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Voltage Thresholds for Distribution Planning

Review of Voltage Standards and Potential Impacts from Steady-State Excursions

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ABSTRACT

Voltage range standards were derived for distribution systems characterized by unidirectional power flows and limited to no visibility of customer voltages. This paradigm is being challenged by the increasing penetration of distributed energy resources (DER), and the on-going rollout of advanced metering infrastructure (AMI). AMI, for example, provides an unprecedented level of visibility in customer voltages that can be used to quantify the magnitude, duration, and frequency of voltage excursions outside of the standard ranges. Most of the existing voltage range standards do not consider the full use of this information. Consequently, distribution planners may be unsure what magnitude, duration, and frequency of steady-state voltage excursions, identified with this new level of visibility, warrant mitigation measures. This challenge is exacerbated by DER, as planners must be concerned with potential overvoltage excursions due to injected power, as well as undervoltages. As a result, it becomes important to understand how equipment sensitivities, changing system operations, and increasing visibility are accounted for, or may impact existing standards. This study provides a foundation for understanding the potential impacts of these types of voltage excursions, as well as the implications of altering existing planning criteria for steady-state voltage magnitudes. This is achieved through a review of current industry standards, along with the identification and assessment of potential impacts needed to guide future research.

Keywords

Steady-state voltage excursions
Steady-state voltage standards
Distribution planning
Planning criteria

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1
INTRODUCTION

The intent of this report is to increase understanding concerning potential implications of altering existing planning criteria for steady-state voltage magnitudes. This is achieved through a review of current industry standards, an assessment of potential impacts, and an examination of future research needs.

Background

Electricity is a product supplied by electric utilities to electricity end users, who use electric energy to operate diverse electric equipment to satisfy various needs. Unlike many other goods, whose properties can be controlled during the manufacturing process, electricity quality is affected by instantaneous events and disturbances that cannot be easily intervened. As a result, electricity characteristics are specified in terms of ranges of values, statistics of occurrence, and by reference to specific operating conditions of the supply system [1]. The quality of electricity (also referred to as power quality or voltage quality [1, 2]) is regulated by various standards that have been established to balance between the needs and desires of three key stakeholder groups: electric utilities, electric equipment manufacturers, and electricity end users as illustrated in Figure 1-1. Electricity end users want power with which their equipment operates as they are designed. Equipment manufacturers design their products to properly operate for specified range of supply voltages. Electric utilities are responsible for supplying the end users with power of specified quality.

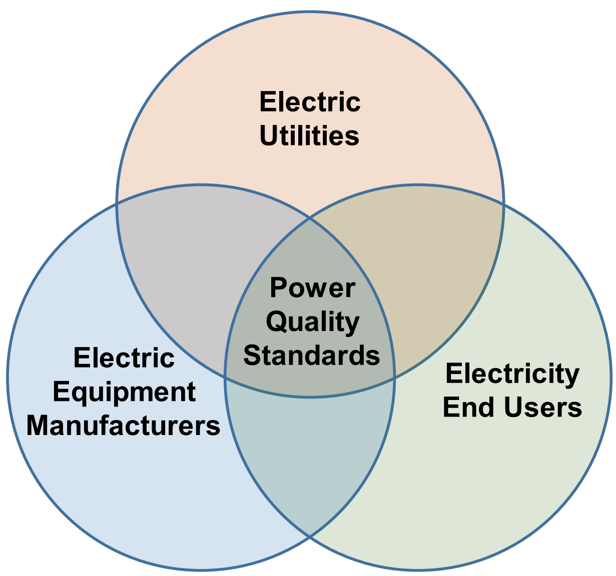

Figure 1-1
Key stakeholders of power quality standards

This report deals with one of the fundamental attributes of power (i.e. voltage) quality: the ranges of the supply voltage magnitude. There are two contrasting perspectives to voltage ranges: power quality (i.e. supply) perspective and electromagnetic compatibility (EMC) or equipment tolerance perspective. From the power quality perspective, distribution systems must be planned and operated in a manner guaranteeing that electric end users' voltages are within ranges defined by various power supply quality standards. Voltages can be maintained within arbitrarily small range. Tighter ranges, however, translate into higher costs for utilities to maintain the voltages within the range. From the EMC perspective, the tolerance of electrical equipment to root-mean-squared (rms) voltage level variations is to a large extent a design factor. Equipment can be designed and manufactured to be less sensitive to voltage variations but this will likely increase the equipment cost and may be counterproductive to other design factors such as equipment efficiency, size, etc. Given these two contrasting perspectives, voltage range standards have been established as an economic compromise between minimizing the overall cost for the utility (and thus to the electricity end users) and maintaining voltages within the ranges and for the electric equipment manufacturers to ensure appropriate equipment operation within the ranges.

The voltage range standards are largely based on the operational characteristics of induction motors, incandescent light bulbs, and other key equipment. However, incandescent bulbs are being replaced with compact fluorescent lights (CFLs) and light-emitting diodes (LEDs), and induction motors are increasingly being coupled with adjustable speed drives (ASDs). Moreover, the voltage range standards were largely determined for distribution systems with one-directional power flows and with limited to no visibility in customer voltages. As a result, the existing standards were formed primarily with undervoltage conditions in mind, not overvoltage. This paradigm is being challenged by the increasing penetration of distributed energy resources (DER) and the on-going rollout of advanced metering infrastructure (AMI). As a result, it becomes important to understand how equipment sensitivities, changing system operations, and increasing visibility are accounted for or may impact existing standards.

For example, DER, such as PV, can cause unprecedented increase in system voltage when injecting power into the system. Conversely, when absorbing power from the system, DER such as electric vehicles or storage, may contribute to voltage drop magnitudes, durations, and frequencies that used to be rare. In general, DER can make it more challenging to maintain voltages within specified ranges. Relaxing the existing voltage standards would allow integrating more DER into the existing distribution systems without the need for costly mitigation measures.

Additionally, AMI and other modern distribution measurement sources provide unprecedented visibility in customer power quality [3], enabling utilities to quantify the magnitude, duration, and frequency of voltage excursions from the standard ranges. Most of the existing voltage range standards do not fully consider the use of this information. Consequently, distribution planners may be unsure when mitigation measures are necessary.

Steady-State Voltage Excursions

This report focuses on steady-state voltage excursions, i.e., steady-state rms voltages that deviate from the ranges specified in existing standards.

When defining steady-state voltage excursions, the report refers to IEEE Std. 1159-2009 classification of long-duration rms voltage variations with durations exceeding one minute [4], see Table 1-1. Investigation of other rms voltage variation classes listed in Table 1-1 as well as other power quality aspects, such as transient voltage variations, oscillatory phenomena, and waveform distortions, are not within the scope of this report. However, voltage sags and swells that have shorter duration and larger excursion magnitude are touched upon where appropriate. Figure 1-2 illustrates the magnitude and duration of voltage excursions of focus in relationship with the Information Technology Industry Council (ITIC) curve, discussed in Chapter 2.

Table 1-1
IEEE 1159-2009 classification of rms voltage variations [4]

Duration	Type	Duration	Magnitude
Instantaneous variations	Sags / dips	0.5 – 30 cycles	0.1 – 0.9 pu
	Swells	0.5 – 30 cycles	1.1 – 1.8 pu
Momentary variations	Interruptions	0.5 cycles – 3 s	<0.1 pu
	Sags / dips	30 cycles – 3 s	0.1 – 0.9 pu
	Swells	30 cycles – 3 s	1.1 – 1.4 pu
Temporary variations	Interruptions	>3s – 1min	<0.1 pu
	Sags / dips	>3s – 1min	0.1 – 0.9 pu
	Swells	>3s – 1min	1.1 – 1.2 pu
Long Duration Variations	Sustained Interruption	>1 min	0.0 pu
	Undervoltage	**>1 min**	**0.8 – 0.9 pu**
	Overvoltage	**>1 min**	**1.1 – 1.2 pu**

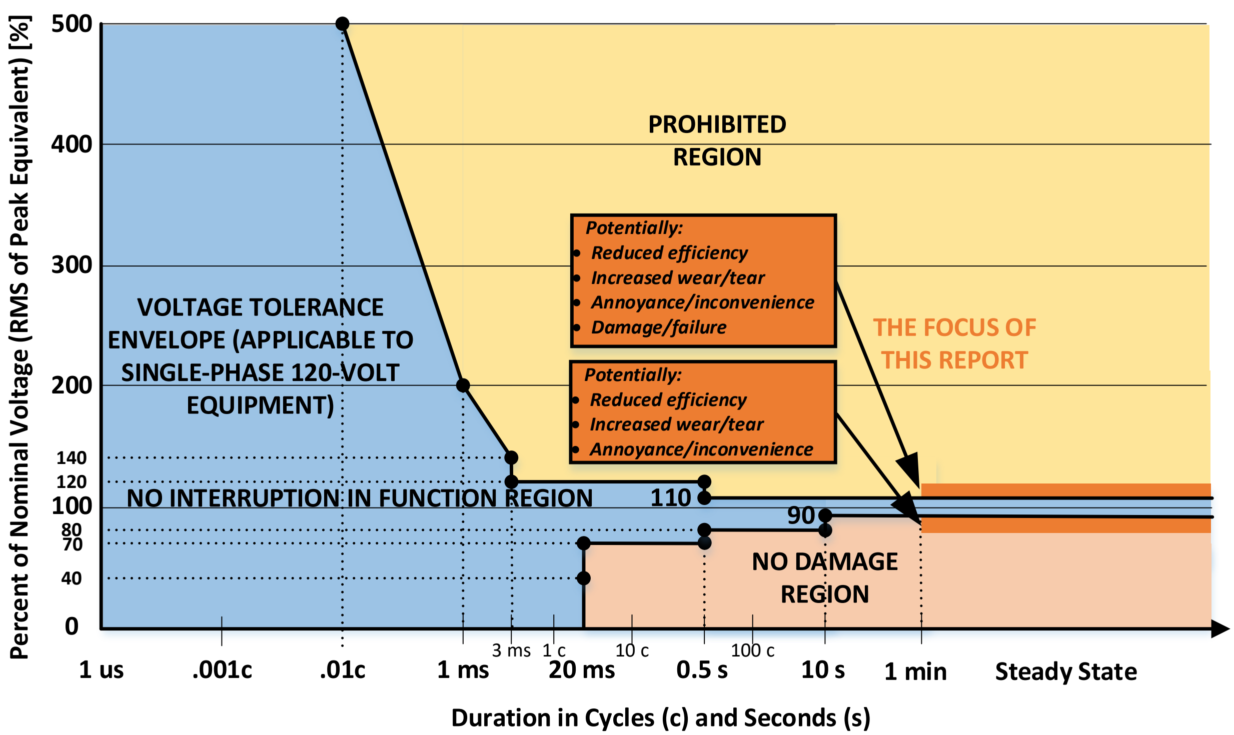

Figure 1-2
Steady-state voltage excursions of focus illustrated on the ITIC curve

There are many types of voltage range standards that apply to different locations and have different purposes, and many of these are reviewed in detail in Chapter 2. To illustrate the nature of these voltage ranges, some different voltage range types using the ANSI Std. C84.1 are illustrated in Figure 1-3. Other standards may utilize slightly different terminology but the concepts are very similar. First, service and utilization voltages must be distinguished. Utilization voltage is the voltage at the equipment location in the end-use facility. Power quality standards, such as ANSI C84.1, specify permissible ranges for utilization voltages to ensure proper operation of end-use equipment. Typically, utilization voltages are the responsibility of the end-use facility. On the other hand, service voltage is defined as the voltage at the point where the utility and end-use facility interface, which is also the common metering point. This term may be referred to as supply voltage in some standards. Power quality standards specify permitted ranges for service voltages by leaving some headroom for voltage drop, and potentially voltage rise, at the end-use facility.

