

IEEE Std 3001.3™-2024

Recommended Practice for the
Design of Industrial and Commercial
Power Systems: Voltage
Considerations



IEEE STANDARDS ASSOCIATION

IEEE Recommended Practice for the Design of Industrial and Commercial Power Systems: Voltage Considerations

Developed by the

Industrial & Commercial Power Systems Standards Development Committee
of the
IEEE Industry Applications Society

Approved 12 November 2024

IEEE SA Standards Board

Abstract: Information concerning system voltage nomenclature and the preferred voltage ratings of distribution apparatus and utilization equipment are contained in this recommended practice. This is essential to proper voltage identification throughout a power distribution system. The dynamic characteristics of the system and the proper principles of voltage control applied so that satisfactory voltages will be supplied to utilization equipment under operating conditions are discussed. An understanding of system voltage nomenclature and the preferred voltage ratings of distribution apparatus and utilization equipment is essential to help ensure proper voltage identification throughout a power distribution system. The dynamic characteristics of the system need to be recognized, and the proper principles of voltage control applied so that satisfactory voltages will be supplied to all utilization equipment under all normal conditions of operation.

Keywords: flicker, IEEE 3001.3, motor starting, power factor, sag, unbalanced voltage, voltage, voltage drop, voltage ratings, voltage tolerance

The Institute of Electrical and Electronics Engineers, Inc.
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PDF: ISBN 979-8-8557-1663-4 STD27611
Print: ISBN 979-8-8557-1664-1 STDPD27611

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When this project is completed, the technical material included in the 13 "color books" will be included in a series of new standards. Approximately 60 "dot" standards, organized into the following categories, will provide in-depth treatment of many of these topics:

- Power Systems Design (3001 series)
- Power Systems Analysis (3002 series)
- Power Systems Grounding (3003 series)
- Protection and Coordination (3004 series)
- Emergency, Stand-By Power, and Energy Management Systems (3005 series)
- Power Systems Reliability (3006 series)
- Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a "dot" standard comes from a particular chapter of a particular color book. In other cases, material from several color books has been combined into a new "dot" standard.

The material in this recommended practice replaces Chapter 3 of IEEE Std 141™-1993 [B54] and Chapter 3 of IEEE Std 241™-1990, [B56].

IEEE Std 3001.3™

This publication provides a recommended practice for the electrical design of commercial and industrial facilities. It is likely to be of the greatest value to power-oriented engineers with limited commercial or industrial plant experience. It can also aid all engineers responsible for the electrical design of commercial and industrial facilities. However, it is not intended as a replacement for the many excellent engineering texts and handbooks commonly in use, nor is it detailed enough to be a design manual. It should be considered a general reference on electrical design for commercial and industrial facilities.

Tables, figures, charts, and other information that have been extracted from codes, standards, and other technical literature are included in this publication. Their inclusion is for illustrative purposes; where technical accuracy is important, the latest version of the referenced document should be consulted.

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IEEE Recommended Practice for the Design of Industrial and Commercial Power Systems: Voltage Considerations

1. Overview

1.1 Scope

This recommended practice contains information concerning system voltage nomenclature and the preferred voltage ratings of distribution apparatus and utilization equipment. This is essential to proper voltage identification throughout a power distribution system. The recommended practice also discusses the dynamic characteristics of the system and the proper principles of voltage control applied so that satisfactory voltages will be supplied to utilization equipment under operating conditions.

1.2 Purpose

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

⁶ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C84.1, Electric Power Systems and Equipment (60 Hz).⁸

ANSI/NFPA 70®, National Electric Code® (NEC®).⁹

CSA C235, Preferred Voltage Levels for AC Systems, Up to 50 000 V.¹⁰

IEEE Std 519™, IEEE Standard for Harmonic Control in Electric Power Systems.^{11, 12}

IEEE Std 3001.2™, IEEE Recommended Practice for Evaluating the Electrical Service Requirements of Industrial and Commercial Power Systems.

IEEE Std 3001.5™, IEEE Recommended Practice for the Application of Power Distribution Apparatus in Industrial and Commercial Power Systems.

IEEE Std C57.12.20™, IEEE Standard for Overhead-Type Distribution Transformers 500 kVA and Smaller, 67 000 Volts and Below; Low Voltage, 7970/13 800Y V and Below.

NEMA MG 1, Motors and Generators.¹³

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹⁴

3.2 System voltage terms

NOTE—The nominal system voltage is near the voltage level at which the system normally operates. To allow for operating contingencies, systems generally operate at voltage levels about 5% to 10% below the maximum system voltage for which system components are designed.¹⁵

maximum system voltage: The highest system voltage that occurs under normal operating conditions, and the highest system voltage for which equipment and other components are designed for satisfactory continuous operation without derating of any kind.

NOTE—In defining maximum system voltage, voltage transients and temporary overvoltages caused by abnormal system conditions, such as faults, load rejection, and the like, are excluded. However, voltage transients and temporary overvoltages may affect equipment operating performance and are considered in equipment application.

⁸ ANSI publications are available from the American National Standards Institute (<https://www.ansi.org/>).

⁹ The NEC is published by the National Fire Protection Association (<https://www.nfpa.org/>). Copies are also available from the Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

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¹³ NEMA publications are available from the National Electrical Manufacturers Association (<https://www.nema.org/>).

