shunt with a power-supply circuit, the voltage of which is to be measured or controlled. *Syn.:* voltage transformer.[a]

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

3.1.47 power quality: The concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment.[c]

NOTE—Within the industry, alternate definitions or interpretations of power quality have been used, reflecting different points of view. Therefore, this definition might not be exclusive, pending development of a broader consensus.

3.1.48 precision: Freedom from random error.

3.1.49 pulse: An abrupt variation of short duration of a physical an electrical quantity followed by a rapid return to the initial value.

3.1.50 random error: Error that is not repeatable, i.e., noise or sensitivity to changing environmental factors.

NOTE—For most measurements, the random error is small compared to the instrument tolerance.

3.1.51 sag: A decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min. Typical values are 0.1 to 0.9 pu.[b] *See*: **dip.**

NOTE—To give a numerical value to a sag, the recommended usage is “a sag to 20%,” which means that the line voltage is reduced down to 20% of the normal value, not reduced by 20%. Using the preposition “of” (as in “a sag of 20%,” or implied by “a 20% sag”) is deprecated.

3.1.52 shield: A conductive sheath (usually metallic) normally applied to instrumentation cables, 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).[c]

3.1.53 shielding: The use of a conducting and/or ferromagnetic 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.[c]

3.1.54 short duration voltage variation: *See:* **voltage variation, short duration.**

3.1.55 slew rate: Rate of change of ac voltage, expressed in volts per second a quantity such as volts, frequency, or temperature.[a]

3.1.56 sustained: When used to quantify the duration of a voltage interruption, refers to the time frame associated with a long duration variation (i.e., greater than 1 min).

3.1.57 swell: An increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. Typical values are 1.1–1.8 pu.

3.1.58 systematic error: The portion of error that is repeatable, i.e., zero error, gain or scale error, and linearity error.

3.1.59 temporary interruption: *See*: **interruption, temporary.**

3.1.60 tolerance: The allowable variation from a nominal value.

3.1.61 total harmonic distortion disturbance level: The level of a given electromagnetic disturbance caused by the superposition of the emission of all pieces of equipment in a given system.[b] The ratio of the rms of the harmonic content to the rms value of the fundamental quantity, expressed as a percent of the fundamental [B13].[a] *Syn.:* distortion factor.

3.1.62 traceability: Ability to compare a calibration device to a standard of even higher accuracy. That standard is compared to another, until eventually a comparison is made to a national standards laboratory. This process is referred to as a chain of traceability.

3.1.63 transient: Pertaining to or designating a phenomenon or a quantity that varies between two consecutive steady states during a time interval that is short compared to the time scale of interest. A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity.[b]

3.1.64 undervoltage: A measured voltage having a value less than the *nominal voltage* for a period of time greater than 1 min when used to describe a specific type of *long duration variation*, refers to. Typical values are 0.8–0.9 pu.

3.1.65 voltage change: A variation of the rms or peak value of a voltage between two consecutive levels sustained for definite but unspecified durations.[d]

3.1.66 voltage dip: See: **sag.**

3.1.67 voltage distortion: Any deviation from the nominal sine wave form of the ac line voltage.

3.1.68 voltage fluctuation: A series of voltage changes or a cyclical variation of the voltage envelope.[d]

3.1.69 voltage imbalance (unbalance), polyphase systems: The maximum deviation among the three phases from the average three-phase voltage divided by the average three-phase voltage. The ratio of the negative or zero sequence component to the positive sequence component, usually expressed as a percentage.[a]

3.1.70 voltage interruption: Disappearance of the supply voltage on one or more phases. Usually qualified by an additional term indicating the duration of the interruption (e.g., *momentary*, *temporary*, or *sustained).*

3.1.71 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.[c]

3.1.72 voltage variation, long duration: A variation of the rms value of the voltage from nominal voltage for a time greater than 1 min. Usually further described using a modifier indicating the magnitude of a voltage variation (e.g., *undervoltage*, *overvoltage*, or *voltage interruption*).

3.1.73 voltage variation, short duration: A variation of the rms value of the voltage from nominal voltage for a time greater than 0.5 cycles of the power frequency but less than or equal to 1 minute. Usually further described using a modifier indicating the magnitude of a voltage variation (e.g. *sag*, *swell*, or *interruption*) and possibly a modifier indicating the duration of the variation (e.g., *instantaneous*, *momentary*, or *temporary*).

3.1.74 waveform distortion: A steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation [B13].

3.2 Avoided terms

The following terms 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 in relation to the measurement of power quality phenomena:

blackout
blink
brownout (see 4.4.3.2)
bump
clean ground
clean power
computer grade ground
counterpoise ground
dedicated ground
dirty ground
dirty power
frequency shift
glitch
interruption (when not further qualified)
outage (see 4.4.3.3)
power surge
raw power
raw utility power
shared ground
spike
subcycle outages
surge (see 4.4.1)
wink

3.3 Abbreviations and acronyms

The following abbreviations and acronyms are used throughout this recommended practice:

3.3.1 A: amperes

3.3.2 ac: alternating current

3.3.3 ASD: adjustable speed drive

3.3.4 CRT: cathode-ray tube

3.3.5 CT: current transformer

3.3.6 CVT: constant voltage transformer

3.3.7 dc: direct current

3.3.8 DMM: digital multimeter

3.3.9 DVM: digital voltmeter

3.3.10 EFT: electrical fast transient

3.3.11 EMC: electromagnetic compatibility

3.3.12 emf: electromotive force

3.3.13 EMF: electromagnetic field

3.3.14 EMI: electromagnetic interference

3.3.15 ESD: electrostatic discharge

3.3.16 Hz: hertz; cycles per second

3.3.17 LC: inductor-capacitor

3.3.18 MOV: metal-oxide varistor

3.3.19 MCOV: maximum continuous operating voltage

3.3.20 MTBF: mean time between failures

3.3.21 NEMP: nuclear electromagnetic pulse

3.3.22 PC: personal computer

3.3.23 PLC: programmable logic controller

3.3.24 PT: potential transformer

3.3.25 RAM: random-access memory

3.3.26 RFI: radio-frequency interference

3.3.27 rms: root-mean-square (effective value)

3.3.28 RVM: recording voltmeter

3.3.29 SCR: silicon-controlled rectifier

3.3.30 SPD: surge-protective device

3.3.31 THD: total harmonic distortion

3.3.32 TVSS: transient voltage surge suppressor

3.3.33 UPS: uninterruptible power supply

3.3.34 V: volts

3.3.35 VOM: volt-ohm meter

4. Power quality phenomena

4.1 Introduction

The term *power quality* refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system. This clause expands on the definitions of clause 3 by providing technical descriptions and examples of the principal electromagnetic phenomena causing power quality problems.

The increasing application of electronic equipment that can cause electromagnetic disturbances, or that can be sensitive to these phenomena, has heightened the interest in power quality in recent years. Accompanying the increase in operation problems have been a variety of attempts to describe the phenomena. Unfortunately, different segments of the electronics community have utilized different terminologies to describe electromagnetic events. This clause expands the terminology that will be used in the power quality community to describe these common events. This clause also offers explanations as to why commonly used terminology in other communities will not be used in power quality discussions.

4.2 Electromagnetic compatibility

This document uses the electromagnetic compatibility approach to describing power quality phenomena. The electromagnetic compatibility approach has been accepted by the international community in IEC standards produced by IEC Technical Committee 77. The reader is referred to clause 3 for the definition of electromagnetic compatibility and related terms. Reference [B16] provides an excellent overview of the electromagnetic compatibility concept and associated IEC documents.

4.3 General classification of phenomena

The IEC classifies electromagnetic phenomena into several groups as shown in table 1 [B10]. The IEC standard addresses the conducted electrical parameters shown in table 1. The terms *high*- and *low-frequency* are not defined in terms of a specific frequency range, but instead are intended to indicate the relative difference in principal frequency content of the phenomena listed in these categories.

This recommended practice contains a few additional terms related to the IEC terminology. The term *sag* is used in the power quality community as a synonym to the IEC term *dip*. The category *short duration variations* is used to refer to voltage dips and short interruptions. The term *swell* is introduced as an inverse to *sag (dip)*. The category *long duration variation* has been added to deal with ANSI C84.1-1989 [B1] limits. The category *noise* has been added to deal with broad-band conducted phenomena. The category *waveform distortion* is used as a container category for the *IEC harmonics, interharmonics,* and *dc in ac networks* phenomena as well as an additional phenomenon from IEEE Std 519-1992 [B13] called *notching*. Table 2 shows the categorization of electromagnetic phenomena used for the power quality community.

Table 1—Principal phenomena causing electromagnetic disturbances as classified by the IEC

Conducted low-frequency phenomena	Harmonics, interharmonics
	Signal systems (power line carrier)
	Voltage fluctuations
	Voltage dips and interruptions
	Voltage imbalance
	Power-frequency variations
	Induced low-frequency voltages
	DC in ac networks
Radiated low-frequency phenomena	Magnetic fields
	Electric fields
Conducted high-frequency phenomena	Induced continuous wave voltages or currents
	Unidirectional transients
	Oscillatory transients
Radiated high-frequency phenomena	Magnetic fields
	Electric fields
	Electromagnetic fields
	Continuous waves
	Transients
Electrostatic discharge phenomena	—
Nuclear electromagnetic pulse	—

The phenomena listed in table 1 can be described further by listing appropriate attributes. For steady-state phenomena, the following attributes can be used [B10]:

— Amplitude
— Frequency
— Spectrum
— Modulation
— Source impedance
— Notch depth
— Notch area

For non-steady state phenomena, other attributes may be required [B10]:

- Rate of rise
- Amplitude
- Duration
- Spectrum
- Frequency
- Rate of occurrence
- Energy potential
- Source impedance

Table 1 provides information regarding typical spectral content, duration, and magnitude where appropriate for each category of electromagnetic phenomena [B10], [B15], [B16]. The categories of table 2, when used with the attributes mentioned above, provide a means to clearly describe an electromagnetic disturbance. The categories and their descriptions are important in order to be able to classify measurement results and to describe electromagnetic phenomena that can cause power quality problems. The remainder of this clause will discuss each category in detail.

4.4 Detailed descriptions of phenomena

This subclause provides more detailed descriptions for each of the power quality variation categories presented in table 2. These descriptions provide some history regarding the terms currently in use for each category. Typical causes of electromagnetic phenomena in each category are introduced, and are expanded in clause 8.

One of the main reasons for developing the different categories of electromagnetic phenomena is that there are different ways to solve power quality problems depending on the particular variation that is of concern. The different solutions available are discussed for each category. There are also different requirements for characterizing the phenomena using measurements. It is important to be able to classify events and electromagnetic phenomena for analysis purposes. The measurement requirements for each category of electromagnetic phenomenon are discussed.

4.4.1 Transients

The term *transients* has been used in the analysis of power system variations for a long time. Its name immediately conjures up the notion of an event that is undesirable but momentary in nature. The IEEE Std 100-1992 definition of transient reflects this understanding. The primary definition uses the word *rapid* and talks of frequencies up to 3 MHz when defining transient in the context of evaluating cable systems in substations. The notion of a damped oscillatory transient due to a RLC network is also mentioned. This is the type of phenomena that most power engineers think of when they hear the word transient.

Other definitions in IEEE Std 100-1992 are broader in scope and simply state that a transient is “that part of the change in a variable that disappears during transition from one steady-state operating condition to another.” Unfortunately, this definition could be used to describe just about anything unusual that happens on the power system.

Another word used in current IEEE standards that is synonymous with transient is *surge*. IEEE Std 100-1992 defines a surge as “a transient wave of current, potential, or power in an electric circuit.” The IEEE C62 Collection [B14] uses the terms *surge*, *switching surge*, and *transient* to describe the same types of phenomena. For the purposes of this document, *surge* will not be used to describe transient electromagnetic phenomena. Since IEEE Std 100-1992 uses the term *transient* to define *surge,* this limitation should not cause conflicts.

Broadly speaking, transients can be classified into two categories—*impulsive* and *oscillatory.* These terms reflect the waveshape of a current or voltage transient.

Table 2—Categories and typical characteristics of power system electromagnetic phenomena

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	< 50 ns	
1.1.2 Microsecond	1 µs rise	50 ns–1 ms	
1.1.3 Millisecond	0.1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5 kHz	0.3–50 ms	0–4 pu
1.2.2 Medium frequency	5–500 kHz	20 µs	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 µs	0–4 pu
2.0 Short duration variations			
2.1 Instantaneous			
2.1.1 Sag		0.5–30 cycles	0.1–0.9 pu
2.1.2 Swell		0.5–30 cycles	1.1–1.8 pu
2.2 Momentary			
2.2.1 Interruption		0.5 cycles–3 s	< 0.1 pu
2.2.2 Sag		30 cycles–3 s	0.1–0.9 pu
2.2.3 Swell		30 cycles–3 s	1.1–1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s–1 min	< 0.1 pu
2.3.2 Sag		3 s–1 min	0.1–0.9 pu
2.3.3 Swell		3 s–1 min	1.1–1.2 pu
3.0 Long duration variations			
3.1 Interruption, sustained		> 1 min	0.0 pu
3.2 Undervoltages		> 1 min	0.8–0.9 pu
3.3 Overvoltages		> 1 min	1.1–1.2 pu
4.0 Voltage imbalance		steady state	0.5–2%
5.0 Waveform distortion			
5.1 DC offset		steady state	0–0.1%
5.2 Harmonics	0–100th H	steady state	0–20%
5.3 Interharmonics	0–6 kHz	steady state	0–2%
5.4 Notching		steady state	
5.5 Noise	broad-band	steady state	0–1%
6.0 Voltage fluctuations	< 25 Hz	intermittent	0.1–7%
7.0 Power frequency variations		< 10 s	

4.4.1.1 Impulsive transient

An *impulsive transient* is a sudden, nonpower frequency change in the steady-state condition of voltage, current, or both, that is unidirectional in polarity (primarily either positive or negative).

Impulsive transients are normally characterized by their rise and decay times. These phenomena can also be described by their spectral content. For example, a 1.2/50 μs 2000 V impulsive transient rises to its peak value of 2000 V in 1.2 μs, and then decays to half its peak value in 50 μs [B14].

The most common cause of impulsive transients is lightning. Figure 1 illustrates a typical current impulsive transient caused by lightning.

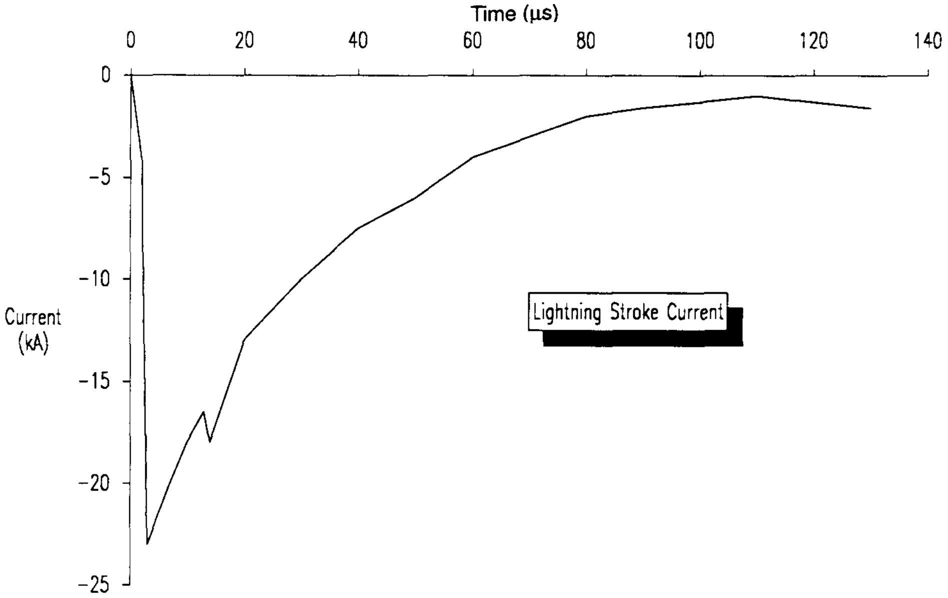


Figure 1—Lightning stroke current that can result in impulsive transients on the power system

Due to the high frequencies involved, impulsive transients are damped quickly by resistive circuit components and are not conducted far from their source. There can be significant differences in the transient characteristic from one location within a building to another. Impulsive transients can excite power system resonance circuits and produce the following type of disturbance—oscillatory transients.

4.4.1.2 Oscillatory transient

An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly. It is described by its spectral content (predominant frequency), duration, and magnitude. The spectral content subclasses defined in table 2 are high, medium, and low frequency. The frequency ranges for these classifications are chosen to coincide with common types of power system oscillatory transient phenomena.

As with impulsive transients, oscillatory transients can be measured with or without the fundamental frequency component included. When characterizing the transient, it is important to indicate the magnitude with and without the fundamental component.

Oscillatory transients with a primary frequency component greater than 500 kHz and a typical duration measured in microseconds (or several cycles of the principal frequency) are considered *high-frequency oscillatory transients*. These transients are almost always due to some type of switching event. High-frequency oscillatory transients are often the result of a local system response to an impulsive transient.

Power electronic devices produce oscillatory voltage transients as a result of commutation and RLC snubber circuits. The transients can be in the high kilohertz range, last a few cycles of their fundamental frequency, and have repetition rates of several times per 60 Hz cycle (depending on the pulse number of the device) and magnitudes of 0.1 pu (less the 60 Hz component).

A transient with a primary frequency component between 5 and 500 kHz with duration measured in the tens of microseconds (or several cycles of the principal frequency) is termed a *medium-frequency transient.*

Back-to-back capacitor energization results in oscillatory transient currents in the tens of kilohertz. This phenomenon occurs when a capacitor bank is energized in close electrical proximity to a capacitor bank already in service. The energized bank sees the de-energized bank as a low impedance path (limited only by the inductance of the bus to which the banks are connected, typically small). Figure 2 illustrates the resulting current transient due to back-to-back capacitor switching. Cable switching results in oscillatory voltage transients in the same frequency range. Medium-frequency transients can also be the result of a system response to an impulsive transient.

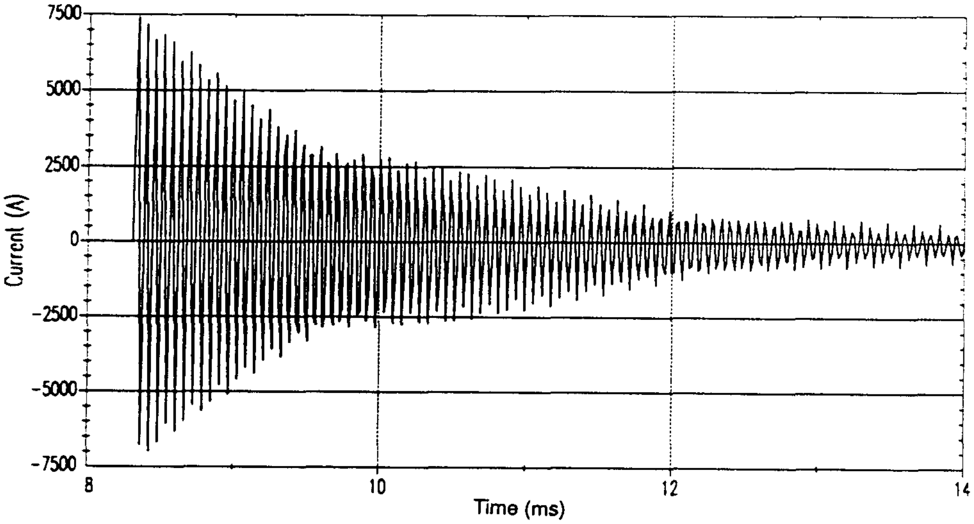


Figure 2—Oscillatory transient caused by back-to-back capacitor switching

A transient with a primary frequency component less than 5 kHz, and a duration from 0.3 to 50 ms, is considered a *low-frequency transient.*

This category of phenomena is frequently encountered on subtransmission and distribution systems and is caused by many types of events, primarily capacitor bank energization. The resulting voltage waveshape is very familiar to power system engineers and can be readily classified using the attributes discussed so far. Capacitor bank energization typically results in an oscillatory voltage transient with a primary frequency between 300 and 900 Hz. The transient has a peak magnitude that can approach 2.0 pu, but is typically 1.3–1.5 pu lasting between 0.5 and 3 cycles, depending on the system damping (see figure 3).

Oscillatory transients with principal frequencies less than 300 Hz can also be found on the distribution system. These are generally associated with ferroresonance and transformer energization (see figure 4). Transients involving series capacitors could also fall into this category. They occur when the system resonance results in magnification of low-frequency components in the transformer inrush current (second, third harmonic) or when unusual conditions result in ferroresonance.

IEEE Std C62.41-1991 [B14] describes surge waveforms deemed to represent the environment in which electrical equipment and surge protective devices will be expected to operate. Reference [B14] covers the origin of surge (transient) voltages, rate of occurrence and voltage levels in unprotected circuits, waveshapes of representative surge voltages, energy, and source impedance.

