

IEEE Guide for Identifying and Improving Voltage Quality in Power Systems



IEEE Power & Energy Society

Sponsored by the
Transmission and Distribution Committee

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IEEE Guide for Identifying and Improving Voltage Quality in Power Systems

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Transmission and Distribution Committee

of the

IEEE Power & Energy Society

Approved 31 March 2011

IEEE-SA Standards Board

Abstract: The use of some electrical equipment attached to typical power systems creates voltage quality concerns. There is an increasing awareness that some equipment is not designed to withstand the surges, faults, distortion, and reclosing duty present on typical utility distribution systems. Traditional concerns about steady-state voltage levels and light flicker due to voltage fluctuation also remain. These concerns are addressed by this guide by documenting typical levels of these aspects of voltage quality and indicating how to improve them. Other documents that treat these subjects in more detail are referenced.

Keywords: benchmarking, disturbance analyzers, faults, harmonic distortion, IEEE 1250, light flicker, momentary voltage disturbances, noise, performance, power conditioners, susceptible equipment, surge protection, surges, voltage fluctuation, voltage quality

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Introduction

This introduction is not part of IEEE Std 1250-2011, IEEE Guide for Identifying and Improving Voltage Quality in Power Systems.

This guide was developed out of an increasing awareness of the incompatibility of some modern electronics equipment with a normal power system environment. Simply put, much new user equipment is not designed to withstand the surges, faults, distortion, and reclosing duty present on typical electric utility distribution systems or within the user's facility.

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IEEE Guide for ~~Service to Equipment Sensitive to Momentary Voltage Disturbances~~ Identifying and Improving Voltage Quality in Power Systems

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1. Overview

1.1 Scope

The reader of this guide will find discussions of ways to identify and improve voltage quality in power systems, as well as references to publications in this area. More specifically, this guide includes:

- a) Voltage quality levels from benchmarking studies
- b) Factors that affect power system performance
- c) Mitigation measures that improve power system performance
- d) References to current relevant in-depth IEEE standards and other documents

This guide only addresses subjects in depth where no other power quality reference does so. It is a “gateway” document for power quality that points the way to other documents in this field.

~~This guide describes momentary voltage disturbances (short duration transients) occurring in ac power distribution and utilization systems, their potential effects on sensitive equipment, and guidance toward mitigation of these effects. Also provided is a description of the operating environment of sensitive utilization equipment as well as information on harmonic distortion limits.~~

1.2 Purpose of guide

The primary purpose in writing this guide is to assist power delivery system designers and operators in delivering power with voltage quality that is compatible with electrical end-use equipment. Another purpose is to point utility system customers toward power quality solutions that may exist in the power utilization system and equipment.

~~Equipment application problems exist today because of certain incompatibilities among the sensitive equipment and various disturbances present on typical power systems. Some of the newer sensitive loads are particularly vulnerable to momentary disturbances. In addition, some of these loads introduce considerable harmonic content into the system and can be detrimental to other equipment in the area. Because of increasing use of computers and other sensitive equipment, such problems will continue to grow unless corrective measures are taken~~

~~The primary purpose of this guide is to assist in identifying potential problems and to suggest effective ways to satisfy sensitive equipment voltage requirements. This discussion should provide insight into the distinction between those voltage related problems that are controlled by the utility and those that can only be addressed by the user or equipment designer. Cooperation among users, utilities, and equipment designers is needed to ensure both adequate electric service to all users and proper equipment operations. Solutions are presented from the perspectives of both the customer and the utility provider, since the problems users of sensitive equipment experience often originate from either area.~~

~~The secondary purpose of this guide is to help provide the designers of sensitive equipment with an understanding of the environment in which their equipment is expected to operate.~~

1.2 Problem definition

~~Computers, computer like products, and equipment using solid state power conversion have created entirely new areas of power quality considerations. There is an increasing awareness that much of this new user equipment is not designed to withstand the surges, faults, and reclosing duty present on typical distribution systems. In addition to the usual steady state concerns, designers and users of these types of equipment, as well as suppliers of utilities, are concerned with transients, brief momentary disturbances, and harmonics of these often sensitive loads.~~

~~Most voltage problems associated with computers and other sensitive equipment are related to not only high or low steady state voltage levels, but also to momentary voltage disturbances, such as surges, sags, interruptions, or rapid changes in voltage. The starting of a large motor, for example, can result in voltage sag due to the high inrush current. A fault on the utility lines, even though cleared, can result in a momentary sag, surge, or interruption. Momentary voltage disturbances may result from a wide variety of causes on a utility system or within a user's facility.~~

~~Site monitoring with disturbance recorders helps to identify the nature of the problem and the frequency of occurrence. Such information can then be correlated to events on either side of the meter to help identify possible solutions. However, difficulty often arises in matching recorded disturbances to equipment sensitivities.~~

~~A variety of power conditioning equipment is available to buffer the sensitive load from various disturbances (and in some cases, from harmonics) where necessary. Ideally, the power quality tolerance of the particular sensitive equipment should be analyzed to determine the proper solution; however, this information is often unknown. In addition, the user should be aware of some of the nonlinear characteristics of certain types of conditioning equipment.~~

2. References

~~This guide shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply:~~

~~ANSI C84.1-1989, American National Standard Voltage Ratings (60 Hz) for Electric Power Systems and Equipment.¹~~

~~IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).²~~

~~IEEE C62.1-1989 (Reaff 1994), IEEE Standard for Gapped Silicon Carbide Surge Arresters for AC Power Circuits (ANSI).~~

~~IEEE Std C62.41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits (ANSI).~~

2. The power system

2.1 Introduction

This subclause describes typical utility power systems. Understanding the basics of power system design and operation is helpful in understanding the voltage quality characteristics described in Clause 3. Voltage quality characteristics can be affected at various levels of a power system. Electricity is typically generated and delivered at either 50 Hz or 60 Hz.