¹⁴ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

¹⁵ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

nominal system voltage: The voltage by which a portion of the system is designated and to which certain operating characteristics of the system are related.

NOTE—Each nominal system voltage pertains to a portion of the system that is bounded by transformers or utilization equipment.

nominal utilization voltage: The voltage rating of certain utilization equipment used on the system.

service voltage: The voltage at the point where the electric system of the supplier and the electric system of the user are connected.

system voltage: The root-mean-square phase-to-phase voltage of a portion of an ac electric system.

NOTE—Each system voltage pertains to a portion of the system that is bounded by transformers or utilization equipment. (All voltages hereafter are root-mean-square phase-to-phase or phase-to-neutral voltages.)

utilization voltage: The voltage at the line terminals of utilization equipment.

3.3 System voltage classes

extra-high voltage (EHV): A class of nominal system voltages greater than 230 kV but less than 1000 kV.

NOTE—Industrial and commercial power systems are rarely connected to EHV or UHV systems at the service level.

extra-low voltage (ELV). A subset of the low-voltage class. This range of voltages, less than 50 V ac, is considered to have a low risk of electric shock.

high voltage (HV): A class of nominal system voltages equal to or greater than 100 000 V and equal to or less than 230 000 V.

NOTE—Qualified personnel, and to an extent lay people, will recognize the severity of the hazard associated with these terms. These terms are used by trained professionals and qualified personnel to identify the equipment suitable for use within those voltage ranges. When used for identifying hazardous voltages for purposes of assigning a degree of safety, the term *high voltage* applies to a broader range of voltage, from 1000 V and greater.

low voltage (LV): A class of nominal system voltages equal to or less than 1000 V

NOTE—per ANSI C84.1.¹⁶

medium voltage (MV): A class of nominal system voltages greater than 1000 V and less than 100 000 V.

ultra-high voltage (UHV): A class of nominal system voltages equal to or greater than 1000 kV

NOTE—Industrial and commercial power systems are rarely connected to EHV or UHV systems at the service level.

4. General

4.1 Introduction

An understanding of system voltage nomenclature and the preferred voltage ratings of distribution apparatus and utilization equipment is essential to help ensure proper voltage identification throughout a power distribution system. The dynamic characteristics of the system need to be recognized, and the proper principles of voltage control applied so that satisfactory voltages will be supplied to all utilization equipment under all normal conditions of operation. Consideration should be given for transient and momentary voltage variations to improve appropriate performance of utilization equipment.

¹⁶ Information on references can be found in Clause 2.

4.2 Standard nominal 60 Hz system voltages for the United States

These voltages and their associated tolerance limits are listed in ANSI C84.1. The nominal system voltages and their associated tolerance limits and notes have been provided in Table 1, listing all the standard nominal system voltages and their associated tolerance limits for the United States.

The nominal system voltages contained in Table 1 apply to all parts of the system, both of the supplier and user. The ranges are given separately for service voltage and for utilization voltage because they are normally at different locations. The voltage at utilization points is normally somewhat lower than at the service point. In addition, integral horsepower motors, air-conditioning and refrigeration equipment, or both, may constitute a heavy concentrated load on some circuits. The rated voltages of such equipment and of motors and motor control equipment are usually lower than the nominal system voltage. This corresponds to the range of utilization voltages in Table 1. Other utilization equipment is generally rated at nominal system voltage.

Preferred nominal system voltages and voltage ranges are shown in boldface type, while other systems in substantial use that are recognized as standard voltages are shown in regular type. Other voltages may be encountered on older systems, but they are not recognized as standard voltages. The transformer connections from which these voltages are derived are shown in Figure 1.

Two sets of tolerance limits are defined: Range A, which specifies the limits under most operating conditions, and Range B, which allows minor excursions outside the Range A limits.

4.3 Application of voltage classes

The voltage classes have the following applications:

- a) Low-voltage class voltages are used to supply utilization equipment.
- b) Medium-voltage class voltages are used for subtransmission and primary distribution. Medium voltages often supply distribution transformers, which step the medium voltage down to low voltage to supply utilization equipment. Medium voltages may also supply distribution substations that transform the voltage from a higher to a lower voltage in the medium-voltage class. Medium voltages of 13 800 V and below are also used to supply utilization equipment such as large motors (see Clause 8, Table 9, and Table 10).
- c) High-voltage class voltages are used to transmit large amounts of electric power between transmission substations. Transmission substations located adjacent to generating stations step the generator voltage up to the transmission voltage. Other transmission substations transform the high voltage down to medium voltage for subtransmission and primary distribution. Transmission lines also interconnect transmission substations to provide alternate paths for power transmission for higher reliability. Large industrial and commercial facilities may interconnect to electrical utilities at the transmission line level using substations owned by either the utility or the facility owner (see IEEE Std 3001.2™, Clause 10).

