

IEEE Guide for Application of Power Electronics for Power Quality Improvement on Distribution Systems Rated 1 kV Through 38 kV

IEEE Power & Energy Society

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IEEE Guide for Application of Power Electronics for Power Quality Improvement on Distribution Systems Rated 1 kV Through 38 kV

Sponsor

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

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Abstract: Guidelines and performance expectations are provided for the application of power electronic-based equipment on distribution systems of power providers to improve power quality. It is a resource to electric utility providers as they enter into the competitive marketplace. It provides detailed information about custom power devices as options to solve power quality problems.

Keywords: backup stored energy system device, custom power, distribution series capacitors, distribution static compensator, distribution static var compensator, dynamic voltage restorer, flicker, harmonics, IEEE 1409, power conditioning, power quality, static voltage regulator, transfer switch, voltage fluctuations, voltage sags

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Introduction

This introduction is not part of IEEE Std 1409-2012, IEEE Guide for Application of Power Electronics for Power Quality Improvement on Distribution Systems Rated 1 kV Through 38 kV.

This guide introduces and defines the technology of custom power. This technology involves devices and circuit configurations of power electronic equipment used in distribution systems of power providers rated 1 kV through 38 kV for the purposes of mitigating problems associated with power quality. The concept of custom power is the employment of power electronic or static controllers in medium voltage distribution systems for the purpose of supplying a level of power quality that is needed by electric power customers that are sensitive to rms voltage variations. Custom power devices include static switches, converters, injection transformers, master control modules, and/or energy storage modules that have the ability to perform current interruption and voltage regulation functions in a distribution system to improve power quality.

For voltage sag, swell, and interruption mitigation, the following custom power controllers are examined: dynamic voltage restorer (DVR) devices, static voltage regulator (SVR) devices, backup stored energy system (BSES) devices, and transfer switch (TS) devices. For harmonic and reactive compensation, the following devices are reviewed: distribution static compensator (distribution STATCOM) devices, distribution static var compensator (SVC) devices, and distribution series capacitors.

This guide includes definitions, general need guidelines, performance objectives, electrical environments, input/output criteria, performance measurements, case studies, bibliography, and engineering tradeoffs. It also addresses power assessment techniques.

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1. Overview

1.1 Scope

This guide introduces and defines the emerging technology of custom power. This technology involves devices and circuit configurations of power electronic equipment used in utility power distribution systems rated 1 kV through 38 kV for the purposes of mitigating problems associated with power quality. This guide also includes definitions, general need guidelines, performance objectives, electrical environments, input/output criteria, performance measurements, case studies, bibliography, and engineering trade-offs. The proposed document addresses power assessment techniques as specified by IEEE Std 1250TM-2011¹, which defines power quality terms and phenomena, and IEEE Std 1159TM-2009, which provides a recommended practice for measuring power quality.

¹ Information on references can be found in Clause 2.

1.2 Purpose

This document provides guidelines and performance expectations for the application of power electronic-based equipment on utility distribution systems to improve power quality and control in these distribution systems. It can be a resource to utilities as they enter into the marketplace, providing detailed information about custom power devices as options to solving power quality problems.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document 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.²

IEEE Std 519TM-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.³

IEEE Std 1159-2009, IEEE Recommended Practice for Monitoring Electric Power Quality.

IEEE Std 1250-2011, Guide for Identifying and Improving Voltage Quality in Power Systems.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms and Definitions*⁴ should be consulted for terms not defined in this clause.

backup stored energy system (BSES): A device that disconnects a protected load from the power provider supply within milliseconds of the detection of a disturbance and supplies the entire load using stored energy. Typical sources for the stored energy are batteries, flywheels, or superconducting magnetic coils.

BSES: *See:* backup stored energy system.

custom power: The concept of employing power electronic (static) controllers in 1 kV through 38 kV distribution systems for supplying a compatible level of power quality necessary for adequate performance of selected facilities and processes.

custom power controller: An active power electronic device, consisting of equipment, installation, and/or apparatus with the ability to perform current interruption and/or voltage regulation in the distribution system to improve power quality.

custom power park: A concept for providing improved power quality to an industrial or commercial office park development serving multiple tenants with varying power quality requirements utilizing a combination of custom power controllers and other power quality improvement devices. Also referred to as a premium power park, the concept may also include multiple electrical feeds, energy conversion equipment with multiple fuels, and integrated energy storage.

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⁴ *IEEE Standards Dictionary: Glossary of Terms and Definitions* is available at <http://shop.ieee.org>.

dip: *See:* sag.

distribution series capacitor: A fixed capacitor connected in series with the distribution circuit and provided with high-speed mechanical bypass protection. While it can be an effective solution for flicker caused by varying loads, this device is not considered a custom power controller.

distribution STATCOM: A power electronics-based waveform synthesis device that is shunt connected through a transformer to a distribution circuit for the purpose of instantaneous voltage regulation, power factor correction, and reactive power control. The compensator may also have the capability of injecting higher than fundamental frequency current vectors into the distribution circuit at the point of common coupling to perform active filtering (mitigation) of current harmonics. The term distribution STATCOM (distribution static compensator) specifically applies to equipment used for power quality improvement in distribution applications. *See also:* **static shunt compensator**.

DVR: *See:* **dynamic voltage restorer**.

dynamic voltage restorer (DVR): A power electronics-based waveform synthesis device that is series connected directly into the primary distribution circuit by means of a set of series-connected single-phase injection transformers. The principal function of the dynamic voltage restorer is to inject or absorb real power during a short-duration change in the primary feeder voltage. This device may be coupled with energy storage capability. Its controller may also have the capability of injecting higher than fundamental frequency voltage vectors into the distribution circuit to perform active filtering (mitigation) of voltage harmonics.

