PQ Encyclopedia

A product of the EPRI Solutions Power Quality Knowledge-Based Services program

What is Power Quality?

Chapter 1

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No electrical system in any part of the world is without electrical disturbances and power outages. Therefore, an important part of understanding the quality of power delivered to electricity end users is understanding the question, "What is power quality?" This chapter if the EPRI Solutions PQ Encyclopedia provides background on power quality and lays the groundwork for subsequent chapters that explore specific aspects of power quality.

The vast bulk of electric power is of good to excellent quality. In fact, for electric utilities, power quality is something that it is hoped will be invisible to electric power end-users, i.e. that the quality of power will be such that end users won't even think about it on a day-to-day basis.

For end users, power quality is an issue that can seem to appear suddenly and without warning, making decisions about preventing or mitigating PQ problems a potentially vexing one.

One thing is clear: power quality is a dance between the characteristics of both electric power supply and those of the end use devices using that power. A change in either one or both partners can create or solve a power quality issue.

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The EPRI Solutions Power Quality Knowledge-Based Services program provides a wealth of resources in well-designed, readable, and accessible formats. Paramount among these are documents covering a wide range of PQ topics, written not only for use by busy PQ professionals, but also to be shared with important end-use customers and internal utility management. The program's website, www.mypq.net, is the most comprehensive electronic PQ resource available, providing 24-7 access to proven expertise via the PQ Hotline, hundreds of PQ case studies, over 200 PQ technical documents, PQ standards references, indexes, conference presentations, and a wealth of other resources.

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[Power quality is] the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment.

POWER QUALITY DEFINED: A RELATIONSHIP BETWEEN ELECTRIC SUPPLY AND END USE

IEEE Standard 1159-1995, *IEEE Recommended Practice for Monitoring Electric Power Quality*, provides a widely accepted definition of power quality: "[Power quality is] the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment." Implicit in this definition is a recognition by the authors of IEEE 1159 that power quality is defined not only by the characteristic of the supply but also by the end-use devices that are powered.

Discussions about power quality often focus exclusively on technology. While understanding technology is important, understanding the relationships behind power quality is a useful step in ameliorating its impact on operating facilities and minimizing the cost of solving problems.

Power Quality Relationship Number 1: Both Power and End-Use Equipment Define Power Quality

The lynchpin of power quality is the compatibility between the electric power supply and end-use equipment. Although most power quality problems are quickly attributed to faulty power, many power quality problems are caused by the addition of new, more-sensitive equipment to an existing plant. For example, in order to improve productivity and product quality, many facilities employ sophisticated electronic controls in their processes, causing power quality problems to surface. Power that was "just fine" before suddenly becomes inadequate. Investigators of power quality problems must evaluate both the power and the load in order to determine optimal solutions.

Power Quality Relationship Number 2: Electric Power Is a Raw Material

Manufacturers are intimately familiar with the relationship between the quality of raw materials and that of the finished product: If a higher-quality finished product is desired, increasing the quality of essential raw materials is usually a good first step. The relationship between electric power anda manufactured product is no different, and improving power quality is often an essential a step in improving product quality.

Power Quality Relationship Number 3: Knowledge, Not Technology, Solves Power Quality Problems

Keeping a person healthy cannot be done reliably with simple quick-fix measures, such as merely taking a pill. Good health usually requires an ongoing process of maintenance, measurement, correction, and, if necessary, dramatic intervention. Solving power quality problems requires a similar understanding of the broad relationship between electric power and a facility's equipment. Many power quality problems that have a broad impact on a facility (say, shutting down an entire manufacturing line) are caused by the malfunction of a single small component, such as a relay, sensor, or programmable controller. Simply protecting or replacing the sensitive device may be all that is required. Regardless, the solution comes from intimate and fundamental knowledge of how the plant's systems work.

Power Quality Relationship Number 4: Solving Power Quality Problems Requires a Relationship of Trust

A common complaint among power quality mitigation vendors is that facilities will not pay for power quality solutions. Why would a plant that is experiencing, say, losses of $100,000 per year in scrap, misdirected labor, and lost production not be willing to spend

Little question exists that power quality and reliability issues are costly to international businesses.

even half that amount to prevent these losses? When power quality problems strike, facility managers turn first to resources with which they have had long, stable relationships, including local electricians and trusted, familiar vendors. Those same managers shy away from unfamiliar providers, even if they can offer well designed solutions. Establishing credibility before problems strike can build a relationship of trust.

Why Power Quality Is Important: The Costs of Power Quality

Little question exists that power quality and reliability issues are costly to international businesses. But what form do these costs take, and how does outage duration affect the bottom line? Direct business losses can be segregated into four categories:

- Damaged plant equipment
- Spoiled or off-specification product
- Extra maintenance costs
- Cost for repair of failed components

Studies conducted by EPRI have demonstrated that, on average, a typical electric power distribution feeder in the United States will experience approximately 17 significant voltage sags or outages in any given year. Furthermore, nationwide business losses attributable to power quality and reliability issues amount to approximately $119 billion per year and may be as high as $164 billion per year. Among the individual U.S. states, California has the highest costs for both outages and power quality phenomena (between $13.2 billion and $20.4 billion), followed by Texas ($8.3 billion to $13.2 billion)[1], and New York ($8.0 billion to $12.6 billion). Because the economies of these states are comparable to those of many international countries, they provide perhaps more useful metrics for the costs of power quality in countries around the world.

On the other hand, lightning and transients caused by utility capacitor switching can affect many customers at once. Such potentially damaging transients cannot be fully eliminated but they can be mitigated by the supplying utility. The bottom line is that determining "who pays" is a complex question when power quality is considered.

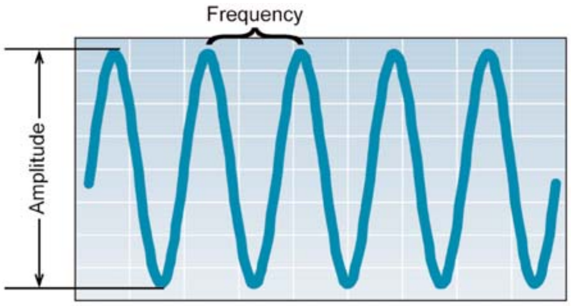
UNDERSTANDING POWER QUALITY PHENOMENA

The Perfect Sine Wave

Flawless electricity is shaped like successive waves; that is, it alternates between positive and negative peaks, completing a cycle (measured from positive peak to positive peak) sixty times every second in the United States (the European standard frequency is fifty times per second).

Electric utilities make every effort to ensure that electricity meets strict standards set by the American National Standards Institute (ANSI), including delivering precisely shaped electricity to the building service panel. However, deformation, surges, sags, and frequency shifts do and will continue to occur.

The Perfect Sine Wave



Amplitude: The standard amplitude of utility-supplied electricity is constant at the rated voltage. The end-user RMS voltages of North American electricity (Peak-to-peak amplitude divided by tow times the square root of two) are 120 and 240 volts for single-phase systems, and 120, 208, 240, 277, and 480 volts for three-phase systems. The maximum and minimum levels of each voltage rating are defined in the ANSI standard C84.1-1989.

Wave Shape: The standard wave shape of utility-supplied voltage is a sine wave.

Frequency: The standard frequency of utility-supplied voltage in North America is sixty cycles per second.

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[1] Shawn McNulty, Primen, *The Cost of Power Disturbances to Industrial and Digital Economy Companies*, IntelliGrid/EPRI, Palo Alto, CA: 2001. 1006274.

When Power Isn't Perfect

Instances of noncompliant electricity—usually called *electrical disturbances or power quality phenomena*—can greatly affect electronic equipment. The perfect sine wave, as shown on the following page, has three properties that are defined in various IEEE/ANSI standards. The first is amplitude. For example, compliant electricity delivered to a residential structure must have a steady-state phase-to-neutral voltage between 108 and 132 volts (the nominal voltage of 120 volts ±10%). The second is the shape of the voltage, which should be a perfect sine wave. And the third is frequency, which is usually 50 or 60 Hz. (depending on location), +/- 0.25 to 0.5 Hz.

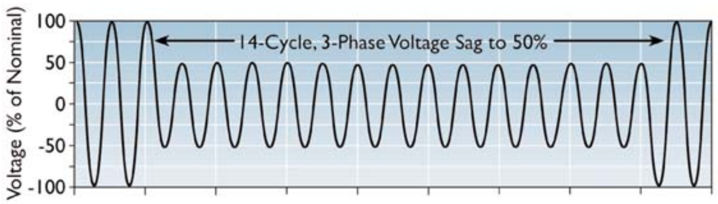
IEEE Standard 1100-1999, *Power and Grounding Electronic Equipment*, describes power quality as a method instead of a property of delivered electricity.

Power quality involves a measure of deviation in the magnitude, form, and frequency of electricity served to the customer from the provider. Distortion of electricity can damage electrical equipment or cause it to malfunction. Some common symptoms of power quality problems are:

- Flashing clocks
- Data loss or computer shutdowns
- Noise on a radio or telephone
- Flickering lights
- Damaged appliances or equipment

Although some symptoms may be obvious, a power quality problem can be complicated, involving the building wiring, natural phenomena such as lightning, interacting appliances, and the connection of equipment to the electric power system. Most power quality problems involve electronic appliances because such appliances are designed to operate with flawless electricity. However, many things can happen to electricity as it travels from the utility to an electronic appliance.

Voltage Sags



Although there may be a remaining voltage during a voltage sag, sensitive equipment, such as the ubiquitous equipment that contains microprocessors and other logic circuits, may malfunction during a sag that lasts a few milliseconds.

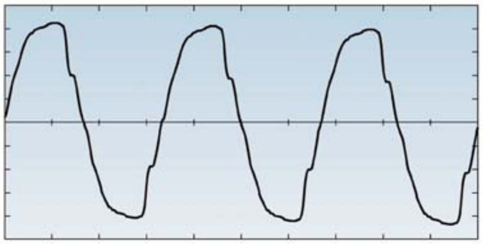
IEEE Standard 1100-1999, *Power and Grounding Electronic Equipment*, describes power quality as a method instead of a property of delivered electricity. Thus power quality is the powering and grounding of electronic equipment such that the equipment operates as intended in its electrical environment and does not produce electrical disturbances that can cause other equipment to malfunction or become damaged. This definition shifts the burden somewhat from the provider of electricity to the end user. But who is really responsible for power quality?

Because electrical disturbances can originate on the utility's side of the meter or the customer's side, delineating responsibility is a difficulty. Some power quality experts claim that both the utility and the end user share responsibility. In their words, the utility is responsible for the voltage, and the end user is responsible for the current. Even if the voltage delivered to an industrial plant complies with the prevailing standard of amplitude, form, and frequency, power quality problems within a plant may be caused by other equipment operating in the plant. Appliances and building wiring account for 80% of all power quality problems.

Problems With Amplitude: Voltage Sags

Experience has shown that the single largest cause of end-user power quality problems is the voltage sag. Given the number of these sorts of events documented by EPRI surveys, this should come as no surprise. The second largest contributor is harmonics (unwanted frequencies in a facility's voltage and/or

Problems With Waveform



The normal operation of electronic equipment can cause voltage distortion that may affect other nearby equipment.

current waveforms). The next largest contributor is grounding and other wiring issues. Collectively, these three power quality issues account for more than 85% of power quality investigations conducted by EPRI over the years.

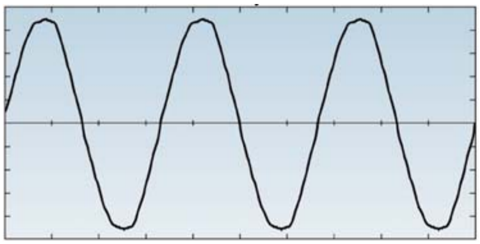
Problems With Waveform

A compliant waveform must be sinusoidal. However, there are many causes and types of waveform deformation. Instantaneous deformations, such as surges, occur during a single cycle. Steady-state deformations, such as voltage distortion or notches, occur during each cycle. The normal operation of some industrial equipment can distort the current to such an extent that the voltage that is delivered to other nearby facilities becomes distorted.

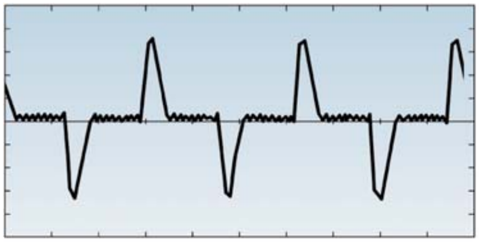
The normal operation of electronic loads can significantly distort the current in a facility. Traditional linear loads, such as motors, draw current that follows the applied voltage, but electronic nonlinear loads, such as adjustable-speed drives that control motors, draw current that does not follow the voltage, creating harmonic distortion.

