

IEEE Guide for Identifying and Improving Voltage Quality in Power Systems

IEEE Power and Energy Society

Sponsored by the
Transmission and Distribution Committee

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Abstract: The use of some electrical equipment attached to typical power systems creates power 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 power quality and indicating how to improve them. Other documents that treat these subjects in more detail are referenced.

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

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IEEE Guide for Identifying and Improving Voltage Quality in Power Systems

1. Overview

1.1 Scope

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

- a) Power 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.

1.2 Purpose

The primary purpose of this guide is to assist power delivery system designers and operators in delivering power with power 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.

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 power quality characteristics described in [Clause 3](#). Power 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. With the proliferation of distributed energy resources (DER) such as wind turbines, solar panels, and fuel cells, generation is no longer centralized into a small number of power plants. DER is connected to transmission, distribution, and consumer low voltage electrical systems. Figure 1 shows a diagram of a changing electrical power system.

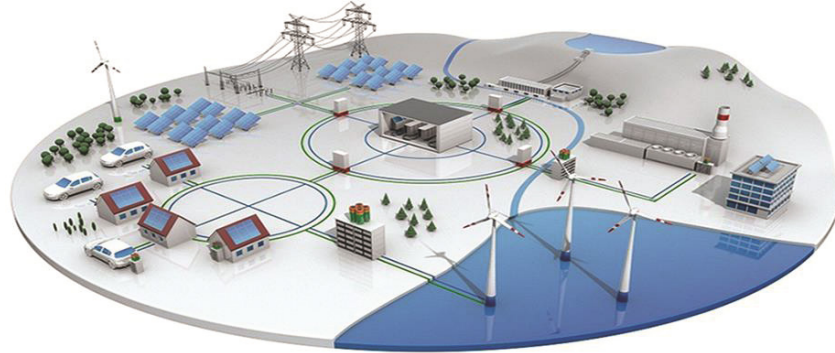


Figure 1—The electric power system

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.

Distribution lines (commonly called primaries) are usually not interconnected but are designed in a radial fashion except in some cities that use a mesh or network distribution scheme. Traditional radial distribution systems consist of a source originating at a substation in which the system voltage is stepped down (see 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. This protection scheme is commonly called line sectionalization. With smart grid becoming more common, another distribution protection scheme called segmentation is being utilized. Segmentation involves electronic line reclosers communicating with one another and isolating the smallest amount of customers closest to the fault location. It also involves switching portions of one circuit over to other circuits in some cases. DER sources can connect to distribution feeders near the substation or out on the feeder. Typically, there is a line protective component placed at the DER metering point.