2.2 Overview of power systems

Power systems are usually thought of as having three main divisions: generation, transmission, and distribution. Figure 1 is an oversimplified diagram of a typical U.S. electric power system. In reality, there are many exceptions such as the fact that some large industrial customers are actually served by substations directly from the transmission system and some small generators may feed directly into the distribution system.

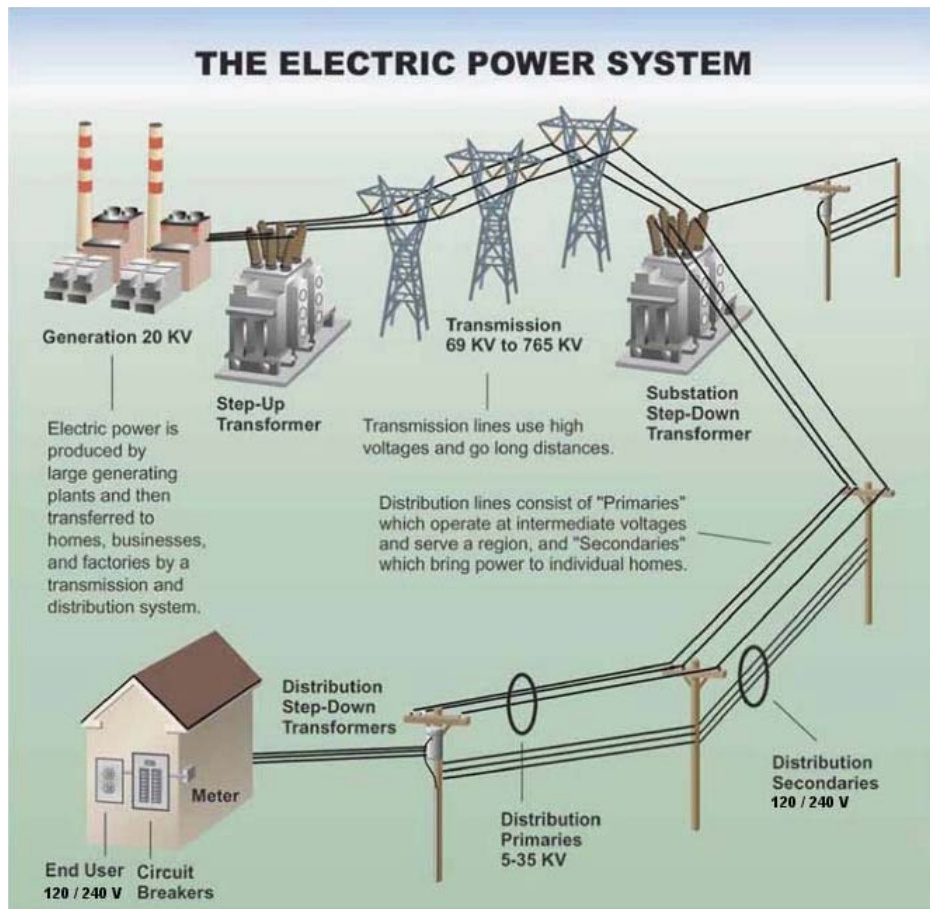


Figure 1—The electric power system

Interconnection of the generation, transmission, and distribution systems takes place in an electrical substation. Substations may include transformers that raise or lower the voltage depending on the need. A substation that has a step-up transformer increases the voltage while decreasing the current, whereas a step-down transformer decreases the voltage while increasing the current for distribution. Electric power may flow through several substations between generating plants and consumers, and it may be changed in voltage several times.

The generation and transmission components are typically connected in an interconnected grid fashion. Within the "grid," the transmission lines transport bulk power for long distances that typically cross multiple service territories and multiple utilities. Figure 2 shows a simple transmission system, referred to as a transmission network, illustrating how most of the substation buses have more than one source. In most circumstances, the loss of a single line or generator should not cause overloads within the remaining network. This offers a high degree of reliability because power can be maintained to most buses even with the loss of a line or source.