Harmonic current distortion is caused by the normal operation of nonlinear loads. The current drawn by a linear load, such as an induction motor, is the same shape as the voltage. Nonlinear loads, on the other hand, draw current during certain portions of the applied voltage.

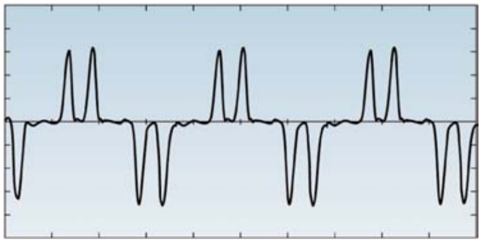
Normal Current Drawn by a Motor



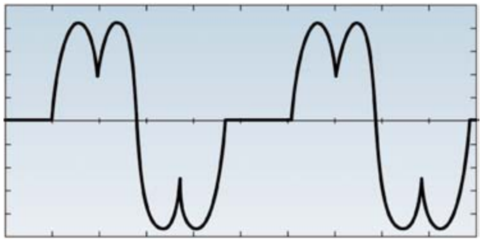
Current Drawn by a Computer Switch-Mode Power Supply



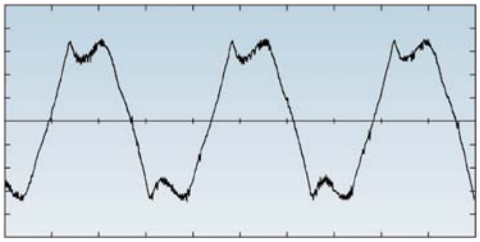
Current Drawn by an AC Motor Drive



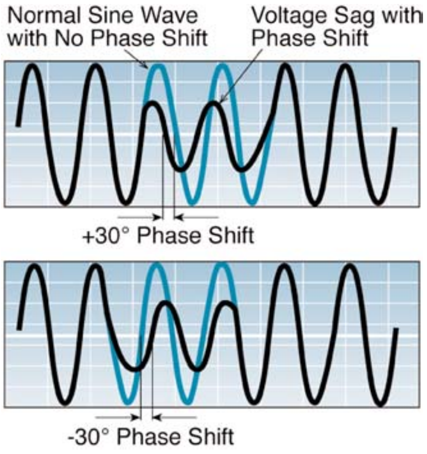
Current Drawn by a DC Motor Drive



Current Drawn by an Electronic Lighting Ballast



Frequency Variations



Phase shift occurs when the zero-crossings of the voltage waveform move in time. One common source of phase shifting is single line-to-ground faults—the voltage on the remaining phases is commonly shifted by 30 degrees from normal under such circumstances.

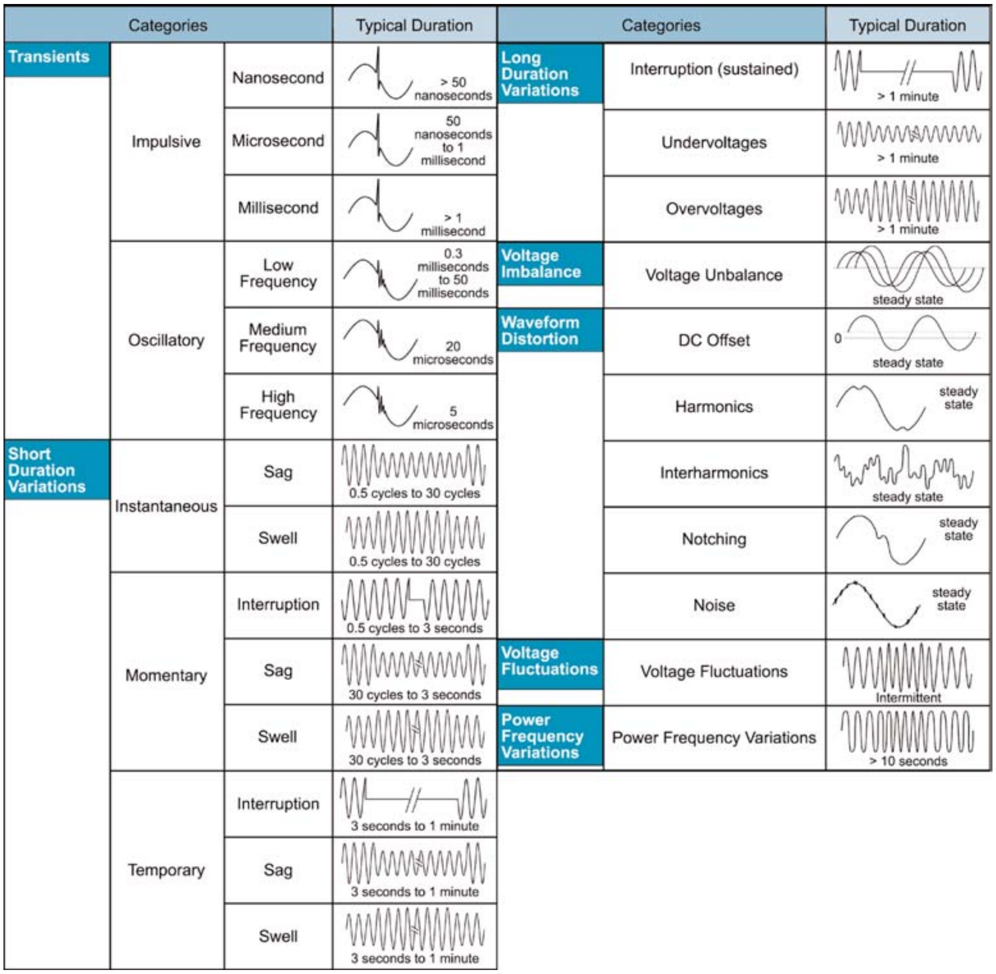
Problems With Frequency

In the United States, the prescribed frequency of delivered voltage is 60 cycles per second (Hz). A sudden shift in frequency, called a phase shift, can cause sensitive electronics to malfunction, or physical damage to electric motors.

Electrical Disturbances

Once an appliance is plugged into an electrical outlet, it becomes part of the electric power system—a network of wires, appliances, equipment, and devices. By plugging in an appliance, you are not only accessing electricity but also connecting that appliance to other appliances, other buildings, and even the utility distribution system. This is why power quality problems can be so complex.

The Panorama of Power Quality Disturbances



Categories			Typical Duration
Transients	Impulsive	Nanosecond	> 50 nanoseconds
		Microsecond	50 nanoseconds to 1 millisecond
		Millisecond	> 1 millisecond
	Oscillatory	Low Frequency	0.3 milliseconds to 50 milliseconds
		Medium Frequency	20 microseconds
		High Frequency	5 microseconds
Short Duration Variations	Instantaneous	Sag	0.5 cycles to 30 cycles
		Swell	0.5 cycles to 30 cycles
	Momentary	Interruption	0.5 cycles to 3 seconds
		Sag	30 cycles to 3 seconds
		Swell	30 cycles to 3 seconds
	Temporary	Interruption	3 seconds to 1 minute
		Sag	3 seconds to 1 minute
		Swell	3 seconds to 1 minute

Categories		Typical Duration
Long Duration Variations	Interruption (sustained)	> 1 minute
	Undervoltages	> 1 minute
	Overvoltages	> 1 minute
Voltage Imbalance	Voltage Unbalance	steady state
Waveform Distortion	DC Offset	0 steady state
	Harmonics	steady state
	Interharmonics	steady state
	Notching	steady state
	Noise	steady state
Voltage Fluctuations	Voltage Fluctuations	Intermittent
Power Frequency Variations	Power Frequency Variations	> 10 seconds

Lightning strikes are a common cause of impulsive transients.

An electrical disturbance can be seen as consisting of four elements: an initiating event, an electrical phenomenon, promoting factors, and the effect of the electrical phenomenon on an appliance. Most power quality problems are chain reactions. An initiating event causes an electrical phenomenon, which is conducted by the building electrical system and promoted by faulty wiring and grounding. The phenomenon eventually reaches an electric device, which can be upset or even damaged, depending upon the energy level of the phenomenon and the tolerance level of the appliance.

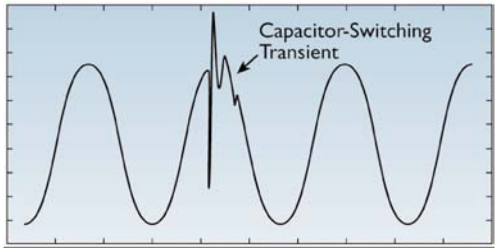
An initiating event is 1) any operation or activity—such as a motor starting or lightning—that disturbs the magnitude, form, or frequency of electricity enough to upset or damage an appliance.

An electrical phenomenon is a specific type of disturbed electricity. An initiating event will disturb electricity by changing magnitude, form, or frequency. The table below shows the most common electrical phenomena found in the electrical system.

Impulsive Transients

Lightning strikes are a common cause of impulsive transients, which are characterized by a rapid rise time followed by a long decay time. As such, they are usually described by their rise and decay times.

Oscillatory Transients



An oscillatory transient caused by switching a capacitor bank onto a distribution circuit can cause electronic equipment to trip or fail.

For example, a 1.1/65-µs 1500-V impulsive transient rises to 1500 volts in 1.1 µs before the voltage decays to 50% of its peak value 65 µs later.

An impulsive transient is a sudden sub-cycle change in the magnitude of voltage, current, or both. It is unidirectional in polarity, either positive or negative. Such disturbances can induce transformer and arrester failures and damage customer equipment. The shape of impulsive transients can be changed quickly by circuit components and may have significantly different characteristics when viewed from different parts of the power system because of the high frequencies involved. They are generally not conducted far from where they enter the power system, but can be conducted for some distance along utility lines. Impulsive transients can excite the natural frequency of power-system circuits and produce oscillatory transients.

Oscillatory Transients

Unlike impulsive transients, oscillatory transients are characterized by sudden changes in the instantaneous value of voltage and/or current that alternate polarity quickly, with a primary frequency greater than 300 kHz. They can be further categorized into the frequency subclasses of low, medium, and high spectral content.

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 neutral conductor can be either common-mode or normal-mode. Common-mode transients may be measured between current-carrying conductors and ground. Normal-mode transients occur between current-carrying conductors.

Although system load changes can cause oscillatory transients, capacitor switching is the most common cause of low-frequency (< 5 kHz) oscillatory voltage transients, which typically have a primary frequency between 300 and 900 Hz. Peak magnitudes are generally between 1.3 and 1.5 per unit and last between 0.5 and 3 cycles. They can result in the tripping of sensitive equipment such as adjustable-speed drives (ASDs). Utility capacitor-switching transients may react with customer low-voltage power-factor-correction capacitors, which can result in magnification of the capacitor-switching transient.

Traveling waves resulting from lightning are an example of a medium-frequency (5 kHz to 500 kHz) oscillatory transient. Local ferroresonance, switching on secondary systems, and lightning-induced ringing can be causes of high-frequency (> 500 kHz) oscillatory transients. Low-voltage power supplies can fail as a result of the high rise rate inherent in such a disturbance.

Voltage Sags

The terms *sag* and *dip* are considered to be synonyms, with sag being the preferred term in the United States power quality community. It is a decrease in the RMS voltage or current to between 10 and 90% of nominal voltage at the power frequency for a duration between 0.5 cycles and 1 minute.

The term sag can be used in a manner that causes confusion. For example, if someone refers to an event as an “80% sag,” the statement can be interpreted as “the voltage dropped to 80% of nominal,” or it can be interpreted as “the voltage dropped to 20% (100% minus 80%) of nominal.” Ambiguity such as this is avoided when the recommended terminology is used. For example, “a sag to 80%” means that the line voltage is reduced by 20% down to 80% of its nominal value.

Sags are typically associated with system faults but can also be caused by the energization of heavy loads.

Sags are typically associated with system faults but can also be caused by the energization of heavy loads or the starting of large motors. For example, an induction motor can draw up to ten times its full-load current when starting, which causes a voltage drop across the impedance of the system. The resulting voltage sag can be significant if the current magnitude is large relative to the available system fault current.

Voltage Swells

The term *momentary overvoltage* is sometimes used as a synonym for the term swell. A swell is caused when the RMS voltage or current increases to between 110 and 180% of nominal at the power frequency for a duration between 0.5 cycles and 1 minute. Characterization of a swell is given by the magnitude of its RMS value and its duration.

Single line-to-ground (SLG) faults are a cause swells. For example, an SLG fault on one phase results in a temporary voltage rise on the other phases. Other causes include the switching off of large capacitor banks and large loads.