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

NOTE—Flicker is defined by IEC 60050-161 [B12].^{5, 6}

gate turn-off (GTO) thyristor: Variant of the thyristor with controlled turn-off initiated by large negative current pulse to gate, capable of slow pulse-width-modulation waveform synthesis.

GTO: *See:* **gate turn-off thyristor**.

high-speed mechanical transfer switch (HSMTS): A transfer switch that utilizes vacuum switches to transfer a load from a primary feed to a secondary with transfer times as fast as 1.5 cycles.

hybrid transfer switch: A transfer switch that employs a static switch in parallel with a vacuum switch to transfer a load from a primary feed to a secondary with transfer times as fast as 1.5 cycles.

IGBT: *See:* **insulated gate bipolar transistor**.

IGCT: *See:* **integrated gate commutated thyristor**.

insulated gate bipolar transistor (IGBT): A power, voltage-controlled semiconductor device with turn-on and turn-off capability, capable of high switching frequencies in pulse-width modulation waveform synthesis.

integrated gate commutated thyristor (IGCT): A variant of the thyristor with turn-off controlled by a large current (up to rating of load current) pulse. The IGCT is faster than an ordinary gate turn-off thyristor.

⁵ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

⁶ The numbers in brackets correspond to those of the bibliography in Annex A.

LES: *See:* **line energy supply.**

line energy supply (LES): A supply scheme for the DVR in which the energy injected into the distribution circuit during voltage sag compensation is drawn from the system during the sag event by a diode bridge rectifier that is connected to the dc-link of the DVR converter.

MCT: *See:* **MOS controlled thyristor.**

mechanical transfer switch (MTS): A transfer switch that utilizes mechanical switching components to transfer a load from a primary feed to a secondary with typical transfer times that range from 100 ms to approximately 10 s. While it is an effective solution for loads that can tolerate a momentary interruption, this device is not considered a custom power controller.

MOS controlled thyristor (MCT): A variant of the thyristor with two internal power MOSFETs controlling the device turn-on and turn-off, with superior turn-on/turn-off performance allowing higher switching frequencies in PWM waveform synthesis.

MTS: *See:* **mechanical transfer switch.**

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

NOTE—Voltage notching characteristics are defined in IEEE Std 519-1992.

phase jump: The change in voltage phase angle during a voltage sag as compared to the phase angle of the voltage before the voltage sag. Also referred to as phase-angle jump or phase shift, it can be different for each of the three phases in a three-phase system.

phase shift: *See:* **phase jump.**

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

NOTE—Power quality is defined in IEEE Std 1100™-2005 [B16].

power quality disturbance: Any deviation of the voltage and/or current from the nominal sinusoidal waveform at rated amplitude and frequency, resulting in disruption, misoperation, or damage to equipment or processes.

premium power park: *See:* **custom power park.**

sag: A decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycles to 1 minute.

NOTE—Sag is defined in IEEE Std 1159-2009.

SCR: *See:* **semiconductor controlled rectifier.**

semiconductor controlled rectifier (SCR): An alternative name used for the reverse-blocking triode-thyristor. *See also:* **thyristor.**

NOTE—The name of the actual semiconductor material (selenium, silicon, etc.) may be substituted in place of the word semiconductor in the name of the components.

SES: *See:* **stored energy system.**

SSB: *See:* **static circuit breaker.**

static circuit breaker or solid-state breaker (SSB): A device usually based on gate turn-off (GTO) and semiconductor controlled rectifier (SCR) thyristors capable of providing sub-cycle interruption on faulted feeders. SSBs that are designed for use at medium or high voltage, utilize snubbing networks across the switching elements (e.g., GTOs or SCRs). The snubbing networks can carry current across the terminals of the SSB, even when the switching elements are in their off-state. The use of an integral series mechanical switch can be used to interrupt the small leakage current, which flows through the snubbing network.

static series compensator: *See:* **dynamic voltage restorer.**

static series/shunt compensator: A power-electronics controller designed to provide voltage compensation to protect a sensitive load from voltage disturbances using a series element. It also provides current compensation using a shunt element to protect a power system from a load that would otherwise impart harmonic distortion, flicker, or power factor problems.

static shunt compensator: A power electronics-based waveform synthesis device that is shunt connected through a transformer to the transmission or distribution circuit for the purpose of instantaneous voltage regulation, power factor correction, and reactive power control. The compensator may also have the capability of injecting higher than fundamental frequency current vectors into the distribution circuit at the point of common coupling to perform active filtering (mitigation) of current harmonics. In the context of this guide, only the application in distribution systems will be considered. *See also:* **distribution STATCOM.**

static transfer switch (STS): A transfer switch that utilizes thyristors or gate-turnoff thyristors to transfer a load from a primary feed to a secondary with subcycle transfer times.

static var compensator (SVC): A shunt-connected device with thyristor switching of passive reactive components (capacitors and reactors) in continuous and/or discrete steps, which exchanges a continuously controlled reactive current with the power system to control electrical parameters of the line at the point of common coupling. SVC is typically used for voltage control, reactive power compensation, and power factor correction in both transmission and distribution applications. In the context of this guide, only the application in distribution systems will be considered.

static voltage regulator (SVR): A controller capable of providing voltage boost during a voltage sag, constituted by a three-phase transformer supplying the load, equipped with thyristor switches that rapidly change taps on one (or more) of the secondary windings. Such a device may also be designed to provide voltage buck during voltage swells.

stored energy system (SES): A supply scheme for the dynamic voltage restorer (DVR) in which the energy injected into the distribution circuit during voltage sag compensation is drawn from the system during normal operation and stored in a proper system to be later released to the dc-link of the DVR converter. The SES may use any storage media with energy extraction/recharge rates suitable for instantaneous voltage sag mitigation.