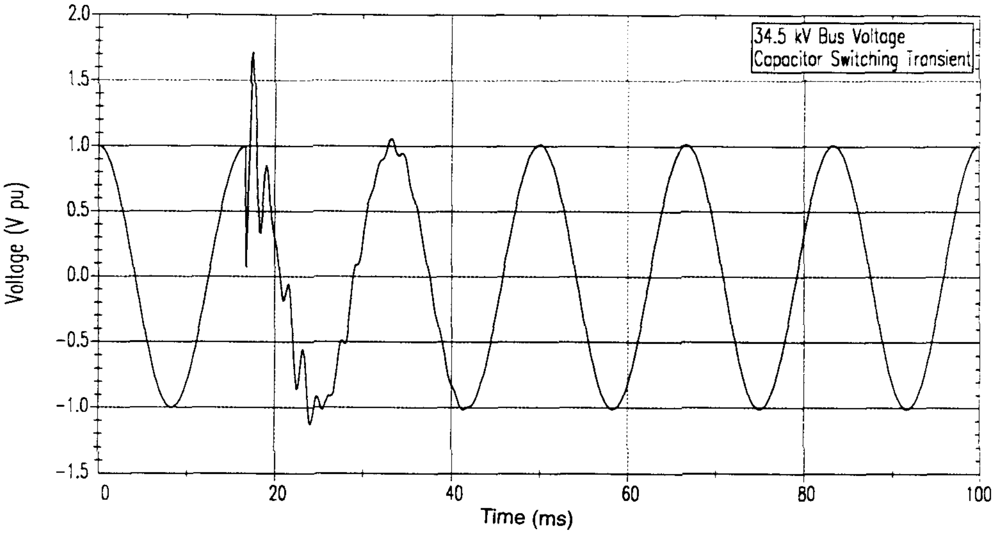


Figure 3—Low frequency oscillatory transient caused by capacitor-bank energization

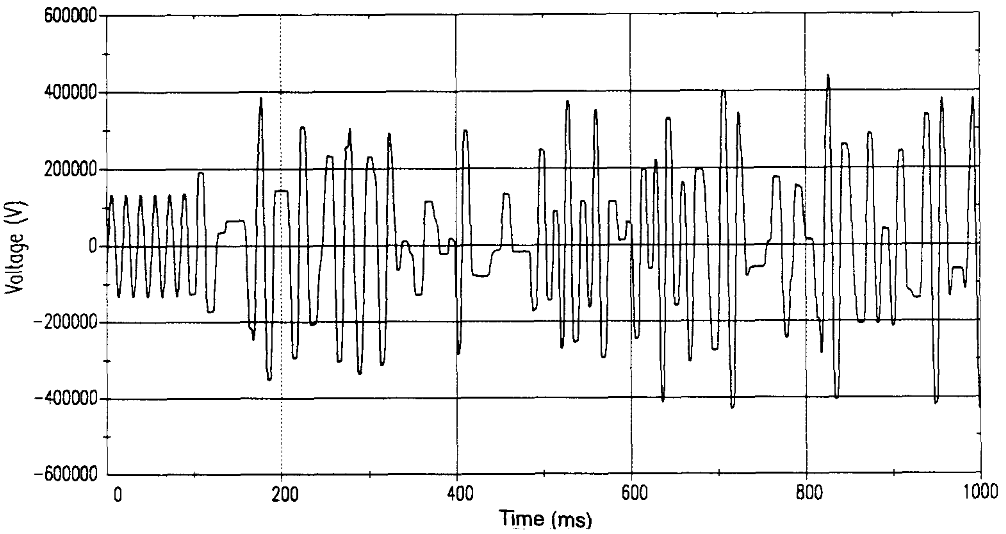


Figure 4—Low-frequency oscillatory transient caused by ferroresonance of an unloaded transformer

4.4.2 Short-duration variations

This category encompasses the IEC category of voltage dips and short interruptions as well as the antithesis of dip or *swell.* Each type of variation can be designated as *instantaneous, momentary,* or *temporary,* depending on its duration as defined in table 2.

Short-duration voltage variations are almost always caused by fault conditions, the energization of large loads that require high starting currents, or intermittent loose connections in power wiring. Depending on the fault location and the system conditions, the fault can cause either temporary voltage rises (swells) or voltage drops (sags), or a complete loss of voltage (interruptions). The fault condition can be close to or remote from the point of interest. In either case, the impact on the voltage during the actual fault condition is a short duration variation. Changes in current which fall into the duration and magnitude categories are also included in short-duration variations.

4.4.2.1 Interruption

An *interruption* occurs when the supply voltage or load current decreases to less than 0.1 pu for a period of time not exceeding 1 min.

Interruptions can be the result of power system faults, equipment failures, and control malfunctions. The interruptions are measured by their duration since the voltage magnitude is always less than 10% of nominal. The duration of an interruption due to a fault on the utility system is determined by utility protective devices and the particular event that is causing the fault. The duration of an interruption due to equipment malfunctions or loose connections can be irregular.

Some interruptions may be preceded by a voltage sag when these interruptions are due to faults on the source system. The voltage sag occurs between the time a fault initiates and the protective device operates. On the faulted feeder, loads will experience a voltage sag followed immediately by an interruption. The duration of the interruption will depend on the reclosing capability of the protective device. Instantaneous reclosing generally will limit the interruption caused by a non-permanent fault to less than 30 cycles. Delayed reclosing of the protective device may cause a momentary or temporary interruption.

Figure 5 shows a momentary interruption during which voltage drops for about 2.3 s. Note from the waveshape plot of this event that the instantaneous voltage may not drop to zero immediately upon interruption of the source voltage. This residual voltage is due to the back-emf effect of induction motors on the interrupted circuit.

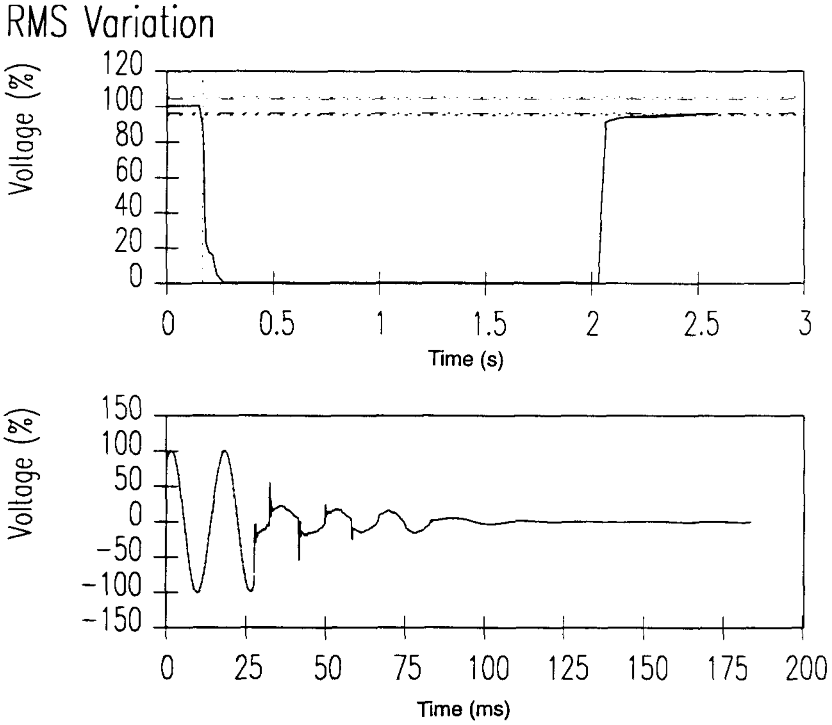


Figure 5—Momentary interruption due to a fault and subsequent recloser operation

4.4.2.2 Sags (dips)

Terminology used to describe the magnitude of a voltage sag is often confusing. The recommended usage is "a sag to 20%," which means that the line voltage is reduced down to 20% of the normal value, not reduced by 20%. Using the preposition "of" (as in "a sag of 20%," or implied in "a 20% sag") is deprecated. This preference is consistent with IEC practice, and with most disturbance analyzers that also report remaining voltage. Just as an unspecified voltage designation is accepted to mean line-to-line potential, so an unspecified sag magnitude will refer to the remaining voltage. Where possible, the nominal or base voltage and the remaining voltage should be specified.

Voltage sags are usually associated with system faults but can also be caused by switching of heavy loads or starting of large motors. Figure 6 shows a typical voltage sag that can be associated with a single line-to-ground (SLG) fault. Also, a fault on a parallel feeder circuit will result in a voltage drop at the substation bus that affects all of the other feeders until the fault is cleared. Typical fault clearing times range from 3 to 30 cycles, depending on the fault current magnitude and the type of overcurrent detection and interruption.

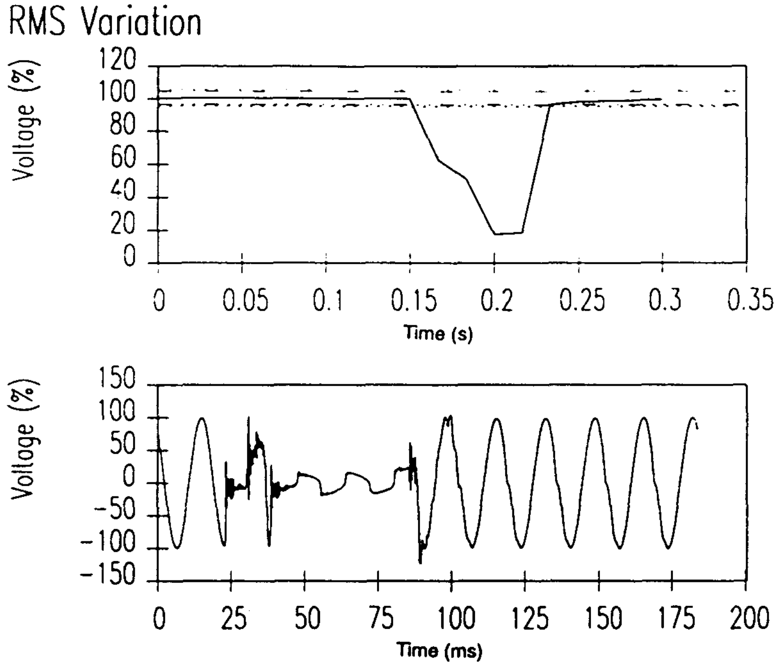


Figure 6—Instantaneous voltage sag caused by a SLG fault

Voltage sags can also be caused by large load changes or motor starting. An induction motor will draw six to ten times its full load current during starting. This lagging current causes a voltage drop across the impedance of the system. If the current magnitude is large relative to the system available fault current, the resulting voltage sag can be significant. Figure 7 illustrates the effect of a large motor starting.

The term *sag* has been used in the power quality community for many years to describe a specific type of power quality disturbance—a short duration voltage decrease. Clearly, the notion is directly borrowed from the literal definition of the word sag. The IEC definition for this phenomenon is *dip*. The two terms are considered interchangeable, with *sag* being preferred in the US power quality community.

Previously, the duration of sag events has not been clearly defined. Typical sag duration defined in some publications ranges from 2 ms (about 1/8 of a cycle) to a couple of minutes. Undervoltages that last less than 1/2 cycle cannot be characterized effectively as a change in the rms value of the fundamental frequency value. Therefore, these events are considered transients; see IEC 1000-2-1 (1990). Undervoltages that last longer than 1 min can typically be controlled by voltage regulation equipment and may be associated with a wide variety of causes other than system faults. Therefore, these are classified as long duration variations in 4.4.3.

Sag durations are subdivided here into three categories—instantaneous, momentary, and temporary—which coincide with the three categories of interruptions and swells. These durations are intended to correlate with typical protective device operation times as well as duration divisions recommended by international technical organizations [B15].

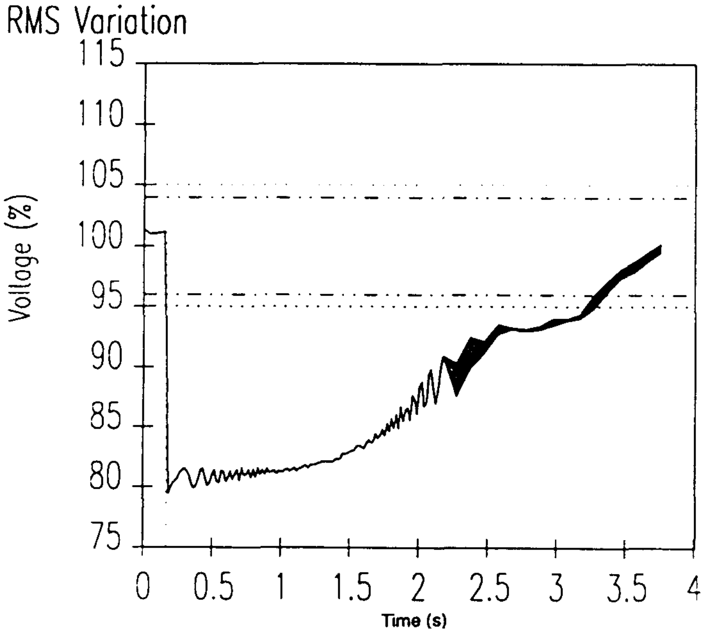


Figure 7—Temporary voltage sag caused by motor starting

4.4.2.3 Swells

A *swell* is defined as an increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. Typical magnitudes are between 1.1 and 1.8 pu. Swell magnitude is also is also described by its remaining voltage, in this case, always greater than 1.0.

As with sags, swells are usually associated with system fault conditions, but they are much less common than voltage sags. A swell can occur due to a single line-to-ground fault on the system resulting in a temporary voltage rise on the unfaulted phases. Swells can also be caused by switching off a large load or switching on a large capacitor bank. Figure 8 illustrates a voltage swell caused by a SLG fault.

Swells are characterized by their magnitude (rms value) and duration. The severity of a voltage swell during a fault condition is a function of the fault location, system impedance, and grounding. On an ungrounded system, the line-to-ground voltages on the ungrounded phases will be 1.73 pu during a line-to-ground fault condition. Close to the substation on a grounded system, there will be no voltage rise on the unfaulted phases because the substation transformer is usually connected delta-wye, providing a low impedance zero-sequence path for the fault current.

In some publications, the term *momentary overvoltage* is used as a synonym for the term *swell.* A formal definition of swell in IEEE Std C62.41-1991 is “A momentary increase in the power-frequency voltage delivered by the mains, outside of the normal tolerances, with a duration of more than one cycle and less than a few seconds [B14].” This definition is not preferred by the power quality community.

4.4.3 Long duration variations

Long duration variations encompass rms deviations at power frequencies for longer than 1 min. The steady-state voltage tolerances expected on a power system are specified in [B1] . These magnitudes are reflected in table 2. Long duration variations are considered to be present when the ANSI limits are exceeded for greater than 1 min.

Long duration variations can be either *overvoltages* or *undervoltages,* depending on the cause of the variation. Overvoltages and undervoltages generally are not the result of system faults. They are caused by load variations on the system and system switching operations. These variations are characterized by plots of rms voltage versus time.

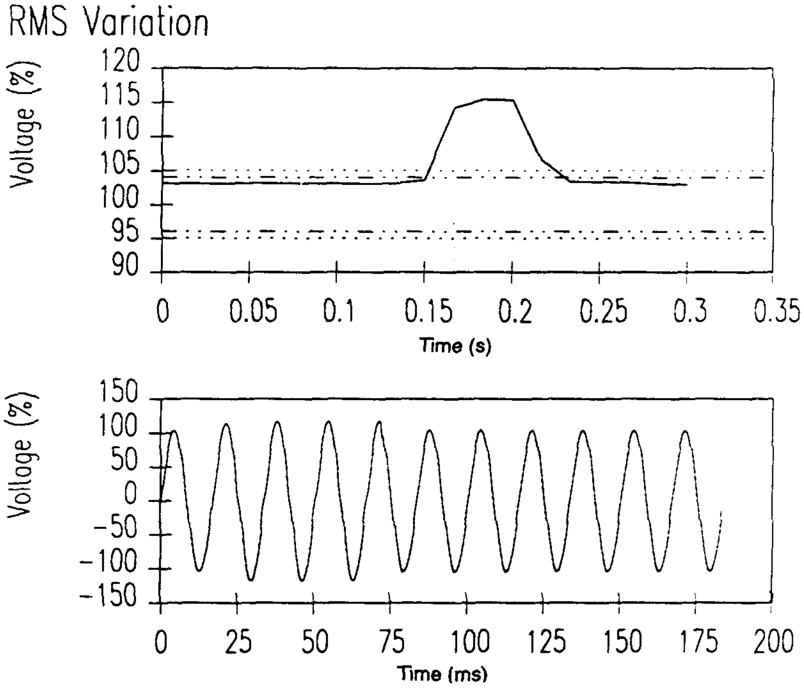


Figure 8—Instantaneous voltage swell caused by a SLG fault

4.4.3.1 Overvoltage

Overvoltages can be the result of load switching (e.g., switching off a large load), or variations in the reactive compensation on the system (e.g., switching on a capacitor bank). Poor system voltage regulation capabilities or controls result in overvoltages. Incorrect tap settings on transformers can also result in system overvoltages.

4.4.3.2 Undervoltage

Undervoltages are the result of the events that are the reverse of the events that cause overvoltages. A load switching on, or a capacitor bank switching off, can cause an undervoltage until voltage regulation equipment on the system can bring the voltage back to within tolerances. Overloaded circuits can result in undervoltages also.

The term *brownout* is sometimes used to describe sustained periods of low power-frequency voltage initiated as a specific dispatch strategy to reduce power delivery. The type of disturbance described by brownout is basically the same as that described by the term undervoltage defined here. Because there is no formal definition for the term brownout, and because the term is not as clear as the term undervoltage when trying to characterize a disturbance, the term brownout should be avoided in future power quality activities in order to avoid confusion.

4.4.3.3 Sustained interruptions

The decrease to zero of the supply voltage for a period of time in excess of 1 min is considered a *sustained interruption*. Voltage interruptions longer than 1 min are often permanent in nature and require manual intervention for restoration. Sustained interruptions are a specific power system phenomena and have no relation to the usage of the term *outage*. Outage, as defined in IEEE Std 100-1992, does not refer to a specific phenomenon, but rather to the state of a component in a system that has failed to function as expected. Also, use of the term *interruption* in the context of power quality monitoring has no relation to reliability or other continuity of service statistics.

4.4.4 Voltage imbalance

Voltage imbalance (or unbalance) is defined as the ratio of the negative or zero sequence component to the positive sequence component. The negative or zero sequence voltages in a power system generally result from unbalanced loads causing negative or zero sequence currents to flow. Figure 9 shows an example of a one-week trend of imbalance measured at one point on a residential feeder.

Imbalance can be estimated as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents, expressed in percent. In equation form

voltage imbalance = 100 × (max deviation from average voltage)/average voltage [B11]

For example, with phase-to-phase voltage readings of 230, 232, and 225, the average is 229. The maximum deviation from the average among the three readings is 4. The percent imbalance is 100 × 4/229 = 1.7%.

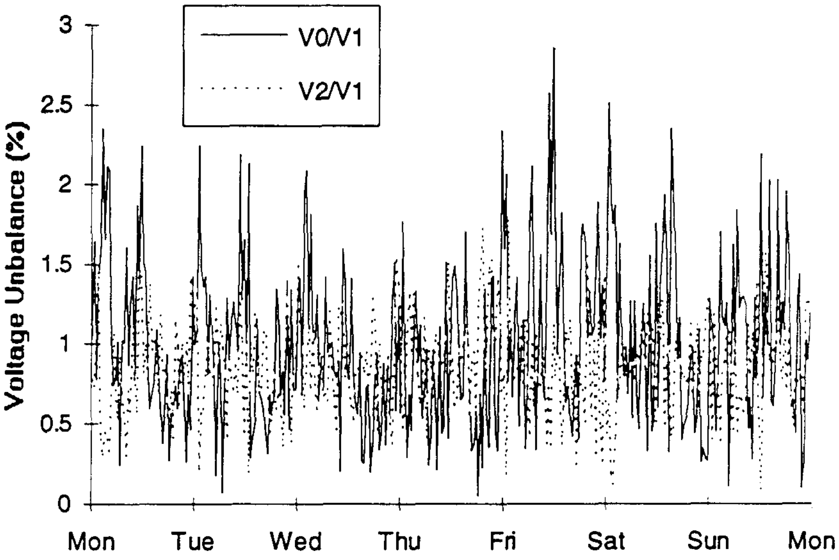


Figure 9—Imbalance trend for a residential feeder

The primary source of voltage imbalance less than 2% is unbalanced single phase loads on a three-phase circuit. Voltage imbalance can also be the result of capacitor bank anomalies, such as a blown fuse on one phase of a three-phase bank. Severe voltage imbalance (greater than 5%) can result from single-phasing conditions.

4.4.5 Waveform distortion

Waveform distortion is a steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.

There are five primary types of waveform distortion as follows:

a) DC offset
b) Harmonics
c) Interharmonics
d) Notching
e) Noise

Each of these will be discussed separately.

4.4.5.1 DC offset

The presence of a dc voltage or current in an ac power system is termed dc offset. This phenomenon can occur as the result of a geomagnetic disturbance or due to the effect of half-wave rectification. Incandescent light bulb life extenders, for example, may consist of diodes that reduce the rms voltage supplied to the light bulb by half-wave rectification. Direct current in alternating current networks can be detrimental due to an increase in transformer saturation, additional stressing of insulation, and other adverse effects.

4.4.5.2 Harmonics

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate (termed the fundamental frequency; usually 50 Hz or 60 Hz) [see IEC 1000-2-1 (1990)]. Harmonics combine with the fundamental voltage or current, and produce waveform distortion. Harmonic distortion exists due to the nonlinear characteristics of devices and loads on the power system.

These devices can usually be modeled as current sources that inject harmonic currents into the power system. Voltage distortion results as these currents cause nonlinear voltage drops across the system impedance. Harmonic distortion is a growing concern for many customers and for the overall power system due to increasing application of power electronics equipment.

Harmonic distortion levels can be characterized by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. It is also common to use a single quantity, the *total harmonic distortion,* as a measure of the magnitude of harmonic distortion.

Harmonic currents result from the normal operation of nonlinear devices on the power system. Figure 10 illustrates the waveform and harmonic spectrum for a typical adjustable speed drive input current. Current distortion levels can be characterized by a total harmonic distortion, as described above, but this can often be misleading. For instance, many adjustable speed drives will exhibit high total harmonic distortion values for the input current when they are operating at very light loads. This is not a significant concern because the magnitude of harmonic current is low, even though its relative distortion is high.

