UNIT I INTRODUCTION TO POWER QUALITY

Terms and definitions: Overloading - under voltage - over voltage. Concepts of transients - short duration variations such as interruption - long duration variation such as sustained interruption. Sags and swells - voltage sag - voltage swell - voltage imbalance - voltage fluctuation - power frequency variations. International standards of power quality. Computer Business Equipment Manufacturers Associations (CBEMA) curve.

General Definition: Power quality is any abnormal behavior on a power system arising in the form of voltage or current, which affects the normal operation of electrical or electronic equipment.

Standard Definition: Any power problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of customer equipment.

Reasons for power quality issues:

1. Newer-generation load equipment, with microprocessor-based controls and power electronic devices, is more sensitive to power quality variations than was equipment used in the past.
2. The increasing emphasis on overall power system efficiency has resulted in continued growth in the application of devices such as high-efficiency, adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic levels on power systems and has many people concerned about the future impact on system capabilities.
3. End users have an increased awareness of power quality issues. Utility customers are becoming better informed about such issues as interruptions, sags, and switching transients and are challenging the utilities to improve the quality of power delivered.
4. Many things are now interconnected in a network. Integrated processes mean that the failure of any component has much more important consequences.

Examples for power quality issues:

AC power systems are designed to operate at a sinusoidal voltage of a given frequency [typically 50 or 60 hertz (Hz)] and magnitude. Any significant deviation in the waveform magnitude, frequency, or purity is a potential power quality problem.

For example,

1. The current resulting from a short circuit causes the voltage to sag or disappear completely, as the case may be.

2. Currents from lightning strokes passing through the power system cause high-impulse voltages that frequently flash over insulation and lead to other phenomena, such as short circuits.

3. Distorted currents from harmonic-producing loads also distort the voltage as they pass through the system impedance. Thus a distorted voltage is presented to other end users.

Therefore, while it is the voltage with which we are ultimately concerned, we must also address phenomena in the current to understand the basis of many power quality problems.

Importance of power quality:

The ultimate reason that we are interested in power quality is economic value. There are economic impacts on utilities, their customers, and suppliers of load equipment.

The quality of power can have a direct economic impact on many industrial consumers. There has recently been a great emphasis on revitalizing industry with more automation and more modern equipment. This usually means electronically controlled, energy-efficient equipment that is often much more sensitive to deviations in the supply voltage than were its electromechanical predecessors.

Impacts of power quality:

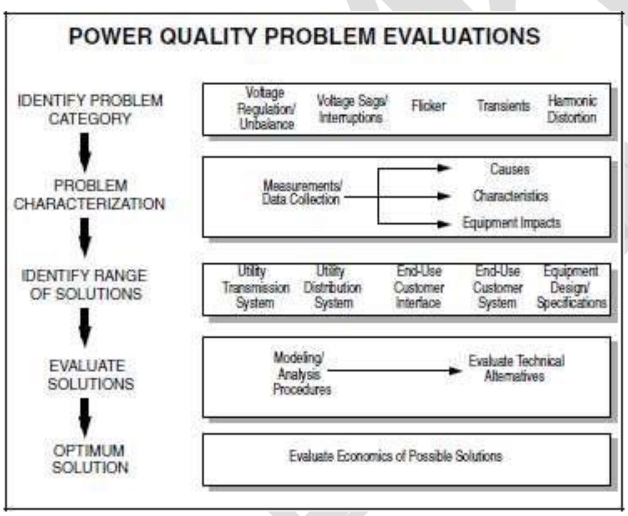
1. Throughout the world, many governments have revised their laws regulating electric utilities with the intent of achieving more cost-competitive sources of electric energy. Deregulation of utilities has complicated the power quality problem. In many geographic areas there is no longer tightly coordinated control of the power from generation through end-use load. While regulatory agencies can change the laws regarding the flow of money, the physical laws of power flow cannot be altered. In order to avoid deterioration of the quality of power supplied to customers, regulators are going to have to expand their thinking beyond traditional reliability indices and address the need for power quality reporting and incentives for the transmission and distribution companies.

2. There has been a substantial increase of interest in distributed generation (DG), that is, generation of power dispersed throughout the power system. There are a number of important power quality issues that must be addressed as part of the overall interconnection evaluation for DG. Therefore, we have added a chapter on DG.