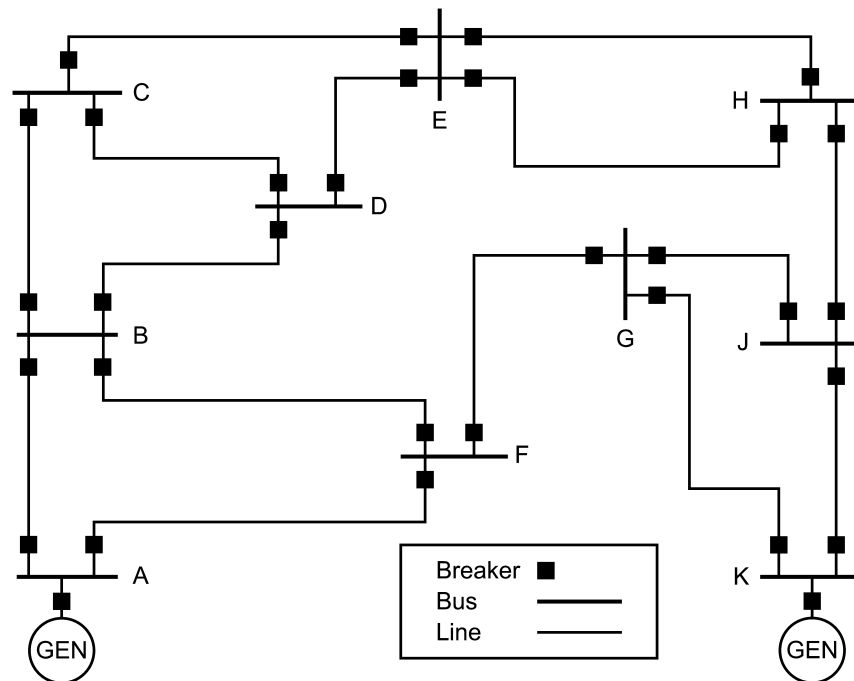


Figure 2—Transmission network showing generators, substations, and line sections

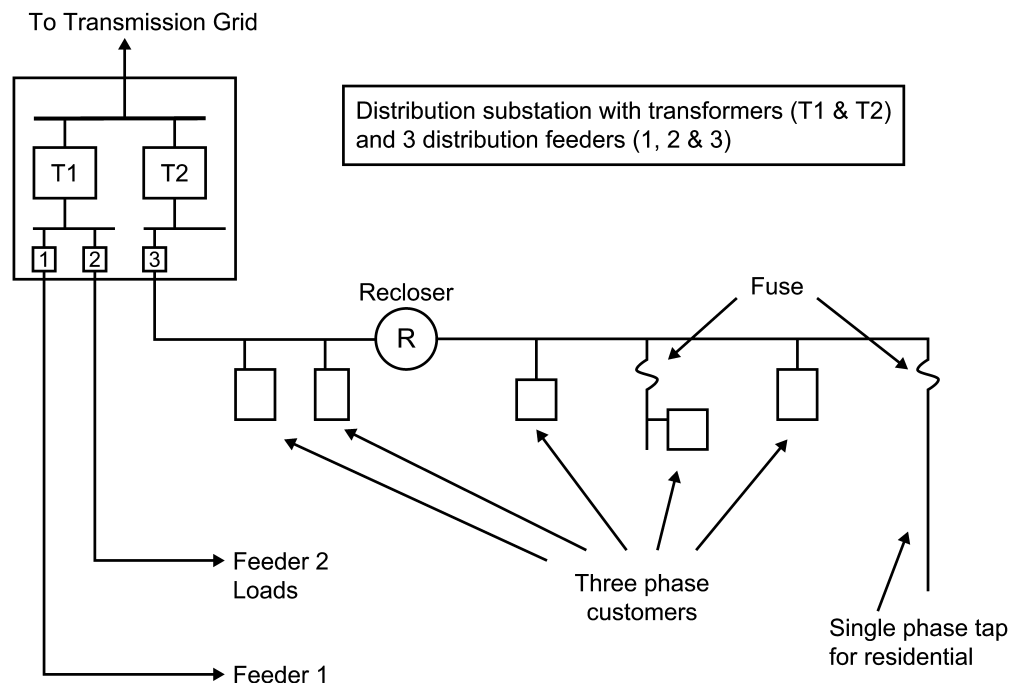


Figure 3—Distribution substation and example of recloser and fuses along line

Power system voltages are typically expressed in line-to-line kV. The line-to-line voltage is $\sqrt{3}$ or 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. However, they may also have lateral tap lines that are only providing one or two phases, 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

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

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 component and then trip or open the proper isolating component to cause the fewest number of customers to experience the loss of power.

3. Identifying power quality in electrical systems

3.1 Introduction

This subclause describes expected power quality characteristics at various levels of a power system. Electric utilities strive to maintain good power quality. Limiting disturbances and distortion that affect power quality minimizes damage and the costs to maintain the network. There are some statutory guidelines, generally put forward by regulatory agencies that provide limits for frequency, voltage, and sometimes reliability (interruptions).

Methods of describing the power quality characteristics are presented along with example benchmarking results. Important characteristics that may impact the power quality characteristics are also described. Finally, most utilities strive to meet their customers' needs for reliability and power quality.

3.2 Basic types of power quality variations

It is useful to divide power quality characteristics into the following two basic categories:

- a) **Steady-state (continuous) power 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 or current? What is the imbalance among the three-phase voltages or current? 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.
- b) **Disturbances.** This refers to power quality variations that occur at random intervals and are not associated with the continuous characteristics of the voltage. The variations include sustained interruptions, 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 power 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 power quality levels in both of these major categories along with example benchmarking results that can provide the basis for establishing targets and limits.