Electric utilities are responsible for maintaining the service voltages within the specified ranges. On the other hand, electric equipment manufacturers are expected to design their products to function properly within the utilization voltage range.

Many but not all equipment types are manufactured to perform optimally in the middle of the utilization voltage band. Some equipment, particularly some electric motors, are manufactured to perform optimally at the most common utilization voltage level, which may be slightly lower than the system nominal voltage. For example, it is common for motors, that are designed for a 120-volt system, to operate optimally at 115 V. To communicate this, some manufacturers assign the equipment nameplate voltages slightly below the nominal system voltage.

Service points are commonly in the low-voltage secondary circuits. It is customary for distribution planners to assign a certain margin for voltage drop/rise over the service transformer and secondary circuit wiring, and to focus much of distribution planning on maintaining the medium-voltages in the resulting tighter voltage range. Secondary circuits are typically designed independently of the medium-voltage circuits to guarantee sufficiently small voltage drops/rises.

The focus of this report is on the *service voltages* since they are the responsibility of the utility to maintain, and voltage range standards focus on service (and utilization) voltages. This report also extensively discusses *utilization voltages* that are the focus of equipment electromagnetic tolerance standards. This report is less concerned with utility medium-voltage ranges that utilities typically derive from service voltage ranges based on their planning guidelines.

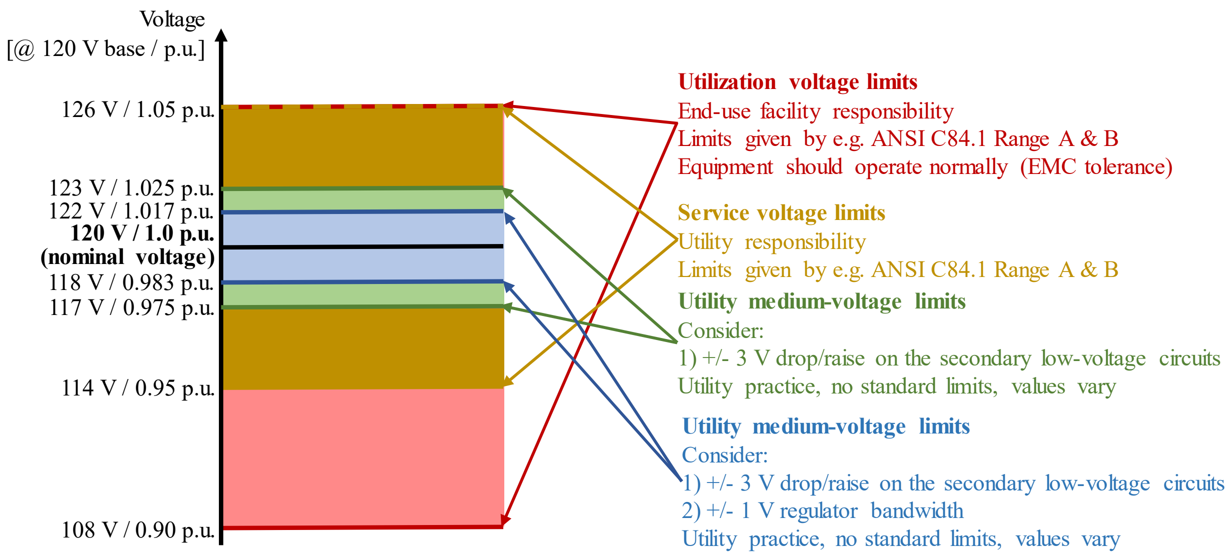

Figure 1-3
Illustration of different voltage ranges (example ANSI C84.1-2011 range A limits)

Two aspects are worth highlighting regarding the voltage ranges:

1. From a utility perspective, neglecting energy conservation and other secondary objectives, any service voltage within the specified voltage range is acceptable. In other words, there is no optimal voltage and the voltage limits must only be met (not exceeded). Electric equipment is required to operate satisfactorily within the specified voltage range although, equipment efficiency and operational properties are allowed to vary for voltages within the specified ranges.
2. Although voltage range standards may permit between +/- 5% or +/- 10% variation in the entire utility territory voltages, the variations allowed in individual customer voltages is much lower than this. For example, an instantaneous shift of 0.5% in voltage can cause a perceptible variation in light intensity of conventional incandescent light bulbs and a less noticeable change in light intensity of gaseous discharge lighting equipment. As a result, distribution systems must be planned and operated to avoid power quality impacts such as flicker. However, these impacts are not within the focus of this report.

Impacts of Steady-State Voltage Excursions

Steady-state voltage excursions have various impacts on end-use devices. Smaller excursions may decrease equipment efficiency and increase equipment wear and tear resulting in reduced equipment life. Excursions with sufficiently high magnitude can also result in annoyance or inconvenience in the form of improper operation. Finally, steady-state overvoltages with sufficiently high magnitudes can result in immediate or rapid equipment failure particularly in electronic equipment. The steady-state overvoltage and undervoltage impacts on end-use devices are discussed in detail in Chapter 3.

Causes of Steady-State Voltage Excursions

Steady-state voltage excursions are typically not caused by system faults but by variations in load and generation and by the system switching and voltage regulation operation [2, 4]. The variations are typically larger further from the substation due to increased short-circuit impedance. In particular, voltages can vary considerably at the "grid edge", especially in the low-voltage secondary circuits, as a result of the constantly varying consumption by large appliances and generation by DER.

Typical causes of steady-state overvoltage include:

- large load switching off
- capacitor switching on
- incorrect/inadequate voltage regulation (especially high transformer taps or capacitors not switched off during low-load periods)
- DER power injection (e.g. PV generation)

Additionally, long-duration overvoltages can also be caused by [5, 6]:

- sustained earth faults (systems earthed with tuned reactance)
- broken neutral on LV network
- voltage unbalance
- malfunctioning voltage regulator or capacitor-bank controller
- poorly installed voltage regulation equipment

On the other hand, typical steady-stage undervoltage causes include [2, 4]:

- large load switching on
- capacitor switching off
- incorrect/inadequate voltage regulation (especially peak load periods on weak feeders),
- DER power consumption (e.g. electric vehicle charging)
- circuit (section such as secondary circuit) overloads
- poor feeder power factor

When voltage regulation set points are close to the upper end of the permissible ranges, some customers close to the voltage regulation equipment may experience sustained overvoltages that leave less margin for short-duration overvoltages such as voltage swells. In some places, this is associated with increased equipment failures [7, 8].

Additionally, excessive load (i.e. current) unbalance results in large voltage unbalance that may cause overvoltages or undervoltages in some of the phases [5].

Measures for Minimizing Steady-Stage Voltage Excursions

Voltage regulation (minimizing steady-state voltage excursions) is a significant focus of distribution planning and operation. In planning, the system is designed to limit steady-state voltage excursions to an acceptable level at the least possible cost. Among other things, this involves designing the system to be adequately strong (sufficiently small short-circuit impedances) and utilizing appropriate voltage regulation measures. In distribution operations, long-term voltage variations are minimized by optimizing the use of the existing voltage regulation equipment. In general, it is more challenging for both planning and operations to minimize the steady-stage voltage excursions in the presence of DER.

Some typical measures to mitigate steady-stage voltage excursions include (a detailed overview can be found in [9], [10]):

- Adjust existing substation load-tap changer (LTC), voltage regulator, line-drop compensator, or switched capacitor settings to achieve more effective voltage regulation
- Add LTC to regulate substation bus voltage
- Add fixed or switched shunt capacitors to compensate reactive power consumption
- Add voltage regulators at the substation feeder or bus to control the voltage magnitude
- Add line voltage regulators on the feeder to control the voltage magnitude
- Re-conductor feeder lines with a larger conductor type to reduce the impedance
- Change (substation or service) transformers to larger sizes to reduced impedance
- Add dynamic reactive power compensation
- Balance loads to reduce voltage unbalance
- Transfer load from highly loaded feeder to a lower loaded feeder

Report Structure

The remaining chapters in the report address the following:

Common U.S. and European standards on power/service quality and equipment tolerance are reviewed in Chapter 2. This is done to discern relevant information on steady-state voltage limits. Where possible, the history and reasoning for the voltage thresholds is identified to better understand how the thresholds were formed and to inform evaluation of future needs.

Impacts that steady-state voltage excursions may have on different types of electric equipment are examined are evaluated in Chapter 3. Also reviewed are relevant testing performed by EPRI and others, that may provide insights into likely impacts.

Considerations related to the important role of steady-state voltage standards and the impacts that their revision may have are presented in Chapter 4. Important areas for future research, particularly for future testing of the impacts of steady-state voltage deviations, are also discussed in this chapter.

Finally, a list of relevant references, including the reviewed voltage standards and reports on past testing, are listed in Chapter 5.

2
EXISTING STANDARDS ON STEADY-STATE VOLTAGE RANGES

Common U.S. and European standards on power/service quality and equipment tolerance are reviewed in this chapter to discern relevant information on steady-state voltage limits. Where possible, the history and reasoning for the voltage thresholds are identified to better understand how the thresholds were formed and to inform evaluation of future needs. A good introductory review on various power quality standards can be also found in [13]. This chapter also introduces some existing – but not widely utilized – power quality indices for steady-state voltage variations.

Summary of Standard Requirements

A simplified summary of the voltage ranges specified in the standards analyzed in this report is provided in Table 2-1. The reviewed standards can be divided into three rough categories.

- Utility power quality standards: ANSI C84.1, EN-50160, and NRS 048-2-2003
- Equipment tolerance / EMC standards: NEMA MG-1 and other NEMA standards, IEC 61000 standard series, CBEMA curve, ITIC curve, and SEMI F47-0200-2000
- Design standards: IEEE 141-1993, IEEE 241-1993, IEEE 1519-2009, and NEC.

The reviewed standards highlight the important interdependence between the utility power quality standards and the equipment tolerance / EMC standards. Due to practical system considerations, utility service voltages are expected to have infrequent steady-state voltage variations at levels that are somewhat higher than frequent voltage variations. Also shown in the table are examples of how the reviewed utility power quality standards address the allowed frequency and duration of steady-state voltage variations. It should be noted that each of the different standards has many of its own nuances that this table does not explore. Furthermore, each standard is discussed in more detail in the following subsections. The literature on steady-state voltage variation impacts to end use equipment is reviewed in Chapter 3.

Table 2-1
Simplified summary of voltage ranges specified in the analyzed standards

Standard	Voltage Range	Comments
ANSI C84.1-2011	Range A service <600 V systems: +5% to -5% Range A service >600 V systems: +5% to -2.5% Range A utilization >600 V systems: +5% to -10% Range A utilization <600 V systems: +4.167% to -10% (+5 V to -12 V @ 120 V) Range B service <600 V systems: +5.83% to -8.33% (+7 V to -10 V @ 120 V) Range B service >600 V systems: +5.83% to -5% (+7 V to -10 V @ 120 V) Range B utilization: +5.83% to -13.3% (+7 V to -16 V @ 120 V)	Applies to 10-minute averages of rms voltages under normal operating conditions Range B occurrence acceptable but should be limited
IEEE 141-1993	N/A	Refers to ANSI C84.1
IEEE 241-1993	N/A	Refers to ANSI C84.1
IEEE 1519-2009	N/A	No voltage ranges specified.
NEMA MG-1	+10 to -10% (+11.5 V to -11.5 V @ 115 V rated voltage)	Applies to rated motor voltages. Motor ratings typically consider voltage drop in the end use facility. For example, 120 V system motor typically rated to 115 V.
Other NEMA Standards	NEMA ICS7, NEMA ICS 2-2000 & NEMA ICS 61800-2 require similar ranges than NEMA MG-1.	It is out of the scope to analyze all NEMA standards.
NEC	N/A	NEC does not specify voltage ranges but recommends <3% voltage drop in branch circuits and feeders with total maximum drop <5%.
EN-50160	+10% to -10% for 95% of the week +10 to -15% for 100% of the week	10-minute averages of rms voltages Applies to normal operating conditions. Percentages calculated from the nominal system voltage Exceptions to remote and other users.
IEC 61000 series	N/A	No steady-state voltage ranges specified.
CBEMA Curve	+6% to -13%	Applies for voltage variations with duration >2 second
ITIC Curve	+10% to -10%	Applies for voltage variations with duration >10 second
SEMI F47-0200-2000	N/A	Requires ride-through capability for voltage sags with duration of 1.0 s and voltage magnitude of 80%. No requirements listed for voltage sags with longer durations.
NRS 048-2-2003	Compatibility levels: Voltage levels <500 V: +10% to -10% for 95% of the week Voltage levels >500 V: +5% to -5% for 95% of the week Maximum voltage deviations: Voltage levels <500 V: +15% to -15% for 95% of the week Voltage levels >500 V: +10% to -10% for 95% of the week	Standard applies to 10-minute averages of r.ms. voltages. No more than two consecutive 10-minute averages should exceed the compatibility levels. No 10-minute average shall exceed the maximum voltage deviations.

