

# POWER QUALITY STANDARDS

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## *Introduction*

Power quality has always been important. However, for many years the equation defining power quality was very simple:

POWER QUALITY = RELIABILITY

Customer loads were linear in nature. When a sinusoidal voltage was supplied to them, they drew a sinusoidal current. They typically fell into the categories of lighting, heating, and motors. In general, they were not very sensitive to momentary variations in the supply voltage, such as transients and voltage sags. The loads were not connected together in networks so grounding issues other than safety were not very critical.

Two major changes in the characteristics of customer loads and systems have completely changed the nature of the power quality equation:

1. **The first is the sensitivity of the loads themselves.** The devices and equipment being applied in industrial and commercial facilities are more sensitive to power quality variations than equipment applied in the past. New equipment includes microprocessor-based controls and power electronics devices that are sensitive to many types of disturbances besides actual interruptions. Controls can be affected by momentary voltage sags or relatively minor transient voltages, resulting in nuisance tripping or misoperation of an important process.
2. **The second is the fact that these sensitive loads are interconnected in extensive networks and automated processes.** This makes the whole system as sensitive as the most sensitive device and increases the problem by requiring a good zero potential ground reference for the entire system.

These changes in the load characteristics have created a growing market for power conditioning equipment that can protect the loads from the wide variety of power quality variations that can cause problems. In order to apply power conditioning equipment effectively, customers must become experts in the types of power quality variations, their causes, their possible impacts, and the solutions available to mitigate them. Since some of the causes are on the utility system, the utility must also understand the full range of these problems.

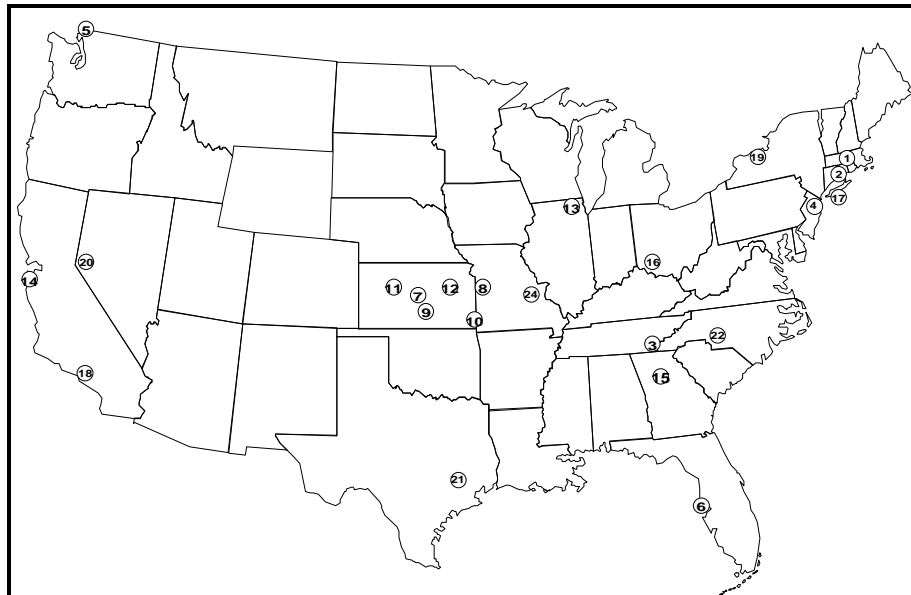
The power quality problems don't always come from the utility system either. Most of the transient voltages in a facility are caused by switching operations within the facility. Wiring and grounding problems increase susceptibility to problems. Power electronics equipment, such as adjustable speed drives, result in a continuous string of transients (notching) as well as steady state harmonic distortion that can cause heating in other loads within the facility.

### ***What are We Doing to Understand the Problems?***

Understanding the problems associated with power quality variations is the first step towards developing standards and the optimum approach to solutions. Understanding means being able to relate the causes of power quality variations to impacts on equipment and processes within customer facilities. This requires an understanding of the utility power system, the customer electrical system, and the equipment characteristics.

There are a number of significant research efforts under way to help improve the understanding of power quality problems. There are three important categories for these investigations:

1. **Monitoring.** Utilities and customers are both doing more and more monitoring of power quality. This monitoring is being performed on the power system and within customer facilities. The Electric Power Research Institute (EPRI) is sponsoring a multi-year project to monitor power quality on distribution systems around the country with 24 host utilities (Figure 1). Some of these utilities are extending the monitoring to include customer facilities so that they can relate events and variations on the distribution system with problems in the customer plant.



*Figure 1. Participants in the EPRI-Sponsored Distribution Power Quality Monitoring Project*

2. **Case Studies.** Case studies are a way of characterizing power quality concerns for individual customers and systems. There are numerous case studies being performed by utilities, their customers, and EPRI. When the results of all these case studies are shared and combined, the results illustrate important general characteristics of power quality concerns for different kinds of customers and equipment. The solutions implemented in particular case studies can be patterns for more general solutions to power quality problems.
  
3. **Analytical Tools.** The results of monitoring efforts and case studies are being used to improve analytical models for simulating system disturbances. There are Users Groups for harmonic analysis and transient analysis that can provide guidance in evaluating problems and the range of possible solutions. The advantage of the simulation approach is that it allows evaluations of systems and conditions that may not yet actually exist (e.g. future expansion plans).

### *The Role of Standards*

Power quality problems ultimately impact the end user. However, there are many other parties involved in creating, propagating, and solving power quality problems (Figure 2). Power quality standards must provide guidelines, recommendations, and limits to help assure *compatibility* between end use equipment and the system where it is applied. The standards affect all of the parties shown in Figure 2.

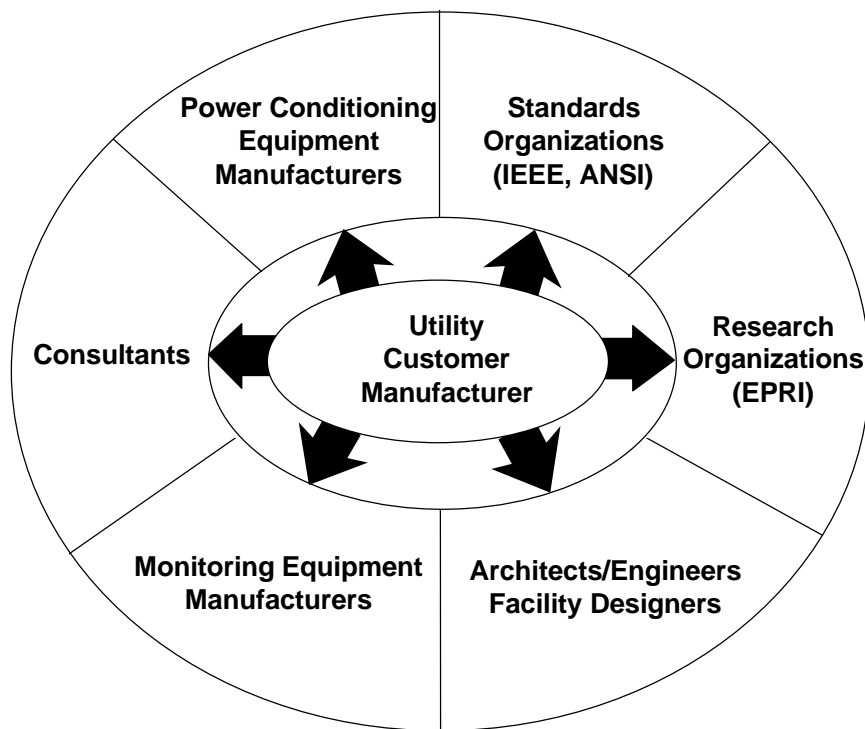


Figure 2. *Players That Influence End-Use Power Quality*

There is active interest in this country as well as the rest of the world to establish power quality standards to deal with these problems. The international standards development organization is the *IEC*. The IEC has defined a category of standards called *Electromagnetic Compatibility (EMC) Standards* that deal with power quality issues. They fall into the following six categories:

1. **General.** These provide definitions, terminology, etc. (IEC 1000-1-x)
2. **Environment.** Characteristics of the environment where equipment will be applied (1000-2-x).
3. **Limits.** *Emission* limits define the allowable levels of disturbances that can be caused by equipment connected to the power system. These standards were formerly the IEC 555 series but now are numbered 1000-3-x. For instance, IEC 555-2 has now become IEC 1000-3-2.
4. **Testing and Measurement Techniques.** These provide detailed guidelines for measurement equipment and test procedures to assure compliance with the other parts of the standards (1000-4-x).
5. **Installation and Mitigation Guidelines.** These are designed to provide guidance in application of equipment, such as filters, power conditioning equipment, surge suppressors, etc., to solve power quality problems (1000-5-x).
6. **Generic and Product Standards.** These will define *immunity* levels required for equipment in general categories or for specific types of equipment (1000-6-x).