3. The globalization of industry has heightened awareness of deficiencies in power quality around the world. Companies building factories in new areas are suddenly faced with unanticipated problems with the electricity supply due to weaker systems or a different climate. There have been several efforts to benchmark power quality in one part of the world against other areas.

4. Indices have been developed to help benchmark the various aspects of power quality. Regulatory agencies have become involved in performance-based rate-making (PBR), which addresses a particular aspect, reliability, which is associated with interruptions. Some customers have established contracts with utilities for meeting a certain quality of power delivery.

The Power Quality Evaluation Procedure



The general procedure must also consider whether the evaluation involves an existing power quality problem or one that could result from a new design or from proposed changes to the system. Measurements will play an important role for almost any power quality concern. This is the primary method of characterizing the problem or the existing system that is being evaluated. When performing the measurements, it is important to record impacts of the power quality variations at the same time so that problems can be correlated with possible causes.

Categories and Characteristics of Power System Electromagnetic Phenomena

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5-ns rise	<50 ns	
1.1.2 Microsecond	1-μs rise	50 ns–1 ms	
1.1.3 Millisecond	0.1-ms rise	>1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	<5 kHz	0.3–50 ms	0–4 pu
1.2.2 Medium frequency	5–500 kHz	20 μs	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 μs	0–4 pu
2.0 Short-duration variations			
2.1 Instantaneous			
2.1.1 Interruption		0.5–30 cycles	<0.1 pu
2.1.2 Sag (dip)		0.5–30 cycles	0.1–0.9 pu
2.1.3 Swell		0.5–30 cycles	1.1–1.8 pu
2.2 Momentary			
2.2.1 Interruption		30 cycles–3 s	<0.1 pu
2.2.2 Sag (dip)		30 cycles–3 s	0.1–0.9 pu
2.2.3 Swell		30 cycles–3 s	1.1–1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s–1 min	<0.1 pu
2.3.2 Sag (dip)		3 s–1 min	0.1–0.9 pu
2.3.3 Swell		3 s–1 min	1.1–1.2 pu
3.0 Long-duration variations			
3.1 Interruption, sustained		>1 min	0.0 pu
3.2 Undervoltages		>1 min	0.8–0.9 pu
3.3 Overvoltages		>1 min	1.1–1.2 pu
4.0 Voltage unbalance		Steady state	0.5–2%
5.0 Waveform distortion			
5.1 DC offset		Steady state	0–0.1%
5.2 Harmonics	0–100th harmonic	Steady state	0–20%
5.3 Interharmonics	0–6 kHz	Steady state	0–2%
5.4 Notching		Steady state	
5.5 Noise	Broadband	Steady state	0–1%
6.0 Voltage fluctuations	<25 Hz	Intermittent	0.1–7% 0.2–2 Pst
7.0 Power frequency variations		<10 s	

All the power quality issues are comprised into following categories

- Transients
- Long-Duration Voltage Variations
- Short-Duration Voltage Variations
- Voltage Imbalance
- Waveform Distortion
- Voltage Fluctuation
- Power Frequency Variations

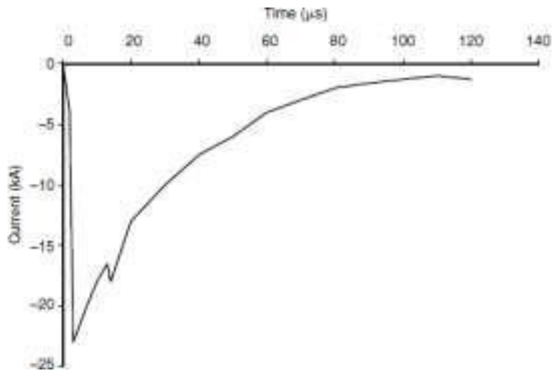
➢ <u>Transients</u>

The term transients has long been used in the analysis of power system variations to denote an event that is undesirable and momentary in nature. The notion of a damped oscillatory transient due to an RLC network is probably what most power engineers think of when they hear the word transient.