To handle this concern for characterizing harmonic currents in a consistent fashion, IEEE Std 519-1992 [B13] defines another term, the *total demand distortion*. This term is the same as the total harmonic distortion except that the distortion is expressed as a percent of some rated load current rather than as a percent of the fundamental current magnitude. Guidelines for harmonic current and voltage distortion levels on distribution and transmission circuits are provided in [B13].

4.4.5.3 Interharmonics

Interharmonics can be found in networks of all voltage classes. They can appear as discrete frequencies or as a wide-band spectrum. The main sources of interharmonic waveform distortion are static frequency converters, cyclo-converters, induction motors, and arcing devices. Power-line carrier signals can also be considered as *interharmonics*.

The effects of interharmonics are not well known, but have been shown to affect power line carrier signaling, and induce visual flicker in display devices such as CRTs. IEC 1000-2-1 (1990) places background noise phenomenon in the interharmonic category. This recommended practice discusses noise separately as a distinct electromagnetic phenomenon later in this subclause.

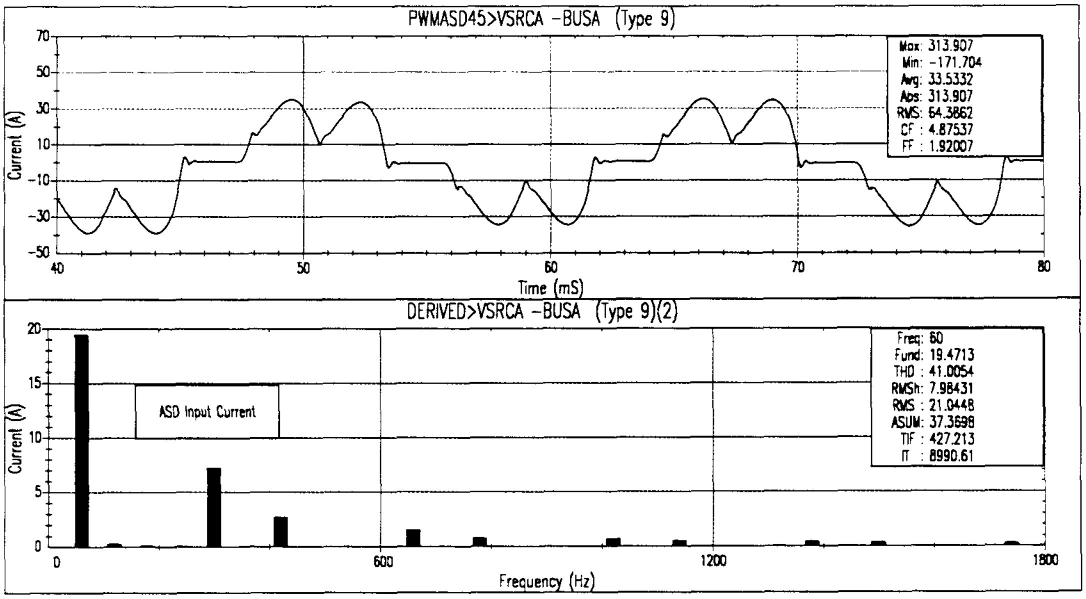


Figure 10—Current waveform and harmonic spectrum for an ASD input current

4.4.5.4 Notching

Notching is a periodic voltage disturbance caused by the normal operation of power electronics devices when current is commutated from one phase to another.

Voltage notching represents a special case that falls between transients and harmonic distortion. Since notching occurs continuously (steady state), it can be characterized through the harmonic spectrum of the affected voltage. However, the frequency components associated with notching can be quite high and may not be readily characterized with measurement equipment normally used for harmonic analysis.

Three-phase converters that produce continuous dc current are the most important cause of voltage notching (see figure 11). The notches occur when the current commutates from one phase to another. During this period, there is a momentary short circuit between two phases. The severity of the notch at any point in the system is determined by the source inductance and the isolating inductance between the converter and the point being monitored. Notching is described in detail in IEEE Std 519-1992 [B13].

4.4.5.5 Noise

Noise is unwanted electrical signals with broadband spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines. Noise in power systems can be caused by power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supplies. Noise problems are often exacerbated by improper grounding. Basically, noise consists of any unwanted distortion of the power signal that cannot be classified as harmonic distortion or transients.

The frequency range and magnitude level of noise depend on the source, which produces the noise and the system characteristics. A typical magnitude of noise is less than 1% of the voltage magnitude. Noise disturbs electronic devices such as microcomputer and programmable controllers. The problem can be mitigated by using filters, isolation transformers, and some line conditioners.

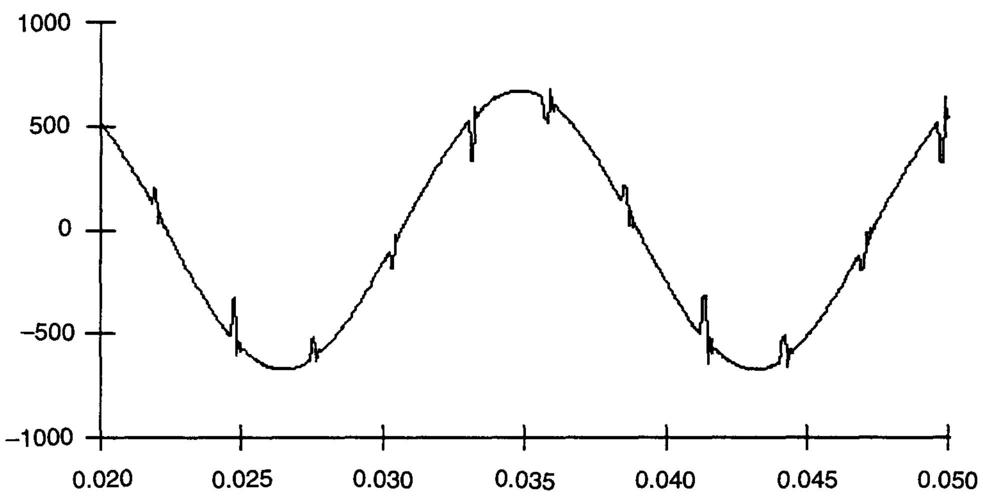


Figure 11—Example of voltage notching caused by converter operation

4.4.6 Voltage fluctuations

Voltage fluctuations are systematic variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed the voltage ranges specified by [B1] of 0.95–1.05 pu.

IEC 555-3, which has been revised as IEC 1000-3-3 (1994) (see [B8]) defines various types of voltage fluctuations. The reader is referred to this document for a detailed breakdown of these types. The remainder of this discussion on voltage fluctuations will concentrate on the IEC 1000-3-3 (1994) Type (d) voltage fluctuations. This type is characterized as a series of random or continuous voltage fluctuations.

Any load that has significant current variations, especially in the reactive component, can cause voltage fluctuations. Loads that exhibit continuous, rapid variations in load current magnitude can cause voltage variations erroneously referred to as *flicker*. The term *flicker* is derived from the impact of the voltage fluctuation on lighting intensity. Voltage fluctuation is the response of the power system to the varying load and light flicker is the response of the lighting system as observed by the human eye. The power system, the lighting system, and the human response are all variables. Even though there is a clear distinction between these terms—cause and effect—they are often confused to the point that the term "voltage flicker" is used in some documents. Such incorrect usage should be avoided.

Arc furnaces are the most common cause of voltage fluctuations on the transmission and distribution system. Voltage fluctuations are defined by their rms magnitude expressed as a percent of the fundamental. Lighting flicker is measured with respect to the sensitivity of the human eye. An example of a voltage waveform that produces flicker is shown in figure 12.

Voltage fluctuations generally appear as a modulation of the fundamental frequency (similar to amplitude modulation of an am radio signal). Therefore, it is easiest to define a magnitude for the voltage fluctuation as the rms magnitude of the modulation signal. This can be obtained by demodulating the waveform to remove the fundamental frequency and then measuring the magnitude of the modulation components. Typically, magnitudes as low as 0.5% can result in perceptible light flicker if the frequencies are in the range of 6–8 Hz.

4.4.7 Power frequency variations

The power system frequency is directly related to the rotational speed of the generators on the system. At any instant, the frequency depends on the balance between the load and the capacity of the available genera-

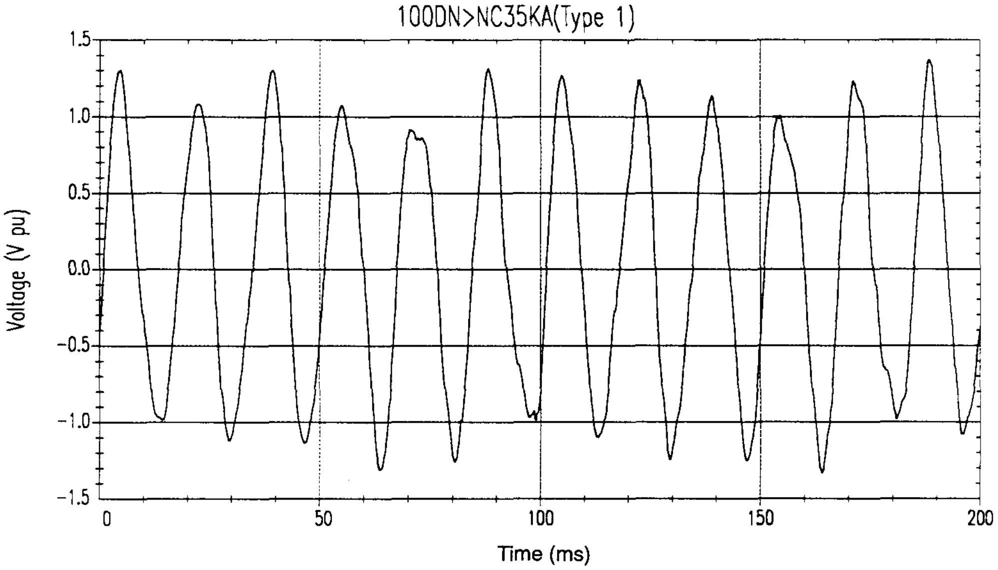


Figure 12—Example of voltage fluctuations caused by arc furnace operation

tion. When this dynamic balance changes, small changes in frequency occur. The size of the frequency shift and its duration depends on the load characteristics and the response of the generation system to load changes.

Frequency variations that go outside of accepted limits for normal steady-state operation of the power system are normally caused by faults on the bulk power transmission system, a large block of load being disconnected, or a large source of generation going off-line.

Frequency variations that affect the operation of rotating machinery, or processes that derive their timing from the power frequency (clocks), are rare on modern interconnected power systems. Frequency variations of consequence are much more likely to occur when such equipment is powered by a generator isolated from the utility system. In such cases, governor response to abrupt load changes may not be adequate to regulate within the narrow bandwidth required by frequency sensitive equipment.

NOTE—Voltage notching can sometimes cause frequency or timing errors on power electronic machines that count zero crossings to derive frequency or time. The voltage notch may produce additional zero crossings that can cause frequency or timing errors.

5. Monitoring objectives

5.1 Introduction

Power quality monitoring is necessary to characterize electromagnetic phenomena at a particular location on an electric power circuit. In some cases, the objective of the monitoring is to diagnose incompatibilities between the electric power source and the load. In others, it is to evaluate the electrical environment at a particular location to refine modeling techniques or to develop a power quality baseline. In still others, monitoring may be used to predict future performance of load equipment or power quality mitigating devices. In any event, the most important task in any monitoring project is to define clearly the objectives of monitoring.

The objectives of monitoring for a particular project will determine the choice of monitoring equipment, the method of collecting data, the triggering thresholds needed, the data analysis technique to employ, and the overall level of effort required of the project. The objective may be as simple as verifying steady-state voltage regulation at a service entrance, or may be as complex as analyzing the harmonic current flows within a distribution network. The resulting data need only meet the objectives of the monitoring task in order for the monitoring to be successful.

The procedure for defining monitoring objectives differs by the type of study. For diagnostic monitoring to solve shutdown problems with sensitive equipment, the objective may be to capture out-of-tolerance events of certain types. Evaluative or predictive monitoring may require collection of several voltage and current parameters in order to characterize the existing level of power quality.

Measurement of electromagnetic phenomena includes both time and frequency domain conducted parameters, which may take the form of overvoltages and undervoltages, interruptions, sags and swells, transients, phase imbalance, frequency aberrations, and harmonic distortion. Non-conducted environmental factors can also have an effect on load equipment, although these types of disturbances are not considered in this document. Such factors include temperature, humidity, electromagnetic interference (EMI), and radio frequency interference (RFI).

5.2 Need for monitoring power quality

There are several important reasons to monitor power quality. The primary reason underpinning all others is economic, particularly if critical process loads are being adversely affected by electromagnetic phenomena. Effects on equipment and process operations can include misoperation, damage, process disruption, and other such anomalies. Such disruptions are costly since a profit-based operation is interrupted unexpectedly and must be restored to continue production. In addition, equipment damage and subsequent repair cost both money and time. Product damage can also result from electromagnetic phenomena requiring that the damaged product either be recycled or discarded, both of which are economic issues.

In addition to resolving equipment disruptions, a database of equipment tolerances and sensitivity can be developed from monitored data. Such a database can provide a basis for developing equipment compatibility specifications and guidelines for future equipment enhancements. In addition, a database of the causes for recorded disturbances can be used to make system improvements. Finally, equipment compatibility problems can create safety hazards resulting from equipment misoperation or failure.

Problems related to equipment misoperation can only be assessed if customer disturbance reports are kept. These logs describe the event inside the facility, the type of equipment that was affected, how it was affected, the weather conditions, and the losses incurred. A sample disturbance report is shown in figure 13.

5.3 Equipment tolerances and effects of disturbances on equipment

The tolerance of various equipment needs to be considered in power quality monitoring. A specific type of equipment, such as an ASD, may be sensitive to an overvoltage or undervoltage condition, for example, while there may also be a significant variation to the same phenomena between ASDs built by other manufacturers. Power quality monitoring should attempt to characterize individual process equipment by matching monitoring results with reported equipment problems. This characterization of individual loads will show which equipment needs protection, and the level of protection required.

5.4 Equipment types

Although there may be a wide variety in the response of specific equipment types manufactured by different companies, there may be some similarity in the response of certain types of equipment to specific disturbance parameters. In any case, it is useful to consider certain specific equipment types or groupings in terms of their immunity to power quality disturbances.

Date of disturbance:_______________ Time of disturbance:_______________

Company:____

Address:____

Contact name:______________________________

Phone number:__________________ FAX number:__________________

Description of disturbance:____

____

Equipment affected:

Equipment type	Manufacturer	Equipment rating

Figure 13—Sample customer disturbance recording form

5.5 Effect on equipment by phenomena type

Clause 4 defines seven major categories of electromagnetic phenomena. The following subclauses describe the observed effects of these phenomena on the operation of various types of equipment.

5.5.1 Transients

Transient voltages caused by lightning or switching operations can result in degradation or immediate dielectric failure in all classes of equipment. High magnitude and fast rise time contribute to insulation breakdown in electrical equipment like rotating machinery, transformers, capacitors, cables, CTs, PTs, and switchgear. Repeated lower magnitude application of transients to these equipment type cause slow degradation and eventual insulation failure, decreasing equipment mean time between failure (MTBF). In electronic equipment, power supply component failures can result from a single transient of relatively modest magnitude. Transients can also cause nuisance tripping of adjustable speed drives due to the dc link overvoltage protection circuitry.

5.5.2 Short duration variations

The most prevalent problem associated with interruptions, sags, and swells is equipment shutdown. In many industries with critical process loads, even instantaneous short duration phenomena can cause process shutdowns requiring hours to restart. In these facilities, the effect on the process is the same for a short duration variation as for long duration phenomena.

Monitoring is important because it is often difficult to determine from the observable effects on customer equipment which electromagnetic phenomena caused the disruption. Further, solution alternatives are much different if the equipment is being affected by sags, for instance, rather than by interruptions.

5.5.2.1 Interruptions

Even instantaneous interruptions may affect electronic and lighting equipment causing misoperation or shutdown. Electronic equipment includes power and electronic controllers, computers, and the electronic controls for rotating machinery. Momentary and temporary interruptions will almost always cause equipment to stop operating, and may cause drop-out of induction motor contactors. In some cases, interruptions may damage electronic soft-start equipment.

5.5.2.2 Sags

Short duration sags, in particular, cause numerous process disruptions. Often, the sag is sensed by electronic process controllers equipped with fault-detection circuitry, which initiates shutdown of other, less-sensitive loads. A common solution to this problem is to serve the electronic controller with a constant-voltage transformer, or other mitigating device, to provide adequate voltage to the controller during a sag. The application challenge is to maintain the electronic controller during sags that will not damage process equipment protected by the fault circuitry, while simultaneously reducing nuisance shutdowns.

Electronic devices with battery backup should be unaffected by short duration reductions in voltage. Equipment such as transformers, cable, bus, switchgear, CTs and PTs should not incur damage or malfunction due to short duration sags. A slight speed change of induction machinery and a slight reduction in output from a capacitor bank can occur during a sag. The visible light output of some lighting devices may be reduced briefly during a sag.

5.5.2.3 Swells

An increase in voltage applied to equipment above its nominal rating may cause failure of the components depending upon the frequency of occurrence. Electronic devices, including adjustable speed drives, computers, and electronic controllers, may show immediate failure modes during these conditions. However, transformers, cable, bus, switchgear, CTs, PTs, and rotating machinery may suffer reduced equipment life over time. A temporary increase in voltage on some protective relays may result in unwanted operations while others will not be affected. Frequent voltage swells on a capacitor bank can cause the individual cans to bulge while output is increased from the bank. The visible light output from some lighting devices may be increased during a temporary swell. Clamping type surge protective devices (e.g., varistors or silicon avalanche diodes) may be destroyed by swells exceeding their MCOV rating.

5.5.3 Long duration variations

Variations in supply voltage lasting longer than 1 min can cause equipment problems. Overvoltage and undervoltage problems are less likely to occur on utility feeders, as most utilities strive to maintain ±5% voltage regulation. Overvoltage and undervoltage problems can occur, however, due to overloaded feeders, incorrect tap settings on transformers, blown fuses on capacitor banks, and capacitor banks in service during light load conditions. Sustained interruptions can result from a variety of causes, including tripped breakers, blown fuses, utility feeder lockouts, and failed circuit components.

5.5.3.1 Sustained interruptions

The effect of a sustained interruption is equipment shutdown, except for those loads protected by UPS systems, or other forms of energy storage devices.

5.5.3.2 Undervoltages

Undervoltages in excess of 1 min can also cause equipment to malfunction. Motor controllers can drop out during undervoltage conditions. The dropout voltage of motor controllers is typically 70–80% of nominal voltage. Long duration undervoltages cause an increased heating loss in induction motors due to increased motor current. Speed changes are possible for induction machinery during undervoltage conditions. Electronic devices such as computers and electronic controllers may stop operating during this condition. Undervoltage conditions on capacitor banks result in a reduction of output of the bank, since var output is proportional to the square of the applied voltage. Generally, undervoltage conditions on transformers, cable, bus, switchgear, CTs, PTs, metering devices, and transducers do not cause problems for the equipment. The visible light output from some lighting devices may be reduced during undervoltage conditions.

5.5.3.3 Overvoltages

Overvoltages may cause equipment failure. Electronic devices may experience immediate failure during the overvoltage conditions; however, transformers, cable, bus, switchgear, CTs, PTs, and rotating machinery do not generally show immediate failure. Sustained overvoltage on transformers, cable, bus, switchgear, CTs, PTs and rotating machinery can result in loss of equipment life. An overvoltage condition on some protective relays may result in unwanted operations while others will not be affected. A sign of frequent overvoltage conditions on a capacitor bank is the bulge of individual cans. The var output of a capacitor will increase with the square of the voltage during an overvoltage condition. The visible light output from some lighting devices may be increased during overvoltage conditions.

5.5.4 Voltage imbalance

In general, utility supply voltage is maintained at a relatively low level of phase imbalance since even a low level of imbalance can cause a significant power supply ripple and heating effects on the generation, transmission, and distribution system equipment. Voltage imbalance more commonly emerges in individual customer loads due to phase load imbalances, especially where large, single-phase power loads are used, such as single-phase arc furnaces. In these cases, overheating of customer motors and transformers can readily occur if the imbalance is not corrected. Phase current imbalance to three-phase induction motors varies almost as the cube of the voltage imbalance applied to the motor terminals. A 3 1/2% voltage imbalance, therefore, results in 25% added heating in both U-frame and T-frame motors (see 3.8 in [B11]). The effects on other types of equipment are much less pronounced, although significant imbalance can cause loading problems on current-carrying equipment such as bus ducts. Desirable levels of imbalance are less than 1% at all voltage levels to reduce possible heating effects to low levels.

Utility supply voltages are typically maintained at less than 1%, although 2% is not uncommon. Voltage imbalance of greater than 2% should be reduced, where possible, by balancing single-phase loads as phase current imbalance is usually the cause. Voltage imbalance greater than 2% may indicate a blown fuse on one phase of a three-phase capacitor bank. Voltage imbalance greater than 5% can be caused by single-phasing conditions, during which one phase of a three-phase circuit is missing or de-energized. Phase monitors are often required to protect three-phase motors from the adverse affects of single phasing.

5.5.5 Waveform distortion

Harmonic current injection from customer loads into the utility supply system can cause harmonic voltage distortion to appear on the utility system supply voltage. This harmonic current and voltage distortion can cause overheating of rotating equipment, transformers, and current-carrying conductors, premature failure or operation of protective devices (such as fuses), harmonic resonance conditions on the customer's electric power system, which can further deteriorate electrical system operation, and metering inaccuracies. Harmonic voltage distortion on a utility system can cause the same problems to a customer's equipment and can cause overheating of utility transformers, power-carrying conductors, and other power equipment. [B13] outlines typical harmonic current limits for customers and harmonic voltage limits for utility supply voltage that customers and utilities in general should attempt to operate within in order to minimize the effects of harmonic distortion on the supply and end-user systems.