This is a very impressive breakdown and organization for power quality standards development. Unfortunately, very few of these standards have actually been written and those that have been drafted are controversial. For instance, it took almost ten years to get IEC 1000-2-2 (IEC 555-2) approved and there are still questions about when it will be implemented.

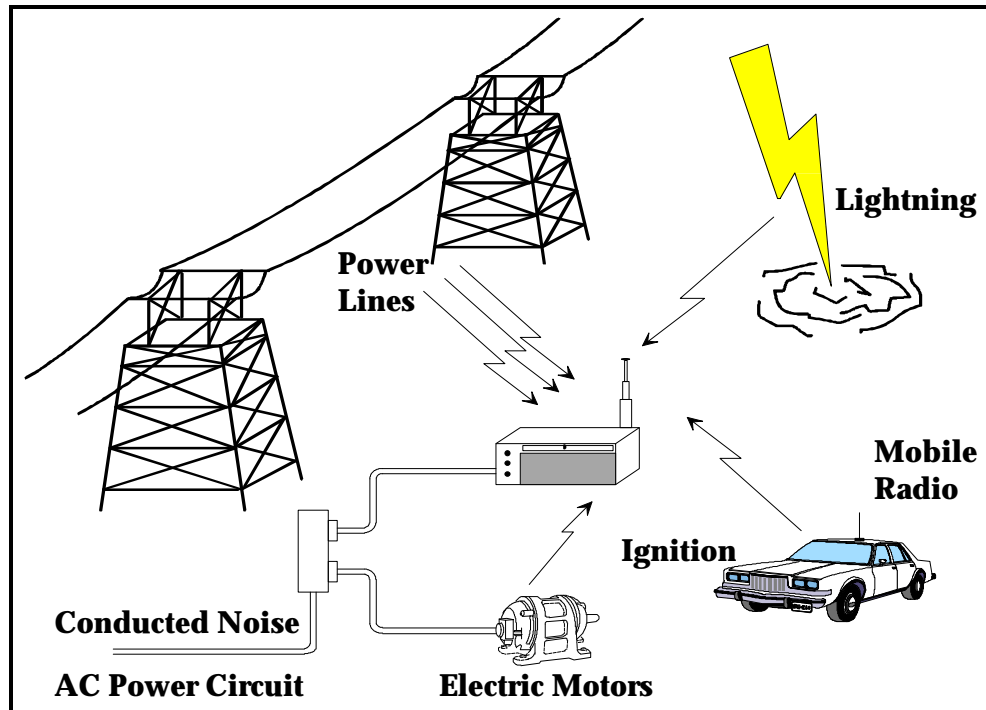


Figure 3. Some factors affecting Electromagnetic Compatibility

These IEC standards are generally adopted by the European Community (CENELEC) and become requirements for equipment sold in Europe. Their application in the rest of the world varies and very few of them are adopted outright in the United States.

### ***Power Quality Standards in the US***

In the United States, standards are developed by the *IEEE*, *ANSI*, and equipment manufacturer organizations, such as *NEMA*. We also have safety-related standards, like the National Electrical Code. We have very few standards that define requirements for specific equipment. Our standards tend to be more application oriented, like IEEE 519-1992, which provides recommendations to limit harmonic distortion levels on the overall power system.

IEEE has formed a Standards Coordinating Committee (SCC-22) that has the job of coordinating standards activities regarding power quality from all the different organizations doing development. Table 1 provides a listing of existing standards and standards under development related to power quality.

Table 1. Listing of Important Power Quality Standards

Organization	Std.	Title/Scope
ANSI/IEEE	141	Industrial Electric Power Systems
	142	Industrial & Commercial Power System Grounding
	241	Commercial Electric Power Systems
	242	Industrial & Commercial Power System Protection
	399	Industrial & Commercial Power System Analysis
	446	Industrial & Commercial Power System Emergency Power
	493	Industrial & Commercial Power System Reliability
	518	Control of Noise in Electronic Controls
	519	Harmonics in Power Systems
	602	Industrial & Commercial Power Systems in Health Facilities
	739	Energy Conservation in Industrial Power Systems
	929	Interconnection Practices for Photovoltaic Systems
	1001	Interfacing Dispersed Storage and Generation
	1035	Test Procedures for Interconnecting Static Power Converters
	1050	Grounding of Power Station Instrumentation & Control
ANSI	C62	Guides & Standards on Surge Protection
	C84.1	Voltage Ratings for Power Systems & Equipment
	C37	Guides and Standards for Relaying & Overcurrent Protection
	C57.110	Transformer Derating for Supplying Nonlinear Loads
IEEE	P487	Wire Line Communication Protection in Power Stations
	1100	Powering and Grounding Sensitive Equipment
	P1159	Monitoring and Definition of Electric Power Quality
	P1250	Guide on Equipment Sensitive to Momentary Voltage Disturbances
	P1346	Guide on Compatibility for ASDs and Process Controllers
NEMA	UPS	Uninterruptible Power Supply Specification
NFPA	70	National Electric Code
	75	Protection of Electronic Computer Data Processing Equipment
	78	Lightning Protection Code for Buildings
NIST	94	Electric Power for ADP Installations
	SP678	Overview of Power Quality and Sensitive Electrical Equipment
UL	1449	Standards for Safety of Transient Voltage Surge Suppressors

There has been a general fear on the part of the utility industry to create any standards that define the level of power quality required of the supply system. This fear is slowly being broken down as utilities realize the need to define the base level of power quality in order to be able to offer any kind of differentiated service for those customers that *require a higher performance level.*

It is worthwhile to look at the current state of standards development related to each important type of power quality problem.

## Standards for Steady State Voltage Regulation and Unbalance

There is no such thing as steady state on the power system. Loads are continually changing and the power system is continually adjusting to these changes. All of these changes and adjustments result in voltage variations that are referred to as **long duration voltage variations**. These can be **undervoltages** or **overvoltages**, depending on the specific circuit conditions. Characteristics of the steady state voltage are best expressed with long duration profiles and statistics. Important characteristics include the voltage magnitude and **unbalance**. According to the latest draft of IEEE P1159, *IEEE Recommended Practice for Monitoring Power Quality*, long duration variations are considered to be present when the limits are exceeded for greater than 1 minute. Harmonic distortion is also a characteristic of the steady state voltage but this characteristic is treated separately because it does not involve variations in the fundamental frequency component of the voltage.

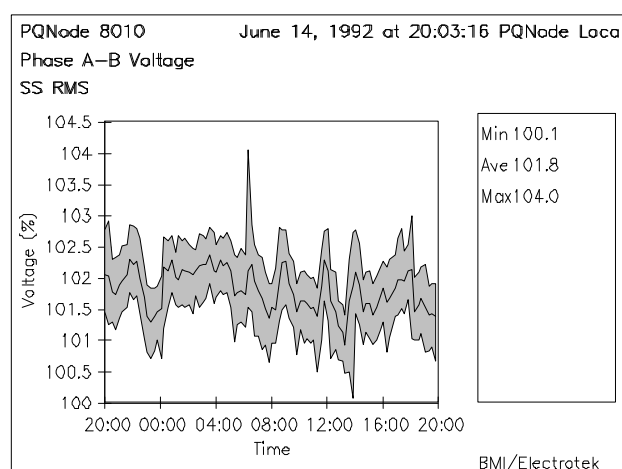


Figure 4. Example 24 hour voltage profile illustrating long duration voltage variations.