Types of transients:

- Impulsive transient
- Oscillatory transient

Impulsive transient

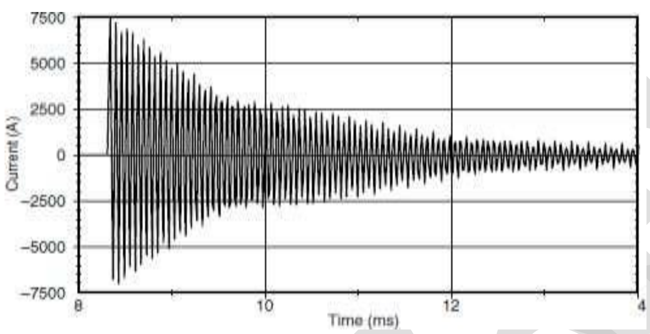


An impulsive transient is a sudden, non–power frequency change in the steady-state condition of voltage, current, or both that is unidirectional in polarity (primarily either positive or negative).

Impulsive transients are normally characterized by their rise and decay times, which can also be revealed by their spectral content. For example, a 1.2 X 50-µs 2000-volt (V) impulsive transient nominally rises from zero to its peak value of 2000 V in 1.2 µs and then decays to half its peak value in 50 µs. The most common cause of impulsive transients is lightning.

Figure illustrates a typical current impulsive transient caused by lightning.

Oscillatory transient



An oscillatory transient is a sudden, non–power frequency change in the steady-state condition of voltage, current, or both, that includes both positive and negative polarity values.

An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly. It is described by its spectral content (predominate frequency), duration, and magnitude. The spectral content subclasses are high, medium, and low frequency. The frequency ranges for these classifications are chosen to coincide with common types of power system oscillatory transient phenomena.

➢ <u>Long-Duration Voltage Variations</u>

Long-duration variations encompass root-mean-square (rms) deviations at power frequencies for longer than 1 min. ANSI C84.1 specifies the steady-state voltage tolerances expected on a power system. A volt age variation is considered to be long duration when the ANSI limits are exceeded for greater than 1 min.

Long-duration variations can be either overvoltages or undervoltages. Overvoltages and undervoltages generally are not the result of system faults, but are caused by load variations on the system and system switching operations. Such variations are typically displayed as plots of rms voltage versus time.

Overvoltage

An overvoltage is an increase in the rms ac voltage greater than 110 percent at the power frequency for a duration longer than 1 min.

<u>*Causes:*</u> switching off a large load or energizing a capacitor bank, Incorrect tap settings on transformers

Undervoltage

An undervoltage is a decrease in the rms ac voltage to less than 90 percent at the power frequency for a duration longer than 1 min. Undervoltages are the result of switching events that are the opposite of the events that cause overvoltages.

<u>*Causes:*</u> A load switching on or a capacitor bank switching off Overloaded circuits

The term ***brownout*** is often used to describe sustained periods of undervoltage initiated as a specific utility dispatch strategy to reduce power demand.

Sustained interruptions

When the supply voltage has been zero for a period of time in excess of 1 min, the long-duration voltage variation is considered a sustained interruption. Voltage interruptions longer than 1 min are often permanent and require human intervention to repair the system for restoration.

The term sustained interruption refers to specific power system phenomena and, in general, has no relation to the usage of the term outage.

➢ Short-Duration Voltage Variations

This category encompasses the IEC category of voltage dips and short interruptions. Each type of variation can be designated as instantaneous, momentary, or temporary, depending on its duration.

Short-duration voltage variations are caused by fault conditions, the energization of large loads which require high starting currents, or intermittent loose connections in power wiring. Depending on the fault location and the system conditions, the fault can cause either temporary voltage drops (sags), voltage rises (swells), or a complete loss of voltage (interruptions).

Interruption

An interruption occurs when the supply voltage or load current decreases to less than 0.1 pu for a period of time not exceeding 1 min.

Causes: Power system faults, equipment failures, and control malfunctions.

Interruption	Magnitude	Duration
Instantaneous	<0.1 pu	0.5 to 30 cycles
Momentary	<0.1 pu	30 cycles to 3 sec
Temporary	<0.1 pu	3 sec to 1 min

Sags (dips)

A sag is a decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 min.

Sag durations are subdivided here into three categories—instantaneous, momentary, and temporary

Causes: Energization of heavy loads or starting of large motors.