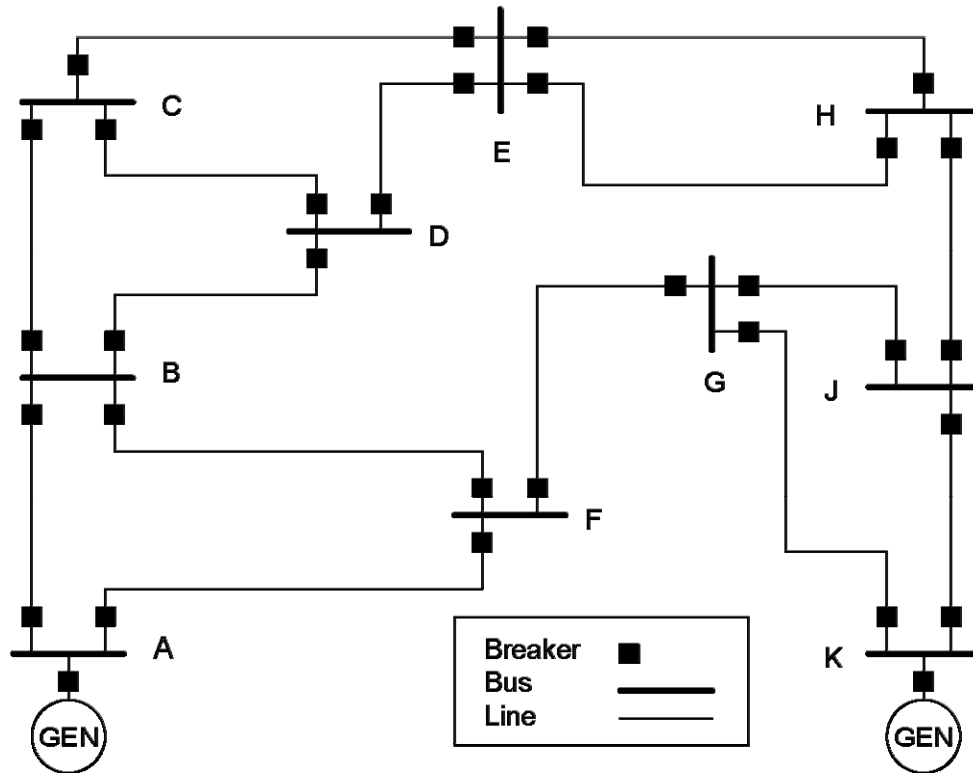


Figure 2—Transmission network showing generators, substations, and line sections

Distribution lines (commonly called primaries) are usually not interconnected but are designed in a radial fashion except in some cities that use a mesh distribution scheme. Radial distribution systems consist of a source originating at a substation in which the system voltage is stepped down (Figure 3). The distribution bus has breakers that feed lines (feeders) that carry the power to many customers in an area. There are usually line protective components (reclosers and fuses) downstream of the substation breaker on distribution lines. These components create situations in which only a portion of the distribution line may need to be de-energized to clear a fault (short circuit), thereby saving many customers on the line from experiencing interruptions unnecessarily.

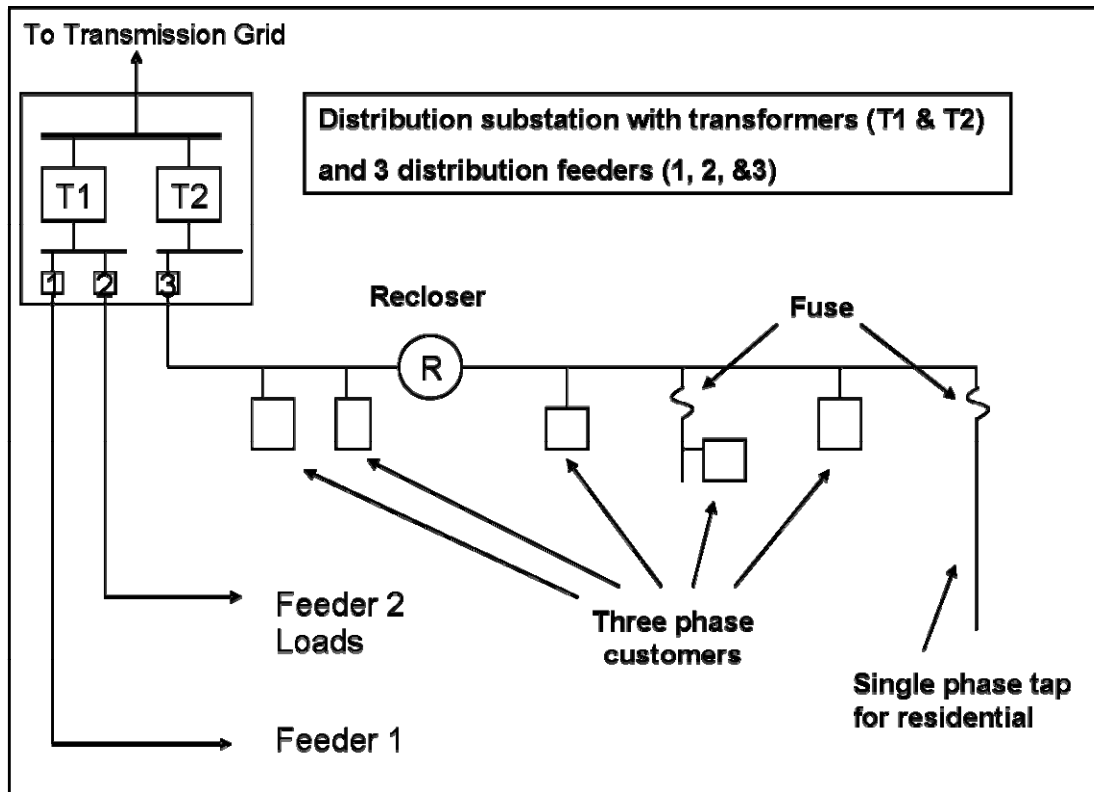


Figure 3—Distribution substation and example of recloser and fuses along line

[Power system voltages are typically expressed in line-to-line kV. The line-to-line voltage is 1.732 times the line-to-neutral voltage on wye systems. Practically all generation and transmission is three phase. Distribution lines typically leave the substation as three phase and may proceed that way for several miles. But they may also have lateral tap lines that are only providing two phases or even a single phase, depending on the loads being served. Electrical services to customers may be from the transmission or the distribution system. Table 1 describes the various components and typical voltage ranges of the utility system.](#)