STS: *See:* **static transfer switch.**

SVC: *See:* **static var compensator.**

SVR: *See:* **static voltage regulator.**

swell: An increase to between 1.1 pu and 1.8 pu in rms voltage or current at the power frequency for durations from 0.5 cycles to one minute.

NOTE—Swell is described further in IEEE Std 1159-2009.

TCR: *See:* **thyristor-controlled reactor.**

thyristor: A bistable semiconductor device comprising three or more junctions that can be switched from the “off” state to the “on” state or vice versa, such switching occurring within at least one quadrant of the principal voltage-current characteristic.

thyristor-controlled reactor (TCR): A reactor whose susceptance is controlled by continuously varying the firing angle of a series static switch constituted by two antiparallel thyristors.

thyristor crowbar: A semiconductor shorting switch consisting of a single (or series connection of multiple) thyristor device(s) used to short circuit the secondary turns of the series injection transformer at the onset of an overcurrent condition in the protected downstream load. The thyristor crowbar is typically rated with sufficient thermal capacity to maintain the shorted secondary current until the primary side mechanical bypass switch can close effectively removing a series compensating device from the circuit during the period of the overcurrent condition.

thyristor switched capacitor (TSC): A capacitor that is switched on and off by timed firing of a series static switch constituted by two antiparallel thyristors.

transfer switch (TS): A switch arranged to permit transferring a conductor connection from one circuit to another without interrupting the current.

NOTE—Transfer switch is defined in IEEE Std C37.100-1992 [B20].

transient: 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.

NOTE—Transient is defined in IEC 60050-161 [B12].

TS: *See:* **transfer switch.**

TSC: *See:* **thyristor switched capacitor.**

uninterruptible power supply (UPS): A backup stored energy system that protects a load from power outages using a stored energy system. Typical sources for the stored energy are batteries or flywheels. The runtime of an uninterruptible power supply is shorter (usually several minutes) than more robust standby power generators that may run for hours, but sufficient to allow time to bring an auxiliary power source on line, or to properly shut down the protected equipment.

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

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

NOTE—Voltage distortion is also defined in IEEE Std 1100-2005 [B16].

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

NOTE—Voltage fluctuation is also defined in IEC 61000-2-1 [B13].

4. General needs

4.1 Definition of custom power

The concept of custom power is the employment of power electronic or static controllers in medium voltage distribution systems for the purpose of supplying a level of power quality that is needed by electric power customers that are sensitive to rms voltage variations and voltage transients. Custom power devices, or controllers, are devices that include static switches, converters, injection transformers, master control modules, and/or energy storage modules that have the ability to perform current interruption and voltage regulation functions in a distribution system to improve power quality.

A custom power controller is part of a special class of all power conditioning devices. Power conditioning technology in general includes all device solutions used to correct the problems faced by end-user loads in response to voltage sags, voltage swells, voltage interruptions, flicker, harmonic distortion, and voltage regulation problems. While the term “power conditioning” has no voltage boundary, the term “custom power” is bound by the scope of this guide to include power conditioners with input and/or output voltage ratings between 1 kV and 38 kV. This scope limits the location of custom power devices to a primary (medium voltage) distribution system. This scope limitation does not mean that there are not similarities between low voltage power conditioning devices and custom power devices; rather, the technologies used at medium voltage and at low voltage are frequently very similar.

4.2 Description of power quality phenomena

The term power quality is often used in conjunction with problems arising from malfunctioning power electric equipment that is supplied with a voltage that is somehow imperfect. The most important cause for the increasing concern about power quality problems is the dramatic increase in sensitive microprocessor and power electronic equipment being used to control assembly line production, to automate office work, and to enhance the home. Important compatibility gaps have developed between power electronics manufacturers, power producers, and power users, in that many of these utilization systems are too sensitive for the electrical environment in which they are being placed.

This article describes the power quality conditions that can exist on a medium voltage distribution system, which custom power controllers are frequently designed to mitigate. This section is drawn from IEEE Std 1159-2009.

4.2.1 Transients

An impulsive transient is a sudden, non-power frequency change in the steady state condition of voltage, current, or both, that is unidirectional in polarity (primarily either positive or negative). Impulsive transients are normally characterized by their rise and decay times. These phenomena can also be described by their spectral content. The most common cause of impulsive transients is lightning. Due to the high frequencies involved, impulsive transients are damped quickly by resistive circuit components and are not conducted far from their source. There can be significant differences in the transient characteristic from one location within a building to another.

An oscillatory transient is a sudden, non-power 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. 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 usually due to some type of switching event. High frequency oscillatory transients are often

the result of a local system response to an impulsive transient. A transient with a primary frequency component between 5 kHz and 500 kHz with a duration measured in the tens of microseconds (or several cycles of the principal frequency) is termed a medium frequency transient. For example, back-to-back capacitor energization results in oscillatory transient currents in the tens of kHz. Cable switching results in oscillatory voltage transients in the same frequency range. A transient with a primary frequency component less than 5 kHz, and with a duration lasting 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 (see Figure 1). Capacitor bank energization typically results in an oscillatory voltage transient with a primary frequency between 300 Hz and 900 Hz.

