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IEEE Recommended Practice for Monitoring Electric Power Quality

IEEE Power and Energy Society

Developed by the
Transmission and Distribution Committee

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USA

IEEE Std 1159™-2019
(Revision of IEEE Std 1159-2009)

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Approved 13 June 2019

IEEE-SA Standards Board

Abstract: The monitoring of electrical characteristics of single-phase and polyphase ac power systems is encompassed in this recommended practice. It includes consistent descriptions of conducted electromagnetic phenomena occurring on power systems. This recommended practice describes nominal conditions and deviations from these nominal conditions that may originate within the source of supply or load equipment or may originate from interactions between the source and the load. Also, this recommended practice discusses power quality monitoring devices, application techniques, and the interpretation of monitoring results.

Keywords: assessment, compatibility, dip, distortion, electromagnetic phenomena, harmonics, IEEE 1159, imbalance, instruments, interference, monitoring, noise, power quality, rms variation, sag, susceptibility, swell, transient, unbalance

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PDF: ISBN 978-1-5044-5928-0 STD23741
Print: ISBN 978-1-5044-5929-7 STDPD23741

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Introduction

This introduction is not part of IEEE Std 1159-2019, IEEE Recommended Practice for Monitoring Electric Power Quality.

This recommended practice provides useful information for individuals interested in power quality monitoring projects. It provides definitions, summaries, and characterizations of typical power quality phenomena that lead to power quality problems. There is discussion on monitoring instruments and selecting the appropriate instrument for the task followed by information on the application of the monitors is provided, including: safety, locations to monitor, sensing inputs, and measurement thresholds. After the monitoring period is completed, there is information on validating the data, extracting the critical data, and interpreting both summaries and critical events.

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IEEE Recommended Practice for Monitoring Electric Power Quality

1. Overview

1.1 Scope

This recommended practice encompasses the monitoring of characteristics of electric power systems. It includes consistent descriptions of conducted electromagnetic phenomena occurring on power systems. This recommended practice presents definitions of nominal conditions and deviations from these nominal conditions that may originate within the source of supply or load equipment or may originate from interactions between the source and the load. This recommended practice also discusses measurement techniques, application techniques, and the interpretation of monitoring results.

1.2 Purpose

This recommended practice provides users with a consistent set of terms and definitions for describing power quality phenomena. An understanding of how power quality phenomena affects the power system and end-use equipment is required in order to make monitoring useful. Proper measuring techniques are required to safely obtain useful, accurate data. Appropriate location of monitors, systematic studies, and interpretation of results will enhance the value of power quality monitoring. The purpose of this recommended practice is to assist users as well as equipment and software manufacturers and vendors by describing techniques for defining, measuring, quantifying, and interpreting electromagnetic phenomena on the power system.

2. Normative references

No normative references apply to this recommended practice. Bibliographical references can be found in Annex D.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[1]

flicker: The subjective impression of fluctuating luminance caused by voltage fluctuations.

fundamental (component): The component of an order 1 (e.g., 50 Hz, 60 Hz) of the Fourier series of a periodic quantity.

imbalance (voltage or current): The ratio of the negative sequence component to the positive sequence component, usually expressed as a percentage. *Synonym:* **unbalance (voltage or current).**

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).

instantaneous: When used to quantify the duration of a short-duration root-mean-square (rms) variation as a modifier, refers to a time range from 0.5 cycles to 30 cycles of the power frequency.

interface: The term “interface” used in this document is a generic use of the word and can be an external interface, such as between transducer’s output and the instrument’s input terminals; an internal interface, such as between the data acquisition section of the instrument and the data storage section; or a user interface such as a graphical user interface (GUI).

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

long-duration root-mean-square (rms) variation: A variation of the rms value of the voltage or current from the nominal for a time greater than 1 min. The term is usually further described using a modifier indicating the magnitude of a voltage variation (e.g., undervoltage, overvoltage, voltage interruption).

momentary interruption: A type of short-duration root-mean-square (rms) voltage variation where the complete loss of voltage (<0.1 pu) on one or more phase conductors is for a time period between 0.5 cycles and 3 s.

noise floor: The artifact of the measuring system, including the transducers, input amplifiers, analog-to-digital converters, etc., which is approximately 1% of the nominal.

root-mean-square (rms) variation: A term often used to express a variation in the rms value of a voltage or current measurement from the nominal. *See:* **momentary interruption, temporary interruption,** and **sustained interruption**.

NOTE—See Clause 4 for information on specific types of events, i.e., sag, swell, undervoltage, and overvoltage.

short-duration root-mean-square (rms) variation: A variation of the rms value of the voltage or current from the nominal for a time greater than 0.5 cycles of the power frequency but less than or equal to 1 min. When the rms variation is voltage, it can be further described using a modifier indicating the magnitude of a voltage variation (e.g., sag, swell, interruption) and possibly a modifier indicating the duration of the variation (e.g., instantaneous, momentary, temporary).

sustained interruption: A type of long-duration root-mean-square (rms) voltage variation where the complete loss of voltage (<0.1 pu) on one of more phase conductors is for a time greater than 1 min.

temporary interruption: A type of short-duration root-mean-square (rms) variation where the complete loss of voltage (<0.1 pu) on one or more phase conductors is for a time period between 3 s and 1 min.

[1]*IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org.

total interharmonic distortion: The ratio of the root mean square of the harmonic content, considering Interharmonic components up to the 50th order and specifically excluding harmonics, expressed as a percent of the fundamental. Interharmonic components of order greater than 50 may be included when necessary.

voltage change: A variation of the root-mean-square (rms) or peak value of a voltage between two consecutive levels sustained for definite but unspecified durations.

voltage fluctuation: A series of voltage changes or a cyclical variation of the voltage envelope.

voltage interruption: The disappearance of the supply voltage on one or more phases. It is usually qualified by an additional term indicating the duration of the interruption (e.g., momentary, temporary, sustained).

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

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 amplifies the definitions of Clause 3 and the glossary in Annex C 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 has been a variety of attempts to describe the phenomena. Unfortunately, different segments of the electronics and power systems community have utilized different terminologies to describe electromagnetic events. This clause expands the terminology that should be used by the power quality community to describe these common events. The clause also explains why commonly used terminology in other communities should not be used by the power quality community.

4.2 Electromagnetic compatibility

This recommended practice uses the electromagnetic compatibility approach to describe power quality phenomena. The electromagnetic compatibility approach has been accepted by the international community in International Electrotechnical Commission (IEC) standards produced by IEC Technical Committee 77. The reader is referred to Clause 3, the glossary in Annex C, and The IEEE *Standards Dictionary Online* for the definitions of electromagnetic compatibility and related terms. UIE-DWG-3-92-G [B53] provides an excellent overview of the electromagnetic compatibility concept and associated IEC documents.

4.3 General classification of phenomena

In IEC 61000-2-5:2017 [B13], the IEC classifies electromagnetic phenomena into several groups as shown in Table 1. The IEC standard addresses the conducted electrical parameters shown in Table 1. The terms high frequency 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. Similarly, the category short- duration variations is used to refer to voltage dips and short interruptions. The term swell was introduced as an inverse to sag (dip). The category long-duration variation was added to deal with the limits in ANSI C84.1-2016 [B2]. The category noise was added to deal with broadband conducted phenomena. The category waveform distortion is used as a container category for the harmonics, interharmonics, and dc in ac networks phenomena in IEC 61000-4-7:2009 [B15] as well as an additional phenomenon from IEEE Std 519-2014 [B27] 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

Group	Examples
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 (CW) voltages or currents
	Unidirectional transients
	Oscillatory transients
Radiated high-frequency phenomena	Magnetic fields
	Electric fields
	Electromagnetic fields
	Continuous waves
	Transients
Electrostatic discharge phenomena (ESD)	—
Nuclear electromagnetic pulse (NEMP)	—

The phenomena listed in Table 1 can be described further by listing appropriate attributes (see IEC 61000-2-5-2017 [B13]). For steady-state phenomena, the following attributes can be used:

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

For nonsteady-state phenomena, other attributes may be required as follows:

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

Table 2 provides information regarding typical spectral content, duration, and magnitude where appropriate for each category of electromagnetic phenomena (see UIE-DWG-3-92-G [B53], IEC 61000-2-5-2017 [B13], and UIE-DWG-2-92-D [B52]). 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. Note that most of the phenomena described in this table apply to measured voltages; however, sometimes a phenomenon can manifest itself in a current. The remainder of this clause discusses 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 history regarding the terms currently in use for each category. Typical causes of electromagnetic phenomena in each category are introduced; additional information and interpretation can be found 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 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 phenomena are discussed.

Table 2—Categories and typical characteristics of power system electromagnetic phenomena (see note)

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[a]
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 root-mean-square (rms) 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 – 3s	< 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
2.2.4 Voltage Imbalance		30 cycles – 3 s	2%–15%
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
2.3.4 Voltage Imbalance		>3 s – 1 min	2%–15%
3.0 Long duration rms 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
3.4 Current overload		> 1 min	

Table continues

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
4.0 Imbalance 4.1 Voltage 4.2 Current		 steady state steady state	 0.5-5% 1.0-3.0%
5.0 Waveform distortion 5.1 DC offset 5.2 Harmonics 5.3 Interharmonics 5.4 Notching 5.5 Noise	 0–9 kHz 0–9 kHz broadband	 steady state steady state steady state steady state steady state	 0–0.1% 0–20% 0–2% 0–1%
6.0 Voltage fluctuations	< 25 Hz	intermittent	0.1–7% 0.2–2 P_{st} [b]
7.0 Power frequency variations		< 10 s	± 0.10 Hz
NOTE—These terms and categories apply to power quality measurements and are not to be confused with similar terms defined in IEEE Std 1366™-2012 [B30] and other reliability-related standards, recommended practices, and guides.			

[a] The quantity *pu* refers to *per unit*, which is dimensionless. The quantity 1.0 pu corresponds to 100%. The nominal condition is often considered to be 1.0 pu. In this table, the nominal peak value is used as the base for transients and the nominal rms value is used as the base for rms variations.

[b] Flicker severity index P_{st} as defined in IEC 61000-4-15:2010 [B17] and IEEE Std 1453™ [B31].

4.4.1 Transients

The term *transient has* been used in the analysis of power system variations for many years. Its name immediately conjures up the notion of an event that is undesirable but momentary in nature. *The IEEE Standards Dictionary Online* definitions of transient reflects this understanding. The notion of a damped oscillatory transient due to a resistor-inductor-capacitor (RLC) network is the type of phenomena that most power engineers think of when they hear the word *transient*.

Another word used in current IEEE standards that is synonymous with transient is *surge*. *The IEEE Standards Dictionary Online* defines a surge as “a transient wave of current, potential, or power in an electric circuit.” IEEE Std C62.41.1-2002 [B23] uses the terms *surge*, *switching surge*, and *transient* to describe the same types of phenomena. For the purposes of this recommended practice, the term *surge* should not be used to describe transient electromagnetic phenomena. Since *the IEEE Standards Dictionary Online* uses the term *transient* to define surge, this limitation should not cause conflicts.

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

4.4.1.1 Impulsive transients

An impulsive transient is a sudden, nonpower frequency change from the nominal condition of voltage, current, or both, that is unidirectional in polarity (primarily either positive or negative). Impulsive transients are normally characterized by their peak value, rise and decay or duration times. These phenomena should also be described by their spectral content. For example, when an impulsive transient voltage is described as having a 1.2/50 waveshape, 1.2 expresses a measure of the rise time (from 10% to 90% of peak) in microseconds and 50 expresses a measure of the duration from start to 50% peak in microseconds (see IEEE Std C62.41.1-2002 [B23] for a precise definition of these measures).

The most common cause of impulsive transients is lightning. Figure 1 illustrates a typical current impulsive transient caused by lightning. Due to the high frequencies involved, impulsive transients are damped quickly by impedance circuit elements.

Impulsive transients can excite power system resonance circuits and produce oscillatory transients, described in 4.4.1.2. There can be significant differences in the transient characteristic from one location to another within a facility.

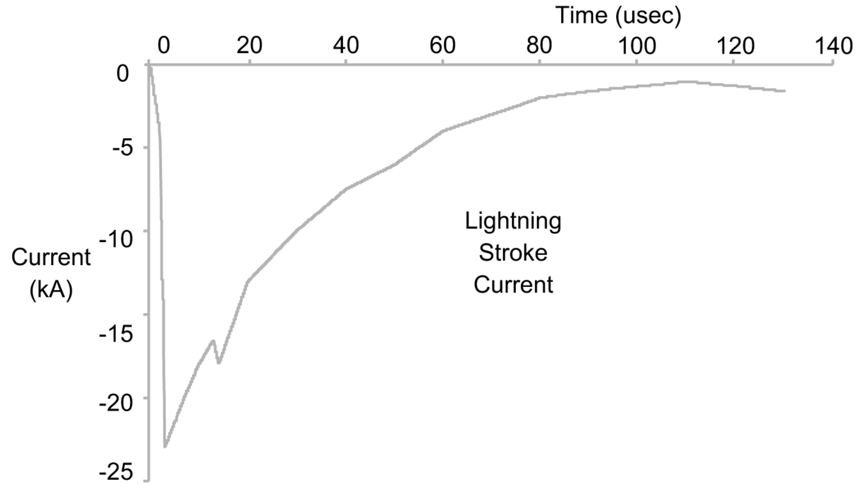


Figure 1—Lightning stroke current that can result in impulsive transients on power system

4.4.1.2 Oscillatory transient

An oscillatory transient is a sudden, nonpower frequency change in the steady-state condition of voltage, current, or both, that includes both positive and negative polarity values. An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly multiple times and normally decaying within a fundamental-frequency cycle. The oscillation is also known as ringing and is described by its magnitude, duration, and spectral content (predominantly frequency that can be used to determine rise time). 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 can 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 up to 0.1 pu (less the 60 Hz component).

A transient with a primary frequency component between 5 kHz and 500 kHz with duration measured in the tens of microseconds (or several cycles of the principal frequency) is considered 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 deenergized bank as a low-impedance path (limited only by the small inductance of the bus to which the banks are connected). 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.

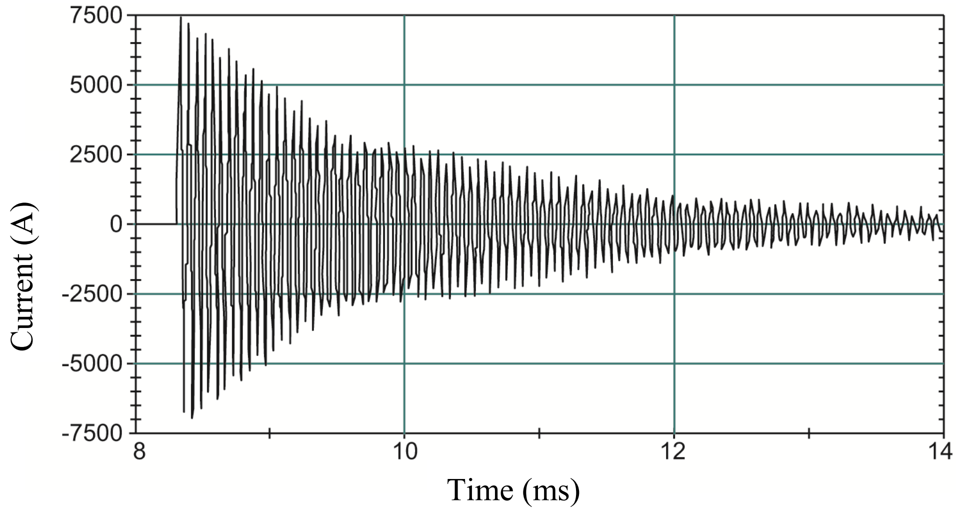


Figure 2—Oscillatory transient caused by back-to-back capacitor switching

A transient with a primary frequency component less than 5 kHz and a duration from 0.3 ms 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 is readily classified using the attributes discussed so far. Capacitor bank energization typically results in an oscillatory voltage transient with a primary frequency between 300 Hz and 1600 Hz. The transient has a peak magnitude that can approach 2.0 pu, but is typically 1.3 pu to 1.5 pu, with durations between 0.5 cycles and 3 cycles of the fundamental, depending on the system damping. See Figure 3.

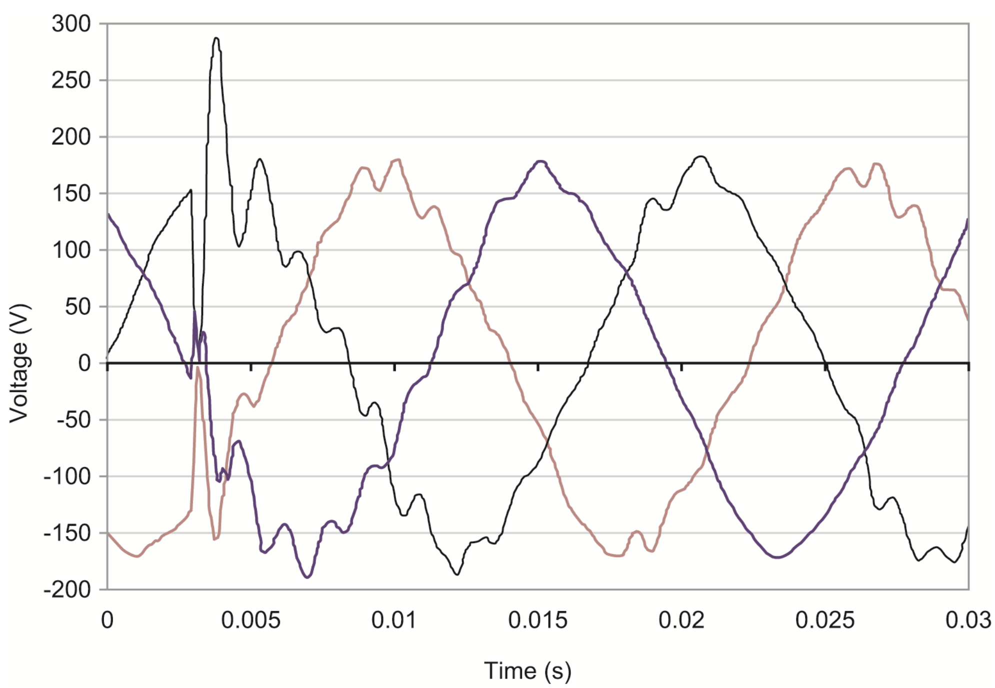


Figure 3—Low-frequency oscillatory transient caused by capacitor-bank energization

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

IEEE Std C62.41.1-2002 [B23] deals with defining standard impulsive and oscillatory transient test waves for the purpose of testing electrical equipment susceptibility and transient suppression technologies. The standard specifies voltage and current levels that certain power system components should be able to withstand.

It is also possible to categorize transients (and other disturbances) according to their mode. Basically, a transient in a three-phase system with a separate ground can be either common mode or normal mode, depending on whether it appears between line or neutral and ground, or between line and neutral.

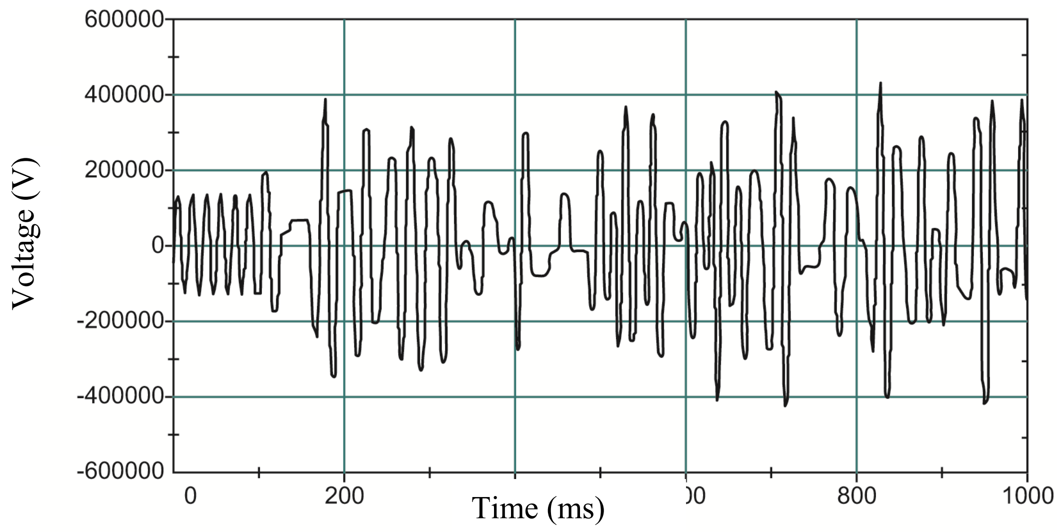


Figure 4—Low-frequency oscillatory transient caused by ferroresonance of unloaded transformer

4.4.1.3 General characteristics

Some of the attributes listed in 4.3 are significant in characterizing transients, including rate of rise, peak amplitude, duration, primary frequency and other spectral components, rate of occurrence and energy potential. Whereas Table 2 in 4.4 defines two categories (impulsive and oscillatory) and uses the typical duration and magnitude to further categorize transients, this subclause describes additional characteristics that are useful in determining the source of the transient, as well as describing the PQ event in words versus images.

In general, the direction that the waveform deviated from the normal sine wave curve is used in the characteristic determination, along with the max/min deviation values for the normal sine wave; the location of the max and min values on the sine wave; whether the signal crossed the zero axis at a point on the wave that it should not normally have; whether there were any ringing or oscillatory signals associated with it; whether the transient is repetitive for multiple cycles at the same point-on-wave; does it only occur near the peaks of the normal sine wave; and so forth.

4.4.1.3.1 Direction

The peak value of the initial transient is subtracted from the value of the sine wave just before the transient and compared to see if the difference is greater than the minimum noise floor level.

none	If the delta is less than the noise floor, the direction cannot be determined accurately
positive	If in the positive half cycle and the delta is positive value, or the negative half cycle and delta is negative. This adds energy to the wave, that is, it heads away from zero.
negative	If in the positive half cycle and the delta is negative value, or the negative half cycle and delta is positive. This subtracts energy from the wave, that is, it heads towards zero.

In the case of a bipolar or oscillatory transient, the direction refers to the first impulsive transient.

Characteristic	**Description**
Unipolar Transient	Deviation in one direction, predominately from the nominal sine wave. Positive deviations: up or adds energy to waveshape. Negative deviations: down or subtracts energy from waveshape.
Bipolar Transient	Deviates in both positive and negative direction from nominal sine wave. Detected by comparing the max and min values in the transient waveform with the nominal waveform values subtracted out. The transient is called bipolar if the polarities are opposite and the ratio of the absolute value of the two values is not too large (called bipolar ratio). If the transient does not contain both directions, then it is unipolar.
Oscillatory Transient	The initial transient is followed by an oscillatory signal superimposed on the normal sine wave, lasting a few milliseconds to quarter cycle, typically, decaying in amplitude over that period. The event is detected if at least three cycles of "visual" oscillation and if the period of the peaks and zero crossings are the same (periodic).
Arcing Transients	A burst of higher frequency noise. Like an oscillation, but random in frequency content. It follows the general envelope of the sine wave, that is, the values do not go to zero.
Multiple Zero Crossing Transients	The transient causes the signal to cross over the zero axes in either direction multiple times, not only at the normal 0 degree or 180 degree points on the sine wave, above the noise floor.
Periodic Notching	A negative transient occurring repetitively with the same approximate amplitude, width, and point on wave.
Capacitor Switching Transient	A special type of oscillatory transient that starts with a negative transient followed by a positive transient of 1.2x to 1.8x the normal value of the sine wave, and then followed by an oscillatory transient of 400−2000 Hz typical, lasting quarter cycle or less. Special characterizations include restrike and back-to-back PF cap switching transients
Energy	The energy of the transient is a product of the voltage squared multiplied by the duration. Given the various shapes that transients have, accurately determining this energy in joules is not commonly found in PQ monitors. Assumptions need to be made about source impedance, whether to use peak or relative voltage and using 50% width points for the voltage value, where on the wave shape to measure duration, and how to deal with bipolar or oscillatory transient.

Figure 5 demonstrates the characteristics in simplistic form, but not as would occur in actual electrical systems.

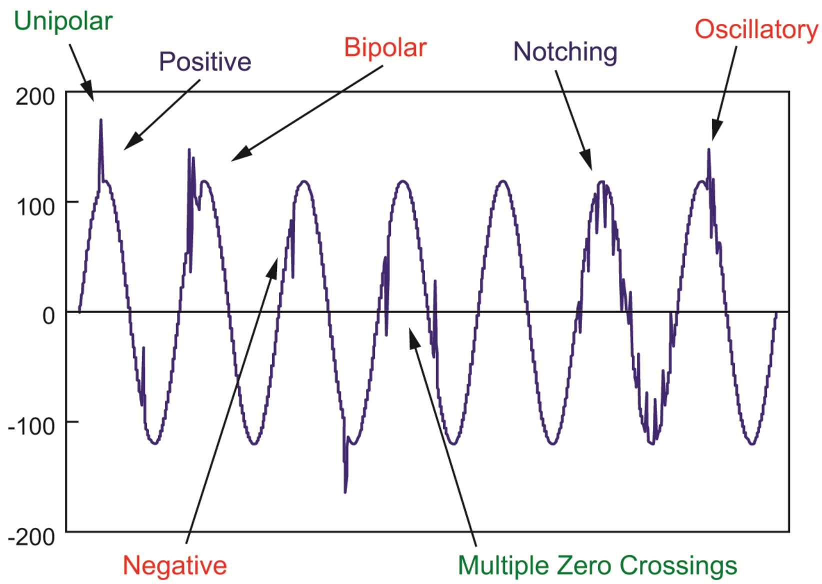


Figure 5—Waveform characteristic

Annex B contains detailed images of waveforms exhibiting most of the aforementioned characteristics. Refer to subclause 8.4 for the effects of transients on equipment, and subclauses 6.5 and 7.4 for measurement instruments for transients. Several clauses in IEEE Std 1250-2011 provide additional information about causes or sources of transients and protection from transients, while Annex C of IEEE Std 519-2014 provides additional information specifically on notches.

4.4.2 Short-duration rms variations

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

Short-duration voltage variations are usually 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 temporary voltage rises (swells), voltage dips (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 that fall into the duration and magnitude categories are also included in short-duration variations.

