



IEEE Recommended Practice for Monitoring Electric Power Quality

IEEE Power & Energy Society

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Transmission and Distribution Committee

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IEEE Recommended Practice for Monitoring Electric Power Quality

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**Transmission and Distribution Committee
of the
IEEE Power & Energy Society**

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Abstract: This recommended practice encompasses the monitoring of electrical characteristics of single-phase and polyphase ac power systems. 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, imbalance, instruments, monitoring, power quality, rms variation, sag, swell, transient, unbalance

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Introduction

This introduction is not part of IEEE Std 1159-2009, IEEE Recommended Practice for Monitoring Electric Power Quality.

This recommended practice encompasses the monitoring of electrical quality of single-phase and polyphase ac power systems. It is important that all power quality monitors, as well as users of monitors and monitoring data, use consistent terminology and definitions of power quality phenomena. Therefore, this recommended practice provides consistent descriptions of electromagnetic phenomena occurring on power systems. It describes nominal conditions of the power supply and of deviations from these nominal conditions that may originate within the power supply or in the load equipment or may originate from interactions between the source and the load.

Monitoring and measurements can be utilized for power system performance studies as well as compatibility assessment. Brief, generic descriptions of load susceptibility to deviations from nominal power supply conditions are presented to identify which deviations may be of interest. Further, this recommended practice discusses the selection of appropriate measuring instruments, limitations of these instruments, application techniques, and the interpretation of monitoring results.

While there is no implied limitation on the voltage rating of the power system being monitored, signal inputs to monitoring instruments are generally limited to 1000 V ac root mean square (rms) or less. Instrument transformers and attenuators enable the use of monitoring equipment on a wide range of voltages and currents. Typically, the frequency ratings of the ac power systems being monitored are in the range of 45 Hz to 450 Hz. Some monitors can also acquire dc signals from the load or control system to assist in the interpretation of load response to deviations from the nominal. The interpretation of dc signals is beyond the scope of this recommended practice. It is also recognized that these instruments may perform monitoring functions for environmental conditions (e.g., temperature, humidity, high-frequency electromagnetic radiation); however, the scope of this recommended practice is limited to conducted electrical parameters derived from ac voltage or current measurements, or both.

The definitions presented and used in this recommended practice are intended solely for characterizing common electromagnetic phenomena to facilitate communication between various sectors of the power quality community. The definitions are not intended to represent performance standards or equipment tolerances. For example, electric power providers (e.g., electric utilities) may utilize different thresholds for undervoltage and overvoltage in the supply from the descriptions in Table 2. On the other hand, sensitive equipment may malfunction due to electromagnetic phenomena that lie within the thresholds of the Table 2 criteria.

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1. Overview

1.1 Scope

This recommended practice encompasses the monitoring of electrical characteristics of single-phase and polyphase ac 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. Also, this recommended practice discusses measurement techniques, application techniques, and the interpretation of monitoring results.

1.2 Purpose

The use of equipment that causes and is susceptible to various electromagnetic phenomena has heightened the interest in power quality. An increase in operational problems has led to a variety of attempts to describe the phenomena. Because different segments of the technical community have used different terminologies to describe these electromagnetic events, this recommended practice provides users with a consistent set of terms and definitions for describing these events. An understanding of how power quality events impact 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 disturbances on the power system.

2. Normative references

The following referenced documents are indispensable for the application of this recommended practice (i.e., they must be understood and used; therefore, each referenced document is cited in text and its relationship to this recommended practice is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

No normative references apply to this recommended practice.

3. Definitions

For the purposes of this recommended practice, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B18]¹ should be referenced for terms not defined in this clause.

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

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

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

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

3.5 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.

3.6 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).

3.7 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).

3.8 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.

3.9 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:* **sag, swell, momentary interruption, temporary interruption, sustained interruption, undervoltage, overvoltage.**

¹ The numbers in brackets correspond to the numbers of the bibliography in Annex C.

3.10 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).

3.11 sustained interruption: A type of long-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 greater than 1 min.

3.12 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.

3.13 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.