Table 1—Common parts of the power system

<u>Generation</u>	<u>Converts sources of energy such as fuel, falling water, or nuclear material to electricity.</u>
<u>Transmission</u>	<u>Bulk power transport connecting generating stations to substations serving load areas.</u>
	<u>Generally 230 kV to 765 kV.</u>
	<u>Long lines with few, if any, taps or customer connections.</u>
	<u>May be overhead or underground; underground circuits are short because of charging current limitations.</u>
	<u>Loading limits for lines and loading areas including normal, long-term emergency, and short-term emergency limits.</u>
	<u>Loading may be limited by system stability, voltage control, or conductor temperature.</u>
	<u>Loading follows a cycle with time of day, season, and weather.</u>
<u>Subtransmission</u>	<u>Not distinguished in many systems; lower level bulk power connecting transmission and distribution substations.</u>
	<u>Generally 46 kV to 161 kV.</u>
	<u>May serve large loads directly.</u>
<u>Distribution</u>	<u>Local connections to supply customers or groups of customers.</u>
	<u>4 kV to 35 kV.</u>
	<u>Short lines with many taps, laterals, or branches; direct customer connections; may be reconfigured from time to time.</u>
	<u>Loading is especially variable as customers turn devices ON and OFF.</u>
	<u>May be overhead or underground, with underground especially in urban or new residential areas.</u>

A significant goal related to the operation of the utility power system is to provide reliable power with a minimum number of interruptions. The utility systems are designed to isolate problem areas quickly and to interrupt as few customers as possible. The system protection schemes must quickly identify a faulted line section and then trip or open the proper isolating component to cause the fewest number of customers to experience the loss of power.

3. Identifying voltage quality in power systems

3.1 Introduction

This subclause describes expected voltage quality characteristics at various levels of a power system. Methods of describing the voltage quality characteristics are presented along with example benchmarking results. Important characteristics that may impact the voltage quality characteristics are also described.

3.2 Basic types of voltage quality variations

It is useful to divide voltage quality characteristics into two basic categories.

Steady-state (continuous) voltage quality characteristics. This refers to the quality of the normal voltage supplied to a facility. How much can the voltage magnitude vary from the nominal value? How distorted is the voltage? What is the imbalance among the three-phase voltages? What is the magnitude, frequency, and angle of each phase? All of these characteristics can be quantified, and limits for the variations can be developed.

Disturbances (including reliability). This refers to voltage quality variations that occur at random intervals and are not associated with the continuous characteristics of the voltage. The variations include sustained interruptions (reliability), momentary interruptions, voltage sags (and swells), and transients. All of these disturbances can impact a facility, depending on the equipment susceptibility and investments that have been made in power conditioning.

Each of these two basic categories has indices associated with it. Indices provide the foundation for characterizing the supply system voltage quality levels in a consistent manner. Indices can be used to establish baselines of performance as a function of system characteristics. The following subclauses describe indices that can be used to describe voltage quality levels in both of these major categories along with example benchmarking results that can provide the basis for establishing targets and limits.

3.2 Differing usage of technical terms

~~Some of the terms used to describe voltage disturbances are defined differently by utility engineers and by manufacturers and users of disturbance analyzers and power conditioners [B25]. Table 1 defines the terms, and figure 1 illustrates the waveforms, as they are commonly understood by these two groups.~~

Table 1—Voltage terminology differences

Term	Utility meaning	Monitoring equipment manufacturer or user meaning
Impulse	Unidirectional surge	Same
Momentary interruption	Complete loss of line voltage for a duration of 30 cycles to 2 min, while automatic equipment is acting to resolve an abnormal circuit condition	Complete loss of line voltage for a duration of a half cycle or more
Notch	An impulse that subtracts from the fundamental frequency wave	Same
Sustained interruption	The complete loss of line voltage for a duration greater than 2 min	Complete loss of line voltage for a duration of half cycle or more
Sag	Momentary undervoltage at fundamental frequency lasting from a half cycle to a few seconds	Same
Surge	Unidirectional surge	Momentary overvoltage at fundamental frequency lasting from a half cycle to a few seconds
Swell	Momentary overvoltage at fundamental frequency lasting from a half cycle to a few seconds	Same

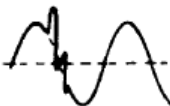
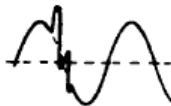
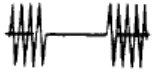
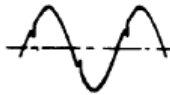
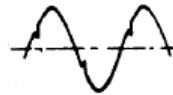
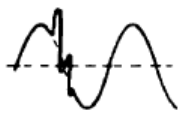
Term	Utility Meaning	Monitoring Equipment Manufacturer or User Meaning
Impulse		
Momentary Interruption		
Notch		
Sustained Interruption		
Sag (dip)		
Surge		
Swell		

Figure 1—Voltage terminology differences

~~Power quality is a broadly used term that has been applied to voltage, service availability, and even harmonic content. Except for clause 1, this guide has purposely avoided the use of this term.~~

~~Voltage quality is a term used to describe the relative amount of voltage disturbances or variations—particularly interruptions, sags, surges, and harmonics—as measured at a specific point. This usage of the term, applied from a utility viewpoint, refers to the quality level measured at the point of service; from the customer viewpoint, it refers to the quality level measured at the point of utilization. At the point of utilization, a customer's perception of poor voltage quality may result from disturbances elsewhere on the customer's system, from a nearby customer, or from the utility system. Specific voltage quality requirements, from the customer viewpoint, can differ from one customer to another, and depend on the special needs of the equipment involved.~~