3.3 Steady-state (continuous) voltage characteristics

Steady-state power quality characteristics must meet minimum requirements to assure the proper operation of equipment. The basic concepts of voltage levels are established in ANSI C84.1 [B3]¹ where service voltage ranges and utilization voltage ranges are stated. There are two ranges, range A and range B. The service voltage is at the point where the electrical system of the supplier and the electrical system of the user are connected. The utilization voltage is at the line terminals of utilization equipment.

The concepts of compatibility levels are established in IEC 61000-2-2:2002 [B20]. 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 50160-2010/A1:2015 [B14] 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 relationship between the severity of network events (left-most curve) and the sensitivity of end-use equipment to those events (right-most curve). The goal is for the severity of all network events to be below a pre-defined level of compatibility (center) and for all equipment to also be immune to misoperation for all events below that same compatibility level. Various planning, alarm, and immunity levels are established and maintained in order to help achieve this outcome.

¹ The numbers in brackets correspond to those of the bibliography in Annex C.

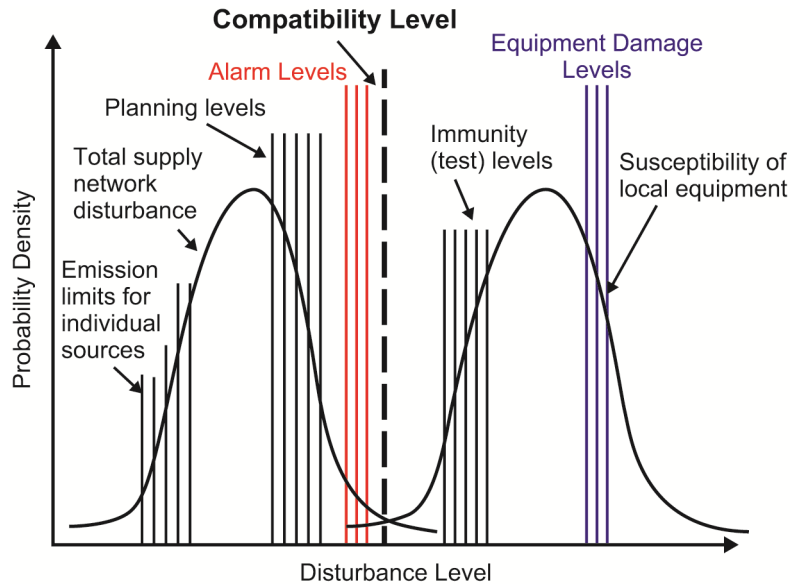


Figure 4—Concept of compatibility levels for the electric supply system and the immunity characteristics of equipment