Steady-State Voltage Variation Indices

Utilities have not conventionally kept track of customer steady-state overvoltages or undervoltages since their impacts are often not immediate. On the other hand, utilities have commonly tracked service reliability indices, such as system average interruptions duration index (SAIDI) and system average interruption frequency index (SAIFI), that measure the service continuity (but not quality).

EPRI has developed indices for tracking service quality [11]. Like conventional reliability indices, such as SAIDI and SAIFI, the service quality indices can be used for benchmarking and comparing the performance of feeder sections, entire feeders, distribution areas, or even entire utility service territories. Additionally, some of these indices provide useful information at individual customer levels. In the past, utilities have not commonly recorded these or other service quality metrics due to the lack of measurement data. Now, smart meter data has made it more practical to track these metrics. Next, four of the most relevant indices are introduced. Details of the indices and their application can be found in [11, 12].

System Average Overvoltage Frequency Index$_{\text{Voltage}}$ (SAOFI$_{\text{X}}$) is given by

$$\boldsymbol{SAOFI_X} = \frac{\sum \boldsymbol{NO_i}}{\boldsymbol{N_T}}, \qquad \textbf{Eq. 2-1}$$

where X is the specified rms overvoltage magnitude threshold (e.g. 110%), NO_i is the number of customers experiencing overvoltage i for which the average magnitude over the duration of the overvoltage is above X%, and N_T is the number of customers served from the assessed system.

System Average Undervoltage Frequency Index$_{\text{Voltage}}$ (SAUFI$_{\text{X}}$) is defined analogously.

SAOFI$_{\text{X}}$/SAUFI$_{\text{X}}$ gives the occurrence rate of overvoltages/undervoltages with an average magnitude exceeding/below the specified thresholds.

System Average Overvoltage Duration Index$_{\text{Voltage}}$ (SAODI$_{\text{X}}$) is given by

$$\boldsymbol{SAODI_X} = \frac{\sum (\boldsymbol{NO_i} \times \boldsymbol{T_i})}{\boldsymbol{N_T}}, \qquad \textbf{Eq. 2-2}$$

where X, NO_i, and N_T are equal to the SAOFI$_{\text{X}}$ definition above, and T_i is the duration of the ith steady-state rms variation measurement event recorded during the assessment period.

System Average Undervoltage Duration Index$_{\text{Voltage}}$ (SAUDI$_{\text{X}}$) is defined analogously.

SAODI$_{\text{X}}$/ SAUDI$_{\text{X}}$ gives the total minutes that the average customer experiences an overvoltage exceeding a specified threshold.

These indices are examples of ways that steady-state voltage variations could be benchmarked between distribution feeders and utilities. The following subsections review standards relevant to steady-state voltage ranges.

ANSI C84.1-2011 American National Standard for Electric Power Systems and Equipment – Voltage Ratings (60 Hertz)

ANSI C84.1 standard defines the preferred voltage ratings and the voltage operating tolerances for 60 hertz electric power systems above 100 volts [14]. The preferred voltage ratings are provided for maximum system voltage up to and including 1200 kV. The standard discusses only steady-state voltages defined in the standard as 10-minute averages of the root-mean squared (rms) values. The maximum system voltages listed in the standard exclude voltage transients and temporary overvoltages. Voltage ranges listed in the standard do not apply for momentary voltage excursion caused by switching operations or events such as motor starting. In addition to steady-state voltage ratings and voltage ranges, ANSI C84.1-2011 also specifies a 3% maximum voltage unbalance limit. Finally, ANSI C84.1 lists several standards for voltage ratings of different equipment including rotating machines, static power converters, and air-conditioning applications.

While the National Electric Manufacturers Association (NEMA) administered the standard’s development and the American National Standards Institute (ANSI) approved the standard, it is important to note that neither NEMA nor ANSI enforce compliance with the standard or do any kind of certification, testing, etc. of equipment, designs, etc.

ANSI C84.1 voltage ranges were originally set to ensure appropriate operation on induction machines that comprise a large share of end-use equipment [11]. The intent of ANSI C84.1 is to ensure that the utilization voltages are within acceptable limits. The voltage ranges do not directly apply for the primary distribution system. Therefore, the utility has the flexibility to deliver the utilization voltages either by maintaining the primary system voltages or by using service transformer (off-load) taps.

The standard defines service voltage as the voltage at the point where the electricity user is connected to the electricity supplier. Utilization voltage is defined as the voltage at the point of the utilization equipment terminals.

ANSI C84.1 also defines ranges A and B for both service and utilization voltages. Voltage range A is defined as the voltage range that most service voltages are expected to be within during normal conditions. The standard states that utilization equipment shall be designed and rated to operate in a satisfactory manner for voltages in Range A. Voltage Range B is defined in the standard as voltages that are a part of normal operations, but their occurrence should be “limited in extent, frequency, and duration”. Utilization equipment are also specified in the standard to be designed (if practical) such that acceptable performance is achieved in the extremes of range B. However, this performance is subjective and does not necessarily need to be as good as that achieved within range A.

ANSI C84.1 also states that there may be infrequent periods when sustained voltages outside range B limits will occur, but under these conditions utilization equipment may not operate properly and protective devices may operate to protect the equipment. The standard also states that swift corrective action should be taken when voltages outside range B occur. However, the standard states that the urgency of such actions depend on many factors such as location and nature of loads, and extent and frequency of deviation from range B limits.

Figure 2-1 illustrates ANSI C84.1 voltage ranges for 120-600 V systems at 120 V voltage base. Voltage ranges for other nominal system voltages can be calculated from these ranges.

The following aspects are worth highlighting:

- The difference between service voltage range and utilization voltage range is larger for systems >600 V to account for voltage drop over transformers.
- Previous version of ANSI C84.1 used to have a higher (more restrictive) lower bound for service voltages of circuits with lighting equipment. However, this special range was removed in ANSI C84.1-2011 since modern lighting equipment needs no special treatment.
- Range A and range B apply for 10-minute averages. The ranges do not apply for momentary voltage excursion caused by switching operations, or other events such as motor starting.
- Conservation voltage reduction (CVR) should always be designed to operate within range A voltages.
- Voltage ratings of some motors and motor control equipment is lower than the nominal system voltage to account for high voltage drops caused by the equipment.

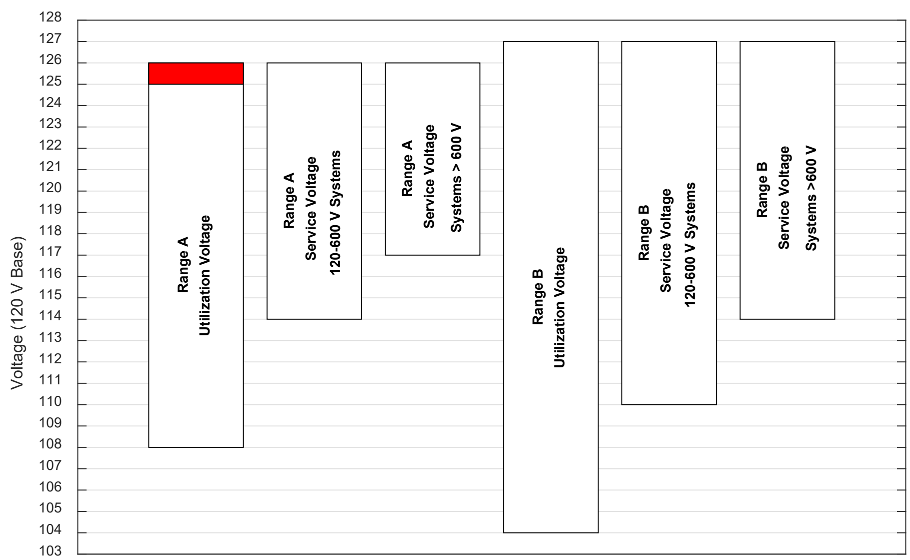

Figure 2-1
Illustration of ANSI C84.1-2011 voltage ranges at 120 V base (the area shown in red does not apply to 120-600 V systems)

IEEE 141-1993 - IEEE Recommended Practice for Electric Power Distribution for Industrial Plants

IEEE Std. 141-1993, commonly referred to as the “IEEE Red Book”, discusses recommended practices for electric power distribution in industrial plants [15]. Section 3 of the standard discusses the voltage considerations including voltage regulation, voltage ratings, voltage bands, and many other voltage quality aspects.

The standard notes that most equipment carries a nameplate voltage rating that is equal to the system voltage level where the equipment is intended to be utilized. The notable exception to this are motors, and equipment containing motors, which are often given a lower nameplate voltage than the system voltage; e.g., motors operating on 120-volt system often have nameplate voltage ratings of 115 V. This practice enables more optimal operation of equipment at typical utilization voltages.

The Red Book also provides an interesting overview on how ANSI C84.1-1989 voltage thresholds were derived. The discussion is summarized as follows and illustrated in Figure 2-2.

- ANSI C84.1-1989 voltage tolerance limits were based on the NEMA MG 1-1993, which listed voltage tolerance limits for electric motors with nameplate voltages between 230 V and 460 V. The reason for this was that motors made up of a major portion of utilization equipment.
- A 460 V nameplate for a 460V motor on 120 V base is 115 V. NEMA MG-1 specified motor voltage tolerance band of 10% around 115 V is 103.5 V to 126.5 V. ANSI C84.1 Range B utilization voltage band was obtained by raising the lower bound to 104 V and upper bound to 127 V.
- From the 23 V tolerance band (between 104 V and 127 V), a 13 V voltage drop allowance was assigned to the primary distribution system resulting in a minimum utility primary circuit service voltage of 114 V. Further, a 4 V voltage drop allowance was left for the service transformer and secondary circuit wiring providing a 110 V minimum utility secondary service voltage. The 5% (6 V) difference to the minimum utilization voltage of 104 V was allocated to the plant wiring following the recommendations of ANSI/NFPA 70-1993.

It should be noted that the process discussed above did not consider voltage rise that may be caused by distributed generation.