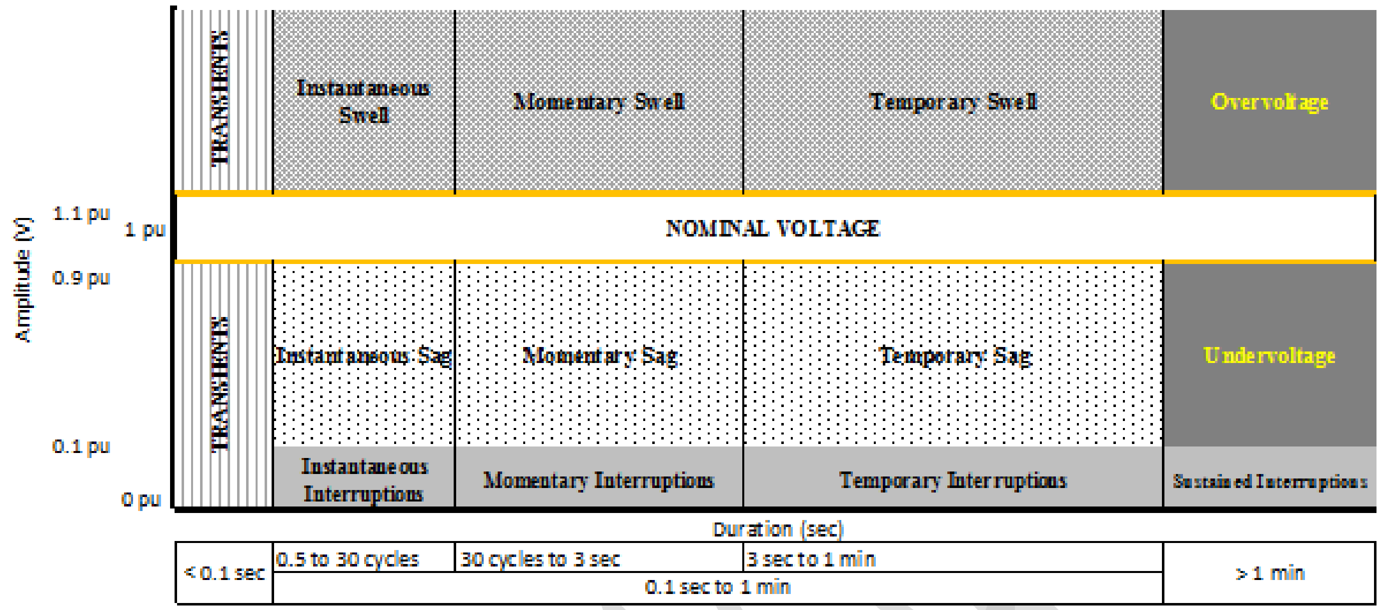
Voltage Sag	Magnitude	Duration
Instantaneous	0.1 to 0.9 pu	0.5 to 30 cycles
Momentary	0.1 to 0.9 pu	30 cycles to 3 sec
Temporary	0.1 to 0.9 pu	3 sec to 1 min

Swells

A swell is defined as an increase to between 1.1 and 1.8 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 min.

Causes: temporary voltage rise on the unfaulted phases during an SLG fault and switching off a large load or energizing a large capacitor bank.

Voltage Swell	Magnitude	Duration
Instantaneous	1.1 to 1.8 pu	0.5 to 30 cycles
Momentary	1.1 to 1.4 pu	30 cycles to 3 sec
Temporary	1.1 to 1.2 pu	3 sec to 1 min