3.3 Steady-state (continuous) voltage quality characteristics

Steady-state power quality characteristics must meet minimum requirements to assure the proper operation of equipment. The basic concepts of compatibility levels are established in IEC 61000-2-2:2002 [B4].¹ This concept applies to all steady-state types of power quality. It is not as applicable to disturbances, such as voltage sags (dips), interruptions, and transients. The normal variations of steady-state power quality characteristics allow them to be characterized with trends over time and with statistical distributions. The statistical nature of these characteristics lends them to being represented by specific statistical levels. For instance, the limits in EN 50160-1999 [B2] for steady-state power quality are evaluated at the 95% probability level. Recent discussions have indicated that other probability levels may also be appropriate for fully characterizing performance. Figure 4 illustrates the concept that applies for steady-state power quality characteristics. The power quality performance of the supply system is characterized statistically, and this can be compared with the statistical characteristics of the equipment immunity to determine the likelihood that equipment will be affected by the voltage quality variations. The objective is to define a voltage quality level that can be achieved with reasonable investment in the power system and will also have a low probability of causing equipment problems. This level is called the “compatibility level.” It is defined with statistics. As indicated previously, a typical way of defining the compatibility level for performance evaluations is the level that can be exceeded only 5% of the time (95% probability that the level will not be exceeded).

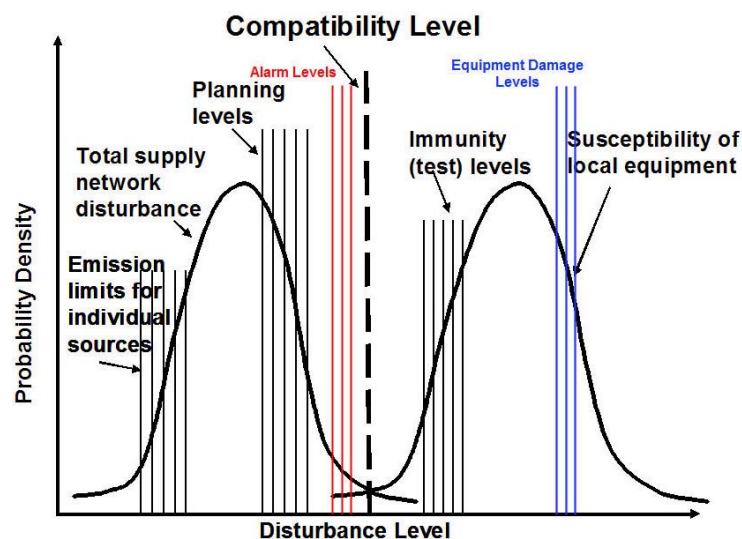


Figure 4—Concept of compatibility levels for the electric supply system and the immunity characteristics of equipment

^LThe numbers in brackets correspond to those of the bibliography in Annex B.

Figure 5 illustrates the concept of the “compatibility level” compared to a time trend of a steady-state voltage quality characteristic (for example, harmonic distortion). Other important voltage quality levels are also shown in both Figure 4 and Figure 5.

Disturbance magnitude

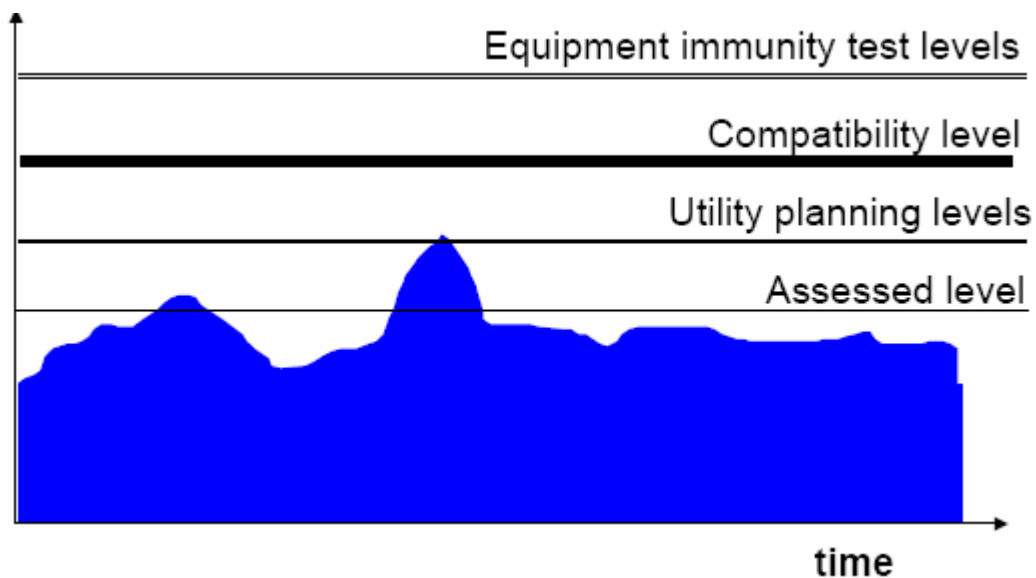


Figure 5—Important concepts for evaluation of the steady-state voltage quality characteristics of the supply system

Equipment damage level—This is the level of quality that may pose a threat to equipment health if it is exceeded. Such conditions are important to identify when they occur and to prevent if possible. Examples may include harmonic resonance, ferroresonance, high neutral currents, conditions that may cause overheating, and so on. There should be some margin between the compatibility level for the supply and the equipment damage level.

Equipment immunity level—This is the level of quality that may affect equipment performance if it is exceeded. It is also defined statistically. There should be some margin between the compatibility level for the supply and the equipment immunity level.

Alarm level—This is the level of quality at which notification will occur (i.e., the level at which an investigation or other response may be warranted). The alarm level should be above the planning level but below equipment immunity, equipment damage, and safety levels.