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

3.15 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).

3.16 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 chapter amplifies the definitions of Clause 3 and the glossary in Annex B 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 which 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 will be used by the power quality community to describe these common events. The clause also offers explanations of why commonly used terminology in other communities will 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 B, and *The Authoritative Dictionary of IEEE Standards Terms* [B18] for the definitions of electromagnetic compatibility and related terms.

UIE-DWG-3-92-G [B43] provides an excellent overview of the electromagnetic compatibility concept and associated IEC documents.

4.3 General classification of phenomena

In IEC 61000-2-5:1995 [B12], 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* is introduced as an inverse to sag (dip). The category *long-duration variation* has been added to deal with the limits in ANSI C84.1-2006 [B2]. The category *noise* has been 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 61000-4-7:2002 [B14] as well as an additional phenomenon from IEEE Std 519™-1992 [B24] 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 61000-2-5:1995 [B12]). 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:

- 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 [B43], IEC 61000-2-5:1995 [B12], and UIE-DWG-2-92-D [B42]). 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 particular variation that is of concern. The different solutions available are discussed for each category. There are also different requirements for characterizing the phenomena using measurements. It is important to be able to classify events and electromagnetic phenomena for analysis purposes. The measurement requirements for each category of electromagnetic 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 μ s rise	50 ns – 1 ms	
1.1.3 Millisecond	0.1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5 kHz	0.3–50 ms	0–4 pu ^a
1.2.2 Medium frequency	5–500 kHz	20 μ s	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 μ s	0–4 pu
2.0 Short-duration 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 – 3 s	< 0.1 pu
2.2.2 Sag		30 cycles – 3 s	0.1–0.9 pu
2.2.3 Swell		30 cycles – 3 s	1.1–1.4 pu
2.3 Temporary			
2.3.1 Interruption		>3 s – 1 min	< 0.1 pu
2.3.2 Sag		>3 s – 1 min	0.1–0.9 pu
2.3.3 Swell		>3 s – 1 min	1.1–1.2 pu
3.0 Long duration 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	
4.0 Imbalance			
4.1 Voltage		steady state	0.5–2%
4.2 Current		steady state	1.0–30%
5.0 Waveform distortion			
5.1 DC offset		steady state	0–0.1%
5.2 Harmonics	0–9 kHz	steady state	0–20%
5.3 Interharmonics	0–9 kHz	steady state	0–2%
5.4 Notching		steady state	
5.5 Noise	broadband	steady state	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™-2003 [B27] 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 61000-4-15:2003 [B15] and IEEE Std 1453™-2004 [B28].

4.4.1 Transients

The term *transients* 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 Authoritative Dictionary* [B18] definition of transient reflects this understanding. The primary definition uses the word *rapid* and describes frequencies up to 3 MHz when defining transient in the context of evaluating cable systems in substations. The notion of a damped oscillatory transient due to a resistor-inductor-capacitor (RLC) network is also mentioned. This is the type of phenomena that most power engineers think of when they hear the word *transient*.

Other definitions in *The Authoritative Dictionary* [B18] are broader in scope and simply state that a transient is the “part of the change in a variable that disappears during transition from one steady-state operating condition to another.” Unfortunately, this definition could be used to describe just about anything unusual that happens on the power system.

Another word used in current IEEE standards that is synonymous with transient is *surge*. *The Authoritative Dictionary* [B18] defines a surge as “a transient wave of current, potential, or power in an electric circuit.” IEEE Std C62.41™-1995 [B20] 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* will not be used to describe transient electromagnetic phenomena. Since *The Authoritative Dictionary* uses the term *transient* to define surge, this limitation should not cause conflicts.

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

4.4.1.1 Impulsive transient

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 rise and decay times. These phenomena can 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 in microseconds and 50 expresses a measure of the decay time in microseconds (see IEEE Std C62.41-1995 [B20] 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 resistive 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.