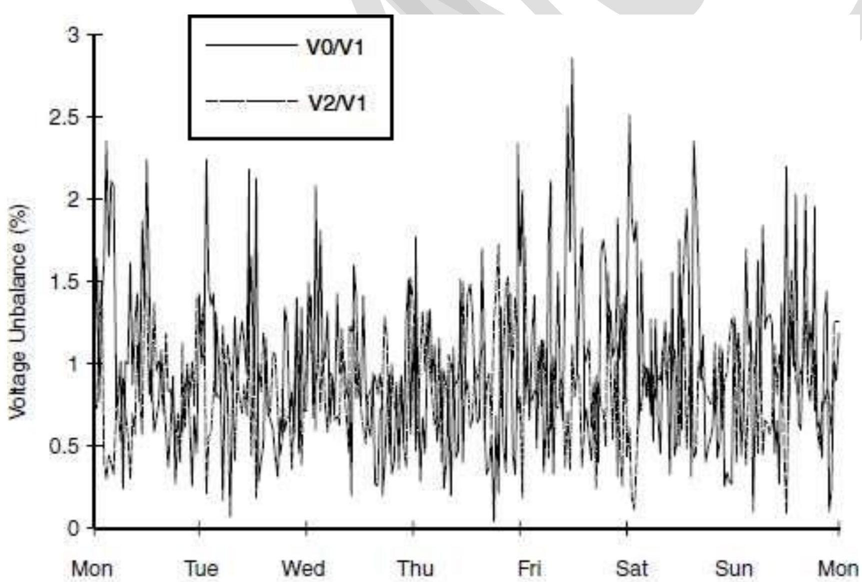


➢ Voltage Imbalance

Voltage imbalance (also called voltage unbalance) is sometimes defined as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents, expressed in percent.

Imbalance is more rigorously defined in the standards 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: The primary source of voltage unbalances of less than 2 percent is single-phase loads on a three-phase circuit. Voltage unbalance can also be the result of blown fuses in one phase of a three-phase capacitor bank. Severe voltage unbalance (greater than 5 percent) can result from single-phasing conditions.



Voltage unbalance trend for a residential feeder.

➢ Waveform Distortion

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

There are five primary types of waveform distortion:

- DC offset
- Harmonics
- Interharmonics
- Notching
- Noise

DC offset.

The presence of a dc voltage or current in an ac power system is termed dc offset. This can occur as the result of a geomagnetic disturbance or asymmetry of electronic power converters.

Examples: Incandescent light bulb life extenders may consist of diodes that reduce the rms voltage supplied to the light bulb by half-wave rectification. Direct current in ac networks can have a detrimental effect by biasing transformer cores so they saturate in normal operation. This causes additional heating and loss of transformer life.

Harmonics.

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate (termed the fundamental frequency; usually 50 or 60 Hz). Periodically distorted waveforms can be decomposed into a sum of the fundamental frequency and the harmonics.

The total harmonic distortion (THD), is a measure of the effective value of harmonic distortion. IEEE Standard 519-1992 defines another term, the total demand distortion (TDD).

Total harmonic distortion (THD) The ratio of the root mean square of the harmonic content to the rms value of the fundamental quantity, expressed as a percent of the fundamental

Total demand distortion (TDD) The ratio of the root mean square of the harmonic current to the rms value of the rated or maximum demand fundamental current, expressed as a percent.

Causes: Originates in the nonlinear characteristics of devices and loads on the power system.

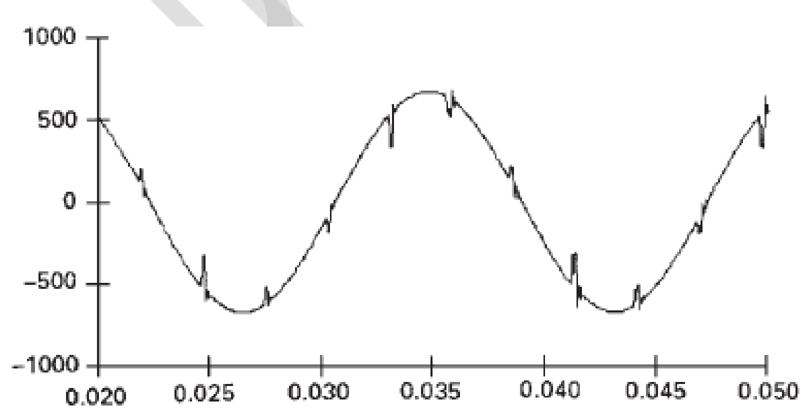
Example: Adjustable-speed drives (ASD) will exhibit high THD values for the input current when they are operating at very light loads.

Interharmonics.

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

Causes: Static frequency converters, cycloconverters, induction furnaces, and arcing devices. Power line carrier signals can also be considered as interharmonics.

Notching.



Notching is a periodic voltage disturbance caused by the normal operation of power electronic devices when current is commutated from one phase to another. Since notching occurs continuously, it can be characterized through the harmonic spectrum of the affected voltage. However, it is generally treated as a special case. The frequency components associated with notching can be quite high and may not be readily characterized with measurement equipment normally used for harmonic analysis.