Planning level—This is the level of quality that the electric utility establishes as its design objective. Usually, the planning level is defined at some level below the compatibility level to help assure that the actual compatibility level will not be exceeded. For instance, the compatibility level for harmonic voltage distortion might be 8%, but the planning level might be 5% to help make sure that the 8% level is not exceeded.

Assessed level—This is the actual level existing on the system, usually based on measurements. For instance, the evaluation of performance for the European standards requires measurements over a 1 week period and then the assessed level for comparison with the minimum performance requirements (based on the compatibility levels) is the level that is exceeded for 5% of the measurements (one measured value every 10 min).

We are interested in defining the steady-state power quality levels that should allow proper operation of virtually all customer equipment. Thus, if these power quality levels are met at the supply point, the steady-state quality should be considered acceptable and should not result in customer problems. There is little value to providing even better power quality if these levels are not likely to cause problems. Extremely susceptible equipment that requires even better quality justifies special power conditioning and should not be the basis of the overall system requirements.

Recommendations for these minimum requirements for the steady-state characteristics are developed in the following subclauses. Important standards and references that are the basis of the recommendations are cited and described as appropriate. In addition, the typical levels of these steady-state characteristics are provided from two important sources.

- The EPRI Distribution Power Quality (DPQ) project (Sabin et al. [B52] and [B53]; Sabin and Standler [B54]) describes steady-state power quality characteristics for distribution systems in the United States. Note that these statistics are based on the evaluation of single-cycle samples of the three-phase voltages. These samples are then analyzed to determine the root mean square (rms) voltage magnitudes, the imbalance, and the harmonic distortion levels. Flicker levels were not characterized in the EPRI DPQ project. This method of evaluating steady-state power quality characteristics is different than the method recommended in IEC 61000-4-30:2008 [B8] and related standards. These methods use 10 min rms values as the basis for characterizing the steady-state power quality. The 10 min calculations can involve smoothing compared with the single-cycle samples.

- In the CIGRE C4.07 Working Group Report [B36], this working group gathered survey information describing both steady-state power quality and disturbances from systems around the world. In general, the surveys referenced in this report used IEC methods for characterizing performance.

The steady-state power quality levels should be evaluated using the measurement procedures outlined in IEC 61000-4-30:2008 [B8]. This standard provides a convenient reference to make sure that all systems are being evaluated in the same manner. The IEEE Std 1159 working group has developed a similar set of recommended characterization procedures (IEEE Std 1159™-2009 [B15]) that are consistent with the methods in the IEC standard.

3.3.1 Voltage regulation

The ability of equipment to handle steady-state voltage variations varies from equipment to equipment. The steady-state voltage variation limits for equipment are usually part of equipment specifications. The Information Technology Industry Council (ITIC) specifies equipment withstand recommendations for IT equipment according to the ITIC Curve [formerly the Computer Business Equipment Manufacturer's Association (CBEMA) curve]. The 1996 ITIC Curve specifies that equipment should be able to withstand voltage variations within $\pm 10\%$ (variations that last longer than 10 s).

3.3.1.1 Example limits

Voltage regulation standards in North America vary from state to state and utility to utility. The most commonly applied standard in the United States is ANSI C84.1-2006 [B1]. Voltage regulation requirements are defined in the following two categories.

- Range A is for normal conditions, and the required regulation is $\pm 5\%$ on a 120 V base at the service entrance (for services above 600 V, the required regulation is -2.5% to $+5\%$).
- Range B is for short durations or unusual conditions. The allowable range for these conditions is 8.3% to $+5.8\%$. A specific definition of these conditions is not provided.

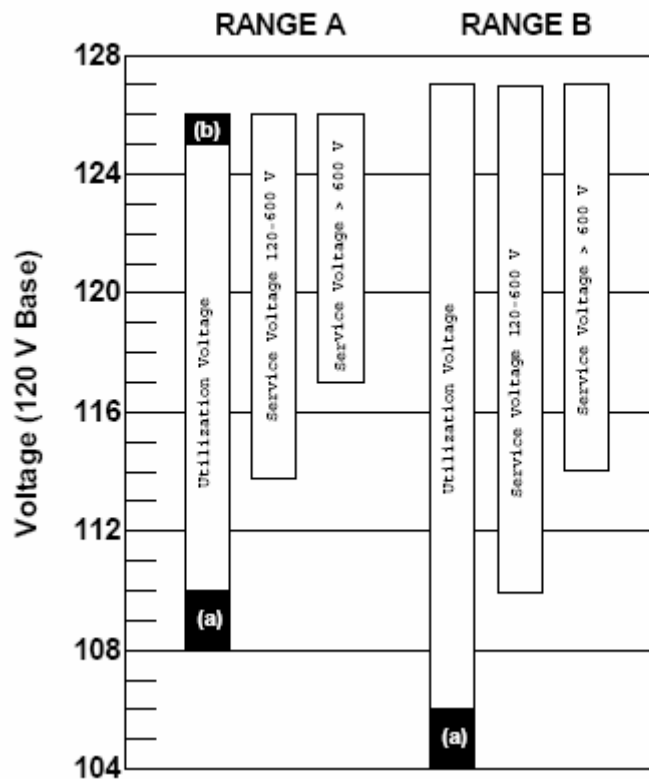


Figure 6—Voltage regulation requirements from ANSI C84.1-2006 [B1]

IEC 61000-2-2:2002 [B4] mentions that the normal operational tolerances are $\pm 10\%$ of the declared voltage. This is the basis of requirements for voltage regulation in EN 50160-1999 [B2] for the European Community. EN 50160-1999 [B2] requires that voltage regulation [at the low-voltage (LV) point of common coupling] be within $\pm 10\%$ for 95% of the 10 min samples in a 1 week period. All 10 min samples should be within -15% to $+10\%$, excluding voltage dips.