The severity of a voltage swell during a fault condition is a function of several factors, including fault location, system impedance, and grounding. On an ungrounded system with infinite zero-sequence impedance, the line-to-ground voltages on the ungrounded phases will be 173% of nominal during an SLG fault condition. There will be little or no voltage rise on unfaulted phases that are close to a substation on a grounded system with transformers connected delta-wye because a low-impedance zero-sequence path exists for the fault current. Faults at different points along four-wire, multi-grounded feeders induce varying degrees of voltage swells on the unfaulted phases. Impacts of swells include overvoltage of equipment and failure of MOVs that are forced into conduction.

A decrease in RMS voltage or current to less than 10% of nominal is called an interruption.

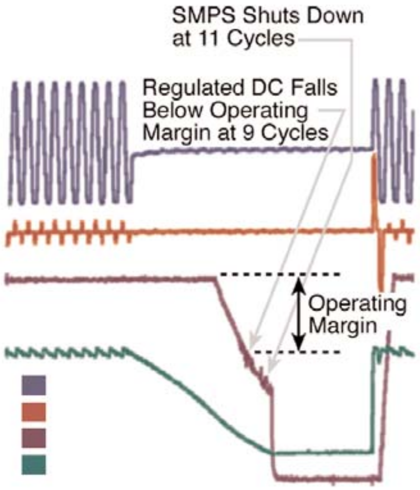
Overvoltages

An increase in the RMS voltage to between 110 and 120% of nominal at the power frequency for a duration longer than 1 minute is defined as an overvoltage. Typical causes of overvoltages include energizing a capacitor bank, large loads being switched off, and faulty voltage regulation. Incorrect tap settings on transformers can also result in system overvoltages. Equipment that requires constant steady-state voltage can be negatively impacted by overvoltages.

Undervoltages

A decrease in the RMS voltage to between 80 and 90% of nominal at the power frequency for a duration longer than 1 minute is defined as an undervoltage. Typical causes of undervoltages include switching a capacitor bank off, large loads being switched on, and faulty voltage regulation. Also, overloaded circuits can cause undervoltages. Equipment that requires constant steady-state voltage can be negatively impacted by undervoltages.

Interruptions



Laboratory tests demonstrate the susceptibility of computer equipment to brief interruptions of voltage. The first trace of the figure above shows the input voltage with a 16-cycle (270-millisecond) sag. The second trace shows the current drawn by a switch-mode power supply (SMPS) used in modern computers. The third trace shows the regulated DC voltage, and the fourth shows the unregulated DC. After nine cycles of zero voltage, the regulated DC voltage falls below the operating margin of the power supply. Two cycles later, the power supply shuts down, causing the computer to shut down as well.

Interruptions

A decrease in RMS voltage or current to less than 10% of nominal is called an *interruption*. Duration is the only measure typically used for interruptions because magnitude is always less than 10% of nominal. The duration of a *momentary interruption* ranges from 0.5 cycles to 3 seconds. The duration of a *temporary interruption* ranges from 3 seconds to 1 minute. The duration of a *sustained interruption* is greater than 1 minute. Sustained interruptions frequently require human intervention for repairs because their cause is seldom transitory or self-correcting. They happen infrequently on a typical urban circuit because most power lines are underground. In rural areas, most power comes through overhead lines that are exposed to the elements. Sustained interruptions happen more often in these areas and for longer durations. Even interruptions lasting a few milliseconds can cause microprocessors to shut down or scramble data.

Voltage Unbalance

Voltage unbalance is the maximum single-phase deviation from the average voltage of the three phase voltages divided by the average of the three phase voltages, expressed in percent. In equation form, this can be described as:

Voltage unbalance = 100 * (maximum deviation from average) / average

Unbalance can also be defined using symmetrical components. The ratio of either the negative- or zero-sequence component to the positive-sequence component can be used to specify the percent unbalance.

Causes of voltage unbalance include:

- Single-phase loads on a three-phase circuit (unbalance > 2%)
- Blown fuses in one phase of a three-phase capacitor bank
- Single-phasing conditions (unbalance > 5%)
- Blown fuses on a three-phase capacitor bank

Voltage unbalance is most detrimental to rotating three-phase machinery. A voltage unbalance can cause a motor to overheat.

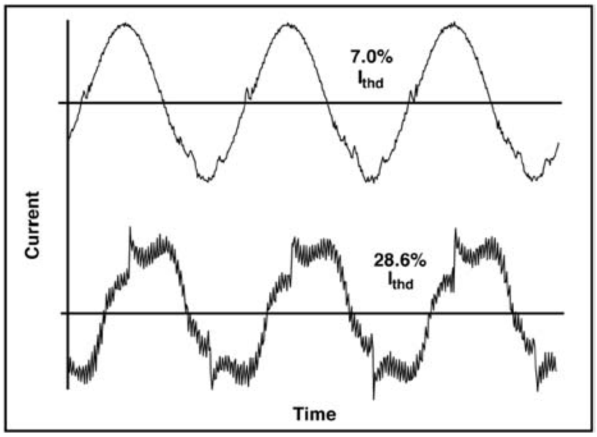
Interharmonics can be found in networks of all voltage classes.

Waveform Distortion

Waveform distortion is a steady-state deviation from an ideal sine wave of the fundamental power frequency characterized by the spectral content of the deviation. The five primary types of waveform distortion are:

- DC offset
- Harmonics
- Interharmonics
- Notching
- Noise

Harmonics



Electronic ballasts are much more energy-efficient the magnetic ballasts, but normal operation of an electronic ballast causes harmonic distortion. Two cases are represented here. One ballast causes 7.0% total harmonic current distortion while another model causes 28.6% or four-times as much.

DC Offset

DC voltage or current in an AC power system is called *DC offset*. Causes of DC offsets in an AC power system include geomagnetic disturbances and the effects of half-wave rectification. Transformer saturation and insulation stress are negative consequences of DC offset.

Harmonics

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental power frequency. Harmonic distortion exists because of the operation of nonlinear devices and loads in the power system. Harmonic distortion levels can be characterized by the harmonic spectrum with magnitudes and phase angles of each individual harmonic component. Total harmonic distortion (THD) is a quantity commonly used to express the sum of all harmonic components divided by the fundamental voltage or current. Harmonic currents, and the voltage distortion they create as they flow through the system impedance, can reduce equipment operating reliability and service life. Failure of sensitive equipment and capacitor failures, fuse blowing, and telephone interference can be consequences of excessive harmonics.

Interharmonics

Voltages or currents having frequency components that are not integer multiples of the power frequency 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, cyclo-converters, induction motors, and arcing devices. Powerline-carrier signals can also be considered as interharmonics. Interference with power-line carrier signals and visual flicker in monitors can be effects caused by interharmonics.

Notching

A periodic voltage disturbance called *notching* can occur during commutation of current between phases, which can happen as a result of the normal operation of power electronic devices. Notching can be considered to be similar to harmonic distortion. However, because the high-frequency components that occur with notching can be quite high, such frequencies may not be readily measurable with equipment typically used for harmonic analysis. Also, notching can be considered to be similar to transients. However, unlike transients, which are momentary in nature, notching occurs continuously (steady-state).

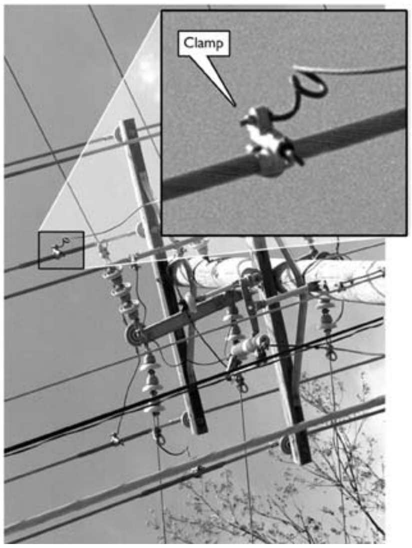
An major cause of voltage notching is three-phase converters that produce continuous DC current. Notching can also be caused by arcing power conductors, which can interfere with communication equipment. The severity of notching is affected by the source inductance and the isolating inductance between the converter and the point being monitored.

Noise

Noise is any unwanted electrical signals with a broadband spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase, neutral, or signal conductors. Any unwanted distortion of the power signal other than harmonic distortion or transients is noise. Noise of less than 1% of nominal is typical.

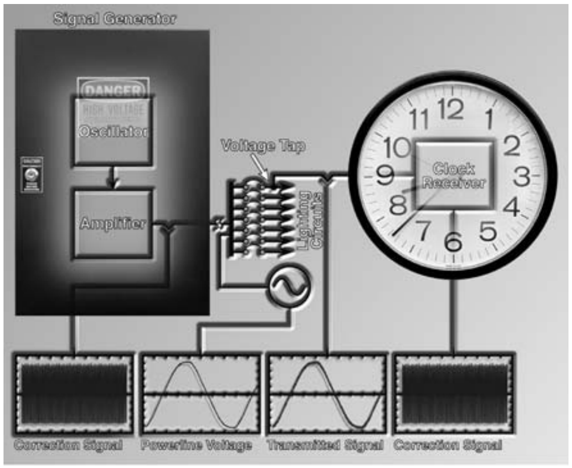
Notching

A faulty hot-line clamp caused arcing at an assisted-living center. The faulty clamp created notches that propagated throughout the distribution system. Patients at the center wore ankle bracelets that prevented the doors to the outside from opening (called a patient wandering system, or PWS). However, the notches caused by the defective hot-line clamp interfered with the proper operation of the automate doors, enabling patients to wander out of the now unsecure building. (See waveforms on p. 11.)



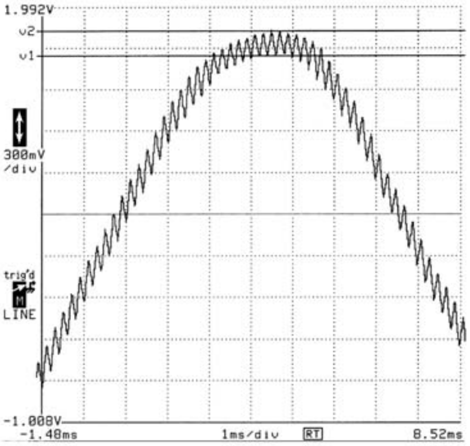
Noise

Equipment such as an automatic clock system uses the existing power conductors in a building to transmit and receive signals that control clock settings. (See waveforms below.) Noise on the power conductors can cause faulty clock settings and inadvertent alarms.



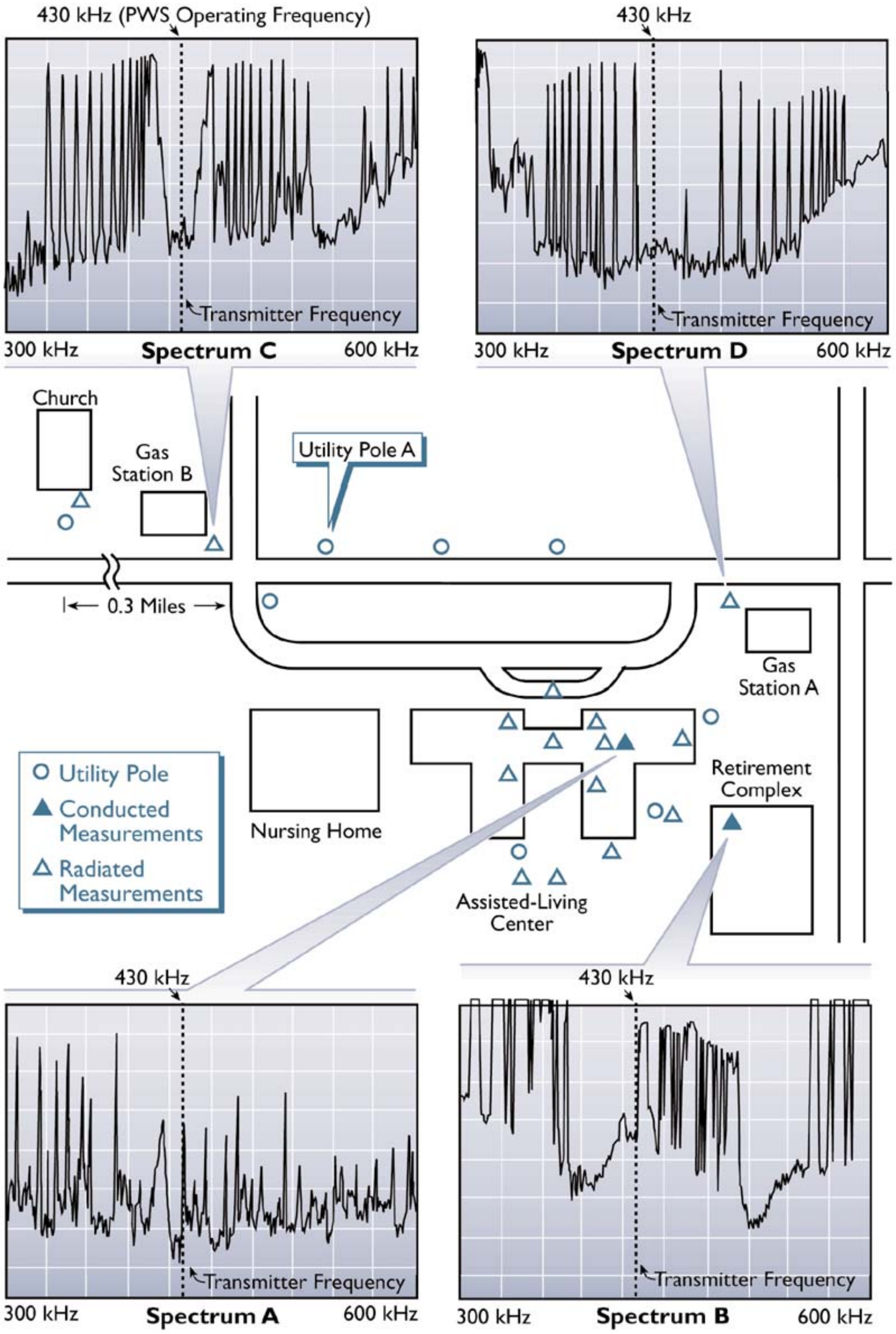
Waveform of voltage in a public school building during no communication between the clocks and the master control unit.