5.5.6 Voltage fluctuations

Fluctuations in the supply voltage are most often manifested in nuisance variations in light output from incandescent and discharge lighting sources. A sudden voltage decrease of less than 1/2% can cause a noticeable reduction in light output of an incandescent lamp and a less noticeable reduction in light output of gaseous discharge lighting equipment. Voltage fluctuations less than 7% in magnitude have little effect on other types of customer loads [B11].

5.5.7 Power-frequency variations

In general, utilities maintain very close control of the power system frequency. Slight variations in frequency on an electric system can cause severe damage to generator and turbine shafts due to the subsequent large torques developed. In addition, cascading system separations can result with even slight deviations in frequency since electric systems are closely connected and operate in synchronism. Frequency variations are more common on customer-owned generation equipment systems. Generator over-speed can result in a frequency increase on small systems operating independent of utility sources.

Frequency synchronization errors can sometimes occur on a customer feeder that serves large rectifier loads. These loads can cause voltage notching severe enough to register extra zero crossing events on electronic loads that count zero crossings of the ac voltage to obtain frequency. While these events are recorded as frequency errors by electronic controllers, the fundamental frequency has not changed.

6. Measurement instruments

6.1 Introduction

Instruments used to monitor electromagnetic phenomena can be as simple as an analog voltmeter to an instrument as sophisticated as a spectrum analyzer. Selecting and using the correct type of monitor requires the user to understand the capabilities and limitations of the instrument, its responses to power system variations, and the specific objectives of the analysis. This clause will focus on the capabilities and limitations of various monitoring equipment.

Instrument features required are dependent on the monitoring location and objectives. If assessing power quality at the service entrance, for example, the emphasis may be only on long-term steady-state conditions and utility-transmitted anomalies. The level of detail required—rms voltage stripcharts or high-speed waveform captures—is indicated by the type of phenomena likely to be causing problems.

6.2 AC voltage measurements

The analog electromechanical voltmeter is the oldest type of voltmeter and is the one that is most familiar. Once the correct scale is selected, voltage is read directly from an analog scale. AC measurements made with this type of instrument require an understanding of the waveform to be measured. The ac scales are calibrated on the basis of a sinusoidal wave form. If the voltage being measured does not have a sinusoidal waveform, the voltage reading is not correct. Internally, the voltage being measured is rectified with either a half-wave or a full-wave bridge, and the resulting average dc voltage is measured. The meter scale is then calibrated with a conversion factor to obtain the correct ac voltage readings.

Another type of ac voltmeter is the digital voltmeter (DVM). These meters are more accurate and are easier to use than their electromechanical counterparts. Two common measurement techniques used in these meters are *average* and *peak-sense*. As with the analog meter discussed above, the averaging meter takes the average of the absolute value of the instantaneous voltages over a cycle, and the peak sense meter detects the highest instantaneous voltage during a cycle. Most digital voltmeters use some form of average conversion for ac measurements as this is the easiest and least expensive measurement technique to implement. Both of these techniques, average and peak-sense, are calibrated for a sinusoidal waveform. An average sense meter is calibrated to display 1.11 times the average voltage, and the peak sense meter is calibrated to display 0.707 times the peak voltage. If the waveform being measured is sinusoidal, these calibration factors will yield ac voltage measurements that will agree with measurements being made with a true rms voltmeter. True rms meters accurately measure the effective heating value of current, distorted or sinusoidal.

6.3 AC current measurements

The measurements of ac currents may be accomplished with the use of an ac probe, a Hall effect probe (also used for dc current measurement), or a shunt resistor. It is important to note that the techniques and limitations discussed above concerning analog and digital voltmeters also apply to the measurement of ac currents in the power system. The ac current probe makes use of transformer action to detect current. This type of probe, also referred to as a current transformer (CT), has a limited bandwidth. Limits at the lower frequencies occur due to saturation of the probe and at higher frequencies due to parasitic inductances and capacitances. Further, the excessive amplitude of the signal may cause saturation. Wide bandwidth transformers are available, which are more than adequate for power quality measurements.

The bandwidth problems encountered with CTs can be eliminated through the use of a Hall effect probe. The Hall effect probe does not use a transformer but senses the magnetic field produced by the electrical current flow using a semiconductor device. The output of the probe is proportional to the current flowing in the wire, which is then read with a meter. The advantage of using this type of probe is that it will accurately measure distorted wave forms without the concerns of limited bandwidth as experienced by the current transformer technique.

The oldest method of measuring current is the shunt resistor. The shunt resistor is a low value precision resistor that is inserted into the circuit to be measured. Current flow produces a voltage drop across the resistor in direct proportion to the shunt resistance. The resulting voltage is then converted into a current value. Using a shunt requires breaking into the circuit, and thus can be difficult to install and use. One major benefit of the shunt is that it does not suffer from the bandwidth limitations that are experienced with the current transformer technique.

6.4 Voltage and current considerations

6.4.1 True-rms readings

When ac voltage or current measurements are to be made on non-sinusoidal or distorted wave forms, a DVM or digital ammeter using true-rms conversion techniques should be used. There are three true-rms conversion techniques in use today. These are best described as thermal, analog, and digital. The thermal true rms conversion is based on the heating of a resistive load with the input signal. The amount of heat generated by this load is directly proportional to the rms value of the signal. A thermocouple is placed adjacent to the load in an evacuated chamber. The dc voltage output of the thermocouple is proportional to the generated heat. The output of the thermocouple is then routed to the meter where the rms value is read. A feedback circuit containing a second thermocouple may be included to account for the nonlinearity of the primary thermocouple.

The analog-based true-rms converters use circuits that measure the input voltage, and then calculate its square, mean of its squares, and the square root of the mean. The time constant of the conversion circuits is set by an averaging circuit that may be adjusted from a few milliseconds to several hundred milliseconds. The longer time constant yields less fluctuation on the output signal but may lead to a poorer response when dealing with rapidly oscillating loads. In some cases, this conversion technique may not be able to deal with high slew rates, rapidly-changing signals, or large crest factors.

True-rms converters based on a digital approach sample the input signals at approximately 100 times the anticipated signal frequency and convert the samples to digital values. A mathematical processor squares each of the values, sums the squares along with some previously squared samples, and then calculates the square root of the sum. This technique will yield a true rms value on any arbitrary waveform.

Some meters will measure and display peak values as well as true-rms values. This feature can be beneficial if diagnosing potential harmonic overheating concerns.

6.4.2 Current transformers

A number of power monitoring instruments have the capability for simultaneous voltage and current monitoring. Since it is difficult to perform in-line measurements of current without affecting the power system, a CT is typically used. CTs clamp around a cable or busbar to facilitate non-intrusive measurement. When selecting CTs for power monitoring applications, the following four points should be considered:

a) The accuracy of the readings (a combination of CT and instrument accuracy)
b) Phase shift if the instrument is capable of providing measurements of phase relationships
c) Response and phase shift over the measurement bandwidth
d) The crest factor capability

6.5 Monitoring instruments

6.5.1 Oscilloscopes

Oscilloscopes can be used to provide a visual representation of voltages and, when combined with current probes as discussed above, current. Digital oscilloscopes can store voltage and current waveforms. Further, some digital scopes allow the direct calculation of peak, average, rms, and other values. A waveform from a Hall effect current probe, a voltage probe, or other device may be fed into the oscilloscope for analysis. The use of a de-coupler permits safe measurement of the 60 Hz voltage waveform as well as the high-frequency normal mode and common mode noise into the RF spectrum. This measurement technique is useful to determine the ambient noise levels and can also be used to identify possible noise sources.

Measurement of current waveforms can also be conducted with a clamp-on CT. As mentioned earlier in this document, caution should be used in the selection of the CT to assure the frequency response is high enough to measure harmonic currents as well as the fundamental frequency of concern. Frequency response to the 50th harmonic (3000 Hz) is normally sufficient for most applications. Power waveforms can be displayed and measured by storing a voltage and current waveform. A digital oscilloscope can increase the quality and ease of data collection.

One area of major concern during the use of the oscilloscope to make measurements is the practice of “floating the scope.” This practice typically revolves around disconnecting the ground connection to the scope chassis. It is essential that the equipment grounding conductor for the chassis of the scope not be bypassed or defeated in any manner that results in operator exposure to electrical shock. If a standard scope, with one side of the input connected to the chassis, is used, the voltage shall be isolated using an instrument-grade potential transformer.

6.5.2 Disturbance monitors

Disturbance monitors are power monitoring instruments that are specifically designed to detect and record data on power system variations. Typically, power-line disturbance monitors are portable instruments that contain a wide and varied number of features. These features may include a number of monitoring channels, data storage and display formats, and other features that enhance the instrument’s capabilities.

Disturbance monitor designs can be viewed in terms of the range of frequencies to be measured, how the data is collected, and how the data is displayed. Once these design parameters are understood, the user can then select a design that will best meet the intended application.

As an example, some power monitoring applications require rather slow measurement of voltages and/or currents. An inexpensive instrument that measures voltages a few times a second may meet the needs of this application. On the other hand, some applications require very high speed measurements of voltage. This may be the case when high-frequency transients in the power system may be the source of a potential problem. This measurement would require a more sophisticated power monitoring instrument. These sophisticated instruments can detect and collect data on numerous power system variations that may include voltage swells and sags, transients, frequency errors, electrical noise, distortion, and notching among others.

A power monitor that looks at a broad range of frequencies may use multiple measurement techniques. For example, a digital sampling technique may be used to measure rms voltages and distortion, but an analog circuit may be used to capture transients.

Factors that determine the proper measurement technique not only include accuracy, dynamic range, and frequency response, but how the data is to be processed and presented. As an example, if a fast fourier transform (FFT) is to be applied to capture an event, then the instrument shall employ a digital sampling technique.

Power-line disturbance monitors can be divided into four basic types. The monitors may be classified as event indicators, text monitors, solid-state recording volt/ammeters, and graphical display monitors.

6.5.2.1 Event indicators

Event indicators are the simplest and least expensive of all power-line disturbance monitors. These indicators collect and display data that are generated by power system variations. They may be dedicated to a single type of power system variation or, more typically, they may classify several types of events. Data generated by the electromagnetic phenomena may be displayed with indicator lights, an illuminated bar graph, an audible alarm, or some combination of the three. Typically, the time of occurrence of the power system variation is not recorded by this type of device.

Event indicators collect power system variation data by comparing the steady-state condition of the power system with one or more threshold parameters. These parameters may be preset or user adjustable. In the event that the threshold(s) are exceeded, a power system variation is detected and recorded. Comparison of the steady-state condition and the power system variation is accomplished through the use of analog and/or digital circuit techniques. These threshold parameters dictate the types and number of power system variations that are detected by this type of monitor.

Once a power system variation is detected, it may be stored as an amplitude or a total number of occurrences that exceed the thresholds. Data may be displayed as a numerical value for amplitude or a total count of the individual power system variations. Some type of illuminated indicator and audible alarms may also be used to display the data.

6.5.2.2 Text monitors

A second type of power-line disturbance monitor is referred to as a text monitor. As with the event indicators, these devices collect and display power system variations but include several important differences. Individual power system variations are displayed with an alphanumeric description. Further, these variations are usually logged as to time of occurrence. The output from this type of monitor may be recorded on paper tape, electronic media storage, or a combination of the two.

Generally, text monitors employ the same threshold comparison techniques as those used in the event indicators. The steady-state condition of the power system is compared with preset or user adjustable thresholds. In the event that one or more of the thresholds is exceeded, measurement data is collected and stored in the instrument. Electronic circuitry used to perform the comparisons may be based on analog as well as digital techniques. As with the event indicators, these threshold parameters dictate the number as well as the type of power system variations that are recorded for future analysis.

The data display techniques offered by the text monitors provide improvements in the quality of data collected for future analysis. When power system variations are detected, a descriptive alphanumeric message is generated that represents the variations. Accuracy of the data collected and displayed is dependent upon the measurement parameters and techniques. A further feature of this instrument is that the time of occurrence of the power system variation is recorded to aid in future data reduction and analysis.

6.5.2.3 Recording volt/ammeters

The third type of power-line monitor may be referred to as the recording volt/ammeter (rvm). The classical rvm is the pen and ink chart recorder. There are tens of thousands of these devices in use today and more are being purchased. They have provided the basic measure of power quality at the service entrance for decades. They provide essential information as to what is the steady-state condition. The device shall be calibrated to an external voltage source each time it is used.

Solid-state rvms are also commercially available. They are programmed by a computer, and digitally record steady-state data at a user-selected sampling or averaging rate. Some sample for two to four cycles and calculate an average value. Others sample once every two to 30 cycles. Some average the data samples over seconds, minutes, or hours to extend the total length of time they can store data, as data storage is limited by memory amount.

The data is downloaded to a computer and is displayed graphically or printed. The steady-state values represent average quantities. Solid-state rvms measure true-rms values, and can be programmed to capture out-of-limit events, which are stamped with the time and date of occurrence.

Another version of the solid-state rvm is also available. This device is capable of sampling each cycle, has more memory for increased storage of events, and calculates true-rms values by a digital sampling technique. The user selects the sampling rate and/or the averaging period. Another enhancement is that the data stored in memory can either be "stop when full" mode or "wraparound" mode. This feature can be useful to limit the required memory and only record data that is directly related to a problem.

Users of rvms should understand exactly how their particular device handles sampling technique and rate. Data storage capacity is an important consideration when specifying the optional memory requirements. It can be very useful to have the extra detail permitted by higher sampling rates which require extra memory.

6.5.2.4 Graphical display monitors

The fourth type of power-line disturbance monitor is a graphical display monitor. These instruments collect and record power system variations in a graphical format that is enhanced with alphanumeric descriptions that are similar to the text monitors previously discussed. Power system variations are recorded by the time of the occurrence with a graphical representation of the variation. These variations are further enhanced with alphanumeric descriptions. The data collected may be displayed on a paper tape, a CRT type of display, or stored on some type of electronic media.

Data collection used in the graphical display monitors is based on fixed or variable sampling techniques that break down the ac voltage waveform into a series of discrete steps that can be stored. This stored data is then recombined to present a representation of the original ac waveforms. The speed of the sampling rate dictates the degree of detail available to reconstruct the ac waveform.

Steady-state values are recorded either at some manufacturer-selected interval, or can be recorded when a user-selected sensitivity threshold is surpassed. In addition, out-of-limits data is recorded when a power system variation exceeds the threshold parameters preset in the machine or adjusted by the user. These variables include, but should not be limited to, sags and swells, waveform distortion, and impulsive transients. As in the previous instrument, comparison circuits may be analog and/or digital.

Thresholds for triggering in the event of a power system variation are based on software controls. Comparison algorithms are installed in the system software that allow a wide range of thresholds to be established for the collection of data.

When a power system variation that exceeds the established thresholds is detected, the digitized data of the variation is stored in memory. This data is then measured in numerous ways to establish the parameters of the power system variation. Once these measurements are complete, the digitized data is used to provide a detailed graphical representation of the power system variation.

As mentioned earlier, reporting of the data collected may be provided through a paper tape record or transferred to some form of electronic media for storage and future reference. Graphical representation may also be displayed through the use of a CRT type of display.

These monitors may be set to collect large amounts of data and many events over a period of time. The subsequent analysis is time consuming and difficult. Prior planning and thoughtful application of thresholds may be required to control data collection and analysis.

6.6 Instrument power

6.6.1 Power supply and monitoring compatibility

As mentioned earlier in this clause, whatever one measures will be affected by what devices are used to make the measurement. The goal when using power monitoring instruments should be to minimize the instrument's impact on the measurement of the power system. By employing voltage connections and CTs, this is relatively simple to accomplish. However, problems may enter into the measurement process not through the connections, but through the power supply of the instrument. Even though most power monitoring instruments require little power, their power supplies may significantly distort the measurements. The following issues should be considered before choosing to power the instrument at the monitoring location. Refer to the instruments' application manual to resolve these issues.

a) What is the level of isolation between the instrument power supply and the instrument measurement circuits?
b) Does the instrument power supply generate noise or cause additional power system variations?
c) Will the power consumption of the instrument influence the measurements?
d) Does the instrument power supply contain transient protective devices that may affect the measurements made with the instrument?
e) Will the instrument operate correctly during power system variations that may induce power quality problems?
f) Are parasitic power cables being used that may introduce false readings in the instrument?

Many of the issues discussed may become irrelevant when powering the instrument and measuring from different locations. However, other concerns, such as the following, come to the forefront with this approach:

a) What is the quality of the power supplied to the instrument and will it affect the measured data?
b) Have "ground loops" been introduced into the measurement setup?
c) Does the placement of the instrument require excessively long power cords, voltage, and/or current leads which might degrade the accuracy of the measurements?

6.6.2 DC power

Depending upon the location of the power system to be measured, a power monitoring instrument may use dc power for instrument operation. Further, dc power may be employed internally to the instrument to provide emergency backup power. DC power may be used internally or externally to the instrument. When using dc power, several points should be considered. Once again, refer to the device application manual for guidance.

a) If using external power, are the power cables properly sized?
b) Has the instrument been properly grounded?
c) Does the dc power come from a battery pack that can build up a "memory," which will shorten the backup time available from the batteries?
d) If an external charger is used and connected to an ac outlet, what is the charger's isolation capability and what effect will the charger have on the power system?

7. Application techniques

This clause offers application techniques that can assure safe and effective collection of electromagnetic phenomena events. It is neither intended to be a step-by-step requirement for conducting power quality surveys, nor does it present an exhaustive listing of issues to consider. Familiarity with this clause, however, will help ensure the safe collection of useful data.

This clause begins with safety considerations. Monitoring often involves intruding in some fashion upon electrical circuits that have the potential to injure people and damage equipment. Steps for the typical monitoring techniques related to monitoring location, test equipment connection, threshold settings and programming, and determining a monitoring duration are discussed.

7.1 Safety

The manner in which a disturbance monitor is attached to the circuit under evaluation may impact the audit in areas other than the accuracy of the data being captured. It is imperative that the attachment of the sense leads be made in a fashion that does not jeopardize the safety of site personnel as well as the integrity of existing connections. While most hookups are temporary in nature and may not utilize the same practices as for permanent installations, the National Electrical Code (NEC) [B2] and local codes should not be compromised.

7.1.1 Hard-wired connections

Sense lead connections that shall be made in load center panel boards or junction boxes should be attached in a manner that does not violate the listed use of the devices to which they are attached. This generally includes returning doors, cover plates and access panels to their in-use position (i.e., closed, mounted with a full set of screws, etc.). If panels must remain open during monitoring, adequate means shall be provided to limit access to the area and inform others about the monitoring setup and the responsible on-site contact. Leads may be connected to existing circuit overcurrent protection devices if the device is designed for the attachment of multiple conductors.

Sense leads should not be twisted around existing wires or inserted in circuit breaker connectors that are designed to receive a single connector. Alligator clips are totally inappropriate for this type of connection as they can be easily dislodged and it is difficult at best to properly insulate or strain-relieve them.

An alternative to using existing screw- or clamp-type attachment points is to use an approved pigtail-type connection. For example, pigtails should be used where sense leads must be connected in a panel board or junction box. To execute this type of connection, the power to the circuit should be de-energized; the conductor to be monitored should be removed from its connection; a four- or five-inch pigtail of insulated electrical wire rated at the same current-carrying capacity as the removed conductor should be installed in the original connection; and then the pigtail, the conductor to be monitored, and the sense lead can be connected together with an approved wire nut or fastener. This new connection should be taped to ensure proper insulation and safety of the connection.

7.1.2 Plug- and receptacle-type connections

Some sense cords have insulated plugs capable of being stacked one on top of the other. Caution shall be exercised so that when stacking, only common connections are made rather than creating an inadvertent short circuit. Always double-check the jumpers to assure that short circuits have not been introduced. Also, connect the sense leads to the monitored circuit only after the leads have been connected (stacked) to the rear of the analyzer and checked for correctness.

7.1.3 Guarding of live parts

Often panel covers are removed for hook-up or during the monitoring period. If so, all live parts must be adequately protected and the area should be kept inaccessible. If screw terminals are used in the monitoring equipment, exposed wire should be kept to a minimum and appropriate covers used to insulate the terminations. Connecting multiple common wires with single set screws should be avoided.

7.1.4 Monitor placement

The monitor should be placed securely so that there is no chance of the instrument moving or loosening connections. If a paper printer is used for reporting disturbances, adequate precautions should be taken to ensure that accumulating paper does not present a hazard. Monitors should not be left where excessive heat, moisture, or dust may damage the equipment or jeopardize the data collection process.

A monitor should not be placed in a heavily traveled hallway. The monitor should be placed so that it does not pose a safety hazard to those working in the area. A protective enclosure or barrier can sometimes be used to alleviate this concern. Also, the location should not pose an undue safety hazard to the person installing the monitor. There are many locations that are too cramped, or in other ways, physically constrained, to allow safe connection of monitoring leads. In these situations, an alternative location should be selected.

Any number of external environmental factors may affect the performance of a power monitoring instrument. These environmental factors may include temperature, humidity, RFI fields, static discharge, and mechanical shock and vibration.

Temperature is a critical factor in any microprocessor-based power monitoring instrument. The internal physical geometry of the various electronic components are so small that signal path lengths, impedances, and clearances may be affected if the temperature of the environment exceeds the specifications of the instrument.