Table 1—Standard nominal system voltages and voltage ranges

Voltage class	Nominal system voltage ^a			Nominal utilization voltage ^b	Voltage range A ^b			Voltage range B ^b																																													
	2-wire	3-wire	4-wire		Maximum	Minimum		Maximum	Minimum																																												
					Utilization and service voltage ^c	Service voltage	Utilization voltage	Utilization and service voltage	Service voltage	Utilization voltage																																											
Low voltage (see Note 1)	Single-phase systems																																																				
	120			115	126	114	110	127	110	106																																											
		120/240		115/230	126/252	114/228	110/220	127/254	110/220	106/212																																											
	Three-phase systems																																																				
			208Y/120 ^d	200	218Y/126	197Y/114	191Y/110	220Y/127	191Y/110 (see Note 2)	184Y/106 (see Note 2)																																											
			240/120	230/115	252/126	228/114	220/110	254/127	220/110	212/106																																											
		240	480Y/277	450	504Y/291	456Y/263	440Y/254	508Y/293	440Y/254	424Y/245																																											
	480		460	504	456	440	508	440	424																																												
	600 ^e		575	630 ^e	570	550	635 ^e	550	530																																												
		690Y/400																																																			
Medium voltage		2400			2520	2340	2160	2540	2280	2080																																											
			4160Y/2400		4370/2520	4050Y/2340	3740Y/2160	4400Y/2540	3950Y/2280	3600Y/2080																																											
					4370	4050	3740	4400	3950	3600																																											
					5040	4680	4320	5080	4560	4160																																											
					7240	6730	6210	7260	6560	5940																																											
			8320Y/4800		8730Y/5040	8110Y/4680		8800Y/5080	7900Y/4560																																												
			12 000Y/6930		12 600Y/7270	11 700Y/6760		12 700Y/7330	11 400Y/6580																																												
			12 470Y/7200		13 090Y/7560	12 160Y/7020	f	13 200Y/7620	11 850Y/6840	f																																											
			13 200Y/7620		13 860Y/8000	12 870Y/7430		13 970Y/8070	12 504Y/7240																																												
			13 800Y/7970		14 490Y/8370	13 460Y/7770		14 520Y/8380	13 110Y/7570																																												
		13 800			14 490	13 460	12 420	14 520	13 110	11 880																																											
			20 780Y/12000		21 820Y/12 600	20260Y/11 700		22 000Y/12 700	19 740Y/11 400																																												
			22 860Y/13200		24 000Y/13 860	22 290Y/12 870		24 200Y/13 970	21 720Y/12 540																																												
	23 000			24 150	22 430		24 340	21 850																																													
		24 940Y/14400		26 190Y/15 120	24 320Y/14 040		26 400Y/15 240	23 690Y/13 680																																													
	34 500	34 500Y/19920		36 230Y/20 920	33 640Y/19 420		36 510Y/21 080	32 780Y/18 930																																													
				36 230	33 640		36 510	32 780																																													
					NOTES (1) Minimum utilization voltages for 120 V to 600 V circuits not supplying lighting loads are as follows: <table><tr><td></td><td>Nominal system</td><td>Range A</td><td>Range B</td><td></td></tr><tr><td></td><td>120</td><td>108</td><td>104</td><td rowspan="5">(2) Many 220 V motors were applied on existing 208 V systems on the assumption that the utilization voltage would not be less than 187 V. Caution should be exercised in applying the Range B minimum voltages of this table to existing 208 V systems supplying such motors.</td></tr><tr><td rowspan="4">Note 2</td><td>120/240</td><td>108/216</td><td>104/208</td></tr><tr><td>208Y/120</td><td>187Y/108</td><td>180Y/104</td></tr><tr><td>240/120</td><td>216/108</td><td>208/104</td></tr><tr><td>240</td><td>216</td><td>208</td></tr><tr><td></td><td>480Y/277</td><td>432Y/249</td><td>416Y/240</td><td></td></tr><tr><td></td><td>480</td><td>432</td><td>416</td><td></td></tr><tr><td></td><td>600</td><td>540</td><td>520</td><td></td></tr><tr><td></td><td>120/240</td><td>108/216</td><td>104/208</td><td></td></tr></table>							Nominal system	Range A	Range B			120	108	104	(2) Many 220 V motors were applied on existing 208 V systems on the assumption that the utilization voltage would not be less than 187 V. Caution should be exercised in applying the Range B minimum voltages of this table to existing 208 V systems supplying such motors.	Note 2	120/240	108/216	104/208	208Y/120	187Y/108	180Y/104	240/120	216/108	208/104	240	216	208		480Y/277	432Y/249	416Y/240			480	432	416			600	540	520			120/240	108/216	104/208	
	Nominal system	Range A	Range B																																																		
	120	108	104	(2) Many 220 V motors were applied on existing 208 V systems on the assumption that the utilization voltage would not be less than 187 V. Caution should be exercised in applying the Range B minimum voltages of this table to existing 208 V systems supplying such motors.																																																	
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	240	216	208																																																		
	480Y/277	432Y/249	416Y/240																																																		
	480	432	416																																																		
	600	540	520																																																		
	120/240	108/216	104/208																																																		

^a Three-phase three-wire systems are systems in which only the three-phase conductors are carried out from the source for the connection of loads. The source may be derived from any type of three-phase transformer connection, grounded or ungrounded. Three-phase, four-wire systems are systems in which a grounded neutral conductor is also carried out from the source for the connection of loads. Four-wire systems in this table are designated by the phase-to-phase voltage, followed by the letter Y (except for the 240 V/120 V delta system), a slant line, and the phase-to-neutral voltage. Single-phase services and loads may be supplied from either single-phase or three-phase systems. The principal transformer connections that are used to supply single-phase and three-phase systems are illustrated in Figure 1.