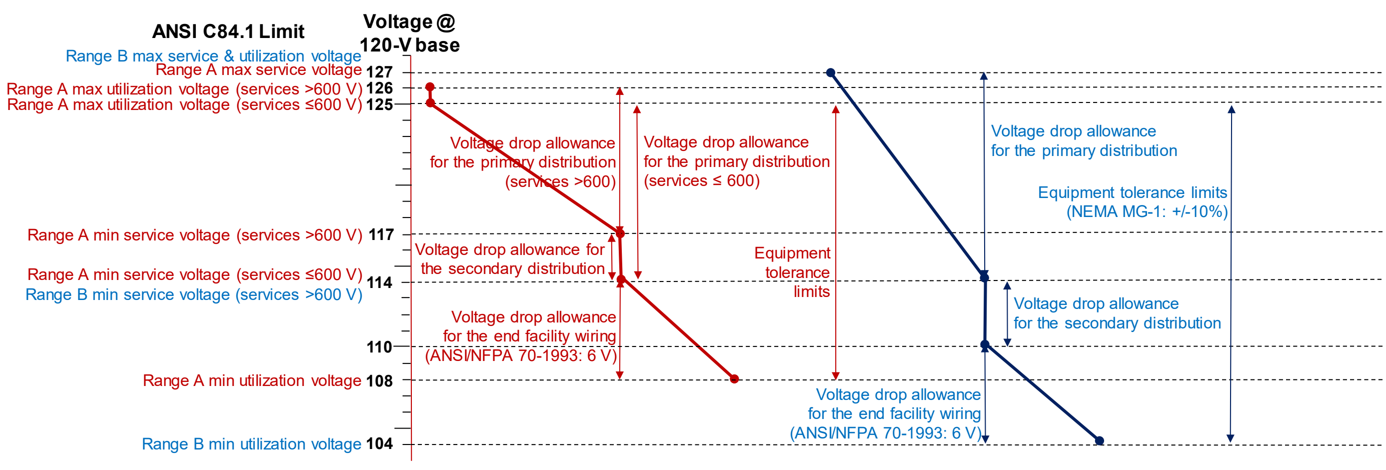

Figure 2-2
Voltage profile illustration of voltage tolerances (range A is denoted in red and range B in blue)

IEEE 141-1993 also discusses the impacts of voltage variations on low-voltage and medium-voltage utilization equipment. These aspects are discussed in detail in chapter 3 of this report.

IEEE 241-1993 - IEEE Recommended Practice for Electric Power Systems in Commercial Buildings

IEEE 241-1993, also known as the IEEE Grey Book, discusses recommended practices for electric power systems in commercial buildings [16]. Regarding steady-state voltage thresholds and other aspects relevant to this report, IEEE 241-1993 recommendations are very similar, if not identical, to IEEE 141-1993.

IEEE 1159-2009 - IEEE Recommended Practice for Monitoring Electric Power Quality

IEEE 1159-2009 provides recommended practices for monitoring electric power quality [4]. The standard specifies categories for different power quality phenomena and lists some of their causes and impacts. The standard does not address steady-state voltage ranges for utilities or equipment manufacturers.

NEMA MG-1-2009

National Electric Manufacturers Association (NEMA) standard NEMA MG-1-2009 standard [17] was developed to assist users in proper selection and application of motors and generators. The standard covers many specific aspects related to the performance and construction of electric motors and generators. NEMA MG-1-2009 requires motors and generators to operate successfully with +/-10% voltage variations of the rated motor voltage. The standard discusses in detail the operating conditions and other aspects under which successful operation is expected.

It must be emphasized that the rated voltage in the NEMA MG-1 standard and the nominal supply system voltage in ANSI C84.1 are not the same. NEMA MG-1 standard takes a voltage drop in the end-use facility into consideration and assumes that the nominal utilization voltage is 115 V (@ 120 V voltage base). Thus, the +/- 10% of NEMA range at 115 V motor/generator rated voltage is equal to 103.5 – 126.5 V [38]. It should be noted that the NEMA MG-1 standard has many nuances specific to different motor and generator types that are not discussed here.

Other NEMA Standards

Other NEMA standards relevant to this report include NEMA ICS7-2000, NEMA ICS 2-2000 and NEMA ICS 61800-2. NEMA ICS7-2000 standard addresses adjustable-speed drives [18]. The standard lists steady-state voltage ranges for different drive service categories. The categories II, III, and IV list steady-state voltage variation ranges of +/-10% whereas service category I lists +10/-5% range. NEMA ICS 2-2000 discusses industrial control and system controllers [19]. The standard mainly deals with relays and contactors that are used for motor controllers. NEMA ICS 2-2000 states that motor contactors with DC coils shall withstand 110% of their rated voltage continuously and shall close successfully at 80% of their rated voltage. For motor contactors with AC coils, NEMA ICS 2-2000 indicates the withstand as 110% of their rated voltage continuously and shall close successfully at 85% of their rated voltage. The NEMA ICS 61800-2 standard addresses voltage requirements for adjustable-speed drives (ASDs) [20]. NEMA ICS 61800-2 states that the voltage for uninterrupted operation shall be ±10% of the rated input voltage at the point of common coupling [13].

NEC 2011

NFPA 70 also known as the National Electric Code (NEC) discusses electrical safety in residential, commercial, and industrial occupancies. NEC 2011 (NEC 210-19, 215-2, 310-15) provides recommendations for voltage drops within the end-use facility. Specifically, the standard recommends <3% of voltage drop in branch circuits between the sub-panel to utilization equipment [21]. NEC 2011 also recommends <3% of voltage drop between the main panel and the sub panel. The standard recommends a combined maximum voltage drop (of branch and feeder) of <5%.

EN 50160

European Norm (EN) 50160 is a European standard [22] that specifies the main parameters of voltage quality in public low-, medium-, and high-voltage electricity networks. The standard applies for normal operating conditions[1]. The standard discusses steady-state voltages, frequency, fast and slow voltage variations, flicker, voltage sags, short and long-term interruptions, etc. For some power quality aspects, the standard lists specific bounds, whereas for other aspects the standard only provides recommendations. EN 50160 limits should not be considered as equipment compatibility or emission levels. EN 50160 is compared to the ANSI C84.1 standard in [23].

EN 50160, as other EN standards related to electrotechnical engineering, is a European standard ratified by CENELEC[2], the organization responsible for European standardization in the area of electrotechnical engineering [22]. CENELEC is the regional mirror body of the International Electrotechnical Commission (IEC). EN standards are largely (85%) based on standards created by the IEC. CENELEC does not distribute/sell EN standards, but the standards and other approved documents can be obtained from the CENELEC national committees and affiliates. Standards developed by CENELEC are voluntary but the European Union (EU) and European Free Trade Agreement (EFTA) member countries are required to ratify them as national standards. As a result, EN standards are identical in all CENELEC member countries. Moreover, the member countries are not allowed to have national standards contradicting with EN standards. Standards developed by CENELEC are also adopted in many countries outside of Europe that follow European technical standards.

For this report, SFS-EN 50160:2010 [22], the English edition of Finland's implementation of the EN 50160:2010 standard, was arbitrarily chosen. There should be no (considerable) differences between the national implementations of EN 50160.

Supply Voltage Ranges

EN 50160 specifies voltage ranges for low-voltage (<1 kV), medium-voltage (≥1 kV, <36 kV), and high-voltage (≥36 kV) systems, separately. EN 50160: 2010 does not specify any requirements for high-voltage customer limits, stating that because only few large customers are

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[1] EN 50160 does not apply in conditions such as faults, planned outages, when end user equipment does not comply with relevant technical requirements including emission limits, etc. In particular, EN 50160 supply voltage limits do not apply to interruptions.

[2] A French abbreviation for Comité Européen de Normalisation Électrotechnique with the English translation: European Committee for Electrotechnical Standardization.

directly supplied at high-voltage level, their supply voltage limits can be individually agreed. The medium-voltage level customer limits are identical to the low-voltage level customer limits; the only difference is that the medium-voltage levels apply 100% of the time. The remainder of this section focuses on EN 50160 requirements for steady-state voltage requirements of customers supplied at low-voltage level.

For low-voltage level supply voltages, EN 50160 specifies that during each week, the range of variation of the 10-minute average rms values of the low-voltages is +/- 10% for 95% of the week. Additionally, EN 50160 specifies that supply voltages may vary within +10/-15% of the nominal voltage for remote users[3] and in systems that are not interconnected with a transmission system. The standard also requires that, under normal operating conditions, 100% of the 10-minute averages of the rms voltages must be within +10/-15%[4].

Like many other power quality standards, EN 50160 has been established as a compromise between the electricity supplier and electricity end users. The standard determines the minimum voltage that the supplier must provide. Most suppliers considerably exceed the requirements although they are not required to do so. Because EN 50160 covers a wide range of European countries, the standard was developed to allow encompassing all member countries. As a result, the power quality limits were selected as the lowest common value that all member countries could agree upon [24]. Some of the European national regulators enforce a tighter voltage band and/or a shorter time-interval for averaging the measurements [25]. For example, a Norwegian regulation requires 100% of the 1-minute averages of rms voltage magnitudes to be within +/-10% of the nominal voltage [25].

Arguments have been made for both tightening and relaxing the +/-10% voltage excursion threshold. It has been suggested that EN 50160 requirements are not very tight for the electricity suppliers and many voltage disturbance events fall under the exclusions of the standards [27]. This has lead some groups to conclude that the EN 50160 voltage limits may not guarantee sufficient levels of power quality for sensitive customers [27]. European Regulator's Group for Electricity and Gas (ERGEG) has also released a report recommending tightening the +/-10% on the basis that in most systems, power quality was already better [26]. The ERGEG report also recommends to move to an averaging time interval shorter than 10 minutes to better capture short duration voltage variations. Contrary to the above references, an extensive revision process of EN 50160, completed in 2010, almost resulted in a change to the clause that rms voltages must remain within +/-10% during 95% of the week to two new clauses:

- 100% of the 10-min averages of the supply voltage rms values must remain within an interval of +/-15%
- 99% of the 10-min averages of the supply voltage rms values must remain within an interval of +/-10% [27].

Ultimately, the original wording of +/-10% during 95% of the week was not revised as a result of extensive stakeholder feedback. More details of the revision process can be found in [27]. As

[3] The standard does not specify what remote users are since their definition varies between member countries.

[4] It should be noted that EN 50160 defines voltage dips (swells) as temporary reduction (increase) of the rms. voltage below 90% (above 110%) of the reference voltage.

discussed in [27], it is very important to involve utilities, manufacturers, and end users in the revision process of a voltage threshold standard. Moreover, proper coordination between regulators and standard developers is very important in revising standards involving voltage/power quality [27].

Connection Between EN 50160 and IEC 61000 Standard Series

IEC 50160 is closely related to the EMC standard series IEC 61000. The requirements of EN 50160 and EN 61000 series are compared in [28]. Despite the close relation, there are considerable differences between the standards for the following reasons:

- EN 50160 deals with the supply (or service) voltage whereas IEC 61000 is concerned with utility (or utilization) voltages. These voltages differ due to the voltage drop (or rise) in the end use facility between the supply and utilization points, and due to the disturbances from the utility network and the facility.
- EN 50160 provides general limits that are technically and economically achievable by the electricity supplier.
- EN 50160 does not apply to abnormal conditions such as:
    - post-fault operation or when the scope of an outage is minimized
    - when customer equipment or installation does not meet existing standards and other requirements
    - when generation units do not meet applicable standards and other requirements
    - in other abnormal circumstances that the distribution utility cannot affect including weather events or events caused by external entities.

IEC 61000 Series

IEC 61000 is a broad series of standards related to electromagnetic compatibility (EMC) [29]. The IEC 61000 standard series consists of 7 parts: Part 1: General, Part 2: Environment, Part 3: Limits, Part 4: Testing and Measurement Practices, Part 5: Installation and Mitigation Guidelines, Part 6: Generic Standards, and Part 7: Miscellaneous. The most relevant part for this report is 61000-2, which deals with low-frequency conducted disturbances and their limits. IEC 61000-2 series consists of 14 standards including 61000-2-2: Compatibility Levels for Low-Frequency Conducted Disturbances and Signaling in Public Low-Voltage Supply Systems, which deals with the compatibility levels for low-frequency conducted disturbances and signaling in public low-voltage supply systems.

IEC 61000-2-2 covers the frequency ranges from 0 Hz (D.C.) to 9 kHz (and extending up to 148.5 kHz in main signaling systems). The standard deals with the point of common coupling (PCC) between the electricity supply system and the electricity end user (compare to service voltage of ANSI C84.1-2011). IEC 61000-2-2 specifies compatibility levels for a broad range of conducted low-frequency disturbances (that are defined in IEC 61000-2-1):

- voltage fluctuations
- flicker
- harmonics and inter-harmonics (up to 50th harmonic)
- voltage distortions (above 50th harmonic)

- voltage dips/short interruptions
- voltage unbalance
- transient overvoltages
- power frequency.