Most end use equipment is not very sensitive to these voltage variations, as long as they are within reasonable limits. ANSI C84.1-1989 specifies the steady state voltage tolerances expected on a power system. It recommends that equipment be designed to operate with acceptable performance under extreme steady state conditions of +6% and -13% of nominal 120/240 volt system voltage. Protective devices may operate to remove the equipment from service outside of this range. Figure 5 illustrates the major requirements of the standard. Two ranges of permissible voltages are provided. Range A is for normal conditions. Range B is for short duration or unusual system conditions. The service voltage is the voltage at the end user service entrance. The utilization voltage is the voltage at the actual end use equipment, allowing for voltage drop across facility wiring.

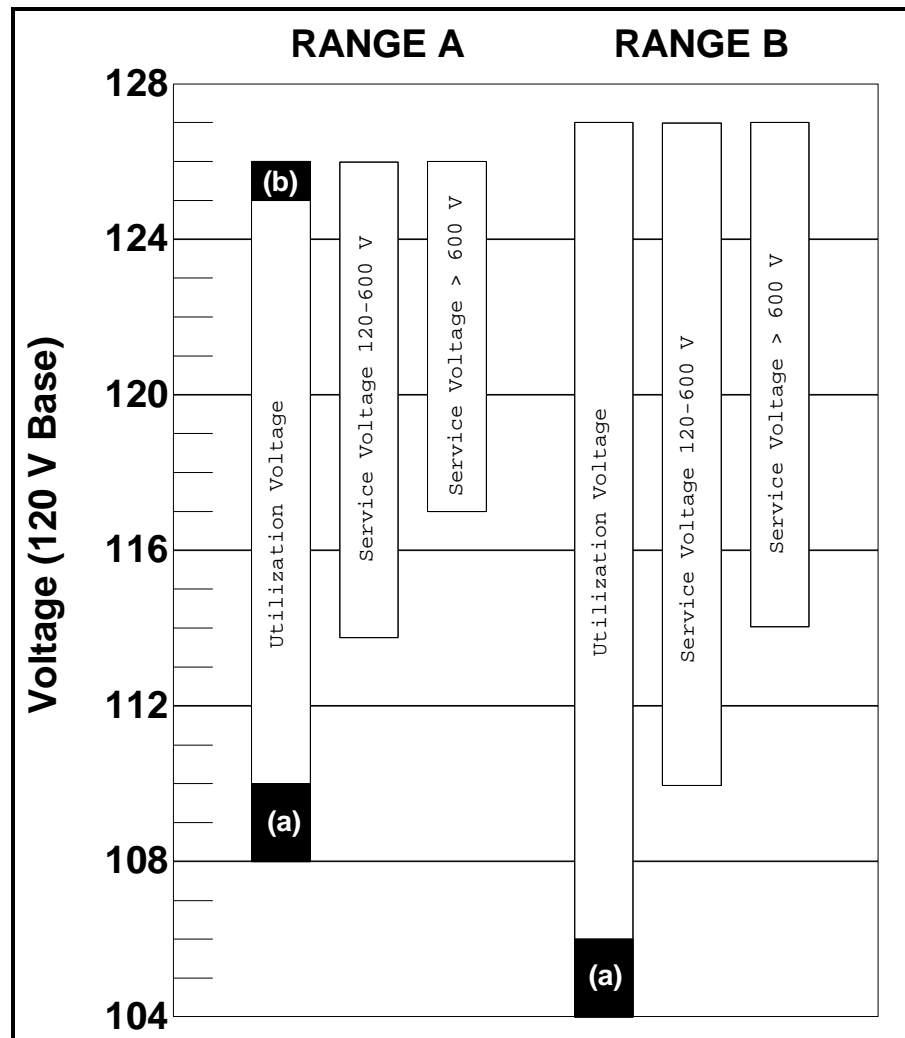


Figure 5. ANSI C84.1-1989 steady state voltage limits

(Notes: (a) these shaded portions do not apply to circuits supplying lighting loads,  
(b) this shaded portion of the range does not apply to 120-600 volt systems..

The most recent version of this standard (1989) includes recommended limits for voltage unbalance on the power system. Unbalance is a *steady state quantity 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.* Unbalance can also be quantified using symmetrical components. The ratio of the negative sequence component to the positive sequence component is used to specify the percent unbalance.

The primary source of voltage unbalance less than two percent is unbalanced single phase loads on a three-phase circuit. Voltage unbalance can also be the result of capacitor bank anomalies, such as a blown fuse on one phase of a three-phase bank. Severe voltage unbalance (greater than 5%) can result from single-phasing conditions.

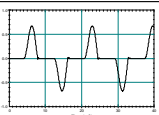
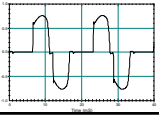
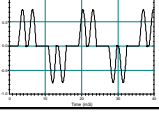
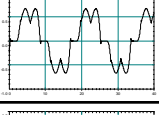
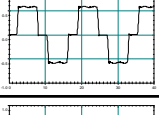
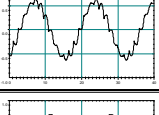
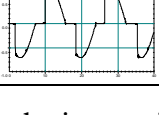
Voltage unbalance is most important for three phase motor loads. ANSI C84.1-1989 recommends that the maximum voltage unbalance measured at the meter under no load conditions should be 3%. Unbalance greater than this can result in significant motor heating and failure if there are not unbalance protection circuits to protect the motor.



### Standards for Harmonics

Harmonic distortion of the voltage and current results from the operation of nonlinear loads and devices on the power system. The nonlinear loads that cause harmonics can often be represented as current sources of harmonics. The system voltage appears stiff to individual loads and the loads draw distorted current waveforms. Table 2 illustrates some example current waveforms for different types of nonlinear loads. The weighting factors indicated in the table are being proposed in the *Guide for Applying Harmonic Limits on the Power System (Draft 2)* for preliminary evaluation of harmonic producing loads in a facility.

Table 2. Example current waveforms for various nonlinear loads.

Type of Load	Typical Waveform	Current Distortion	Weighting Factor ( $W_i$ )
Single Phase Power Supply		80% (high 3rd)	2.5
Semiconverter		high 2nd,3rd, 4th at partial loads	2.5
6 Pulse Converter, capacitive smoothing, no series inductance		80%	2.0
6 Pulse Converter, capacitive smoothing with series inductance > 3%, or dc drive		40%	1.0
6 Pulse Converter with large inductor for current smoothing		28%	0.8
12 Pulse Converter		15%	0.5
ac Voltage Regulator		varies with firing angle	0.7

Harmonic voltage distortion results from the interaction of these harmonic currents with the system impedance. The harmonic standard, *IEEE 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, has proposed two way responsibility for controlling harmonic levels on the power system. End users must limit the harmonic currents injected onto the power system. The power supplier will control the harmonic voltage distortion by making sure system resonant conditions do not cause excessive magnification of the harmonic levels.

Harmonic distortion levels can be characterized by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. It is also common to use a single quantity, the *Total Harmonic Distortion*, as a measure of the magnitude of harmonic distortion. For currents, the distortion values must be referred to a constant base (e.g. the rated load current or demand current) rather than the fundamental component. This provides a constant reference while the fundamental can vary over a wide range.

Harmonic evaluations are often going to involve a combination of measurements and analysis (possibly simulations). It is important to understand that harmonics are a continuous phenomena, rather than a disturbance (like a transient). Because harmonics are continuous, they are best characterized by measurements over time so that the time variations (Figure 6) and the statistical characteristics (Figure 7) can be determined. These characteristics describing the harmonic variations over time should be determined along with snapshots of the actual waveforms and harmonic spectrums at particular operating points.