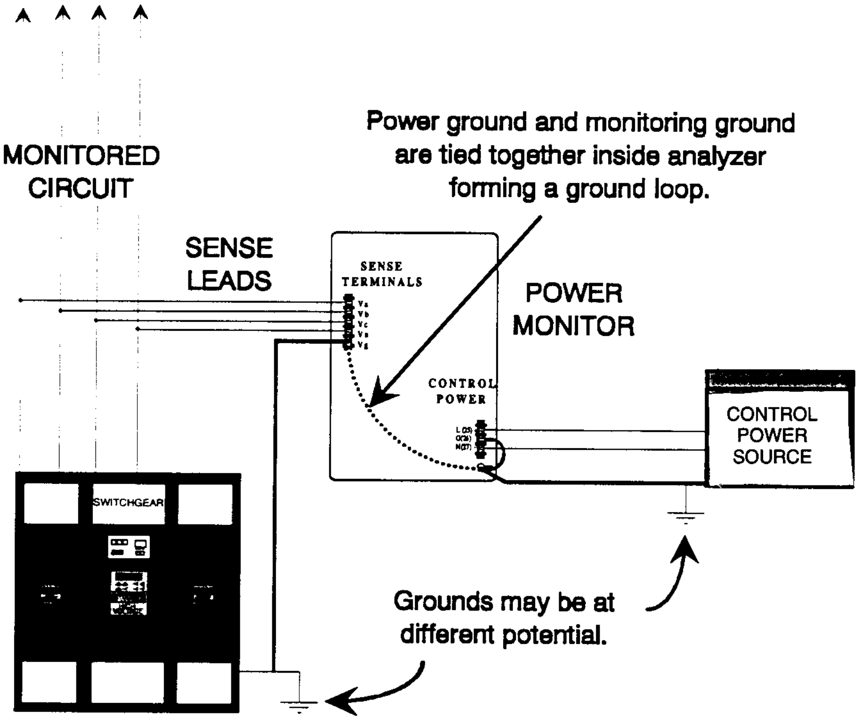
Humidity, like temperature, is critical for the sensitive electronics enclosed in the power monitoring instrument. Excessive humidity may cause condensation inside the instrument, which can lead to electrical shorts, arcing, corrosion, and ultimately, erroneous data. Air that is too dry invites static discharge that can damage electronic components within the instrument. Other symptoms of static discharge are signal disruption or difficulties in programming the instrument.

Erroneous data may be generated when monitors are installed in areas that are exposed to various levels of radio frequency interference. Interference may be induced into the instrument through the input leads. If the data collected looks unrealistic, it may be the result of external radio-frequency interference.

Mechanical shock and vibration can create stresses inside the instrument that weaken mechanical connections and cause arcing and erroneous data generation. When the instrument is installed in an area that is susceptible to mechanical stresses, the user should be careful to assure that the instrument can withstand and function correctly in the environment. Due to vibration and mechanical stresses in transporting instruments to the monitoring site, instrument operation prior to use should be verified.

7.1.5 Grounding

All instruments are capable of developing internal faults; the instrument's power supply should be properly grounded through a three-wire cord. Faults may also develop in the attenuator modules receiving the input voltage sense leads. The attenuator should be tied through an effective grounding path to the measured circuit ground reference. If the attenuator ground is connected to the power supply or chassis ground (as is common), an inadvertent ground loop may result as shown in figure 14. In this case, the equipment power supply grounding means should not be isolated. See 7.2.3.



Power ground and monitoring ground are tied together inside analyzer forming a ground loop.

Grounds may be at different potential.

Figure 14—Ground loops introduced by monitoring instrument

7.1.6 Sense lead overcurrent protection or current limiting

Fused voltage sense connectors are available and are recommended. Connections should always be made downstream of existing overcurrent protection devices.

7.1.7 Routing of sense cables (strain relief)

Sense cables should be routed away from exposed conductors, sharp objects, electromagnetic fields, and other adverse environments. They should be strapped or tied to a solid object to prevent inadvertent disconnection.

7.2 Monitoring location

7.2.1 Objective

The characteristics of some power system variations will change depending on the monitor's proximity to the source, the distribution system impedances, and the dynamics of the load. As an example, a voltage transient will dissipate energy through impedances that will change the leading edge rise time, peak amplitude, and oscillation frequency.

The initial location to install a power quality monitor will be dependent upon the objective of the survey. If the monitoring objective is to diagnose an equipment performance problem then the monitor should be placed as close to the load as possible. This applies to performance problems with both sensitive electronic loads such as computers and adjustable speed drives, and electrical distribution equipment such as circuit breakers and capacitors. After the voltage fluctuations are detected, the monitor may be moved upstream on the circuit to determine the source of the disturbance.

If the affected equipment is currently supported by a means of power conditioning or filtering, a decision must be made as to the sequence of monitor placement. At the minimum, a monitor should be installed at the affected equipment attachment location to the electrical supply (between the power conditioning equipment and the affected equipment). This will determine if the power supplied to the device falls within the manufacturer's recommended operational specifications.

Once this characterization has been made, the monitor can be relocated to the input (source) side of the conditioning device or filter in order to determine whether the level of disturbances presented to it are within its conditioning or filtering capability. If the disturbances fall within this range, attention should be directed to whether the conditioning or filtering device is defective or if an interaction is occurring between the load and the conditioner or filter.

If the monitoring objective is to investigate the overall quality of a facility then the monitor should be placed on the secondary of the main service entrance transformer, which is usually 600 V class service equipment. The monitor will record the quality of power supplied to the facility as well as the effect of major loads within the facility. The monitor may then be moved downstream in the electric distribution system to record the power quality on individual feeders.

If harmonics are of concern, the monitor should be placed at capacitor or filter locations to measure harmonic currents and distorted voltage. Capacitor magnification of switching transients can also be investigated by connecting a monitor at the capacitor bank. Refer to figure 15.

7.2.2 Knowledge of the electrical circuit

It is important to consider the entire electrical environment prior to connecting a monitoring device. This can best be done by drawing or obtaining a single-line diagram of the electrical circuit being monitored. This single-line sketch may encompass the utility service, neighboring electrical customers, and internal wiring and loads. Awareness of this environment will facilitate consideration for safety, proper connection, and interpretation of data. Some specific items to include on the diagram are described below.

In order to maintain reliability, a utility sometimes has more than one alternative for feeding electrical service to a particular area. Both the normal and alternate utility distribution circuits should be identified. These circuits can then be examined for devices that may produce events on a monitor during operation.

Electrical loads at neighboring facilities may affect the electrical quality at the monitoring site. Large individual loads operated nearby should be identified, as is practical. The proximity and type of interface between this equipment and the monitoring site will determine the severity of the effect. For example, if the neighbor is served from the same electrical transformer, then there is a direct path between the two end

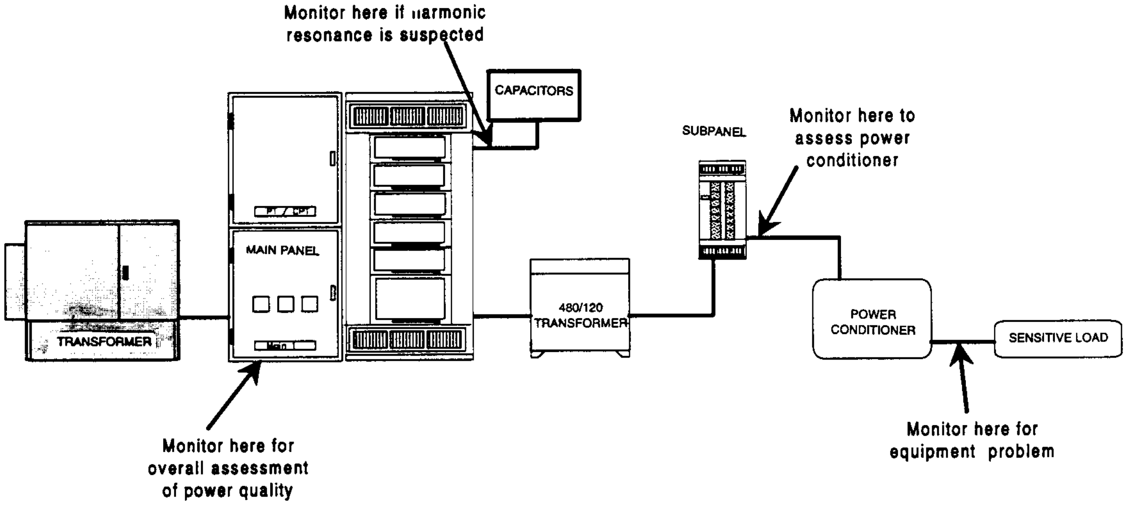


Figure 15—Suggested monitoring locations on a typical low voltage system

users. Therefore, the magnitude of the electrical events associated with the neighbor's equipment will be greater than if it were somewhat isolated by service through a separate transformer.

Construction that is located near a monitoring site should also be considered. Often local connection standards are different between temporary and permanent electrical service. The temporary service may have more or less isolation. In either case, the type of construction equipment to be operated during a monitoring period should be considered.

Due to proximity, electrical equipment and the mechanical aspects of electrical distribution at a monitoring location will have the greatest effect on electrical quality. Close examination from the main electrical feed to the end-use equipment is a prerequisite to monitoring. This entire system should be inspected for clean, tight connections. This will resolve many problems. This inspection should also include making a log of devices and equipment throughout the circuits to serve as a reference when interpreting the data. Especially, the connection and operation schedule of backup power sources and mitigating devices such as uninterruptible power supplies should be determined.

7.2.3 Diagnosing an equipment performance problem

The power quality monitor should be placed as close to the symptomatic load as possible. A physical inspection should be made to ensure that filters, transformers, or other treatment devices are not connected between the monitor and the symptomatic load. The monitor should be connected to mirror the electrical connections of the load's power supply, as mentioned earlier. This installation will permit the monitor to record the absolute magnitudes of voltage fluctuations that are directly being applied to the load without the effect of circuit impedances and filtering. This location will also permit monitoring of the load's direct current bus (power supply output) or communications ports without extended runs of monitor leads.

If the symptomatic load is powered from a wall receptacle, then the monitor should be connected to a spare receptacle in the same outlet. If this is not possible, then a receptacle in an adjacent outlet may be used, but it should be electrically verified that this receptacle is on the same circuit as the load and that it is wired properly.

To monitor the power to a load connected to an isolated-ground receptacle (orange in color), the power monitor should be connected to the same receptacle. These receptacles are designed for use with two grounding conductors. The non-insulated grounding conductor (sometimes conduit) is bonded to the outlet housing. The isolated grounding conductor (green-insulated wire) is terminated at the receptacle grounding terminal. The preferred practice is not to daisy-chain the isolated grounding conductor but to run a separate insulated green wire from the isolated ground bus in the subpanel, or separately-derived source, to each orange receptacle. (See article 250-74, exception number 4 in the NEC [B2].)

It is sometimes impossible to connect the monitor at the load. Voltage connection points may be inaccessible; the load may be in a hazardous environment or there may be security considerations. In this situation the monitor may be connected at the closest subpanel feeding the load. Monitoring at a subpanel has the advantage that the circuit conductors are accessible for current measurements.

7.2.4 Facility power quality survey

A power quality survey of an entire facility usually starts as far upstream in the electrical distribution as possible. Prior to monitoring, a thorough check of the mechanical condition of important electrical circuits should be completed. It is usually unnecessary to monitor circuits greater than 480 V unless loads are directly connected to those higher voltages. The initial monitor location is typically the secondary side of the main service transformer. This location is generally 600 V class service equipment. It may also be useful to monitor simultaneously at more than one location within a facility.

If monitoring of higher voltages is required, then special voltage divider circuits or PTs and clamp-on CTs may be required. These transducers should have a frequency response that permits the capture of transient disturbances. Existing voltage transformers and CTs, used for metering, may not have the frequency response to provide power monitors with accurate transient information. They can be used by a power monitor, however, to record low frequency voltage fluctuations at the distribution level voltage. Special safety rules apply to working with greater than 600 V class service equipment.

7.2.5 IEEE Std 519-1992

IEEE Std 519-1992 [B13] recommends harmonic current injection and voltage distortion guidelines. To monitor for distortion levels related to these guidelines, the harmonics monitor should be placed at the point of common coupling as specified in the standard.

7.2.6 PT and CT specifications

Monitoring location	Voltage transducer current	Transducer
Substation	Metering PTs Voltage dividers Bushing taps	Metering CTs Relaying CTs
Overhead feeder	Metering PTs	Metering CTs
Underground feeder	Metering PTs Voltage dividers	Metering CTs
Service entrance	Direct connection	Metering CTs Clamp-on CTs
In facility	Direct connection	Clamp-on CTs

7.3 Equipment connection

7.3.1 Sense inputs

The monitoring analyzer should be connected in a manner that does not violate manufacturer's recommendations for voltage or current limits. In accordance with 7.1, the installation must be completed in a safe manner.

The sense lead connections in any monitoring will have to cover all disturbance modes that could impact the proposed devices. As the number of circuit conductors increases, the necessary monitoring modes will also increase. For example, if the device is powered by a 120 V plug without an equipment grounding conductor (such as audio visual equipment for household use) phase-to-neutral monitoring is the only valid configuration, whereas a 120 V rms plug with an equipment grounding conductor should be monitored in a phase-to-neutral, phase-to-ground, and neutral-to-ground configuration. A three-phase data processing unit with interconnected single-phase peripherals may have to be monitored phase-to-phase, phase-to-neutral, phase-to-ground, and neutral-to-ground. The number of monitoring modes could be reduced through awareness of the device's capability to withstand these different modes of disturbance.

The best mode in which to connect to three-phase loads is to match the configuration of the affected equipment. If the sensitive equipment, for example, is connected in delta (three wire without a neutral), the monitor should be configured likewise. A phase-to-ground channel should be included if possible. If the sensitive equipment is connected in wye, the analyzer should be configured in wye as well, and a neutral-to-ground reference should be included.

7.3.2 Ground terminals

There are two purposes for connecting to ground terminals—safety and performance. The instrument should be referenced at the same ground potential as the circuits being monitored. Caution should be exercised since the instrument's power supply equipment grounding conductor may be at a different potential than the sense lead connected to the monitored circuit ground. If the power supply equipment grounding conductor is internally connected to the instrument chassis and also connected to the safety/reference terminals (as is usually the case), ground loops and noise can result. The ground sense lead should be tapped to the ground bus being monitored prior to connection. If a spark results, a ground loop exists.

7.3.3 Instrument power and invasive monitoring

Instrument power is generally supplied by a single-phase three-wire outlet and a standard power cord. If the circuit being monitored is the same as that supplying the instrument, the user should be aware of the effect of the instrument on the metered circuit. Voltage change due to the instrument current draw is generally not large but can be noticeable, especially on a neutral-to-ground measurement. If the instrument power supply is protected by parallel, clamping transient voltage suppressors such as metal oxide varistors and avalanche diodes, the instrument's ability to accurately capture the disturbance will be compromised. The instrument power should be supplied by another circuit, or, as allowed by some equipment, a dc source (battery). If another circuit is used, ground loops should not be introduced and excessively long power cords or sense leads should not be used. If a battery is used (and there is no grounding provided through the power cord), the instrument should be properly grounded.

7.3.4 Hard-wired connections

For long-term monitoring, hard wire connections should be made. The connecting means should be in conformance with other applicable standard practices or code requirements. It should be ensured that the terminating means is compatible with the wire type.

7.3.5 Plug and receptacle type connections

Standard three-wire sense cords are usually supplied with the instruments for standard National Electrical Manufacturer's Association (NEMA) outlet connections. The outlet should be checked first for wiring errors such as reversed polarity and open ground. Inexpensive circuit checkers are good for finding simple errors but should not be relied upon for ensuring the wiring integrity. Sense cables for other than 15 A single-phase, grounded receptacles may not be supplied with the instruments. If one is required, break-out cords are often constructed to accommodate the need. Caution should be exercised so that the connectors used do not violate their listed purpose.

7.3.6 Quality of voltage sense connections

The voltage sense connections represent the interface between the power system and the monitor. They are an extension of the monitor's inputs, not an extension of the power system. This means that any loose connection or faulty cable should be remedied before useful data can be recorded. Otherwise, the disturbance data may be the result of the connection and not of an anomaly in the system.

When an enclosure is opened to allow connections of the power line monitor, the integrity of the equipment's shielding has been compromised, which may introduce an artifact in the monitoring, or may affect equipment operation. Monitoring equipment sense leads are particularly susceptible to EMI/RFI. To minimize the erroneous effects, two wires should be run to each monitoring channel input and not the popular one wire per channel with a single common or other daisy-chained connection. Twisted pair and/or shielded input wiring is desired yet not typically provided. In some cases, analyzers have incorrectly reported events such as transient voltages that resulted from sense wiring crosstalk or EMI/RFI. This is particularly troublesome when the monitors are available with very low disturbance thresholds (e.g., 25–50 V on a 480 V system).

Shielded input sense cables are not readily available, but practical techniques should be employed to reduce EMI/RFI interference. For example, two wires per channel can be used. These wires should be twisted together and routed against the grounded enclosure chassis instead of looped out in free air.

7.3.7 Current monitoring

If simultaneous voltage and current monitoring can be performed, the information available for problem solving is increased tremendously. Clamp-on CTs can be used to measure the current associated with the voltage deviation. If rms current increases substantially at the time when rms voltage drops, the voltage drop is a result of a fault or load downstream of the monitoring point being energized. Fast changes in current (< 1 ms) may not be accurately measured by some CTs. When CTs are used, they should be arranged such that panel covers or some means of covering the service power source is possible. CTs should not be clamped-on to the conductor to be measured until they are connected to the monitoring instrument.

As with the voltage connections, the quality of the current connections can affect the recorded data. The following are three common problems when using clamp-on CTs:

a) The conductor or bus bar is not properly positioned within the clamped area.
b) The two split core ends do not make a solid contact.
c) The wrong type or number of conductors are enclosed within the CT.

Included in this last item is the improper polarity problem where a CT is positioned backwards or the CT polarity is incorrect.

CT specifications typically assume the conductor or bus bar is positioned dead center within the clamped area. Any other location will incur some accuracy error. If the clamp ends do not mate solidly, then the resulting gap between the ends will also introduce error into the measurement. Unlike the error from positioning, however, this gap error may also affect recorded waveshapes. Whenever multiple conductors are being measured, care should be taken to ensure that no return conductors are also being measured. This would cancel some or all of the magnetic field of the conductor being measured, thus changing the reading.

7.4 Monitoring thresholds

7.4.1 Objectives

Once the monitor is connected to the circuit, it must be programmed to record the desired electromagnetic phenomena. The process of selecting monitor thresholds is dependent upon the objective of the survey. If the survey objective is to solve an equipment performance problem, then the monitor's threshold settings should be related to the susceptibility of the equipment. Thus, the monitor should be programmed with magnitudes for the voltage (and/or current) that will trigger the monitor to produce exception reports for disturbance events that are expected to exceed the susceptibility limits of the sensitive electronic equipment under investigation.

If the objective is to perform a general power quality survey, or to profile a single circuit, then the monitor's threshold settings will be dependent upon the limitations of the monitor's event storage media, either paper and/or RAM.

Different manufacturers have adopted different philosophies with regard to programming, data capture, and display. Instruments can generate erroneous data depending on the measurement systems, grounding, shielding, and hookups. Thus, an understanding of the internal workings of the power monitoring instrument is critical if the data collected is to have value in the diagnosis and solution to power system variations.

The first point to consider is the triggering level of the power monitoring instrument. Trigger thresholds tell the monitor to ignore power system variations below the threshold and only trigger on those variations that exceed the threshold. It is important to remember that missing disturbance recordings do not necessarily indicate absence of electromagnetic phenomena. It only means that the power system variation did not trigger the monitor. There are several techniques for triggering on various power system variations. These techniques will vary depending on the manufacturer's design.

The second point to consider is the method or technique used to report the data collected by the power monitoring instrument. The display of the data can be a "hard copy" as with a data tape, visual display in a format similar to an oscilloscope, or data may be stored on a disk or be transferred to a computer terminal or PC for further analysis.

All power monitoring instruments are a compromise between cost, portability, and completeness. Instruments are limited by their processing speed, data storage, printing speed, and memory buffers. Given that literally thousands of threshold excursions can occur in less than a second, these limits may be reached causing lost data or uncaptured power system variations. Further, instruments that simply indicate a certain disturbance occurred cannot accumulate data to represent the number of occurrences, the characteristics, or the relationship between the different power system variations.

Some power monitoring instruments allow various report formats to be turned on or off. Depending on the application, these features can be used to make more efficient use of the instrument. Graphical instruments may allow the user to view various waveforms in either visual format or on a hard copy printout. Both formats give a “snapshot” of the situation and not a real-time picture as would be available from an oscilloscope. However, these snapshots are very convenient for setting up the power monitoring instrument and understanding the conditions existing on the electrical distribution system. In some cases, snapshots are sufficient for identifying the source or cause of a power system variation. In many cases, the end user wants to measure the steady-state conditions. This requires an instrument capable of recording and conveniently displaying steady state conditions for the complete monitoring period, which could be weeks or months.

7.4.2 Preparation

At first, set up the monitor and let it run in the summary mode for a half hour or so in order to obtain first order estimates of electrical environment characteristics. It may even be useful to let the monitor run for a 24-hour period in summary mode before final threshold settings are made. One purpose is to keep from filling up the memory with too many exceptions and/or printing-out the entire roll of paper unnecessarily. This results in superfluous data if any of the settings are too sensitive relative to the magnitude of disturbances in the environment.

7.4.3 Electrical environment considerations

Selection of monitor thresholds can be a simple task if the objective of the survey is to monitor an equipment performance problem in a benign electrical environment (where there are no significant waveform fluctuations). The monitor’s thresholds may be set just below the susceptibility levels of the equipment under test. The waveform disturbance can then be extracted from the body of waveform fluctuation records based upon a time correlation with the equipment malfunction, or when the fluctuation clearly exceeds the equipment’s susceptibility levels.

NOTE—Thresholds must be set lower than the equipment’s susceptibility levels to ensure that the disturbance waveform is recorded.

Selecting thresholds for an electrically active environment (such as the input to an adjustable-speed drive) is more difficult. If the thresholds are too low, continuous fluctuations will incapacitate the monitor, possibly preventing it from capturing more significant disturbances.