Waveform of voltage in the same building during communication between the clocks and the master control unit.



Notching from a Faulty Hot-Line Clamp

The notching caused by a faulty hot-line clamp at an assisted living center was measured all over the surrounding neighborhood: at the center, at two gas stations, and at an adjacent retirement complex.



> **Voltage fluctuations are systematic or random voltage changes in voltage level that are typically between 95 and 105% of nominal.**

Causes of noise include improper grounding, normal operation of electronic equipment, arcing devices, control circuits, loads with solid-state rectifiers, and switching power supplies. Electronic devices such as microcomputer and programmable controllers can be impacted by noise. The use of power filters, isolation transformers, and line conditioners can mitigate the problem.

Equipment such as an automatic clock system uses the existing power conductors in a building to transmit and receive signals that control clock settings. Noise on the power conductors can cause faulty clock settings and inadvertent alarms.

Voltage Fluctuations

Voltage fluctuations are systematic or random voltage changes in voltage level that are typically between 95 and 105% of nominal. Voltage fluctuations are defined by their RMS magnitude expressed as a percent of the fundamental frequency.

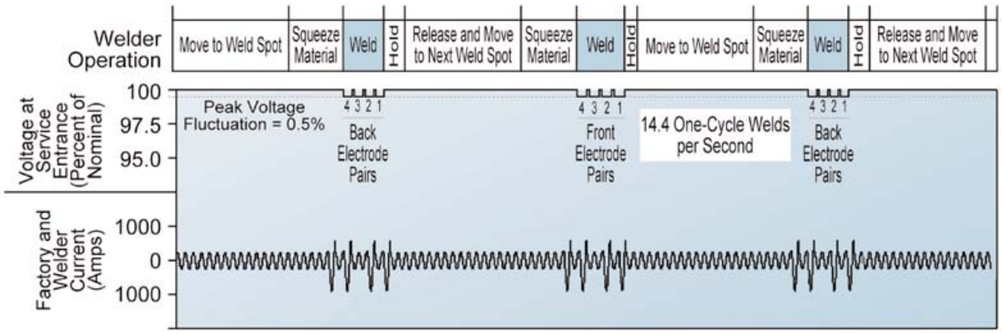
The term *flicker* and *voltage fluctuation* are sometimes used interchangeably, but are not synonymous. Voltage variations caused by rapid variations in load current can cause the intensity of lighting to vary in such a manner that the human eye can detect the changes. The variations in lighting intensity is called *flicker*. Therefore, flicker is a visual phenomenon, which may be caused by the variation in voltage known as *voltage fluctuation*. Loads having significant current variations can cause voltage fluctuations. For example, arc furnaces are a common cause of voltage fluctuations.

Power-Frequency Variations

The deviation of the power-system fundamental frequency from its specified nominal value is a *power-frequency variation*. The rotational speed of the generators on the system is directly related to the frequency of the power system. Poor speed regulation of local generation, faults on the bulk-power transmission system, disconnection of large loads, and the disconnection of a large source of generation are all causes of power-frequency variations.

Promoting Factors

Promoting factors are elements within the electrical system—such as faulty electrical wiring—that enable or help an electrical disturbance to upset or damage appliances. Most promoting factors involve incorrect and sometimes unsafe wiring and grounding practices or wiring and grounding that are



Voltage Fluctuations

In one case where residential customers near a welding operation complained of light flicker, the source of the voltage fluctuations was traced to a spot welder that had a predictable pattern of large current draws, causing the voltage at its service entrance to dip 14.4 times per second.

Promoting Factors

Microprocessors and other integrated circuits are often the weak links in equipment tolerance of electrical disturbances.

not up to standards, such as wiring and grounding in an old building. Other promoting factors include damaged or misapplied data cables, inadequate shielding of appliances, or an electrical phenomenon that compounds the power quality problem.

The **effects** of electrical disturbances on appliances and equipment range from relatively benign blinking clocks to overheated wires in modular office panels and air-conditioning compressors, which pose a fire hazard. However, the most common effect is *upset*—loss of data or microprocessor lock-ups—which may not pose a physical threat but can be costly to business and industry.

EPRI Distribution Power Quality Project

The DPQ Project involved almost 300 distribution system sites at 24 different electric utilities across the United States.

Microprocessors and other integrated circuits are often the weak links in equipment tolerance of electrical disturbances.

WHY POWER QUALITY IS IMPORTANT

Power Quality Variations Across the United States

No part of the United States is without electrical disturbances. An important part of understanding the quality of power delivered to end users is first understanding power quality levels across the nation. Significant and important work has been done to understand the level of power quality and reliability being delivered to users of electric power.

EPRI Distribution Power Quality Project

The EPRI Distribution Power Quality (DPQ) Project set the *de facto* standard for power quality levels on distribution systems in the United States simply by measuring a number of power quality parameters on a significant number of feeders (surges, sags, harmonics, and so on) and calculating the average system performance, among other metrics.[2] The project involved almost 300 distribution system sites at 24 different electric utilities across the United States.

The results of monitoring at these sites for two and a half years were analyzed to develop benchmark power quality statistics that represent the power quality performance of distribution systems across the nation from June 1993 to August 1995, comprising 100 distribution feeders in the voltage range of 4 kV to 33 kV. The data collected during the measurement period provides a statistically valid sample of the range of power quality events typically found in electrical distribution systems.

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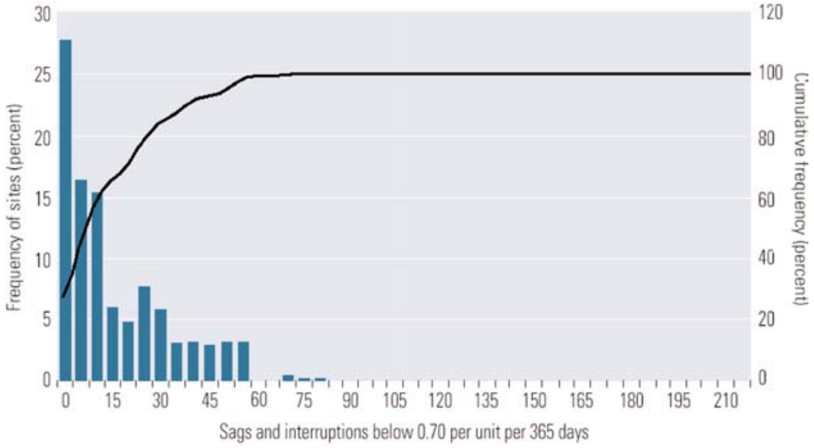
2. *An Assessment of Distribution System Power Quality: Volumes 1-3*; TR-106294-V1, TR-106294-V2, TR106294 V3, EPRI, Palo Alto, CA, 1995.

Frequency of Sags and Interruptions



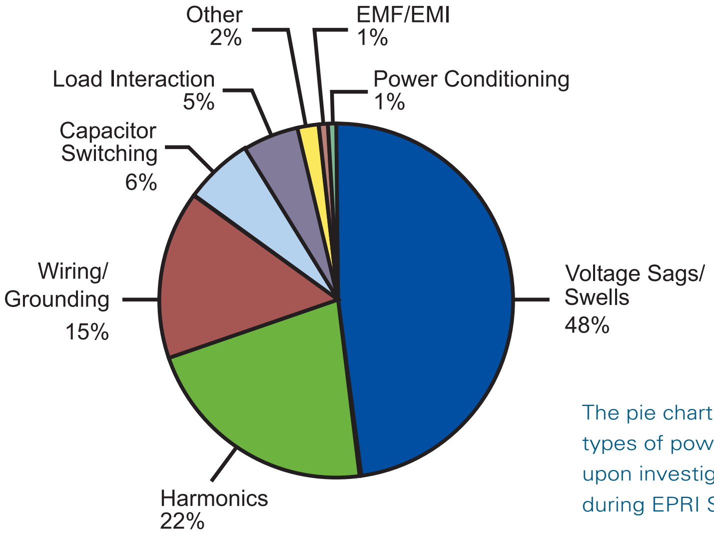
Above is a representation of some results from the EPRI DPQ study to quantify the electrical environment based on the monitoring results. The data shows that, on average, distribution systems in the United States experience approximately 17 voltage sags (below 70% of nominal) or interruptions per year.

Average Events Per Year

Monitor location	SARFI$_{10}$	SARFI$_{50}$	SARFI$_{70}$	SARFI$_{90}$
Substation average	2.88	7.89	17.24	56.93
Feeder average	4.67	12.07	20.64	54.63

Above are the composite results for all DPQ study sites. As one would expect, the average number of annual shallow voltage sags (SARFI90) is considerably greater than the deeper sags to 10, 50, and 70% of nominal voltage. Electrical distribution feeders, on average, experience between four and five very deep voltage sags (or outages) per year, as reflected in the SARFI10 results.

Causes of PQ Problems Based on 500 EPRI Solutions Investigations



The pie chart to right shows a snapshot of the types of power quality phenomena that have, upon investigation, turned out to be the culprit during EPRI Solutions investigations.

Results From the EPRI Distribution Power Quality Study

One important set of data gathered by the EPRI DPQ project was an assessment of the number and severity of voltage sags on electric distribution systems. EPRI has developed a metric for measuring sags called "SARFI," which stands for System Average RMS (Variation) Frequency Index (SARFI$_x$), where the "x" refers to how deep the sag may be below nominal voltage. For example, SARFI$_0$ refers to voltage sags where the voltage dropped to a value of zero (that is, a complete power interruption). SARFI$_{70}$, the most common voltage level used for benchmarking with SARFI, refers to voltage sags that dipped below 70% of nominal.

SARFI$_x$ was developed as part of an EPRI project designed to create a set of service quality metrics that included the effects of electrical disturbances such as voltage sags. SARFI and its various versions have been documented in the IEEE literature and provide the basis of discussion for a proposed IEEE task force charged with standardizing power quality indices. Several U.S. utilities are using SARFI for such applications as benchmarking, proactive maintenance planning, and developing premium-service contracts.

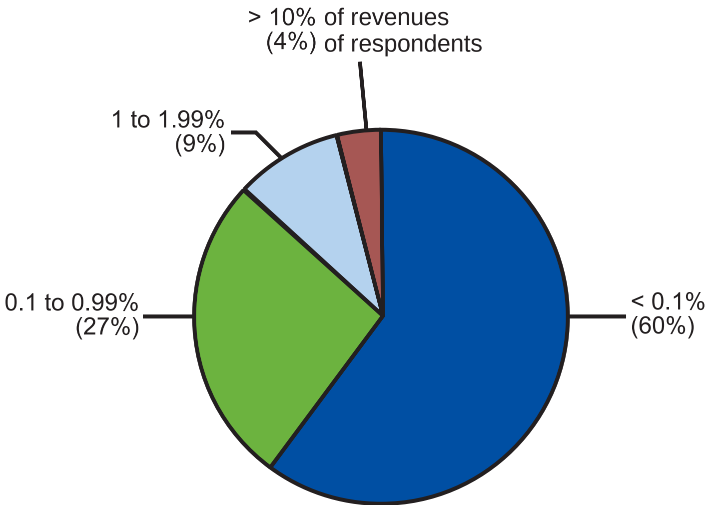
Results From EPRI Solutions Investigations of End-User Power Quality

EPRI Solutions has conducted more than 500 investigations of power quality and reliability-related problems at end-user facilities. These investigations have spanned the spectrum of standard industry classifications (SIC) codes ranging from commercial buildings to transportation to food processing to plastics, printing, and chemical processing.