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

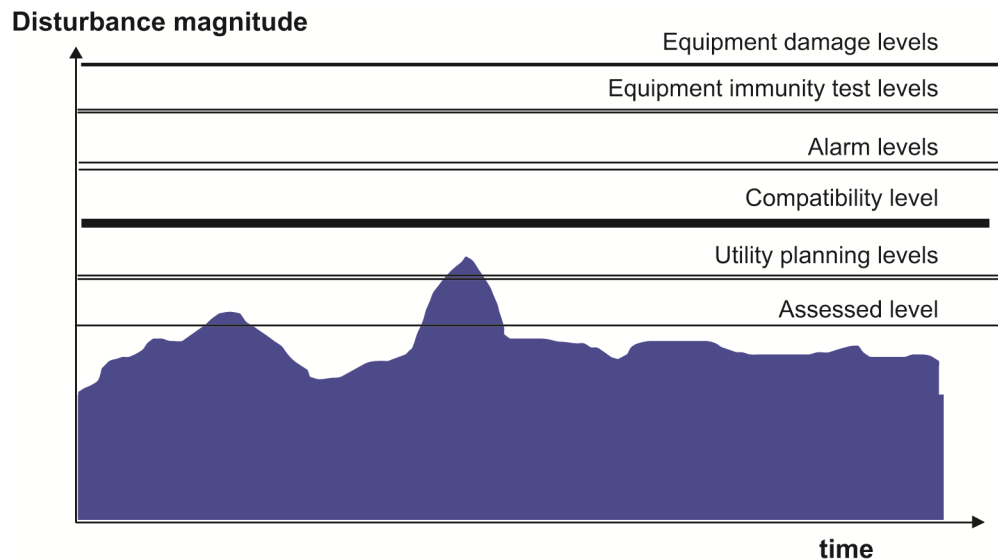


Figure 5—Important concepts for compatibility levels of the steady-state power quality characteristics of the supply system

The following is a list of the characteristics illustrated in Figure 5:

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.

Compatibility level—This is the level of quality that, if exceeded, could affect equipment performance, or objectionable flicker observed.

Utility 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).

Additionally, this level should define the steady-state power quality levels that 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.

The steady-state power quality levels should be evaluated using the measurement procedures outlined in IEC 61000-4-30: 2015 [B24]. This standard provides a convenient reference to make sure that all systems are being evaluated in the same manner. The IEEE 1159 working group has developed a similar set of recommended characterization procedures (IEEE Std 1159™-2009 [B31]) that are consistent with the methods in the IEC standard.

Studies of the typical levels of these steady-state characteristics are provided from the following two important sources:

- The EPRI Distribution Power Quality (DPQ) project ([B15]) 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 from the method recommended in IEC 61000-4-30: 2015 [B24] 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 [B10], 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.

3.3.1 Voltage regulation

The ability of equipment to handle steady-state voltage variations varies. 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 that last longer than 10 s within $\pm 10\%$ of equipment nominal.

Steady-state voltage will vary at different points along the electric supply network. As load current flows through the lines and transformers, voltage drops are caused by the impedances. Utilities use various design strategies and equipment to control or regulate the voltage levels on the network to provide the end users with suitable voltage levels.

Voltage regulation of a system is affected by the electrical equipment from the generators to the end user. However, voltage regulation is tied most closely with the distribution system. The distribution system will typically have voltage-regulating transformers that can either increase or decrease the voltage that is supplied to the voltage input of service transformers. These voltage-regulating transformers are commonly capable of increasing or decreasing the distribution voltage up to 10%, usually in multiple steps of either 0.625% or 1.25% per step. The wide operating range allows the distribution voltage to correct automatically for the varying load conditions and voltage variations on the system. The voltage-regulating feature can either be built into the substation distribution transformer itself or be separate regulating transformers located downstream of the substation transformer. Substation transformers with regulating capabilities are called either tap changing under load (TCUL) or on load tap changing (OLTC) transformers. They have multitapped transformer windings usually designed into the low-voltage winding of the transformer. All three phases will change steps simultaneously either to raise or lower the voltage by changing the transformation ratio. Single-phase voltage regulators are also used extensively on distribution systems downstream of the substation transformer. They are often installed at strategic points along distribution lines to maintain proper voltage levels and can be cascaded along the circuit.

The current that flows to provide the reactive power requirements of inductive loads, such as motors, on the network is a significant cause of line voltage drop. A phase angle relationship exists between the reactive and real currents drawn by loads on a power system. A properly sized capacitor located near an inductive load will serve to counteract the reactive power conducted through the power system by the inductive load. By using capacitor banks to provide reactive power for inductive loads, such as motors, the total current flowing from the substation is reduced, and so the voltage drop along the distribution line is reduced also. Utilities use capacitor banks located on distribution lines or in substations to help control voltage by controlling reactive power flow. Utility capacitor banks either will be switched by automatic controls or will be manually switched seasonally. Automatic capacitor switching controls use such things as voltage level, temperature, time of day, or reactive power flow to determine whether to close or open a particular capacitor bank.

3.3.1.1 Recommended limit and assessment method

Because the objective is to define minimum acceptable requirements based on an evaluation at the Point of Common Coupling (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.