The standard defines compatibility levels as the level of disturbance that can be expected in the environment. The standard allows a small probability of exceeding the compatibility level. The standard also states that on one hand, compatibility level can be maintained with practical emission limits (equipment emission limits) and on the other hand, equipment must be able to tolerate disturbances at the compatibility level (equipment tolerance limits). It is important to note that compatibility level depends both on the emission level and on the immunity level. From these, equipment immunity level can be controlled, whereas it is possible to control some emission (equipment caused) but not all emissions (e.g. lighting and some faults). Moreover, controllable emissions can have a complex relationship with the compatibility levels due to interaction of emissions from various equipment, etc. Finally, although most emissions are currents, the actual disturbance of interest is the voltage. Thus, it is necessary to consider the system impedances. A more detailed discussion can be found in the standard.

IEC 61000-2-2 does not specify steady-state voltage ranges. However, IEC 61000-2-2 states that following large load changes or switching operations, tens of seconds of operation outside the normal voltage ranges are allowable until on-load tap changers (OLTC) or HV/MV transformers operate. It should be noted that ANSI C84.1-2011 inherently considers voltage regulation delays by defining voltage ranges for 10-minute average rms voltages.

IEC 61000-2-2 also defines the concept of a planning level as the value adopted by the body responsible for planning and operating the power system in a particular area. The standard also states that the planning level cannot be higher than the compatibility level, and it is typically lower by a margin that depends on the disturbance type, the supply network characteristics, etc. A good discussion of the different types of limits can also be found in [30]. Figure 2-3 visualizes the differences between disturbance level, planning level, compatibility level, voltage characteristics, immunity level, and susceptibility level.

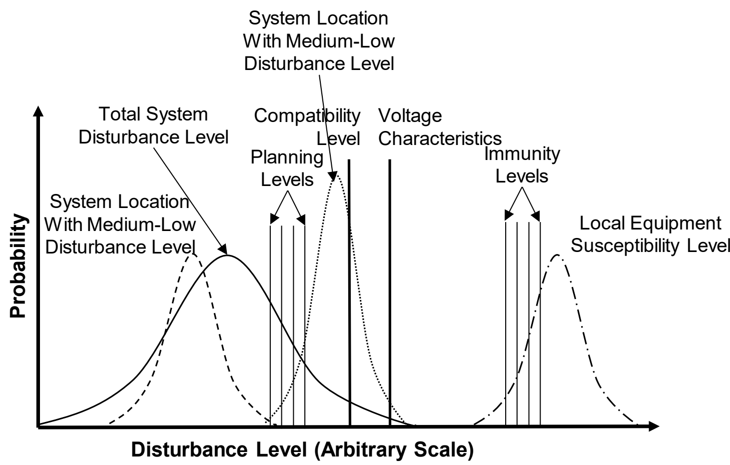

Figure 2-3
Relationship between compatibility, immunity, planning, and emission levels adjusted from [30]

CBEMA Curve (IEEE 446-1995)

IEEE 446-1995 - IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications [31], commonly known as the “Orange Book”, includes the well-known “CBEMA curve” shown in Figure 2-4. The curve was originally developed by the Computer Business Equipment Manufacturers Association (CBEMA), hence its name. The CBEMA curve was an attempt to describe equipment ride-through capability against rms voltage variations. Since its creation, the CBEMA curve has been adopted in various standards. A good overview of the CBEMA curve history can be found in [32]. It should be noted that the CBEMA curve is not a test standard. In other words, computers do not need to be certified to pass a test. Instead, the curve is used to inform power system designs with respect to potentially sensitive equipment.

Despite its wide adoption and utilization, the CBEMA curve has the following disadvantages [32]:

- The curve was developed in a time of IBM mainframe computers. As a result, it may not represent the tolerance of modern computer equipment well. The curve was never intended to represent all electronic-based (or other) equipment.
- The CBEMA curve has been commonly used to evaluate the impact of individual disturbances. However, since equipment sensitivity varies, the curve is not necessarily a good predictor of whether a given disturbance will affect individual equipment. In many cases, equipment may trip even though the disturbance follows within the curve tolerance.
- The CBEMA curve may not be a useful design standard for computer (or other equipment) manufacturers as small voltage sags outside the standard tolerance bands may be common at the far ends of distribution systems, and can result in frequent equipment trips [12].
- The original CBEMA curve was plotted on a logarithmic scale that made it difficult to reproduce.

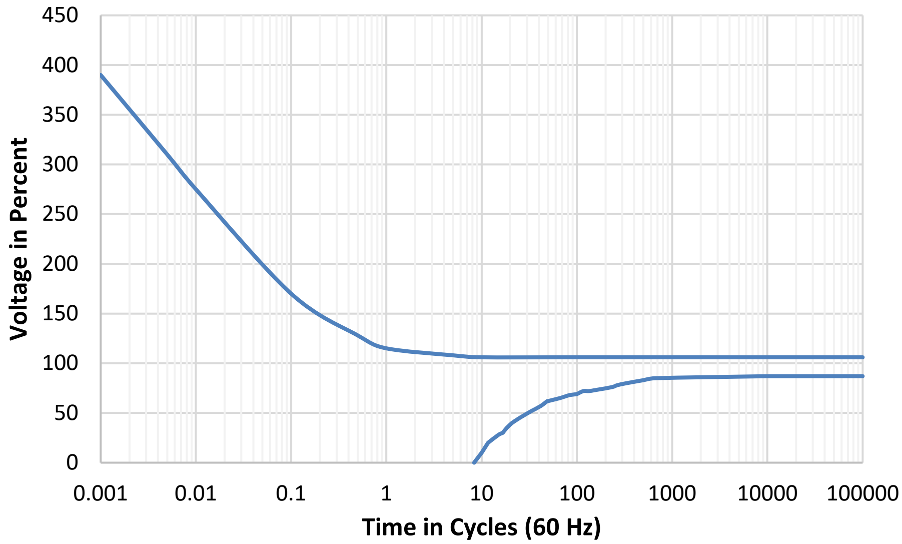

Figure 2-4
CBEMA curve [12]

ITIC Curve

The Computer Business Equipment Manufacturers Association (CBEMA) organization has been succeeded by the Information Technology Industry Council (ITIC) organization. Due to the limitations of the CBEMA curve listed above, ITIC has developed a new recommended curve for single-phase data processing equipment operating at 120 volts [32]. This curve is widely known as the "ITIC curve". The ITIC curve has two major improvements over the CBEMA curve. First, the ITIC curve provides an easier graphical format for reproducing the curve. Second, the ITIC curve requires a ride-through capability for minor voltage sags. Similar to the CBEMA curve, it should be noted that the ITIC curve is not an actual tested standard (computers do not need to be certified to pass a test). [9]

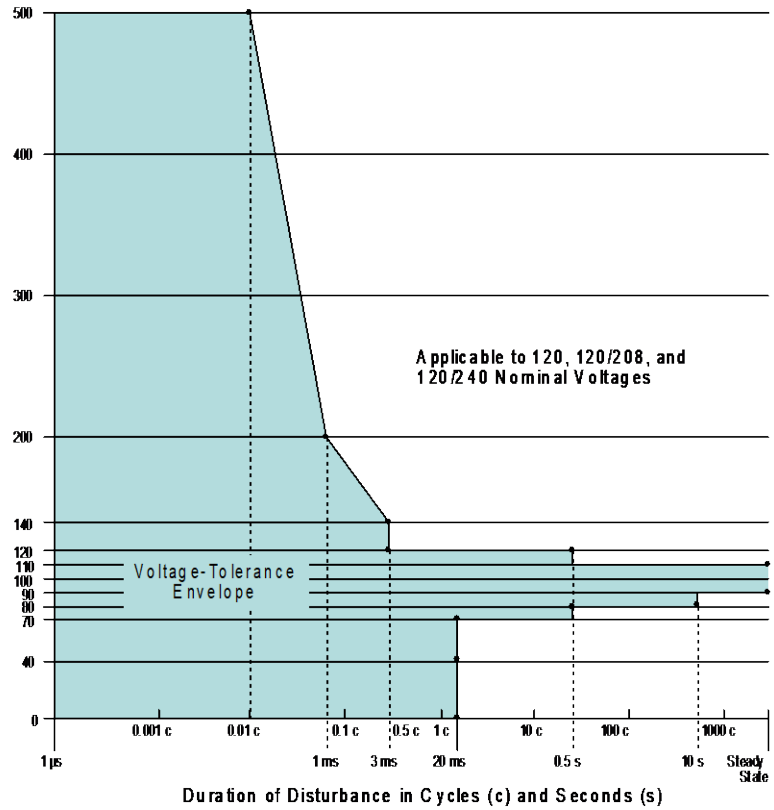

Figure 2-5
Information Technology Industry Council (ITIC) curve [9]

SEMI F47-0200-2000

Semiconductor Equipment and Materials International (SEMI) is a global semiconductor industry trade associated that was founded in the United State in 1970, but has since become a global organization. To address the semiconductor industry sensitivity to voltage sags, SEMI F47-0200-2000 defines voltage-sag ride-through capabilities for equipment used for semiconductor processing, metrology, and automated test equipment [32]. In contrast to CBEMA and ITIC curves, SEMI F47-0200-2000 is an actual test standard for the equipment. In other words, to meet the standard requirements, equipment must pass a series of voltage sag tests [9]. The standard focuses on voltage sags for 1-phase equipment. Multiple tests are needed for 3-phase equipment. SEMI F47-0200-2000 is more restrictive than the CBEMA and the ITIC curves except for very short voltage variations [9]. A good comparison of CBEMA, ITIC, and SEMI F47-0200-2000 can be found in [33].

SEMI F47-0200-2000 does not specify steady-state voltage ranges but specifies ride-through requirements for voltage sags of different magnitudes and durations. The standard requires ride-through capability for voltage sags with duration of 1.0 s and voltage magnitude of 80%. The standard does not list requirements for voltage sags with longer durations.

NRS 048-2-2003

NRS 048-2-2003 [34] is a South African standard specifying power quality metrics and the respective limits. Where applicable, the standard has been guided by IEC, CENELEC, and IEEE standards. The standard applies similar steady-state voltage limits as EN-50160. The standard specifies compatibility levels of +/-10% and +/-5% for voltage levels <500 V and ≥500 V, respectively. The standard further specifies that 95% of the weekly values over the full measurement time period shall not deviate from the compatibility levels and that not more than two consecutive 10-minute periods shall exceed the compatibility levels.

NRS 048-2-2003 also specifies maximum voltage deviations from the standard/declared voltage to be +/-15% and +/-10% for voltage levels <500 V and ≥500 V, respectively. The standard sets lower values for voltage levels above 44 kV. The standard states that the maximum deviation of the 10-minute values from declared voltage over the full measurement time period shall not deviate from the maximum voltage deviation limits. Finally, the standard also discusses short-duration voltage variations that however are not in the scope of this report.

3 STEADY-STATE VOLTAGE EXCURSION IMPACTS ON END-USE DEVICES

Impacts that steady-state voltage excursions may have on different types of electric equipment are examined in this chapter. The nature of these impacts is widely varied. Smaller excursions may decrease equipment efficiency and increase equipment wear and tear, resulting in reduced equipment life. Larger excursions can also result in annoyance or inconvenience in the form of improper operation. Finally, steady-state overvoltages with sufficiently large magnitudes can result in immediate or rapid equipment failure particularly in electronic equipment. Examples of the potential impacts are listed in Table 3-1. The table was created as a simplified summary of the literature that was reviewed on the steady-state voltage excursion impacts on equipment. The impacts are discussed in more detail by equipment class in the subsequent sections.