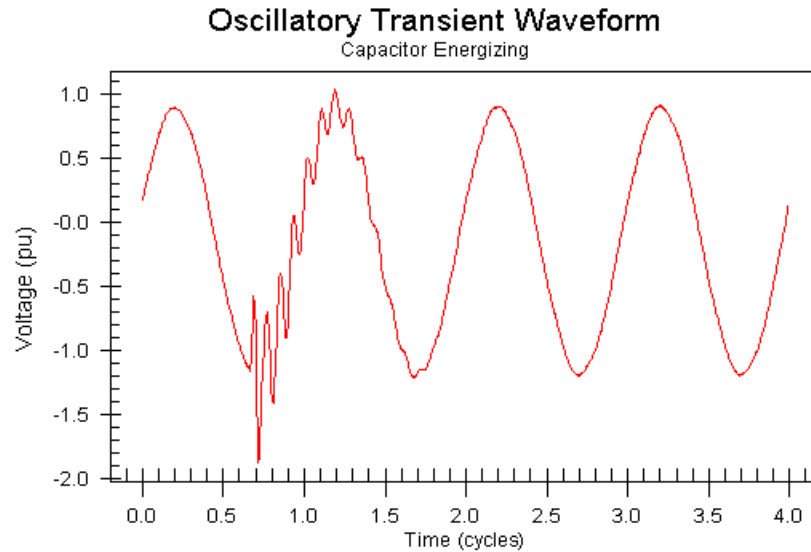


Figure 1—Example oscillatory transient waveform caused by a capacitor energizing

4.2.2 Short duration RMS voltage variations

IEEE Std 1159-2009 describes the characteristics of a voltage sag as a decrease to between 0.1 pu and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycles to 1 m. It also describes a voltage swell as an increase to between 1.1 pu and 1.8 pu in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 m. An interruption is the complete loss of voltage (<0.1 pu) on one or more phase conductors for a period between 0.5 cycles and 60 s. The voltage sag characteristics will often depend upon the fault location and other system conditions. A power system fault can cause either temporary voltage rises (swells) or voltage drops (sags), or a complete loss of voltage (interruptions). See Figure 2, Figure 3, and Figure 4 for example events.

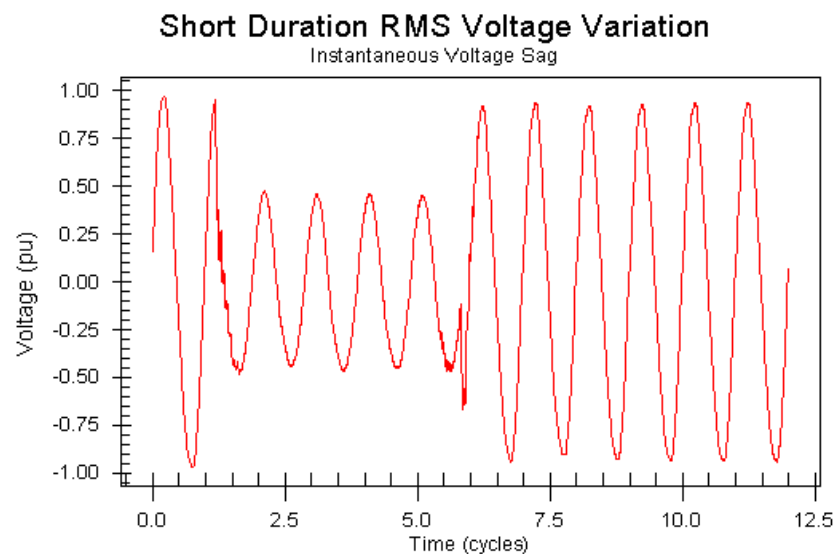


Figure 2—Example waveform of a voltage sag

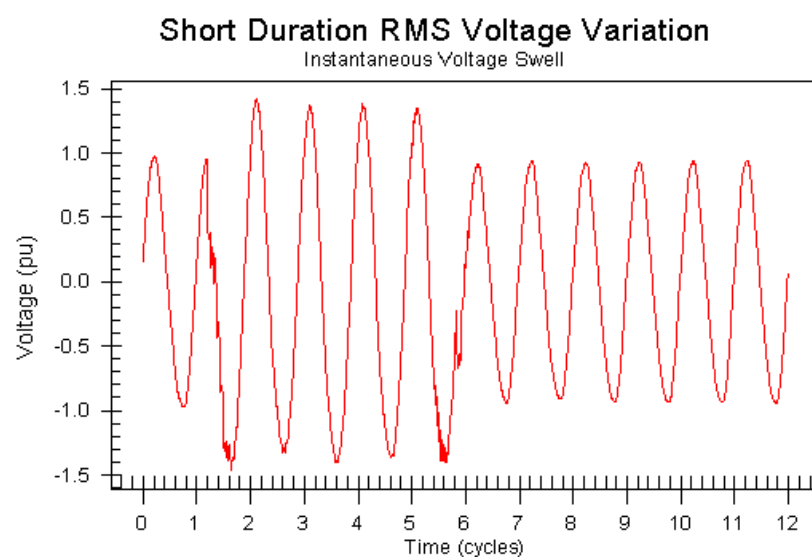


Figure 3—Example waveform of a voltage swell

NOTE—This waveform occurred on an unfaulted phase of the event depicted in Figure 2.