3.3.1.2 Example survey

Figure 6 illustrates the statistics of voltage regulation levels obtained in the EPRI DPQ project [B15]. Voltage regulation is described in this case as the range of voltage over the period of the day expressed as a percent of nominal. Although the percent regulation is given as an absolute value, 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%.

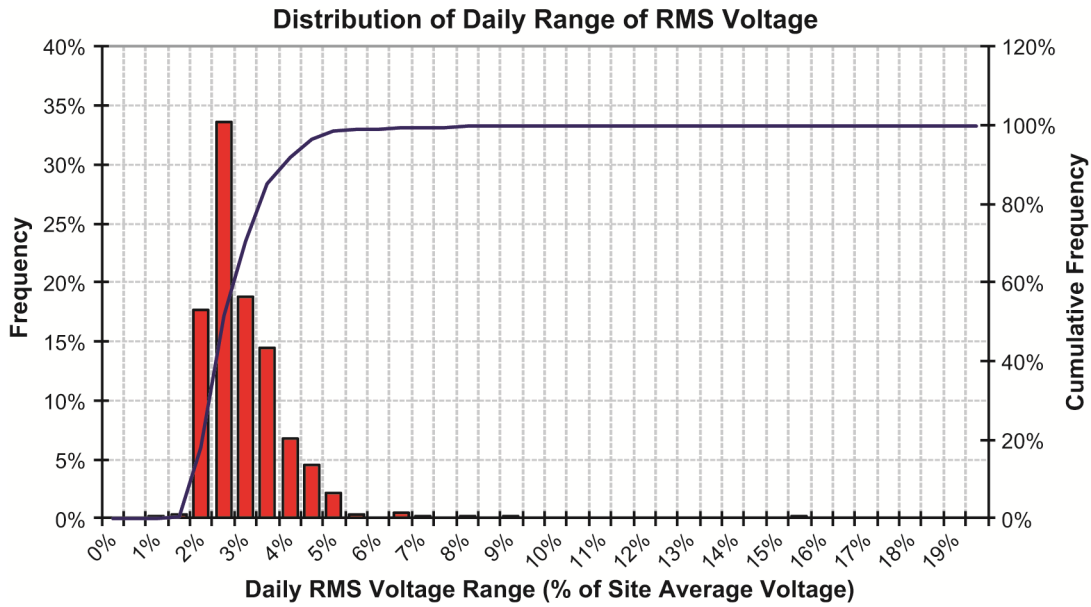


Figure 6—Voltage regulation statistics (total daily voltage variation range) from EPRI DPQ project (1 June 1993 to 1 June 1995) [B15]

3.3.2 Voltage imbalance

Voltage balance is referred to as unbalance or imbalance and both are used interchangeably with one another throughout the industry, even *IEEE Standards Dictionary Online* list both together. In this subclause, the term voltage imbalance is used.²

There are many reasons for voltage imbalance on utility distribution systems. It is well known that the most common cause of voltage imbalance on a utility distribution system is current imbalance on the system itself. Depending on the length of the circuit and the circuit make up, the system may seem to be balanced at the substation but out on the circuit it could have a current imbalance causing a voltage imbalance situation. Current imbalance can become a challenge on utility circuits because the utility system has single-phase customers on the system, along with underground networks and long overhead networks in rural areas. This can create a voltage imbalance at different points on the distribution system and at different times of day. Another cause of voltage imbalance in a utility distribution system is non-transposition of transmission lines. In a transmission system with long circuits with no phase transposition, the coupling with high load balanced current will cause voltage imbalance and current imbalance. The transposing of lines to cancel the effect of the circuit will help keep this type of voltage imbalance at a minimum. VAR balances with capacitor banks and loads on the system can also create balance issues for utility distribution systems. There are two effects from a three-phase capacitor banks when opening a single fuse. One effect is that the VAR imbalance may cause a voltage imbalance on the system. The other effect is the loss of one fuse will cause a voltage drop on that phase, and the remaining phase will have the associated voltage rise. VARs are also developed from underground cable capacitance. Single-phase underground networks can cause imbalances due to VAR loading from the cabling on the system. A larger underground circuit on one phase vs. another phase can cause the same effect as a blown fuse on a three-phase capacitor bank.