4.4.2.1 Instantaneous, momentary, and temporary interruptions

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 are 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 experience a voltage sag, followed immediately by an interruption. The duration of the interruption depends on the reclosing capability of the protective device. Instantaneous reclosing generally limits the interruption caused by a nonpermanent fault to less than 30 cycles. Delayed reclosing of the protective device can cause a momentary or temporary interruption.

Figure 6 shows a momentary interruption during which voltage drops to zero for about 1.7 s. Note that the upper plot depicts the rms variation of the entire event over a range of approximately 2.5 s, whereas the lower trace depicts the instantaneous voltage during the initiation of the event only. Furthermore, notice from the waveshape plot of this event, the instantaneous voltage might not drop to zero immediately upon interruption of the source voltage. In this example, the residual voltage is due to the back-electromotive-force effect of induction motors on the interrupted circuit.

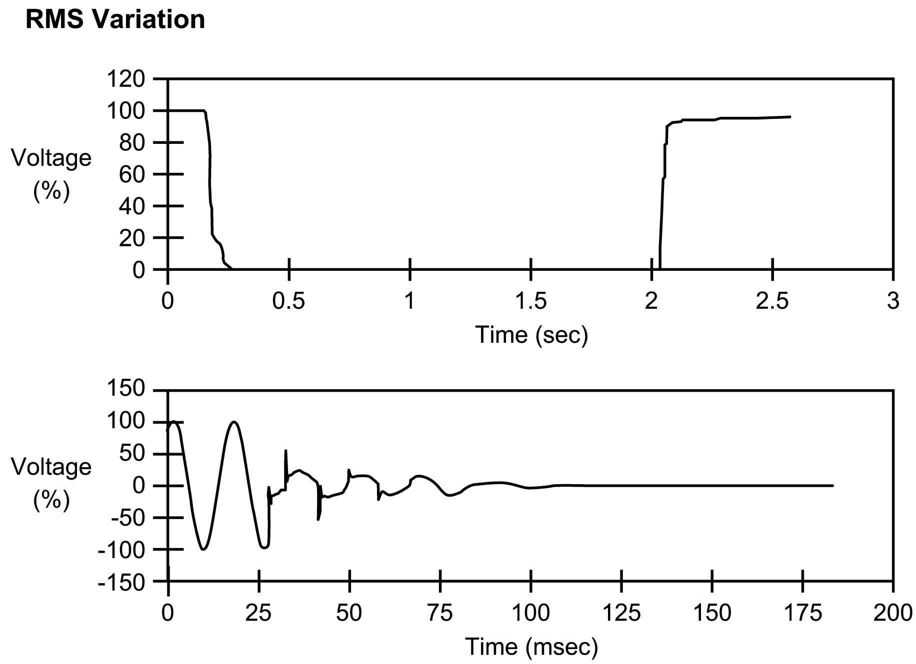


Figure 6—Momentary interruption due to fault and subsequent recloser operation

4.4.2.2 Sags(dips)

A sag is a decrease in rms voltage to between 0.1 pu and 0.9 pu for durations from 0.5 cycles to 1 min. Typical values are between 0.1 pu and 0.9 pu. Terminology used to describe the magnitude of a voltage sag is often confusing. A “20% sag” sometimes refers to a sag that results in a voltage of 0.8 pu or 0.2 pu. The preferred terminology when describing rms variations is *retained voltage* or *remaining voltage*. Therefore, in the absence of guidance, remaining voltage is assumed throughout this recommended practice. Just as an unspecified voltage designation is accepted to mean phase-to-phase voltage, so an unspecified sag magnitude will refer to the remaining voltage. For example, an 80% sag refers to a disturbance that resulted in a voltage of 0.8 pu. Where possible, also specify the nominal, or base, voltage level. Expanding on the previous example, an 80% sag will result in different voltage levels if the nominal is 460 V (remaining voltage of 368 V) or 480 V (remaining voltage of 384 V).

Voltage sags are usually associated with system faults but can also be caused by switching heavy loads or starting large motors. Figure 7 shows a typical voltage sag that is associated with a single line-to- ground (SLG) fault downstream of the monitoring point that was cleared by a downstream protective device. A fault on a parallel feeder circuit results in a voltage drop at the substation bus, which affects all of the other feeders until the fault is cleared, but often these do not result in such deep sags as shown in Figure 7. Typical fault clearing times range from 3 cycles to 30 cycles, depending on the fault current magnitude and the type of overcurrent protection detection and interruption.

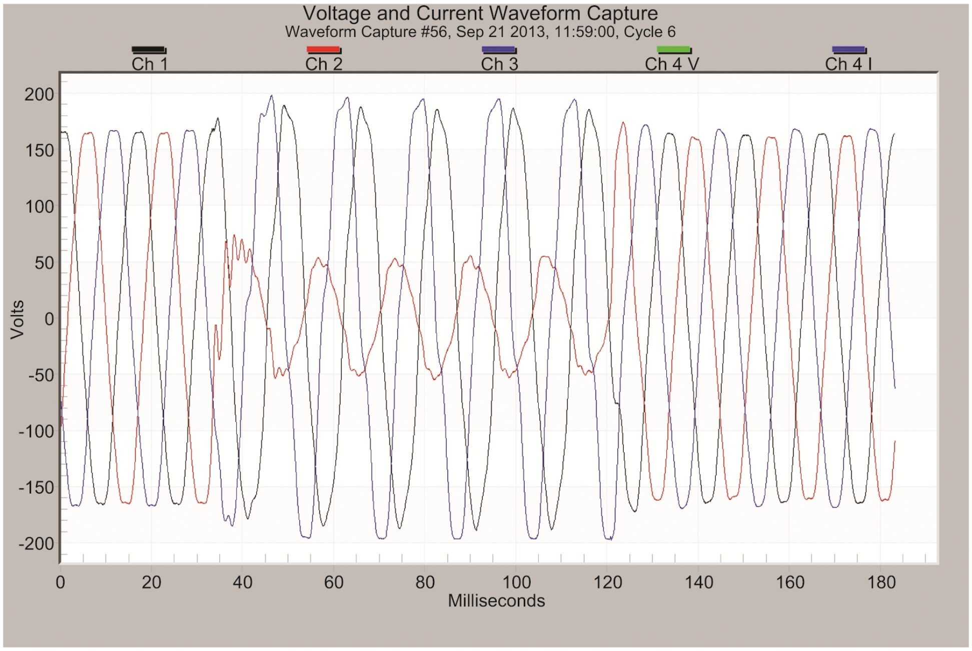


Figure 7—Instantaneous voltage sag caused by SLG fault

Voltage sags can also be caused by large load changes or the starting of large motors. An induction motor can draw six to ten times its full load current during starting. This large 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 8 illustrates the effect of starting a large motor.

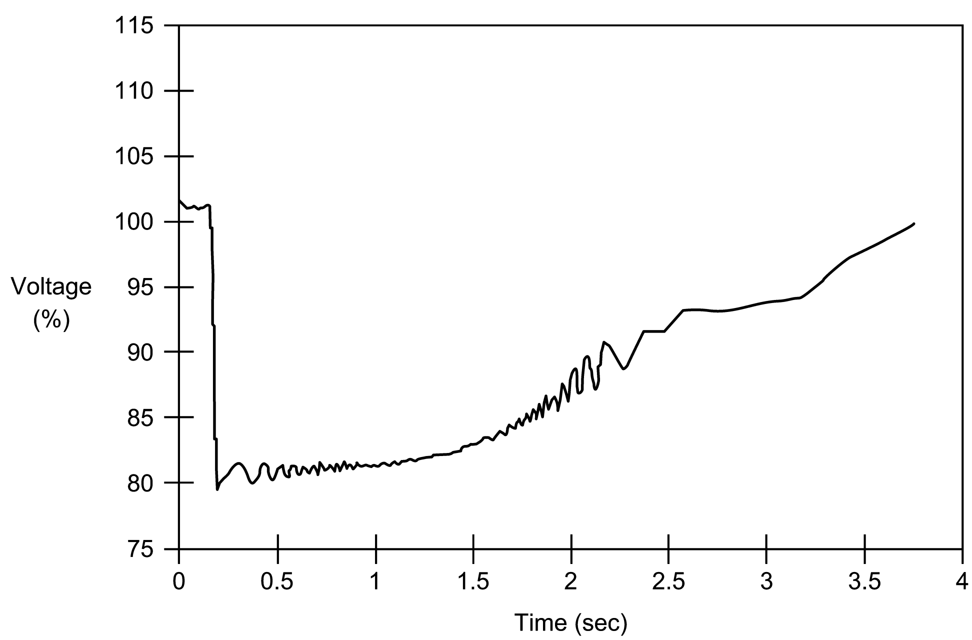


Figure 8—Temporary voltage sag caused by motor starting

The term *sag* has been used in the power quality community for many years to describe a short-duration voltage decrease. Clearly, the notion is directly borrowed from the literal definition of the word *sag*. (This term should not to be confused with the term related to sagging aerial conductors.). The IEC definition for this phenomenon is *dip*. The two terms are considered interchangeable, with *sag* being preferred in the North American power quality community.

The duration of sag events has been defined by IEC 6100-4-30 and other standards. Sags have been defined from 2 ms (about one-eighth of a cycle) to several minutes in various publications. Undervoltages that last less than one-half cycle cannot be characterized effectively as a change in the rms value of the fundamental frequency value. Therefore, these short events are considered transients, per UIE-DWG-3-92-G [B53]. Undervoltages that last longer than 1 min can typically be controlled by voltage regulation equipment and might 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 in this recommended practice 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 (see UIE-DWG-2-92-D [B52]).

4.4.2.3 Swells

A swell is an increase in rms voltage above 1.1 pu for durations from 0.5 cycle to 1 min. Typical magnitudes are between 1.1 pu and 1.2 pu. Swell magnitude is also described by its remaining voltage and hence is greater than 1.0 pu.

As with sags, swells are usually associated with system fault conditions, but they are much less common than voltage sags. An SLG fault on the system can cause a swell to occur, resulting in a temporary voltage rise on the unfaulted phases. Swells can also be caused by switching off a large load, load shedding, or switching on a large capacitor bank. Figure 9 illustrates a voltage swell caused by an SLG fault. The lower graph depicts the instantaneous voltage and the upper graph shows the rms value of the instantaneous voltage in the lower plot. Note the different time scales on the upper and lower plot, and note that the initiation and end times of the rms plot and instantaneous plots do not correspond precisely.

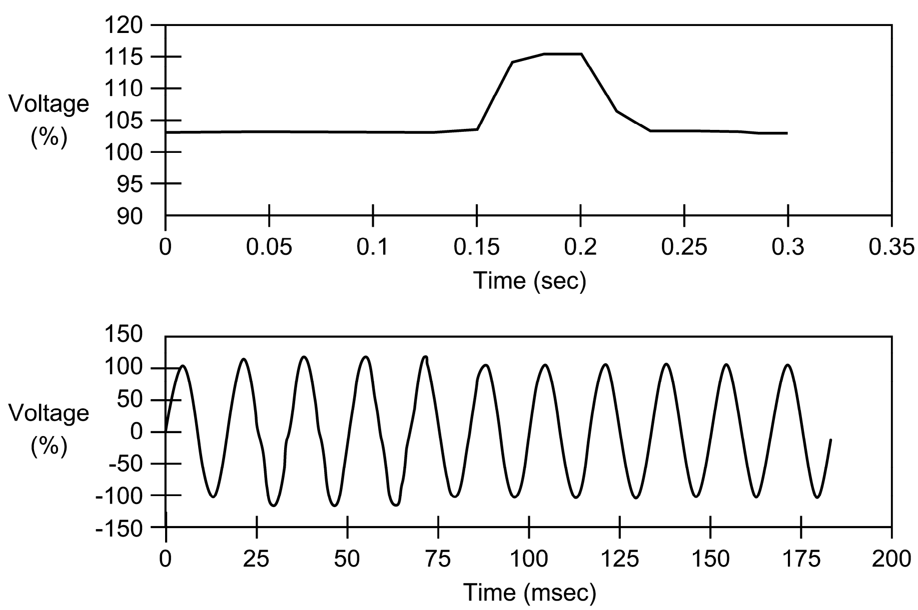


Figure 9—Instantaneous voltage swell caused by SLG fault

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 unfaulted phases are 1.73 pu during a line-to-ground fault condition. Close to the substation on an effectively grounded system, there is no voltage rise on the unfaulted phases because the substation transformer is usually connected delta-wye and provides a low-impedance zero-sequence path for the fault current.

The term *momentary overvoltage* is sometimes used as a synonym for the term *swell*. The formal definition of swell in IEEE Std C62.41.1-2002 [B23] 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.” This definition is not preferred by the power quality community.

4.4.3 Long-duration rms variations

Long-duration variations encompass rms deviations at power frequencies for longer than 1 minute. ANSI C84.1-2016 [B2] specifies the steady-state voltage tolerances expected on a power system. These magnitudes are reflected in Table 2.

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.

4.4.3.1 Overvoltage

An overvoltage is an rms increase in ac voltage greater than 1.1 pu for a duration longer than 1 min. Typical values are 1.1 pu to 1.2 pu.

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

4.4.3.2 Undervoltage

An undervoltage is a decrease in rms voltage less than 0.9 pu for a duration longer than 1 min. Typical values are between 0.8 pu and 0.9 pu.

Undervoltages are the result of the events that are the opposite 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 also result in undervoltages.

The term *brownout* is sometimes used to describe sustained periods of low voltage initiated as a specific generation 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. However, to avoid confusion (because there is no formal definition for brownout and because the term is not as clear as the term *undervoltage* when trying to characterize a disturbance), the term *brownout* should not be used.

4.4.3.3 Sustained interruptions

The decrease of the supply voltage to less than 10% of nominal 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 phenomenon and have no relation to the usage of the term *outage*. Outage, as defined in *The IEEE Standards Dictionary*

Online, 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

Imbalance (sometimes called *unbalance*) in a three-phase system is defined as the ratio of the magnitude of the negative sequence component to the magnitude of the positive sequence component, expressed as a percentage. This definition can be applied for either voltage or current. Typically, the voltage imbalance of a three-phase service is less than 5%. The current imbalance can be considerably higher, especially when single-phase loads are present. Mathematically, the voltage imbalance is represented by Equation (1).

$$\%\ \text{Imbalance} = \frac{|V_{\text{neg}}|}{|V_{\text{pos}}|} \times 100\% \tag{1}$$

Measuring instruments often use a definition of voltage imbalance based on ANSI C84.1-2016 [B2], which defines imbalance as the ratio of the maximum deviation of a voltage from the average voltage to the average voltage, expressed in percent, using phase-to-phase voltage measurements (also see IEEE Std 141™-1993 [B24]). This computation is readily made using measurements from meters that collect only rms values. Other standards, such as the NEMA MG-1-2016 [B43], which uses the term unbalance instead of the equivalent imbalance throughout the document, also use this definition. The reader is cautioned to carefully examine the definition being used by the monitor if imbalance results are important.

The negative-to-positive sequence ratio method defined in this recommended practice is preferred because it directly represents the phenomena of interest without approximation. Some documents refer to the negative-to-positive sequence ratio as the "true unbalance" (e.g., Pillay and Manyage [B47] and Bollen [B4]). The ANSI C84.1-2016 [B2] definition provides results that closely match the preferred definition based on sequence components if the harmonic content is low, phase-to-phase measurements are used, and the system zero sequence content is small.

A chief concern among adopters of the preferred definition is the apparent inability to determine sequence components in the field with simple rms meters. Since the imbalance is computed using a ratio of sequence components, the value of those components independently is not required. Therefore, the imbalance using the preferred definition can be implemented using only phase-to-phase rms measurements without angle with the following equations (see Ghijselen and Van den Bossche [B10] and Kennelly [B40]):

$$\%\ \text{Imbalance} = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \times 100\% \tag{2}$$

where

$$\beta = \frac{|V_{\text{AB}}|^4 + |V_{\text{BC}}|^4 + |V_{\text{CA}}|^4}{\left(|V_{\text{AB}}|^2 + |V_{\text{BC}}|^2 + |V_{\text{CA}}|^2\right)^2} \tag{3}$$

Note that each of the voltages in Equation (3) are rms phase-to-phase voltages. In contrast, Equation (1) is always valid using either phase-to-neutral or phase-to-phase measurements. Equation (2) and Equation (3) are valid only if the system zero sequence component is zero. Thus, Equation (2) and Equation (3) are valid if the voltage measurements are phase-to-phase. This is consistent with the measurements used when applying the ANSI C84.1 definition. Care should be taken if Equation (2) and Equation (3) are used for current imbalance.

For example, they do not apply in a wye-connected system with neutral return; in this case, Equation (1) should be used. The following examples of using these equations with voltage measurements are provided:

Example 1:

Consider a field measurement where the phase-to-phase voltage phasors are $230\angle 0°$, $237\angle -118°$, and $240.6\angle 119.6°$ volts, respectively. The sequence components are as follows:

$$V_{\text{pos}} = \frac{1}{3}\left(V_{\text{AB}} + V_{\text{BC}} \times 1\angle 120° + V_{\text{CA}} \times 1\angle -120°\right) = 235.8\angle 0.5° \text{ V}$$
$$V_{\text{neg}} = \frac{1}{3}\left(V_{AB} + V_{\text{BC}} \times 1\angle -120° + V_{\text{CA}} \times 1\angle 120°\right) = 6.18\angle -159.4° \text{ V}$$

The imbalance using sequence components is as follows:

$$\%\text{ Imbalance } = \frac{6.2}{235.8} \times 100\% = 2.6\%$$

For contrast, the imbalance using the ANSI C84.1 method is now calculated using these measurements.

The average rms voltage is 235.9 V. The maximum deviation from the average among the three measurements is due to the lowest reading: 230 V. The percent imbalance is as follows:

$$\%\text{ Imbalance (ANSI)} = \frac{235.9 - 230}{235.9} \times 100\% = 2.5\%$$

Because phase-to-phase voltages are used, the two methods provide nearly the same result. Next, the imbalance is computed using the alternative method (which uses only phase-to-phase rms magnitudes) as follows:

$$\beta = \frac{|230|^4 + |237|^4 + |240.6|^4}{\left(|230|^2 + |237|^2 + |240.6|^2\right)^2} = 0.3338$$

$$\%\text{ Imbalance} = \sqrt{\frac{1 - \sqrt{3 - (6)(0.3338)}}{1 + \sqrt{3 - (6)(0.3338)}}} \times 100\% = 2.6\%$$

Note that this alternative method provides the same results as Equation (1) without requiring phase angles. If phase-to-neutral voltages were used, the results would not match if zero sequence was present.

Example 2:

The AN, BN, CN phase-to-neutral voltages in a wye-connected 480 V system are measured to be: $281\angle 0°$, $288\angle -115°$, and $270\angle 125°$ V, respectively. Note that this voltage set has zero sequence content. While Equation (1) can use phase-to-neutral voltages, the ANSI C84.1 method and the preferred method using Equation (2) and Equation (3) require the use of phase-to-phase quantities. The phase-to-phase voltages for this system are as follows:

$$V_{\text{AB}} = V_{\text{AN}} - V_{\text{BN}} = 281\angle 0° - 288\angle -115° = 479.9\angle 32.9° \text{ V}$$
$$V_{\text{BC}} = V_{\text{BN}} - V_{\text{CN}} = 288\angle -115° - 270\angle 125° = 483.3\angle -86.1° \text{ V}$$
$$V_{\text{CA}} = V_{\text{CN}} - V_{\text{AN}} = 270\angle 125° - 281\angle 0° = 488.8\angle 153.1° \text{ V}$$

The ANSI definition for the imbalance on these line voltages are computed first. The average of these three voltages is 484 V rms. The % imbalance is computed to be as follows:

$$\%\ \text{Imbalance (ANSI)} = \frac{488.8 - 484}{484} \times 100\% = 1.0\%$$

Now consider the preferred method using symmetrical components. The positive and negative sequence components are as follows:

$$V_{\text{pos}} = \frac{1}{3}\left(V_{\text{AB}} + V_{\text{BC}} \times 1\angle 120° + V_{\text{CA}} \times 1\angle -120°\right) = 484\angle 33.3°\ \text{V}$$
$$V_{\text{neg}} = \frac{1}{3}\left(V_{\text{AB}} + V_{\text{CB}} \times 1\angle -120° + V_{\text{CA}} \times 1\angle 120°\right) = 5.16\angle -109.1°\ \text{V}$$

The % imbalance is computed to be:

$$\%\ \text{Imbalance} = \frac{5.16}{484} \times 100\% = 1.1\%$$

Using Equation (2) and Equation (3) yields β = 0.3334 and also % imbalance = 1.1%. Note that the % imbalance computed by the preferred method is very close to that computed using the ANSI method since the zero sequence content is absent in the phase-to-phase voltages.

The zero sequence voltage of the phase-to-neutral voltages is relatively high: $|V_{\text{zero}}|$ = 40.1 V, which results in considerable differences if phase-to-neutral voltages are used in the ANSI method or Equation (2) and Equation (3). The magnitudes of the positive and negative sequence are 279.4 V and 2.98 V, respectively. Equation (1) still provides the correct answer using the phase-to-neutral values: 2.98/279.4 = 1.1%. However, using Equation (2) and Equation (3) yield % imbalance = 3.7%. The ANSI method yields 3.5% imbalance.

This example has demonstrated that the preferred method of Equation (1) provides the same results, whether phase-to-neutral or phase-to-phase values are used. However, if the phase-to-neutral values have zero sequence content, then the use of phase-to-neutral quantities with Equation (2) and Equation (3) leads to incorrect results. The advantage of using Equation (2) and Equation (3) is the ability to use rms measurements only (without phase angles), unlike Equation (1), which requires phasor values.

Figure 10 shows an example of a one-day trend of imbalance measured at one point on a residential feeder. The trace labeled “V Neg-Seq Imb Total” is using the preferred definition of imbalance. The trace of “V Zero-Seq Imb Total” is the ratio of the zero-sequence-to-positive-sequence voltage. This is sometimes helpful to understand sources of asymmetry in the power system, particularly due to single-phase loads connected phase to neutral or three phase motors. The trace labeled “V Imb Avg LN” is using the ANSI-type maximum deviation from the average definition, but on line-to-neutral quantities.

The primary source of minor voltage imbalance (< 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 or use of single-phase line regulators. Severe voltage imbalance (greater than 5%) can result from single-phasing conditions such as an open protective device upstream of the monitoring point.

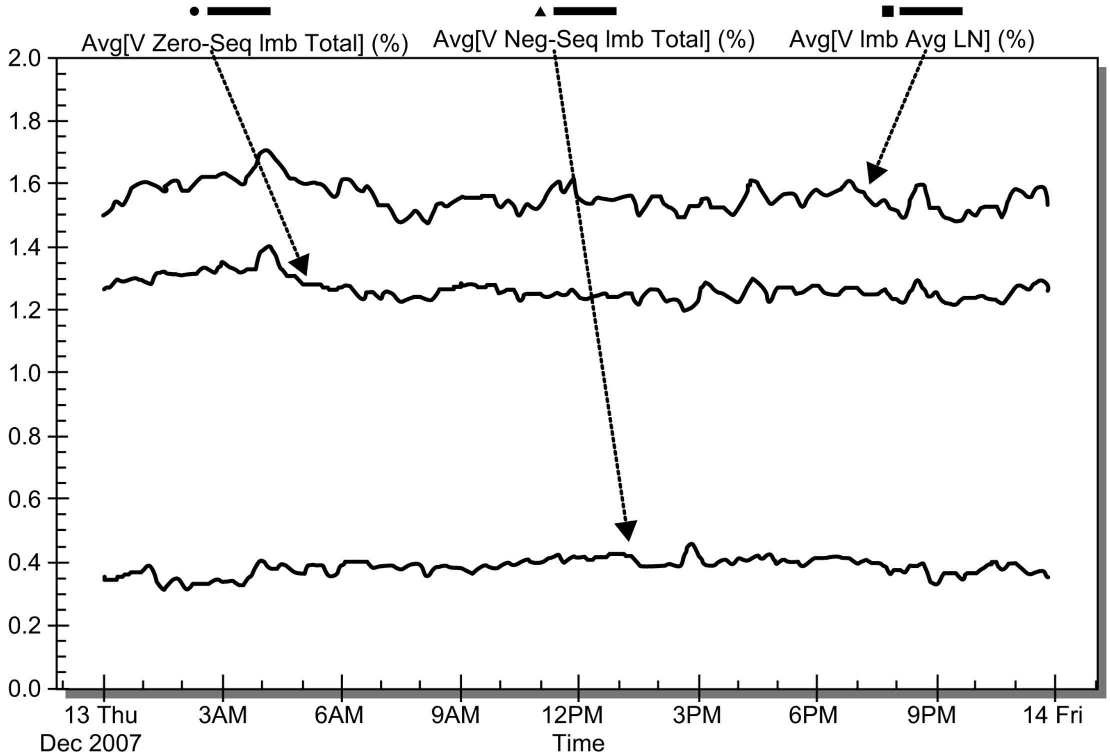


Figure 10—Voltage imbalance trend for three-phase residential feeder

4.4.5 Waveform distortion

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

There are five primary types of waveform distortion as follows:

- DC offset
- Harmonics
- Interharmonics
- Notching
- Noise

Each of these are discussed separately in 4.4.5.1 through 4.4.5.6.

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. For example, incandescent light bulb life extenders can consist of diodes that reduce the rms voltage supplied to the light bulb by half-wave rectification. DC in ac networks can be detrimental due to an increase in transformer saturation and associated heating, which can lead to additional stressing of insulation, among other adverse effects.

4.4.5.2 Harmonics

As described in UIE-DWG-3-92-G [B53], 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). Combined with the fundamental voltage or current, harmonics produce waveform distortion. Harmonic distortion exists due to the nonlinear characteristics of devices and loads on the power system.

Rectified input, switching power supplies often used in electronic-based equipment is a major contributor of harmonics in the power system. Some of these devices and loads (e.g., diode brides and line-commutated converters) can usually be modeled as current sources that inject harmonic currents into the power system. Other devices (e.g., pulse-width modulated inverters used for distributed energy resources and regenerative drives and rotating machines) are much more accurately represented as harmonic voltage sources in series with the devices internal impedance. 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* (THD), as a measure of the magnitude of harmonic distortion.

Harmonic currents result from the normal operation of nonlinear devices on the power system. Figure 11 illustrates the waveform and harmonic spectrum for a typical adjustable speed drive (ASD) input current.