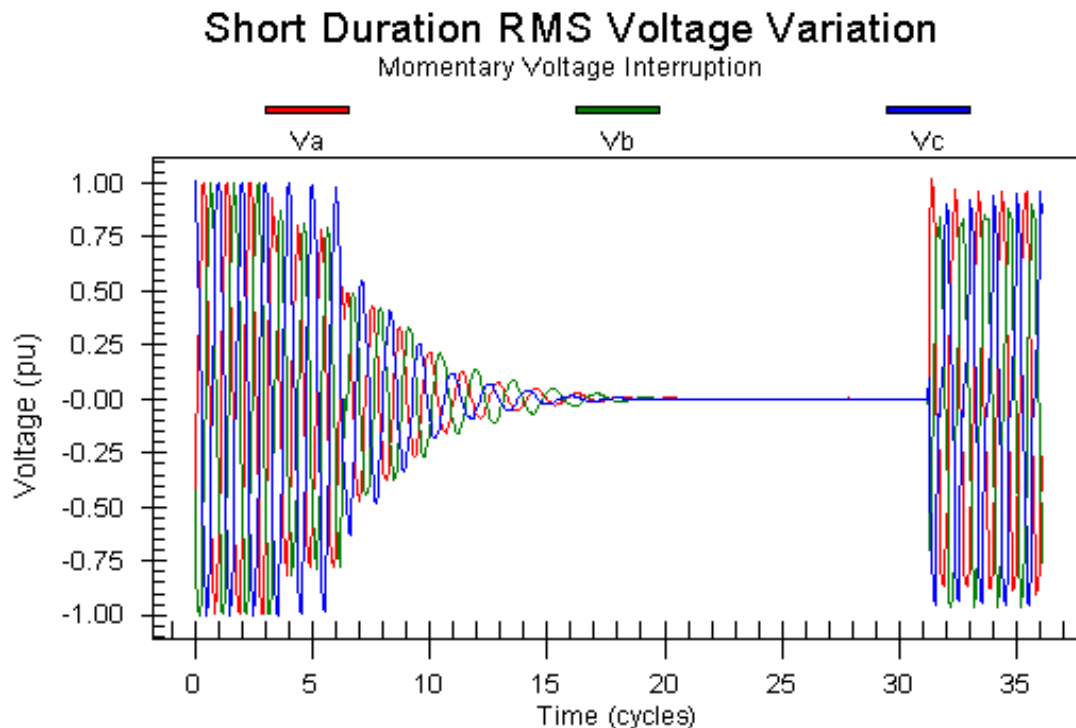


Figure 4—Example waveforms of a voltage interruption

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. This guide will indicate the remaining voltage throughout. Just as an unspecified voltage designation is accepted to mean line to line potential, so an unspecified sag magnitude will refer to the remaining voltage. For example, an 80% sag refers to a disturbance that resulted in a remaining voltage of 0.8 pu.

4.2.3 Long duration RMS voltage variations

Long duration variations can be either overvoltages or undervoltages depending on the cause of the variation. Overvoltages can be the result of load switching (e.g., switching off a large load), or variations in the reactive compensation on the system (e.g., switching on a capacitor bank). Poor system voltage regulation capabilities or controls result in overvoltages. Incorrect tap settings on transformers can also result in system overvoltages. Figure 5 presents an overvoltage caused by a transformer failure. Undervoltages are the result of the events that are the reverse of the events that cause overvoltages. A load switching on or a capacitor bank switching off can cause an undervoltage until voltage regulation equipment on the system can bring the voltage back to within tolerances. Figure 6 presents an undervoltage initiated by a power provider. Overloaded circuits can also result in undervoltages. The decrease to zero of the supply voltage for a period of time in excess of one minute is considered a sustained interruption. Voltage interruptions longer than one minute are often permanent in nature and require manual intervention for restoration. Figure 7 presents a sustained interruption due to the operation of an upline circuit breaker.

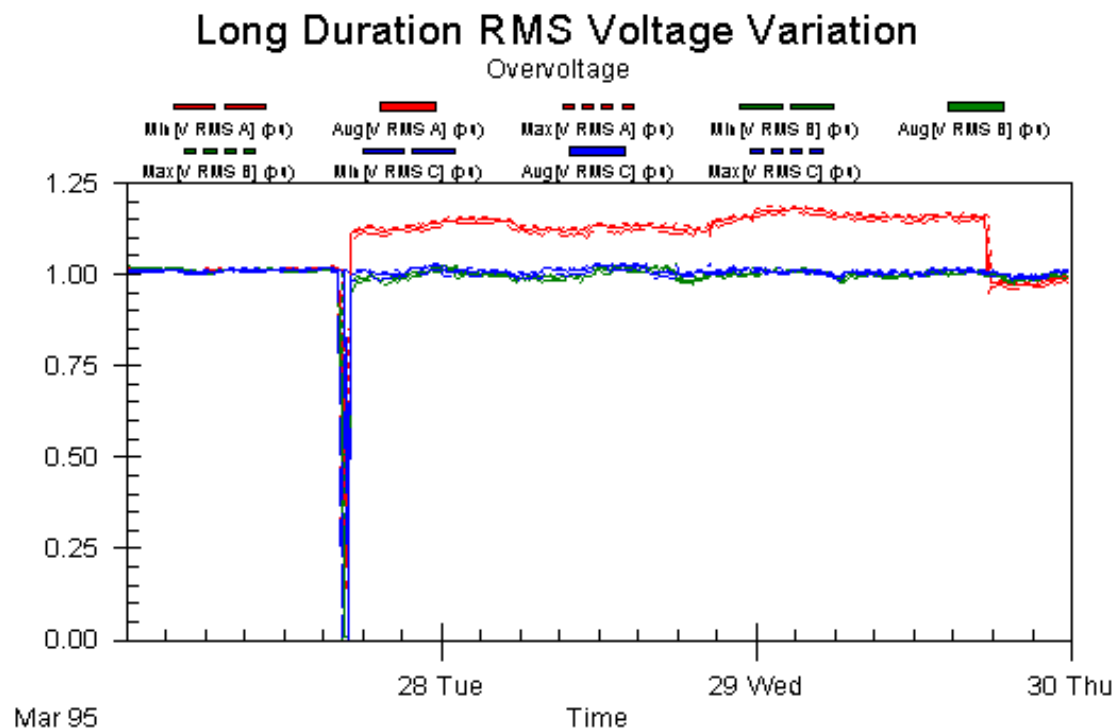


Figure 5—Overvoltage on Phase A with a 48-hour duration due to transformer failure