Noise.

Noise is defined as unwanted electrical signals with broadband spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines.

Causes: Power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supplies.

The problem can be mitigated by using filters, isolation transformers, and line conditioners.

➢ Voltage Fluctuation

Voltage fluctuations are systematic variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed the voltage ranges specified by ANSI C84.1 of 0.9 to 1.1 pu. IEC 61000-2-1 defines various types of voltage fluctuations.

Loads that can exhibit continuous, rapid variations in the load current magnitude can cause voltage variations that are often referred to as *flicker*. The term *flicker* is derived from the impact of the voltage fluctuation on lamps such that they are perceived by the human eye to flicker. To be technically correct, voltage fluctuation is an electromagnetic phenomenon while flicker is an undesirable result of the voltage fluctuation in some loads. However, the two terms are often linked together in standards.

IEC 61000-4-15 defines the methodology and specifications of instrumentation for measuring flicker. The IEEE Voltage Flicker Working Group has recently agreed to adopt this standard as amended for 60- Hz power systems for use in North America. This standard devises a simple means of describing the potential for visible light flicker through voltage measurements. The measurement method simulates the lamp/eye/brain transfer function and produces a fundamental metric called short-term flicker sensation (Pst). This value is normalized to 1.0 to represent the level of voltage fluctuations sufficient to cause noticeable flicker to 50 percent of a sample observing group. Another measure called long-term flicker sensation (Plt) is often used for the purpose of verifying compliance with compatibility levels established by standards bodies and used in utility power contracts. This value is a longer-term average of Pst samples.

**IEC TR 61000-2-1:1990 >>>Electromagnetic compatibility (EMC) - Part 2:Environment-Section 1*

**IEC 61000-4-15:2010 >>>Electromagnetic compatibility (EMC) - Part 4-15: Testing and measurement techniques*

➢ Power Frequency Variations

Power frequency variations are defined as the deviation of the power system fundamental frequency from it specified nominal value (e.g., 50 or 60 Hz).

The power system frequency is directly related to the rotational speed of the generators supplying the system. There are slight variations in frequency as the dynamic balance between load and generation changes. The size of the frequency shift and its duration depend on the load characteristics and the response of the generation control system to load changes.

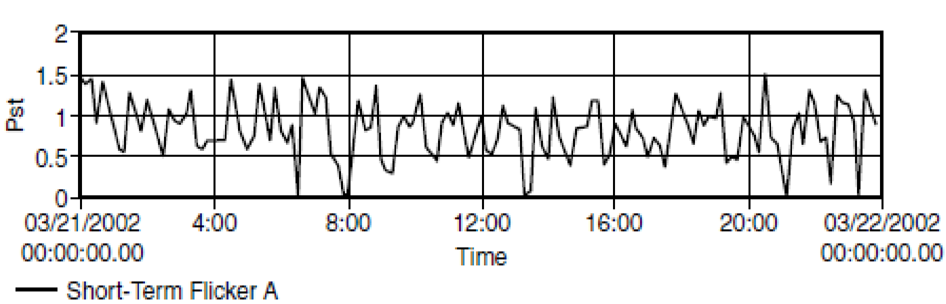


Figure illustrates frequency variations for a 24-h period on a typical 13-kV substation bus.

Frequency variations that go outside of accepted limits for normal steady-state operation of the power system can be caused by faults on the bulk power transmission system, a large block of load being disconnected, or a large source of generation going off-line. On modern interconnected power systems, significant frequency variations are rare. Frequency variations of consequence are much more likely to occur for loads that are supplied by a generator isolated from the utility system. In such cases, governor response to abrupt load changes may not be adequate to regulate within the narrow bandwidth required by frequency-sensitive equipment.

➢ International Standards of power quality:

IEEE Standards:

IEEE power quality standards: Institute Of Electrical and Electronics Engineer.
IEEE power quality standards: International Electro Technical Commission.
IEEE power quality standards: Semiconductor Equipment and Material International.
IEEE power quality standards: The International Union for Electricity Applications
IEEE Std 519-1992: IEEE Recommended practices and requirements for Harmonic control in Electric power systems.
IEEE Std 1159-1995: IEEE Recommended practices for monitoring electrical power
IEEE std 141-1993, IEEE Recommended practice for electric power distribution for industrial plants.
IEEE std 1159-1995, IEEE recommended practice for Monitoring electrical power quality.

