

IEEE Recommended Practice for Monitoring Electric Power Quality

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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.

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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*

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Mark Andresen
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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
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Daniel J. Ward
Charles H. Williams

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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:

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Richard B. Engelman
Robert E. Hebner
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Rochelle L. Stern
IEEE Standards Project Editor

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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 $\pm 10\%$ 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 100-1992³ 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.

¹IEC publications are available from IEC Sales Department, Case Postale 131, 3, rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse. IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

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

³Information on references can be found in clause 2.

⁴The 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 (V_n): 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 or 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	frequency shift
blink	glitch
brownout (see 4.4.3.2)	interruption (when not further qualified)
bump	outage (see 4.4.3.3)
clean ground	power surge
clean power	raw power
computer grade ground	raw utility power
counterpoise ground	shared ground
dedicated ground	spike
dirty ground	subcycle outages
dirty power	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 μ s 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 μ s	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 μ s	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.

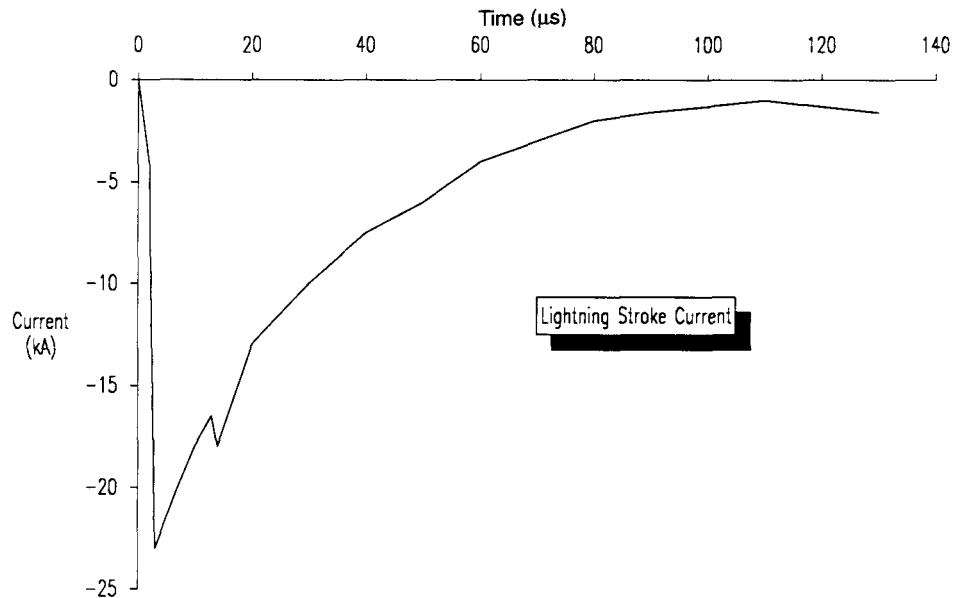


Figure 1—Lightning stroke current that can result in impulsive transients on the power system

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.

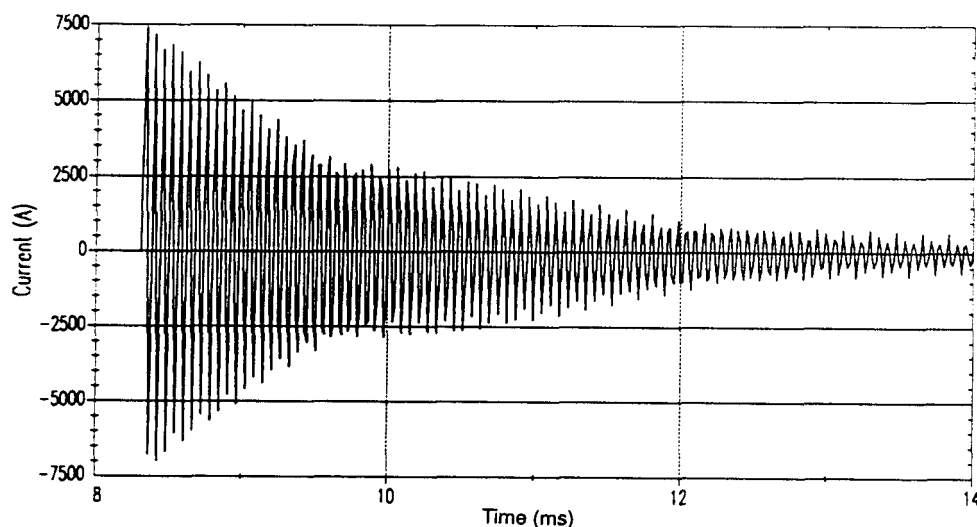


Figure 2—Oscillatory transient caused by back-to-back capacitor switching

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.