Banking of transformers can cause voltage imbalance if the transformer impedances are not matched within a certain percentage of their %Z rating. When installing a three-phase bank, the bank impedances should be within 7.5% of each other for %Z rated values more than 2.5% and 10% for values %Z rated values 2.5%

²IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>.

and less (IEEE Std C57.12.00-2015 [B37]). This will help ensure that the loading on the bank will not cause excessive voltage drop difference on each bank thus causing a voltage imbalance.

With a renewed emphasis on voltage reduction to decrease loading on the utility system, other challenges are presented. Specifically, single-phase regulators on a utility system installed to level the voltage profile along the circuit, may create voltage imbalance. Most regulator controls are phase to ground (neutral) sensing for voltage regulation. In most cases, the single-phase regulator will improve voltage balance. However, if a system has imbalanced current, single-phase regulators may raise or lower each phase-to-neutral voltage in significantly different amounts, and could make the system have a greater voltage imbalance, when measuring phase-to-phase voltage, due to a phase angle shift. Even a 1 to 2 degree phase angle shift can have a great effect on the voltage imbalance at the measured point in the system.

Understanding the effects of voltage imbalance is important to recognize an issue on the electrical system. Voltage imbalance has an influence on heating of three-phase devices such as motors, transformers, drives, and rectifier circuits. This excess heating can cause damage to the device. For example, according to Figure 7, a three-phase motor running at full load should be de-rated if the voltage imbalance exceeds 1%.

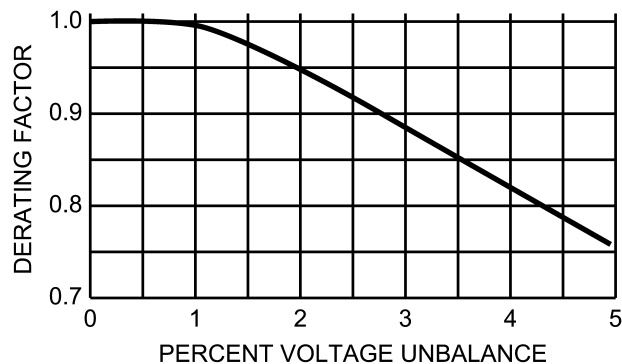


Figure 7—Figure 14-1 in NEMA MG 1 [B50]

The efficiency of the device can be reduced as well. Experimentation has shown that when voltage imbalance is between 3% and 5% the efficiency of a motor can decline by 1% to 3% (see Agamloh, Peele, and Grappe article [B1]). ANSI C-84.1 [B3] standard Annex C field survey results states that “approximately 98% of the electric supply systems surveyed were within the 0% to 3% voltage imbalance range.” A 1% voltage imbalance can cause approximately 7% to 8% current imbalance in traditional poly-phase motors. Effects on VSD and rectifying load can cause even higher current imbalances. Motors typically have circuit protection installed in the circuit to trip them off, when they experience imbalance conditions above a threshold value. This includes the extreme case of voltage imbalance known as single phasing. This is where one of the incoming phases serving the loads has been lost. Single phasing can originate on the primary source voltage or the secondary source voltage. Protection relays use three basic sensing techniques, thermal, current, or voltage, depending on their function. Many of the devices installed to protect the motor and the circuit, are protection relays and fall into different categories such as Thermal Overload Relay, Over Current relay, Over and Under Voltage Relay, Single Phasing Relay, and Imbalance relay.

Voltage imbalance relays typically operate by sensing an imbalance in the phase-to-phase voltage, such that once the sensed imbalance exceeds a specified threshold, a control signal is generated that may be used to interrupt power flow to the protected device (by tripping a circuit breaker or contactor). These devices can be put on each individual motor for protection, or with the advent of shunt trip breakers, on entire circuits or facilities. Some facilities have also started implementing Voltage Imbalance relays on their main switchgear.

There are different ways to calculate voltage imbalance and they have been well defined in many papers and documents. NEMA’s definition of voltage imbalance in Equation (1) is the most useful definition