Although current distortion levels can be characterized by a THD as described previously, this can often be misleading. For instance, many ASDs exhibit high THD values for the input current when they are operating at very light loads. This is not a significant concern because the total rms magnitude of harmonic current is low, even though its relative distortion is high.

To characterize harmonic currents in a meaningful way, IEEE Std 519-2014 [B27] defines another term, the *total demand distortion* (TDD). This term is the same as the THD except that the distortion is expressed as a percent of current selected load current, such as the peak demand, rather than as a percent of the rms fundamental current magnitude. IEEE Std 519-2014 [B27] provides guidelines for harmonic current and voltage distortion levels on distribution and transmission circuits.

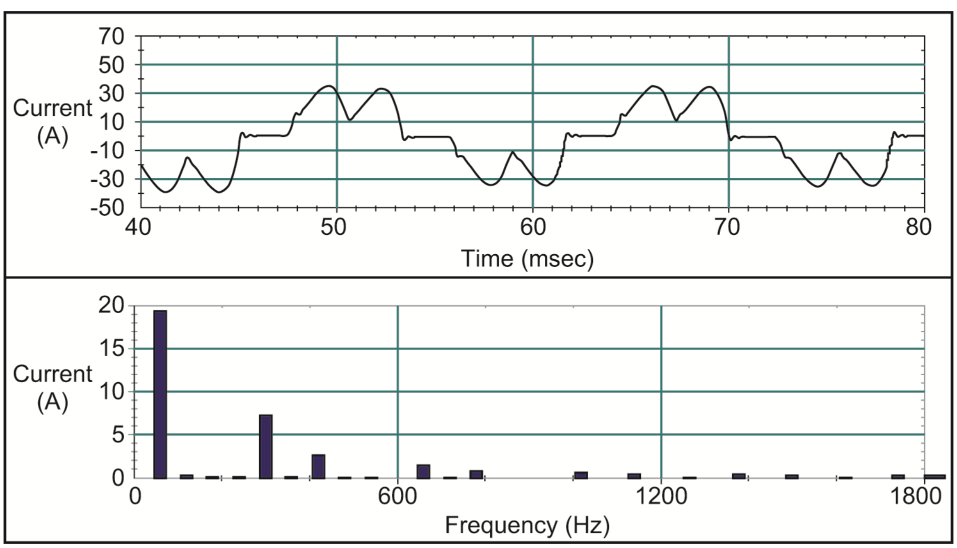


Figure 11 —Current waveform and harmonic spectrum for an ASD input current

4.4.5.3 Interharmonics

Voltages or currents having frequency components that are not integer multiples of the frequency at which the supply system is designed to operate (e.g., 50 Hz, 60 Hz) are called *interharmonics*. They can appear as discrete frequencies or as a wideband spectrum.

Interharmonics can be found in networks of all voltage classes. The main sources of interharmonic waveform distortion are pulse-widge modulated inverters (e.g., such as those used for distributed energy resources), static frequency converters, cycloconverters, induction furnaces, and arcing devices, especially those whose control is not synchronized with the power system frequency. 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 to induce visual flicker in display devices such as cathode ray tubes (CRTs). Additionally, Yacamini [B54] reports low-frequency torsional oscillations in motors due to low subsynchronous frequency components. In IEC 61000-2-2 [B12] the IEC places background noise phenomenon in the interharmonic category. This recommended practice discusses noise separately as a distinct electromagnetic phenomenon in 4.4.5.6.

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 is periodic, yet has frequency content that is quite high. Thus, it has attributes that could be considered both transients and harmonic distortion. Since notching occurs continuously (steady-state), it can be characterized through the harmonic spectrum of the affected voltage. However, due to the high-frequency components associated with notching, characterization of such may not be possible with the typical harmonic measurement equipment.

Three-phase converters that produce continuous dc output are the most important cause of voltage notching (Figure 12). 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, the magnitude of the current, and the point being monitored. Notching is described in detail in IEEE Std 519-2014 [B27].

Voltage notching can sometimes cause frequency or timing errors on power electronic circuits that count zero crossings to derive frequency or time. It is possible for the voltage notch to produce additional zero crossings that can cause frequency or timing errors. These are not, however, power frequency variations. Phase-locked-loop systems with large time constants can be slow to track frequency excursions (phase shifts) and cause gating errors on thyristor-based systems.

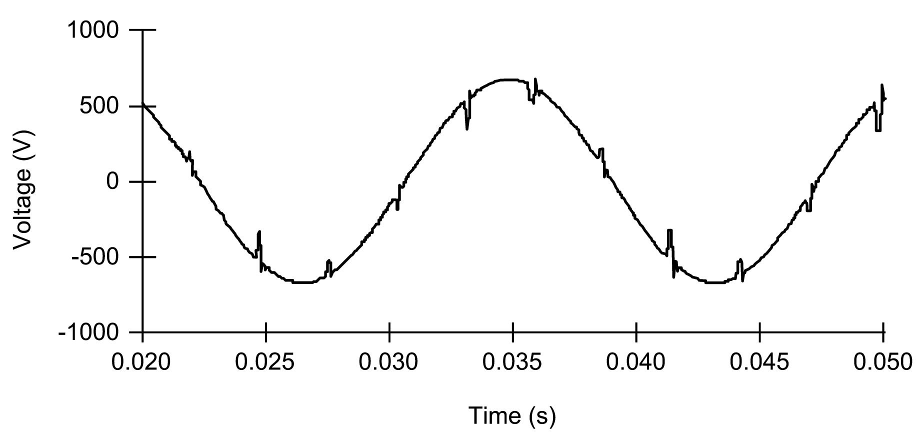


Figure 12—Example of voltage notching by converter operation

4.4.5.5 Voltage notching ringing

Voltage notching ringing is a variant of voltage notching, when a system resonance results in a ringing response at each of the commutation notches. It typically occurs on utility distribution systems that feed large (>500 hp) commutating converter drive equipment at medium voltage. The ringing frequency is a result of the system resonance. The problem has been mitigated by changing the system resonance conditions through harmonic filters or capacitor banks.

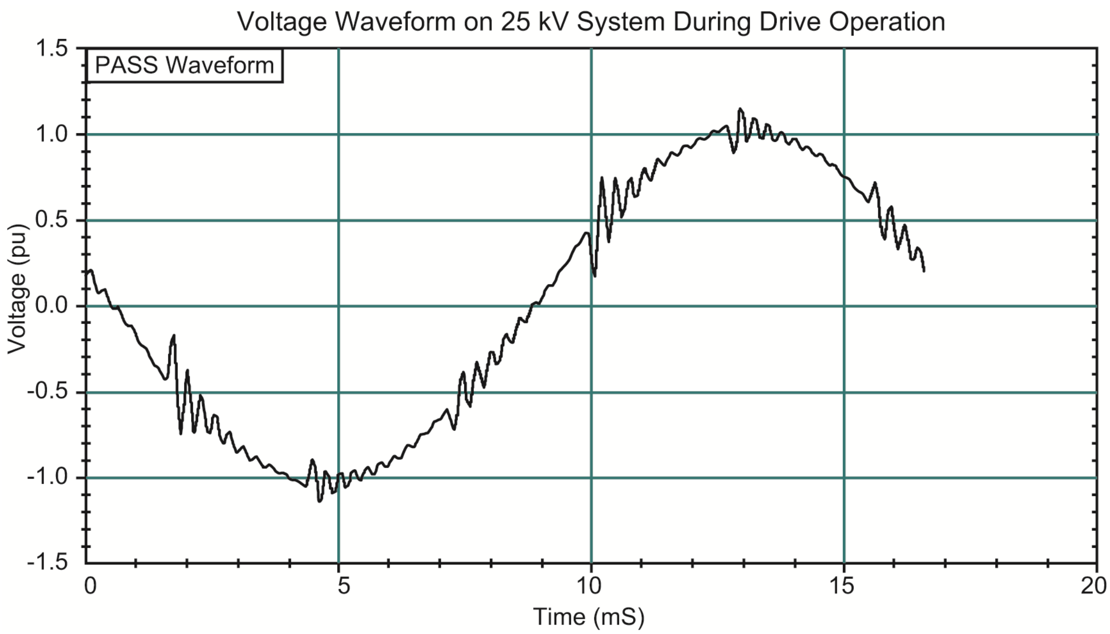


Figure 13—Example waveform of voltage notching ringing caused by large drive

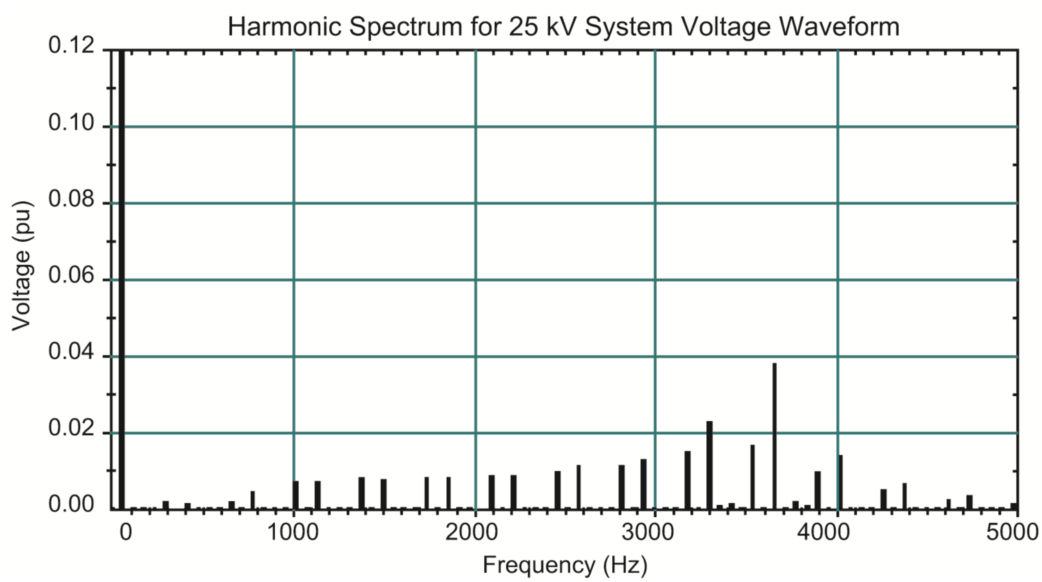


Figure 14—Frequency spectrum of voltage notching ringing caused by large drive

4.4.5.6 Noise

Noise is unwanted electrical signals with broadband spectral content typically lower than 200 kHz superimposed upon the power system voltage or current in the phase conductors or unwanted electrical signals found on neutral conductors or signal lines. Basically, noise consists of any unwanted distortion of the power signal that cannot be classified as harmonic distortion or transients. 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.

The frequency range and magnitude level of noise depend on the source that produces the noise and the system characteristics. Typical magnitude of noise is less than 1% of the voltage magnitude. Noise disturbs electronic devices such as microcomputers and programmable controllers. Problems caused by noise can often be mitigated by using filters, isolation transformers, and line conditioners.

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 ANSI C84.1-2016 [B2] of 0.95 pu to 1.05 pu. Such voltage fluctuations can be perceived by humans by changes in lamp illumination intensity. IEC 61000-3-3-2017 [B14] defines various types of voltage fluctuations, and IEEE Std 1453-2015 [B31] incorporates the IEC methodology for these measurements. The reader is referred to these documents for a detailed discussion of the types of fluctuations and their measurement. The remainder of this subclause on voltage fluctuations concentrates on IEC 61000-3-3 [B14] Type (d) voltage fluctuations. This type is characterized as a series of random or continuous voltage fluctuations.

Any load that has significant cyclic 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 an electromagnetic phenomenon, and flicker is an undesirable result of that phenomenon on lighting. Even though there is a clear distinction between these terms, the ANSI/IEEE standards link them together. They are often confused to the point that the term *voltage flicker* is used in some documents when the term voltage fluctuation should be used. Such incorrect usage should be avoided. In this recommended practice, any use of the term *flicker* should be considered in its appropriate context.

Arc furnaces are the most common cause of voltage fluctuations on the transmission and distribution system. (Lamp flicker is measured with respect to the sensitivity of the human eye.) An example of a voltage waveform that produces lamp flicker due to an arc furnace is shown in Figure 15.

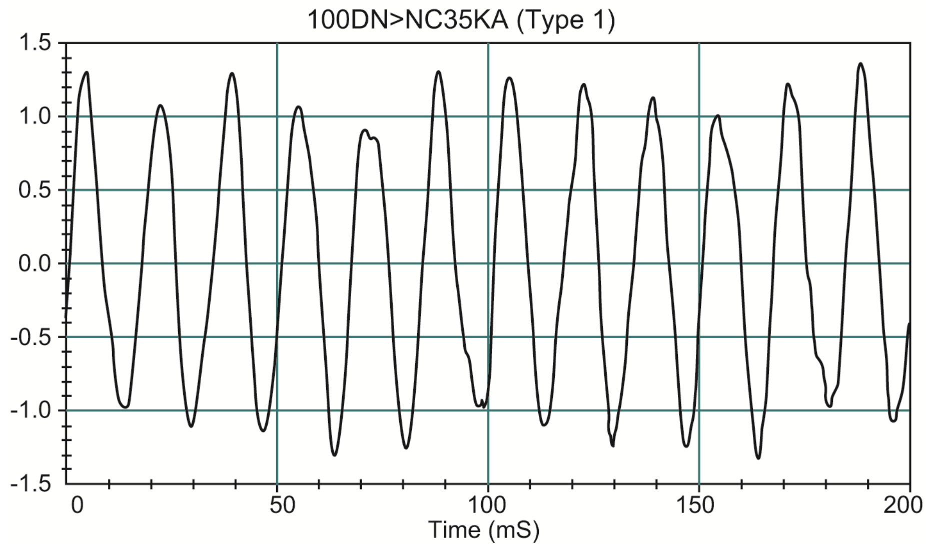


Figure 15—Example of voltage fluctuations caused by arc furnace operation

Voltage fluctuations generally appear as a modulation of the fundamental frequency waveform (similar to amplitude modulation of an AM radio signal). Therefore, for flicker attributable to voltage fluctuation, it is straightforward 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. The parameter Pst for Perceptibility Short Term is used to for comparing and planning the levels of voltage fluctuations and related light flicker. Generally, a Pst less than 1 is not perceived by most people in normal environments ("and add to end of last sentence," which produce a Pst of approximately 1). Magnitudes as low as 0.25 percent difference can result in perceptible light flicker if the frequencies are in the range of 6 Hz to 8 Hz.

4.4.7 Power frequency variations

Power frequency variations are the deviation of the power system fundamental frequency from its specified nominal value (e.g., 50 Hz, 60 Hz). The steady-state 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 generation. When this dynamic balance changes, small changes in frequency occur. The magnitude of the frequency shift and its duration depends on the load characteristics and the response of the generation system to load changes. Small, instantaneous frequency changes occur almost continuously due to load switching, etc. These changes are due to phase shift in voltages as the result of changing current flowing through the system impedance. (Note that frequency is the rate of change of phase angle.) These minor frequency variations are "local" (more pronounced at the load), and the generation system generally does not react to them.

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. Islanded power systems that are relatively weak can have frequency variations due to low inertia, tuning issues of the control systems, large load changes, etc.

Fundamental frequency variations that should affect the operation of rotating machinery, or processes that derive their timing from the power frequency, 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 as mentioned above. The relative capacity of such generators is usually small and the inertia relatively low. In such cases, governor response to abrupt load changes are sometimes not adequate to regulate within the narrow bandwidth required by frequency sensitive equipment. However, the design and implementation of frequency synchronization systems can influence the behavior of equipment both in steady state and during frequency excursions.

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 is 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 clearly define the objectives of monitoring.

The objectives of monitoring for a particular project 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 can be as simple as verifying steady-state voltage regulation at a service entrance or 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 example, when diagnostic monitoring is used to solve shutdown problems with sensitive equipment, the objective should be to capture out-of-tolerance events of certain types. Evaluative or predictive monitoring should 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 can take the form of overvoltages and undervoltages, interruptions, sags and swells, transients, phase imbalance, frequency deviations, 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 recommended practice. Such factors include temperature, humidity, electromagnetic interference (EMI), and radio frequency interference (RFI).

Power quality monitoring can be provided by the utility, the end user, or a third party. Often the term *customer* is used to describe the end user since this entity is the customer of the electric power provider. This is the context in which this term is used throughout this recommended practice.

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 should 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 be either 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 be assessed only if customer disturbance reports are kept. These logs describe the event inside the facility: what equipment was affected, how it was affected, what were the weather conditions, and what losses were incurred.

5.3 Equipment tolerances and effects of disturbances on equipment

The tolerance of equipment needs to be considered in power quality monitoring. For example, a specific ASD can be sensitive to an overvoltage or undervoltage condition, but there can also be a significant variation to the same phenomena among 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 shows which equipment needs protection and what level of protection is required. IEEE Std 1250 Clause 4 provides a good description of the effects of electromagnetic phenomena on various power system equipment loads.

5.4 Equipment types

Although there can be a wide variety in the response of specific equipment types manufactured by different companies, there can 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.

6. Measurement instruments

6.1 Introduction

Instruments used to monitor electromagnetic phenomena can range from a simple analog voltmeter to a sophisticated multiple-site, permanently installed power quality monitoring system. Selection and use of the correct type of instrument 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 focuses on the capabilities and limitations of various types of monitoring equipment. Terms such as power quality analyzer, power disturbance analyzer, PQ meter, PQ monitor and revenue meter with PQ have been used without formal definition in the industry for years, often interchangeably, to describe instruments that measure the parameters typically associated with the power quality phenomena defined in Table 2. In this clause, the phrase "power quality monitor will be used interchangeably with instrument. In addition, IEEE Std C37.2 [B21] includes the PQM acronym function that can be used to show the power quality monitor on all drawings related to the device. This even applies to multifunction devices where the PQM function is just one of many supported in the device.

Power quality monitor features required are dependent on the monitoring location and objectives. For example, if the power quality at the service entrance is being assessed, the emphasis should be trends of long-term steady-state conditions and determining if power quality disturbances originated from the electric power provider or from within the facility itself. 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 History: four generations

The first generation of dedicated power quality monitors began in the mid-1970s. The output of these monitors was primarily text-based, indicating a disturbance by the event type and magnitude. The second generation of monitors included graphical outputs of the waveforms that were captured as part of the event. The mid-1980s saw the third generation of power quality monitors with megahertz sampling rates to provide detailed information on medium- and high-frequency transients. The present or fourth generation of power quality monitors has decoupled the various components within the systems and utilizes standards-based communication protocols and measurement techniques. This allows for increased flexibility and sophistication while reducing costs. This subclause is an overview of power quality monitors and is not for the purpose of designing or evaluating a power quality monitor for a given application. Refer to the standards listed below and other related standards for detailed information:

- IEEE Std 519-2014 [B27], IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.
- IEEE Std 1159.3-2009 [B29], IEEE Recommended Practice for Power Quality Data Interchange Format (PQDIF).
- IEEE Std 1453-2015 [B31], IEEE Recommended Practice for Measurement and Limits of Voltage Flicker on AC Power Systems.
- IEEE Std 1564-2014 [B32], IEEE Guide for Voltage Sag Indices.
- IEC 61000-4-7:2009 [B15], Testing and measurement techniques—General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto.
- IEC 61000-4-15:2010 [B17], Testing and measurement techniques—Flickermeter—Functional and design specifications.
- IEC 61000-4-30:2015 [B18], Testing and measurement techniques—Power quality measurement methods.
- IEC 61850-90-17 [B20], Communication networks and systems for power utility automation.

6.3 Reasons to monitor versus type of monitor

The type of monitor that is utilized is based on the need to monitor. In general, portable/handheld monitors are used to troubleshoot problems in facilities or electric distribution systems in the reactive approach, although they can also be used for shorter-term compliance monitoring. Permanently installed units are used for monitoring longer-term system performance and reliability as well as providing data and/or alarms when power-quality-related problems occur. Permanently installed monitors include dedicated power quality monitors, and other electrical power system devices that have a variety of power quality measurement capabilities. This can include revenue meters, protection relays, capacitor bank controllers, and statistical survey/compliance monitors. Some mitigation equipment also provides limited power quality information, such as in a UPS, surge suppression system, and distributed generation equipment. The data can also be integrated into customer-owned, enterprise-level process control software to correlate variations in the quality of the supply to the quality of the process.

6.4 Parameters to be measured

6.4.1 Primary measurements

Voltage and current are the primary two measurements for power quality phenomena. Most instruments use analog-to-digital converters that sample and store the voltage and current waveforms. These data can be used to compute any number of desired parameters, the most basic of which is the true rms value for each cycle. Some of the older analog electromechanical meters were calibrated for sinusoidal waveforms and might not read properly in the presence of distorted waveforms that are common today. There are only a few digital meters that use average or peak sensing. An average sensing meter is calibrated to display 1.11 times the rectified average voltage, and the peak sensing meter is calibrated to display 0.707 times the peak voltage, which can also be inaccurate in presence of distortion. True rms meters accurately compute the effective value of the voltage or current using established algorithms, whether distorted or sinusoidal.

6.4.2 AC current measurement

The measurements of ac current is accomplished with the use of an ac probe, a Hall effect probe (also used for dc current measurement), or a shunt resistor.

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, although there are probes available that have bandwidths of 1 MHz or better. Limits at the lower frequencies occur due to saturation of the core and at higher frequencies due to parasitic inductances and capacitances. Further, the excessive amplitude of the signal can cause saturation. One type of CT is referred to as the "clamp-on" or "split core," which can be placed unobtrusively around a conductor or bus bar without having to interrupt the circuit. When these CTs are used on the secondary of metering CTs, the accuracy is the combination of both devices, whereas the bandwidth is the smaller of the two. There is a misconception that metering CTs have a bandwidth that holds rated accuracy only to around 1 kHz and, therefore, are unusable for harmonics above the 15th and transients. Laboratory measurements reveal that many solid-core, toroidal CTs that are not overburdened can be linear in amplitude and phase up to frequencies in tens of kHz. An example is shown in Figure 16. However, it is important to obtain the data for the CTs that are being used, as there can be significant inaccuracies in amplitude and/or phase over the frequency range of interest.

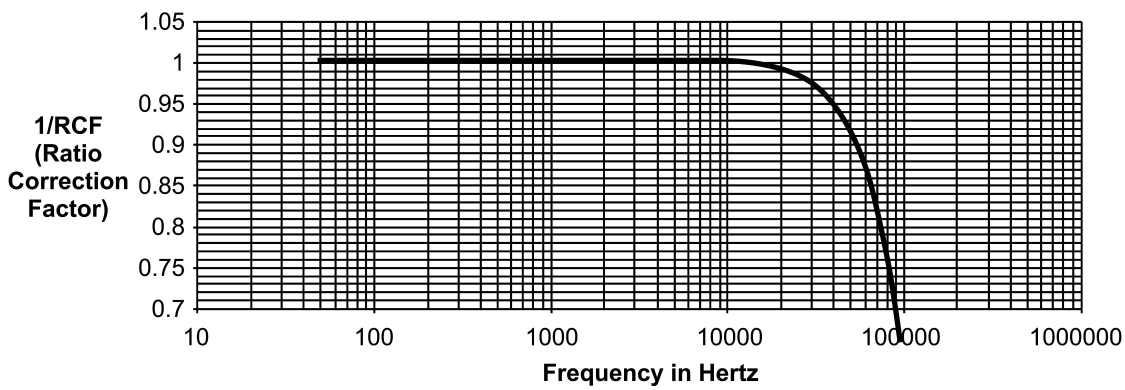


Figure 16—Frequency response of typical CT used for monitoring

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 advantage of using this type of probe is that it accurately measures distorted waveforms over a wider frequency range, including dc. These devices require external power and are more expensive than ordinary CTs.

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 and converts the current into a proportional voltage. Using a shunt requires breaking into the circuit and splitting the conductors 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 CT technique. However, the shunt resistor is affected by heating and should be compensated for appropriately. Furthermore, the voltage drop is just a few millivolts and thus the system is susceptible to noise and EMI.

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) The overcurrent maximum versus the nominal range, in applications where fault currents need to be measured without clipping.

d) The peak value versus the full-scale rms value (crest factor capability) for distorted waveforms.

6.4.3 AC voltage measurement

Measurement of voltage within a facility can be done directly with the power quality monitor provided that its input range capability matches the voltage range expected to be measured. Many instruments are capable of direct connection up to 600 V (rms). The points for consideration for the instrument are similar to the aforementioned points for CTs. However, for measurements of higher voltages, PTs are required. (Note that IEEE Std C57.13™ [B21] uses *voltage transformer* instead of potential transformer or PT.) When using a PT, its response should be considered along with the cabling associated with it. Whereas the PT itself can act as a low pass filter, the amplitude and phase response when coupled with the cables and the input impedance of the monitor can be significantly altered and have multiple resonant points. Figure 17 and Figure 18 show the frequency response, as a ratio correction factor (RCF), vs. frequency for an example PT circuit.