Costs of Power Quality to the U.S. Economy

This topic is covered more completely in Chapter 2 of the *Power Quality Encyclopedia*, "The Economics of Power Quality." However, there can be no question that electrical disturbances can greatly affect business profits in a wide variety of ways. For example, an electric utility with nearly 1.5 million residential customers estimated that voltage sags and short interruptions of electricity resulted in losses to its customers of over 4 million dollars worth of time and data. Moreover, unscheduled interruptions in electricity at a major data-processing center can result in a business loss of ten thousand dollars every minute.

End User Reliability Costs vs. Revenues



To assess the level of loss because of electric power reliability and power quality issues, it is best to examine how much companies say they are losing as a percentage of their revenues. The pie chart above shows the percentage of industrial businesses in the United States that suffer high levels of economic loss because of power quality and reliability problems. Just more than 4% report crippling losses greater than 10% of revenues. Nearly 13% report losses exceeding 1% of revenues. This implies that approximately one in eight industrial customers would benefit significantly from technologies and techniques that would (1) improve the quality of electric power supply, (2) make end-user processes less sensitive to power supply problems, or (3) otherwise reduce the economic impact of less-than-perfect electric power supply.

End-User Issues With Power Quality

Process Interruption

Electrical disturbances can cause process equipment to malfunction or shut down. For example, voltage sags, momentary interruptions, overvoltages, and current unbalance can cause adjustable-speed drives (ASDs) to trip offline. The motor that is driven by an ASD will likely grind to a stop, perhaps causing an entire process line to stop. In a facility that requires bright lighting to maintain a safe working environment, voltage sags and momentary interruptions can extinguish high-intensity discharge (HID) lamps and metal-halide lamps.

Equipment Damage

Surges caused by lightning and load switching, among others, can damage sensitive semiconductors in residential, commercial, and industrial equipment. Surges can propagate through the building wiring system in a number of ways. Surges impinging upon the power conductors can be coupled to data and signal wires that interconnect equipment. For example, in process facilities, ASDs and programmable logic controllers (PLCs) are often connected via a data cable. The longer the cable, the greater the chance that surges will be coupled into the cable, affecting both the ground wires and the signal wires.

Communication Disruption

In equipment that uses digital circuits for communication—such as computers and peripherals, digital telephones, and energy-management systems—voltage variations can confuse the streaming bits of ones and zeros. This type of communication disruption will become more prevalent as the logic voltage of digital circuits decreases from the once-standard 5 volts.

Reduced Efficiency: Effects of Power Quality on Energy-Efficient Induction Motors

While induction motors can precipitate power quality problems, they can also be victims of poor power quality. The following sections discuss the effect of voltage unbalance and harmonic voltage distortion on energy-efficient motors and other equipment connected to the same bus.

Effects of Voltage Unbalance on Induction Motors

Electric power is almost universally distributed in the form of three-phase power—consisting of at least three conductors operating at the same (or nearly the same) voltage but 120 degrees out of phase with each other. Electrical machines that use three-phase power—such as the majority of induction motors—are designed to have the three phase voltages equal, or nearly so. When the phase voltages are not equal, significant problems can occur, often manifesting in two of the biggest threats to the longevity of rotating equipment: excessive heat and vibration.

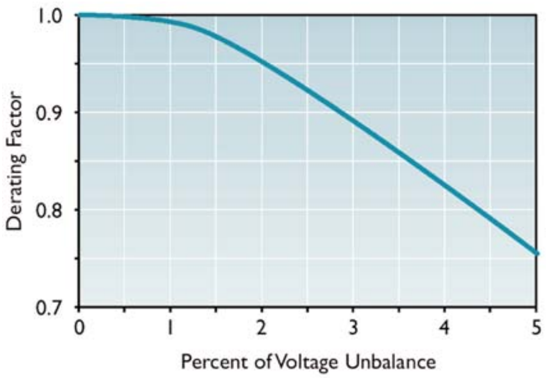
Temperature Rise Because of Voltage Unbalance: An unbalanced, three-phase voltage causes three-phase motors to draw unbalanced current—a current that contains a negative-sequence component (one that creates magnetic fields that oppose the motor's normal direction of rotation and can cause the rotor of a motor to overheat). In fact, the temperature rise caused by unbalanced current is much greater than the rise caused by the motor current alone. A voltage unbalance results when phase voltages at the point of utilization are unequal. Common causes of voltage unbalance include:

- Faulty operation of automatic, power-factor-correction equipment and voltage regulators in the utility distribution lines
- Unevenly distributed single-phase loads in a facility
- An unbalanced transformer bank

According to Appendix D of American National Standards Institute (ANSI) Standard C84.1, *Electric Power Systems and Equipment*, approximately 98% of surveyed electric power-supply systems are within 3% voltage unbalance, with 66% of the systems at 1% or less. ANSI C84.1 recommends that electric power-supply systems have no more than 3% voltage unbalance when measured at the revenue meter during no-load conditions. NEMA Standard MG 1-14.35 recommends derating an induction motor when the voltage unbalance exceeds 1% and recommends not operating a motor at all when the voltage unbalance exceeds 5%.

Derating Motors Because of Voltage Unbalance: Operating a motor during a voltage unbalance generally requires the motor to be derated to ensure long life. If the motor is not equipped with an embedded temperature detector or if incorporating the detector into a protection scheme is not feasible, then the end user should consult with the motor manufacturer to determine the maximum level of current unbalance that is acceptable for all loading conditions.

??? Derating Motors Because of Voltage Unbalance



Voltage Unbalance	Approximate Derating
1%	None
2%	95%
3%	88%
4%	82%
5%	75%

For motors rated greater than 500 horsepower, derating must be calculated in consultation with the vendor.

Essentially, the operation of a motor under unbalanced voltage conditions requires that the motor be derated. For standard motors, NEMA provides guidance for derating. For voltage unbalances between 1 and 5%, NEMA suggests derating motors according to the graph shown below (from National Electrical Manufacturers Association MG-1-1993). NEMA has not yet established a derating graph for energy-efficient motors. However, because energy-efficient motors have lower losses during balanced as well as unbalanced voltage conditions, applying the derating graph above to energy-efficient motors will yield conservative derating factors.

For example, the effect of a 10% current unbalance on a motor that is fully loaded is greater than the effect on the same motor if the motor is loaded at only 50%.

Unbalanced Currents in Induction Motors

When a standard-efficiency motor is replaced with an energy-efficient motor, the protection scheme against excessive unbalanced current may cause nuisance tripping, especially when the scheme is configured to disconnect the motor based upon the percent of relative current unbalance and not the temperature of the motor. To overcome nuisance tripping caused by current unbalance, the end user has two options:

Monitor the Temperature: The best way to protect a motor stator against unbalanced current is to monitor the temperature rise of the motor. Many motors, especially large motors, are equipped with an embedded temperature detector. If a protection scheme were to include an input from a temperature detector, the motor could be taken offline when the motor temperature exceeded a predetermined level rather than taken offline when the current unbalance exceeded a predetermined level.

Provide Time Delay: Most of the faults in a utility distribution system are single-phase. The voltage sags resulting from these faults are usually very unbalanced, causing a severe voltage unbalance at the motor terminals. However, the duration of a voltage sag is typically only a few cycles, the time it takes utility protection devices to clear a fault. In some cases, a motor will trip during a momentary voltage unbalance because of the resulting current unbalance. Also, sensitive relays in the motor-protection circuit may drop out, disconnecting the motor from the line. To prevent nuisance motor tripping or disconnection during unbalanced voltage sags, a time delay can be incorporated into the motor-protection circuit.

Effects of Harmonic Voltage Distortion on Induction Motors

One effect of the widespread use of power electronic converters such as variable-frequency drives is an increase in voltage distortion—the presence of unwanted frequencies in the voltage other that the normal 60-Hz fundamental. The higher frequencies associated with harmonic voltage distortion (usually in the range of 300 to 3000 Hz) can increase energy losses in iron and copper, resulting in increased motor heating and higher operating temperatures. Typically, background harmonic distortion (harmonic distortion that already exists in a wiring system) is comprised of harmonics of odd multiples such as 3rd, 5th, and 7th harmonics. As with voltage unbalance, some specific harmonic components such as the 5th and 11th can cause the rotor to dramatically overheat.

To compensate for harmonic voltage distortion, end users can derate induction motors. In the absence of any established guidelines for energy-efficient motors, end users should follow the procedure for derating motors in NEMA MG-1-1993, Section IV, Part 30. Following this procedure will typically yield conservative derating factors for the operation of energy-efficient motors under distorted-voltage conditions.

PREVENTING POWER QUALITY PROBLEMS

Facility Design Considerations

Market studies indicate that consumers are spending more than $5 billion annually on power quality today, and the compound annual growth rate (CAGR) of spending is estimated at a conservative rate of 8% up to a more pessimistic rate of 16%. So, based on the inherent sensitivities and associated downtime costs of microprocessor-based technologies and the growing power-conditioning market, power quality is a growing business.

But with all this attention and dollars being poured into power quality, how does wiring and grounding fit into the picture? Facility wiring and grounding can and does affect power quality. In fact, wiring and grounding are considered the foundation for proper operation of equipment. EPRI and other studies indicate that as many as 70% of all failures of electronic equipment attributed to power quality result from inadequate wiring or grounding or interactions with other electrical loads. Therefore, before considering a purchase of power-conditioning equipment, commercial and industrial customers should check their own facilities carefully to determine the causes of electronic malfunctions. Sometimes the solution to a power quality problem is simply to tighten a loose connection or replace a corroded conductor.

Although the wiring, distribution equipment, and installation must meet all local building-code requirements, most local codes currently do not address power quality and performance issues. In the United States, most local codes are based on recommendations outlined in the NFPA 70 National Electrical Code (NEC). The NEC states within its purpose:

> *The purpose of this Code is the practical safeguarding of persons and property from hazards arising from the use of electricity...but not necessarily efficient, convenient, or adequate for good service or future expansion of electrical use.*[3]

While the NEC's primary goal is for personnel and equipment safety, many practices and techniques recommended by the NEC can increase performance while maintaining a safe electrical system. Once wiring and grounding have been verified to be in compliance and performance is still not adequate, power conditioning should be considered to enhance performance.

Equipment-Level Compatibility

As the power-conditioning technology is moved from inside the facility toward the service entrance, the cost of power conditioning increases. In contrast, to move the point of application farther inside the plant, more knowledge of the process equipment is necessary. As an example, if one knows nothing about the particulars of the process equipment but has unlimited budget, then power conditioning can be approached at the utility level with very large-scale devices or expensive system modifications. On the other hand, if one has the time to invest in evaluating the performance of the equipment inside the facility, then the solution may be applied at a lower voltage level and at smaller subcomponents of the process. This would lead to significant cost savings in equipment.

Naturally, the least expensive option for improved ride-through of a process is to include the ride-through requirements in the specifications for the equipment. If ride-through standards exist, this merely requires that the specification list the standard to be met. Unfortunately, most industries do not have such standards in place.

To protect equipment controls from electrical disturbances, the electrical system must be studied. However, there is usually some correlation between process shutdown and the control circuits used in the system. Therefore, power conditioning can be applied to the control circuit or control devices responsible for shutdown of the system. While this may not remove all the sensitivity of the system to voltage variations, it will, in all likelihood, take care of 80% of that sensitivity. At this level, the power conditioners are the least costly in the market.

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[3] *NFPA 70 National Electrical Code, Section 90-1(c).*

At the panel feeding the process line or lines, power-conditioning devices must be larger scale, on the order of tens to hundreds of kW. They will also carry a higher price. In this case, the knowledge of the process equipment is not required in as much detail, and the improvement in system performance may be even better than 80%. The drawback is that power conditioning may be applied to loads that do not actually need it. In addition, some engineering will be necessary to install such a device, which increases the final cost.

At the service entrance to the plant, power-conditioning devices must support the entire plant load. This could be anywhere from 1 to 50 MW. As such, this is the most costly approach. Hopefully, the technology chosen for this level is such that 100% of the process sensitivity is removed. However, as is true at the panel level, it is possible that the majority of protected equipment does not require protection.

Designed Compatibility (SEMI F47)

One of the best ways to interface equipment to electric power while taking power quality into account is through the application of compatibility curves. Equipment compatible with the curves will tolerate (that is, continue to operate without interruption) voltage sags that are on or above the curve. Sags below the curve may interrupt the device's operation, particularly as the sags become longer and deeper.