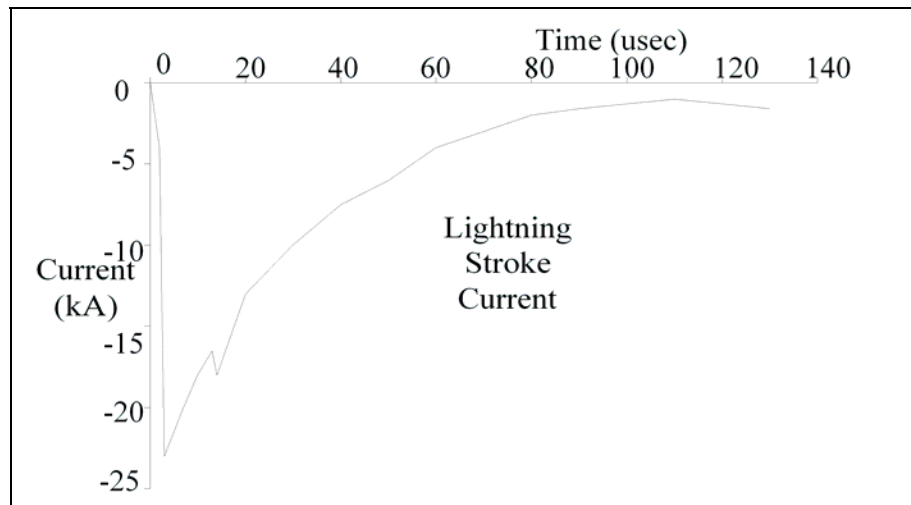


Figure 1—Lightning stroke current that can result in impulsive transients on power system

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. It is described by its magnitude, duration, and spectral content (predominantly frequency). 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.

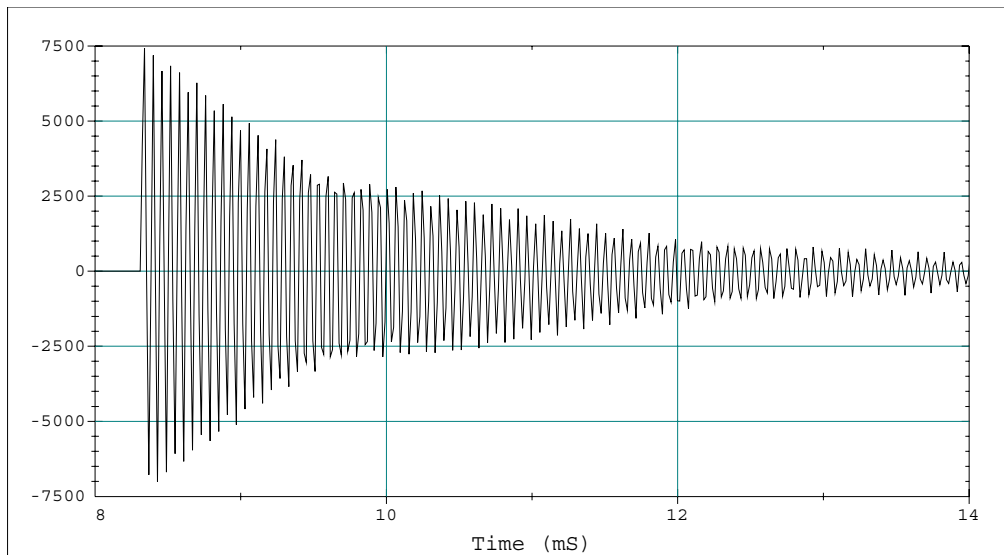


Figure 2—Oscillatory transient caused by back-to-back capacitor switching

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 can be readily classified using the attributes discussed so far. Capacitor bank energization typically results in an oscillatory voltage transient with a primary frequency between 300 Hz and 900 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.