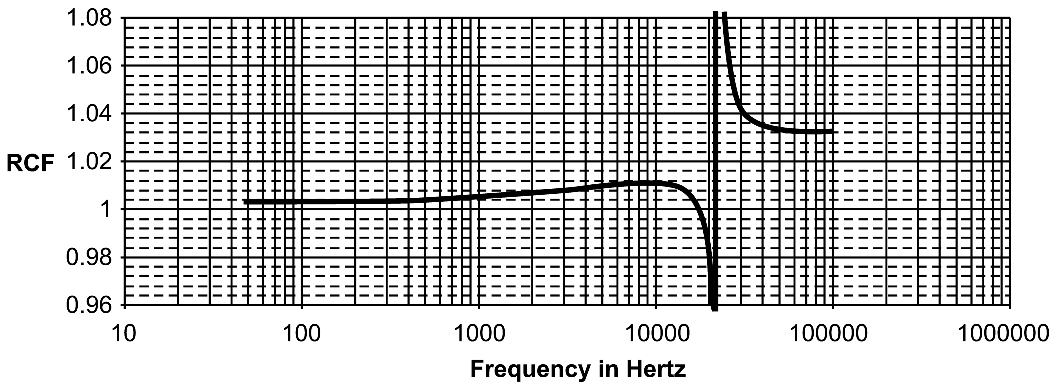


Figure 17—Frequency response of standard PT with 1 MΩ burden

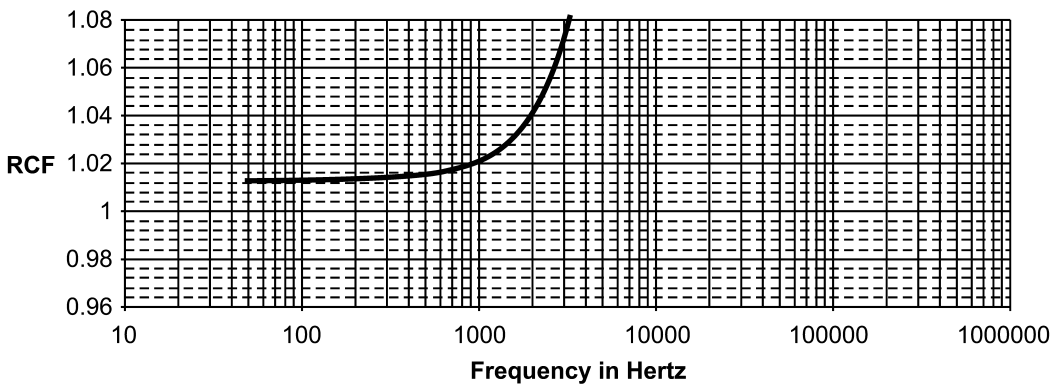


Figure 18—Frequency response of standard PT with 100 Ω burden

If connections are made to a capacitor-coupled voltage transformer, only the power frequency voltage signals for which they are tuned should be considered as accurate.

6.4.4 Additional parameters

Once the voltage and current waveforms have been properly acquired, digitized, and stored in the monitor's memory, then other useful parameters can be computed using suitable algorithms. Some of these are shown in Figure 19.

ANSI transformer derating factor	Interharmonic rms current	True power factor
Arithmetic sum power factor	Interharmonic rms voltage	Unsigned harmonic power
Arithmetic sum displacement power factor	Current-time product	Vector sum displacement factor
Arithmetic sum volt-amperes	Negative sequence current	Vector sum power factor
Current crest factor	Negative sequence voltage	Vector sum volt-amperes
Current THD	Net current	Voltage crest factor
Current THD (rms)	Positive sequence current	Voltage THD
Current total interharmonic distortion (TID)	Positive sequence voltage	Voltage THD (rms)
Current TID (rms)	Residual current	Voltage TID
Current imbalance	RMS current	Voltage TID (rms)
Displacement power factor	RMS current individual harmonics	Voltage telephone interference factor (TIF)
Frequency	RMS harmonic current (total)	Voltage TIF (rms)
Fund frequency arithmetic sum volt-amperes	RMS voltage	Voltage imbalance
Fund frequency vector sum volt-amperes	RMS voltage individual harmonics	Watt hours
Harmonic power (sum)	Total fund frequency reactive power	Zero sequence current
IEEE 519 current TDD	Transformer K factor	Zero sequence voltage

Figure 19—Parameters that can be determined from acquired voltage and current data

6.5 Monitoring instruments

6.5.1 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 can be dedicated to a single type of power system variation, or more typically, they classify several types of events. Data generated by the electromagnetic phenomena should 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 should be preset or user adjustable. In the event 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 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 should be stored as an amplitude or a total number of occurrences that exceed the thresholds. Data should be displayed as numerical values for amplitude or a total count of the individual power system variations. Some type of illuminated indicator and audible alarm should also be used to display the data.

6.5.2 Oscilloscopes or waveform data recorders

Oscilloscopes can be used to provide a visual representation of voltages and currents when supplied with appropriate probes. 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 can be fed into the oscilloscope for analysis. The use of a decoupler permits safe measurement of the 60 Hz voltage waveform as well as the high-frequency normal-mode and common-mode noise into the radio frequency 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 recommended practice, caution should be used in the selection of the CT to verify 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. However, to measure harmonics in circuits with rectified input, switching power supplies, such as the inverters used in VFDs with an active front ends or VFD output circuits, it may be necessary to use a CT with frequency response to 20 kHz or higher. Power waveforms can be displayed and measured by storing a synchronized voltage and current waveform. A digital oscilloscope can increase the quality and ease of data collection. Generally, oscilloscopes are designed for user intervention after each measurement and are not designed to capture and store repetitive power quality events or trigger on typical power quality events (like rms variations).

An area of major concern when using an oscilloscope is the practice of “floating the scope” when the possibility of ground loops exists. The shield conductor of single-ended oscilloscope inputs is normally electrically tied to the equipment grounding conductor on the cord and plug of the oscilloscope. Thus, differential measurements using these inputs can result in ground loops if the circuit measured is also referenced to the same ground without isolation. The preferred method to avoid ground loops is to use instrument-grade PTs or optically isolated voltage probes in conjunction with the oscilloscope.

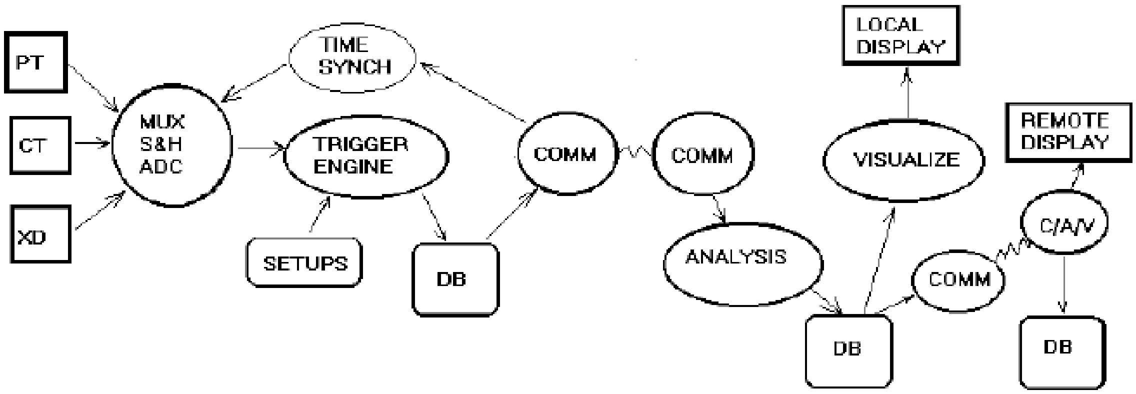
6.5.3 Power quality disturbance monitors

6.5.3.1 Overview of power quality monitors

Instruments designed specifically for measuring the quality of the electric supply at the distribution or load points have gone through four significant generations of functionality. However, the overall architecture has remained essentially the same from a block diagram point of view, as illustrated in Figure 20. The block diagram does not define what is contained within a single enclosure. Some instruments separate the different stages into different packages to address different applications, such as when the measurement input interface is within an enclosed panel and the data storage, analysis, and user interface is a tablet, laptop computer, or a server located in a remote facility.

The first stage in the process is data acquisition. Typically, this stage includes high-impedance resistor divider networks and possibly optical couplers for the voltage and includes current-to-voltage converters for the current inputs. For instruments that monitor transients, these inputs are divided into two paths, one for the transients and one for the low-frequency data (fundamental to nth harmonic). These signals are digitized with analog-to-digital converters and further processed by the acquisition hardware and/or firmware.

The next stage is the database management of the waveforms and calculated parameters, including determination of what information should be stored and when. Additional analysis and characterization usually takes place at this point. This information is then passed over to the communication stage for output to either the local display or to remote visualization tools, such as a web browser.



Legend:

PT – potential transformer	ADC – analog-to-digital converter
CT – current transformer	DB – database
XD – transducers	Comm – communication link
MUX – multiplexers	C/A/V – communication link/analysis/verification
S&H – sample and hold	PQ – power quality

Figure 20—Block diagram of typical power quality monitor

6.5.3.2 Data acquisition

The interface of the monitors to the "real world" is usually through transducers or instrument transformers, such as PTs and CTs for voltage and current, respectively. Some systems also include physical parameters, such as torque, pressure, and temperature, which require specialized transducers. The CTs should use toroid, clamp-on, or flexible cores, with Hall effect probes for dc measurements, which are becoming more commonplace. The output of different types of the transducers is typically a voltage proportional to the original signal, which is accounted for in the scale factors within the instrument to allow for measurements with the actual engineering units.

The analog-to-digital conversion process for power quality monitoring generally uses sophisticated phase-locked-loop sampling techniques to improve the chances that the first and subsequent samples of each cycle are in the same point-on-wave, even while monitoring highly distorted, reduced amplitude, and phase-shifted waveforms. The low-frequency signals are generally sampled at 128, 256, or 512 samples/cycle. The rms values for voltage and current are computed using fixed window (e.g., half cycle steps) or sliding windows. The high-frequency transient signals can be captured using fast response, narrow window, resettable dual peak detectors, or, typically, 1–10 MHz high-speed analog-to-digital converters.

From these raw samples and rms values, many additional parameters are calculated every cycle or over every x ms window, depending on the parameter. For example, the voltage is usually measured on a cycle-by-cycle basis, where x would be 20 ms or 16.66 ms for 50 Hz or 60 Hz, respectively. For harmonic measurements, this window is usually 200 ms. These parameters include the power and energy parameters (e.g., W, VA, var, pf), harmonic parameters (e.g., THD, nth harmonic and interharmonic, TIF), sequence components, and with some systems, the aforementioned physical parameters (e.g., torque, strain, pressure, temperature, humidity). Standards have been developed for a number of the parameters, such as IEEE Std 519 [B27] and IEC 61000-4-7-2009 [B15] for harmonic and interharmonics and IEEE Std 1453-2015 [B31] and IEC 61000-4-15:2010 [B17] for voltage fluctuations that result in light flicker. IEC 61000-4-30:2015 [B18] defines the methods for measurement and interpretation of results for power quality parameters. Use of standard measuring techniques and definitions means that the data reported from monitors of different vendors for the same disturbance would be the same. Prior to these standards, this was not necessarily the case.

The continuous processing of data is a feature not found in some test and measurement instrumentation. Since the occurrence of a power quality disturbance is highly unpredictable, power quality monitors should be continually recording and processing the data to improve record time. The data cannot be saved on every cycle for every parameter indefinitely, in spite of the increasing availability of inexpensive memory. Flexible but complex trigger engines (combination of hardware and firmware) are used to determine what data and how much data is to be saved. Trigger methods include fixed and floating limits and sensitivities, subcycle waveshape changes, specific event characteristic parameters, and repetitive and time-based adaptive thresholds. In addition, steady-state or trended data of user-specified parameters are saved periodically. These methods optimize the probability that what is important to the user is captured and stored. All power quality monitors have some threshold-based trigger engines, without which megabytes of storage would be filled in just a few seconds. The downside is some high-impedance faults can be missed due to the trigger levels not set sensitive enough. Set too sensitive and memory is again filled in a few seconds.

The databases that save this type of data are often found only in power quality instruments. Besides the fixed-size data of trended data, the systems deal with the variable-length, binary records of the waveform data. Since the duration and magnitude of the disturbance are both unpredictable relative to the actual occurrence, the architecture should be flexible enough to accommodate this unpredictability, but efficient enough to not burden the database size and communication durations with megabyte or even gigabyte files. Compression and other storage optimization techniques are used to meet this requirement (see Bingham [B3]).

Data captured across geographically remote locations can be time synchronized to the accuracy required for the application. The use of global positioning systems (GPS), network time protocol (NTP) RFC-5905 [B37], and Inter-Range Instrument Group (IRIG) are a few of the methods for providing time synchronization, refer to IEEE Std 2030.101 [B34]. This synchronization means that the system-wide effect of disturbances affecting the voltage distribution system can be accurately observed and analyzed.

6.5.3.3 Communication

IEEE Std 1159.3-2009 [B29] defines a standardized format for power quality data transfer, based on the work sponsored by the Electric Power Research Institute (EPRI) for power quality data interchange format from the distribution power quality project (see Sabin [B50]). This data format allows for measurements from different instruments to be post-processed on different software programs, independent of the original vendor formats. IEC 61850-90-17 [B20], which is a technical report, provides a way of exchanging power quality data between instruments whose functions include measuring, recording and possibly monitoring power quality phenomena in power supply systems, and clients using them in a way that is compliant to the concepts of IEC 61850.

Other communication standards that are used to allow multi-vendor systems to communicate together as well as manufacturers to separate the various blocks of the system in an open architecture (nonproprietary) manner include Ethernet communications (IEEE 802® series of standards), Transmission Control Protocol and Internet Protocol (TCP/IP), HyperText Markup Language (HTML) and Extensible Markup Language (XML) used over most Internet applications. Communication between parts of the system and on the enterprise level can be carried out over RS485, USB 3.0, 10base2 and 10baseT Ethernet, fiber optic, land phone line, and wireless modems. As with any communication system, the security of the transmitted data requires careful consideration. Specific security measures are beyond the scope of this document. Refer to the National Institute of Standards and Technology (NIST) Cybersecurity Framework [B47], the Electricity Subsector Cybersecurity Capability Maturity Model (ES-C2M2) [B48], the NERC CIP framework [B44], the ISO/IEC 27000 Series of standards [B38] and others for information on the subject.

6.5.3.4 Visualization

The human brain is an efficient processor of visual data, able to turn complex images into simple information relatively quickly. Most power quality monitoring systems display the information graphically in time plots or trend lines, voltage and current waveforms of the disturbance, histograms of cumulative probabilities of parameter values, susceptibility curves (such as CBEMA ITIC, SEMI F47), and sortable event lists (see Bingham [B3]). Bingham describes proposed characterization algorithms that separate the computation of parameters from data acquisition mechanisms to allow post-processing in order to obtain additional characteristics, such as the ringing frequency of oscillatory transients, along with temporal aggregation. Events can be sorted by characteristics, including types of event, channels or phases, magnitude, and duration. Automatic reporting mechanisms generate generic or customized survey reports.

Instruments have a wide range of visualization and analysis software available. On one end of the spectrum are stand-alone instruments, with all visualization on the instrument itself. Simple export (download) programs allow viewing data on personal computers, and such viewing is required for the “black box” type instruments with no user interface contained within them. Use of industry standard data formats, such as PQDIF (IEEE Std 1159.3-2009 [B29]), allow different vendors’ instruments to be used with visualization and analysis software from other vendors.

Increased use of network communication has allowed web-viewable interfaces to be available. Visualization can take place from remote locations using standard web browsers. This method of visualization has reduced past problems of having proprietary software running on the users’ personal computers, with the inevitable conflicts and upgrades. The information is post-processed and presented as downloadable HMTL or XML files and images over the Internet. Some systems allow the same interactive flexibility of the previous generation of software with zooming, interlinked timeline and waveform displays, and customized property settings. Email, pager, and Supervisory Control and Data Acquisition (SCADA) provide means for notification of events including information about what happened and where. For larger systems with multiple instruments, or wide-area power quality, enterprise-wide software is used to manage the more complex progress of setups, databases, visualization, and analysis across multiple units and very large (often gigabyte size) databases. This is further extended when the power quality data are integrated into the plant level using process management software that allows for correlation of the quality of supply and process parameters.

6.5.3.5 Advanced analysis

Power quality analysts can readily attest to the problem of too much information generated from a monitoring study. “Utilities have struggled with the issue of efficiently processing the massive amounts of operating data generated from these devices (continuous monitors in substation). In other words, once you outfit your substation, you better have a system in place to properly manage and filter this newfound wealth of information or you soon find yourself with a case of ‘information overload’” (from Bingham [B3]). Due to a lack of personnel resources, many of the users today do not have the time or the expertise to quickly and accurately diagnose the cause and effect of power quality phenomena on their systems.

Encapsulating the visual analysis process of power quality experts into software algorithms requires use of numerous methodologies and a large database of disturbances with known causes to validate the algorithms. Expert rules-based, fuzzy logic, and neural network techniques, along with mathematical transforms such as wavelets, are being used to distinguish a power factor capacitor switching transient and its direction (upstream/downstream) from the monitoring point or to identify a malfunction of rectifiers in an ASD by the harmonic content, sags caused by motor starts, or the distance to a fault on a radial feeder. Stand-alone software programs have been developed that provide such automated analysis, or they can be incorporated into the power quality monitoring system itself.

Expert systems also incorporate notification schemes (e.g., text messages, pager, email, or contact closures) to send immediate information to the user about what happened, where, and why. This notification scheme can greatly reduce the time it takes to get the production line or data center back on line and thereby curtail the financial impact of the disturbance.

6.5.4 Other monitoring instruments

Other types of equipment that can provide power quality information include, but are not limited to, microprocessor-based multifunction meters, revenue meters, protective relays, digital fault recorders, and capacitor bank controllers. Since these devices are not designed for power quality measurements as their primary function, there can be limitations of their data collection, analysis, and reporting capabilities.

6.6 Pitfalls/Cautions

6.6.1 Instrument power supply and monitoring compatibility

As mentioned previously in this clause, whatever one measures can be affected by the devices that 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 high-impedance voltage connections and CTs, this is relatively easy to accomplish. However, problems can 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 can significantly distort the measurements. The following issues should be considered before choosing to power the instrument at the monitoring location. Refer to the instrument's application manual to resolve these issues.

- What is the level of isolation between the instrument power supply and the instrument measurement circuits?
- Does the instrument power supply generate noise or cause additional power system variations?
- Does the power consumption of the instrument influence the measurements?
- Does the instrument power supply contain transient protective devices that can affect the measurements made with the instrument?
- Does the instrument operate correctly during power system variations that can induce power quality problems?
- Are power cables that are susceptible to EMI/RFI being used that can introduce false readings in the instrument?

Many of the issues discussed are irrelevant when powering the instrument by a source different from the measuring point. However, other concerns come to the forefront with this approach, such as the following:

- What is the quality of the power supplied to the instrument, and does it affect the measured data?
- Have "ground loops" been introduced into the measurement setup?
- Does the placement of the instrument require excessively long power cords, voltage, and/or current leads that might degrade the accuracy of the measurements?
- Could the long power cords or leads be subject to inadvertent disconnection?

6.6.2 Data quality

Worse than not getting the data one is expecting is getting bad data that is thought to be good. Often this type of data is overlooked and passed on to algorithms where it can contribute to significant errors. Causes of bad data can typically stem from human configuration/connection error, hardware malfunctions, or errors in algorithms. Some common examples include the following and are shown in Figure 21.

— Missing data: Large gaps of data are often noticed; however, small gaps in data can easily be missed.

— Latched data:Another often overlooked anomaly is latched data. Most parameters should have some form of randomness. If consecutive values are giving you the same number out to a significant decimal value, it is most likely latched. This can be caused by a malfunction in processing, or communications handling. This can also show up as a false positive for latching if a measured value is using a fraction of bits' resolution from the analog to digital converter.

— Abnormal range: This is when trend data goes outside the normal range of operation. The cause can typically be a misconfiguration in a PT or CT multiplier (software or hardware configuration).

— Extreme values: Sometimes values go outside a range that does not seem physically possible. This could be due to glitch in the processor, or a parameter algorithm not processing data correctly. Leaving these type of values unchecked can significantly affect the accuracy of post-processed statistical data.

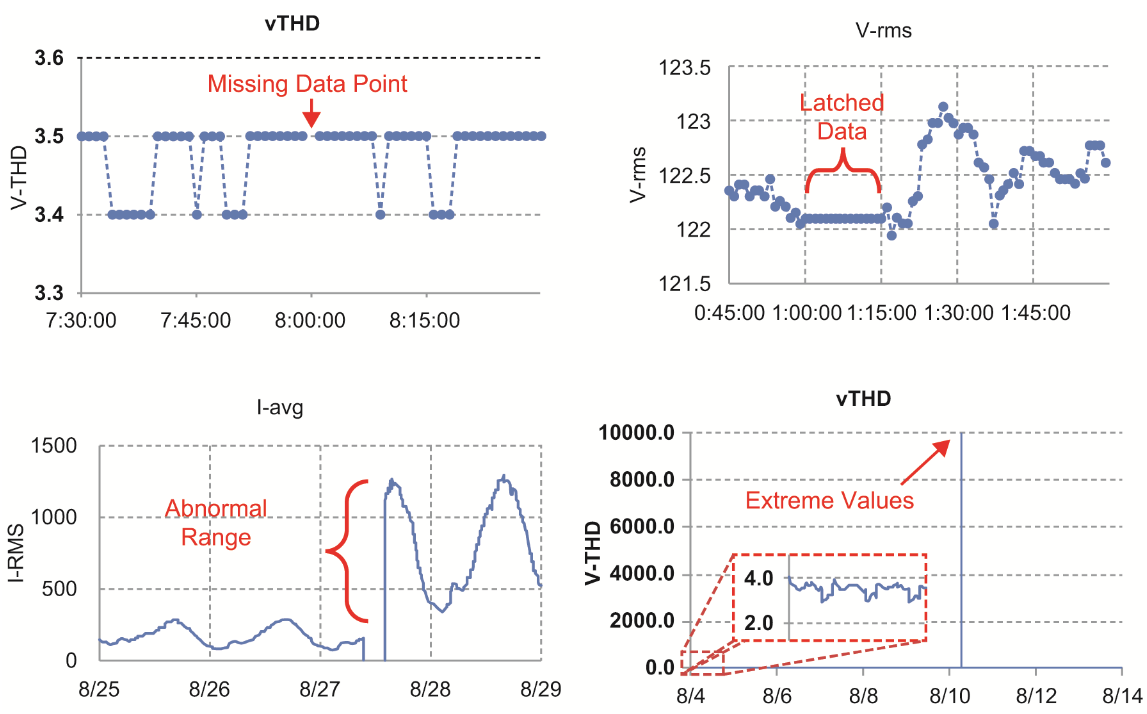


Figure 21 —Data quality errors

6.6.3 DC power

Depending upon the location of the power system to be measured, a power monitoring instrument should use dc power for instrument operation. Further, dc power should be employed internally to the instrument to provide emergency backup power. DC power can be used internally or externally to the instrument.

When using dc power, several points should be considered. Once again, refer to the device's application manual for guidance.

— If using external power, are the power cables properly sized?
— Has the instrument been properly grounded?
— Does the dc power come from a battery pack whose capacity is unknown or possibly degraded?
— If an external charger is used and connected to an ac outlet, what is the charger's isolation?
— What effect does the charger have on the power system?
— Is the charger capable of charging and conditioning the battery quickly and adequately without damage?

6.6.4 Safety

There are numerous concerns with regard to safety, including personal safety, equipment safety, and system safety. For safety reasons, power monitoring equipment should pass the safety standards that are appropriate for the jurisdiction where the equipment is used. Additionally, good grounding practices should be observed so that the touch potential of the enclosure should be within safe limits and ground loops are not created. The placement/mounting of the instrument, either directly or within the properly rated NEMA-type enclosure for the environment, should not interfere with normal facility operations, especially safety-related measures such as light curtains. Connection of the measuring inputs is covered in Clause 7; however, improper connection of communication equipment (e.g., telephony, Internet, instrumentation-PLC I/O, RS232/485, radio, powerline carrier) can affect not only those media, but also the measurements themselves.

7. Application techniques

7.1 Introduction

This clause offers application techniques that reduce safety risks and enable effective collection of electromagnetic phenomenon events. It is not intended to be a step-by-step requirement for conducting every power quality survey, but does provide a recommended practice to follow for a typical power quality survey. This clause presents a listing of issues to consider although it should not be considered to be inclusive of all available information. Familiarity with this clause, however, should reduce safety risks associated with the collection of useful data.

Clause 5 established the monitoring objectives, and Clause 6 described the equipment that should be used to accomplish the objectives. Clause 7 develops a methodology of applying the objectives and equipment to gather the information necessary for a successful exercise of monitoring power quality. A successful exercise is one where the information desired in the objective is gathered in a safe manner while avoiding excessive data gathering.

Clause 7 begins with safety considerations. Monitoring often involves intruding in some fashion upon electrical circuits and/or processes, which have the potential to injure people and damage equipment. This clause then steps through the typical monitoring techniques related to the following:

— Monitoring location
— Equipment connection

— Measurement thresholds

— Installation time frame

For the installer of a power quality monitor, by following the procedures outlined from monitoring location through installation time frame, a typical monitoring procedure can be derived.

7.2 Safety

The safety of personnel involved in the installation of the monitoring equipment as well as the site personnel and/or general public should not be jeopardized for the sake of collecting data. While most connections are temporary in nature and should not utilize the same practices as for permanent installations, the National Electrical Code® (NEC®) (NFPA 70-2017) [B45] and local codes should not be compromised.

Where possible, installation of monitoring equipment should be performed on de-energized circuits that have been placed in an electrically safe work condition using the methods prescribed in NFPA 70E, Standard for Electrical Safety in the Workplace (NFPA 70E) [B46] In some installations, the removal of power can create additional hazards or be infeasible due to factors such as continuous process or a critical care facility. This clause covers the installation and removal of monitoring equipment in energized and de-energized situations.

7.2.1 Personal safety considerations

Installation of monitoring equipment should be performed by a qualified person as defined by the NEC®. [B45]. Knowledge of the electrical equipment design and operation is necessary to identify common hazards prior to beginning the installation so that the appropriate level of personal protective equipment (PPE) is selected.

When connection to live circuits is unavoidable, personal safety is of utmost importance. Often during connection, site personnel who are familiar with the electrical system have a tendency to skip over, avoid, or hold in contempt the standing safety procedures provided by the Occupational Safety and Health Administration (OSHA), the site, and other authorities. It is critical that installers realize that personal safety is their personal responsibility.

7.2.2 OSHA requirements

OSHA publishes many rules and regulations regarding safe working conditions around electrical systems. These regulations are often made a part of law and should be followed. Additionally, many of the OSHA regulations refer to other regulations such as NFPA 70E [B46] and OSHA 29CFR 1910 subparts I and S. The installer should be familiar with these specific regulations prior to commencement of the installation.

7.2.3 NFPA requirements

NFPA 70E [B46] provides requirements for the selection of PPE when working on or near energized electrical equipment, which includes the following:

— Performing an incident energy analysis for the specific equipment and task being performed, or;

— Using the Hazard/Risk Categories tables.

Many facility owners have performed incident energy analysis of equipment, where a label is affixed to the equipment, identifying the hazards. The user should understand the limitations of such labeling including the proper operation of the circuit protective device and any recent changes to the electrical system. Where the label values are in question, refer to the recommendations and tables contained in NFPA 70E [B46] regarding appropriate risk reviews and associated PPE requirements.