3.3.1.2 Survey results

Figure 7 illustrates the statistics of voltage regulation levels obtained in the EPRI DPQ project. Voltage regulation is described in this case as the range of voltage over the period of the day expressed as a percent of nominal. The voltage regulation was not described in terms plus or minus from nominal because of difficulties of defining the nominal voltage at different points on the distribution system. However, the results illustrate that almost all sites achieve a total variation level within 10%. The 95% for the entire sample of sites is a voltage regulation range of 8.5%.

3.3.1.3 Recommended limit and assessment method

Because the objective is to define minimum acceptable requirements based on an evaluation at the PCC (realizing that the voltage variations inside a facility may be greater than the voltage variations on the system or at the supply point), the recommended level is $\pm 5\%$ with an evaluation at the 95% probability level.

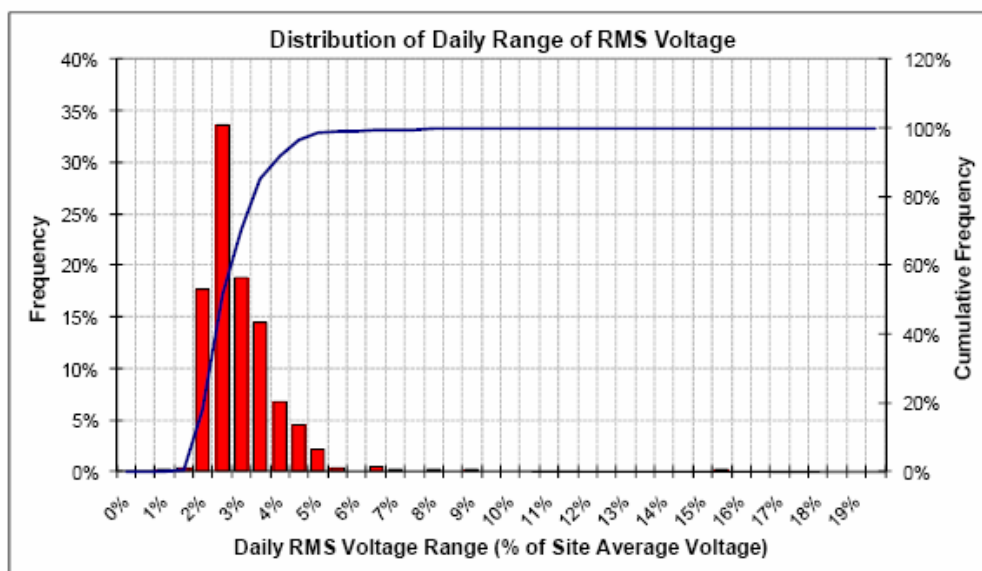


Figure 7—Voltage regulation statistics (total daily voltage variation range) from EPRI DPQ project (1 June 1993 to 1 June 1995)

3.3.2 Voltage imbalance

Voltage imbalance causes increased heating in motors and can result in unbalanced currents and noncharacteristic harmonics for electronic equipment like adjustable speed drives. High-efficiency motors can be more susceptible to problems with unbalanced voltages due to lower negative sequence reactance values.

Voltage imbalance measured as the negative sequence component of the voltage divided by the positive sequence component is most important for motor loads and is the basis of most international standards for imbalance.

3.3.2.1 Example limits

[ANSI C84.1-2006 \[B1\]](#) recommends that voltage imbalance be limited to 3%. It is measured as the maximum deviation divided by the average of the three phases. This value can be influenced by the zero sequence voltage as well as by the negative sequence voltage. When using this method, line-to-line voltage measurements should be used to improve the accuracy and more closely match the sequence component method of voltage imbalance determination.

[IEC 61000-2-2:2002 \[B4\]](#) specifies a compatibility level of 2% for voltage imbalance, recognizing that systems with large single-phase loads may have voltage imbalance levels as high as 3%.

[EN 50160-1999 \[B2\]](#) requires that utilities maintain voltage imbalance less than 2% for 95% of the 10 min samples in 1 week. For systems with significant single-phase loads, the imbalance can be as high as 3%.

3.3.2.2 Survey results

Negative sequence voltage imbalance statistics from the EPRI DPQ project are given in Figure 8. It shows that the 95% level for negative sequence imbalance over all the sites in the project was about 1.3%.