^b The voltage ranges in this table are illustrated in ANSI C84.1 Annex B.

^c For 120 V to 600 V nominal systems, voltages in this column are maximum service voltages. Maximum utilization voltages would not be expected to exceed 125 V for the nominal system voltage of 120, nor appropriate multiples thereof for other nominal system voltages through 600 V.

^d A modification of this three-phase, four-wire system is available as a 120/208Y-V service for single-phase, three-wire, open-wye applications.

^e Certain kinds of control and protective equipment presently available have a maximum voltage limit of 600 V; the manufacturer, power supplier, or both should be consulted to assure proper application.

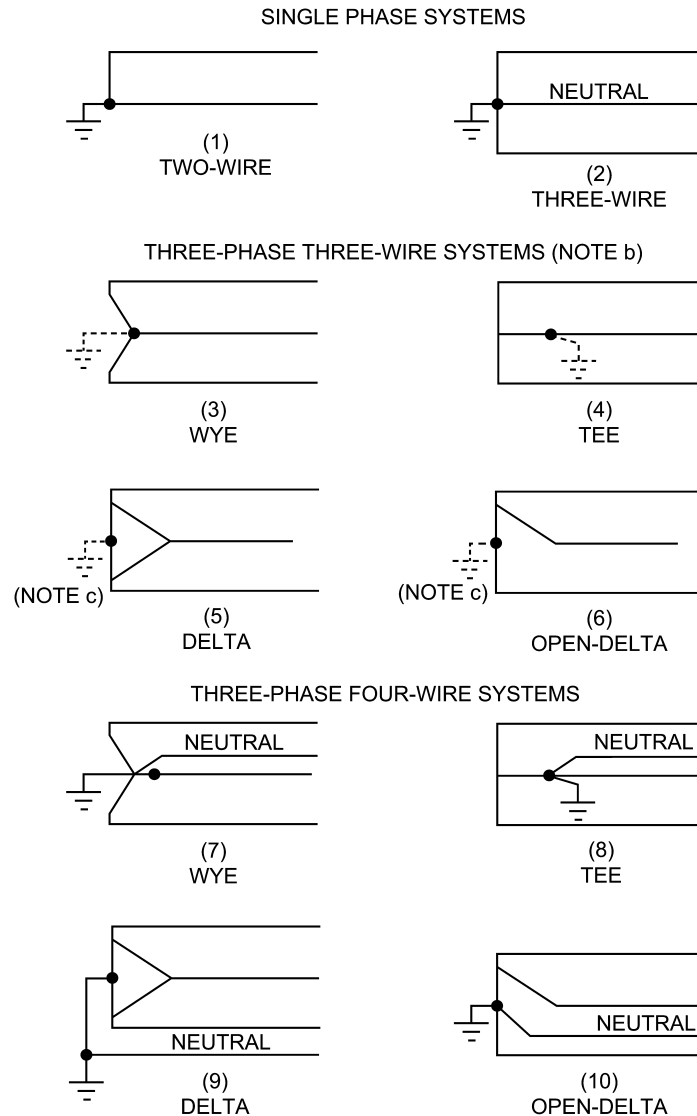
^f Utilization equipment does not generally operate directly at these voltages. For equipment supplied through transformers, refer to limits for the nominal system voltage of transformer output.

^g For these systems, range A and range B limits are not shown because, where they are used as service voltages, the operating voltage level on the user's system is normally adjusted by means of voltage regulators or load tap-changers to suit their requirements.

^h Nominal utilization voltages are for low-voltage motors and control.

ⁱ Many 220 V motors were applied to existing 208 V systems on the assumption that the utilization voltage would not be less than 187 V. Caution should be exercised in applying the Range B minimum voltages of ANSI C84.1 Table 1 to existing 208 V systems supplying such motors.

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NOTE a—These diagrams show connections of transformer secondary windings to supply the nominal system voltages of Table 1. Systems of more than 600 V are normally three-phase and supplied by connections (3), (5) ungrounded, or (7). Systems of 120 V to 600 V may be either single-phase or three-phase and all the connections shown are used to some extent for some systems in this voltage range.

NOTE b—Three-phase, three-wire systems may be solidly grounded, impedance grounded, or ungrounded, but are not intended to supply loads connected phase-to-neutral (as the four-wire systems are).

NOTE c—In connections (5) and (6), the ground connection may be at the midpoint of one winding as shown (if available), to one phase conductor (corner grounded), or omitted entirely (ungrounded).

NOTE d—Single-phase services and single-phase loads may be supplied from single-phase systems or from three-phase systems. They are connected phase-to-phase when supplied from three-phase, three-wire systems and either phase-to-phase or phase-to-neutral from three-phase, four-wire systems.