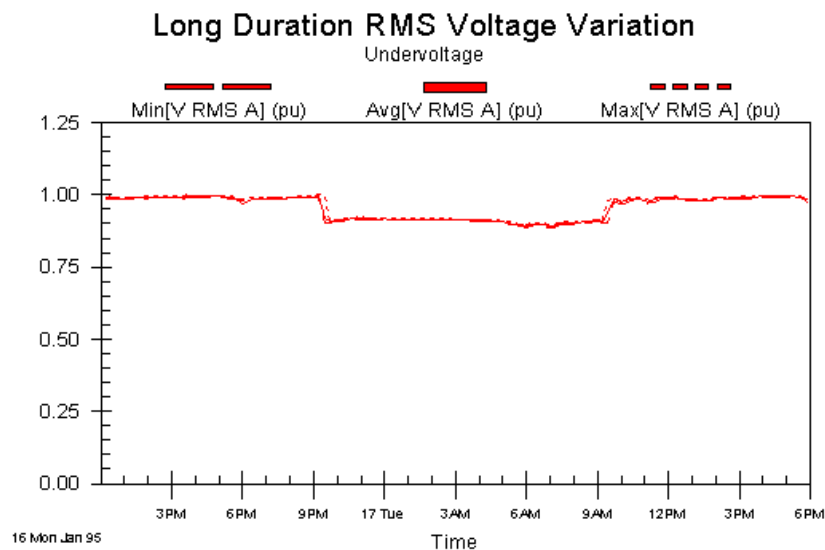


Figure 6—Undervoltage with a 12-hour duration due to voltage reduction initiated by power provider

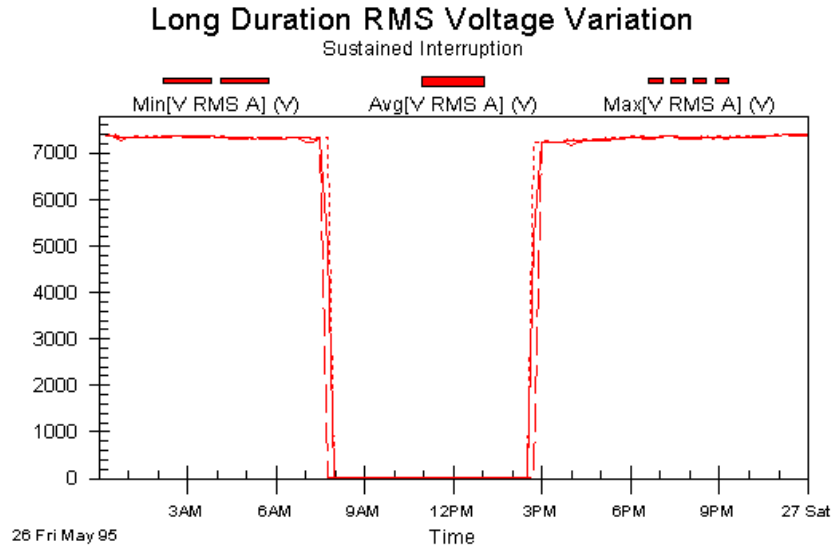


Figure 7—Sustained interruption with a 7-hour duration due to an upline fault

4.2.4 Voltage imbalance

Voltage imbalance (or unbalance) is defined as the ratio of the negative or zero sequence component to the positive sequence component. The negative or zero sequence voltages in a power system generally result from unbalanced loads causing negative or zero sequence currents to flow. Imbalance can be estimated as the maximum deviation from the average of the three phase voltages or currents, divided by the average of the three phase voltages or currents, expressed in percent. The voltage imbalance estimation will be close to the sequence components ratio if phase-to-phase measurements are used, the harmonic content is low, and the zero sequence content is small. The primary source of voltage imbalance less than two percent will usually be from unbalanced single-phase loads on a three-phase circuit. Voltage imbalance can also be the result of capacitor bank anomalies, or voltage regulator misoperation. Severe voltage imbalance (greater than 5%) will often be the result from single-phasing conditions.

4.2.5 Waveform distortion

Waveform distortion is defined as a steady state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation. There are five primary types of waveform distortion: dc offset, harmonics, interharmonics, notching, and noise.

4.2.5.1 DC offset

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

4.2.5.2 Harmonics

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate (termed the fundamental frequency; usually 50 Hz or

60 Hz). Harmonic distortion exists due to the non-linear characteristics of devices and loads on the power system. Harmonic currents result from the normal operation of non-linear devices on the power system. IEEE Std 519-1992 provides guidelines for harmonic current and voltage distortion levels on distribution and transmission circuits. Figure 8 and Figure 9 show example voltage and current waveforms with harmonic distortion.