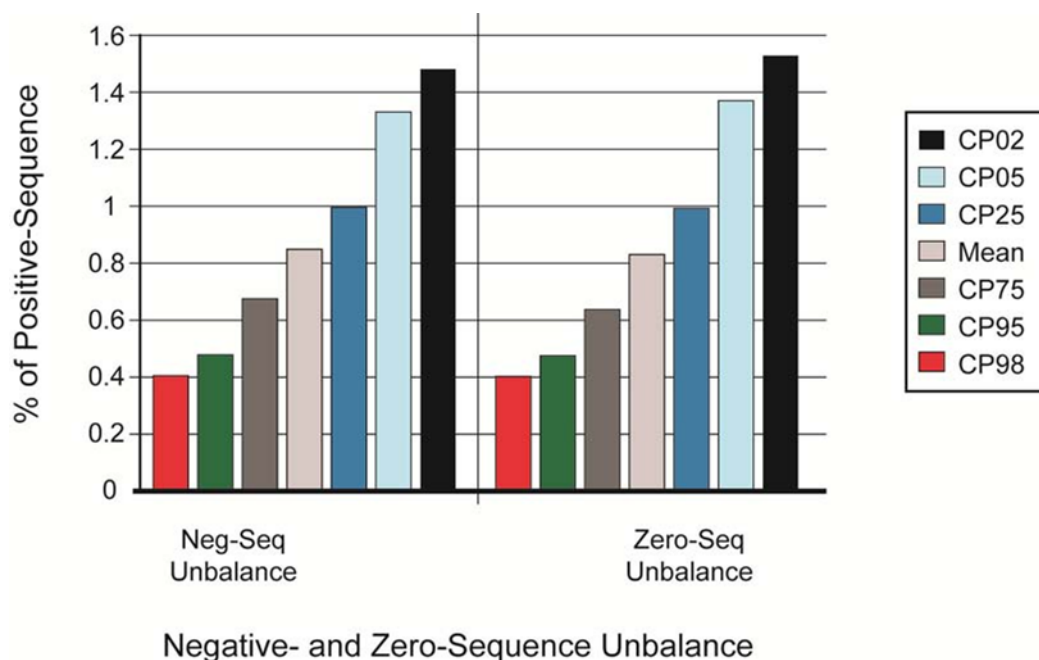


Figure 8—Voltage imbalance statistics (entire data set for all sites) from EPRI DPQ project (1 June 1993 to 1 June 1995)

The CIGRE C4.07/CIRED Working Group [B36] gathered survey data from around the world. Only a few surveys actually compiled information about imbalance, but the results are still informative for developing a recommended minimum performance level. Figure 9 illustrates the results (95% probability level over 1 week of measurements at each site) for the different system voltage levels. The medium voltage (MV) results are most interesting. In this case, none of the sites had an imbalance level exceeding 2% at the 95% probability level.

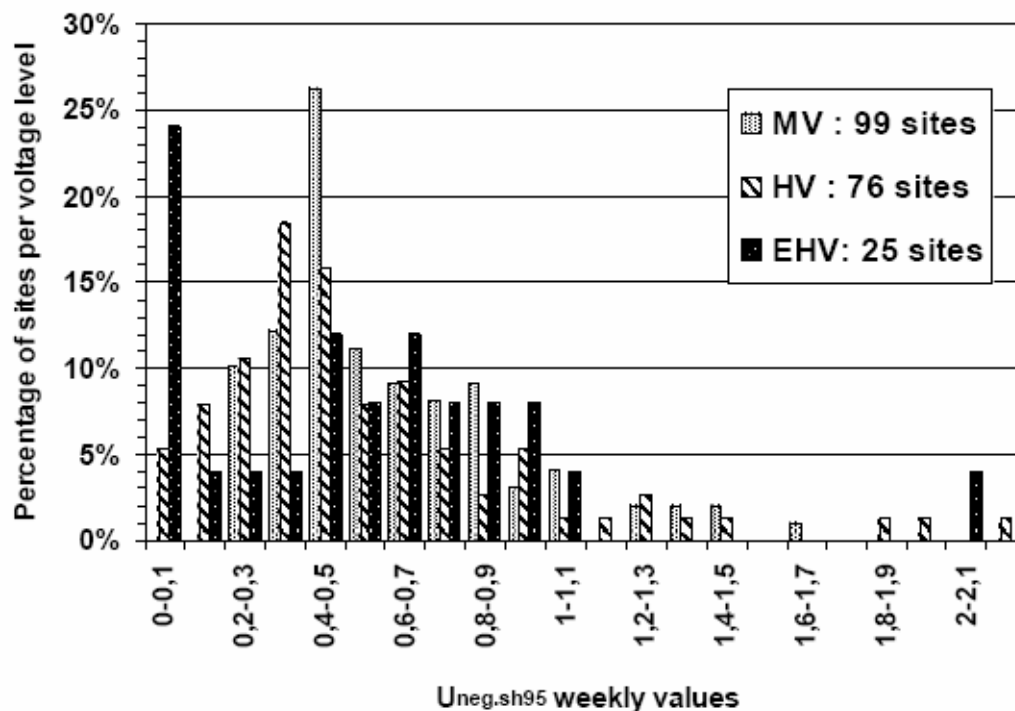
3.3.2.3 Recommended limit and assessment method

The CIGRE working group recommends that the 95% value for weekly measurements of the 10 min imbalance values be used for comparison with recommended imbalance limits (voltage characteristics). The most commonly used value for this characteristic is 2%. It seems to be a value that is very achievable and also has minimal consequences for customer equipment applied at low voltage. Equipment applied at medium voltage might have more stringent requirements for voltage balance.

3.3.3 Voltage distortion

Harmonic distortion in the supply voltage results in increased heating in transformers, motors, capacitors, and conductors. This increased heating is usually the most important effect. However, voltage distortion in the supply system can excite resonances and overload customer power factor correction equipment. Sensitivity of customer equipment to voltage distortion may be dependent on both the magnitude of the distortion levels and the specific harmonic components. For instance, transformer eddy current losses increase with approximately the square of the frequency.

Very short-term effects of harmonics can include the misoperation of electronic controls or the operation of uninterruptible power supplies. There may be a need for limits on the short-term harmonics as well as on the long-term levels that cause heating.



NOTE—The use of commas is the European convention instead of the U.S. decimal point convention.²

Figure 9—Measurement data for voltage unbalance at MV, high voltage (HV), and extremely high voltage (EHV)—all sites (CIGRE C4.07/CIRED Report [B36])