While this chapter largely focuses on the impacts that steady-state voltage excursions of different magnitude and duration can directly cause, it is important to emphasize that equipment sensitivity may depend on several additional factors, including but not limited to [12]:

- *Voltage unbalance*: equipment sensitivity characteristics to unbalanced and balanced voltage excursion such as voltage sags may be significantly different. On one hand, equipment may be more tolerant to voltage sags that affect only one of the phase-phase voltages than sags that affect all the three phases. On the other hand, a relatively small voltage unbalance can result in considerable current unbalance that can result in semiconductor damage and fuse blowing due to overcurrents under voltage sags.
- *Point of wave*: voltage sag point of wave can also play a considerable role in determining the influence of the sag.
- *Equipment transformer connection*: the way that unbalanced voltage excursions on the primary distribution circuit transfer to the equipment (low-voltage) side of the transformer, depend largely on the transformer connection. Transformer connection is not important for balanced voltage excursions.

While a large amount of testing has been performed by EPRI and others on equipment tolerances to short-duration voltage variations, only limited test has been performed on equipment tolerances to longer temporary overvoltages (TOV) with relatively high magnitudes. Temporary overvoltages, while not within the scope of this report, are relevant in examining the results from tests with durations of several hours. Nonetheless, this report targets impacts of steady-state voltages deviating slightly from the standard ranges. As discussed in this chapter, these impacts are well known for some equipment such as incandescent light bulbs and electric motors but less so for some other equipment. Impacts of temporary overvoltages (TOV) are first discussed for various equipment types followed by steady-state voltage excursion impacts by equipment type.

Table 3-1
Examples of steady-state overvoltage and undervoltage impacts

Impact Category	Potential Impact	High Voltages	Low Voltages
Reduced performance	Reduced light intensity of incandescent light bulbs, compact fluorescent bulbs, and many commercial lights		X
	Reduced induction motor starting & running torque		X
	Reduced induction motor full load speed		X
Reduced efficiency	Higher no-load losses in transformers (decreased efficiency	X	
	Overheating of induction machines (increased wear/tear, reduced life)		X
	Reduced induction motor efficiency	X	X
Increased wear/tear	Shorter lifetime of incandescent light bulbs	X	
	Increased heating of induction machines that can stress motor insulation		X
	Excessive heating of ballasts of compact fluorescent bulbs	X	
	Flickering of compact fluorescent bulbs		X
	Switching off of commercial lighting		X
Annoyance / Inconvenience	Equipment stops working but may resume to work after voltage returns within acceptable range	X	X
	Shrinking of cathode ray tube (CRT) television screen picture	X	X
	Tripping of sensitive loads / DER	X	X
	Increased equipment sensitivity to voltage sags and other low-voltage incidents		X
	Increased induction motor magnetic noise	X	X
	Tripping of ASD protection	X	X
	Stalling of both stand-alone motors and equipment with motors as components including refrigerators		X
	Tripping of industrial and commercial equipment	X	X
Damage/failure	Equipment failure	X	
	Failure of equipment built-in surge protective devices		X
	Tripping of internal equipment protection including fuses	X	
	Increased sensitivity to voltage spikes due operating closer the design limits	X	
	Sufficiently high overvoltages may transfer through electronic power supplies and damage supplied equipment	X	
	Failure of surge protective devices	X	

General Impacts of Temporary Overvoltages on Equipment

EPRI test results of U.S. 120-volt single-phase equipment tolerance to temporary overvoltages are shown in [6]. The tested equipment types include surge protection device (SPD), programmable logic controllers (PLC), PCs, and incandescent light bulbs. The tolerances were tested for five types of TOVs that were selected to mimic common causes of TOVs. The tested voltage magnitudes, durations, and represented cause of the tested TOVs are:

- 1.15 pu – 6 hour (poor voltage regulation)
- 1.30 pu – 2 second (during a fault)
- 1.50 pu – 4 hour (loss of secondary neutral)
- 2.0 pu – 1 min (ferroresonance)
- 3.0 pu – 1 sec (contact to high-voltage circuits).

This report is less concerned with short-duration TOVs. Thus, from the tested TOV types, 1.15 pu – 6 hr (poor voltage regulation) and 1.50 pu – 4 hour (loss of secondary neutral) are the most relevant for this report. None of the tested equipment failed for 1.15 pu – 6 hr TOV type and three of the seven tested SPDs failed for the 1.50 pu – 4 hour TOV type. The results indicate that the tested types of U.S. 120 V single-phase equipment may be able to tolerate overvoltages well beyond the existing ANSI C84.1 utilization voltage limits.

EPRI continued this TOV tolerance testing for additional equipment in [35]. This time, the equipment was exposed to TOV magnitudes of 1.5 pu, 2.0 pu, 2.5 pu, or 3.0 pu for up to four hours or until the equipment failed. The tested equipment consisted of 3 types of clock radios, 2 types of VCRs, 3 types of DVD players, 3 types of surge protectors, 3 types of microwaves, 1 type of television, 1 type of computer, and 1 type of incandescent bulb. For more than half of the equipment groups, at least one of the tested pieces failed at every TOV level. The internal equipment components that were observed to be particularly prone to fail included metal-oxide varistors (MOVs), front-end power frequency transformers, and rectifier circuit front-end capacitors with 200 V voltage rating. In many cases, the internal equipment protection, such as fuses or circuit breakers, operated for higher-magnitude TOVs, thus avoiding additional internal equipment component damage. Interestingly, TOVs with lower magnitudes did not trigger the internal equipment protective components that resulted in internal equipment component damage. Many more details of the equipment failure modes can be found in the report [35].

It is important to emphasize that these studies did not evaluate equipment impacts other than failure. This would be an important area of future testing but would require a significantly large effort and require obtaining sufficient numbers of equipment to provide statistically meaningful results.

Test results for TOV tolerance of European (Norwegian) residential 230-volt equipment can be found in [7, 8]. The tested equipment included a circular saw, kitchen mixer, microwaves, vacuum cleaners, and home electronics including a CD player, DVD players, home entertainment system, PCs, PC monitors, printers, radios, a stereo system, TVs, and VHS players.

In [7], 62 different objects were tested for their overvoltage tolerances with magnitudes up to 1.40 pu and durations of up to 100 seconds. Only three of the 62 pieces of equipment were damaged during the testing. Additionally, 4 of the 62 pieces of tested equipment stopped working at elevated voltages but continued to work normally as the voltages were reduced back to the nominal level.

The testing was extended in [8] with an additional 60 electrical devices for TOVs with magnitudes up to 1.74 pu and durations up to 30 minutes. The cumulative number of damaged pieces of equipment is listed in Table 3 2. Most equipment operated well with voltages considerably beyond the EN-50160 +10% upper limit.

It is important to note that the testing done in [7, 8] did not consider the overvoltages' potential reduction in equipment life. Additionally, although the testing roughly distinguished between proper and improper equipment operation, the testing did not analyze other impacts such as reduced operational efficiency or annoyances such as increased noise, vibration, etc. Finally, only overvoltages were tested.

Table 3-2
Cumulative number of malfunctioned and damaged test equipment [8]

Voltage Level [pu @ 230 V]	1.15	1.20	1.25	1.30	1.40	1.52	1.74
Cumulative # of malfunctioned (excluding damaged) equipment	2	3	2	2	5	5	5
Cumulative # of damaged equipment	1	1	3	4	8	16	42
Total	3	4	5	6	13	21	47

Widening the UK voltage thresholds as well as the potential impacts to equipment have been discussed in [36, 37]. The report shows limited new test results.

Lighting Technology

Incandescent Lights

Steady-state voltage excursion impacts on incandescent lighting are very well known.

Higher/lower operating voltages result in higher/lower luminosity of incandescent light bulbs. For example, reducing the bulb operating voltage to 0.95 pu, decreases the bulb luminosity by ~15%. On the other hand, increasing the bulb operating voltage to 1.20 pu increases the bulb luminosity by 20%. ANSI C84.1-2006 and earlier versions considered the reduction in incandescent light bulb luminosity by increasing the low end of the permitted voltage range for lighting circuits from 108V (90%) to 110V (91.7%). Modern lighting equipment no longer needs this special treatment and thus, ANSI C84.1-2011 no longer includes this adjustment [14].

It should be noted that voltage variations at +/- 5% or +/- 10% level would result in considerable variation of light intensity of incandescent bulbs. The resulting level of discomfort depends on the frequency and duration of voltage excursions. Nevertheless, the magnitude of frequent voltage variations should be much less than the steady-state voltage thresholds imposed by ANSI C84.1 and other standards.

Next to luminosity, increased or reduced voltage also reduces or increases the light bulb lifetime, respectively. For example, operating a bulb at constant 1.05 pu voltage reduces the bulb lifetime by 50% compared to bulb operating at constant 1.00 pu voltage. In practice, the operating voltage is not constant, so lifetime impact is more complicated.

Detailed plots of incandescent light bulb luminosity and lifetime as a function of voltage can be found in [28].

EPRI research has shown that reducing voltage (within the ANSI C84.1 limits), decreases the real power consumption of incandescent light bulbs with a CVR factor of ~ 1.5 [39]. The research also shows that reducing voltage by 1% (within the ANSI C84.1 limits), reduces the lumen output of incandescent light bulbs by ~3.2%. Laboratory testing in [40] has also shown that the active power demand of incandescent bulbs scales almost quadratically with the voltage level. In other words, incandescent bulbs can be considered as constant impedance loads.

Compact Fluorescent Lights

Steady-state voltage excursions are expected to have less of an influence on the luminosity of fluorescent and other modern lighting technologies [15, 38]. However, steady-state voltage excursions may have adverse impacts on the equipment lifetime [15, 38]. High voltages may result in excessive heating of the ballast that may lead the ballast to fail. On the other hand, low voltages may lead to premature failure of bulbs due to flickering from insufficient voltage at the electrodes. CFLs tested by EPRI have withstood sustained overvoltages up to 150% for 4 hours (the maximum test time). Other impacts of sustained steady-state voltage excursions have not been well characterized.

EPRI research has shown that reducing voltage (within the ANSI C84.1 limits), decreases the real and reactive power consumption of CFLs with real and reactive power CVR factors of ~0.76 and ~1.1, respectively [39]. The research also shows that reducing voltage by 1% (within the ANSI C84.1 limits), reduces the lumen output of CFL light bulbs by 1.0%. The research did not analyze the impact of steady-state voltage excursions beyond the ANSI C84.1 range A.

Laboratory testing in [40] has shown that fluorescent and mercury lamps have strong voltage dependency in reactive power. The active power of these lamps was observed to depend less on the voltage and thus, the power factor of the lamps varies with voltage. The testing also analyzed fluorescent lamp switch-off voltage. As the lamp operating voltage carefully reduced, the 230 V lamp switched off at 160 V.

Research conducted in the U.K. has found that some fluorescent and vapor lighting may fail with sustained undervoltages of 10-20% below the rated voltage [36, 37].

Light-Emitting Diode (LED) Lights

The impact of steady-state voltage excursions on light-emitting diode (LED) lights is not widely discussed in the literature but in general, LEDs are expected to be less sensitive to steady-state voltage excursions.

EPRI research has shown that voltage has no considerable impact on LED real power consumption (LED reactive power consumption is typically very small) [39]. In fact, the power consumption of an LED can slightly increase if the voltage is reduced. The research also shows that reducing voltage by 1% (within ANSI C84.1 limits) reduces the lumen output of LED lamps by 0.1%. The research did not analyze the impact of steady-state voltage excursions beyond the ANSI C84.1 range A.

Commercial Lighting

The impact of steady-state voltage excursions on commercial lighting technologies such as high-pressure sodium (HPS) or metal-halide (MH) are not widely discussed in the literature. According to IEEE Std. 141-1993, mercury lamps with typical ballast will have 12% change in light output for a 5% change in terminal voltage [15, 16]. The standard also states that a constant wattage autotransformer ballast results in +/-5% and +/-10% change in wattage for mercury and metal halide lamps, respectively. High-intensity discharge (HID) lamps may extinguish for voltages below 75% of the nominal. HID lamp life is proportional to the number of starts and thus, increased number of starts may reduce the lamp life. On the other hand, high voltages rise the lamp arc temperature that may have detrimental impacts on the life of the enclosure.