IEC Standards:

The International Electrotechnical Commission (IEC), currently with headquarters in Geneva, Switzerland, has defined a category of electromagnetic compatibility (EMC) standards that deal with power quality issues. The term electromagnetic compatibility includes concerns for both radiated and conducted interference with end-use equipment. The IEC standards are broken down into six parts:

Part 1: General.

These standards deal with general considerations such as introduction, fundamental principles, rationale, definitions, and terminologies. They can also describe the application and interpretation of fundamental definitions and terms.

Their designation number is **IEC 61000-1-x.**

Part 2: Environment.

These standards define characteristics of the environment where equipment will be applied, the classification of such environment, and its compatibility levels.

Their designation number is **IEC 61000-2-x.**

Part 3: Limits.

These standards define the permissible levels of emissions that can be generated by equipment connected to the environment. They set numerical emission limits and also immunity limits.

Their designation number is **IEC 61000-3-x.**

Part 4: Testing and measurement techniques.

These standards provide detailed guidelines for measurement equipment and test procedures to ensure compliance with the other parts of the standards.

Their designation number is **IEC 61000-4-x.**

Part 5: Installation and mitigation guidelines.

These standards provide guidelines in application of equipment such as earthing and cabling of electrical and electronic systems for ensuring electromagnetic compatibility among electrical and electronic apparatus or systems. They also describe protection concepts for civil facilities against the high-altitude electromagnetic pulse (HEMP) due to high altitude nuclear explosions.

They are designated with **IEC 61000-5-x.**

Part 6: Miscellaneous.

These standards are generic standards defining immunity and emission levels required for equipment in general categories or for specific types of equipment.

Their designation number is **IEC 61000-6-x.**

IEC standards relating to harmonics generally fall in parts 2 and 3. Unlike the IEEE standards on harmonics where there is only a single publication covering all issues related to harmonics, IEC standards on harmonics are separated into several publications. There are standards dealing with environments and limits which are further broken down based on the voltage and current levels. These key standards are as follows:

IEC 61000-2-2 (1993): Electromagnetic Compatibility (EMC). Part 2: Environment. Section 2: Compatibility Levels for Low-Frequency Conducted Disturbances and Signaling in Public Low-Voltage Power Supply Systems.

IEC 61000-3-2 (2000): Electromagnetic Compatibility (EMC). Part 3: Limits. Section 2: Limits for Harmonic Current Emissions (Equipment Input Current Up to and Including 16 A per Phase).

IEC 61000-3-4 (1998): Electromagnetic Compatibility (EMC). Part 3: Limits. Section 4: Limitation of Emission of Harmonic Currents in Low-Voltage Power Supply Systems for Equipment with Rated Current Greater Than 16 A.

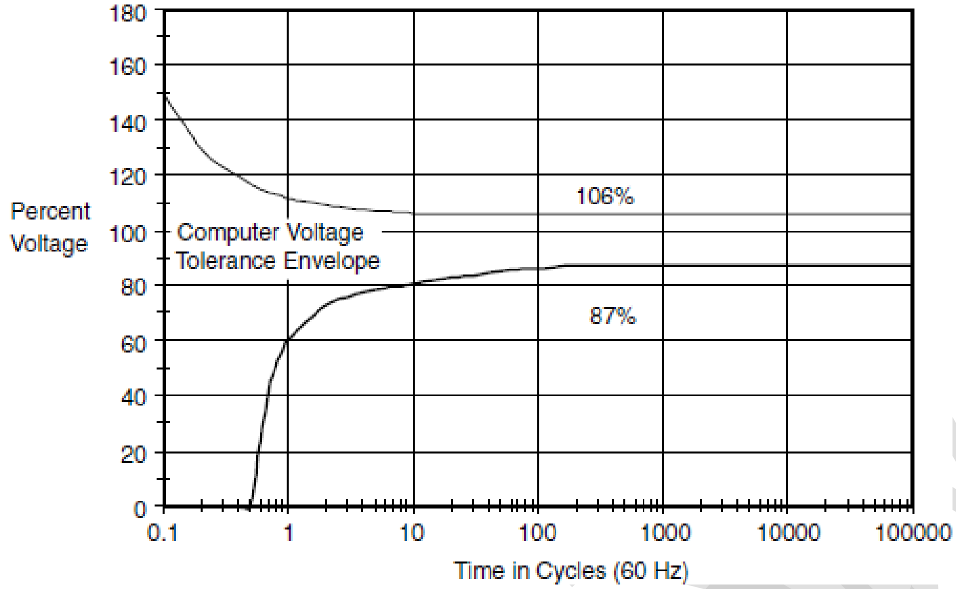
IEC 61000-3-6 (1996): Electromagnetic Compatibility (EMC). Part 3: Limits. Section 6: Assessment of Emission Limits for Distorting Loads in MV and HV Power Systems. Basic EMC publication.