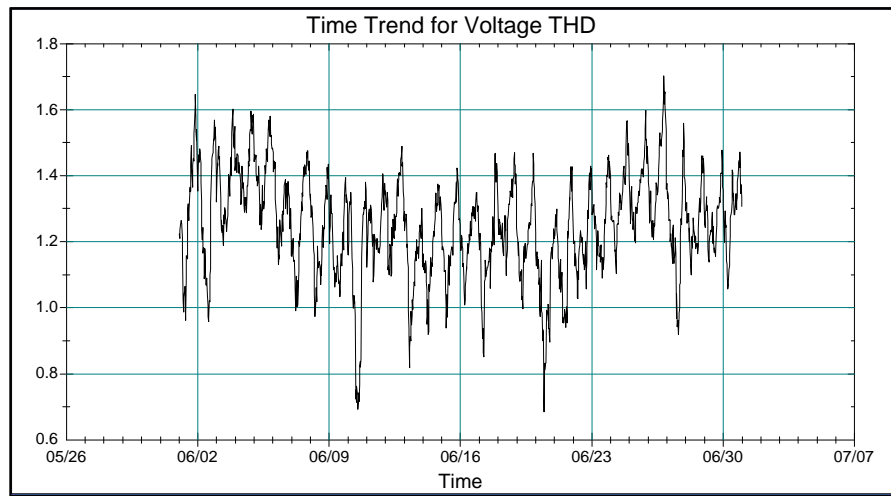


Figure 6. Harmonic variations with time.

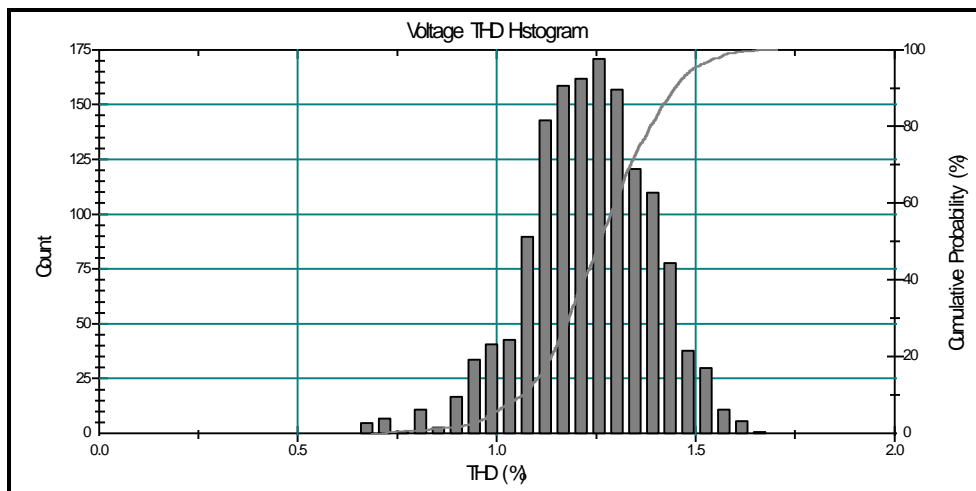


Figure 7. Statistical representation of harmonic variations with time.

### ***Harmonic Evaluations on the Utility System***

Harmonic evaluations on the utility system involve procedures to make sure that the quality of the voltage supplied to all customers is acceptable. IEEE 519-1992 provides guidelines for acceptable levels of voltage distortion on the utility system (Table 3). Note that recommended limits are provided for the maximum individual harmonic component and for the Total Harmonic Distortion (THD).

*Table 3. Recommended Voltage Distortion Limits for General Systems.*

<b>Bus Voltage</b>	<b>Maximum Individual Harmonic Component (%)</b>	<b>Maximum THD (%)</b>
<b>69 kV and below</b>	<b>3.0%</b>	<b>5.0%</b>
<b>115 kV to 161 kV</b>	<b>1.5%</b>	<b>2.5%</b>
<b>Above 161 kV</b>	<b>1.0%</b>	<b>1.5%</b>

These voltage distortion limits apply at the *point of common coupling*, which will be on the medium voltage system for most industrial and commercial customers (Figure 8). This allows for higher voltage distortion levels within the customer facility. Most end use equipment is not affected by voltage distortion levels below 8%. In fact, the *compatibility level* for voltage distortion on LV and MV systems specified in IEC 1000-2-2 is 8% (this is the voltage distortion level that should be exceeded less than 5% of the time).

### ***Harmonic Evaluations for End Use Facilities***

Most harmonic problems occur at the end user level, rather than on the utility supply system. Most nonlinear devices are located within end user facilities and the highest voltage distortion levels occur close to the sources of harmonics. The most significant problems occur when an end user has nonlinear loads and also has power factor correction capacitors that result in resonance conditions.

IEEE 519-1992 was developed to evaluate harmonic voltages and currents at a *point of common coupling (pcc)* between the end user and the utility supply system. The PCC is the location where another customer can be served from the system. The standard allows for the same procedure to be applied by the customer at other locations within a facility but different current limit values could apply in these cases.

The PCC can be located at either the primary or the secondary of a supply transformer depending on whether or not multiple customers are supplied from the transformer (Figure 8). The harmonic current limits for the PCC are summarized in Table 4.

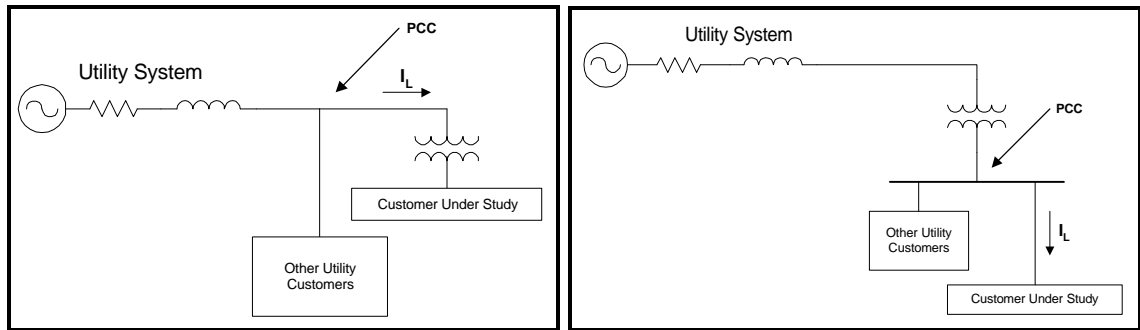


Figure 8. Selection of the PCC where other customers can be supplied.

Using this approach, harmonic limits for individual loads are not specified. The limits for an individual load, such as an adjustable speed drive, depend on the impact of that load on the harmonic levels for the whole facility. This is different from the approach taken in IEC 1000-3-2 (formerly IEC 555-2) where limits for individual loads less than 16 Amps are specified. The IEEE 519 approach provides more flexibility in identifying the most economical location to limit the harmonics.

Table 4. Harmonic Current Limits for Individual End Users from IEEE 519-1992.

HARMONIC CURRENT DISTORTION LIMITS IN % OF $I_L$						
$v \leq 69kV$						
$I_{sc} / I_L$	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
$69kV < v \leq 161kV$						
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20-50	3.5	1.75	1.25	0.5	0.25	4.0
50-100	5.0	2.25	2.0	1.25	0.35	6.0
100-1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
$v > 161kV$						
< 50	2.0	1.0	0.75	0.3	0.15	2.5
$\geq 50$	3.5	1.75	1.25	0.5	0.25	4.0

Notes to current distortion limits:

$I_{SC}$  is the short circuit current at the point of common coupling.

$I_L$  is the maximum demand load current (fundamental frequency component) at the point of common coupling. It can be calculated as the average of the maximum monthly demand currents for the previous 12 months or it may have to be estimated.

\* All power generation equipment applications are limited to these values of current distortion regardless of the actual short circuit ratio  $I_{SC}/I_L$ .

The tables of individual harmonic component limits apply to the odd harmonic components.

Even harmonic components are limited to 25% of the limits in the tables.

Current distortion which results in a dc offset is not allowed.

Total Demand Distortion (*TDD*) is defined as:

$$TDD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_L} \times 100\%$$

where:

$I_n$  = magnitude of individual harmonic components (rms amps)

$n$  = harmonic order

$I_L$  = maximum demand load current (rms amps) defined above

If the harmonic producing loads consist of power converters with pulse number ( $q$ ) higher than six, the limits indicated in the table are increased by a factor equal to

$$\sqrt{\frac{q}{6}}$$

provided that the magnitudes of the noncharacteristic harmonics are less than 25% of the limits specified in the table.