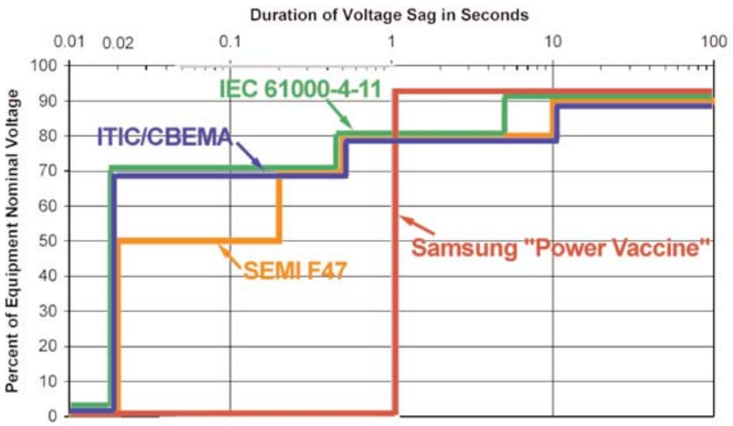
The benchmark curves shown below have specific applications. The ITIC curve is a design goal for North American manufacturers that produce information-technology equipment. To be compliant, the equipment that they produce must operate as intended as long as the applied voltage remains within the tolerance area. The SEMI F47 curve is an international design goal for manufacturers that produce semiconductor-manufacturing equipment. Finally, the IEC 61000-4-34 standard, which is similar to the SEMI F47 standard, is applied to equipment produced in Europe.

Equipment Hardening

Listed below are field-tested, effective power conditioners that can be used to harden equipment to electrical disturbances:

- Motor-generator sets
- Power-conditioning flywheels
- Uninterruptible power supplies (UPS)
- Batteryless ride-through devices (BRTD)
- Power-conditioning ultracapacitors
- Constant-voltage transformers (CVT)
- Magnetic synthesizers
- Isolation transformers
- AC line reactors
- Transfer switches
- Harmonic filters
- Transient voltage surge suppressors (TVSS)

Contrasting Compatibility Curves



The voltage-sag compatibility curves above, while differing slightly, all have the same goal: to specify recommended sensitivity of end-use devices to RMS variations in the voltage supply. If equipment is designed to meet the performance requirements of a curve, then voltage and voltage disturbances above the curve should not affect process operations.

Motor-Generator Sets

A motor-generator set (MG set) is an effective device for isolating electrical systems. Comprised of an electric motor that drives an electric generator, an MG set transforms incoming electrical power into mechanical energy, which is then used to drive a generator, converting the energy into electricity once more. The only connection between the two electrical systems is the mechanical connection of the MG set. Because of this electrical isolation, MG sets are effective at preventing the transmission of transients, harmonics, and electrical noise from one system to another. Because voltage is determined by rotor speed, the inertia of the rotating equipment (rotors and connecting shafts) can help equipment ride through short-duration voltage sags or interruptions. Inertia added to the shaft, in the form of a flywheel, can increase the ride-through duration. MG sets can also be used to change system frequencies and voltages. A relatively new class of MG sets is the Written-Pole^{TM} Roesel Motor-Generator (RMG). The RMG uses Written-Pole^{TM} technology to change or "write" poles onto the stator, ensuring constant frequency and voltage from the generator for as long as possible.

Power-Conditioning Flywheels

Flywheels are one of the oldest and most common mechanical devices in existence. Kinetic energy is stored in a rotating mass (the flywheel), and this energy is drawn upon when needed to smooth the operation of the machine. A flywheel, in essence, is a mechanical battery that stores kinetic energy. However, until recently, flywheels were only useful for short ride-through or output modulation on mechanical devices. Modern power electronics, bearings, and composite technologies are making flywheels a viable way to ride through and smooth out electrical disturbances.

Flywheels are one of the oldest and most common mechanical devices in existence.

Flywheels are available in many sizes, from less than 100 kW to several megawatts. As a straightforward energy-storage device, flywheels are used to replace or augment conventional batteries in supporting a critical DC bus, such as the DC link of a UPS, an adjustable-speed drive (ASD), or a stand-alone power unit (such as those commonly used in telecommunications). Flywheels can also be used to directly support a load at line frequency, although this requires the addition of some line-frequency system components such as static switches, boost transformers, or output inverters. Frequent cycling of flywheel systems does not appreciably diminish useful life.

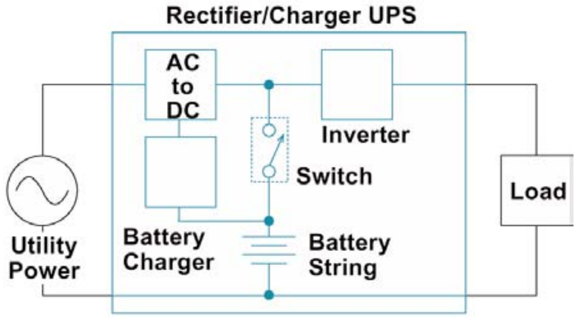
Flywheels are relatively unaffected by extremes in ambient temperature. The rate at which energy can be exchanged into or out of the flywheel is limited only by the design of motor-generator sets and power electronics. Therefore, it is possible to withdraw large amounts of energy in a far shorter time than with traditional chemical batteries. Environmental issues present with batteries are not present with flywheel systems.

Uninterruptible Power Supply

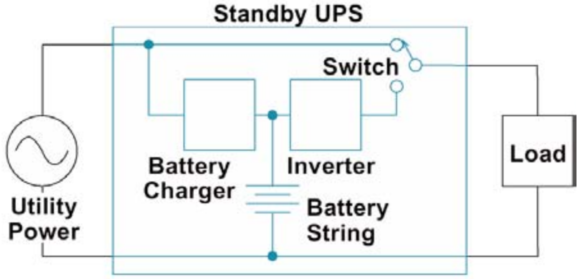
Uninterruptible power supplies have long been used to protect mission-critical equipment from the effects of temporary power interruptions and other electrical disturbances. The UPS comes in a wide array of sizes ranging from just a few hundred VA to as large as one megawatt. The protection capabilities and performance features also vary from model to model, depending on the technology used. The four basic categories used to describe UPS products include on-line UPS, standby UPS, line-interactive UPS, and rotary UPS.

On-Line UPS: The on-line UPS (also called a rectifier/charger or double-conversion UPS) takes the AC input power, rectifies it, and converts it to a DC voltage. The DC is then fed into an inverter and filtered to recreate AC power for the output loads. As with the rotary UPS system, the on-line UPS creates a separately derived source as defined and recommended by the NEC. Advantages of this type of system include isolation between the loads and the normal power source, very good power-conditioning capability, and no break in output power when transferring the loads to and from battery backup. Disadvantages include lower energy efficiencies than other similarly sized units, limited starting-current availability for connected loads, creation of input harmonic current distortion (unless the unit has a power-factor-corrected input), and higher cost than similarly sized standby units.

Online UPS



Standby UPS



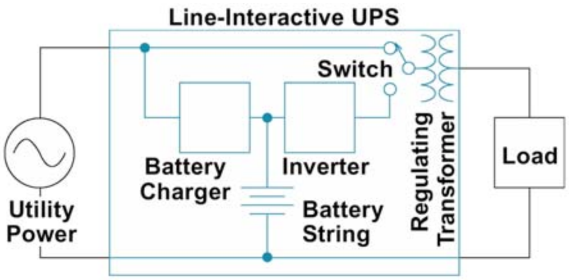
Standby UPS: This type of UPS is typically the least expensive and, depending on the manufacturer, may also be referred to as a UPS (with no other description). A large percentage of these units are used in 1-kVA or less applications supporting PC power supply and peripheral loads. A standby UPS is intended for loads that can tolerate a momentary loss of power during the transfer to and from battery. The unit allows the load to operate on normal AC line voltage as long as the line voltage stays within a predetermined window. If the voltage goes outside this window, the unit transfers the load to battery power. Advantages of this type of power system include low cost, high efficiencies (typically 95 to 99%), and the ability to support high inrush currents. Disadvantages include limited power-conditioning ability and no isolation between the load and the normal power source.

Line-Interactive UPS: The line-interactive UPS has characteristics of both the standby and the on-line topologies. Operation is in a “conditioned” normal AC line mode. If the input voltage gets too high or too low, the line-interactive UPS may be able to correct for this condition without switching to battery power. This voltage regulation is accomplished through the use of a tap-switching transformer, a ferroresonant transformer, or controlled switching of inverter electronic components. Some line-interactive units are capable of supporting the load with no break in output when transferring to and from battery power. Other models are really a hybrid of the standby type, featuring voltage regulation but having a short break in output while transferring to and from battery. Advantages of this type of system include:

- Energy efficiencies in the high 80 to mid 90 percentages (depending on design)

- Isolation between the loads and the normal power source (if an isolation transformer is used in the design)
- Good power-conditioning capability
- Better starting-current availability than the rectifier-charger type (but less than the standby type)
- No break in output power when transferring the loads to and from battery backup (subject to manufacturer design, specification of switching duration should be reviewed if true no-break transfer is required by the load)

Line-Interactive UPS



Disadvantages of line interactive UPS systems include:

- Lower energy efficiencies than the standby type
- Higher cost than similarly sized standby units
- May not supply load isolation
- May not correct induced harmonics

Rotary UPS: Rotary UPS systems have gained in popularity because of the availability of ratings up to 10,000 kVA. This type of UPS system is typically very reliable because of the low parts count. During normal operation, an AC motor turns an AC generator, while the battery bank is charged by a DC generator. During a power failure, a DC motor turns an AC generator, using battery power. The transition to and from battery power is accomplished by motor controls with no contactors or switches so that the AC generator output is totally uninterrupted. This type of design completely eliminates the rectifier/charger, inverter, and static bypass switch of conventional UPSs. Other rotary UPS systems may employ power electronics for the battery-backup portion of the system.

Batteryless Ride-Through Devices

Protection from momentary voltage sags and interruptions is a critical feature for process and stand-alone equipment. Whether the application is a 100-megawatt industrial plant or an individual electronic device such as a relay, reliability depends on the equipment's ability to withstand momentary voltage variations. A variety of ride-through devices have become available recently, serving to reduce the impact of momentary voltage variations and, in some cases, very short-term interruptions.

Batteryless ride-through devices (BRTDs) come in a variety of configurations that make use of the full range of power electronics technology. Capacitors, magnetic components such as transformers and inductors, and electronic devices such as diodes and power switches are used to control and shape electrical energy into a form that improves the ability of the load to tolerate variations in utility power.

The major categories of BRTDs are AC ride-through and DC ride-through. Many different types of energy-storage options are available for BRTDs. For example, flywheel, fuel cell, and ultracapacitors are just a few of the many available alternative sources of energy that may be found in BRTDs. Each alternative source has its relative merits, which generally depend on specific application issues such as size, cost, and availability, but also depend on the progress of technical advancement. As these technologies mature, they may become more popular.

Power-Conditioning Ultracapacitors

Sometimes referred to as super capacitors, ultracapacitors are capacitors with exotic combinations of dielectrics and electrodes, such as carbon composite electrodes and organic electrolytes. Ultracapacitors can store several hundred times as much energy (on a weight and volume basis) as conventional capacitors and can still deliver that energy at high discharge rates. Present day designs have power densities of 2000 to 4000 watts per kilogram of material and specific energy of 5 to 10 W/kg. Capacitor systems have high cycle lifetimes, typically in excess of 500,000 discharge cycles. Individual capacitor voltages are low, typically less than 3 volts, requiring many series-connected units for large power requirements. Each capacitor may store from 1000 to 2700 farads of charge.

When the energy is stored as a voltage, the voltage varies in direct proportion to the state of charge. Electronics may be provided to accommodate wide output voltage range as energy is extracted, or these electronics may be avoided, limiting the discharge of the capacitor to a smaller percentage of the available energy. Because of their relatively high power density and high cycle life, ultracapacitors are a good choice to provide fast ride-through of short electrical disturbances. Ultracapacitors are primarily used as part of a larger system to provide support for the critical DC bus applications such as UPSs, ASDs, DC systems, or telecommunication equipment. When used in conjunction with batteries in a UPS system, ultracapacitors can extend the useful life of the batteries by providing power through short events and decreasing the number of discharge cycles experienced by batteries. Ultracapacitors can also accept and store large power surges from regenerative braking. Therefore, they can be especially useful in ASD applications where regenerative braking is common.