Protection of unqualified persons, including the general public, is also covered and includes limited approach and arc flash boundary distances.

7.2.4 General safety considerations

Prior to commencement of the installation connections, the installer should be familiar with the site that is being monitored. For safety considerations, the installer should be certain of the source of the local circuit to be monitored and note the voltage, ampacity, arc flash exposure level (where available), and next higher circuit interruption device location. Furthermore, the physical surroundings of the circuit being monitored are also to be noted. The installer should observe any obstructions that could fall, move, etc., and cause the installer to be jostled during installation. The installer should be certain that site personnel are aware of the installer's activities and that mobile phones and pagers are turned off and removed from the installer's body as these items often protrude from the body and can startle the installer.

Finally, the installer should ask questions. In many instances, the installer of the equipment is a guest in the facility where the installation is occurring. The site personnel are most familiar with the situation and safety needs.

7.2.5 Live parts

Often panel covers are removed for connection of monitoring equipment and remain partially open or unlocked during the monitoring period. If so, all live parts should be adequately protected, and the area should be kept inaccessible. Where possible, conduit entries can be used along with cable fittings or grommets to allow test leads to enter the enclosure, allowing all covers to be replaced. Upon completion of monitoring a listed knockout blank can be used to close the opening. If screw terminals are used in the monitoring equipment, exposed wires 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.

When removing electrical panels, a visual inspection should be conducted of the mechanics of the panel. For example, in most motor-driven equipment (including sources for ASD equipment), a separate motor disconnect is the most convenient place to connect the power quality monitoring equipment. Typically, these disconnects have as many different configurations for opening as there are models of disconnects. It is possible to open these disconnects without load shut-off, but caution should be taken in opening the disconnect panel cover. In other electrical panels, caution should be exercised upon removing the final supporting screws, as the panel cover can fall and cause inadvertent contact with live electrical components. Finally, the installer should examine the panel for rust, warpage, or other damage that can cause unexpected results upon panel cover removal.

7.2.6 Equipment placement

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

Often times the electrical equipment to be monitored is located in pedestrian traffic areas, including hallways, which should be closed during the installation to safeguard the installer, the site personnel and the public. Proper selection and use of barricades and signage is necessary to safeguard the pedestrian traffic to a safe distance outside the work area. Often the monitoring equipment can be located upstream at the source supplying the electrical equipment, which can be within an electrical equipment room, away from unqualified persons.

Additionally, care should be taken to avoid placing leads where they are not protected from abrasion, pulls, disconnection, etc. (See 7.3.2.) Monitors usually require power, and an appropriate location should have access to power without creating a trip hazard, accidental disconnection, or other undue hazard.

Any number of external environmental factors can affect the performance of a power monitoring instrument. These environmental factors 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 can be affected if the temperature of the environment exceeds the specifications of the instrument. Take care not to defeat or interfere with the cooling of customer equipment, e.g., do not leave doors open.

Humidity, like temperature, is critical for the sensitive electronics enclosed in the power monitoring instrument. Excessive humidity can 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, which can damage electronic components within the instrument. Other symptoms of static discharge are signal disruption or difficulties in programming the instrument.

Erroneous data can be generated when monitors are installed in areas that are exposed to various levels of RFI. Interference can be induced into the instrument through the input leads. If the data collected appears unrealistic, the situation can be the result of external RFI. A common problem is location monitoring equipment too close to ASDs.

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 installer should be careful to verify that the instrument can withstand and function correctly in the environment. Due to vibration and mechanical stresses in transporting instruments to the monitoring site, verify instrument operation prior to use.

7.2.7 Grounding

All instruments are capable of developing internal faults; the instrument's power supply should be properly grounded through a three-wire cord. Faults can also develop in the attenuator modules receiving the input voltage sensing 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 can result as shown in Figure 22. In this case, do not isolate the equipment power supply grounding means. A typical equipment connection panel is shown in Figure 23. Additional information regarding ground loops can be found in 6.5.2.

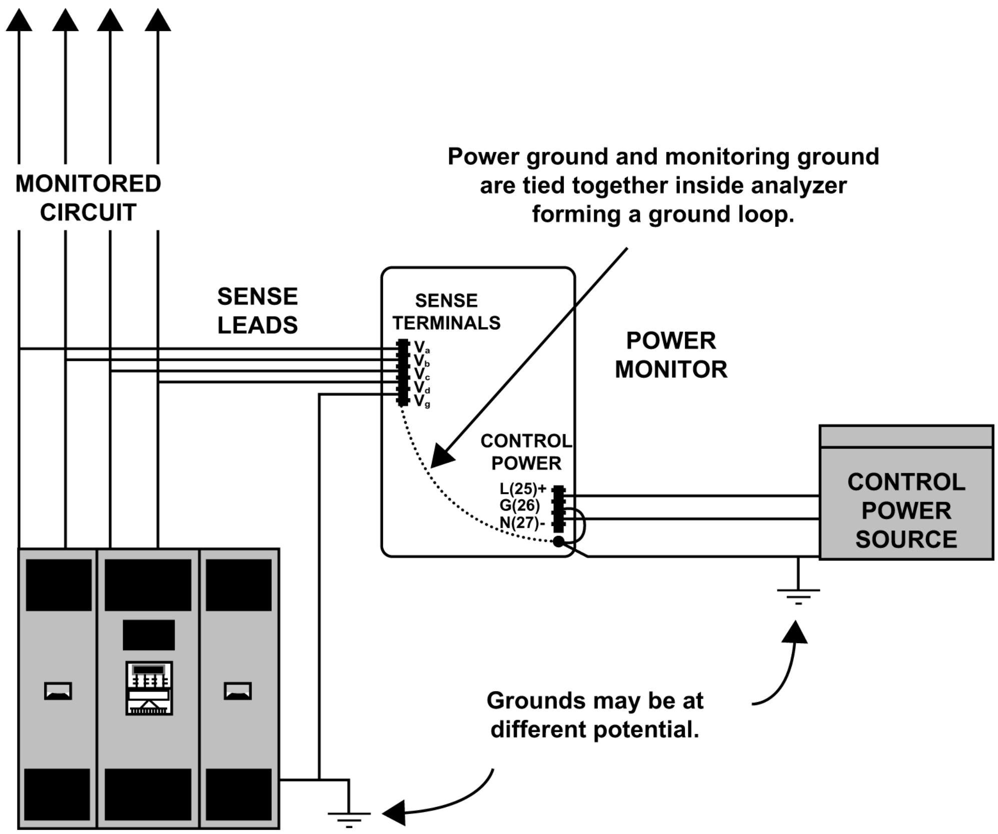
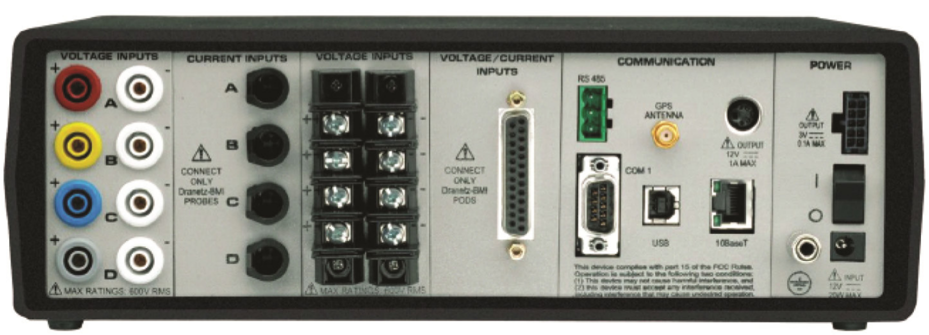


Figure 22—Ground loops, which can be introduced by improper connection of monitoring instruments



Source: Photograph courtesy of Dranetz-BMI [B5].

Figure 23—Typical equipment connection panel[2]

[2] This information is given for the convenience of users of this recommended practice and does not constitute an endorsement by the IEEE of these products. Equivalent products may be used if they can be shown to lead to the same results.

7.3 Monitoring location

7.3.1 Objective

The characteristics of some power system variations 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 dissipates energy through impedances, which changes the leading edge rise time, peak amplitude, and oscillation frequency as it propagates further from the source to the load.

The initial location to install a power quality monitor is 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 ASDs, and electrical distribution equipment, such as circuit breakers and capacitors. After the voltage fluctuations are detected, the monitor can be moved upstream on the circuit to determine the source of the disturbance.

For example, if the affected equipment is currently supported by a means of power conditioning or filtering, a decision should be made about the sequence of monitor placement. At the minimum, a monitor should be installed at the affected equipment location of connection to the electrical supply (between the power conditioning equipment and the affected equipment). This determines whether the power supplied to the sensitive equipment is within the manufacturer's recommended operational specifications.

Once this characterization has been made, the monitor should 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 supply to 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 records the quality of power supplied to the facility as well as the effect of major loads within the facility. The monitor should 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 the affected equipment or filter locations to measure harmonic currents and distorted voltage. Capacitor banks that are affecting harmonics or magnifying switching transients can also be investigated by connecting a monitor at the capacitor bank. Refer to Figure 24.

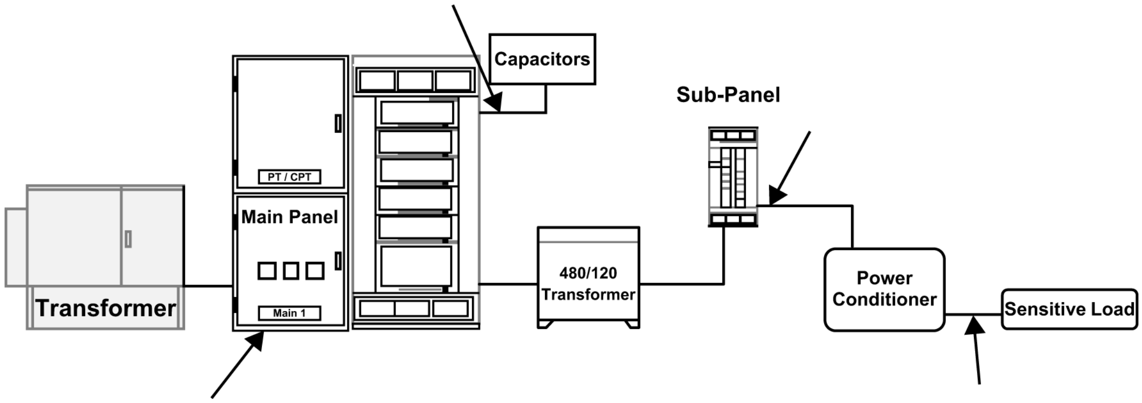


Figure 24—Suggested monitoring locations on typical low-voltage system (Arrows point to suggested location of probes.)

7.3.2 Knowledge of 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 diagram should encompass the power provider's service, neighboring electrical customers, and internal wiring and loads. Awareness of this environment should facilitate consideration for safety, proper connection, and interpretation of data. Some specific items to consider and include on the diagram are described in this subclause.

To maintain reliability, an electric power provider 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 should then be examined for devices that can produce events on a monitor during operation.

Electrical loads at neighboring facilities can affect the electrical quality at the monitoring site. Large individual loads operated nearby should be identified, as practical. The proximity and type of interface between this equipment and the monitoring site determines 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 users. Therefore, the magnitude of the electrical events associated with the neighbor's equipment is greater than if it were 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 should have 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 has the greatest effect on electrical quality. Close examination from the main electrical feed to the end-use equipment is a prerequisite prior to monitoring. This entire system should be inspected for clean, tight connections, which can 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. Also, the installer should determine the connection and operation schedule of backup power sources and mitigating devices such as UPSs. See Table 3.

Table 3—Suggested monitoring locations

Problem	Recommended monitoring location
Specific piece of equipment exhibits problems related to power quality.	At the equipment connection to the facility's electrical system (i.e., circuit breaker).
All equipment connected to a branch of the distribution system within a facility exhibits problems related to power quality.	At the branch connection to the facility's electrical system (i.e., motor control center).
Entire facility exhibits problems related to power quality.	Secondary of the transformer serving the facility (see note).
NOTE—The location might need monitoring on primary of same transformer by electric service provider.	

7.3.3 Diagnosing equipment performance problems

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

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 can 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. Monitors and monitoring adapters are available that allow the load to be plugged into the device so that both voltage and current can easily be captured.

It is sometimes impossible to connect the monitor at the load. Voltage connection points can be inaccessible, the load can be in a hazardous environment, or there can be security considerations. In such situations, the monitor should 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.

7.3.4 Facility power quality survey

A power quality survey of an entire facility usually starts as far upstream in the electrical distribution as possible. It is usually unnecessary to monitor circuits greater than 600 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 is also 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 should be required. These transducers should have a frequency response that permits the capture of transient disturbances. Existing PTs and CTs, used for metering, might not have the frequency response to provide power monitors with accurate transient information. Sometimes the existing PTs are connected in open delta, which can produce erroneous waveform captures. They can be used by a power monitor, however, to record low-frequency voltage fluctuations at the distribution level voltage. If utilizing CTs for monitoring, care should be taken not to open the secondary circuit of the CT, as dangerous high voltages can be developed. Special safety rules apply to working with greater than 600 V class service equipment.

7.3.5 IEEE Std 519

IEEE Std 519-2014 [B27] provides recommended 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.

7.3.6 PT and CT specifications

PTs and CTs have different capabilities and applications depending on where they are located in the power system. Note that metering PTs and CTs are preferred to avoid system interaction. In addition, the voltage provided by metering PTs is typically more appropriate for monitoring equipment. Table 4 provides a summary of available types and their applicability for use in various monitoring locations.

Table 4—Recommendations for types of PTs and CTs

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

7.4 Equipment connection

Monitoring objectives can be compromised by an inappropriate connection to the electrical system. The installer should be aware of the types of issues addressed in 7.3.1 through 7.3.6.

7.4.1 Power measurement

When measuring active power (kilowatt) on a circuit, care should be made to follow the monitoring equipment manufacturer's directions regarding voltage and current connections. Especially important is to take note of the polarity of each current connection and to verify that the voltage and current connections are made to the proper phase (i.e., phase A voltage should be with phase A current).

7.4.2 Electrical circuit connections

During the installation, certain types of circuits are encountered. While listing each type of circuit that can be encountered is beyond the scope of this recommended practice, four common types are described as examples of the type of circuits that can be monitored. For further information regarding the types of circuits that can be encountered, see IEEE Std 141-1993 [B24].

7.4.2.1 Single-phase receptacle

A single-phase receptacle connection is one of the more straightforward connections that can be accomplished using a power quality monitor. Most equipment comes prepackaged with an adapter that allows the voltage of a single-phase receptacle (120 V) to be monitored. However, these kits often do not allow easy connection to measure the current in such a situation. The most straightforward method to gather current information is to attach the single-phase plug load to a separate line that has the individual current conductors available for current monitoring. Simply connecting a current probe around a single-phase cord does not result in appropriate monitoring results since the hot and neutral conductor currents have net zero current in normal operating conditions. Monitors and monitoring adapters are available that allow the load to be plugged into the device so that both voltage and current can easily be captured.

7.4.2.2 Panels serving single-phase loads

Panels serving single-phase loads can contain several different types of voltage arrangements as follows:

- 120 V single phase
- 120/240 V split phase
- 120/208 V three phase

These are examples of the types of panels that can be encountered serving single-phase loads, but by no means represent all examples.

Panels serving single-phase loads are diverse in nature. In the first type, a single-phase configuration can be used to monitor the circuit. However, when encountering the split-phase configuration, most sophisticated monitoring equipment have a specific setup for this connection. Typically, the installer is directed to attach to each hot wire as well as the neutral for proper monitoring. Finally, for the three-phase configuration, the installer is provided with the most complete power quality assessment information by following the procedures for monitoring a three-phase wye circuit configuration. However, it should be noted that a single-phase instrument can be used with the three-phase panel serving single-phase loads by making three separate measurements. In using this approach, the installer attaches the instrument between each phase wire and the neutral wire in succession.

7.4.2.3 Three-phase delta circuit

In many industrial and commercial applications for three-phase power, the circuit to be monitored is a three-phase delta circuit. In these circuits there is no neutral conductor, and the circuit is often referred to as "ungrounded delta." Monitoring requires connection to all three-phase wires and the ground wire. However, since no neutral is used in this type of circuit, the neutral connection is not used.

It is important to note the circuit connections for the ground and neutral or common to be able to properly set up the monitor per the manufacturer's instructions. Monitors with internal power supplies typically specify the ungrounded conductor where configuring the monitor to record phase-to-ground voltage with the ground voltage connection attached to conduit (often the ground connection for this type of circuit) result in voltages being monitored. However, these voltages represent the capacitive charging of the circuit with respect to ground. Equipment supplied by a three-phase delta circuit uses phase-to-phase voltage for power. If the monitor is set up for phase-to-phase, but the connections are phase-to-ground, the voltages seen by the loads are not the voltages seen by the monitor and any power information is not correct.

7.4.2.4 Three-phase wye circuit

Another common installation is the three-phase wye connection to feed equipment. In most cases, this type of circuit serves single-phase load panels for lighting and so-called "plug loads" throughout the facility. The monitoring of this type of circuit again depends on the monitoring objectives, but in most cases, should include connecting sensing leads to each phase. The wye circuit utilizes a neutral conductor and connection on the power quality monitor. For any applications that likely involve analysis of waveshape, phase-to-neutral connections for voltages are more useful that phase-to-phase connections. Phase-to-phase voltages can be reconstructed from the phase-to-neutral waveforms, but not vice versa.

7.4.3 Connection leads

Prior to making any movement of conductors within an electrical installation, it should be assumed that all connections are loose. Electrical equipment is subjected to many heating and cooling cycles as well as vibrations that, over time, can loosen connections. While these connections are sufficient to hold the conductors in place, any movement (e.g., during placement of CTs) can cause the conductor to be dislodged and create a hazardous condition.

Sensing lead connections that are needed 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). Be careful not to compromise cooling airflow. Where possible, conduit entries should be used along with the cable fittings or grommets to allow test leads to enter the enclosure, allowing all covers to be replaced. Upon completion of monitoring a listed knockout blank should be used to close the opening. If panels remain open during monitoring, adequate means should be provided to limit access to the area and inform others about the monitoring setup and the responsible on-site contact. Warning signs, barriers and danger tape should be carefully placed to alert personnel of any hazardous conditions that are created by the alteration of the electrical installation, particularly in the event that circuit breakers or other devices are operated during the monitoring period.

Sensing leads should be connected to existing circuit overcurrent protection devices if the device is designed for the attachment of multiple conductors. Sensing 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. However, often a type of alligator clip connection is made available from the manufacturer. If they are utilized, strain relief of the connection is extremely critical.

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 sensing leads are connected in a panel board or junction box. To execute this type of connection, the power to the circuit should be deenergized; the conductor to be monitored should be removed from its connection; a short length 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 short length of wire (i.e., the pigtail), the conductor to be monitored, and the sensing lead should be connected together with an approved wire nut or fastener. This new connection should be taped, if applicable, for proper insulation and safety of the connection.

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

Fused voltage sensing connectors are available and are recommended. Always make connections downstream of existing overcurrent protection devices.

Sensing 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.

7.4.4 Sensing 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 should be completed in a safe manner.

The sensing lead connections in any monitoring should have to cover all disturbance modes that could impact the proposed devices. As the number of circuit conductors increases, the necessary monitoring modes also increases. 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. 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 should be monitored in a phase-to-phase, phase-to neutral, phase-to-ground, and neutral-to-ground configuration. 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 three-phase delta (three wires without a neutral), configure the monitor likewise. Include a phase-to-ground channel if possible. If the sensitive equipment is connected in three-phase wye, configure the analyzer in wye as well, and include a neutral-to-ground reference. However, if waveshape analysis of the power source is desired and the source is connected in wye, it is generally desirable to measure voltages in a phase-to-neutral configuration.

7.4.5 Ground terminals

Connecting to ground terminals is for two purposes: 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 can be at a different potential than the sensing 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 ground terminal (as is usually the case), ground loops and noise can result. An approved method for detecting ground loops and approved methods such as the methods noted in 7.1 should be used to avoid ground loops.

7.4.6 Instrument power and invasive monitoring

Instrument power is generally supplied either by a single-phase three-wire outlet and standard power cord, or by one of the voltage channels of the instrument. 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 is compromised. Supply the instrument power by another circuit, or, as allowed by some equipment, a dc source (battery). If another circuit is used, be sure that ground loops are not introduced or that excessively long power cords or sensing leads are not used. If a battery is used (and there is no grounding provided through the power cord), be sure that the instrument is properly grounded.

7.4.7 Quality of voltage sensing connections

The voltage sensing 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. In other words, any loose connection or faulty cable should be remedied before useful data can be recorded. Otherwise, the disturbance data can 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, and such compromise can introduce an artifact in the monitoring or affect equipment operation. Monitoring equipment sensing leads are particularly susceptible to EMI/RFI. To lessen the erroneous effects, two wires should be run to each monitoring channel input and not 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 common power quality monitors. (The probes and cables used should be proper and appropriate for the types of measurements to be made.) In some cases, monitors have incorrectly reported events such as transient voltages that resulted from sensing wiring crosstalk or EMI/RFI. This is particularly troublesome when the monitors are available with very low disturbance thresholds (e.g., 25 V to 50 V on a 480 V system).

Shielded input sensing cables are available. However, to monitor higher frequency events without shielded cable, techniques should be employed to reduce EMI/RFI. 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 into free air. It should be noted that this approach does not provide as much immunity to interference as shielded cable, but can be very effective in practical situations.

7.4.8 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 likely a result of a fault or load downstream of the monitoring point being energized. Fast changes in current (< 1 ms) cannot be accurately measured by some CTs. When CTs are used, they should be arranged so that panel covers or some means of covering the service power source is possible. CTs should not be clamped onto 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. There are four common problems when using clamp-on CTs as follows:

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 is enclosed within the CT.
d) The CT is positioned backwards, or the CT polarity is incorrect; either of which situation affects calculated measurements.

CT specifications typically assume the conductor or bus bar is positioned dead center within the clamped area. Any other location incurs some accuracy error. If the clamp ends do not mate solidly, then the resulting gap between the ends also introduces error into the measurement. Unlike the error from positioning, however, this gap error also affect recorded waveshapes. Whenever multiple conductors are being measured, care should be taken to verify 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. Sometimes a feeder consists of parallel runs of conductors, and a CT cannot enclose all conductors. Care should be taken to verify that the current evenly divides among the conductors (by making sure all conductors have identical length, routing, and termination) and the appropriate current division ratio is taken into account in the monitor.

Another issue with CT use is to select the appropriate size for the current expected to be monitored. Using a CT with a rating of 100 A to monitor a single-phase plug load results in skewed results. In the same manner, using a 100 A CT to monitor a very large load results in similarly skewed results. If downstream faults or motor starts are anticipated, be sure the CT is sized accordingly and the monitor is set up with proper range and thresholds.

CT polarity was mentioned previously, but cannot be over-emphasized. In modern equipment that reports power consumption and power factor, it is crucial to have the polarity of the CT connected appropriately. Many CT cases have directives for polarity printed or molded into them. Incorrect polarity does not stop results, but does provide erroneous results.

7.5 Measurement thresholds

Monitors measure data continuously. However, if all data were stored, the monitor would quickly run out of memory. Measurement thresholds or triggers provide a means for determining what is and what is not recorded. (Standards such as IEC 61000-4-30:2015 [B18] and some power quality measurement instruments subdivide the recorded data into groups called events.) Proper setting of the thresholds determines whether the data gathered are useful data to keep. Thresholds set too low results in irrelevant data, and thresholds set too high results in insufficient data.

7.5.1 Objectives

Once the monitor is connected to the circuit, it should 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 trigger the monitor to produce 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 should be dependent upon the limitations of the monitor's event storage media: paper, electronic memory, or magnetic/optical storage.

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 sensing lead connections. Thus, an understanding of the internal logic of the power quality monitor is critical if the data collected are to have value in the diagnosis and solution to power system variations.

The first point to consider is the triggering level of the power quality monitor. Trigger thresholds tell the monitor to ignore power system variations below the threshold and only trigger on the 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 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 quality monitor. Data should be displayed as a "hard copy" as with a data tape or as a visual display in a format similar to an oscilloscope, or data should be stored in memory or on a disk and be transferred to a computer for further analysis.

All power quality monitors 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 can be reached, and then data can be lost or power system variations uncaptured. 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 quality monitors 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 can 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 quality monitor 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 goal requires an instrument capable of recording and conveniently displaying steady-state conditions for the complete monitoring period, which could be weeks or months.

If thresholds are set too low, the monitor can capture apparent events that are not relevant to the monitoring objective. It is, therefore, essential to keep the monitoring objective in mind when setting thresholds so that captured events are meaningful. Events that do not cause undesired symptoms might not represent a problem.

7.5.2 Preparation

At first, set up the monitor and let it run for a half hour or so in order to obtain first order estimates of electrical environment characteristics. It is useful to let the monitor run for a 24-hour period 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 (modern instruments typically do not use paper anymore). This results in superfluous data if any of the settings are too sensitive relative to the magnitude of disturbances in the environment.

7.5.3 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 should 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 that thresholds should be set lower than the equipment's susceptibility levels so that the disturbance waveform is recorded.)

Selecting thresholds for an electrically active environment (such as the input to an ASD) is more difficult. If the thresholds are too low, continuous fluctuations incapacitate the monitor and possibly prevent it from capturing more significant disturbances.

7.5.4 Equipment susceptibility considerations

The best threshold settings relate directly to the susceptibility levels of the sensitive electronic equipment being investigated. Susceptibility levels for an electronic load should 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; however, some industry standard consensus curves do exist. These curves are listed next:

— Information Technology Industry Council ITIC (formerly CBEMA) curve (2000), as found in IEEE Std 446™-1995 [B25]

— IEC 61000-4-11:2004 (less than 16 amps) [B16] and IEC 61000-4-34:2005 [B19] (greater than 16 amps) Type III Test Curve, as found in IEEE Std 1668™-2014 [B33]

— SEMI F47 curve, from SEMI F47-0706 [B51]

These curves define a safe operating area for conforming equipment. These standards plot rms voltage variation versus time. Generally speaking, shorter duration events can have higher excursions from nominal. Equipment that meets one of these standards should not malfunction when the rms voltage varies within the upper and lower bounds of the curves. However, if a voltage sag or swell occurs that exceeds the limit on these curves, the equipment is not required to operate properly (i.e., "ride through" the event).