EPRI research has shown that the impact that voltage has on the power consumption of commercial lighting depends mainly on the type of the ballast utilized (electronic vs. magnetic) [39]. The lighting type has only limited impact on this [39]. The power consumption of lights with electronic ballasts was observed to be quite insensitive to the voltage level. On the other hand, the power consumption of lights with magnetic ballast was lowered as the voltage was reduced. The research has also shown that the lumen output of commercial lights with electronic ballasts does not largely change with the voltage level. On the other hand, the lumen output of commercial lights with a magnetic ballast was observed to reduce by ~2% for a voltage reduction of 1%. The research did not analyze the impact of steady-state voltage excursions beyond the ANSI C84.1 range A.

Laboratory testing in [40] tested commercial lighting switch-off voltages. As the lamp operating voltages were gradually reduced, the tested 230 V mercury lamp, high-pressure sodium lamp and low-pressure sodium lamp switched off at 180 V, 180 V, and 80 V, respectively. The high switch-off voltage of the sodium lamps should be noted.

Electric Motors (Without Power Electronic Drives)

The impacts that varying operating voltage has on directly coupled electric motors (without power electronic drives) are known well. In general, voltages slightly above the motor nameplate rating have less negative impact on motor performance than voltage slightly below nameplate rating [15, 16]. Table 3-3 summarizes general impacts of voltage variations on induction motors.

The impacts may be different for lightly loaded motors or if the motor load can be easily started. In such cases, reducing the motor operating voltage can actually result in an increase in the motor efficiency. For example, experimental results in [41] found that the motor efficiency peak (most efficient loading) shifts to lower (higher) load for undervoltages (or overvoltages). A 10% reduction (increase) in supply voltage was observed to move the efficiency peak to 10% lower (20% higher) loading level.

Table 3-3
General impacts that induction motor operating voltages have on the motor performance [15]

Characteristic	Proportional to	90% of the nameplate voltage	110% of the nameplate voltage
Starting & max running torque	Voltage squared	-19%	+21%
Percent slip	$(1/\text{voltage})^2$	+23%	-19%
Full load speed	Synchronous speed – slip	-0.2 to -1.0%	+0.2 to 1.0%
Starting current	Voltage	-10%	+10%
Full load current	Varies with design	+5 to +10%	-5 to -10%
No load current	Varies with design	-10 to -30%	+10 to +30%
Temperature rise	Varies with design	+10 to +15%	-10 to -15%
Full load efficiency	Varies with design	-1 to -3%	+1 to +3%
Full load power factor	Varies with design	+3 to +7%	-2 to -7%
Magnetic noise (any load)	Varies with design	Slight decrease	Slight decrease

The impacts on synchronous motors are similar to Table 3-3 except that for synchronous motors [15, 16]:

- Speed remains constant provided that the frequency remains constant
- Maximum pull-out torque varies directly with the torque if the field voltage remains constant. This is the case when the field is supplied, e.g., by a generator on the same shaft as the motor.
- Maximum pullout torque varies as the square of the voltage if the field voltage varies with the line voltage. This is the case when the field is supplied by, e.g., a static rectifier source.

NEMA MG-1 [17] also discusses the impacts that varying motor operating voltages have on the motors. For small and medium induction motors, NEMA MG-1 specifies the following impacts of operating voltage:

- A +/- 10% variation in rated voltage may increase the heating at rated power that, under extended operation, may result in deterioration of the motor insulation system.
- A +10% increase (decrease) in voltage usually results in a considerably decrease (increase) in the motor power factor.
- The motor locked-rotor and breakdown torque are proportional to the square of the voltage.
- A +10% increase (decrease) in voltage results in a 17% decrease in slip (a 21% increase in slip). For example, if a rated slip was 5 %, the rated slip would be 6.05% if the voltage was reduced by 10% from the rated voltage.

NEMA MG-1 standard also discusses the impacts of voltage variations on small and medium DC motors operating on a variable voltage supply. These impacts do not directly apply to the utility service voltages without considering the rectifier operation.

Motors may respond differently to voltage excursions depending on their design [15, 28, 38]. Figure 3-1 illustrates commonly seen impacts that the operating voltage magnitude has on modern (T-frame) induction motors [38]. To summarize:

- Low voltage results in decreasing starting torque and starting current as the motor struggles to start or rotate under load.
- Low voltage causes the motor to pull more current to drive its load. An increase in current results in an increase in the motor temperature that can shorten the life of the motor insulation or result in operation of the thermal protection.
- High voltage can result in excessive power consumption or motor protection tripping.
- High voltage can cause magnetic saturation of the motor iron core that makes it harder to further magnetize the core without drawing more current. As a result, the motor draws more current decreasing the motor efficiency and increasing the motor temperature. The increasing motor temperature can shorten the motor lifetime.
- Power factor improves for lower voltages and becomes worse as voltages increase.

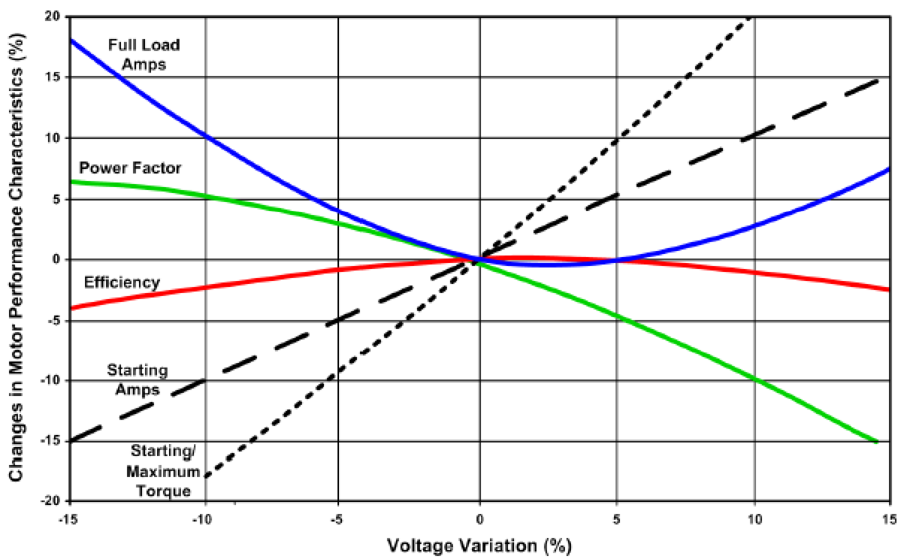

Figure 3-1
Operating voltage impact on T frame induction motors [38]

Induction motor speed-starting current and speed-torque characteristics as a function of supply voltages are well-known. To simplify, the motor speed-starting current and speed-torque curves drop with the supply voltage. For detailed plots, see [41]. Excessively low voltage may result in motors that unsuccessfully start and/or accelerate to running speed. Thus, lower motor operating voltages may require oversizing motors compared to their nominal voltage performance characteristics.

EPRI has evaluated induction motor CVR factors in [39]. For a single-phase induction motor with a fan load, the measured real and reactive power CVR factors were approximately 0.75 and 2.1, respectively. For a three-phase induction motor with a constant torque load, the measured CVR factor was approximately 0.89. In other words, induction motor power consumption will reduce with the voltage. The performed tests measured no significant change in motor speed as a function of the voltage. Tests were not performed for voltages outside the ANSI C84.1 ranges.

Adjustable Speed Drives

Adjustable-speed drives (ASDs), also known as variable-frequency drives (VFDs) or variable-speed drives (VSDs), have three basic parts that are illustrated in Figure 3-2 [38]. Modern ASDs have programmable parameters determining the lower and upper operating voltages. Depending on the ASD design, the control may stop the drive operation due to temperature, voltage or current levels, or other factors. In general, ASDs operate as constant power devices within the normal voltage ranges. At lower voltage levels, the current increases inversely as a function of the real power required to support the motor connected to the ASD. The opposite occurs when the voltage level increases. Operating ASDs at above-normal (under-normal) steady-state voltages may result the drive to drop due to DC bus capacitor overvoltage (undervoltage) condition.

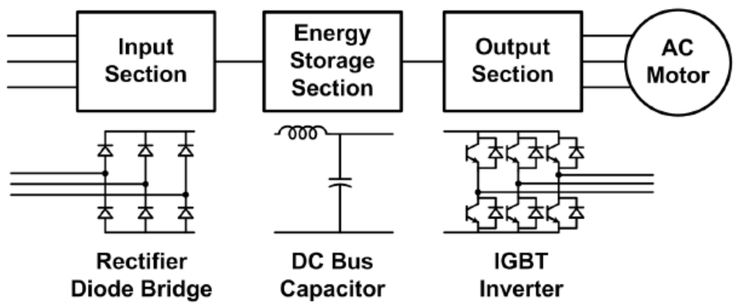

Figure 3-2
Adjustable-speed drive basic parts [38]

Steady-state undervoltages may also make ASDs more susceptible to voltage sags. On the other hand, steady-stage overvoltages may make the rectifier front end of the ASD more sensitive to capacitor switching transients or other surge events. ASDs are known to almost always drop out due to very low or very high voltages such as momentary interruptions [9]. However, the magnitudes at which these occur are outside the region of interest in this report.

Some ASD types are also known to be sensitive to voltage unbalance that may exacerbate the impacts of steady-state voltage excursions. The impacts are expected to be less severe on ASDs with active rectifier.

EPRI tested the CVR factors of motors with ASDs in [39]. The measured real and reactive power CVR factors were ~0.2 and ~0.6, respectively. In other words, a reduction in voltage will result in some reduction in power consumption by the motor with drive. The same tests measured almost no reduction in motor speed as the voltage was reduced. No testing was done for steady-state voltage excursions with magnitudes beyond the ANSI C84.1 limits.

Electronic Power Supplies

Electronic power supplies are commonly used for supplying electronic equipment such as computers with a desired DC voltage level. While electronic power supplies, especially modern switch-mode power supplies, tend to be sensitive to power quality disturbances such as voltage sags [9], they are typically capable of regulating their DC-side voltage to a desired level for a wide range of input AC voltages [38]. However, sufficiently high overvoltage at the power supply AC terminal may transfer to the DC load side. While the power supply itself may be able to tolerate the overvoltage condition, the supplied load is often sensitive to overvoltages. To avoid damaging the supplied equipment, some power supplies have so-called "crowbar" protection that turns off the power supply output voltage during overvoltage conditions. Low and high steady-state voltages can also make power supplies more vulnerable to other power quality disturbances. Low steady-state voltages result in lower storage energy in the DC-link capacitor (energy related to the squared voltage) thus, providing less ride-through capability during voltage sags and similar events.

In addition to the potential for damage and reduced tolerance to disturbances, smaller voltage deviations from the nominal can reduce power supply efficiency that is typically optimal at the nominal voltage.

EPRI testing in [6] indicate that PC power supplies may be quite tolerant to temporary overvoltages (TOVs) of up to 1.50 pu for several hours. The testing also indicated that power supplies that have built-in surge protection devices (SPDs), which are intended to protect against transient voltage spikes, may be less tolerant to TOVs than power supplies without SPDs. For details, see this report's section on TOV impacts.

Air-Conditioning

Air-conditioning equipment are essentially electric motors without or with power electronic drives. However, due to the significant role of air-conditioning, especially in residential load, it is worthwhile to discuss air-conditioning separately. The impact that operating voltage has on air-conditioner performance is very difficult to quantify since air-conditioner performance depends considerably on indoor and outdoor temperatures, humidity, control systems, etc.