Constant-Voltage Transformers

The constant-voltage transformer (CVT) is a popular power conditioner for mitigating the effects of voltage sags on industrial and commercial equipment. A CVT uses a ferroresonant transformer to maintain relatively constant output voltage, despite brief variations in input voltage. CVTs are excellent solutions for momentary voltage sags to approximately 50% of nominal voltage. The CVT's load-support characteristics include:

- Operates in a saturation mode, providing excellent output voltage regulation for connected loads
- Provides an outstanding solution for voltage sags but not a solution for momentary interruptions
- Should be sized at least twice as large as the load VA requirement and at least two times the peak inrush demand of the load or loads

Constant-Voltage Transformers

From left to right: A batteryless ride-through device, constant-voltage transformer, and uninterruptible power supply.

The simple isolation transformer can protect against many high-frequency transients.

Magnetic Synthesizers

Magnetic synthesizers are the equivalent of constant-voltage transformers for three-phase loads. They are more efficient and available up to much higher power ratings (such as 200 kVA). They are used for large computers and other electronic equipment that is sensitive to voltage variations. These are ideal for situations where interruptions are very rare but where ride-through support against voltage sags is needed.

Isolation Transformers

The simple isolation transformer can protect against many high-frequency transients and can prevent nuisance tripping attributable to capacitor switching on the utility side. These transformers are used to attenuate noise and transients as they pass from winding to winding by providing a zero-volt reference for the system. This is accomplished with three different techniques:

- Common-mode rejection
- Electrostatic shielding
- Additional impedance

Active Power-Line Conditioner

Active power-line conditioners (APLC) can involve series- and/or shunt-connected power electronics to condition the voltages and currents supplied to sensitive and distorting loads. Available power levels are continually increasing, and designs for application on higher-voltage systems are becoming available. Series-connected active conditioners can provide voltage regulation and correct for harmonic components in the voltage. The controls can be designed so that the series-connected unit looks like a very high impedance to harmonic components, improving the performance of passive filters (hybrid configuration). Parallel-connected active conditioners are primarily designed to compensate for harmonic components and reactive power from disturbing loads.

AC Line Reactors

AC line reactors are commonly used with adjustable-speed drives to reduce current harmonics, increase power factor, reduce current unbalance, and minimize nuisance trips caused by capacitor-switching transients. The AC line reactor may also be used to minimize the impact of long-lead transient voltages on the output side of an adjustable-speed drive.

Power-Conditioning Static Transfer Switch

For continuous industrial processes, the use of power conditioning on individual process elements is not always cost-effective. Often, power-conditioning solutions require many devices, such as UPSs and CVTs, which have installation and maintenance concerns. An alternative is a centralized approach—the static transfer switch (STS). The STS selects between two or more sources of power and allows the “best” of the sources to supply the electrical load. The basis for the STS is similar to that of the electromechanical switch, which transfers a load from one power source to the other. The significant advantage of the STS is that it can transfer the load much faster than the electromechanical switch, thus resulting in the load being protected against disturbances by an almost seamless transfer from a preferred power source to an alternate power source. In addition to being faster than the electromechanical switch, the performance of the STS is not degraded as a result of repeated transfers.

Harmonic Filters

Nonlinear loads such as arc furnaces, ASDs, battery chargers, computers, UPSs, and welders can cause harmonic distortion of the supply, both voltage and current. If the harmonic content of the supply exceeds a certain level, harmonics can cause overheating in wires and equipment and the malfunction of sensitive loads. When harmonics become a problem, there are several options available to the user. The first option, of course, is to replace the equipment that is generating the harmonics with "cleaner" equipment. However, this option is often extremely expensive, or completely impossible, so the next available option is to eliminate the harmonics with an additional piece of equipment. Line reactors and other similar devices can help to attenuate and minimize the harmonics generated by a particular piece of equipment, but to fully eliminate harmonics, a more sweeping solution is necessary. Two types of harmonic filters can do the job: active and passive.

Active Harmonic Filters: Active harmonic filters are a power electronics solution to harmonic disturbances and can be used to mitigate both voltage and current harmonics, depending on the design. Operating on a principle of harmonic cancellation, an active filter uses power electronics to inject currents (or voltages) into the supply, which cancel problem harmonics. To determine what waveforms are necessary to mitigate a disturbance, active filters monitor the supply. The speed of modern power electronics and digital signal processors enable the filters to quickly adjust to changing conditions. Active filters typically resemble adjustable-speed drives in components and construction, with a capacitive DC link feeding a power electronic inverter. This inverter is used to inject power into the load. Because of the dynamic nature and fast switching of the power electronics, several harmonic orders can be cancelled, and the same device can compensate reactive power. Active filters are typically connected parallel to the supply of a nonlinear load, allowing the injection of currents when necessary.

Passive Harmonic Filters: Passive harmonic filters are used in some instances to attenuate the magnitude of a particular harmonic current. The passive harmonic filter consists of a capacitor and inductor in series, which are tuned to resonate at or below one harmonic order. This effectively traps harmonic currents in the L/C circuit. Each tuned filter or trap is designed to deal with one fundamental harmonic order. Usually, multiple filters are needed to fully address harmonic distortion, each tuned to deal with a specific harmonic (5th and 7th are the most common). Because tuned harmonic filters change the system dynamics, they must be specifically designed to work with other filters and the power system to which they are applied. Properly designed, a passive harmonic filter can be used to eliminate harmonic distortion present on the electrical network, as well as those harmonics generated by a problem load. If improperly applied, however, parallel resonance can occur near the combined system harmonic frequency, exacerbating an existing problem. Because of these complex interrelations, the design and tuning of a passive harmonic filter is a task suitable only for power quality experts; therefore, passive harmonic filters should only be applied after careful and deliberate consideration of all possible harmonic loading issues.

The transient voltage surge suppressor (TVSS) is a popular choice to protect electronic equipment .

Transient Voltage Surge Suppressors

Sensitive electronic equipment has come into widespread use in residential, commercial, and industrial facilities. Most of this equipment can benefit from supplemental protection against damaging transients caused by lightning and/or load switching. The transient voltage surge suppressor (TVSS), also commonly referred to as a surge-protective device (SPD), is a popular choice to protect electronic equipment from potentially disruptive or destructive power disturbances. TVSS devices come in a variety of configurations, and their use depends on the type of installation. For example, to provide 100% protection from transient voltages, a coordinated system of surge suppression is required throughout a facility.

Transient Voltage Surge Suppressors

Surge-protective device installed in a meter socket. The SPD here took a massive surge, at which time it ignited and then cleared.

A high-energy suppressor should be located at the service entrance to protect against lightning-related surges. A suppressor should be located at surge-generating loads within a facility and at sensitive loads. Finally, data-line, modem, and cable-access television (CATV) suppressors should be applied to data and communication wiring. TVSS devices can be broken into three categories that are based on the type of port protected:

- Power-line surge protectors
- Data-line surge protectors
- CATV and modem-port surge protectors

POWER QUALITY MONITORING

Fundamental requirements of power quality monitors include an ability to measure the voltage and/or current at various points in a power system and to depict the "observations" in a form that is suitable for humans. Many different companies manufacture monitoring equipment that meets these generic requirements. Equipment specifications vary with the objectives of the analysis tool being manufactured, so the sophistication of equipment can range from the very simple to the quite complex. For example, a low-quality analog voltmeter and a sophisticated spectrum analyzer can both be used to monitor power quality phenomena.

Such diversity helps vendors achieve market differentiation and provides many options for those interested in monitoring power quality. Such a range helps accommodate the wide array of analysis objectives that exist for utilities interested in measuring power quality. The diversity can also be confusing. Fortunately, the equipment can be grouped into categories with similar characteristics. For example, they can be grouped by their capabilities and limitations.

AC Voltage Measurements

There are two general types of devices used to measure voltage: the *analog electromechanical voltmeter* and the *digital voltmeter* (DVM). DVMs tend to be more accurate and easier to use than their analog counterparts. Analog meters assume that the voltage being read is sinusoidal in nature. They rectify the voltage being measured with a half-wave or a full-wave bridge rectifier to produce an average DC voltage that is then measured. A scaling factor is used for calibration to obtain the proper AC voltage readings. The two measurement techniques most often used in DVMs are *average* and *peak-sense*. Both are calibrated for a sinusoidal waveform. An averaging meter takes the average of the absolute value of the instantaneous voltages over a cycle, whereas a peak-sense meter detects the highest instantaneous voltage during a cycle.

Meters that use true-RMS conversion techniques should be used when measurement objectives include the detection of non-sinusoidal or distorted waveforms.

The three true-RMS conversion techniques in use today are:

- **Thermal:** Based on the heating of a resistive load with the input signal. The amount of heat generated by the load is proportional to the RMS value of the signal.
- **Analog:** Analog circuits are used to calculate the square, mean of the squares, and the square root of the mean of the input voltage.
- **Digital:** Analog-to-digital converters sample input signals at some frequency to generate digital numbers representing instantaneous voltage values. A processor is used to square the values, accumulate the sum of the squares, and take the square root of the sum. This approach generates a true RMS value on any arbitrary waveform.

AC Current Measurements

The techniques and limitations regarding the measurement of voltage are also applicable to the measurement of AC currents. The following approaches can be used to measure AC currents:

- **AC probe:** Also referred to as a current transformer (CT), this probe uses transformer action to detect current. It has a limited bandwidth because of probe saturation at lower frequencies and parasitic inductances and capacitances at higher frequencies. CTs provide non-intrusive measurements by being able to clamp around a cable or bus bar.
- **Hall-effect probe:** The probe senses the magnetic field that is generated by an electrical current. A semiconductor device is used to do this. Bandwidth limitations are not a concern with this approach, which is able to accurately measure distorted waveforms.
- **Shunt resistor:** A low-value, precision resistor is inserted directly into the circuit being measured when this approach is used. A voltage drop occurs across the resistor that is proportional to the current being measured. Bandwidth limitations are not a concern with this approach. However, it is an intrusive method and can be difficult and dangerous to install and use.

Monitoring Instruments

When selecting the proper equipment, numerous monitor characteristics must be considered, such as equipment accuracy, dynamic range, and frequency response. It is also important to consider the requirements of data processing and presentation. For example, a digital sampling technique is required if a fast Fourier transform (FFT) is to be applied to captured data. Also, a means of visually representing voltage and current information is needed when examination of waveforms is required. Two classes of instruments that provide a variety of useful characteristics are oscilloscopes and disturbance monitors.

Oscilloscopes

Probes using various techniques to measure voltage and current were discussed in the AC current and voltage measurements sections above. Typically, the output from these probes may be fed directly into oscilloscopes for analysis. The quality and ease of data collection can be increased through the use of digital oscilloscopes. They allow the direct calculation of peak, average, RMS, and other values and can store voltage and current waveforms and provide a visual representation of them.

Selection of a disturbance monitor is based on its intended application.

Disturbance Monitors

Monitors that are designed specifically to detect and record electromagnetic phenomena are called *disturbance monitors*. Their features typically include multiple monitoring channels, data storage, display capabilities, and portability. Their design can be viewed in terms of the range of frequencies that they are able to measure, the manner in which data is collected, and how data is displayed. Selection of a disturbance monitor is based on its intended application. Disturbance monitors can be categorized into four groups:

- **Event indicators:** These monitors typically gather data on only a few types of disturbances. Indicator lights, audible alarms, or bar graphs are typical ways in which information is displayed. They work by comparing the steady-state condition of the power system to adjustable threshold parameters. System variations are detected and recorded when a threshold is exceeded. The ability to time-stamp events and generate hard-copy output are not typical features of event indicators.
- **Text monitors:** These monitors are similar to event indicators in how they collect and display variations. However, they typically have the ability to log the time of occurrence and record output on media such as paper and/or electronic media. The descriptive alphanumeric capabilities provide an improvement over event indicators.
- **Recording volt/ammeters:** The classic pen and ink chart recorders are an example of this type of meter. They capture and provide information on the steady-state condition of the waveforms being monitored. Their parameters include sampling frequency and resolution. Many have internal memory to store captured data and can transfer this data to computers, where the information can be further processed, displayed, and printed. The memory capacity of a device establishes the level of detail and amount of data that they can hold.
- **Graphical display monitors:** This monitor contains some features in common with the other types of monitors discussed above. For example, data collection is based on fixed or variable sampling techniques, time of occurrence is logged, and threshold parameters can be set so that data is captured when a power system variation exceeds its threshold. Also, comparison circuits may be analog or digital. The ability to present power-system variations in a graphical format that is enhanced with alphanumeric description (such as using a CRT) is a distinction of this type of monitor. The complexity that results from their ability to collect large amounts of data and many events over a period of time mandates prior planning and thoughtful application of thresholds to ease the analysis of information that they capture.