### ***Evaluating Impacts of Harmonic Currents on Transformer Heating***

Transformer heating is one of the primary concerns associated with harmonic current distortion levels in a facility. ANSI/IEEE Standard C57 series states that a transformer can only be expected to carry its rated current if the current distortion is less than 5%. If the current distortion exceeds this value, then some amount of derating is required. ANSI/IEEE Standard C57.110 provides calculation procedures that can be used to evaluate the required derating as a function of the expected current harmonic spectrum and the transformer design. The primary cause of the concern is that the transformers can be overheated by distorted load currents that cause higher eddy current losses inside the transformer than were anticipated by the designer.

The required transformer derating is calculated based on the additional heating that can be expected for a specific harmonic current spectrum and the eddy current loss factor for the transformer. The derating is expressed as the per unit value of a particular distorted current that will cause the same heating as the rated sinusoidal current.

It has become popular to express this derating in terms of the *k-factor* of the load current waveform that the transformer must supply. It is possible to buy transformers with a k-factor rating that can be used without derating for current waveforms that have k-factors up to the k-factor rating of the transformer.

$$I_{rms(derated)} = \sqrt{\sum I_h^2} = \sqrt{\frac{1 + P_{EC-R}}{1 + K * P_{EC-R}}} (pu)$$

where:

$$K = \frac{\sum (I_h^2 * h^2)}{\sum I_h^2} \quad (\text{k-factor})$$

$P_{EC-R}$  = eddy current loss factor

h = harmonic number

$I_h$  = harmonic current

The most common application where transformer derating for harmonics is needed involves a 480/208 volt stepdown transformer where a significant percentage of the load is single phase electronic equipment (e.g. PCs). A typical current waveform, k-factor, and transformer derating as a function of the transformer eddy current loss factor is given in Figure 11.

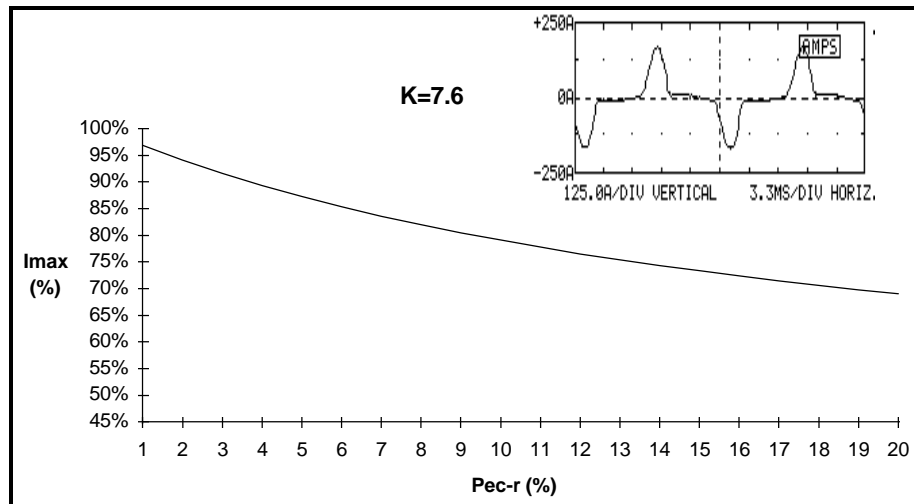


Figure 11. Transformer derating for supplying single phase electronic loads as a function of the transformer eddy current loss factor.

### ***Evaluating Neutral Conductor Loading due to Harmonics***

Single phase nonlinear loads can have significant harmonic components at triplen frequencies (3, 9, 15, etc.). When these loads are combined in a three phase circuit, the triplen harmonics show up as zero sequence components. That means they add in the neutral. If there are 10 amps of third harmonic on each phase in the three phase circuit, the neutral current will include 30 amps of third harmonic.

For this reason, neutral currents in 120/208 circuits in many commercial buildings are actually higher than the phase currents. The neutral currents are dominated by third harmonic components from single phase electronic loads, like PCs. They can be as high as 173% of the rms phase currents (Figure 12 is an example of measured waveforms illustrating this condition). Neutral currents can also be a concern on distribution systems that supply single phase customers or three phase customers with wye-grounded/wye-grounded transformers.

Unfortunately, there are no standards limiting the harmonics from these single phase loads (IEC 1000-3-2 provides limits for the European Community) and there are no requirements that the neutral conductors in these facilities be made larger to handle the higher current magnitudes. This is a problem that the building designer and facility electrical engineer must be aware of to make sure that neutral circuits are not overloaded.

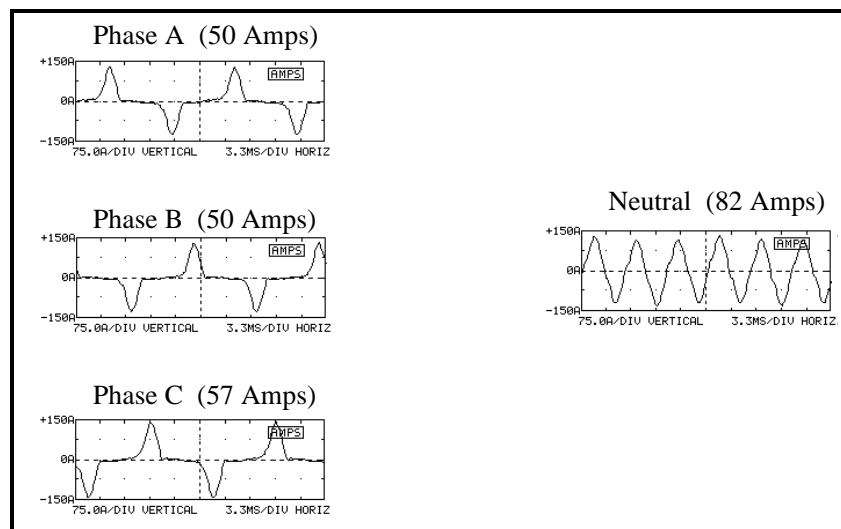


Figure 12. Phase currents and neutral current for a circuit dominated by single phase electronic loads.

### ***Standards for Voltage Fluctuations (Flicker)***

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. These fluctuations are often referred to as *flicker*. They are

characterized by the magnitude of the voltage changes and the frequency with which they occur. A plot of the rms voltage magnitude vs. time can be used to illustrate the variations.

The most important impact of these fluctuations is that they cause variations in the light output of various lighting sources. Sensitivity curves have been developed for incandescent lighting that show how the voltage fluctuations can cause unacceptable variations in the light output (Figure 13), but there is no one curve that is universally applied as a standard. In a survey of electric utility practices, it was found that the GE flicker curve published in 1951 is the most popular curve used to apply limits.

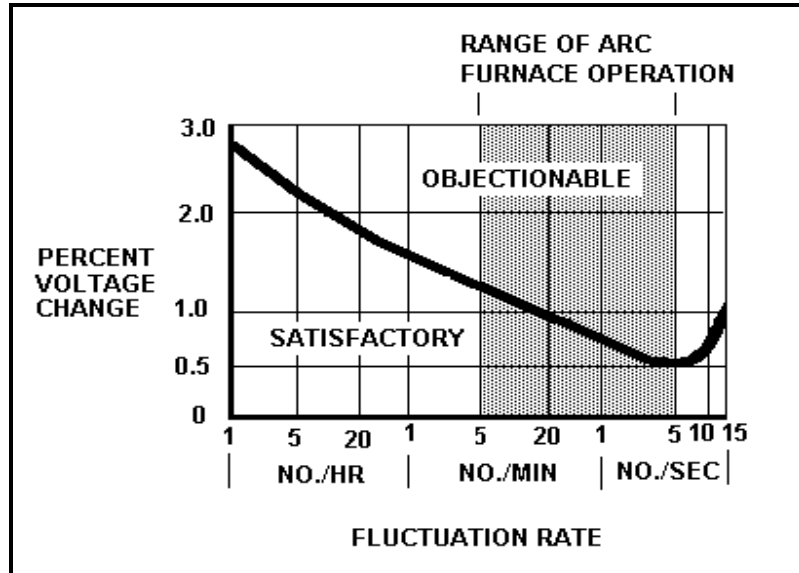


Figure 13. Flicker sensitivity curve.