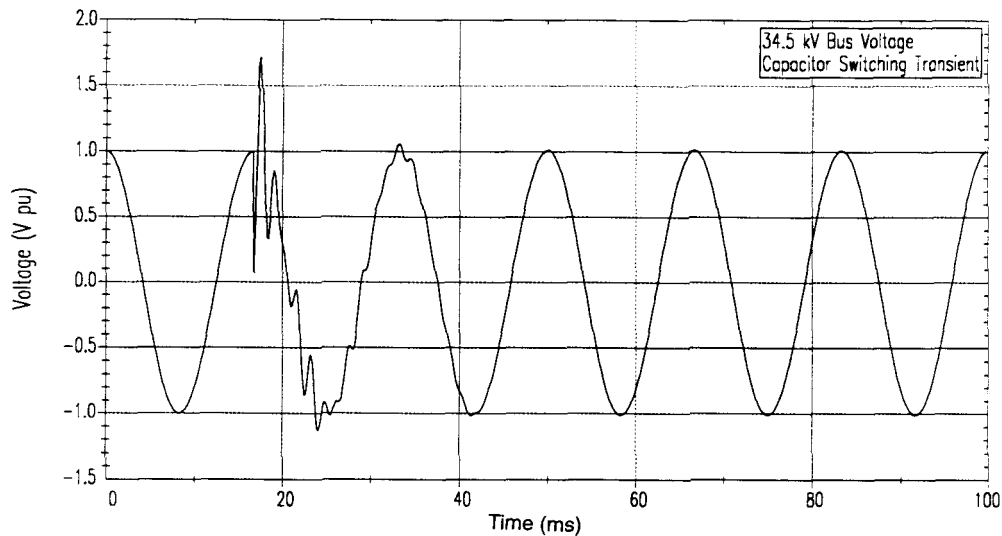


Figure 3—Low frequency oscillatory transient caused by capacitor-bank energization

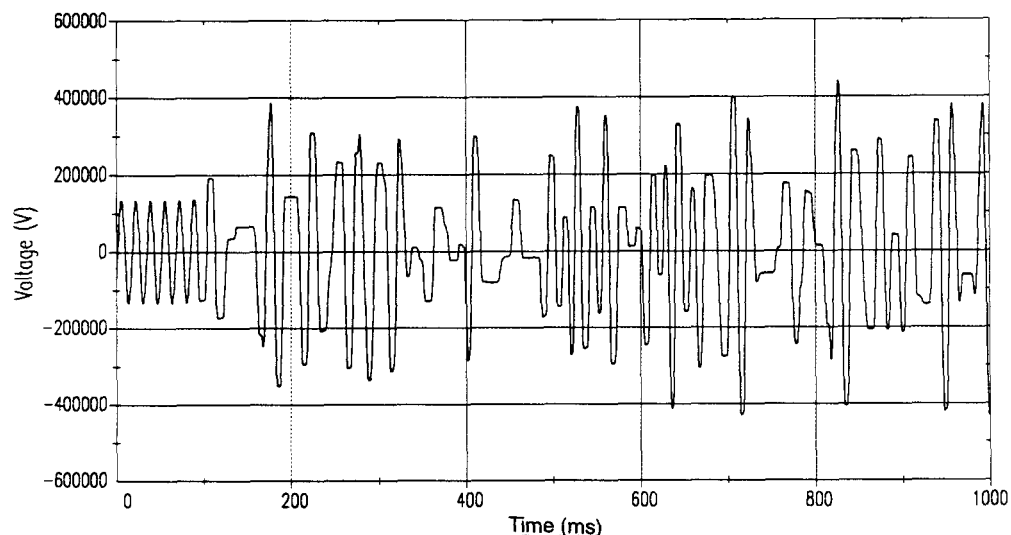


Figure 4—Low-frequency oscillatory transient caused by ferroresonance of an unloaded transformer

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 wave-shape 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.