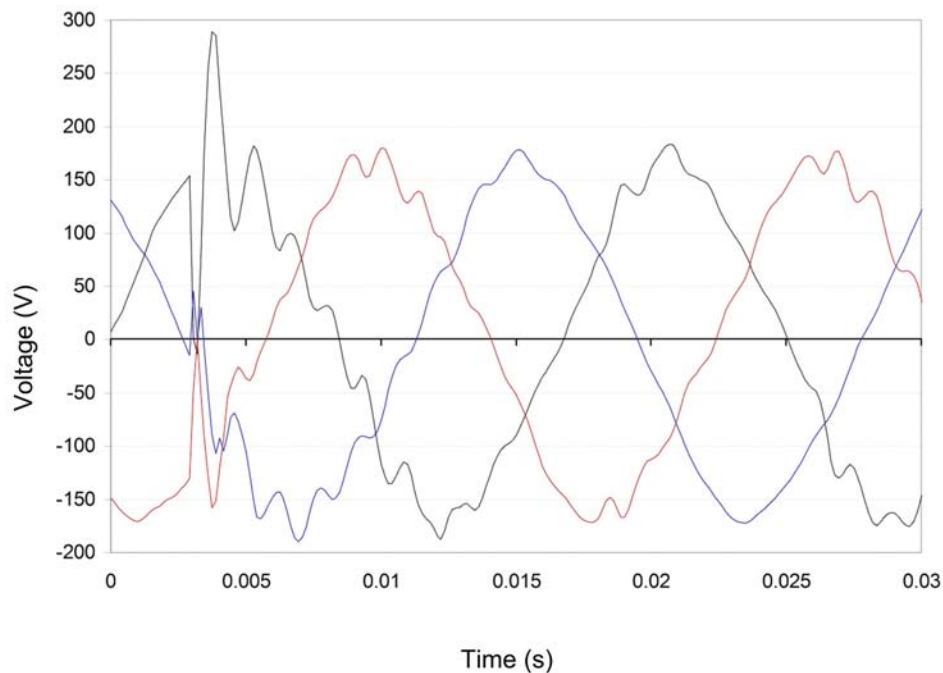


Figure 3—Low-frequency oscillatory transient caused by capacitor-bank energization

Oscillatory transients with principal frequencies less than 300 Hz can also be 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 C62.41-1995 [B20] 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.

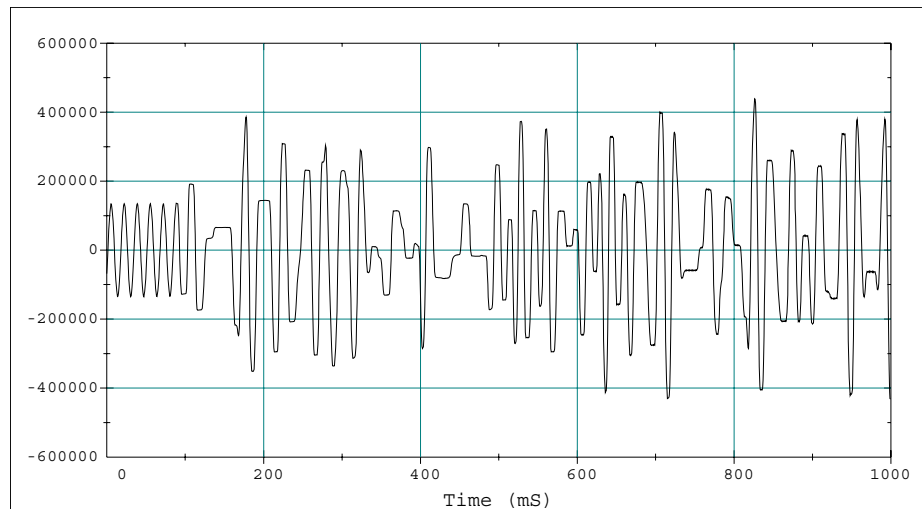


Figure 4—Low-frequency oscillatory transient caused by ferroresonance of unloaded transformer

4.4.2 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 can be designated as instantaneous, momentary, or temporary, depending on its duration as defined in Table 2.

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

Figure 5 shows a momentary interruption during which voltage drops to zero for about 2.3 s. Note that the upper plot depicts the rms variation of the entire event over a range of approximately 3 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 may 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.