7.4.4 Equipment susceptibility considerations

The best threshold settings are those that relate directly to the susceptibility levels of the sensitive electronic equipment being investigated. Susceptibility levels for an electronic load may be obtained from the manufacturer, or from past surveys performed on that particular electronic load. This information is rarely available for any specific piece of equipment (the familiar CBEMA curve used in IEEE Std 446-1987 [B12] and elsewhere is only a consensus guide and as such tends to be conservative.) When specific information is available, the susceptibility levels do not always match the threshold categories of the monitor.

Susceptibility levels derived from generally recognized industry standards (such as CBEMA) often work well, especially when used in conjunction with the manufacturer's specified levels. Subclause 8.2, table II in FIPS PUB 94 [B6], provides some representative power quality attributes for reference. The table lists environmental attributes or disturbances, with values for "typical environment" and also "typical acceptable limits for computers and power sources" (with two categories of "normal" and "critical" limits). After study of this type of information (including FCC emission and immunity/susceptibility considerations) the thresholds might even become "second nature."

Table 3 lists initial thresholds that might be considered as rules of thumb. The thresholds are specified for 120 V equipment in the US, and with general equipment susceptibility considerations as derived from FIPS PUB 94 [B6] and IEEE Std C84.1-1989 [B1]. The specifications in this table fit best for normal 120 V loads that are neither overly sensitive to nor highly tolerant of voltage fluctuations.

Monitor thresholds shall be set below (more sensitive) equipment susceptibility levels to ensure that disturbances are recorded. The aging of equipment, discrepancies between equipment and monitor susceptibility nomenclatures, and the accuracy of the monitor are factors that could result in the malfunction of equipment at voltage levels below its expected susceptibility levels.

7.4.5 Current considerations

Most monitors are capable of monitoring currents; a few monitors will allow monitoring of seven or eight channels. This feature permits users to diagnose current related equipment performance problems such as unwanted circuit breaker tripping, and motor, conductor, and transformer overheating. The proliferation of large, nonlinear loads requires true rms measuring capability and measurement. Setting the current thresholds for these applications usually involves setting the overcurrent thresholds relative to the NEC [B2] limits or just below the manufacturer's nameplate specifications, whichever value is lower.

An important application of current measurements in power system analysis is to help determine the direction, or origin, of the disturbance. Observing the change in current that occurs simultaneously with the voltage disturbance can suggest whether the origin of the disturbance is upstream or downstream from the point being monitored. This technique can help to determine whether a neutral-ground voltage disturbance is grounding conductor-related or power-circuit related. For this application, the current thresholds should be set just above the circuit's steady-state current values. It is a good idea to initially monitor for 1 h to characterize transient/inrush current effects on the voltage levels; then set the monitor above the "normal" levels monitored.

7.4.6 Monitor thresholds summary

The following summarizes the monitoring threshold steps:

a) Determine monitoring objectives.
b) Monitor in scope mode (if available) to observe steady-state waveform fluctuations. Set monitor thresholds just above these values.
c) Let the monitor run with these sensitive thresholds until it captures about 20 events or 30 min, whichever occurs first. This will provide a record of background fluctuations.

NOTE—Background voltage fluctuations, even though below equipment susceptibility levels, may have a cumulative degrading effect on the load equipment.

d) Reset the monitor thresholds above (less sensitive than) the fluctuations recorded using the sensitive threshold settings. If time permits, repeat the process until no more than one event is recorded in a 30-min period.

Table 4—Suggested threshold settings for 120 V loads

	Category	Suggested setting	Comments
Conducted phase voltage thresholds	Sag	108 V rms	Minus 10% of nominal supply voltage
	Swell	126 V rms	Plus 5% of nominal supply voltage
	Transient	200 V	Approximately twice the nominal phase-to-neutral voltage
	Noise	1.5 V	Approximately 1% of the nominal phase-to-neutral voltage
	Harmonics	5% THD	Voltage distortion level at which loads may be affected
	Frequency	±Hz	—
	Phase imbalance	2%	Voltage imbalance greater than 2% can affect equipment. (Three-phase induction motors should be derated when operated with imbalanced voltages [B11]).
Conducted neutral-to-ground differential voltage thresholds	Swell	3.0 V rms	Typical level of interest for neutral and/or ground problems
	Impulsive transient	20 V peak	Ten to twenty percent of phase-to-neutral voltage
	Noise	1.5 V rms	Typical equipment susceptibility level
Current thresholds	Phase/neutral current	Normal load current on true rms basis	Load current threshold may need to be raised well above normal load current, depending on the desired data and the amount of fluctuation in load current.
	Ground current	0.5 A true rms	Consider Section 250-21 of the NEC [B2] for safety, as well as noise currents, that lead to objectionable voltages, from both safety and data error points of view.
	Harmonics	20% THD (for small customers) to 5% THD (for very large customers)	Measured at service entrance (point of common coupling), and relative to maximum demand load current (refer also to IEEE Std 519-1992 [B13]); harmonic distortion reference values or measurements at a subpanel should be chosen relative to concerns about effects of harmonics on equipment in the circuit that is being monitored such as neutral sizing, transformer loading and capacitors.

7.5 Monitoring period

7.5.1 Objective

The monitoring period is a direct function of the monitoring objective. Usually the monitoring period attempts to capture a complete power period, an interval in which the power usage pattern begins to repeat itself. An industrial plant, for example, may repeat its power usage pattern each day, or each shift. Depending on the monitoring objective, it may be necessary to monitor as little as one shift.

7.5.2 Baseline power monitoring

Baseline power monitoring is a relatively short process. Its purpose is to document the power profile at a specific site or location. Primary information is steady-state and transient extremes. Other parameters such as frequency or RFI noise can also be of specific interest. Baseline monitoring is primarily used prior to installing equipment to verify power specification compliance. The recommended monitoring period is defined as a complete working cycle (power period). In all cases, the data obtained is a snap shot of the power quality profile. As the environment changes, repeating the measurements is recommended. The updated (new) site profile should be compared to the original. Site profiles can be seasonally dependent as well.

7.5.3 Problem solving monitoring

Hunting for a power problem that exhibits a specific equipment load malfunction can take days to weeks. This type of activity is intended to find the specific power disturbance that creates the problem and document its repeatability (similar to documenting a software bug). Once the problem is found, a corrective action is implemented. After implementation, power monitoring is conducted to ensure the effectiveness of the solution and to verify that no new types of problems have been created.

7.5.4 Power study monitoring

This type of monitoring is of key importance in understanding how the overall power quality picture is changing as a result of major changes in the environment. Power studies are conducted for long periods of time, usually a few years, at multiple locations. Examples of landmark studies include those conducted throughout the US at computer sites in 1969–1972 (phase 2) reported by Allen and Segall [B19] and those conducted at US telecommunications sites in 1977–1979 and reported by Goldstein and Speranza [B23].

Currently there are two more extensive power quality studies. One is focused on electric utility distribution systems throughout the US in 1991–1993 as reported by H. Mehta and J. C. Smith [B27]. The other study covers end use sites in 1990–1995 throughout continental USA and bordering Canadian provinces reported by R. E. Jerewicz [B24] and by D. S. Dorr [B21]. These studies have ability to compare data with past and future studies.

Finally, the Canadian Electrical Association's National Power Quality Survey [B4] was initiated in response to rising power quality concerns from both the utilities and customers. This concern was largely based on the growth seen in the number of electronic loads sensitive to power quality disturbances (computers, digital clocks, programmable logic controllers) and producers of these same disturbances (variable speed drives and consumer electronics power supplies). The two-year, 600-site survey is the first quantitative look at the system problem. The site selection was made to provide for an even distribution, while sampling the three major customer types—commercial, industrial, and residential against different feeder configurations.

8. Interpreting power monitoring results

8.1 Introduction

Troubleshooting and solving power-related problems involves a number of issues. Many problems are solved by carefully examining the load, others by verifying correct wiring and grounding practices, and still others may require the use of power monitoring equipment. No one practice will handle every problem. A doctor can interpret an electrocardiogram, but would never make a recommendation without also examining the patient's health record, lifestyle, and diet. Similarly, one should not diagnose a power problem simply by looking at only one piece of information.

All of the efforts to obtain information are meaningless unless the investigator has enough knowledge and skill to produce a solution from the available data. Interpreting a power monitor's output is perhaps the most critical part of the process of power monitoring. Given the limits and variety of practical field tools, the tremendous range of distribution system and load characteristics, and the limited research done to date, interpretation still remains very dependent on the experience and skill of the user. This subclause discusses many of the issues which directly impact graph interpretation skills. For further information on analyzing and interpreting data, please refer to [B3] and [B5].

8.2 Interpreting data summaries

One of the first steps in interpreting the data from a power monitor is to examine a summary of the data acquired over some time interval. This interval may be anywhere from an hour to a month, but it generally should be at least one business cycle. See clause 7 for more information on the length of the monitoring period. Looking at the summary of the data will provide an important overview perspective and quickly identify more important data to be examined in greater detail.

8.2.1 Summary preparation

The type and detail of summary data should reflect the initial goals and objectives. This is one reason to have clear goals and to properly set up the power monitor. A summary will typically focus on two items. First, data should be placed on a timeline to allow quick chronological correlation. Second, data should be categorized by disturbance and time. This summarizes the data based on particular disturbances.

Building a summary may focus on either one or both styles depending on the objectives of the monitoring. Keep in mind that data being produced does not necessarily indicate a power problem. If many reports are produced it could be that the thresholds were set too tight and examining each report in detail may be a waste of time. On the other hand, no disturbances recorded may indicate that thresholds were not set tight enough, reports were not turned on, or the monitored time did not coincide with the disturbance.

8.2.2 Summary reality check

The reality check is more of a safeguard technique than an analysis technique, but its importance should not be underestimated. All power disturbance recording devices are just tools subject to the skill and knowledge of the user. No matter how careful we are to eliminate wrong data, some may creep in. No matter how certain we are of an interpretation, it must make sense in the real world. The reality check assures that the recorded data are reasonable based on the circuit configuration and monitor connection method.

A reality check of the summarized data should be performed before attempting to interpret them. This involves making sure such things as magnitudes are reasonable (i.e., how would an L-N sag to 200 V exist on a 120 V system?), time stamps are within the monitoring window, waveforms fit on the graph scale, and so forth.

8.2.3 Interpreting summaries

Once certain the summarized data is valid, the first round of interpretation can take place. This may not achieve the desired goal (more investigation may be needed), but it will provide needed information to proceed in analyzing the data further.

The timeline summary provides a chronological overview of what occurred during the monitoring interval. This histogram should be compared to load cycles, failure logs, equipment specifications, results from personnel interviews, or any other information collected.

If the problem involves equipment malfunctions, isolate the disturbances to which the device is sensitive, if possible. The disturbance/time histogram may quickly show whether any disturbances occurred, and if so, when they happened. Patterns in time or disturbance characteristics may show the true source of the problem.

As an example, consider the following scenario:

A workstation intermittently locks up. No consistent failure pattern, such as time of day, is noticed. Wiring and grounding have been verified. Several lock-ups occurred during the one day monitoring time.

The timeline summary showed the presence of many transients, L-N sags, and N-G voltage increases. Occasionally, an L-N sag and an N-G rise had levels far exceeding the other levels. These excessive levels always occurred simultaneously and at the same time the workstation locked up. The disturbance/time summary showed a definite correlation between the high sag/swell disturbances and the lock-ups.

Further investigation showed the existence of a laser printer and a photocopier on the same circuit as the workstation. These two devices constantly caused small transients, L-N sags, and N-G increases in voltage. However, when both the printer and copier were used at the same time they caused an L-N sag and an N-G increase that were much worse. The magnitude of the intermittent N-G increase was found to be the cause of the lock-ups.

8.3 Critical data extraction

Often the summaries will not provide an actual solution to a problem. They should, however, help determine what data needs to be examined more closely. This data is referred to as *critical data*. In the example of 8.2.3, the summaries showed that the sag and N-G voltage increase had a direct cause and effect relationship. The transients did not. Thus, the sags and N-G increases would be considered critical data.

8.3.1 Determining critical events from multiple disturbances

The next step in interpreting monitored results is to take the critical data and combine them into events. An event is the electromagnetic phenomena that resulted in one or more reports from the power monitor. For example, during the short interruption, which happens while a fault is being cleared, the monitor may report an L-N sag or interruption, one or more transients, and a waveshape fault or two. All of these describe the one event of the interruption.

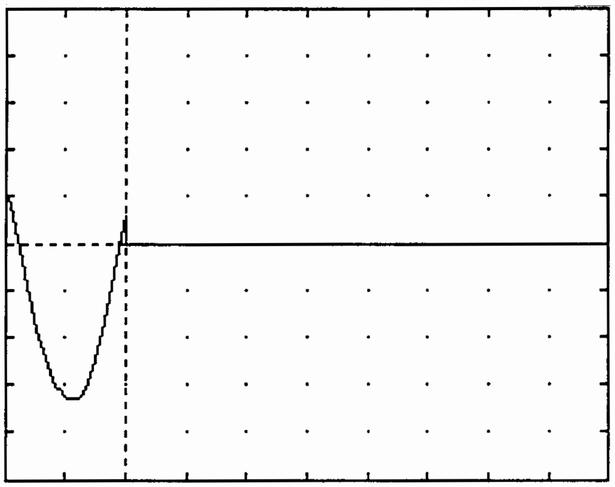
Practically speaking, determining critical events involves collecting all disturbances that appear to describe the same event, and then analyzing each disturbance in light of the whole. If an L-N sag occurred, did an increase in N-G voltage also occur indicating a load change on the monitored circuit? If an interruption occurred were there any waveshape graphs indicating whether the interruption was local or from the utility? Many times an event will be seen as a group of disturbances, each one providing a valuable piece of information needed to put the whole puzzle together.

Isolating an event is done by correlating each graph or report to others with similar time stamps. Be careful to include graph durations when looking at the time stamps. Figure 16 shows three graphs relating to the same event—a brief local interruption. Notice in 16c) that the waveshape disturbance showing the restoration of power has a time stamp equal to the initial waveshape disturbance time plus the interruption duration from the sag graph. This is how events are determined.

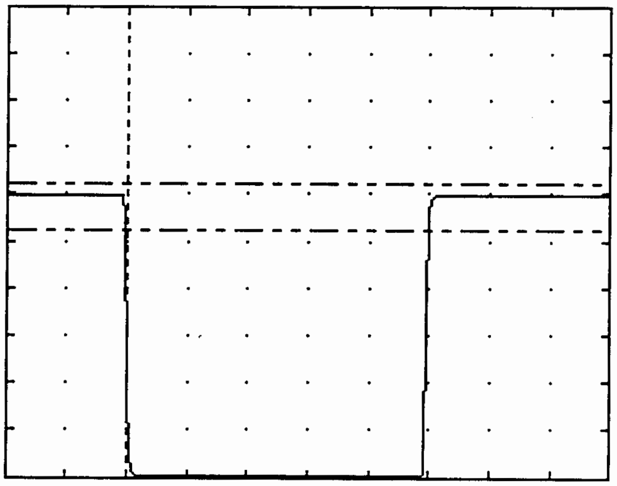
8.3.2 Event reality check

A reality check should also be done on the actual graphs and reports depicting an event. Subclause 8.2.2 defined a reality check as an assurance that recorded data is reasonable based on the circuit configuration and monitoring hookup method. Figures 17 and 18 demonstrate the need for an event reality check.

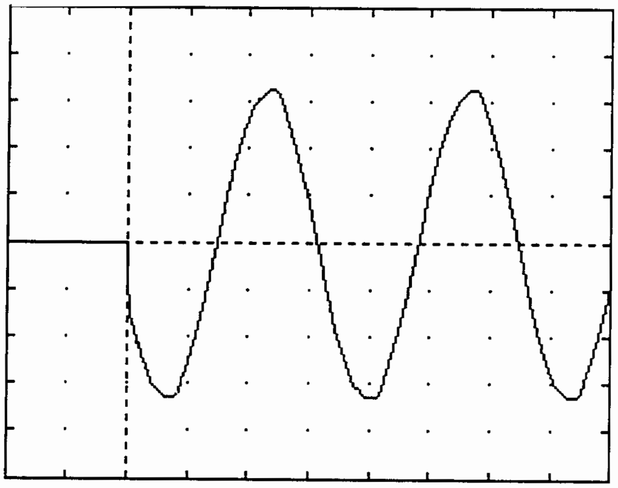
Figure 17 might be interpreted as heavy amounts of pulsed current causing extreme voltage flat-topping. In reality, it is simply the output voltage of a low-end UPS. The real world tells us that it is virtually impossible, in our normal system's operation, to distort the utility's voltage to a square wave.



a) Initial waveshape disturbance—10:55:10



b) L-N temporary interruption with duration = 10 s



c) Final waveshape disturbance—10:55:20

Figure 16—Three graphs describing a local temporary interruption event

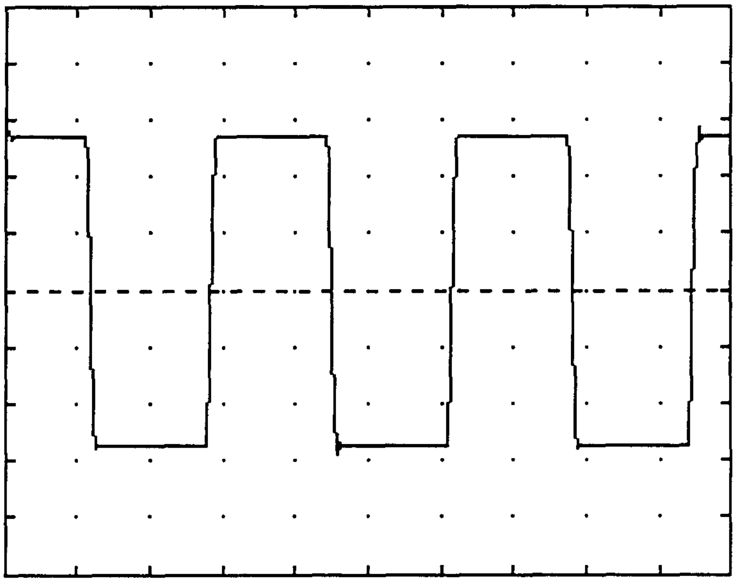


Figure 17—UPS square voltage output

Figure 18 appears to be a fast impulse, perhaps a static discharge. But on closer examination we see that the impulse, with a magnitude of over 400 V, reaches full scale and returns to zero instantly with no overshoot. It is highly unlikely, even when using mitigating devices, that the normally linear power system would respond to an impulse in this fashion. Electrical inertia in the system's impedance would certainly cause some overshoot. This impulse fails the reality check and is most likely the result of instrument error.

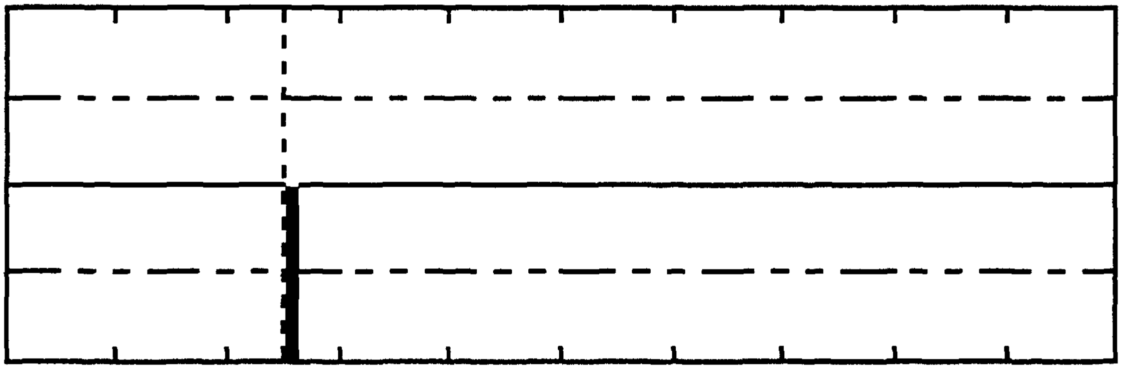


Figure 18—Impulse resulting from instrument error

8.4 Interpreting critical events

Once the critical events have been determined and checked, the next step in interpretation begins. If the analysis of the summaries identified particular events, these should now be examined. If no specific events were identified, then each should be inspected based on its chronological order. Keep in mind that an event may consist of more than one graph or report.

Table 5, shown below, is a reference chart for data interpretation. For the conditions given, it identifies the analysis technique to be used and locates that by subclause number. Each subclause then discusses the characteristics and possible causes.

Table 1—Reference chart for problem analysis

Typical problems	Disturbance type	Possible causes	Subclause
Overheated neutral Intermittent lock-ups Frequency deviations	Steady-state	Shared neutrals Improper or inadequate wiring High source impedance SCR/Rectifiers and notching Harmonics	8.4.2
Interruption Garbled data Random increases in harmonic levels		Utility faults Inrush currents Inadequate wiring	8.4.3
Intermittent lockups Lights flicker Garbled data	Sag/swell	Source voltage variations Inrush/surge currents Inadequate wiring	8.4.4
Component failure Dielectric breakdown Lock-ups Garbled data Wavy CRTs	Impulses EMI/RFI	Lightning Load switching Capacitor switching Static discharge Hand-held radios Loose wiring/arcing	8.4.5
Overheated transformers Voltage distortion Current distortion Overheated motors Garbled Data Lock-ups	Harmonics	Electronic loads SCR/rectifier Loads bandwidth of source impedance	8.4.6
Problems occur at the same time Problems occur at regular intervals	All	Timed loads Cyclical loads	8.4.7
SPS and/or automatic transfer switch does not work Excessive frequency shift	Discontinuities	Switching to alternate sources Non-synchronized power switching	8.4.8

8.4.1 Signature analysis

Signatures are characteristic graphical representations of electromagnetic phenomena. For example, the energization of a certain type of load may consistently generate the same waveshape disturbance. This waveshape would be called its *signature*. Seeing this signature in a monitoring situation identifies the presence of that load.