In the IEC standards, a much more rigorous approach is used for flicker evaluations. IEC 868 provides a detailed specification for the flickermeter which must be used to characterize flicker levels. This instrument provides an output which is per unitized to 1.0 for the level of flicker that should be noticeable with a 40 Watt bulb on a 220 volt supply.

Unfortunately, light bulbs on 120 volt systems behave differently (larger filaments) so the output of the flickermeter must be adjusted for use in this country. IEC 1000-3-3 (formerly IEC 555-3) also provides limits for individual appliances in terms of the voltage fluctuations that can be caused.

Voltage fluctuations are caused by changing load characteristics. Arc furnaces, motor starting, sawmills, and arc welding are typical sources of voltage fluctuations. Controlling the fluctuations can be very difficult. Some of these loads, such as arc furnaces, are continually varying at a rate that requires compensation with very fast response. This can be accomplished with continuously varying compensation, such as a static var system. Other power electronics-based technologies with real time control (active series voltage regulator) are under development.



## Standards for Voltage Sags and Interruptions

Voltage sags fall in the category of short duration voltage variations. According to IEEE P1159 and IEC definitions, these include variations in the fundamental frequency voltage that last less than one minute. These variations are best characterized by plots of the **rms voltage** vs time (Figure 14) but it is often sufficient to describe them by a voltage magnitude and a duration that the voltage is outside of specified thresholds. It is usually not necessary to have detailed waveform plots since the rms voltage magnitude is of primary interest. The voltage variations can be a momentary low voltage (**voltage sag**), high voltage (**voltage swell**), or loss of voltage (**interruption**).

Voltage sags are typically caused by a fault somewhere on the power system. The voltage sag occurs over a significant area while the fault is actually on the system. As soon as a fault is cleared by a protective device, voltage returns to normal on most parts of the system, except the specific line or section that is actually faulted. The typical duration for a transmission system fault is about six cycles. Distribution system faults can have significantly longer durations, depending on the protection philosophy. The voltage magnitude during the fault will depend on the distance from the fault, the type of fault, and the system characteristics.

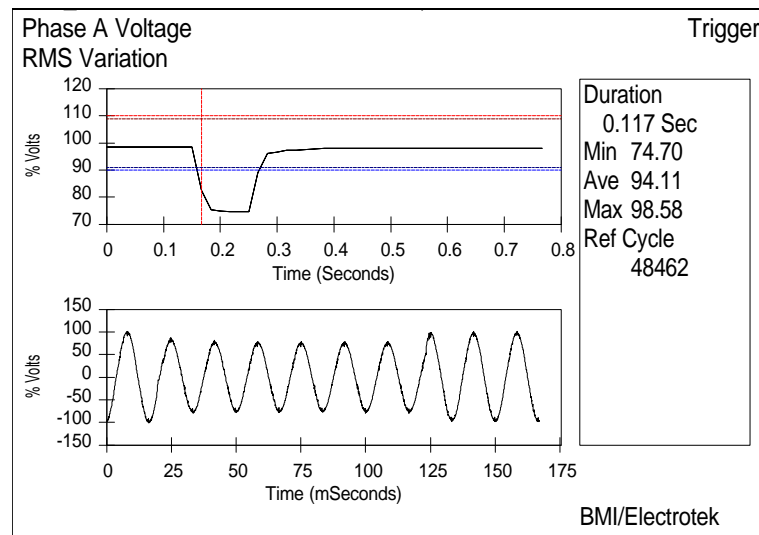


Figure 14. Voltage sag that could cause equipment misoperation. It is caused by a remote transmission line fault condition on the power system

### Characterizing equipment sensitivity to voltage sags

Voltage sags are the most important power quality variation affecting many types of industrial customers. As industrial processes have become more automated, the equipment has become increasingly sensitive to these momentary undervoltages. If a single piece of equipment in the process is affected by the voltage sag, the entire process can be interrupted.

Since we characterize the voltage sags with a magnitude and duration, it is useful to describe equipment sensitivity in the same manner. This is done with a magnitude/duration plot (Figure 15). The Computer and Business Electronics Manufacturers Association (CBEMA) was the first to use this concept to describe equipment sensitivity. They came up with the “CBEMA curve” that has become the benchmark for describing equipment susceptibility. The curve is reproduced in IEEE Standard 446 (*The Orange Book*). Unfortunately, equipment doesn’t behave according to the CBEMA curve. Some equipment is less sensitive and some equipment, like the ASD in Figure 15, is much more sensitive. A working group in IEEE (IEEE P1346) is currently working on guidelines for compatibility of industrial process equipment.

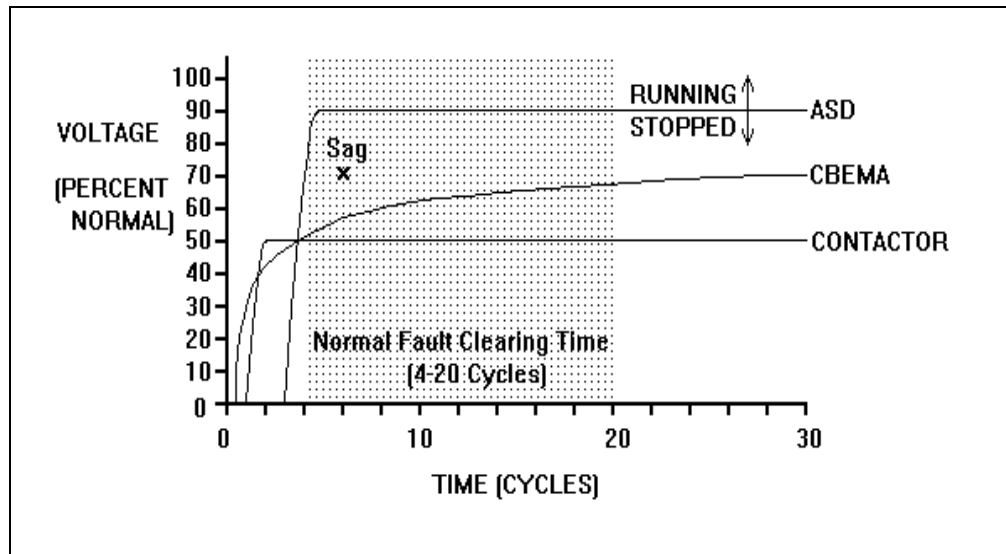


Figure 15. Example of equipment sensitivity to voltage sags.

### ***Characterizing system performance***

End users can evaluate the economics of power conditioning equipment if they have information describing the expected system voltage sag performance. A chart like the one in Figure 16 can be used in conjunction with equipment sensitivity characteristics to estimate the number of times the process will be interrupted and the associated costs. There are currently no standards describing how to provide this information to customers.

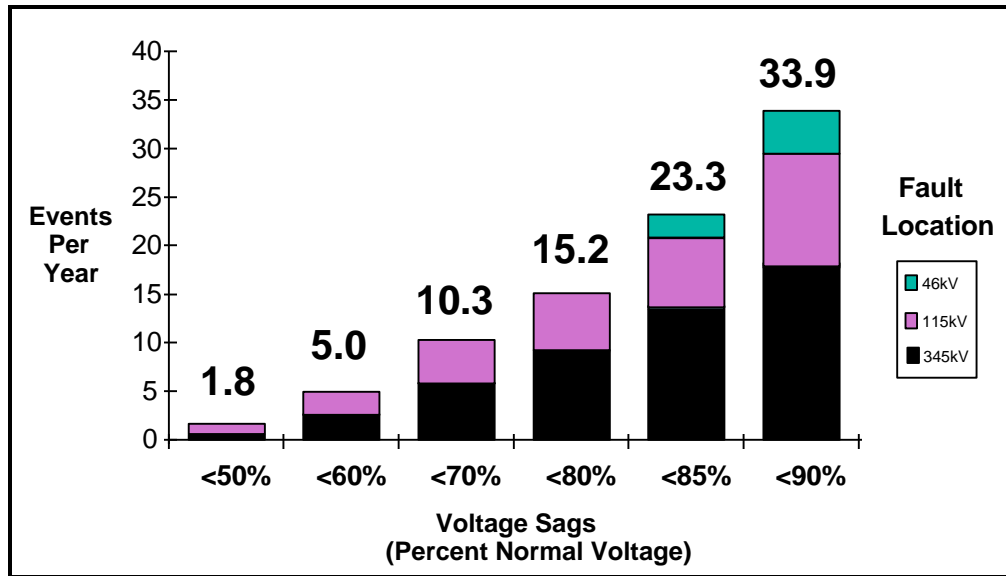


Figure 16. Example of expected voltage sag performance at a customer location.