***Safety Note:** It is important that sense leads of monitors be attached in a manner that does not jeopardize the safety of personnel. The National Electrical Code (NEC) and local codes must not be compromised during the installation and use of power quality monitors.*

A time-based approach to preventive maintenance is a step up from a reactive approach.

Application of Power Quality Monitoring at Utilities

Traditionally, utilities have used a time-based preventive-maintenance approach, where maintenance personnel periodically take equipment out of service and "tear it down" for maintenance checks. This is a step beyond a reactive approach, where equipment is allowed to fail before action is taken. Although reactive maintenance may be indicated for less critical equipment, such an approach is not well suited for the vital equipment that comprises a power system.

A time-based approach to preventive maintenance is a step up from a reactive approach, but it has drawbacks too. For example, the equipment has to be taken out of service so that diagnostic tests can be performed. Frequently, "tear-downs" and diagnostic tests indicate no problem. Therefore, time is spent and no improvements result. This is an inefficient use of manpower in an already manpower-intensive approach.

Another big drawback in preventive maintenance is the inducement of problems that otherwise would not have occurred. Failures that occur shortly after maintenance checks that result from equipment not being reassembled properly and the "infant mortality" that is associated with newly replaced equipment are examples of problems that can result from a preventative-maintenance program.

An approach that anticipates failure is a step up from a preventative-maintenance approach. This is more efficient because fixing only the equipment that is about to break minimizes or eliminates the downtime associated with the reactive approach that allows failures to occur before action is taken. Also, a proactive approach minimizes the manpower required to maintain systems because only the equipment that is likely to break is scheduled for maintenance. This optimizes effort by avoiding the unnecessary attention that is shown to healthy equipment in a preventive approach. As such, a predictive-maintenance program is desirable on a variety of fronts.

The Role of Power Quality Monitoring in Maintenance

The role of power quality monitoring is becoming more and more an integral part of the maintenance equation for utilities. For example, monitoring is used in both a reactive and a preventive capacity today. Consider the following as an illustration.

An informal survey of utilities indicates that they use power quality monitor data in a variety of ways:

- **Not used:** "We have too much data to look at with the people that we have."
- **Used in response to customer complaints/problems:** This is a reactionary use of monitoring, which is common. Data from monitors that are close to the customers who are complaining or close to where a problem was known to have occurred is examined to determine problem causes. Power quality databases are queried, and the results are sent to customer service engineers or account representatives. For example, a customer notices that a motor trips because of a power disturbance. The customer contacts the utility, where the voltage-unbalance trend of the circuit is examined to help characterize the unbalance condition to determine its cause.

- **Problem detection:** Used to give utilities a “heads-up” that a problem has happened on the system. For example, a power quality engineer is paged when a monitor detects a voltage sag that occurs to a certain depth for a certain number of cycles.
- **Periodic reports generated:** Reports are generated and examined manually to help identify causes of problems that are occurring. This is a diagnostic use. Also, a more rare use of the reports is their manual examination by a power quality engineer to detect anomalous behavior that is indicative of problems that exist but are unknown to the utility. For example, a Var imbalance could be part of a trend report that is noticed by a power quality engineer and is indicative of a blown fuse in a capacitor bank.

Typically, power quality data is not used in a proactive manner today. Situations where they are used proactively typically do not involve automation—that is, they are manual. For example, the periodic generation of power quality reports and their manual review for signs of pending failure are a proactive use of the data that is manual in nature. As such, there are inherent limitations regarding the volume of information that can be scrutinized using this approach. This is a problem because of the large volume of power quality data that is currently accumulating and because of the fact that more monitors are being installed every day. A consequence of this “data overload” is the under-utilization of existing power quality data.

The predominant use of power quality monitoring at utilities is reactionary in nature and makes use of only a small percentage of the available data. It is desirable to move toward an automated, predictive mode of operation that minimizes required labor and provides a thorough “mining” of all available data. Getting ahead of the curve in this manner will allow utilities to respond more effectively to their post-deregulation charge of doing more with less. Running the vast amounts of data through an automated, intelligent sieve reduces the data to useful information that can be used in a proactive manner to anticipate failures and to make system improvements while minimizing manpower.

GLOSSARY OF COMMON POWER QUALITY TERMS

Active Filter
A power electronics-based device configured with controls to provide cancellation of harmonic current components created by nonlinear loads.

Area of Vulnerability
Defined with respect to the voltage-sag sensitivity of a particular end user or equipment, this is the area of the power system where a fault can cause the malfunction of end-user equipment.

Average Maximum Demand Load Current (IL)
Maximum load current expected for an end user at the point of common coupling. IEEE Standard 519-1992 recommends that this current be calculated as the average of the maximum demand currents for a twelve-month period.

Capacitor-Switching Voltage Magnification
The phenomena where the transient voltage during energizing of a capacitor bank is magnified at a lower-voltage capacitor bank due to system resonance conditions.

Common-Mode Voltage
The noise voltage that appears equally and in phase from each current-carrying conductor to earth.

Commercial Power
Electrical power furnished by the electric power utility company.

Constant-Voltage Transformer (CVT)
A ferroresonant transformer used for voltage regulation in single-phase applications.

Coupling
Circuit elements or a network that may be considered common to the input mesh and the output mesh and through which energy may be transferred from one to the other.

Current Transformer (CT)
An instrument transformer intended to have its primary winding connected in series with the conductor carrying the current to be measured or controlled.

Dip
Another term for sag, commonly used in Europe.

Distortion Factor (DF)
The ratio of the root-mean-square value of the harmonic content to the root-mean-square value of the fundamental quantity, expressed as a percent of the fundamental. Also known as *total harmonic distortion* (THD).

Dropout
A loss of equipment operation (discrete data signals) due to noise, sag, or interruption.

Dropout Voltage
The voltage at which a device will release to its de-energized position (for this document, the voltage at which a device fails to operate).

Eddy Current Loss Factor (PEC-R)
The portion of a transformer's total losses that can be attributed to eddy currents, expressed in per unit or percent of the total transformer losses at full-load conditions.

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
Any electromagnetic phenomena that may degrade the performance of a device, equipment or system or adversely affect living or inert matter.

Electromagnetic Environment
The totality of electromagnetic phenomena existing at a given location.

Electromagnetic Susceptibility
The inability of a device, equipment, or system to perform without degradation in the presence of an electromagnetic disturbance. Note that *susceptibility* is a lack of immunity.

Equipment Earthing Conductor
The conductor used to connect the non-current-carrying parts of conduits, raceways, and equipment enclosures to the grounded conductor (neutral) and the earthing electrode at the service equipment (main panel) or secondary of a separately derived system (such as an isolation transformer). See NFPA 70-1990, Section 100 [B12].

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

Frequency Deviation
An increase or decrease in the power frequency. The duration of a frequency deviation can be from several cycles to several hours.

Fundamental (Component)
The component of an order 1 (50 Hz or 60 Hz) of the Fourier series of a periodic quantity.

Earth
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. Note: It is used for establishing and maintaining the potential of the earth (or of the conducting body) or approximately that potential, on conductors connected to it, and for conducting earth currents to and from earth (or the conducting body).

Earth Loop
In a radial earthing system, an undesired conducting path between two conductive bodies that are already connected to a common (single-point) earth.

Harmonic (Component)
A component of order greater than one of the Fourier series of a periodic quantity.

Harmonic Content
The quantity obtained by subtracting the fundamental component from an alternating quantity.

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

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

Impulsive Transient
A sudden non-power 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 variation as a modifier, refers to a time range from 0.5 cycles to 30 cycles of the power frequency.

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 (for example, 50 Hz or 60 Hz).

Interruption, Momentary
A type of short-duration variation. The complete loss of voltage (<0.1 per unit) on one or more phase conductors for a time period between 0.5 cycles and 3 seconds.

Interruption, Sustained
A type of long-duration variation. The complete loss of voltage (<0.1 per unit) on one of more phase conductors for a time greater than 1 minute.

Interruption, Temporary
A type of short-duration variation. The complete loss of voltage (<0.1 per unit) on one or more phase conductors for a time period between 3 seconds and 1 minute.

Isolation
Separation of one section of a system from undesired influences of other sections.

K-Factor (K)
A characteristic of a current waveform that weights harmonic components according to the square of the harmonic number.

Long-Duration Variation
See *Variation, Long Duration.*

Magnetic Synthesizer
A transformer-based voltage regulator for three-phase loads.

Momentary
When used to quantify the duration of a short-duration variation as a modifier, refers to a time range at the power frequency from 30 cycles to 3 seconds.

Noise
Unwanted electrical signals in the circuits of the control systems in which they occur.

Nominal Voltage (Vn)
A nominal value assigned to a circuit or system for the purpose of conveniently designating its voltage class (as 208/120, 480/277, 600, and so on).

Nonlinear Load
Steady-state electrical load that draws current discontinuously or whose impedance varies throughout the cycle of the input AC voltage waveform.

Normal Mode Voltage
A voltage that appears between or among active circuit conductors.

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.

Oscillatory Transient
A sudden, non-power frequency change in the steady-state condition of voltage or current that includes both positive or negative polarity value.

Overvoltage
When used to describe a specific type of long-duration variation, refers to a measured voltage having a value greater than the nominal voltage for a period of time greater than 1 minute. Typical values are 1.1 to 1.2 per unit.

Phase Shift
The displacement in time of one waveform relative to another of the same frequency and harmonic content.

Point of Common Coupling (PCC)
The point of interface between two different parts of the power system where the propagation and characteristics of a power quality variation can be evaluated. With respect to evaluation of harmonic voltage and current limits at the supply to an end user, this is the point on the system where another end user can be supplied.

Potential Transformer (PT)
An instrument transformer intended to have its primary winding connected in shunt with a power-supply circuit, the voltage of which is to be measured or controlled. Also called a *voltage transformer*.

Power Disturbance
Any deviation from the nominal value (or from some selected thresholds) of the input AC power characteristics.

Power Quality
The concept of powering and earthing sensitive equipment in a manner that is suitable to the operation of that equipment.

Sag
A decrease in RMS voltage or current at the power frequency for durations of 0.5 cycles to 1 minute. Typical values are 0.1 to 0.9 per unit.

Service Voltage
Voltage at the end-user service entrance.

Shield
As normally applied to instrumentation cables, refers to a conductive sheath (usually metallic) applied over the insulation of a conductor or conductors for the purpose of providing means to reduce coupling between the conductors so shielded and other conductors that may be susceptible or that may be generating unwanted electrostatic or electromagnetic fields (noise).

Shielding
Shielding is the use of a conducting and/or ferromagnetic barrier between a potentially disturbing noise source and sensitive circuitry. Shields are used to protect cables (data and power) and electronic circuits. They may be in the form of metal barriers, enclosures, or wrappings around source circuits and receiving circuits.

Short-Duration Variation
See *Variation, Short Duration*.

Slew Rate
Rate of change of a quantity such as volts, frequency, or temperature.

Static Var Compensator (SVC)
Configuration of reactive power compensation equipment (reactors and capacitors) with power electronics switching to achieve continuous control of the reactive compensation provided to the power system.

Sustained

When used to quantify the duration of a voltage interruption, refers to the time frame associated with a long duration variation (that is, greater than 1 minute).

Swell

An increase in RMS voltage or current at the power frequency for durations from 0.5 cycles to 1 minute. Typical values are 1.1 to 1.8 per unit.

Temporary

When used to quantify the duration of a short-duration variation as a modifier, refers to a time range from 3 seconds to 1 minute.

Tolerance

The allowable variation from a nominal value.

Total Demand Distortion (TDD)

The total (RSS) harmonic current distortion in percent of the average maximum demand load current (15 or 30 minute demand).

Total Harmonic Distortion (THD)

The ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity, expressed as a percent of the fundamental. Also referred to as *distortion factor*.

Transient

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

Transmission Line Fault Performance

The expected or actual number of faults per year (defined for each type of fault separately) on a transmission line.

Undervoltage

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 one minute. Typical values are 0.8 to 0.9 per unit.

Utilization Voltage

Voltage at end-use equipment.

Variation, Long Duration

A variation of the RMS value of the voltage from nominal voltage for a time greater than 1 minute. Usually further described using a modifier indicating the magnitude of a voltage variation (for example, *undervoltage*, *overvoltage*, or *voltage interruption*).

Variation, Short Duration

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

Voltage Change

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

Voltage Dip

See *Sag*.

Voltage Distortion

Any deviation from the nominal sine wave form of the AC line voltage.

Voltage Fluctuation

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

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 Interruption

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

Voltage Regulation

The degree of control or stability of the RMS voltage at the load. Often specified in relation to other parameters, such as input-voltage changes, load changes, or temperature changes.

Waveform Distortion

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