Many, but by no means all, electromagnetic phenomena have signatures that can be recognized and analyzed. The more information provided by a graph, the greater the possibility that a disturbance can be identified by its signature. Sag/swell graphs, for example, showing simultaneous voltage and current, may more quickly lead to correct conclusions than those showing a voltage sag or swell alone.

8.4.2 Steady-state waveshape analysis

8.4.2.1 Scope

There is much that can be learned from examining the normal, steady-state waveshape of loads or the power system. This type of analysis does not focus on disturbances, but rather on what might be happening when there are no disturbances. Typically, waveshape analysis is more useful at the facility level or further downstream as opposed to the utility level.

Steady-state waveshape analysis provides information regarding the following:

a) Type of loads
b) Adequacy of power system
c) Verification of wiring practices (shared vs. dedicated neutral)

8.4.2.2 Analysis tips

As various loads are turned on, both instantaneous voltages and currents are affected due to Ohm's Law and system impedance. This impact will be both in magnitude (a voltage drop), and in terms of waveshape. For example, if the load is a PC or other electronic load that draws current in large pulses, then the voltage drop will occur at the peak of the voltage waveform. This causes the peak to be flattened somewhat, a condition known as flat-topping.

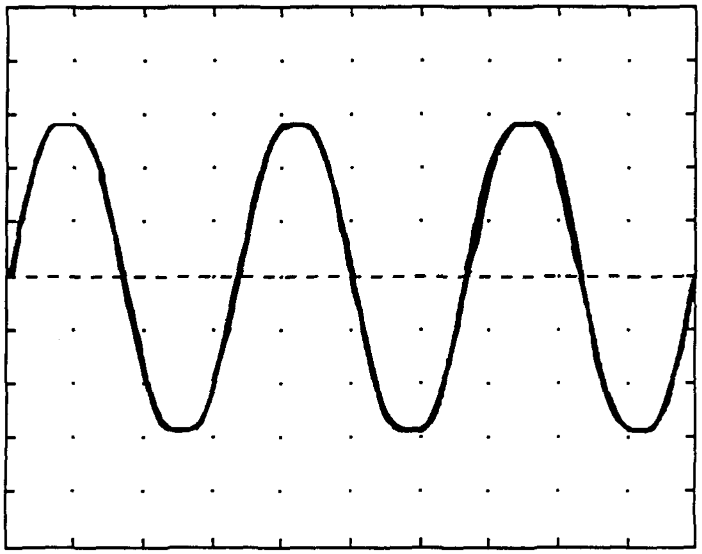


Figure 19—Waveform graph illustrating flat-topping due to switch-mode power supplies

In systems that have neutral-to-ground bonds, a great deal of information is available from the neutral-to-ground voltage and waveshape. Ohm's Law predicts that the neutral-to-ground voltage is proportional to the current in the neutral conductor. The voltage at low frequencies with zero ground conductor current is directly proportional to the neutral current. Consequently, the neutral-to-ground waveshapes and voltages can allow conclusions about the current through the neutral.

This can be especially useful in examining "dedicated" single-phase circuits that are intended to operate electronic loads exclusively. If the neutral-to-ground voltage waveshape shows a large sine wave component, as opposed to the typical pulsed current drawn by electronic loads, there is a non-electronic load sharing the dedicated circuit.

It can also be useful in determining the cause of a low-voltage situation at a load. If the neutral-to-ground voltage on a 120 V circuit is less than a few volts, it implies that the voltage drop across the neutral is low, so presumably the drop across the line conductor is low as well. On the other hand, if the neutral-to-ground voltage is more than a few volts, the voltage drop across the neutral is high, so it is likely that the distribution wiring and connectors are undersized for the load.

Conventional wisdom says that the current in a shared neutral conductor of a balanced three-phase system (i.e., a three-phase system in which the current in each phase is equal) is zero, so the neutral conductor can have a smaller cross-section than the phase conductors. When dealing with single-phase electronic loads, especially ones with switching power supplies, this conventional wisdom is faulty.

Because electronic loads tend to draw all of their current in pulses near the peak of the sine wave, the harmonic currents in each phase fail to cancel even in a perfectly balanced system, and the neutral current can be as much or greater than the current in each phase conductor. The current waveshape may be roughly sinusoidal, but at 180 Hz, it is often referred as the third harmonic neutral current. For single-phase electronic loads sharing a common neutral between phases, the neutral conductor should have twice the cross-sectional area of each of the phase conductors.

Keep in mind also that not only is the neutral-ground rms voltage proportional to the neutral current, but also its waveshape. So if the neutral current is 180 Hz, so will be the neutral-ground voltage. Since the neutral current can be very high, this neutral-ground voltage may also become excessive. Also, remember that a change in neutral-ground voltage can occur due to a change in impedance (e.g., loose connection) in the neutral circuit, or due to abnormal current in the ground circuit.

8.4.3 Waveshape disturbance analysis

8.4.3.1 Scope

Waveshape disturbances are those phenomena that cause a significant change in the voltage or current waveshape from one cycle to the next, or from some representative wave. Typically, waveshape disturbances are associated with voltages rather than currents since the dynamic load variations in a facility constantly and dramatically alter the current waveshape.

Waveshape disturbances provide information regarding system adequacy and the nature of loads inside a facility. Some faults help determine the appropriate source of disturbances such as interruptions, while others may identify the cause of distortion.

8.4.3.2 Analysis tips

An ac electrical system contains inertia, which requires consideration of system response characteristics. The power system, and all the loads connected to it at any given time, conduct and consume power on a continual basis. Major disruptions of this flow will result in changes to the actual waveshapes, but not instantaneously. Current may cease to flow abruptly, but there may be energy dumped into the system from the collapsing fields. Many loads, such as motors, do not stop instantaneously when supply voltage is interrupted. They can regenerate voltage as they spin down, making an interruption take up to several seconds to go to 0 V.

8.4.4 Sag/swell analysis

8.4.4.1 Scope

Similar to waveshape disturbances, sags and swells describe variations with the waveshapes of the voltage or current. However, sags and swells are typically 1/2 cycle to 1 min in duration, and are referred to as rms events. This means that instead of looking at the instantaneous waveshape, we examine the rms value of the wave. If this value is 10% below or above nominal, then a sag or swell has occurred. Occurrences of rms voltage 10% above or below normal that last longer than 1 min are overvoltages or undervoltages.

8.4.4.2 Analysis tips

Sudden changes in current will produce changes in the L-N or the N-G voltage for similar periods of time. For example, if a load is energized that has a 1.5-s in-rush current, an L-N sag and an increase in N-G voltage will be generated for the same 1.5 s. In fact, the N-G voltage rise will be about one-half the magnitude of the L-N sag. The sag is a product of the voltage drops of the line and neutral conductors, while the N-G voltage is only a product of the neutral (see figures 6 and 7).

Recognizing that most sag or swell conditions result from changes in current can help determine the cause of most of these types of disturbances. Whenever both voltage and current are known, it is even easier to identify the possible causes. Depending on the monitoring location with respect to the entire power system, electrical inertia may also contribute to sags and swells.

8.4.5 High frequency analysis

8.4.5.1 Scope

Many disturbances other than those at power frequencies exist in the power system. Some of these disturbances are continuous, low-voltage, high-frequency signals conducted on the power lines. Others are very brief medium- to high-voltage signals known as transients. When these disturbances are injected into the power system, it responds differently than it would at low frequency.

8.4.5.2 Analysis tips

At higher frequencies, the power system is subject to capacitive coupling, and other phenomena not significant in low-frequency analysis. High-frequency models are used when examining transients and other disturbances with frequency components above about 20 times the fundamental frequency of the power system. For example, above about 1.2 kHz on 60 Hz systems the high frequency effects cannot be ignored.

Field data has shown that transients can travel from one wire to another, even if the wires are not connected (presumably by capacitive coupling). They can travel through open-circuit breakers, and can appear across what appears to be an open circuit at lower frequencies. The high-frequency characteristics of the power system need to be considered in the frequency range discussed earlier. Reflections at high frequencies can also occur (remember the half-wavelength of 1 MHz is only 150 m), although they are generally damped out rapidly by capacitive loads on the line.

Transients are generally caused by adding or removing reactive loads from the line. Obviously environmental causes such as lightning occur, but far less often than load induced transients (see figures 1 and 4). A very simplistic model of a capacitor and an inductor are shown in figure 20.

A capacitor being added to a power system is typically in its discharged state. When it is turned on, it draws up to 1000% of its nominal current for 1 to 5 cycles. This causes a switching transient. The transient reflects the energy draw of the capacitor. This means that the transient's leading edge will be opposite in polarity from the ac waveform since energy is being drawn from the source. If the capacitive load is turned on at the positive half cycle of the ac, then the transient's leading edge will be negative.

As a capacitive load is introduced into the inductive power system, it may also alter the frequency response of the system. An LC system has resonant frequencies that may be excited by the capacitive transient, leading to a damped oscillatory transient.

On the other hand, when an inductor is applied to the power system, not much happens in the transient realm. The inductor will draw current and generate its magnetic field. The inductor, however, causes a transient at de-energization. If the switch controlling the inductive load is opened, three things happen. First, the

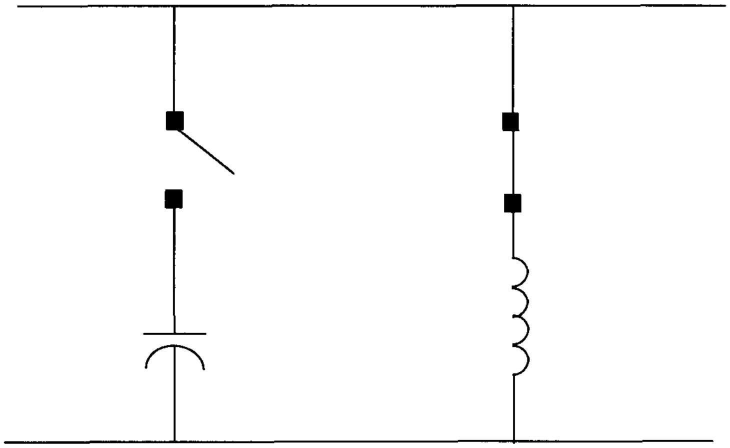


Figure 20—Model for generation of load induced transients

magnetic field collapses creating a transient. This is called inductive kickback. Since this transient is adding energy back into the system, its position on the ac waveform will be in the same polarity.

Second, the switch trying to break the flow of current may arc slightly. Arcing is seen as very fast "noise" superimposed on the inductive transient. The degree of arcing can also indicate proximity to the source of the transient.

Third, depending on the amount of current being interrupted, the switch may bounce. Switch bounce produces a second, smaller transient immediately following the first.

8.4.6 Harmonic analysis

8.4.6.1 Scope

Harmonics produce steady-state distortion of a voltage or current signal when compared to a pure sine wave. Although harmonics have always been present in the power system, the advent of computers and power conversion devices has forever altered the "sine wave mentality" of electrical theory, design, and practical application.

8.4.6.2 Analysis tips

Three techniques for analyzing harmonics will be examined in subclauses 8.4.6.2.1 through 8.4.6.2.3. The first involves several simple ways of determining whether harmonics are present in the power system. The second provides help in determining what particular type of load may be contributing to harmonic distortion. The last looks at how harmonic data can be used to produce an impedance spectrum of the power system.

8.4.6.2.1 Harmonic presence

Before expensive harmonic-measuring equipment is rented or purchased, several easy tasks can be done to determine if harmonics are present. The measurement requires both true rms and conventional measuring devices. If the answer to any of the following questions is yes, then harmonics are present (see figure 10).

- — Is the crest factor (ratio of peak to rms) of the voltage or current different than 1.4?
- — Is the form factor (ratio of rms to average) of the voltage or current different than 1.1?
- — Do the readings from a true rms meter differ from those of an averaging type meter?
- — Is the neutral current in a panel greater than what is expected due to simple imbalance?

8.4.6.2.2 Generic harmonic spectrums

If harmonics are present in the power system, then further investigation typically requires the use of a harmonics analyzer. Such a device can provide specific information about harmonic levels. Some of these provide only the total harmonic distortion (THD), while others provide THD and a full harmonic spectrum. Harmonic spectrums can be very useful in gaining insight into the general type of load(s) which may be contributing to the overall distortion.

Three generic harmonic spectrum signatures are described in the following. Keep in mind that these are general descriptions only.

a) If there are significant even order harmonics, then the signal is not symmetrical with respect to the zero axis.
b) Single-phase power conversion devices will typically produce high third harmonic current distortion with an exponential decay of each successive odd harmonic.
c) Three-phase rectifiers will produce higher current harmonics in accordance with

$$h = k \times q \pm 1$$

where

h is the harmonic order
k is constant 1, 2, etc.
q is the number of pulses of rectifier

The highest harmonic will occur at $k = 1$ and +1, the next at $k = 1$ and –1. Each successive set of harmonics will be smaller. Thus, a six-pulse rectifier will have a high fifth and seventh ($1 \times 6 \pm 1$), then smaller eleventh and thirteenth ($2 \times 6 \pm 1$), and so forth. See [B13].

8.4.6.2.3 Impedance spectrums

The last technique to be examined is the impedance spectrum. An example is shown in figure 21. This method takes both voltage and current harmonic data and graphs the impedance vs. frequency of the power system. It provides useful information regarding system frequency response, resonant points, and potential problems due to harmonic distortion. See [B13].

To generate the impedance spectrum, the desired current harmonic data and the difference in voltage harmonic data at the point of interest needs to be measured. The difference in voltage harmonic data is the difference between the no-load and full-load voltage harmonic data resulting from the load(s) in question. The no-load data can either be obtained from turning the loads off, or possibly using the harmonic data from some point near the source, say, at the source transformer or service entrance.

With this data, the impedance can be calculated at each harmonic frequency and plotted. The subsequent graph will provide insight into the frequency characteristics of the power system seen at the point of measurement. Should a high impedance exist due to resonance at a harmonic frequency, for example, then care should be taken to reduce any harmonic currents of that frequency, and so reduce possible voltage distortion.

8.4.7 Pattern recognition

8.4.7.1 Scope

Becoming familiar with particular electromagnetic signatures is helpful in quickly interpreting graphical data, but many times it is not the graphs that are the most important issue. Other patterns, such as time of

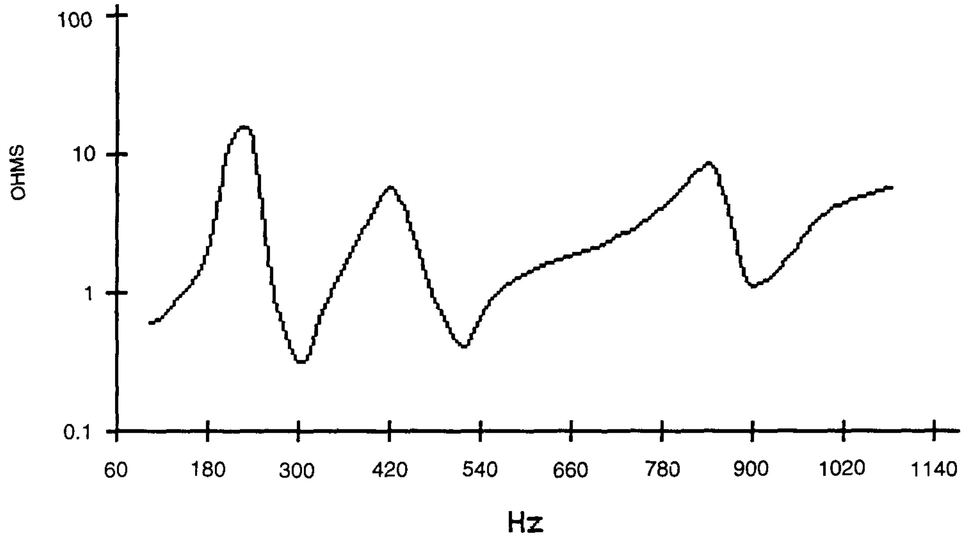


Figure 21—Z vs. F example showing resonant frequencies due to power factor correction capacitor

day, often provide the key to data interpretation. Patterns do not have to be graphical, but can also be textual in nature. Recognizing these additional patterns will be of great benefit in solving the power system puzzle.

8.4.7.2 Analysis tips

The key to pattern recognition is that few disturbance patterns occur naturally—most are man-made. Analyzing them involves simply tracking down what might be the cause and how might this cause impact the operation of other equipment. The following table shows some typical examples of these timing relationships.

Table 2—Pattern recognition

Patterns	Possible causes
Time of day	Power factor correction capacitors being turned on automatically Parking lot lights turning on or off either automatically or with photoelectric switches HVAC/Lighting systems on automatic control
Duration of disturbance	Cyclical loads such as pumps and motors Laser printer heating elements cycling on for only 10–30 s Timing controls on process/manufacturing equipment
Frequency of occurrence	Continuous cycling of heating element in laser printer, copiers Transients from SCR controlled devices occurring every cycle Vending/Soda machine compressor motor creating transients at turn on

8.4.8 Discontinuities

8.4.8.1 Scope

Discontinuities refer to the radical departure of some system component from the norm, which the models cannot explain. In a sense they are a subset of signatures because they do exhibit a graphical pattern, yet they are different because they represent the existence of outside influencing factors. The two most prominent outside factors are mitigating devices and alternate sources.

8.4.8.2 Analysis tips

The single most important technique to identify discontinuities is an understanding of how the power system should behave. Departures from normal electrical system response (forced or natural) usually indicate the existence of some outside factor. The following list is helpful in discovering whether or not there has been outside influence.

- Did the frequency of the signal abruptly change?
- Do the zero crossings of the signal remain continuous?
- Did a magnitude change occur instantaneously, or did it take a little time to settle?
- Did the signal suddenly lose a portion of a cycle consistent with loose wiring?

8.5 Verifying data interpretation

Although this is the last subclause of this clause, it is by no means the least important. This clause has primarily focused on taking clues, piecing them together, and arriving at a solution, or at least a very good guess. The final step in the process of data interpretation is to double check the solution (or guess) to see if it is, indeed, the right one for the problem. This can be easily done through examining the following guidelines in 8.5.1 and 8.5.2 for post-monitoring.

An alternative verification is to utilize computer simulation tools. Many such programs are available that allow a user to “test” the validity of a proposed solution, especially if trial and error methods are risky or too expensive.

8.5.1 Post-monitoring for verification

Once a solution has been implemented, post-monitoring determines the success of the solution. It attempts to answer the following questions:

- Is the failing equipment now operating correctly?
- Is there a reduction or elimination of the disturbance(s) in question?

If the answer is “no” to either of these questions, then further investigation is warranted. This is not to say that the solution is wrong. Sometimes it may be, but often, solving one problem simply allows the next to surface.

8.5.2 Post-monitoring for system interaction

Since the power system is just that, a system, changing one part of the system may affect other parts. It is entirely possible that the “solution” to a problem may actually introduce another problem into the system. For example, if the problem is that a vending machine injects transients into the power lines and disrupts a workstation, the solution may be to plug the vending machine into a different receptacle. This works fine for workstation #1, but now workstation #2 has problems because the vending machine is now plugged into its receptacle. Post-monitoring helps to determine if any other concerns have come up due to the implementation of a solution.

Annex A

(informative)

Calibration and self testing

A.1 Introduction

Electrical measurements and the ancillary field of meter calibration are two aspects of the same industry. As new advances are made in measurement instrument technology, new calibration technology is demanded to keep these instruments at peak performance and maintain their traceability to national standards.

Calibration requirements should be based upon monitoring objectives and the nature of loads, not on the specific instrument used. We should ask ourselves, "What are the consequences if the measurements do not meet specification?" If we are measuring voltage to ANSI C84.1-1989 [B1] specifications, the tolerance is ±5%, steady state. There can be occasional excursions outside this boundary. What are the accuracy and calibration requirements for compliance with ANSI C84.1-1989? The document does not describe any. It does say that the measured values must be in rms values but does not indicate whether the values can be determined by means of peak recording volt-meter technology that uses an algorithm to convert to rms. This method is not accurate with distorted waveshapes. ANSI C84.1-1989 defines steady-state as sustained voltage levels and not momentary voltage excursions. What if, however, we use an instrument that takes periodic snapshots and then calculates an average? Is that method accurate? How can one say that calibration has meaning to that instrument in an absolute sense?

Other factors to be considered include the assumptions of the instrument maker. If we are to measure true rms values accurately under all distorted conditions, then there are only two options to consider—we can either digitally sample multiple points on the wave of a whole cycle and calculate the true rms value, or we can measure the heat generated in a resistor. Can one sample a token number of cycles and average them? Possibly, except that voids in the data may result.

The accuracy of measuring the magnitude of the ac voltage both steady-state and transient disturbances cannot be separated from the process of how the instrument records the measurement. Peak detecting, averaging and special algorithms only work where there is limited waveform distortion.