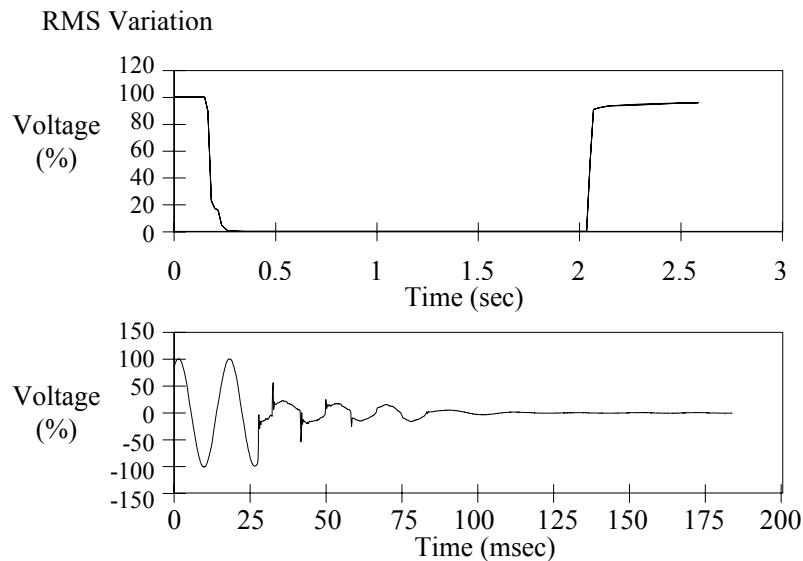


Figure 5—Momentary interruption due to fault and subsequent recloser operation

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” can refer 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 6 shows a typical voltage sag that can be 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 will result in a voltage drop at the substation bus, which affects all of the other feeders until the fault is cleared, but often these will not result in such deep sags as shown in Figure 6. Note the different time scales used on the upper and lower plot, and note the smoothing of the instantaneous voltage by the rms computation. 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.

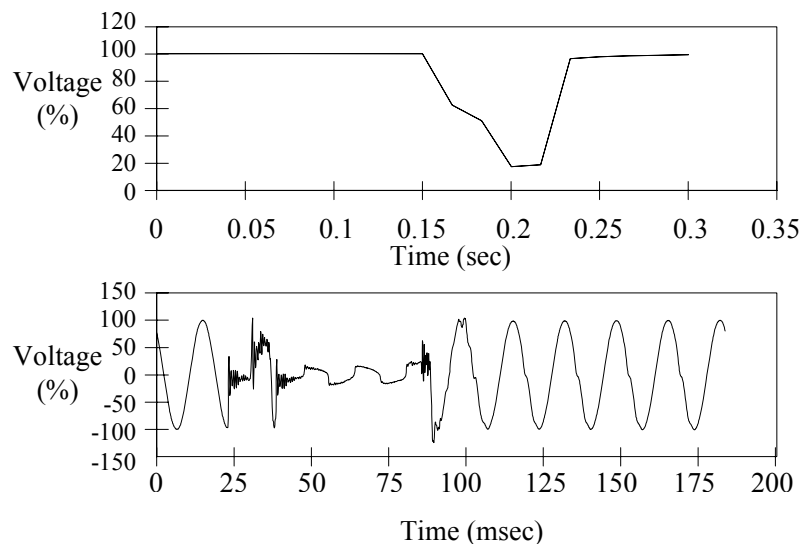


Figure 6—Instantaneous voltage sag caused by SLG fault

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 7 illustrates the effect of starting a large motor.