Figure 1—Principal transformer connections to supply the system voltages of Table 1

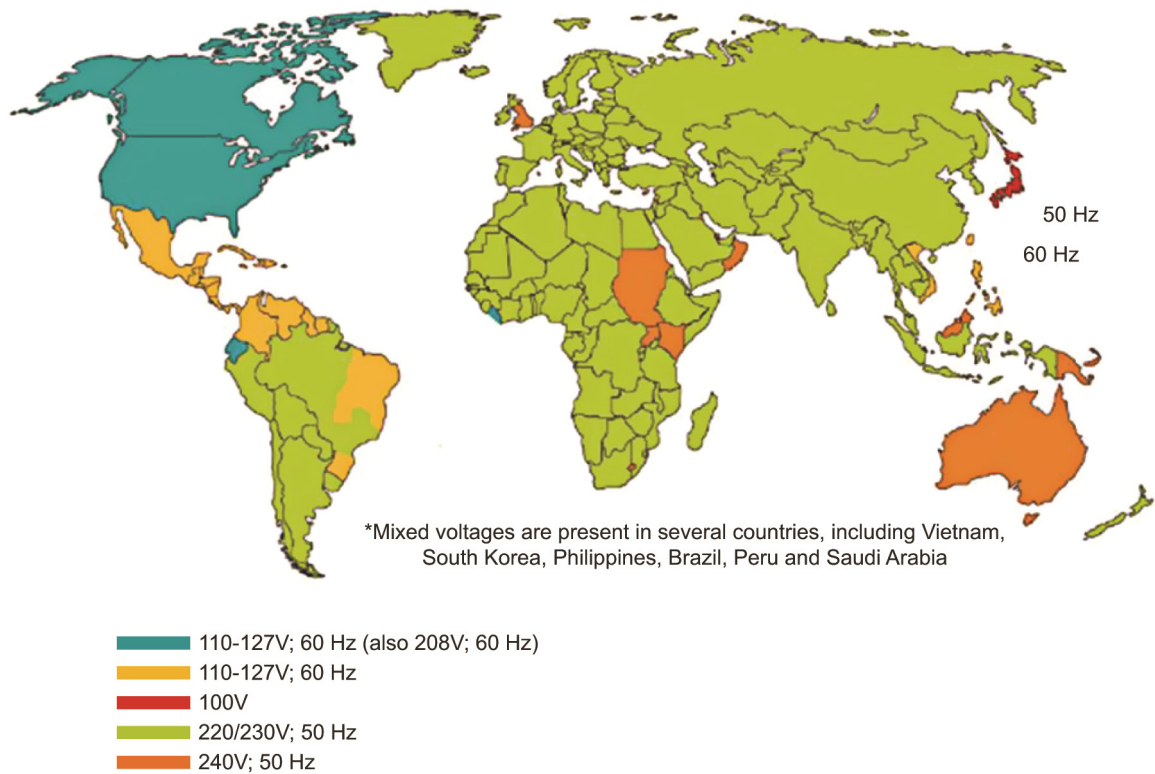
4.4 Voltage systems outside of the United States

In general, equipment rated for use in the United States cannot be used outside of the United States, and equipment rated for use outside of the United States cannot be used in the United States. Voltage systems in other countries generally differ from those in the United States. For example, 415Y/240 V and 400Y/230 V are widely used as utilization voltages, even for residential service. Also, the frequency in many countries is 50 Hz instead of 60 Hz, which affects the operation of some equipment such as motors. Motors on 50 Hz systems run approximately 17% slower than in the United States. Plugs and receptacles are generally different, and this helps to prevent utilization equipment from the United States from being connected to the wrong voltage. However, ANSI-based panelboards and switchboards rated for 600 V and smaller can be suitable for residential applications in countries that use a system voltage of 400 V.

Users should check with the equipment manufacturer before attempting to operate equipment on a voltage or frequency for which the equipment is not specifically rated. Equipment rated for use with one voltage and frequency often cannot be used or may not give adequate performance on another voltage or frequency. Some equipment has multiple voltage and/or frequency ratings for application on a variety of systems. If electric equipment made for use on one system must be used on a different system, information on the voltage, frequency, and type of plug required should be obtained. If the difference is only in the voltage, transformers are generally available to convert the available supply voltage to match the equipment voltage.

Figure 2 shows the standard single-phase voltages used by each country around the world. Several references are available that list this information, as well as standard three-phase voltage and frequency. Table 2 provides further details including three-phase voltage and frequency for the listed countries. These voltages should be reconfirmed as they can change and some are in the process of being changed. Up-to-date lists can be found easily on the internet. Among those available at this time are WorldStandards 0¹⁷, Generator Source, LLC [B36], and React Power Solutions, LLC [B99].

¹⁷ The numbers in brackets correspond to those of the bibliography in Annex A.



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Figure 2—Standard single-phase voltages applied worldwide