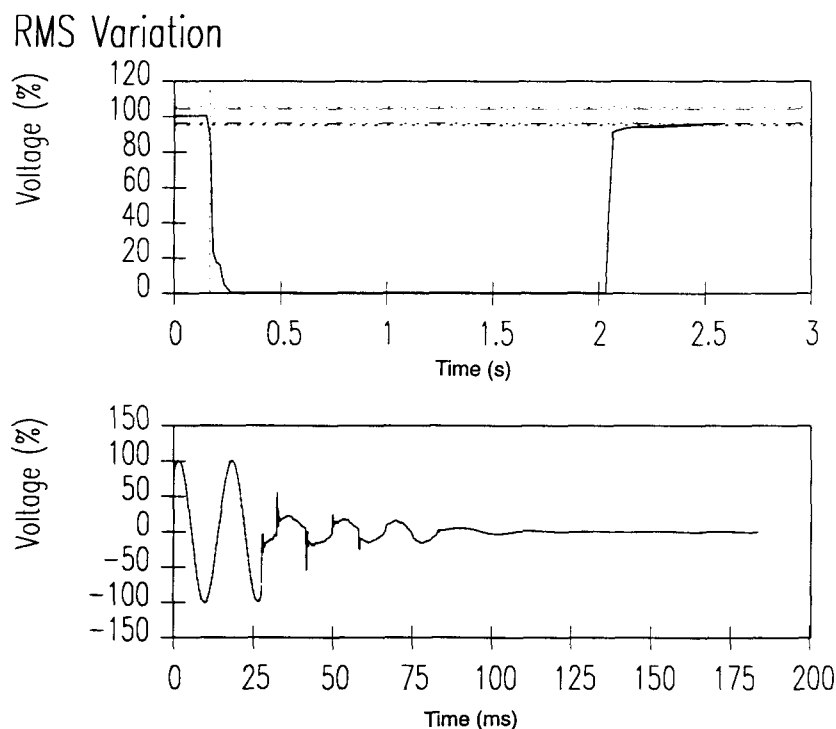


Figure 5—Momentary interruption due to a fault and subsequent recloser operation

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.

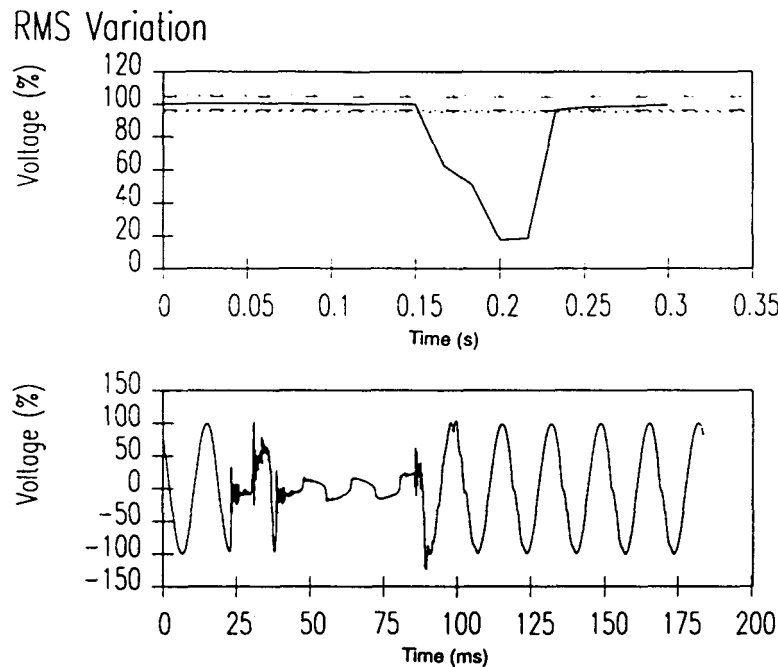


Figure 6—Instantaneous voltage sag caused by a SLG fault

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].