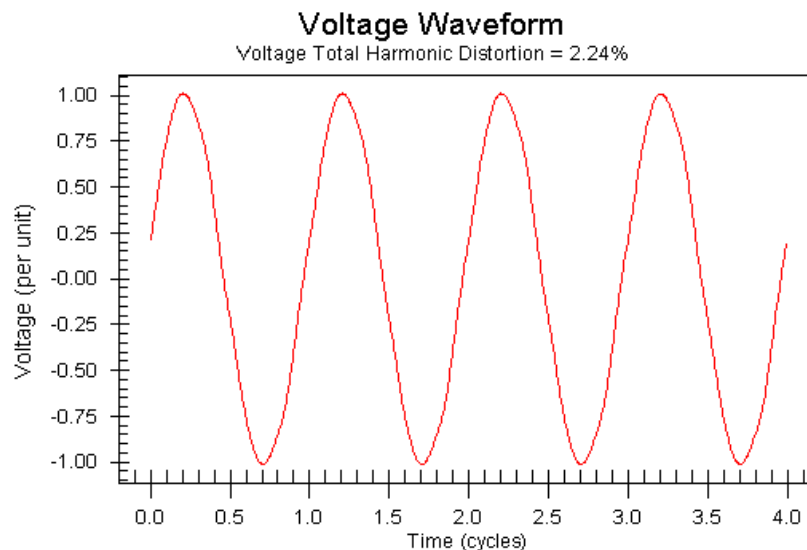


Figure 8—Example voltage waveform with 2.24% total harmonic distortion

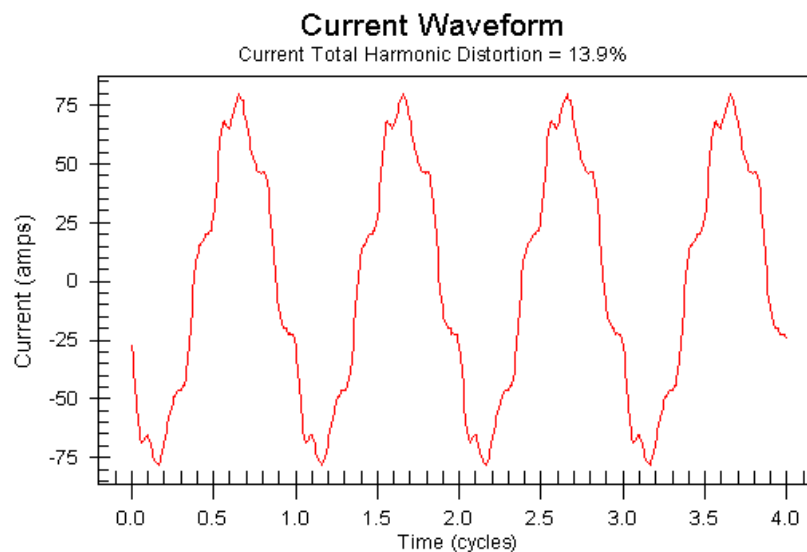


Figure 9—Example current waveform with 13.9% total harmonic distortion

4.2.5.3 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 or 60 Hz) are called interharmonics. They can appear as discrete frequencies or as a wide-band spectrum. Interharmonics can be found in networks of all voltage classes. The main sources of interharmonic waveform distortion are static frequency converters,

cycloconverters, induction furnaces, and arcing devices. Power line carrier signals can also be considered as interharmonics.

4.2.5.4 Notching

Notching is a periodic voltage disturbance caused by the normal operation of power electronics devices when current is commutated from one phase to another. Voltage notching represents a special case that falls between transients and harmonic distortion. Since notching occurs continuously (steady state), it can be characterized through the harmonic spectrum of the affected voltage. However, the frequency components associated with notching can be quite high and may not be readily characterized with measurement equipment normally used for harmonic analysis. See Figure 10.

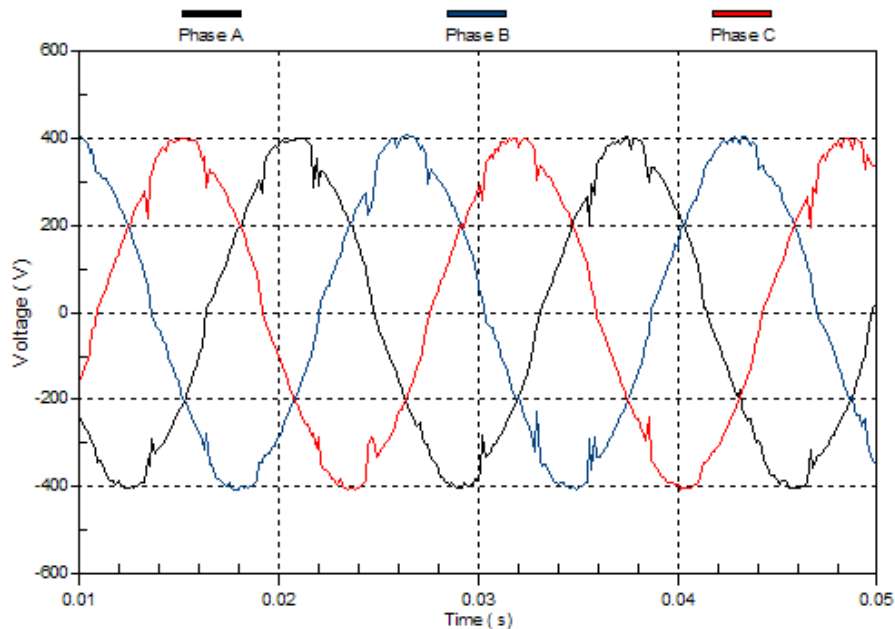


Figure 10—Example waveform with notching

4.2.5.5 Noise

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

4.2.6 Voltage fluctuations

Voltage fluctuations are systematic variations of the voltage envelope or a series of random voltage changes. Any load that has significant time variations, especially in the reactive component, can cause voltage fluctuations. Continuous, rapid variations in load current magnitude can cause voltage variations often referred to as flicker. The term flicker is derived from the impact of the voltage fluctuation on lighting intensity. Arc furnaces are the most common cause of voltage fluctuations on the transmission and

distribution system. See Figure 11. Refer to IEEE Std 1453™-2011 [B18] for a recommended practice for a measurement protocol and limits for flicker.