Table 2—Worldwide single-phase and three-phase voltages

Country	1-phase voltage (V)	3-phase voltage (V)	Freq. (Hz)	Country	1-phase voltage (V)	3-phase voltage (V)	Freq. (Hz)	Country	1-phase voltage (V)	3-phase voltage (V)	Freq. (Hz)
Afghanistan	220	380	50	Gaza	230	400	50	New Caledonia	220	380	50
Albania	230	400	50	Georgia	220	380	50	New Zealand	230	400	50
Algeria	127/220	400	50	Germany	220–230	400	50	Nicaragua	120	208	60
American Samoa	120/240	208	60	Ghana	220	400	50	Niger	220	380	50
Andorra	230	400	50	Gibraltar	240	400	50	Nigeria	240	415	50
Angola	220	380	50	Greece	220–230	400	50	Northern Ireland	240	400	50
Anguilla	110	415	60	Greenland	220	400	50	Norway	220–230	400	50
Antigua	230	400	60	Grenada	230	400	50	Okinawa	110/120	200/230	60
Argentina	220	380	50	Guadeloupe	220	380	50	Oman	240	415	50
Armenia	230	400	50	Guam	110–120	190	60	Pakistan	230	400	50
Aruba	115/127	220	60	Guatemala	120	208	60	Palau	120	208	60
Australia	240	415	50	Guinea	220	380	50	Panama	110/220/120	220/240	60
Austria	220–230	400	50	Guinea-Bissau	220	380	50	Papua New Guinea	240	415	50
Azerbaijan	220	380	50	Guyana	110	190	50/60	Paraguay	220	380	50
Azores (Portugal)	220	400	50	Haiti	110–120	190	50/60	Peru	110/220	220/380	50/60
Bahamas	120	208	60	Honduras	110	190	60	Philippines	115	380	60
Bahrain	230	400	50	Hong Kong	220	380	50	Poland	230	400	50
Balearic Islands	230	400	50	Hungary	230	400	50	Portugal	230	400	50
Bangladesh	220	380	50	Iceland	230	400	50	Puerto Rico	120	480	60
Barbados	115	200	50	India	220–250	400	50	Qatar	240	415	50
Belarus	230	400	50	Indonesia	230	380	50	Réunion Island	220	400	50
Belgium	220–230	400	50	Iran	230	400	50	Romania	220	400	50
Belize	110	190/380	60	Iraq	230	400	50	Russia	230	400	50
Benin	220	380	50	Ireland	230	400	50	Rwanda	230	400	50
Bermuda	120	208	60	Isle of Man	230	400	50	Saudi Arabia	230	400	60
Bhutan	230	400	50	Israel	230	400	50	Scotland	220	400	50
Bolivia	110–115/220	400	50	Italy	220–230	400	50	Senegal	230	400	50
Bosnia-Herzegovina	230	400	50	Ivory Coast	220	380	50	Serbia	230	400	50
Botswana	230	400	50	Jamaica	110	190	50	Seychelles	240	400	50
Brazil	110–127/220	220/380/440	60	Japan	100	200	50/60	Sierra Leone	230	400	50
Brunei	240	415	50	Jordan	220	400	50	Singapore	230	400	50
Bulgaria	230	400	50	Kazakhstan	230	400	50	Slovakia	230	400	50
Burkina Faso	220	380	50	Kenya	240	415	50	Slovenia	230	400	50
Burundi	220	380	50	Korea, North	120/220	380	50/60	Somalia	110/220	380	50
Cambodia	120/220	400	50	Korea, South	220	380	50/60	South Africa	220–230	400	50
Cameroon	220–230	380	50	Kosovo	230	400	50	Spain	220–230	400	50
Canada	120	208/240/600	60	Kuwait	240	415	50	Sri Lanka	230	400	50
Canary Islands (Spain)	220	400	50	Kyrgyzstan	220	380	50	St. Kitts & Nevis	230	400	60
Cape Verde	220	400	50	Laos	220	400	50	St. Lucia	240	400	50
Cayman Islands	120	208	60	Latvia	220	400	50	St. Vincent	230	400	50
Central African Republic	220	380	50	Lebanon	110–220	400	50	Sudan	240	400	50
Chad	220	380	50	Lesotho	220	380	50	Surinam	115	220	60
Channel Islands	240	400	50	Liberia	120	208	60	Swaziland	230	400	50
Chile	220	380	50	Libya	127–230	220/400	50	Sweden	220–230	400	50
China	220	380	50	Liechtenstein	230	400	50	Switzerland	220–230	400	50
Colombia	110–220	480	60	Lithuania	230	400	50	Syria	220	380	50
Congo	230	380	50	Luxembourg	230	400	50	Tahiti	220	380	50
Congo, Dem. Rep. of	220	400	50	Macau	230	380	50	Taiwan	110/220	220/380	60
Cook Islands	240	415	50	Macedonia	230	400	50	Tajikistan	220	380	50
Costa Rica	120	240	60	Madagascar	220	220/380	50	Tanzania	230	415	50
Croatia	230	400	50	Madeira (Portugal)	220	400	50	Thailand	220/230	380	50
Cuba	110	190	60	Malawi	230	400	50	Togo	220	380	50
Cyprus	240	400	50	Malaysia	240	415	50	Tonga	240	415	60
Czech Republic	230	400	50	Maldives	230	400	50	Trinidad & Tobago	115/230	230/240	60
Denmark	220–230	400	50	Mali	220	380	50	Tunisia	220	400	50
Djibouti	220	380	50	Malta	230	400	50	Turkey	230	400	50
Dominica	230	400	50	Martinique	220	380	60	Turkmenistan	220	380	50
Dominican Republic	120	208/227/480	60	Mauritania	220	220	50	Uganda	240	415	50
Ecuador	120	208/480	60	Mauritius	230	400	50	Ukraine	230	380	50
Egypt	220	380	50	Mexico	127	220/380	60	United Arab Emirates	220/230	380	50
El Salvador	115	440	60	Moldova	220	400	50	United Kingdom	240	400	50
England	230–240	400–415	50	Monaco	230	400	50	United States	120	277/480	60
Estonia	230	400	50	Mongolia	220	400	50	Uruguay	230	380	50
Ethiopia	220	380	50	Montserrat	230	400	60	Uzbekistan	220	380	50
Falkland Islands	240	415	50	Morocco	220	380	50	Venezuela	120	240	60
Faroe Islands	230	400	50	Mozambique	220	380	50	Vietnam	120/220	380	50
Fiji	240	415	50	Myanmar	230	400	50	Virgin Islands	120	190	60
Finland	220–230	400	50	Namibia	220–250	380	50	Wales	220	400	50
France	220–230	400	50	Nauru	240	415	50	Western Samoa	230	400	50
French Guiana	220	380	50	Nepal	220	400	50	Yemen	220	400	50
Gabon	220	380	50	Netherlands Antilles	120–127/220	220/380	50/60	Zambia	220	380	50
Gambia	220	400	50	Netherlands	220–230	400	50	Zimbabwe	220	415	50