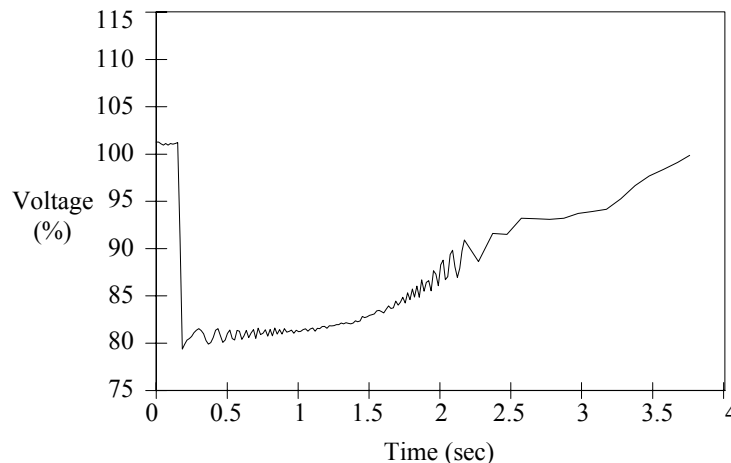


Figure 7—Temporary voltage sag caused by motor starting

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 be confused with the term related to sagging aerial conductors.) Although the term used in the power quality community has not been formally defined in *The Authoritative Dictionary* [B18], it has been increasingly accepted and used by utilities, manufacturers, and end users. 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 not been clearly defined. 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 [B43]. Undervoltages that last longer than 1 min can typically be controlled by voltage regulation equipment and may be associated with a wide variety of causes other than system faults. Therefore, these are classified as long-duration variations in 4.4.3.

Sag durations are subdivided 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 [B42]).

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 will always be 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 8 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.

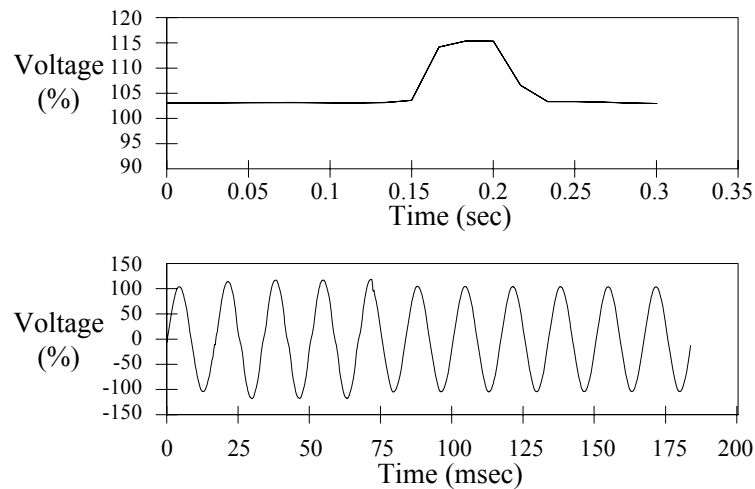


Figure 8—Instantaneous voltage swell caused by SLG fault

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 will be 1.73 pu during a line-to-ground fault condition. Close to the substation on an effectively grounded system, there will be 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 C62.41-1995 [B20] 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 min. ANSI C84.1-2006 [B2] specifies the steady-state voltage tolerances expected on a power system. These magnitudes are reflected in Table 2. Long-duration variations are considered to be present when these limits are exceeded for more than 1 min.

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

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 Authoritative Dictionary* [B18], 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 3%. The current imbalance can be considerably higher, especially when single-phase loads are present. Mathematically, the voltage imbalance is represented by Equation (1).

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

Measuring instruments often use a definition of voltage imbalance based on ANSI C84.1-2006 [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 [B21]). This computation is readily made using measurements from meters that

collect only rms values. Other standards, such as the NEMA MG-1-2006 [B35], may 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 [B38] and Bollen [B4]). The ANSI C84.1 definition will provide 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 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 [B9] and Kennelly [B32]):

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

where

$$\beta = \frac{|V_{AB}|^4 + |V_{BC}|^4 + |V_{CA}|^4}{(|V_{AB}|^2 + |V_{BC}|^2 + |V_{CA}|^2)^2} \quad (3)$$

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 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 must 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) must 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 $230\angle 0^\circ$, $237\angle -118^\circ$, and $240.6\angle 119.6^\circ$ volts, respectively. The sequence components are as follows:

$$V_{pos} = \frac{1}{3}(V_{AB} + V_{BC} \cdot 1\angle 120^\circ + V_{CA} \cdot 1\angle -120^\circ) = 235.8\angle 0.5^\circ \text{ V}$$

$$V_{neg} = \frac{1}{3}(V_{AB} + V_{BC} \cdot 1\angle -120^\circ + V_{CA} \cdot 1\angle 120^\circ) = 6.18\angle -159.4^\circ \text{ V}$$