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 ITIC) often work well. Some typical susceptibility limits and compatibility guidance can be found in IEEE Std 1100-2005 [B28] and IEEE Std 493-2007 [B26], for example.

Table 5 lists initial thresholds that might be considered as rules of thumb. The thresholds are specified for 120 V equipment in the United States, with general equipment susceptibility considerations. 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 should be set below (more sensitive) equipment susceptibility levels so that disturbances are recorded that may not initially affect equipment but may lead to problems in the future. 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.

Table 5—Suggested threshold settings for 120 V loads

Conducted phase voltage thresholds		
Sag	108 V rms	Minus 10% of nominal supply voltage.
Swell	132 V rms	Plus 10% of nominal supply voltage.
Transient	200 V peak	Approximately twice the nominal phase-neutral voltage.
Noise	1.5 V	Approximately 1% of the nominal phase-neutral voltage.
Harmonics	5% THD	Voltage distortion level at which loads can be affected.
Frequency	± 0.1 Hz	—
Phase imbalance	2%	Voltage imbalance greater than 2% can affect equipment. (Three-phase induction motors should be derated when operated with imbalanced voltages; see IEEE Std 141-1993 [B24].)
Conducted phase to neutral 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-neutral voltage.
Noise	1.5 V rms	Typical equipment susceptibility level.

7.5.5 Current considerations

Most monitors are capable of monitoring currents; a few monitors allow monitoring of seven or eight channels of voltages and currents. Current measurements permit 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 trigger current thresholds for these applications usually involves setting the overcurrent thresholds relative to NEC [B45] limits or just below the manufacturers' 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-to-ground voltage disturbance is related to a grounding conductor or power circuit. 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 hour to characterize transient/inrush current effects on the voltage levels and to then set the monitor above the "normal" levels monitored.

7.5.6 Monitor thresholds summary

In summary, the following steps should be taken to determine monitor thresholds:

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 provides a record of background fluctuations. Note that background voltage fluctuations, even though below equipment susceptibility levels, can 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 (unless there is an unusually high level of real activity).

7.5.7 Installation time frame

The installation time frame refers to the monitoring period or duration and the time during which monitoring is occurring (e.g., time of year, day, week). Gathering data at the appropriate time and for the appropriate duration is necessary to properly diagnose power quality events.

7.5.7.1 Objective

The monitoring period is a direct function of the monitoring objective. Usually the monitoring period attempts to capture a complete power period, i.e., an interval in which the power usage pattern begins to repeat itself. However, for seasonal problems, the monitoring period might be for months.

An industrial plant, for example, can repeat its power usage pattern each day or each shift. Depending on the monitoring objective, it can be necessary to monitor as little as one shift. A school system can have days without students in the classroom; a commercial building can host a special event. The appropriate time to monitor is the time corresponding with the power quality symptom that is being investigated, although gathering baseline information during nonsymptomatic times can also prove useful.

It is most important understand what time periods the data represent and not to assume that no changes in facility operation have occurred.

7.5.7.2 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 information 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.

7.5.7.3 Problem solution monitoring

Locating a power problem that causes 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 check the effectiveness of the solution and to verify that no new types of problems have been created.

Plant personnel should be instructed to keep a log of equipment malfunctions, including time of occurrence, equipment affected, trip codes, operating mode of equipment, and other pertinent information. Correlating this information with power quality monitoring results is invaluable for locating sensitive equipment and resolving the problems.

7.5.7.4 Power supply 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 early studies include studies conducted throughout the United States at computer sites in 1969 to 1972 and reported by Allen and Segall [B1] and studies conducted at U.S. telecommunications sites in 1977 to 1979 and reported by Goldstein and Speranza [B11].

Recent studies of multiple location power quality monitoring include the National Power Laboratory study (see Jurewicz [B39]), the EPRI distribution power quality study (see Sabin [B50]), the Canadian Electricity Association (CEA) study (see Ethier and Simard [B9]), and the Australian power quality monitoring project (see Elphick et al. [B8]).

8. Interpreting power monitoring results

8.1 Introduction

Troubleshooting and solving power-related problems involves a number of issues. Many problems are solved by the following methods: careful evaluation of the loading and loads, verification of correct wiring and grounding of the electrical system, installing power monitoring equipment to obtain system data and characteristics, and/or involving the local power provider to understand if there were coincidental events on their system. Keep in mind however that no single method handles every problem and that one should not limit oneself to diagnosing 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 and the tremendous range of distribution system and load characteristics, interpretation still remains very dependent on the experience and skill of the investigator. This clause discusses many of the issues that directly impact power monitor data interpretation skills. For further information on analyzing and interpreting data, refer to the guides by McEachern [B41], Dranetz-BMI [B5], and EPRI [B6].

8.2 Interpreting data summaries

One of the first steps in interpreting the data from a power monitor is to examine the power monitor configuration and confirm that it matches the power system monitored. Settings to be verified include single phase or three phase, line-to-neutral or line-to-line monitoring, wye or delta, thresholds (e.g., nominal voltage, transient limits), and installed location. In addition, an accurate summary of the data acquired typically requires monitoring over some time interval. This interval can be anywhere from minutes to years, but it generally should be at least one power period. See Clause 7 for more information on the length of the monitoring period, thresholds, and connections. Looking at the summary of the data provides an important overview perspective and quickly identifies more important data to be examined in greater detail.

8.2.1 Measurement validation

Measurement validation 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 and are subject to the skill and knowledge of the user and the monitor's design limitations. No matter how carefully users work to eliminate invalid data, some spurious measurements can still be included in the analysis data set. This step's purpose is to assure that the data set is reasonable based on the circuit configuration, monitor capabilities, and monitor connection method.

A validity check of the summarized data should be performed before attempting to interpret them. This involves making sure such things as magnitudes are reasonable (e.g., how would a line-to-neutral sag of 200 V exist on a 120 V system?), time stamps are within the monitoring window, and so forth. A measurement of power (if the load and power factor are known) and/ or a graph of the voltage and current vectors would help in verifying that the connection type and polarities of the PT/ Voltage probes and CTs are correct.

8.2.2 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 prior to data interpretation. For example, two broad and generic goals are given:

— **State goal(s):** To install a power quality monitor to capture events that can be related to the misoperation of a piece of equipment.

— **State objective(s):** To determine the cause of the problems related to the equipment misoperation and determine the devices or methods available for event mitigation.

A data summary table is typically focused on power monitoring measurement, their details, and ordered chronologically to allow quick correlation with a power quality problem (e.g., process misoperation). Table 6 shows some possible column headings of a summary table. The disturbance types given in the second column should follow the types given in Table 2.

Table 6—Power monitor data summary table

Date and time of disturbance	Disturbance type	Event characteristics (magnitude and duration)	Related to goal (Yes/No)	Other equipment affected

Keep in mind that every measurement recorded by a power quality monitor does not necessarily indicate a power quality problem. If many measurements were recorded during a period of time, it could be that the monitor's measurement triggers were set too close to nominal conditions and examining each measurement is irrelevant. On the other hand, no disturbances recorded could indicate that thresholds were set far from nominal conditions, the monitor was improperly configured, measurements were lost, the memory was full, or the monitored time did not coincide with the disturbance.

8.2.3 Interpreting summaries

Once certain the summarized data is valid, the first round of interpretation can take place. This step provides needed information to proceed if further analysis is needed.

A chronological overview of what occurred during the monitoring interval can be reviewed. 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 can quickly show whether any disturbances occurred and, if so, when they happened. Patterns in time or disturbance characteristics can 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 to be correct. A monitor was installed. Several lockups occurred during the one-day monitoring time.

The timeline summary showed the presence of many transients, line-to-neutral sags, and neutral-to-ground voltage increases. Occasionally, a line-to-neutral sag and a neutral-to-ground 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 lockups.

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, line-to-neutral sags, and neutral-to-ground increases in voltage. However, when both the printer and copier were used at the same time they caused a line-to-neutral sag and a neutral-to-ground increase that were much worse. The magnitude of the intermittent neutral-to-ground increase was found to be the cause of the workstation lock-ups.

8.3 Critical data extraction

Often the summaries do not provide an actual solution to a problem. They should, however, help determine what data need to be examined more closely. These data are referred to as critical data. In the example of 8.2.3, the summaries showed that the deep sag and neutral-to-ground voltage increase had a direct cause-and-effect relationship. The transients did not. Thus, the sags and neutral-to-ground 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 that happens while a fault is being cleared, the monitor can report a line-to-neutral 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 as a part of the whole. If a line-to-neutral sag occurred, did an increase in neutral-to-ground voltage also occur? This combination indicates an upstream fault (with a ground potential rise) or 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 power provider? Many times an event is 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 when looking at time stamps to determine what goes with what. More recent monitors keep an event together, but an older monitor might separate the single event into multiple pieces, which have to be correlated by the user. For example, Figure 25 shows a momentary interruption (both instantaneous and rms values of one line voltage), including a few cycles of pre- and post-event waveform data.

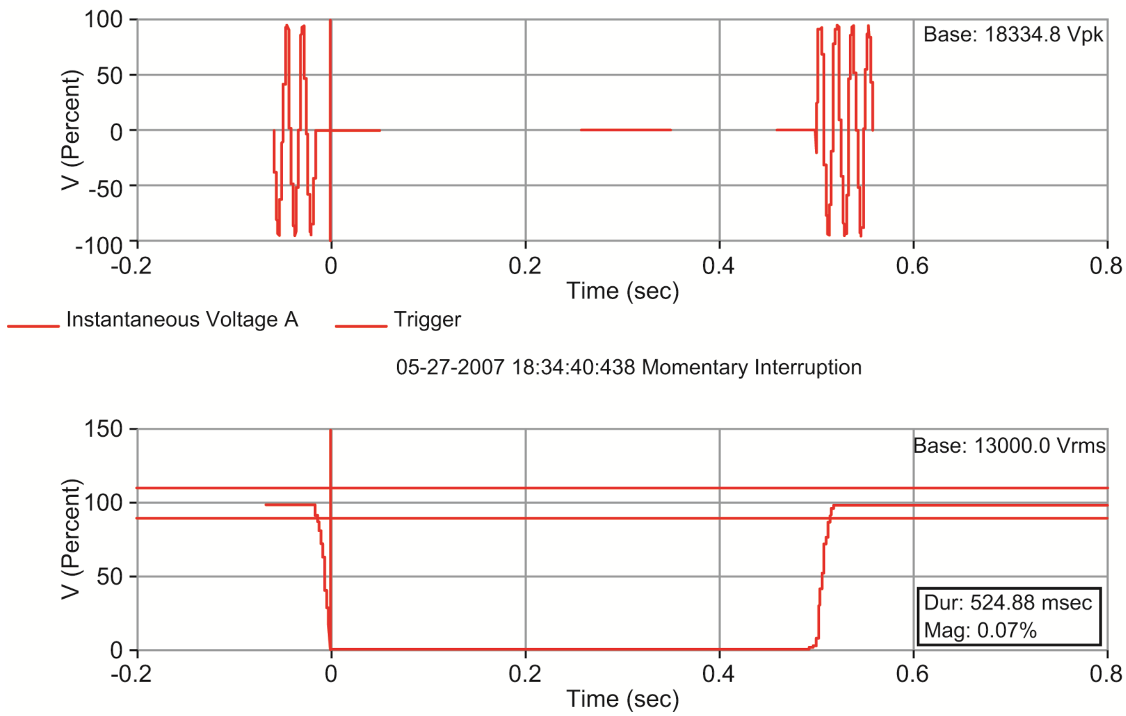
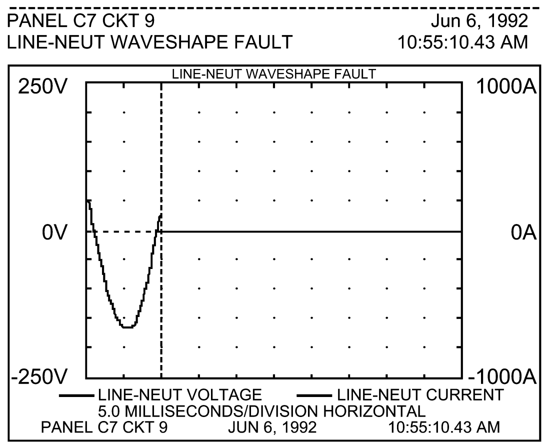
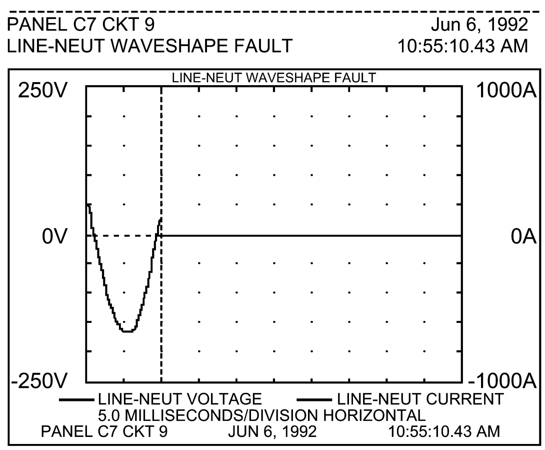


Figure 25—Momentary interruption captured by modern monitor

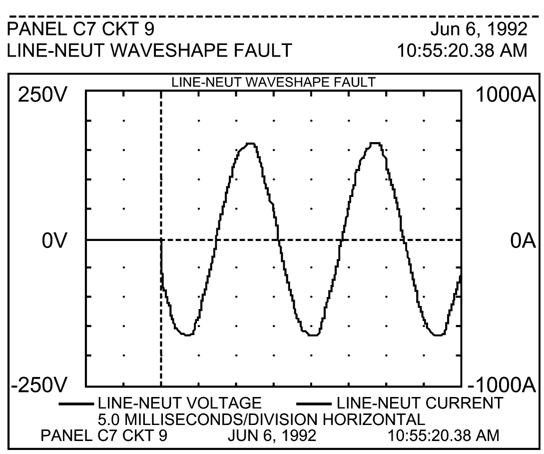
Figure 26 a) to Figure 26 c) show the results of an older monitor, which generated three graphs relating to the same event. Notice in Figure 26 c) that the waveshape disturbance showing the restoration of power has a time stamp equal to the initial waveshape disturbance time plus the interruption duration from the sag graph. This type of correlation is very useful to identify critical events.



a. Initial waveshape disturbance—10:55:10



b. RMS plot of the line-to-neutral temporary interruption with duration = 10 s



c. Final waveshape disturbance—10:55:20

Figure 26—Momentary interruption captured by older monitor, split into three separate events

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 described a reality check as an assurance that recorded data are reasonable based on the circuit configuration and monitoring connection method. Figure 27, Figure 28, and Figure 29 demonstrate the need for an event reality check.

Figure 26 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 reality check confirms that it is virtually impossible, in a normal system's operation, to distort the power provider's voltage to a square wave.

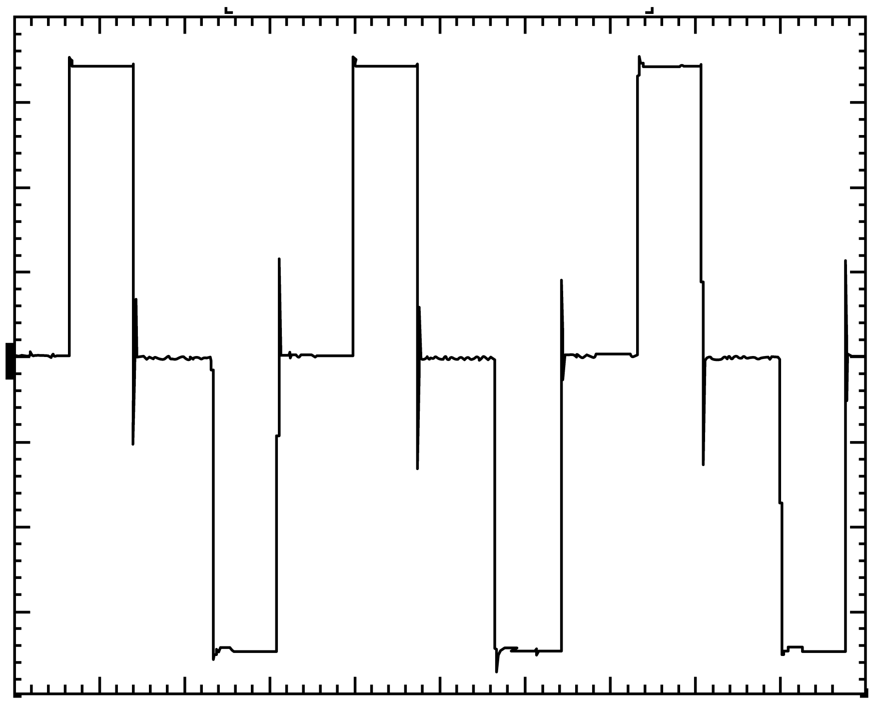


Figure 27—UPS square wave voltage input

Figure 28 and Figure 29 appears to be multiple fast impulses, perhaps a static discharge. But on closer examination, it is apparent that the impulses, with a magnitude of over 400 V, reaches full scale and returns to zero instantly with no undershoot. It is highly unlikely that, even when using mitigating devices, the normally linear power system would respond to impulses in this fashion. Electrical inertia in the system's impedance would certainly cause some undershoot. These impulses fail the reality check and are most likely the result of instrument error.

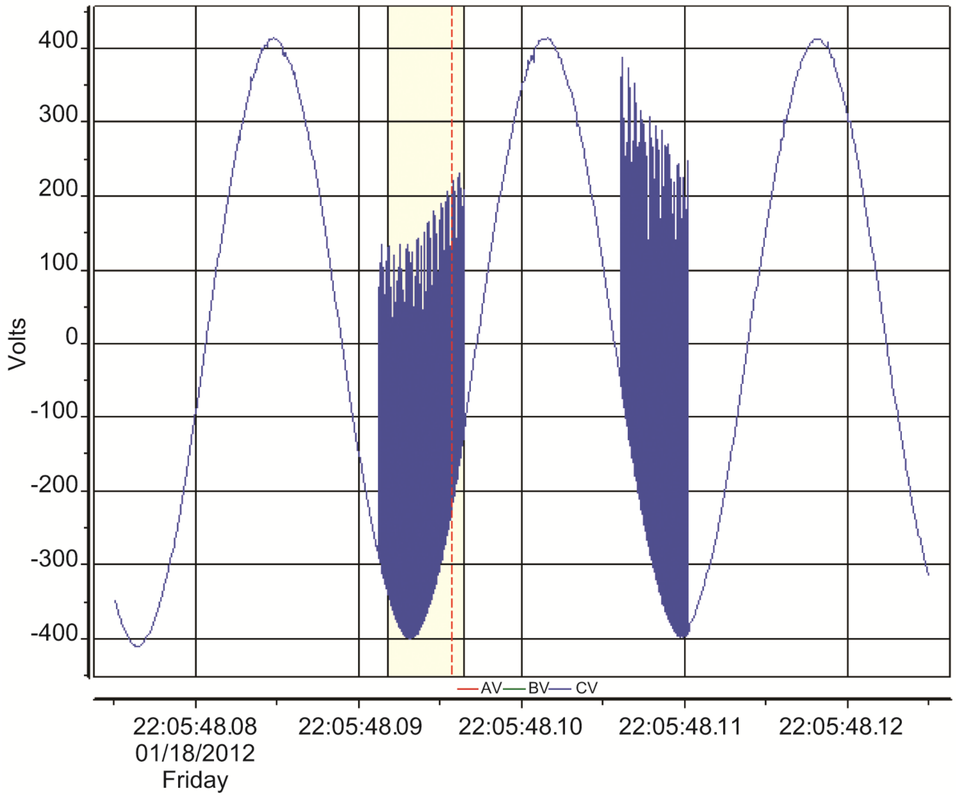


Figure 28—Distortion resulting from instrument error

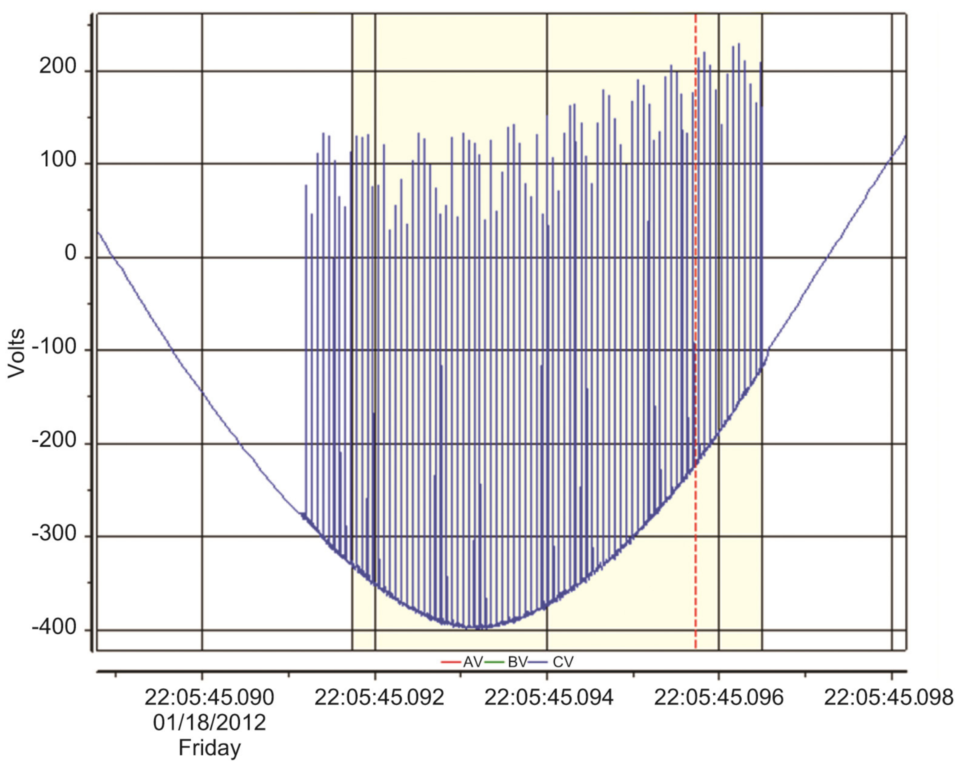


Figure 29—Zoomed view of Figure 28

8.4 Interpreting critical events

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

Table 7 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. A discussion of the characteristics and possible causes are included in each subclause.

Table 7—Reference chart for problem analysis

Typical problems	Disturbance type	Possible causes	Subclause location
Overheated neutral Intermittent lockups Frequency deviations Voltage imbalance Current imbalance	Steady-state	Shared neutrals Improper or inadequate wiring High source impedance Silicon-controlled rectifier (SCR)/rectifiers Notching Harmonics Current imbalance Capacitor banks Single-phase loads SCR/rectifier Voltage imbalance	8.4.2
Interruption Garbled data Random increases in harmonic levels	—	Utility faults Inrush currents Bonding and grounding Inadequate wiring Capacitor banks SCR/rectifier load	8.4.3
Intermittent lockups Lights flicker Garbled data	Sag/Swell	Source voltage variations Inrush currents Inadequate wiring	8.4.4
Component failure Dielectric breakdown Lockups 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 Lockups	Harmonics	Electronic loads SCR/rectifier loads Bandwidth of source impedance Voltage imbalance	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 Nonsynchronized power switching Differences in source Impedance	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 can 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 (see Dranetz-BMI [B5], McEachern [B41], and EPRI [B7]).

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 can more quickly lead to correct conclusions than graphs showing a voltage sag or swell alone.

8.4.2 Steady-state waveshape analysis

8.4.2.1 Background

Much 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. It sets a baseline for comparison for any anomalies. Typically, waveshape analysis is more useful at the facility level close to the load equipment.

Steady-state waveshape analysis provides information regarding the following:

— Type of loads
— Adequacy of power system
— Verification of wiring practices (shared versus dedicated neutral)
— Harmonic distortion
— Normal load cycling and switching

8.4.2.2 Analysis tips

As various loads are turned on, both instantaneous voltages and currents are affected due to load current flowing through the system impedance. This impacts both in magnitude (a voltage drop) and in waveshape. For example, if the load is a personal computer or other electronic rectifier load that draws current in large pulses as its dc capacitor charges, then the voltage drop occurs at the peak of the voltage waveform. This causes the peak to be flattened somewhat (a condition known as flat-topping) and is demonstrated in Figure 30.

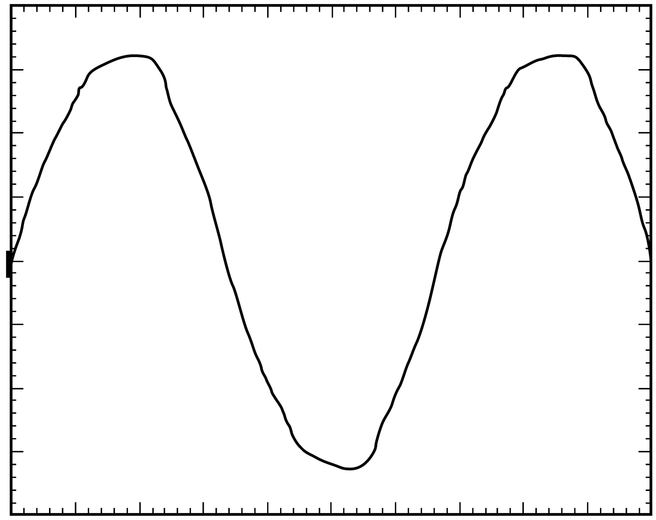


Figure 30—Waveform graph illustrating flat-topping due to switch-mode power supplies

In systems that have neutral-to-ground bonds, a great deal of information is available from the neutral-to-ground voltage and waveshape. According to Ohm's Law, 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.

Neutral-to-ground information 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 nonelectronic load sharing the dedicated circuit.

Neutral-to-ground information 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, and 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; therefore, it is likely that the distribution wiring and connectors are undersized for the load.

Because loads with rectified input power supplies 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 as or greater than the current in each phase conductor. The current waveshape may appear to be roughly sinusoidal, but at 180 Hz, and is often referred to as the third harmonic neutral current. For single-phase electronic loads sharing a common neutral between phases, the amount of load current returning can be greater than the load on a single-phase conductor. In the United States, sizing of the neutral conductor should be done according to the National Electrical Code [B45].