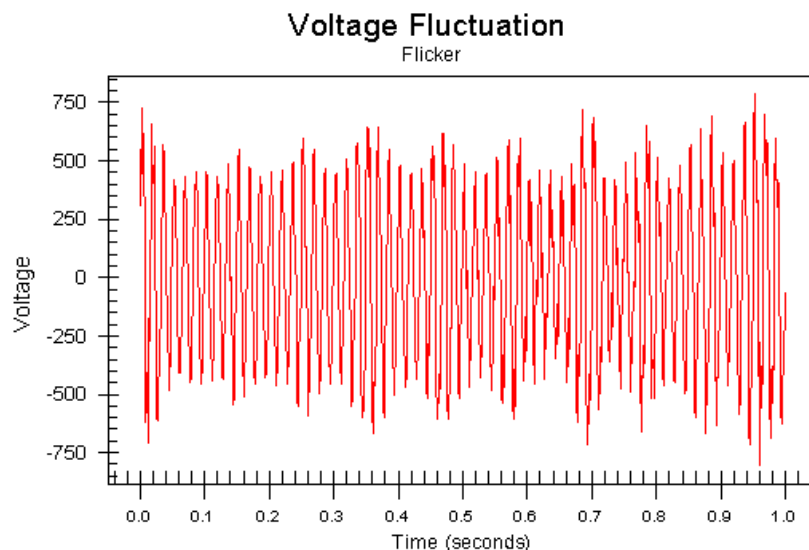


Figure 11—Example voltage waveform showing flicker due to an arc furnace

4.3 Typical rate and range of power quality phenomena in distribution systems

Table 1 presents voltage sag rates for rms variation less than 60 s in duration for various voltage magnitudes as determined by the results of a survey of distribution substations and primary distribution feeders, described by Sabin [B30]. The survey was conducted by EPRI from 1993 to 1995 and included 277 monitoring locations across the United States at system voltages ranging from 4 kV to 33 kV. Monitors were installed at substation locations and on distribution feeder locations. The feeder locations were mostly downline from a substation circuit breaker.

Table 1—Short duration RMS variation rates for substation locations of the EPRI DPQ project, from 6/1/1993 to 6/1/1995, rates in events per 365 days, 60 s temporal aggregation, treated using sampling weights

	RMS voltage				
	< 0.9 pu	< 0.8 pu	< 0.7 pu	< 0.5 pu	< 0.1pu
Minimum	0.0	0.0	0.0	0.0	0.0
CP05	11.9	5.6	0.0	0.0	0.0
CP50	44.0	22.8	12.1	5.2	1.5
Mean	56.3	28.7	18.4	8.9	3.6
CP95	135.2	66.3	51.0	27.0	13.5
Maximum	207.6	103.4	70.5	56.3	35.7

In Table 1, the CP05, CP50, and CP95 values are the 5th, 50th, and 95th percentile values, respectively. From Table 1, the average EPRI DPQ substation monitor experienced about 29 short duration voltage sags and interruptions per 365 days in which the rms voltage fell below 0.8 pu. Additionally, from the CP95 value listed for events less than 0.9 per unit we can say that less than 5% of the substation locations experienced more than 135 sags per year with a retained voltage less than 0.9 per unit. The CP05 value listed for events less than 0.9 per unit says that less than 5% of the substations experienced less than 11.9 voltage sags per year with a retained voltage less than 0.9 per unit. From Table 2, the average feeder location also experienced about 31 sag and interruption events per 365 days.

Table 2—Short duration RMS variation rates for feeder locations of the EPRI DPQ project from 6/1/1993 to 6/1/1995, rates in events per 365 days, 60 s temporal aggregation, treated using sampling weights

	RMS voltage				
	< 0.9 pu	< 0.8 pu	< 0.7 pu	< 0.5 pu	< 0.1pu
Minimum	0.0	0.0	0.0	0.0	0.0
CP05	0.0	0.0	0.0	0.0	0.0
CP50	40.9	25.0	16.6	8.4	2.2
Mean	56.3	30.7	21.2	12.5	4.9
CP95	153.9	76.8	55.2	31.7	15.6
Maximum	225.2	121.9	97.1	85.7	61.7

Table 3 presents voltage harmonic distortion indices from the EPRI DPQ Project. The EPRI DPQ Project statistics are computed from the 95 substations that were active from 6/1/1993 to 3/1/1995. From Table 3, the typical EPRI DPQ substation measured an average of 1.35% voltage total harmonic distortion (THDV). The typical feeder location monitored during the project had an average value of THDV of 1.68%. From Table 3, 95% of the measurements at the EPRI DPQ Project substations were below 1.89%, and 99% of the measurements at the substations were below 2.17%.

Table 3—Average THDV rates for monitoring project locations of EPRI DPQ project from 6/1/1993 to 3/1/1995, based on 16 million three-phase, single-cycle waveform snapshots

Monitor location	Average of THDV	95 th Percentile of THDV	99 th Percentile of THDV
Substation average	1.35%	1.89%	2.17%
Feeder average	1.68%	2.34%	2.70%

The CEA Canadian PQ survey was conducted from 1996 to 2000. Each of the 413 sites was surveyed for a continuous period of one week. The survey covered nine utilities covering all of Canada. The statistic validity for each index of the survey is detailed in the CEATI Report [B3]. The results were also published in 2001 by Ethier et al. [B10]. Table 4 shows the voltage THD (95th percentile) recorded during the same survey, for medium voltage and low voltage sites. Table 5 presents aggregated data (phase and temporal over one minute) for dips, swells, and short interruptions for 405 sites.

NOTE—For each index measured, some data may have been rejected for miscellaneous reasons. This is why the total number of sites reported in Table 4 and Table 5 is different, and in both cases lower than the total number of sites monitored.