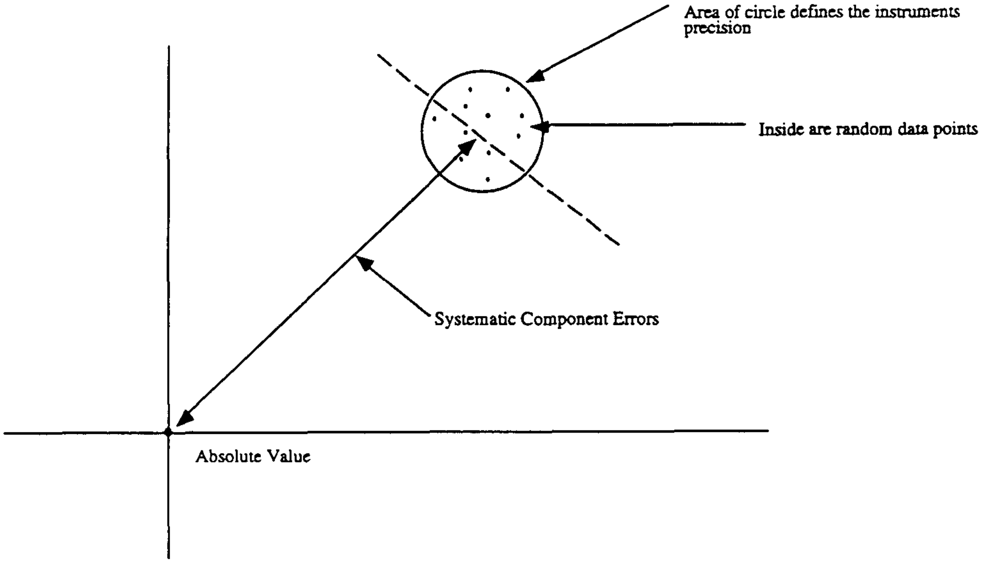


Figure A.1—Instrument accuracy is the combination of (a) random errors and (b) systematic component errors

A.2 Calibration issues

A.2.1 Drift rate

The time span of a specification indicates the length of time an instrument can be expected to remain within the specified limits. One to two years are common time spans for portable instruments. Uncertainties will increase for longer time spans due to a drift rate. If a drift rate specification is included, a buyer can calculate the uncertainty for the time span required.

A.2.2 Temperature coefficient

This represents the amount that uncertainty increases with temperature variation from a specified temperature spread. A typical temperature spread is 23 °C (73°F) ±5 °C. A wide temperature spread and a small temperature coefficient permit on-site calibration since the instruments are outside the protected environment of the calibration laboratory.

A.2.3 Where to calibrate

Calibrating a working instrument in its real environment is inherently more accurate because local affects are taken in account, and on-site calibration is safer since the instrument is not subject to damage in transit. Also, the instrument is out of commission a shorter time. Contrary argument says, “should ‘local effects’ be included or purposely deleted from calibration?” If it affects and creates a more accurate measurement at one site, does not that naturally mean it may produce less accurate data at another site?

A.2.4 Calibration intervals

A broad guideline is provided by military specification MIL-L-45662B [B28]. Test equipment and standards should be calibrated at intervals established on the basis of stability, purpose, degree of usage, precision, accuracy and skills of personnel utilizing the equipment.

Some instruments offer built-in calibration. It is important to know exactly what a built-in calibrator is testing. Internal self-test can be limited by its own processing procedure, so it is important to determine what type it uses. Internal testing can be limited by providing only a couple of points on a spectrum to try to validate performance whereas a laboratory calibrator would generate a whole spectrum of points; 80 points might be an average. Internal test may only test one section at a time and at low signal levels. The user must determine if that method is adequate. Built-in self-calibration and self-test may not be able to generate high voltages necessary to test the front end circuitry of the instrument. A calibration laboratory would normally use a standard that is four times more accurate than the instrument being calibrated to validate accuracy. This standard is difficult to reproduce with a built-in device.

A.2.5 Calibration points

Manufacturer's manuals for the instruments that will be calibrated are an important reference. Normally, these manuals include recommended calibration procedures along with a set of calibration points, for example, a DMM's calibration points would include voltage levels, frequencies, and resistances.

A.2.6 Self testing

Self testing is a built in feature of some instruments that by means of firmware and special circuitry it can make some limited internal checks.

The ability to run internal calibration checks between external calibration allows the operator to monitor the performance between calibrations and helps to avoid data problems. If the instrument's internal references are well controlled and impervious to environmental changes, then these calibration checks can be performed with the instrument in its working environment. This instills confidence without the need to return the instrument to the calibration lab. Note that these calibration checks do not adjust the instrument's output, but merely evaluate the instrument's output against internal references. Comparison of the internal reference values to external traceable standards is necessary to make traceable internal adjustments.

A.2.7 Practical field checks

On multi-channel analyzers, link all channels together and create a disturbance. If all channels indicate same event/magnitude/duration then calibration is probably adequate.

Annex B

(informative)

Bibliography

B.1 Definitions and general

[B1] ANSI C84.1-1989, American National Standard for Electric Power Systems and Equipment—Voltage Ratings (60 Hz).

[B2] ANSI/NFPA 70-1993, National Electrical Code (NEC).

[B3] "Basic Measuring Instruments," *Handbook of Power Signatures,* Second Edition, 1993.

[B4] "Canadian Electrical Association National Power Quality Survey," CEA Publication Number 220-D711A, 1995.[5]

[B5] "Dranetz Technologies," *The Dranetz Field Handbook for Power Quality Analysis,* 1991.

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

[B7] IEC 1000-2-2 (1990) Electromagnetic Compatibility (EMC)—Part 2: Environment. Section 2: Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems, Section 2, 1990.

[B8] IEC 1000-3-3 (1994) Electromagnetic compatibility (EMC)—Part 3: Limits. Section 3: Limitation of voltage fluctuations and flicker in low-voltage supply systems for equipment with rated current ≤ 16 A.

NOTE—This standard supersedes IEC 555-3 (1982).

[B9] IEC 1000-4-7 (1991) Electromagnetic Compatibility (EMC)—Part 4: Testing and Measurement Techniques. General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected hereto, Section 7.

[B10] IEC Technical Committee 77, Working Group 6 (Secretariat) 110-R5, Classification of Electromagnetic Environments. Draft, January 1991.

[B11] IEEE Std 141-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (Red Book) (ANSI).

[B12] IEEE Std 446-1987, IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (Orange Book) (ANSI).

[B13] IEEE Std 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems (ANSI).

[B14] IEEE Surge Protection Standards Collection (C62), 1992 Edition.

---

[5] Canadian Electrical Association publications are available from the Canadian Electrical Association, 1 Westmount Square, Suite 1600, Montreal, Canada H3Z 2P9.

[B15] UIE-DWG-2-92-D, UIE Guide to Measurements of Voltage Dips and Short Interruptions Occurring in Industrial Installations, October 1993.

[B16] UIE-DWG-3-92-G, *Guide to Quality of Electrical Supply for Industrial Installations*, "Part 1: General Introduction to Electromagnetic Compatibility (EMC), Types of Disturbances and Relevant Standards," Advance UIE Edition, Disturbances Working Group GT 2, 1994.

[B17] UL 1478 (1989), Fire pump relief valves.

[B18] UL 1950 (1993), Safety of information technology equipment, including electrical business equipment.

B.1.1 Introductory

[B19] Allen and Segall, "Monitoring of Computer Installations for Power Line Disturbances," *IEEE PES,* C74 199-6, 1974.

[B20] Burke, James; Griffith, David; and Ward, Dan, "Power Quality—Two Different Perspectives," *IEEE Transactions on Power Delivery,* vol. 5, no.3, pp. 1501–1513, July 1990.

[B21] Dorr, D. S., "AC Power Quality Studies IBM, AT&T and NPL," *INTELEC '91*, Koyoto, Japan.

[B22] Douglas, John, "Quality of Power in the Electronics Age," *Electric Power Research Institute EPRI Journal,* Nov. 1985.

[B23] Goldstein and Speranza, "The Quality of US Commercial Power" *INTELEC,* CH1818-4/82-0000-002B, 1982.

[B24] Jerewicz, R. E., "Power Quality Study 1990-1995," *INTELEC,* CH 29289-0/90/0000/0443.

[B25] Key, Thomas S., "Diagnosing Power-Quality-Related Computer Problems," *IEEE Transactions on Industry Applications*, IA-I5, No. 4, July/Aug. 1979.

[B26] Lawrie, Robert J., Ed., *Electrical Systems for Computer Installations*. New York: McGraw-Hill, 1988.

[B27] Mehta, H. and Smith, J. C., "Important Power Quality Concerns on the Supply Network," *PQA '91,* Paris, France, 1991.

[B28] MIL-L-45662B, Calibration Systems Requirements.

[B29] Nailen, Richard L., "How To Combat Power Line Pollution," *Electrical Apparatus,* Dec. 1984.

[B30] Reason, John, "End-Use Power Quality: New Demand on Utilities," *Electrical World,* Nov. 1984.

[B31] Rechsteiner, Emil B., "Clean, Stable Power for Computers," *EMC Technology & Interference Control News,* vol. 4, no. 3, July–Sept. 1985.

B.1.2 In-depth overview

[B32] Clemmensen, Jane M. and Ferraro, Ralph J., "The Emerging Problem of Electric Power Quality," *Public Utilities Fortnightly,* Nov. 28, 1985.

[B33] Martzloff, François D. and Gruzs, Thomas M., "Power Quality Site Surveys: Facts, Fiction, and Fallacies," *IEEE Transactions on Industry Applications,* vol. 24, no. 6, Nov./Dec. 1988.

[B34] Smith, J. Charles, "Power Quality: End User Impacts," *Proceedings of Energy Technology Conference XV*, Washington, D.C., Feb. 1988.

B.2 Susceptibility and symptoms—voltage disturbances and harmonics

B.2.1 Voltage disturbances

[B35] Standler, Ronald B., "Transients on the Mains in a Residential Environment," *IEEE Transactions on Electromagnetic Compatibility,* vol. 31, no. 2, May 1989.

B.2.2 Harmonics

[B36] Arrillaga, Bradley, and Bodger, *Power System Harmonics*. John Wiley & Sons, 1985.

[B37] Fuchs, E. F., "Investigations on the Impact of Voltage and Current Harmonics on End-Use Devices and Their Protection," *The U.S. Department of Energy,* contract no. DE-AC02-80RA 50150, Jan. 1987.

[B38] Lowenstein, Michael Z., Holley, Jim, and Zucker, Myron, "Controlling Harmonics While Improving Power Factor," *Electrical Systems Design,* March 1988.

[B39] Shuter, T. C., Volkommer, Jr., H. T., and Kirkpatrick, T. L., "Survey of Harmonic Levels on the American Electric Power Distribution System," *IEEE Transactions on Power Systems,* Oct., 1989, pp. 2204–2210.

B.3 Solutions

B.3.1 Utility approach

[B40] Clemmensen, Jane M. and Samotyj, Marek J., "Electric Utility Options in Power Quality Assurance," *Public Utilities Fortnightly,* June 11, 1987.

[B41] Tempchin, Richard S. and Clemmensen, Jane M., "Transforming Power Quality Problems into Marketing Opportunities," *Electric Perspectives,* July-Aug. 1989.

B.3.2 Wiring and electrical design

[B42] Freund, Arthur, "Double the Neutral and Derate the Transformer—Or Else," *EC&M,* Dec. 1988.

[B43] Lazar, Irwin A., "Designing Reliable Power Systems for Processing Plants," *Electrical Systems Design,* July 1989.

[B44] Lewis, Warren, "Application of the National Electrical Code to the Installation of Sensitive Electronic Equipment," *IEEE Transactions on Industrial Applications,* vol IA-22, May/June 1986.

[B45] McLoughlin, Robert C., "Power Line Impedance and Its Effect on Power Quality," *EMC Technology & Interference Control News,* vol. 7, no. 6, Sept. 1988.

[B46] Schram, Peter J., "Coping with the Code— Another Revision is Just Around the Corner," *Electrical Systems Design,* July 1989.

[B47] Sopkin, Louis, "Capacitors Correct Power Factor, Line Voltage, and Wave Distortion," *Electrical Systems Design,* March 1988.

B.3.3 Surge suppression

[B48] Martzloff, François D., "Matching Surge Protective Devices to their Environment," *IEEE Transactions on Industrial Applications,* vol. IA-21, no. 1, Jan./Feb. 1985.

[B49] Shakarjian, D. R. and Standler, "AC Power Disturbance Detector Circuit," *IEEE Transactions on Power Delivery,* vol. 6: pp. 536-540, April 1991.

[B50] Smith, S.B. and Standler, "The Effects of Surges on Electronic Appliances," *IEEE Transactions on Power Delivery,* vol. 7, pp. 1275–1282, July 1992.

[B51] Standler, *Protection of Electronic Circuits from Overvoltages*. New York: Wiley-Interscience, May 1989.

B.3.4 UPS and power conditioning

[B52] Cooper, Edward, "Power Line Conditioning," *Measurements and Control,* June 1985.

[B53] Edman, James, "Selecting a UPS for Today's Systems Requirements," *EMC Technology & Interference Control News,* vol. 4, no. 3, July–Sept. 1985.

[B54] Griffith, David C., "Selecting and Specifying UPS Systems," *Electrical Consultant for Designers and Specifier of Electrical Systems,* May/June and July/Aug., 1981.

[B55] Madoo, Timothy and Rynone, William, "Choosing a UPS System—Consider Before You Buy," *Electrical Systems Design,* May 1987.

[B56] Madoo, Timothy and Rynone, William, "Choosing a UPS System," *Electrical Systems Design,* June 1987.

[B57] Madoo, Timothy and Rynone, William, "What You Can Tell Your Client About High-Powered UPS Systems," *Electrical Systems Design,* April 1987.

[B58] Meirick, R. P., "The Evolution of Uninterruptible Power Supplies," *PCIM Power Conversion & Intelligent Motion,* Oct. 1989.

[B59] Sturgeon, Jeffrey B., "UPS—Providing Power You Can Count On When Things Go Wrong," *Electrical Systems Design,* May 1989.

[B60] Walsh, John J., "UPS/M-G: Quality Computer Power," *Electrical Systems Design,* May 1989.

B.3.5 Electrostatic discharge

[B61] Boxleitner, Warren, "How to Defeat Electrostatic Discharge," *IEEE Spectrum,* Aug. 1989.

B.3.6 Harmonics solutions

[B62] Griffith, David C. and Resch, Robert J., “Working with Waveform Distortion in Digital Systems,” *Powertechnics,* Sept. 1986.

[B63] McGranaghan, Mark and Mueller, Dave, *Designing Harmonic Filters for Adjustable Speed Drives to Comply with New IEEE Std 519 Harmonic Limits*. IEEE Industrial Applications Society, 40th Annual Conference, 1993.

[B64] McGranaghan, Mark; Grebe, Thomas; and Samotyj, Marek, “Solving Harmonic Problems in Industrial Plants and Harmonic Mitigation Techniques for Adjustable-Speed Drives,” Paper Presented at Electrotech 92, Montreal, Canada, 1992.

B.4 Existing power quality standards

Existing power quality standards are listed in this subclause in order to provide resource information that may be of particular interest when making power quality measurements. Standards relating to power quality that exist or are under development at this time are listed below. A brief scope is annotated following most of the sources, and availability information is listed in the footnotes.

[B65] ANSI C84.1-1989, Electric Power Systems and Equipment—Voltage Ratings (60 Hz).[6]
[Voltage rating for power systems and equipment.]

[B66] ANSI C141 Flicker (1975 Edition).

[B67] ANSI/NFPA 70-1993, National Electrical Code (NEC).
[Installation grounding, ADP equipment, interconnected electric power production sources.]

[B68] FIPS PUB94, Guideline on Electrical Power for ADP Installations, 1983.[7]
[Electric power for ADP installations.]

[B69] IEC 1000 Series, Electromagnetic Compatibility (EMC).

[B70] IEEE Std 141-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (IEEE Red Book) (ANSI).
[Industrial electrical power systems.]

[B71] IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book) (ANSI).
[Industrial and commercial power system grounding.]

[B72] IEEE Std 241-1990, IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (IEEE Gray Book) (ANSI).
[Commercial electric power systems.]

[B73] IEEE Std 242-1986, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book) (ANSI).
[Industrial and commercial power system protection.]

---

[6] ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

[7] FIPS publication are available from the National Technical Information Service, US Department of Commerce, Springfield, VA 22161.

[B74] IEEE Std 399-1990, IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (IEEE Brown Book) (ANSI).
[Industrial and commercial power system analysis.]

[B75] IEEE Std 446-1987, IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications (IEEE Orange Book) (ANSI).
[Industrial and commercial power system emergency power.]

[B76] IEEE Std 487-1992, IEEE Recommended Practice for the Protection of Wire Line Communications Facilities Serving Electric Power Stations.

[B77] IEEE Std 493-1990, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (IEEE Gold Book) (ANSI).
[Industrial and commercial power system reliability.]

[B78] IEEE Std 518-1982, IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources (Reaff 1990) (ANSI).
[Guide on noise control.]

[B79] IEEE Std 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems (ANSI).
[Recommended practice on harmonics in power systems.]

[B80] IEEE P519a (D4, 9/95), Guide for Applying Harmonic Limits on Power Systems.[8]

[B81] IEEE Std 602-1986, IEEE Recommended Practice for Electric Systems in Health Care (ANSI).
[Industrial and commercial power system in health facilities.]

[B82] IEEE Std 739-1984, IEEE Recommended Practice for Energy Conservation and Cost-Effective Planning in Industrial Facilities (IEEE Bronze Book) (ANSI).
[Energy conservation in industrial power systems.]

[B83] IEEE Std 929-1988 (Reaff 1991), IEEE Recommended Practice for Utility Interface of Residential and Intermediate Photovoltaic (PV) Systems (ANSI).
[Interconnection practices for photovoltaic power systems.]

[B84] IEEE Std 1001-1988, IEEE Guide for Interfacing Dispersed Storage and Generation Facilities with Electric Utility Systems (ANSI).
[Interfacing dispersed generation and storage.]

[B85] IEEE Std 1035-1989, IEEE Recommended Practice: Test Procedure for Utility-Interconnected Static Power Converters (ANSI).
[Test procedures for interconnecting static power converters.]

[B86] IEEE Std 1050-1989, IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations (ANSI).
[Grounding of power station instrumentation and control.]

[B87] IEEE Std 1100-1992, IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment (Emerald Book) (ANSI).
[Power and grounding sensitive equipment.]

---

[8] Standard project IEEE P519a was not approved by the IEEE Standards Board at the time this went to press. It is available from the IEEE.

[B88] IEEE Std 1250-1995, IEEE Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances (ANSI).

[B89] IEEE P1346 (D2.0, 9/95), Recommended Practice or Evaluating Electric Power System Compatibility With Electronic Process Equipment.[9]

[B90] IEEE Std C57.110-1986 (Reaff 1992), IEEE Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents (ANSI).

[B91] IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits (ANSI).

[B92] IEEE Distribution, Power, and Regulating Transformers Standards Collection, 1995 Edition (C57) (ANSI).

[B93] IEEE Surge Protection Standards Collection, 1995 Edition (C62) (ANSI).

[B94] NEMA-PE1 (1992), Uninterruptible Power Systems.[10]
[Uninterruptible power supply specifications.]

[B95] NEMA MG1 (1993), Motors and Generators.
[Polyphase induction motors.]

[B96] NFPA-75 (1995), Protection of electronic computer data processing equipment.[11]
[Protection of electronic computer data processing equipment].

[B97] NFPA-780-95, Lighting protection code.
[Lighting protection code for buildings.]

[B98] NIST-SP768, Information poster on power quality.[12]
[Overview of power quality with respect to sensitive electrical equipment.]

[B99] UL 1449 (1995), Transient voltage surge suppressors.[13]
[Standards for safety of transient voltage surge suppressors (tvss).]

---

[9] Standard project IEEE P1346 was not approved by the IEEE Standards Board at the time this went to press. It is available from the IEEE.

[10] NEMA publications are available from the National Electrical Manufacturers Association, 2101 L Street NW, Suite 300, Washington, DC 20037, USA.

[11] NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA.

[12] NIST publication SP868 (order number PB89237986) is available from the National Technical Information Service 1-800-553-6847.

[13] UL publications are available from Underwriters Laboratories, Inc., 333 Pfingsten Road, Northbrook, IL 60062-2096, USA.

The following table lists topics with corresponding relevant standards. For additional information on these standards, refer to the noted bibliography references.

Table B.1—Power quality standards by topic

Topics	Relevant standards				
Grounding	IEEE Std 446 [B75]	IEEE Std 141 [B70]	IEEE Std 142 [B71]	IEEE Std 1100 [B87]	ANSI/NFPA 70 [B67]
Powering	ANSI C84.1 [B65]	IEEE Std 141 [B70]	IEEE Std 446 [B75]	IEEE Std 1100 [B87]	IEEE Std 1250 [B88]
Surge protection	IEEE C62 series [B93]	IEEE Std 141 [B70]	IEEE Std 142 [B71]	NFPA 78 [B97]	UL 1449 [B99]
Harmonics	IEEE Std C57.110 [B90]	IEEE Std 519 [B79]	IEEE P519a [B80]	IEEE Std 929 [B83]	IEEE Std 1001 [B87]
Disturbances	ANSI C62.41 [B91]	IEEE Std 1100 [B87]	IEEE Std 1159[a]	IEEE Std 1250 [B88]	
Life/fire safety	FIPS PUB94 [B68]	ANSI/NFPA 70 [B67]	NFPA 75 [B96]	UL 1478 [B17]	UL 1950 [B18]
Mitigation equipment	IEEE Std 446 [B75]	IEEE Std 1035 [B85]	IEEE Std 1100 [B87]	IEEE Std 1250 [B88]	NEMA-UPS [B94]
Telecommunications equipment	FIPS PUB94 [B68]	IEEE Std 487 [B76]	IEEE Std 1100 [B87]		
Noise control	FIPS PUB94 [B68]	IEEE Std 518 [B78]	IEEE Std 1050 [B86]		
Utility interface	IEEE Std 446 [B75]	IEEE Std 929 [B83]	IEEE Std 1001 [B84]	IEEE Std 1035 [B85]	
Monitoring	IEEE Std 1100 [B87]	IEEE Std 1159 (see note f)			
Load immunity	IEEE Std 141 [B70]	IEEE Std 446 [B75]	IEEE Std 1100 [B87]	IEEE Std 1159[a]	IEEE P1346 [B89]
System reliability	IEEE Std 493 [B77]				

[a] IEEE Std 1159-1995 is this standard.