Keep in mind also that not only is the neutral-to-ground rms voltage proportional to the neutral current, but also its waveshape. For example, if the neutral current is made up of only 180 Hz, the resulting neutral to ground voltage is also 180 Hz. Since the neutral current can be very high, this neutral-to-ground voltage can also become excessive. Also, remember that a change in neutral-to-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. When a combination of linear and nonlinear loads exist in a single-phase circuit, or if the linear loads are not balanced on the three-phase circuit, the neutral return current contains both fundamental and triplen harmonics. The resulting voltage drop between neutral and ground, when both fundamental and triplen harmonics are present, is shown in Figure 31.

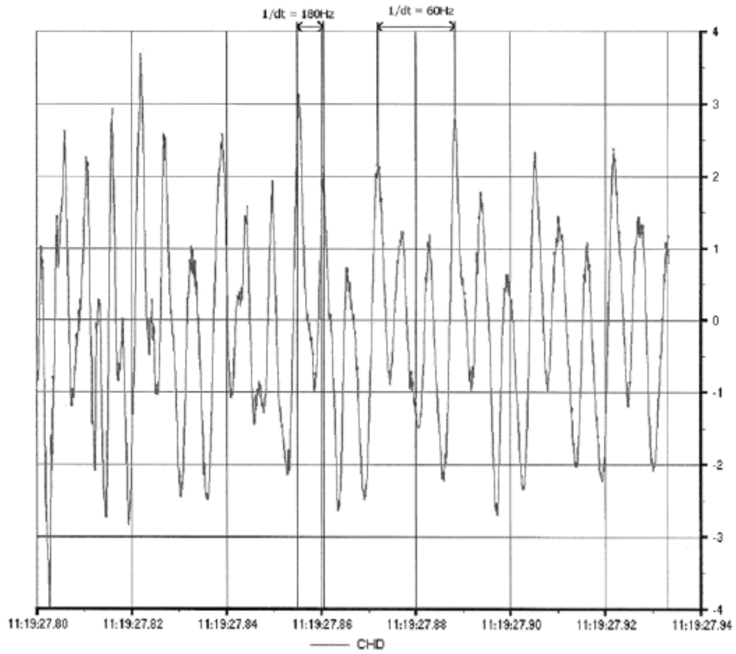


Figure 31 —Neutral-to-ground voltage at pole ground showing harmonic distortion

8.4.3 Waveshape disturbance analysis

8.4.3.1 Background

Waveshape disturbances are 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 can identify the cause of distortion.

8.4.3.2 Analysis tips

An ac electrical system, supplied by rotating generators, contains inertia, which requires consideration of system response characteristics. The power system, and the loads connected to it at any given time, conduct and consume power on a continual basis. Major disruptions of this flow results in changes to the actual waveshapes, but not instantaneously. Current can cease to flow abruptly, but there can 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 zero volts for certain types of motors (synchronous) and loads (high speed and inertia).

8.4.4 Sag/Swell analysis

8.4.4.1 Background

Similar to waveshape disturbances, sags and swells describe variations with the waveshapes of the voltage or current. However, sags and swells are defined as being one-half cycle to 1 min in duration and are categorized as short-duration rms variations. In other words, instead of looking at the instantaneous waveshape, the rms value of the wave should be examined for quantification. 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 can produce changes in the line-to-neutral or the neutral-to-ground voltage for similar periods of time, depending on such things as current magnitude, source impedance, and how fast the current changes (di/dt). This is most apparent in single-phase circuits and unbalanced three-phase circuits. For example, if a load is energized that has a 1.5 s inrush current, then a line-to-neutral sag and an increase in neutral-to-ground voltage is generated for the same 1.5 s. In general, the neutral-to-ground voltage rise is about one-half the magnitude of the line-to-neutral sag. (This example assumes the impedance of the neutral is equal to the impedance of the ground conductor, and that assumption is not always the case in actual installations.) The sag is a result of the voltage drops of the line and neutral conductors, while the neutral-to-ground voltage is a result of only the neutral.

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 and source of the event. For example, an event whose measurements show a voltage sag with a significant corresponding current increase is known to have a cause downstream of the monitoring location. If there is no corresponding current increase, the cause is most likely upstream of the monitoring location. Depending on the monitoring location with respect to the entire power system, electrical inertia can also contribute to sags and swells.

While rms analysis is important, it is suggested that the waveshape be examined to see if other issues are occurring. For example, the point-in-wave of the initiation of the event might cause contactors or relays to misoperate, and misoperation, in turn, could cause the equipment to trip off. By investigating the phases individually, one could determine how the control power is connected and if it is powered from the devices involved in the sag.

8.4.5 High-frequency analysis

8.4.5.1 Background

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 10 kHz of the power system.

Field data have shown that transients can travel from one wire to another, even if the wires are not physically connected (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 (the half wavelength of 1 MHz is only 150 m), although they are generally reduced by loads and the impedance of 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.

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 large switching current transient causes a corresponding voltage transient. The transient reflects the energy draw of the capacitor. In other words, the voltage transient's leading edge is 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 is negative. An example of this behavior is shown in Figure 32. Care should be taken when installing capacitor banks, since resonance and amplified switching transients could occur. Figure 32 shows the effect of switching in a shunt capacitor bank. Even if the capacitors are located at a nearby high-voltage substation, a similar waveform appears on 120 V receptacles. It should be noted that when capacitor banks are switched out, other transients can also occur.

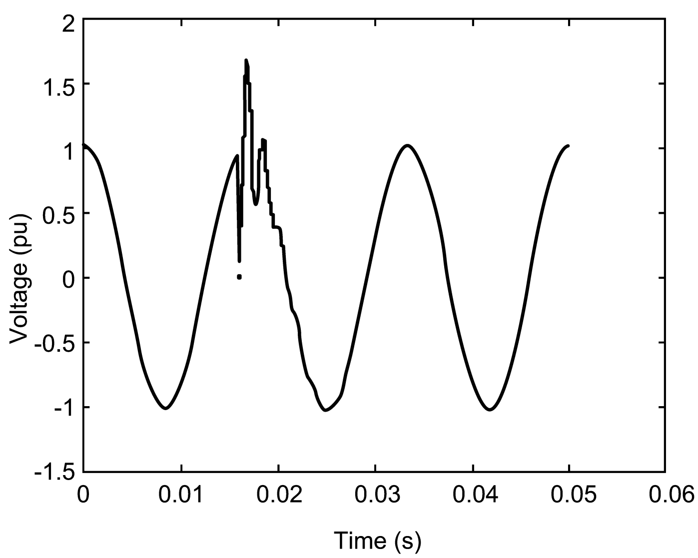


Figure 32—Effect of capacitor switching transient on voltage waveform

As a capacitive load is introduced into the inductive power system, it can also alter the frequency response of the system. An inductive-capacitive system has resonant frequencies, which can be excited by the capacitor induced voltage and current transients and lead to a damped oscillatory transient.

On the other hand, when an inductive load is applied to the power system, transients are usually minor. The inductor draws current and generates its magnetic field. The inductor, however, causes a transient at deenergization depending on point-in-wave. If the switch controlling the inductive load is opened, three things happen. First, the magnetic field collapses, and the collapse creates a voltage transient. This situation is sometimes called inductive kickback. Since this transient is adding energy back into the system, its position on the ac waveform is in the same polarity. Second, the switch trying to break the flow of current can arc slightly. Arcing is seen as high-frequency 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 can bounce. Switch bounce produces a second, smaller transient immediately following the first.

8.4.6 Harmonic analysis

8.4.6.1 Background

Harmonics produce steady-state distortion of a voltage or current signal when compared to a pure sine wave. Although harmonics have been present in power systems since fluorescent lighting was first introduced, the proliferation of rectified input power supplies, such as used in adjustable speed drives and information technology equipment, has required engineers to forgo the sinusuoidal assumptions that dominated conventional electrical theory and design in the past. While voltage distortion is usually fairly small, the current distortion in practical power systems can be significant, depending on the type of loads.

8.4.6.2 Analysis tips

Three techniques for analyzing harmonics are examined. The first involves several simple ways of determining whether harmonics are present in the power system (see 8.4.6.2.1). The second provides help in determining what particular type of load is contributing to harmonic distortion (see 8.4.6.2.2). The third looks at how harmonic data can be used to produce an impedance spectrum of the power system (see 8.4.6.2.3).

8.4.6.2.1 Harmonic presence

Before harmonic-measuring equipment is rented or purchased, several easy tasks can be done to determine whether harmonics are present. If the answer to any of the following questions is yes, then harmonics are present:

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

8.4.6.2.2 Generic harmonic spectra

If harmonics are present in the power system and further investigation is warranted, a harmonics analyzer is normally required. Some relatively inexpensive oscilloscopes and handheld devices can be used for this analysis. Such devices can provide specific information about harmonic levels. Some of these devices provide only the THD, while others provide THD and a full harmonic spectrum. Harmonic spectra can be very useful for gaining insight into the general type of load(s) that are contributing to the overall distortion.

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

If there are significant even-order harmonics, then the signal's positive half cycle and negative half cycle are not symmetrical with respect to the zero axis.

— Single-phase power conversion devices typically produce high third harmonic current distortion with an exponential decay of each successive odd harmonic.
— Three-phase rectifiers produce higher current harmonics in accordance to the following formula:

$h = k \times q \pm 1$ where h = harmonic order
k = integer constant (1, 2, 3….)
q = number of pulses or paths of conduction or poles of rectifier

The largest magnitude harmonics usually occur when $k = 1$, then reduce in amplitude as k increases. For example, a full wave, three-phase rectifier (also called a 6 pulse rectifier), has dominate harmonics at the 5th and 7th harmonic, using the formula $h = 1 \times 6 \pm 1$. then next harmonics, 11th and 13th, are normally smaller magnitude then 5th and 7th, and so forth (see IEEE Std 519-2014 [B27]).

8.4.6.2.3 Impedance spectra

The last technique to be examined is the impedance spectrum. An example is shown in Figure 33. This method takes both voltage and current harmonic data and then graphs the impedance versus frequency of the power system. It provides useful information regarding system frequency response, resonant points, and potential problems due to harmonic distortion.

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 be obtained from either turning the loads off or possibly using the harmonic data from some point near the source, e.g., at the source transformer or service entrance.

With these data, the impedance can be calculated at each harmonic frequency and plotted. The subsequent graph provides 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, therefore, reduce possible voltage distortion.

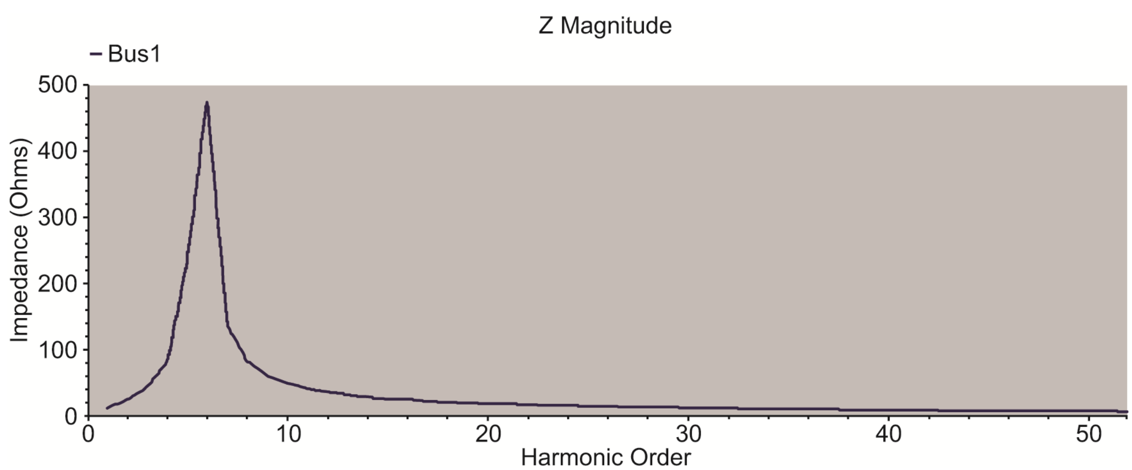


Figure 33—Sample impedance spectrum showing resonant frequencies due to power factor correction capacitor

8.4.7 Pattern recognition

8.4.7.1 Background

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 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 are 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. Table 8 shows some typical examples of these timing relationships.

Table 8—Pattern recognition

Pattern	Examples
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 s to 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 or turn-off.

8.4.8 Discontinuities

8.4.8.1 Background

Discontinuities refer to the radical departure of some system component from the norm when the models cannot explain such departures. 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 of questions is helpful in discovering whether 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

Clause 8 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 check can be accomplished through examining the 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 was wrong. Sometimes it can be, but, many times solving one problem simply allows the next problem 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 can affect other parts. It is entirely possible that the solution to a problem can 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 can 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 whether any other concerns have arisen because of 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. Users should ask, “What are the consequences if the measurements are out of spec?” If users are measuring voltage to ANSI C84.1 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 C84.1-2016 [B2]. The document does not describe any. It does say that the measured values should be in rms values, but does not indicate whether the values can be determined by means of peak recording voltmeter technology that uses an algorithm to convert to rms. This method is not accurate with distorted wave shapes. ANSI C84.1-2016 [B2] defines steady state as sustained voltage levels and not momentary voltage excursions. What if, however, users have an instrument that takes periodic snapshots and then calculates an average? Is that method accurate? How can users say that calibration has meaning to that instrument in an absolute?

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

The accuracy of measuring the magnitude of the both steady-state and transient ac voltage disturbances cannot be separated from the process of how the instrument records the measurement. Peak detecting, averaging, and special algorithms work only where there is limited waveform distortion. See Figure A.1.

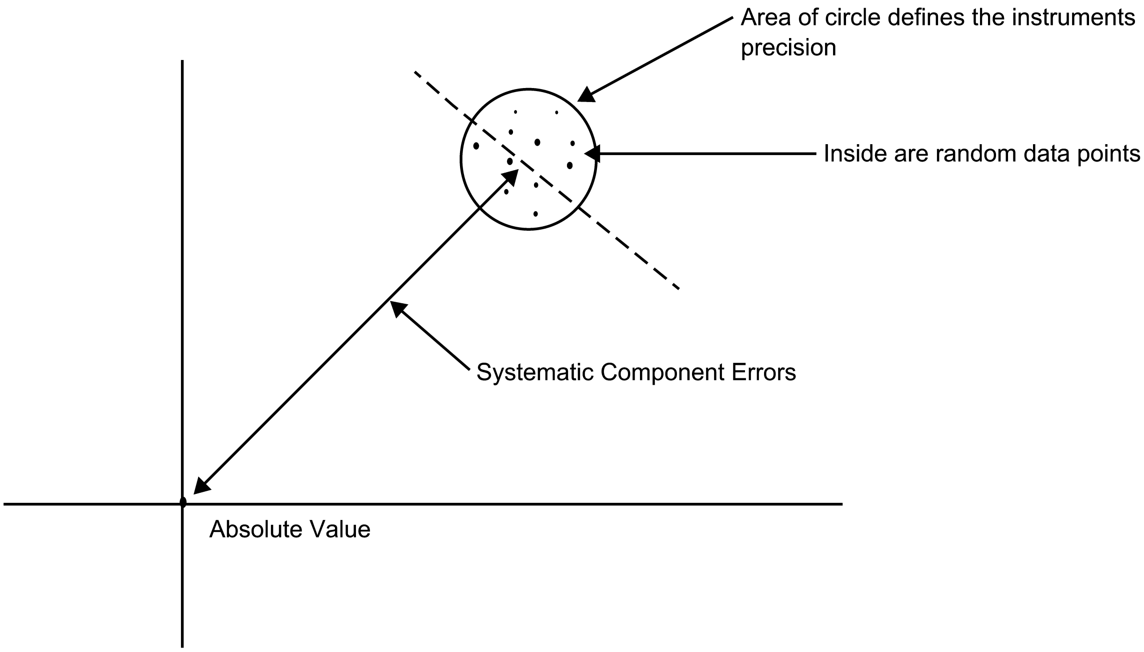


Figure A.1—Instrument accuracy: the combination of (1) random errors and (2) systematic component errors

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 increase for longer time spans due to a drift rate. If a drift rate specification is included, a buyer of a measuring instrument can calculate the uncertainty for the time span required.

A.2.2 Temperature coefficient

Temperature coefficient 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 effects are taken in account, and on-site calibration is preferable since the instrument is not subject to damage in transit. Also, the instrument is out of commission for a shorter time. A contrary argument is as follows: Should "local effects" be included or purposely deleted from calibration? If inclusion or deletion affects and creates a more accurate measurement at one site, does not that naturally mean inclusion or deletion can produce less accurate data at another site?

A.2.4 Calibration intervals

A broad guideline is provided by military specification MIL-STD-45662A [B42]. Test equipment and standards should be calibrated at intervals established on the basis of stability, purpose, degree of usage, precision, accuracy, and the skills of the 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; therefore, 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. The internal test can test only one section at a time and at low signal levels. The user determines whether that method is adequate. Built-in self-calibration and self-test might 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 to be calibrated are an important reference. Normally, these manuals include recommended calibration procedures along with a set of calibration points, for example, a digital multimeter'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 where, by means of firmware and special circuitry, an instrument can make some limited internal checks. The ability to run internal calibration checks between external calibrations 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 and can instill 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 multichannel analyzers, link all channels together and create a disturbance. If all channels indicate the same event/magnitude/duration, then calibration is probably adequate.

Annex B

(informative)

Typical characteristics of transients

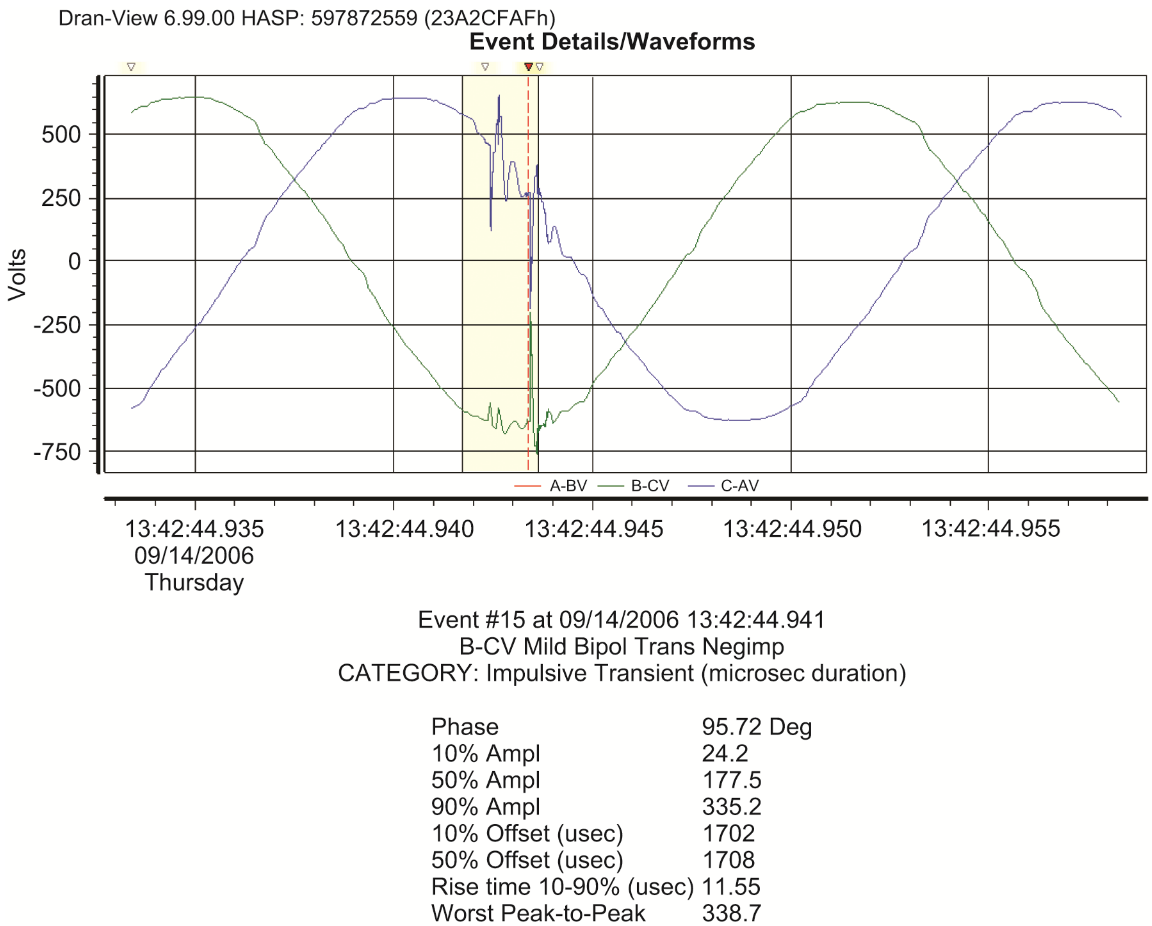
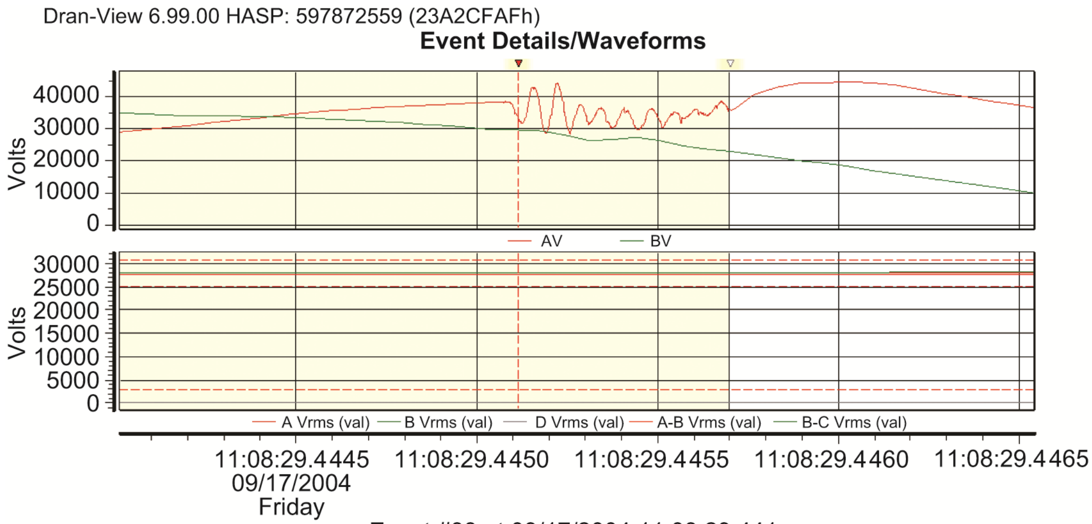


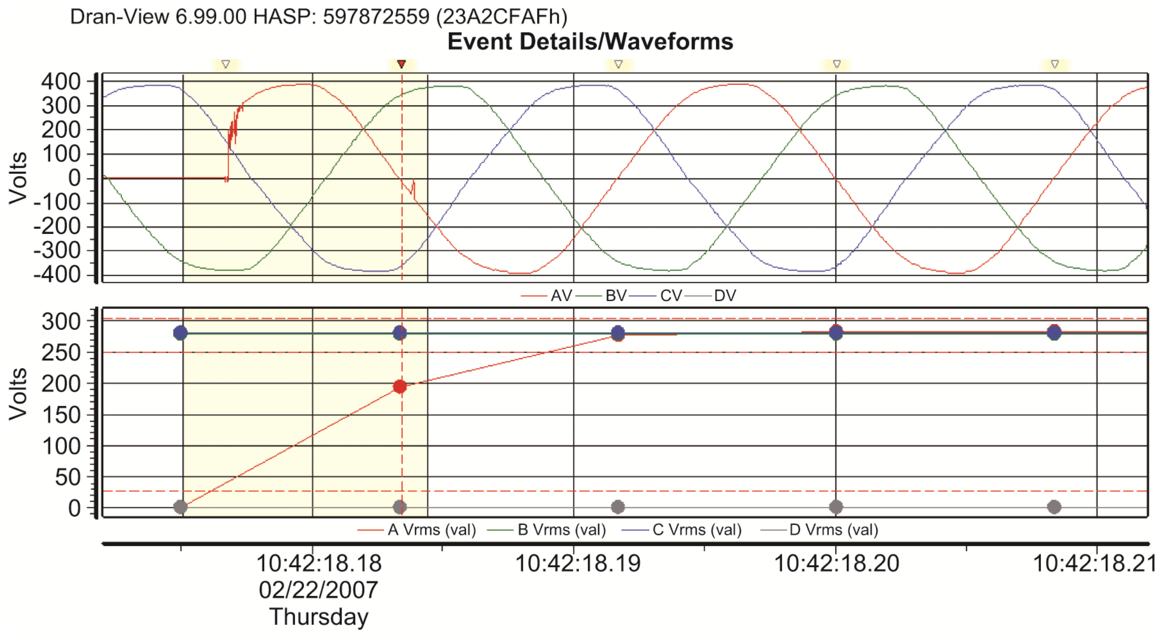
Figure B.1—Two waveforms of a mild bipolar transient with initial negative impulsive transient



Event #33 at 09/17/2004 11:08:29.441
AV Mild Osc Trans Negimp
CATEGORY: Oscillatory Transient (Medium Freq.)