EPRI testing in [39] saw a reduction in air-conditioner energy consumption as the voltage was reduced from 1.05 pu to 0.9 pu. The reduction in energy consumption resulted in from an increase in the efficiency of the air-conditioner. The testing also showed that the gain in efficiency depends on the outdoor temperature. As the outdoor temperature increases, the efficiency of an air conditioner decreases. The reason for this is that the efficiency of the air-conditioner compressor, which takes 80-87% of air-conditioner power consumption, reduces with increasing outdoor temperatures. Similar results apply to air-conditioner operating in heat pump mode: the air-conditioner efficiency increases as the voltage is lowered (within ANSI C84.1 limits). Analogously, the efficiency of the compressor of an air-conditioner operating as a heat pump is smaller for lower outdoor temperatures. Thus, reducing the voltage has a smaller impact on the air-conditioner energy consumption. No testing was done for steady-state voltages outside the ANSI C84.1 ranges.

Surge Protective Devices

Surge protective devices (SPDs) are designed to protect sensitive equipment from voltage spikes. An EPRI study [38] has found out that sustained steady-state overvoltages can decrease the protection effectiveness of SPDs against voltage spikes. Sustained undervoltages are not expected to impact the operation of these devices. SPD tolerance to TOVs has is discussed in the beginning of this chapter.

Other Residential Equipment

EPRI testing on CVR factors of various residential equipment can be found in [39]. No testing was done for voltages outside of ANSI C84.1 range A limits. The key findings for residential equipment are summarized as follows:

- Slightly negative (from -0.015 to -0.026) CVR factors were measured for LCD/LED TVs. In other words, the power consumption of modern TVs is not very sensitive to the voltage level. The modern LCD/LED TVs were also measured to operate very close to unity power factor.
- Similar to modern TVs, modern computer power supplies were measured to have slightly negative (from -0.018 to -0.035) CVR factors and to operate with almost unity power factor.
- Conventional cooking range and oven use purely resistive elements to convert electricity into heat. As a result, the power consumption will increase/decrease with the square of the voltage, leading to shorter/longer times to generate the same amount of heat. The net change in energy consumption is not expected to be significant. The testing validated these points.
- Similar to cooking range/oven, the power consumption of a clothes dryer reduces as the voltage is lowered but the overall energy consumption does not, as shown by the prior EPRI work [39].
- The CVR factors of refrigerators were shown to vary largely based on the manufacturing year [39]. The power consumption of the tested refrigerators decreased as the voltage was lowered.

The voltage dependence of some residential equipment, including refrigerators, has been analyzed in [40]. The impacts of increased voltage ranges on UK residential equipment has been discussed in [36, 37]. The reports note that especially older refrigerators and freezers may stall with very low operating voltages that may result in food going bad.

Other Industrial Equipment

In automated processes, the entire process may shut down if one part of the process shuts down. Therefore, to understand the sensitivity of an entire process, the sensitivity of the “weakest link” of the process must be known [12]. Equipment that is particularly vulnerable to temporary undervoltages include relays, contactors, programmable logic controllers (PLCs), and other control equipment [12].

Discussion on the voltage variation impact on other industrial and commercial equipment can be found in [15] and [16], respectively. Power quality impacts on automation and robotic equipment has been discussed in [42]. Automation and robotic systems vary greatly in topologies, complexity, physical environment, etc. However, all automation and robotic systems use electrically similar components including sensors, servomotors, PLCs, relays, and control networks. The report does not address steady-state voltage variation impact on automation and robotic equipment.

Other Medical Equipment

An EPRI case study has shown that overvoltages can affect the quality of the images produced with an x-ray machine [38].

Distributed Energy Resources

Distributed energy resources (DER) is a very broad category encompassing solar photovoltaics (PV), electric vehicles (EV), energy storage, etc. PV and other DER generators can cause unexpected overvoltages. On the other hand, EVs and DER loads can considerably decrease end user voltages. Although DER is expected to increase the magnitude and duration of steady-state voltage excursions, many DER types are also expected to be very sensitive to voltage variations. For example, PV systems may go offline if voltages exceed 126 V. Depending on the type of DER power conversion system, the potential impacts of steady-state voltage variations on the DER itself are expected to be somewhat similar to equivalent rotating machines or inverter based loads/generator. However, a more thorough literature review is needed to understand the behavior of DER internal control and protection logic under steady-state voltage excursions.

Summary

A literature review on the steady-state voltage excursion impacts on end-use devices has been presented in this chapter. A simplified summary of the impacts can be found in Table 2-1. The impacts vary based on equipment type and many other factors. The impacts are known in detail for some equipment types and less in detail for other types of equipment, particularly equipment with power electronics on the front-end. Considerations and next steps relevant to the research discussed in this report will be discussed in the next chapter.

4
CONSIDERATIONS AND NEXT STEPS

Steady-state rms voltage magnitude is a fundamental aspect of power quality. Several standards have been established to regulate steady-state voltage ranges. Different standards have different scopes and objectives. The standards have been established to balance the diverse needs of different stakeholders, which are electric utilities, electric equipment manufacturers, and electricity end users. The standards are largely based on the tolerances of key equipment, including incandescent light bulbs and electric motors. Moreover, the standards were also largely implemented during the paradigm of one-way power flows to the end users and limited, if any, visibility of end user power quality. This paradigm has been shattered by DER that causes reverse power flows and by AMI that has tremendously increased the visibility of end user power quality.

The various parts of this report clearly highlight the complexity associated with steady-state voltage thresholds. If the thresholds were to be revised, it would be of utmost importance to make revision through a process that involves all the relevant stakeholders. Past efforts with the goal to adjust steady-state voltage threshold standards have highlighted the importance of an inclusive process. For example, some utility perspective on reducing voltage thresholds can be found in [43]. Additionally, some discussion on customer perception of potentially lowered power quality can be found in [36]. Finally, an example of regulator perspective can be obtained in [26].

For electric utilities, steady-state voltage standards play a fundamental role in the planning, design, and operation of the electric distribution system. Thus, any changes in these standards are likely to have far-reaching consequences for distribution planning and operations. For example, if relaxed voltage thresholds resulted in operating distribution systems at higher voltages, the overall energy consumption may be increased, which is counterproductive to energy conservation objectives and conservation voltage reduction (CVR). Operating distribution equipment at higher voltage may also make the equipment more susceptible to damage under fault conditions. On the other hand, operating distribution equipment at lower voltages may make it more susceptible to shut-down during voltage sags. Relaxing the voltage ranges may also result in wider voltage ranges in both the medium and low-voltage networks. Not all the utility equipment may tolerate this well. For example, utility low-voltage cables may not have sufficient margin in their insulation levels in the U.K. to increase the voltages [37].

Electric equipment manufacturers design and manufacture the equipment to operate satisfactorily for any voltage within expected voltage ranges. Moreover, equipment manufacturers typically design the equipment to operate with optimal efficiency and performance with the most common steady-state voltage magnitude. Any relevant voltage range changes should also be reflected to the respective equipment tolerance standards so that new equipment is designed and manufactured with respect to appropriate tolerance levels. However, it should be noted that old electric equipment is likely operated for years, if not decades, after voltage range standard revision. Thus, any changes to the steady-state voltage ranges may result in the existing equipment to operate less efficiently or with a reduced performance for years to come. Changes in voltage ranges may also result in existing equipment to operate at voltages outside of their designed tolerances that may manifest itself as unsatisfactory operation of some equipment. It may also lead into increased wear/tear that may reduce the equipment lifetime. In some cases, it may even result in immediate equipment damage.

An overview of some of the known impacts that voltage excursions beyond current standard ranges may have is provided in Chapter 3. The impacts vary largely based on equipment type, manufacturer, model, manufacturing year, etc. The impacts may also vary largely based on other power quality aspects including but not limited to voltage unbalance, short-term voltage variations, and harmonics. For some equipment types, such as incandescent bulbs, CFL light bulbs, and induction motors, the impacts are either very well or relatively well known. For other equipment, such as LED light bulbs, ASDs, and power supplies of various home electronics, the impacts are less clear. The general expectation is clearly that modern equipment with a power electronic front end – be it the chip of an LED bulb or a power supply of a computer – are less sensitive to steady-state voltage variations. However, it appears that only limited testing has been done on these impacts. Some testing has been done on equipment tolerance to very low voltages (e.g. voltage sags) or very high voltages (e.g. 1.50 pu for few hours). Limited testing has been done on equipment tolerance to long-duration (several hours and longer) overvoltages and undervoltages outside the current steady-state standard voltage ranges.

Some of the impacts of equipment operating at slightly elevated or reduced voltages may be identified relatively easily. For example, experienced inconvenience or reduced performance may be easy to identify, although it may be harder to quantify. However, other impacts may be hard to identify. For example, equipment may properly operate at 1.2 pu overvoltage or 0.80 pu undervoltage without damage or any experienced inconvenience. However, operation at this voltage level may result in slightly increased wear/tear, e.g., in the form of increased heating, that may lead to a reduction of expected equipment life. It may be very hard to identify or quantify the importance of such impacts. For example, if the average life of a refrigerator is reduced by one year, it might not be noticed. It may be very hard to prove that a change in standard voltage thresholds resulted in the reduced life.

This report has largely focused on the steady-state voltage magnitudes. However, in most standards, there are multiple voltage ranges that allow a certain probability of occurrence. If existing steady-state voltage thresholds were to be revised, the question is not only what the magnitude of the permitted steady-state voltages should be but also what the permitted duration and frequency of variations should be. The current standards address this differently. ANSI C84.1 defines two voltage ranges A and B and states that voltage magnitudes in range B should be infrequent; EN 50160 refers to 95% of the time. In the past, due to the lack of measurement data, the durations were not very important since it was not possible to quantify whether or not they were observed. However, smart meter data has made it practical to track the frequency of overvoltages and undervoltages. If steady-state voltage standards were to be revised, it would be reasonable to consider the added visibility.

The voltage measurement time-interval specified in the steady-state voltage threshold standards is very important. For example, 10-minute averages may not capture shorter duration rms voltage variations that can damage equipment [26]. With today's smart meters, it may be possible to cost-effectively obtain additional measurements of shorter-duration voltage variations. Alternatively, it may be worth considering shortening the time-averaging interval.

Some utilities globally, e.g., ESKOM in South Africa, apply different voltage ranges for different customer segments and/or different distribution feeder types. For example, residential customers may be less sensitive to voltage excursions than commercial/industrial customers that may have a large number of induction motors. Moreover, rural feeders may be forced to apply relaxed voltage standards due to long lines.

Tighter voltage bands could also be offered to sensitive customers through premium power products. This would allow targeting the cost of necessary investments to the customers needing the service instead of socializing the cost to all customers. Moreover, offering tighter voltage ranges as a premium product would allow customers to perform cost-benefit analysis on whether the required investments are justified compared to the cost associated with voltages operating within wider ranges. Such premium power contracts could follow the ranges already used for voltage sags and other power quality incidents. The contracts may require the utility to have access to the customer facility and to install equipment either in the distribution system or at the customer facility.

To summarize, there seems to be limited understanding of the impacts of steady-state overvoltages and undervoltages with long duration but limited magnitude. More testing is needed to understand these impacts. Moreover, there seems to be limited understanding of the impacts on some of the modern electrical equipment, particularly equipment with power electronic front end. More testing should be performed on the steady-state voltage excursion impacts on such equipment including LEDs, ASDs, and home electronics. Finally, a further literature review is needed to understand the impacts on PV systems and DER.

This report discusses many standards related to steady-state voltage thresholds. However, there are other standards that were not reviewed for this report. For example, there are many international IEC standards and equipment class standards that were not reviewed. This report also does not contain a thorough review of steady-state voltage standards in different countries.

Finally, there is limited understanding of the current frequency of overvoltage and undervoltage events. DER is expected to increase the frequency and magnitude of voltage variations. Some utilities have already expressed challenges with this. However, the current scope of this problem is not well known.

5
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