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4.5 Voltage standard for Canada

The voltage standard for Canada is CSA C235. This standard differs from the U.S. standard in both the list of standard nominal voltages and the tolerance limits. While many nominal voltages are the same as ANSI C84.1, leading some to assume there are no differences, a notable difference is the inclusion of 600/347 as a preferred voltage and the acknowledgment of 480/277 as existing but not preferred. While many medium-voltage schemes are included in both standards, the CSA standard does not include 8320/4800, 12 000/6930, 13 200/7620, 20 780/12 000 and 22 860/13 200, for example. Maximum voltages are generally similar but not identical; minimum voltages are usually somewhat higher in the CSA standard than in the ANSI standard.

4.6 IEC voltage standards

Table 1 in IEC 60038-2009 specifies nominal system voltages between 100 V and 1000 V inclusive. System voltage of 400/230 V is specified for residential and industrial applications, whereas 690/400 V system voltage is specified for industrial applications.

4.7 Designation of ac voltage levels in some common standards

Voltage classes are used differently in various codes and standards, which often contributes to confusion in their application. The definition and use of different voltage classes which vary from ANSI C84.1, are illustrated for a small number of standards in Table 3. In general, the safety-oriented codes and standards (e.g., installation codes) generally define “high voltage” as anything higher than “low voltage” and completely ignore “medium voltage.”

In some cases, there is also a category for “extra-low voltage” where a relaxation of some safety criteria is justified. There are different focuses in various safety standards, leading to apparently contradictory statements, which, once considered, are generally appropriate and well thought out. While a general safety limit of 50 V for extra-low voltage is common in the literature (e.g., IEEE Std 3007.3 [B71] 4.2.1. a)), the National Electrical Code® (NEC®) (ANSI/NFPA 70®, National Electric Code® (NEC®)).¹⁸

NFPA 70 generally treats extra-low voltage as below 30 V and the Canadian Electrical Code (CE Code) uses 30 V. The North American electrical workplace safety standards (NFPA 70E 2021 [B92] Clause 130.1 and CSA Z462 [B30]) generally include 50 V or greater, in their scope, with some conditions. However, CSA M421 [B29] uses 100 V as a safety limit; its focus is the risk of shock due to transfer of potential from a ground fault in mining equipment connected by long trailing cables.¹⁹

Equipment construction standards contain voltage definitions based on equipment capabilities. For example, while the installation codes define low voltage as below 1 kV, the cable standards generally include 2 kV because the same cable designs are equally appropriate at those voltages. Conversely, switchgear and motor controllers follow the low voltage distinctions in the installation codes because this represents a natural change in design philosophy for these types of equipment. The ANSI C84.1 category of medium voltage is divided in most equipment standards for similar reasons. The equipment design that was appropriate for metal-clad switchgear below 38 kV is not used above that voltage, and cable designs that are appropriate below 46 kV need to be modified above 46 kV. Also note that in the ANSI standards, the voltage limits for air-insulated metal-clad switchgear are different from those for gas-insulated switchgear.

This varying usage of the term *medium voltage* is a global phenomenon and is acknowledged in IEC 60050-601 1985 [B47]: “The boundaries between medium and high voltage levels overlap and depend on local circumstances and history or common usage. Nevertheless, the band of 30 kV to 100 kV frequently contains the accepted boundary.” While this statement was written with a primary focus on regions other than ANSI regions, it is equally useful in ANSI regions.

An awareness of these discrepancies and the sources of them is essential for the proper application of the power systems and equipment, as well as for communication between power systems professionals. Care is advised as these standards evolve, and as ANSI and IEC definitions blend and are harmonized.

¹⁸ The NEC is published by the National Fire Protection Association (<https://www.nfpa.org/>). Copies are also available from the Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

¹⁹ These thresholds must not be confused with the intrinsic safety and non-incendive protection criteria used in hazardous location schemes, where the concern is the risk of igniting a combustible atmosphere.