Phase	74.3 Deg
Frequency	15060 Hz
10% Ampl	32050
50% Ampl	32050
90% Ampl	32050
10% Offset (usec)	3445
50% Offset (usec)	3445
Fall time 10-90% (usec)	22.0
Worst Peak-to-Peak	15881

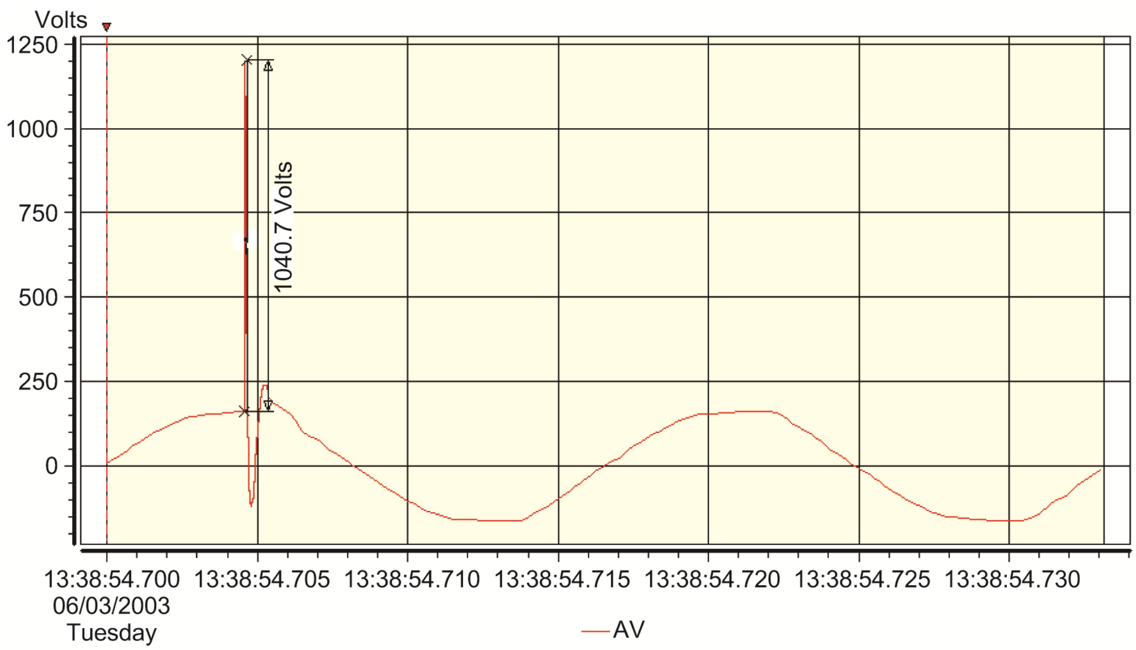
Figure B.2—Waveform of mild amplitude, medium frequency oscillatory transient



Event #1227 at 02/22/2007 10:42:18.175
AV Drop out 1/16 Cyc
Phase 360.1 Deg

	A	B	C	D	A–B	B–C	C–A
Vrms	193.2	280.0	281.7	0.1164	379.5	486.7	403.9
VPeak	390.6	383.0	386.4	0.2734			
Irms	2.914	2.514	2.752	2.677			
IPeak	7.445	5.912	5.930	7426			

Figure B.3—Waveform of an 1/8 Cycle dropout transient



Magnitude (V) 1038
Phase (Deg.) 113.0

Figure B.4—Positive Impulsive with a fast rise time, followed by negative kickback

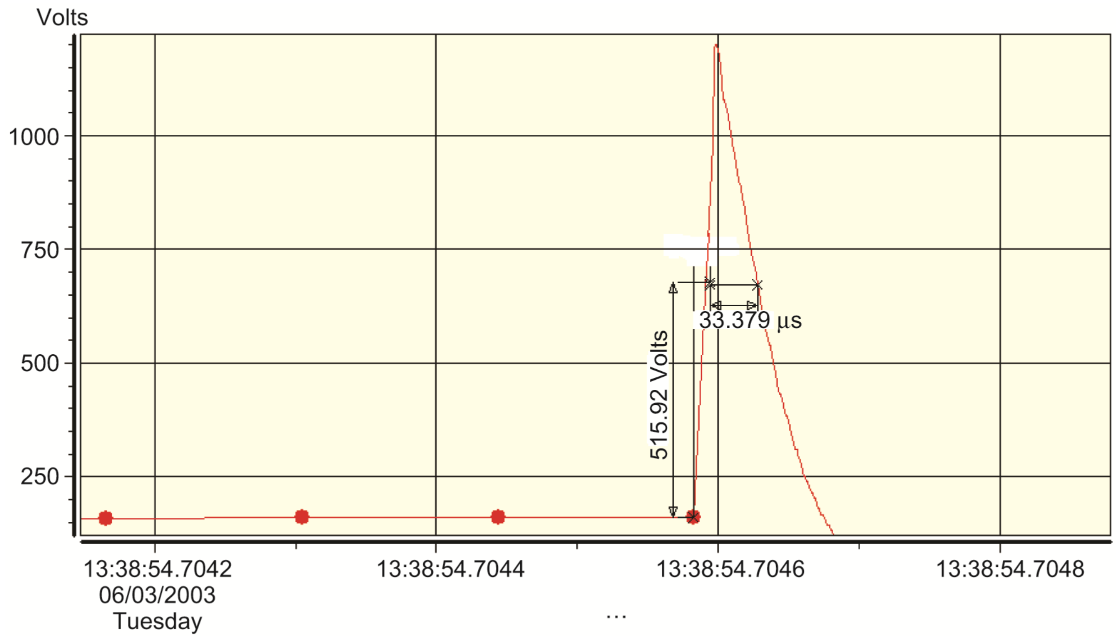


Figure B.5—Zoomed in detail of impulsive transient rise and fall duration

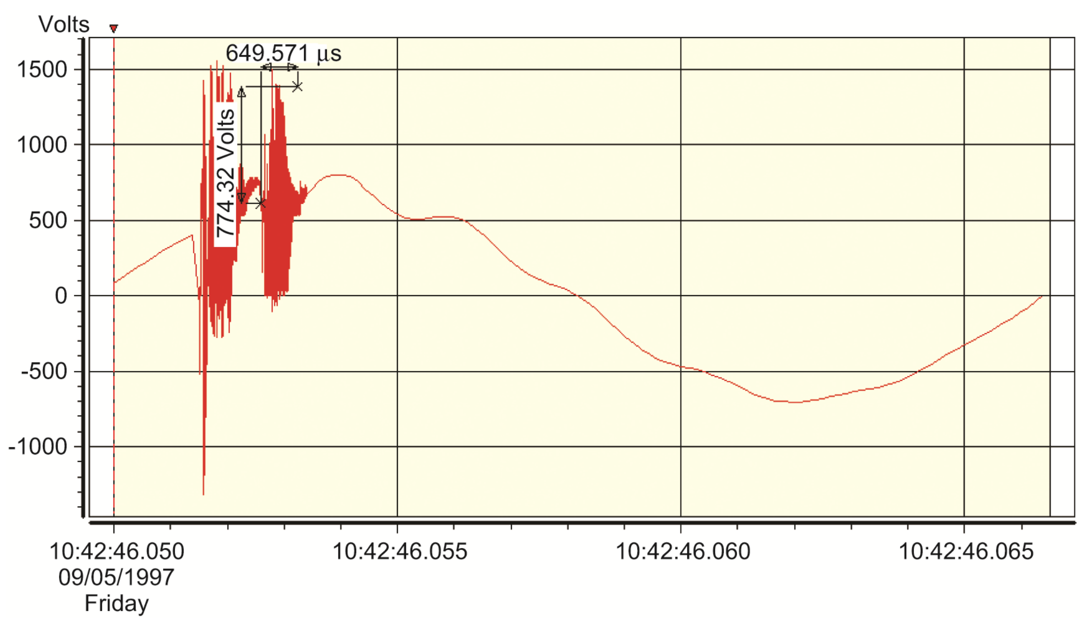
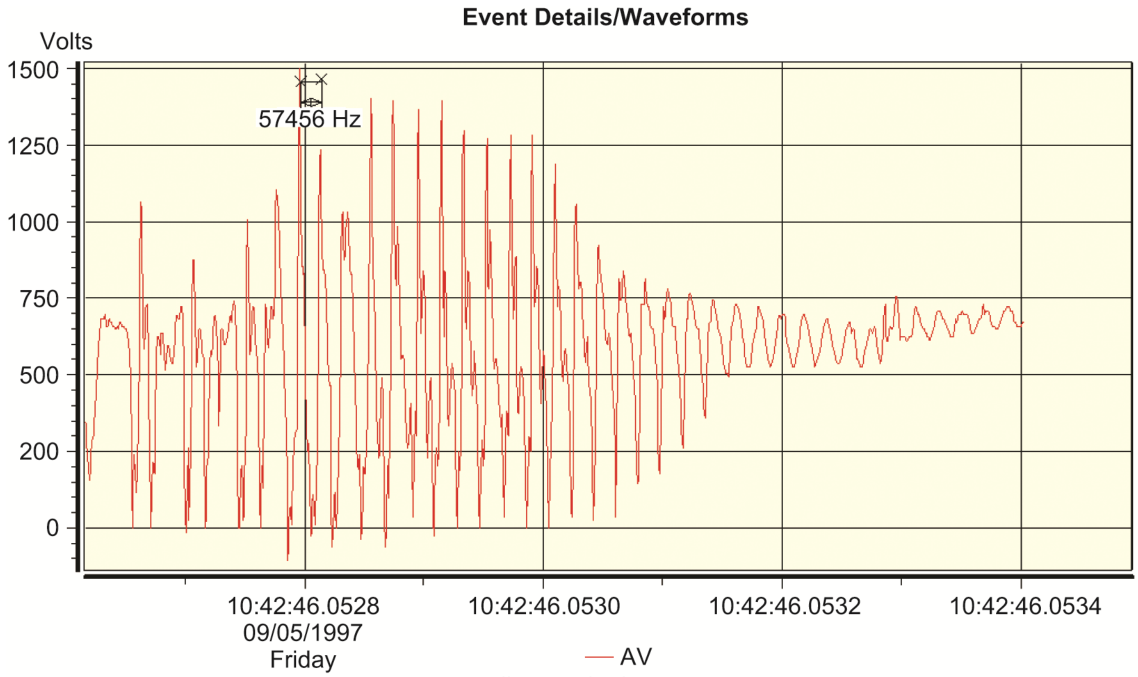


Figure B.6—Back-to-back arcing transients



Event #7 at 09/05/1997 10:42:46.049
AVTrans, BVTrans, DVTrans Impulse event

	AV	BV	CI	DV
High threshold (V)	500.0	500.0		500.0
Magnitude (V)	-1765	2180		-1707
PrevRMS (V)	474.4	474.5	416.0	476.5
MinRMS (V)	485.4	492.8	449.0	502.1
MaxRMS (V)	485.4	492.8	449.0	502.1
Phase (Deg.)	39.0	273.0		159.0
Hits	1	1		1

Figure B.7—Zoom in detail of arcing transients

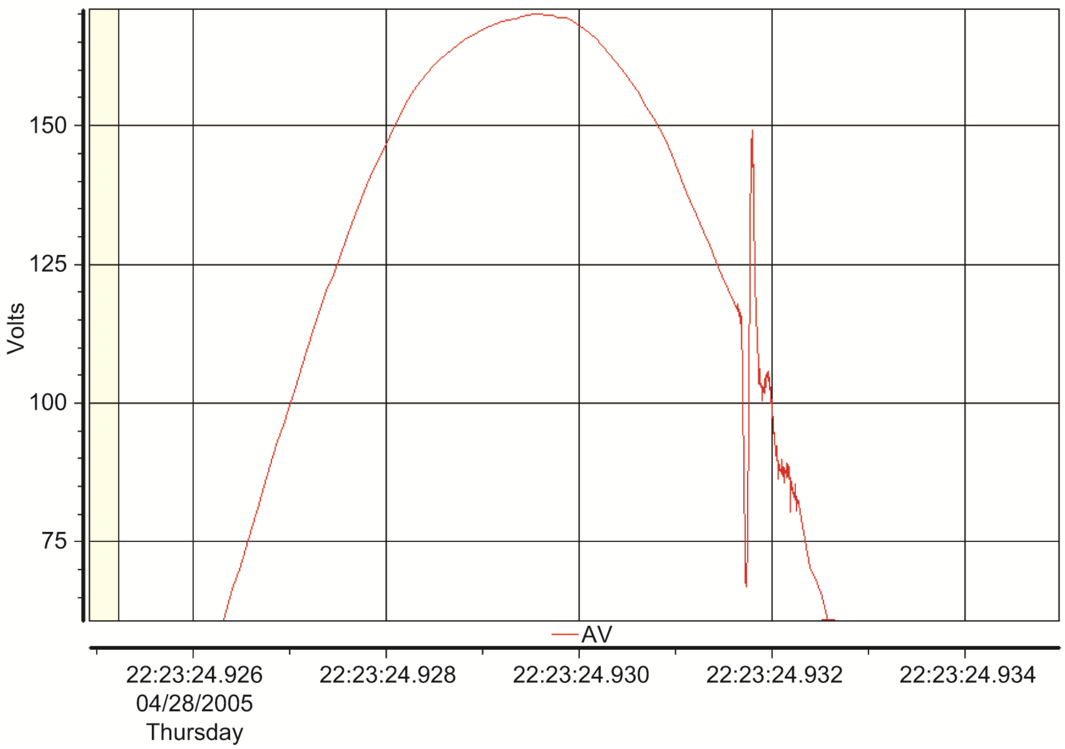


Figure B.8—Negative and positive impulsive transient followed by arcing

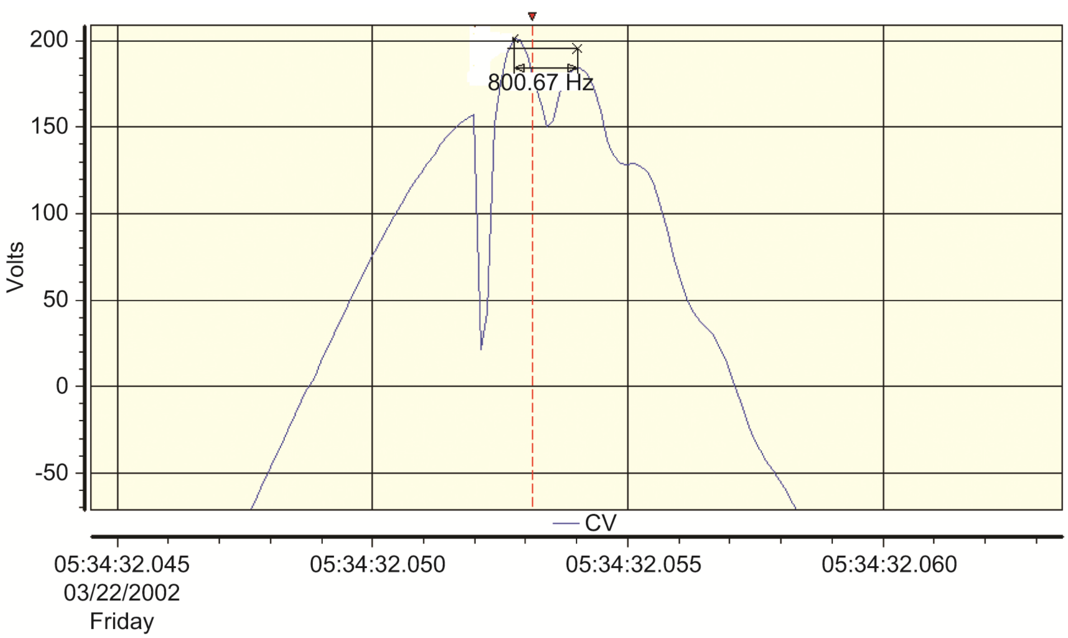


Figure B.9—Negative transient with ringing or oscillation following

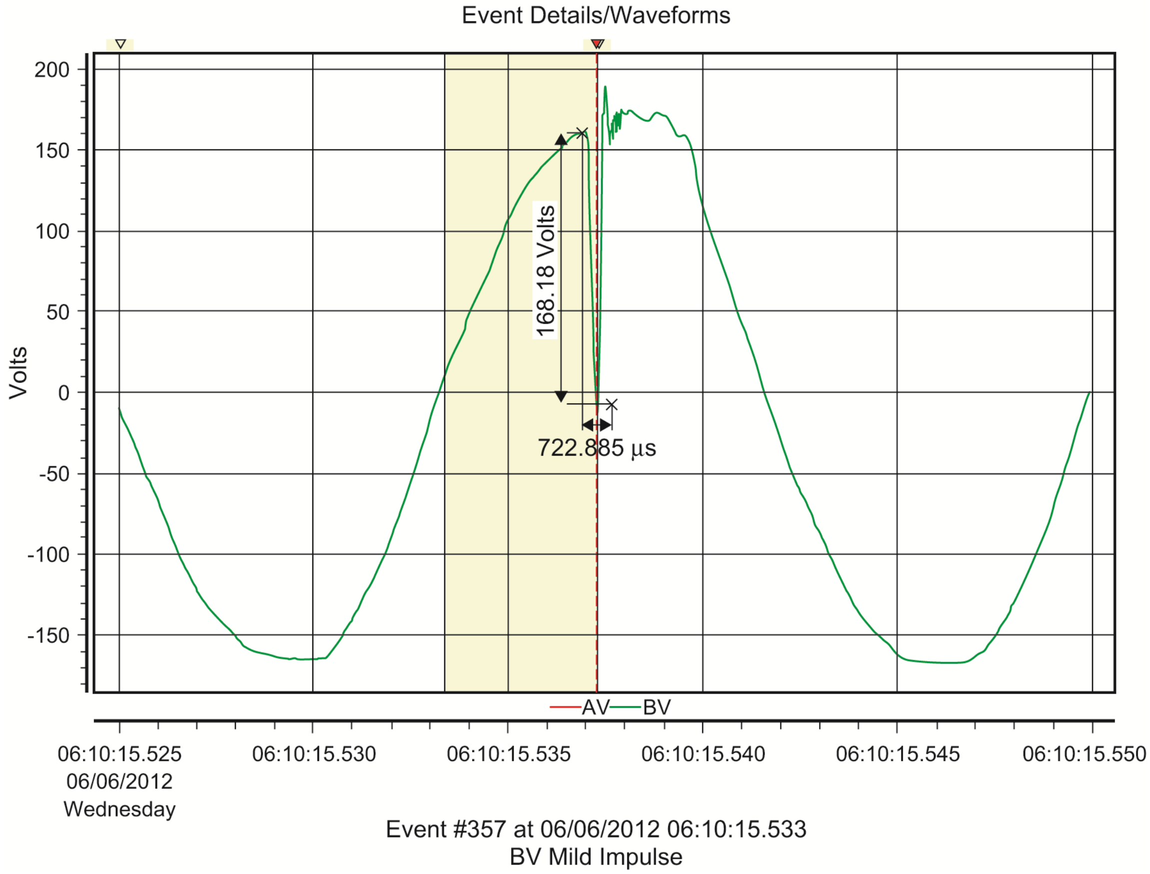


Figure B.10—Negative impulsive transient causing zero crossing

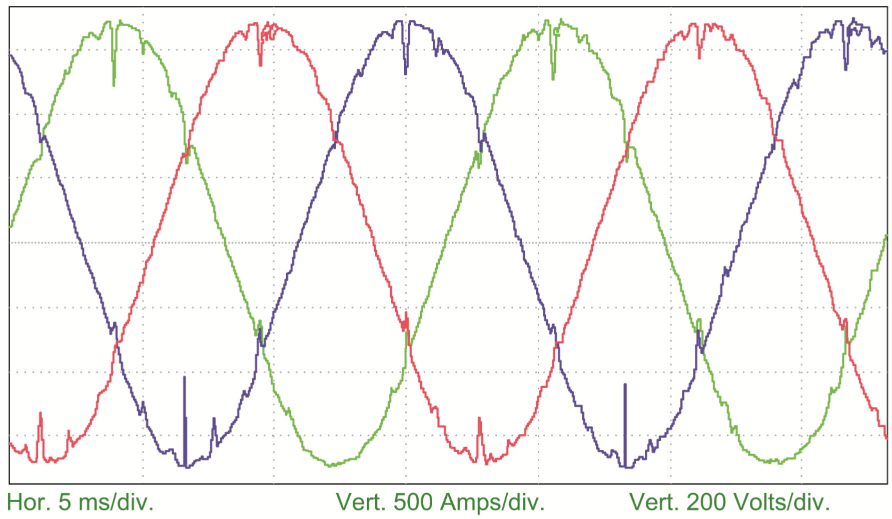


Figure B.11—Repetitive notches

Annex C

(informative)

Glossary

For the purposes of this standard, the following terms and definitions apply. These and other terms within IEEE standards are found in *The IEEE Standards Dictionary Online*.

accuracy: (1) (instrumentation and measurement) The quality of freedom from mistake or error, that is of conformity to truth or to a rule. (7) (indicated or recorded value) The accuracy of an indicated or recorded value is expressed by the ratio of the error of the indicated value to the true value. It is usually expressed in percent. See: accuracy rating of an instrument.

calibration: (3) The adjustment of a device to have the designed operating characteristics, and the subsequent marking of the positions of the adjusting means, or the making of adjustments necessary to bring operating characteristics into substantial agreement with standardized scales or marking. (4) (metering) Comparison of the indication of the instrument under test, or registration of the meter under test, with an appropriate standard.

common-mode voltage: (1) The voltage that, at a given location, appears equally and in phase from each signal conductor to ground.

coupling: (7) The association of two or more circuits or systems in such a way that power or signal information can be transferred from one system or circuit to another.

current transformer (CT): (2) (metering) An instrument transformer designed for use in the measurement or control of current.

dropout: (3) A loss of equipment operation (discrete data signals) due to noise, voltage sags, or interruption.

electromagnetic compatibility (EMC): (1) (supervisory control, data acquisition, and automatic control)(station control and data acquisition) A measure of equipment tolerance to external electromagnetic fields. (2) (control of system 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.

electromagnetic disturbance: (1) An electromagnetic phenomenon that can be superimposed on a wanted signal. (2) (overhead power lines) Any electromagnetic phenomenon that can degrade the performance of a device, a piece of equipment, or a system.

equipment grounding conductor: (2) The conductor used to connect the noncurrent-carrying parts of conduits, raceways, and equipment enclosures to the grounding electrode at the service equipment (main panel) or secondary of a separately derived system.

failure mode: (4) The manner in which failure occurs; generally categorized as electrical, mechanical, thermal, and contamination.

frequency deviation: (5) An increase or decrease in the power frequency from nominal. The duration of a frequency deviation can be from several cycles to several hours.

ground: (3) (A) A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth, or to some conducting body of relatively large extent that serves in place of the earth. (B) High-frequency reference. Note: Grounds are used for establishing and maintaining the potential of the earth (or of the conducting body) or approximately that potential, on conductors connected to it, and for conducting ground currents to and from earth (or the conducting body).

ground loop: (2) A potentially detrimental loop formed when two or more points in an electrical system that are nominally at ground potential are connected by a conducting path such that either or both points are not at the same ground potential.

harmonic: A sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency. Note: For example, a component, the frequency of which is twice the fundamental frequency, is called a second harmonic.

harmonic components: The components of the harmonic content expressed in terms of the order and root-mean-square (rms) values of the Fourier series terms describing the periodic function.

harmonic content: (1) The function obtained by subtracting the dc and fundamental components from a nonsinusoidal periodic function. (2) The deviation from the sinusoidal form, expressed in terms of the order and magnitude of the Fourier series terms describing the wave. (3) Distortion of a sinusoidal waveform characterized by indication of the magnitude and order of the Fourier series terms describing the wave.

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

impulse: (1) (mathematics). A pulse that begins and ends within a time so short that it is regarded mathematically as infinitesimal although the area remains finite. (4) A surge of unidirectional polarity.

isolated equipment ground: An isolated equipment grounding conductor run in the same conduit or raceway as the supply conductors. This conductor should 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.

isolation: (3) Separation of one section of a system from undesired influences of other sections.

maximum demand: (1) (power operations) The largest of a particular type of demand occurring within a specified period.

momentary: When used as a modifier to quantify the duration of a short-duration variation, refers to a time range from 30 cycles to 3 s.

momentary interruption: 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.

noise: (11) Electrical noise is unwanted electrical signals that produce undesirable effects in the circuits of the control systems in which they occur.

nominal voltage: (3) A nominal value assigned to a circuit or system for the purpose of conveniently designating its voltage class (as 208/120, 480/277, 600).

nonlinear load: A load that draws a nonsinusoidal current wave when supplied by a sinusoidal voltage source.

normal-mode: (1) (transverse or differential) The voltage that appears differentially between two signal wires and that acts on the circuit in the same manner as the desired signal.

notch: (2) A switching (or other) disturbance of the normal power voltage waveform, lasting less than a half cycle, which is initially of opposite polarity than the waveform and is thus subtracted from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to a half cycle.

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

overvoltage: (9) 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 to 1.2 pu.

phase shift: (4) The displacement in time of one waveform relative to another of the same frequency and harmonic content.

potential transformer (PT): (1) (voltage transformer). An instrument transformer that is intended to have its primary winding connected in shunt with a power-supply circuit, the voltage of which is to be measured or controlled.

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

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

pulse: (4) A wave that departs from an initial level for a limited duration of time and ultimately returns to the original level.

sag: (2) A decrease in root-mean-square (rms) voltage or current for durations of 0.5 cycles to 1 min. Typical values are 0.1 to 0.9 pu.

shield: (7) (instrumentation cables) (cable systems). A metallic sheath, usually copper or aluminum, applied over the insulation of a conductor or conductors for the purpose of providing means for reducing electrostatic coupling between the conductors so shielded and others which can be susceptible to or which can be generating unwanted (noise) electrostatic fields.

shielding: (3) The process of applying a conductive barrier between a potentially disturbing noise source and electronic circuitry. Shields are used to protect cables (data and power) and electronic circuits. Shielding can be accomplished by the use of metal barriers, enclosures, or wrappings around source circuits and receiving circuits.

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).

sustained interruption: A type of long-duration variation. The complete loss of voltage (<0.1 pu) on one of more phase conductors for a time greater than 1 min.

swell: (3) An increase in root-mean-square (rms) voltage or current for durations from 0.5 cycles to 1 min. Typical values are 1.1 pu to 1.8 pu.

temporary: When used as a modifier to quantify the duration of a short-duration variation, refers to a time range from 3 s to 1 min.

temporary interruption: 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.

total demand distortion (TDD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmoincs, expressed as a percent of the maximum demand current. Harmonic components of order greater than 50 may be included when necessary.

total harmonic distortion (THD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the fundamental. Harmonic components of order greater than 50 may be included when necessary.

transient: (7) Pertaining to or designating a phenomenon or a quantity which 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.

undervoltage: (1) When used to describe a specific type of long-duration variation, refers to a measured voltage having a value less than the nominal voltage for a period of time greater than 1 min. Typical values are 0.8 pu to 0.9 pu.

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

voltage imbalance: (unbalance), polyphase systems. The ratio of the negative or zero sequence component to the positive sequence component, usually expressed as a percentage.

voltage regulation: (6) The degree of control or stability of the root-mean-square (rms) voltage at the load. Often specified in relation to other parameters, such as input-voltage changes, load changes, or temperature changes.

Annex D

(informative)

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