The imbalance using sequence components is as follows:

$$\% \text{ Imbalance} = \frac{6.18}{235.8} \times 100\% = 2.6\%$$

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: 230V. 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:

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

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

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 $281\angle 0^\circ$ V, $288\angle -115^\circ$ V, and $270\angle 125^\circ$ 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:

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

The ANSI definition for the imbalance on these line voltages will be 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:

$$\begin{aligned} V_{pos} &= \frac{1}{3} (V_{AB} + V_{BC} \cdot 1\angle 120^\circ + V_{CA} \cdot 1\angle -120^\circ) = 484\angle 33.3^\circ \text{ V} \\ V_{neg} &= \frac{1}{3} (V_{AB} + V_{BC} \cdot 1\angle -120^\circ + V_{CA} \cdot 1\angle 120^\circ) = 5.16\angle -109.1^\circ \text{ V} \end{aligned}$$

The % imbalance is computed to be as follows:

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

Using Equation (2) and Equation (3) yields $\beta = 0.3334$ 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: $|V_{zero}| = 40.1$ V, which will result 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) will still provide the correct answer using the phase-to-neutral values: $2.98/279.4 = 1.1\%$. However, using Equation (2) and Equation (3) will yield % imbalance = 3.7%. The ANSI method will yield 3.5% imbalance.

This example has demonstrated that the preferred method of Equation (1) will provide 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) will lead 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 9 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. The trace labeled “V Imb Avg LN” is using the ANSI-type maximum deviation from the average definition, but on line-to-neutral quantities.

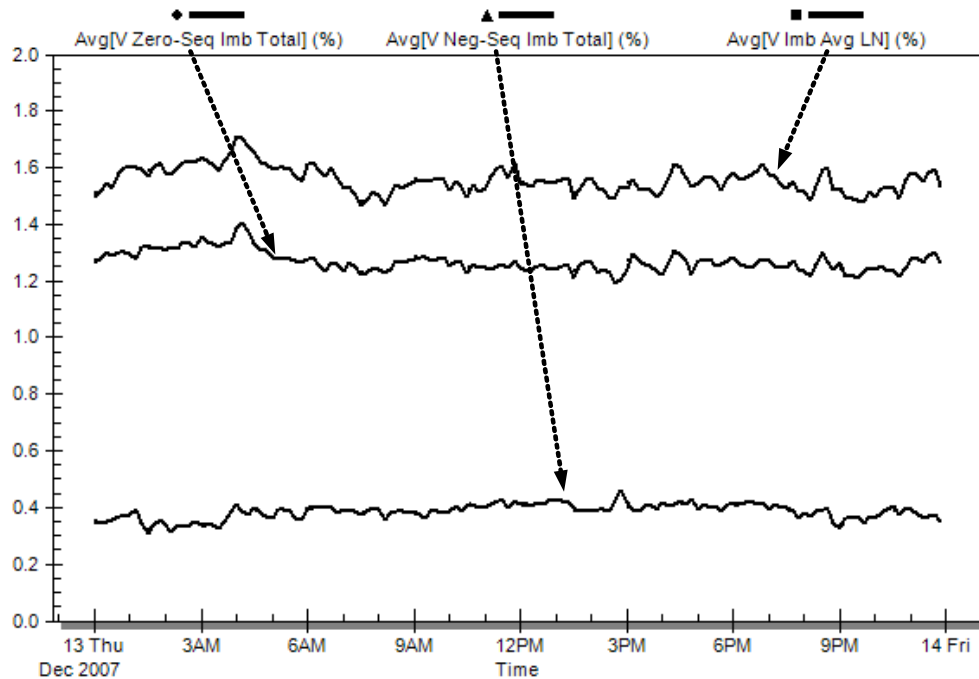


Figure 9—Voltage imbalance trend for three-phase residential feeder