What can customers expect in terms of the number of voltage sags per year? This number changes from year to year and is dependent on many factors which are specific to the customer location (lightning flash density, feeder lengths, animals, trees, etc.). However, it is possible to develop some average numbers that provide a benchmark for comparison. The Distribution Power Quality Monitoring project sponsored by the Electric Power Research Institute is characterizing average performance on distribution systems across the country. The results in Figure 17 represent one year of monitoring at 24 different utilities, as reported in a paper presented at the PQA 94 conference in Amsterdam.

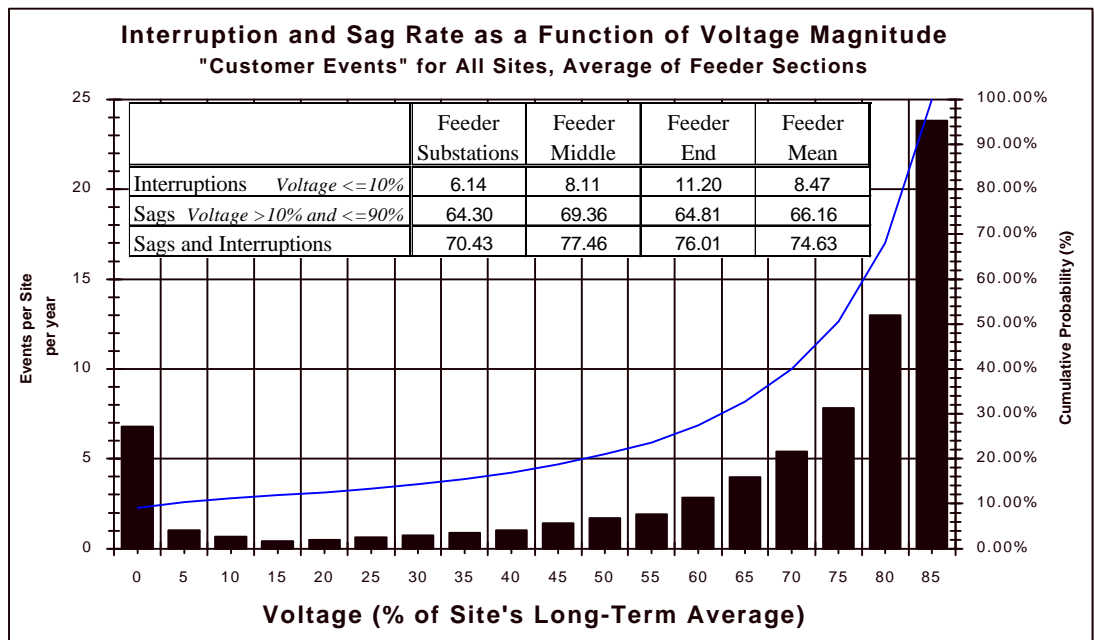


Figure 17. Voltage sag and momentary interruption performance for a distribution system sites in the United States (preliminary results from EPRI DPQ project).

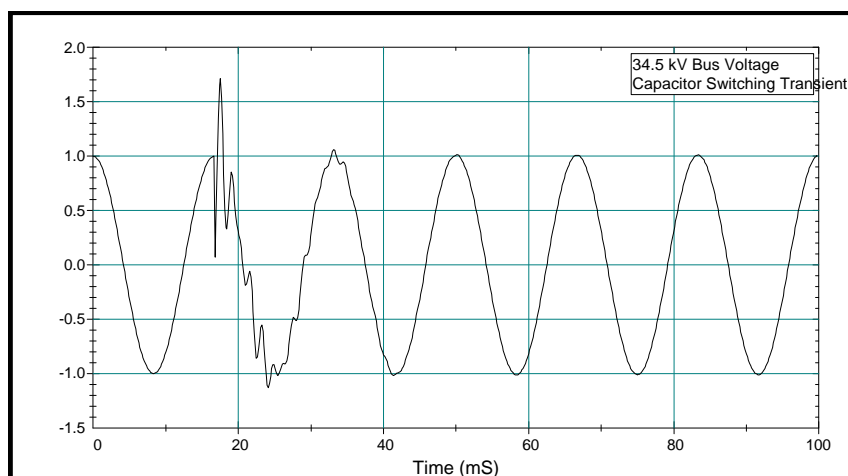
The results presented in Figure 17 are very important because they begin to define the baseline power quality that can be expected at a typical distribution feeder supply point. Customers can use this information to help define the voltage variations that their equipment must be able to withstand. It is useful to illustrate the use of the information with an example:

Assume that we want to know how many voltage sags occur per year where the voltage goes below 70% of nominal voltage at a typical distribution system supply point. The data on the plot is for the average of all feeder sites in the project (the *feeder mean* in the table). Using the cumulative probability line and the right side axis, we can see that 40% of the events resulted in sags below 70%. The total number of events per year (including interruptions) is given in the table as 74.63. Therefore, the number of sags below 40% (including interruptions) will be 40% of 74.63, or about 30 events per year.

## ***Standards for Transient Voltages and Surge Suppression***

The term *transients* is normally used to refer to fast changes in the system voltage or current. Transients are disturbances, rather than steady state variations such as harmonic distortion or voltage unbalance. Disturbances can be measured by triggering on the abnormality involved. For transients, this could be the peak magnitude, the rate of rise, or just the change in the waveform from one cycle to the next. Transients can be divided into two subcategories, impulsive transients and oscillatory transients, depending on the characteristics.

Transients are normally characterized by the actual waveform, although summary descriptors can also be developed (peak magnitude, primary frequency, rate-of-rise, etc.). Figure 18 gives a capacitor switching transient waveform. This is one of the most important transients that is initiated on the utility supply system and can affect the operation of end user equipment. Other important causes of transient voltages include lightning surges and switching operations within a facility.



***Figure 18. Capacitor Switching Transient***

Transient problems are solved by controlling the transient at the source, changing the characteristics of the system affecting the transient or by protecting equipment so that it is not impacted. For instance, capacitor switching transients can be controlled at the source by closing the breaker contacts close to a voltage zero crossing. Magnification of the transient can be avoided by not using low voltage capacitors within the end user facilities. The actual equipment can be protected with filters or surge arresters.

### ***ANSI/IEEE C62.41-1991***

The most well-known standard in the field of transient overvoltage protection is ANSI/IEEE C62.41-1991, *IEEE Guide for Surge Voltages in Low Voltage AC Power Circuits*. This standard defines the transient environment that equipment may see and provides specific test waveforms that can be used for equipment withstand testing. The transient environment is a function of the equipment or surge suppressor location within a facility:

- **Category A:** Anything on the load side of a wall socket outlet.
- **Category B:** Distribution system of the building.
- **Category C:** Outside the building or on the supply side of the main distribution board for the building.

Test waveforms are probably the most important contribution of C62.41. The standard recommends five different surge waveforms: two as *basic waveforms* and three as *supplementary waveforms*. The listing of these five types of waveforms is not meant to imply that all equipment should be tested with respect to all five waveforms. The supplementary waveforms are "less common in most environments and may be included when sufficient evidence is available to warrant their use." These are the waveforms:

**1.2/50 - 8/20 microsecond Combination Wave (Basic Wave).** Traditionally, the 1.2/50 us voltage waveform was used for testing the basic insulation level (BIL) of insulation which is approximately an open circuit until the insulation fails. The 8/20 us current waveform was used to inject large currents into surge protective devices. Since both the open circuit voltage and the short circuit current are different aspects of the same phenomenon, such as an overstress caused by indirect lightning, it is reasonable to combine them into a single waveform.