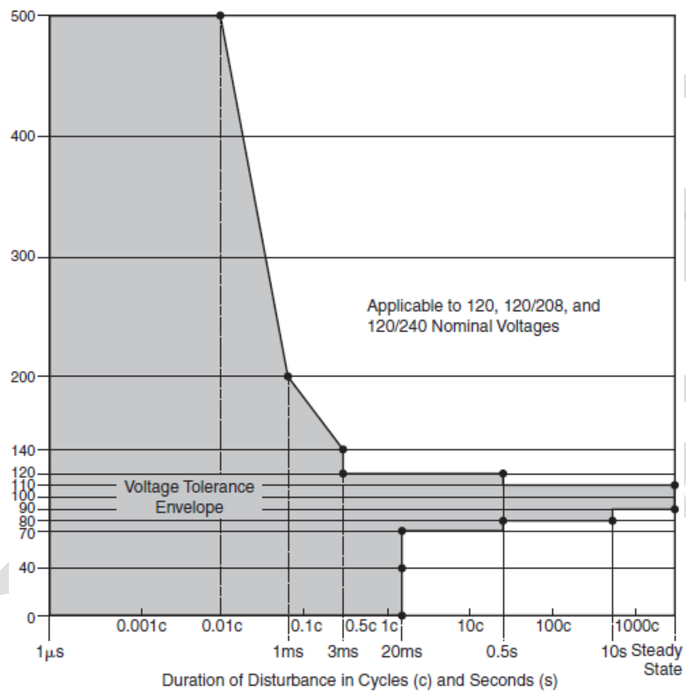
CBEMA and ITI Curves

A set of curves published by the Information Technology Industry Council (ITI) representing the withstand capabilities of computers connected to 120-V power systems in terms of the magnitude and duration of the voltage disturbance. The ITI curve replaces the curves originally developed by the ITI's predecessor organization, the Computer Business Equipment Manufacturers Association (CBEMA).

One of the most frequently employed displays of data to represent the power quality is the so-called CBEMA curve. A portion of the curve adapted from IEEE Standard 4469 that we typically use in our analysis of power quality monitoring results is shown in Fig. This curve was originally developed by CBEMA to describe the tolerance of mainframe computer equipment to the magnitude and duration of voltage variations on the power system. While many modern computers have greater tolerance than this, the curve has become a standard design target for sensitive equipment to be applied on the power system and a common format for reporting power quality variation data.

The axes represent magnitude and duration of the event. Points below the envelope are presumed to cause the load to drop out due to lack of energy. Points above the envelope are presumed to cause other malfunctions such as insulation failure, overvoltage trip, and over-excitation. The upper curve is actually defined down to 0.001 cycle where it has a value of about 375 percent voltage. We typically employ the curve only from 0.1 cycle and higher due to limitations in power quality monitoring instruments and differences in opinion over defining the magnitude values in the subcycle time frame.





ITI curve for susceptibility of 120-V computer equipment.

The CBEMA organization has been replaced by ITI and a modified curve has been developed that specifically applies to common 120-V computer equipment. The concept is similar to the CBEMA curve. Although developed for 120-V computer equipment, the curve has been applied to general power quality evaluation like its predecessor curve. Both curves are used as a reference in this book to define the withstand capability of various loads and devices for protection from power quality variations. For display of large quantities of power quality monitoring data, we frequently add a third axis to the plot to denote the number of events within a certain predefined cell of magnitude and duration. If restricted to just the two-dimensional views shown in Fig below, the plot tends to turn into a solid mass of points over time, which is not useful.