**0.5 usec - 100 kHz Ring Wave.** This is a decaying oscillatory wave with an initial rise time of 0.5 usec. Different characteristics are specified for Category A and Category B environments. The short circuit current waveform for the 100 kHz ring wave is not specified. It is suggested that the 100 kHz ring wave is an appropriate test waveform for electronic equipment that operates in a building, but not for surge protective devices.

**10/1000 microsecond Unidirectional Wave (Supplementary Wave).** This waveform has an extended tail in order to test insulation which may be sensitive to the duration of the transient. Some transformer insulation falls in this category.

**5 kHz Ring Wave (Supplementary Wave).** This waveform is designed to represent a class of transients that can occur associated with switching of capacitors or coupling of capacitor switching transients into the LV environment.

**Electrical Fast Transient (Supplementary Wave).** This waveform and the coupling to the mains are specified in IEC 801-4. The EFT is only intended for testing electronic equipment for susceptibility to upset by showering arcs from using a mechanical switch in series with an inductive load. Since the energy levels are so low, this waveform is generally not required for surge protective devices.

## ***UL 1449***

Underwriters Laboratories is a nonprofit company in the USA that tests electrical and electronic apparatus for safety and flammability. UL defines requirements for *transient voltage surge suppressors* in their standard 1449. Two classes are defined for tests:

1. permanently connected (C62.41 Category B)
2. cord-connected or direct plug-in (C62.41 Category B or A)

An important part of the UL 1449 certification is the assignment of a "*transient suppression voltage rating*". UL 1449 uses the combination wave described in C62.41 for testing permanently connected SPDs with a peak short circuit current of 3 kA. For the cord-connected and direct plug-in SPDs, the peak short circuit current is only 0.5 kA. All SPDs are tested only with surge waveforms that have a peak open-circuit voltage of 6 kV.

The average of 6 test measurements of clamping voltage is rounded to the next higher standard rating from the following list:

0.33 kV, 0.4 kV, 0.5 kV, 0.6 kV, 0.8 kV, 1.0 kV, 1.2 kV, 1.5 kV, 2.0 kV, 2.5 kV, 3 kV, 4 kV, 5 kV, 6 kV

This suppression rating was intended as a guide to selecting SPDs for insulation coordination (as in IEC 664) and not protection of electronic equipment, which is why there are no voltages below 330 Volts in the list of standard values.

## ***What Still Needs to be Done?***

In the area of standards, we need to develop guidelines for system performance. These performance standards should include at least:

- Interruptions (including momentary)
- Voltage sags
- Steady state voltage regulation
- Voltage unbalance (negative sequence)
- Harmonic distortion in the voltage
- Transient voltages

The EPRI DPQ Project will provide an excellent statistical database that may be the basis for developing some of these standards. In turn, equipment manufacturers must be able to provide information describing the sensitivity of their equipment to these variations. With information on typical system performance based on historical and calculated data along with information on equipment sensitivity, customers will be able to perform economic evaluations of power conditioning alternatives.

Ongoing monitoring efforts and case studies will provide the information to characterize system performance and to understand the susceptibility of different types of customer systems. Monitoring of power quality should become a more standard part of the overall system monitoring (both at the utility level and the customer level). These monitoring efforts should be coordinated between the utility and the customer with emphasis on remote monitoring and data collection systems with more automated data analysis capabilities.

Analytical tools will also benefit from the increased level of monitoring and characterization. Models should be improved and the tools themselves should become easier to use.

The overall focus needs to be on economics using a systems approach (Figure 19). We need to develop tools that can help find the optimum system design including power conditioning for sensitive equipment. The alternatives should include improved immunity at the equipment level, power conditioning at the equipment level, power conditioning at more centralized locations within the customer system, and measures to improve performance on the utility system.

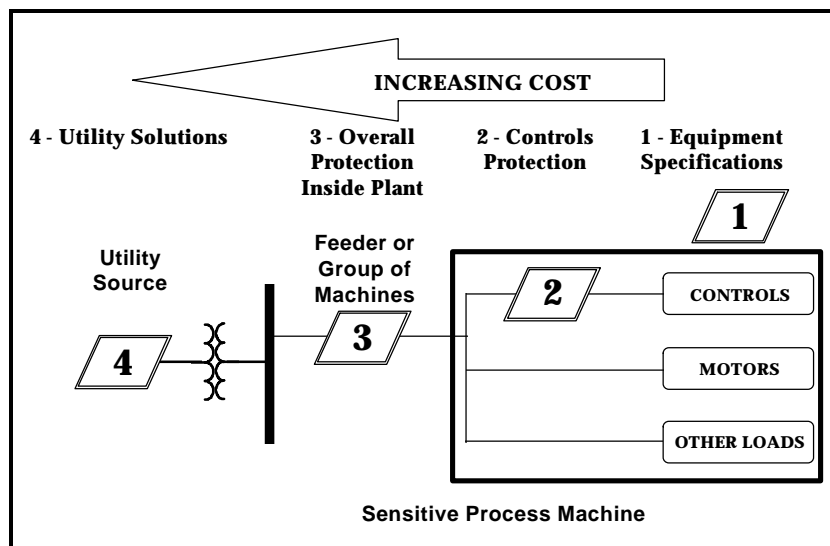


Figure 19. Economic Evaluation of Alternatives for Power Quality Improvement

**Standards Organizations***Table 5. Important Standards Organizations*

<b>Organization</b>	<b>Types of Standards</b>	<b>Address</b>
ANSI	Steady state voltage ratings (ANSI C84.1)  All IEC documents also available	American National Standards Institute 11 West 42nd Street, 13th Floor New York, NY 10036 (212) 302-1286
CBEMA	Equipment guides	Computer & Business Equip. Mfctrs. Assoc. 1250 Eye St. NW Washington DC 20005 (202) 737-8888
EPRI	Signature newsletter on PQ standards	Electric Power Research Institute Attn: Marek Samotyj 3112 Hillview Ave. Palo Alto, CA 94304 (415) 855-2980
IEEE	Standards Bearer Standards Catalog Individual standards IAS Color Book Series	Institute of Electrical & Electronic Eng. 445 Hoes Lane Piscataway, NJ 08855-1331 (908) 562-3833
NEMA	Equipment standards	National Electrical Manufacturers Assoc. 2101 L Street NW Washington DC 20037 (202) 457-8474
NFPA	Lightning protection National Electrical Code	National Fire Protection Assoc. 1 Batterymarch Park Quincy, MA 02269-0101 (800) 344-3555
NIST	General information on all standards	National Center for Standards and Cert. National Institute of Standards and Tech. Gaithersburg, MD 20899 (301) 975-4037
UL	Safety standards for equipment	Underwriters Laboratories 333 Pfingsten Rd. Northbrook IL 60062-2096 (708) 272-8800



## *Summary of Trends*

Ongoing standards development should help make all parties more aware of power quality concerns and provide better tools and techniques for developing the optimum solutions to problems. Some important trends that should result include:

1. **End-Use Equipment.** Equipment must become less sensitive to power quality variations. As we understand the economics involved, the immunity characteristics of the equipment will become part of the purchase decision making process. When this happens, manufacturers will consider it important enough to improve the immunity. In the long run, the most economical place to solve most power quality problems will be in the end-use equipment itself.
2. **Customers.** Customers will have a better understanding of power quality concerns and will include these concerns in their facility designs. The electrical system layout will consider the power conditioning requirements of sensitive and critical equipment. Power conditioning options will be part of the design stage. Power factor correction and harmonic control will be considered together.
3. **Utilities.** Utilities will be able to provide more detailed information to customers regarding the expected system performance as it may affect customer loads. The utility may also offer alternatives for higher levels of performance that may involve additional investment on the supply system or working with the customer to implement power conditioning options within the customer system.

These trends seem inevitable. However, getting there may be a long road and will require continued and improved coordination between utilities, their customers, and equipment manufacturers. The coordination is usually achieved through the development of standards that all parties consider acceptable.