Table 3—AC nominal voltage usage in some standards

Reference voltages	ANSI/NEMA C84.1 2016 ^a	NEC ^b	CE code ^c	IEC vocabulary ^d		IEC standard voltages ^e	ANSI motor controllers	IEEE standard definitions for switchgear ^{h,1}		UL cables	ICEA cables	AEIC cables	
24 V to 30 V	LV ≤ 1 kV	ELV ≤ 30 V ^s	ELV ≤ 30 V	LV < 1 kV		< 120 V (4.6)	LV ≤ 600 V UL 845 ^f	≤ 1 kV ⁱ		300 V power limited ⁿ	300 V to 1000 V ^u		
300 V		LV ≤ 1 kV	LV ≤ 1 kV										
1 kV		LV ≤ 1 kV	LV ≤ 1 kV										
2 kV	1 kV < MV < 100 kV	HV > 1 kV	HV > 1 kV	HV > 1 kV	MV (some areas) > 1 kV to 35 kV	> 1 kV to 35 kV (4.3)	751 V to 15 kV UL 347 ^g	> 1 kV and < 100 kV ^l	1kV >MV ≤ 38 kV for AIS ^j or ≤ 52 kV for GIS ^k	600 V to 2 kV thermoset ^o (5 kV Canada)	≤ 2 kV ^m		
15 kV													
38 kV to 46 (or 52) kV					MV (some areas) could extend to 100 kV								
100 kV						> 35 kV to 230 kV (4.4)							
230 kV	100 kV ≤ HV ≤ 230 kV			HV > 100 kV	HV > 100 kV		> 245 kV (4.5)			≥ 100 kV ^l		> 46 kV to 500 kV ^q	> 46 kV to 345 kV ^t
500 kV	230 kV < EHV < 1000 kV												
1000 kV													
> 1000 kV	UHV ≥ 1000 kV												

^a ANSI/NEMA C84.1 2016 clause 3

^b NFPA 70 2020, National Electrical Code

^c CSA C22.1 2021, Canadian Electrical Code, Part I

^d IEC 60050-601 1985, Amendment 1 1998 [B47]

^e IEC 60038:2009 [B46]

^f UL 845 [B108], CSA C22.2 No. 254 [B28], NMX-J-353-ANCE [B93]

^g UL 347 [B106], CSA C22.2 No. 253 [B27], NMX-J-564/106-ANCE [B95]

^h IEEE Std C37.20.10TM [B76]

ⁱ IEEE Std C37.20.1TM-2015 [B73]

^j IEEE Std C37.20.2TM-2022 [B74]

^k IEEE Std C37.20.9TM-2019 [B75]

^l IEEE Std C37.04TM [B72] characterizes circuit breakers for < 100 kV and ≥ 100 kV separately

^m ANSI/NEMA WC 70/ICEA S-95-658 [B11]

ⁿ UL 13 2019 [B104]

^o UL 44 [B105], CSA C22.2 No. 38 [B26], NMX-J-451-ANCE 2018 [B94]

^p ANSI/NEMA WC 74, ICEA S-93-639 [B12]

^q ICEA S-108-720 [B41]

^r AEIC CS8 2020 [B2]

^s While not specifically defined, see NEC articles 110.26 (A) (1) (b), 393.6 (A), 411.1, 424.101 (A), 620.5 (D), 646.20 (A), 725, and others

^t AEIC CS9 2015 [B3]

^u ANSI/NEMA WC 57/ ICEA S-73-532 [B10]

^v UL 1072 2018 [B109]

5. Voltage control in electric power systems

5.1 Principles of power transmission and distribution in utility systems

Power supply systems and utilization equipment should be designed to be compatible. This requires coordinated efforts and standards that place requirements on voltage ranges supplied by utilities, allowable voltage drops in facility distribution systems, and voltage ranges for utilization equipment. This section outlines these coordinated efforts and standards associated with assuring good operation of the utilization equipment.

To understand the principles of voltage control required to provide satisfactory voltage to utilization equipment, a general understanding of the principles of power transmission and distribution in utility systems is necessary since most facilities obtain most of their electric power from the local electric utility. Figure 3 shows a simplified one-line diagram of a typical utility power generation, transmission, and distribution system.

Most utility generating stations are located near convenient sources of fuel and water, often a considerable distance from major load areas. The generated power, except for station requirements, is transformed in a transmission substation located at the generating station up to a transmission voltage generally of 69 000 V or higher for transmission to major load areas. These transmission lines are usually interconnected in large free-flowing networks. For example, most transmission lines in the eastern half of the United States are interconnected to form one network. Utilities are constantly adjusting generation to match the load. They adjust generation to regulate the 60 Hz frequency, keeping clocks on time within a few seconds.

Transmission lines are generally classified as unregulated because the bulk energy transfer and voltage is usually controlled only to keep the lines operating within normal voltage limits and to facilitate power flow. ANSI C84.1 specifies only the nominal and maximum but no minimum values of voltage for systems over 34 500 V.

Transmission line networks supply distribution substations equipped with transformers that step the transmission voltage down to a primary distribution voltage, generally in the range of 4160 V to 34 500 V with 12 470 V, 13 200 V, and 13 800 V in the widest use. However, there is an increasing trend in the electric utility industry to use 23 kV and 34.5 kV for distribution as the load density increases. Installation of these medium-voltage systems requires additional skills not used in low-voltage systems. When medium voltage is used for primary distribution within a building or facility, qualified electricians experienced in these additional skills, such as making splices and terminations, should be secured to obtain a good installation.

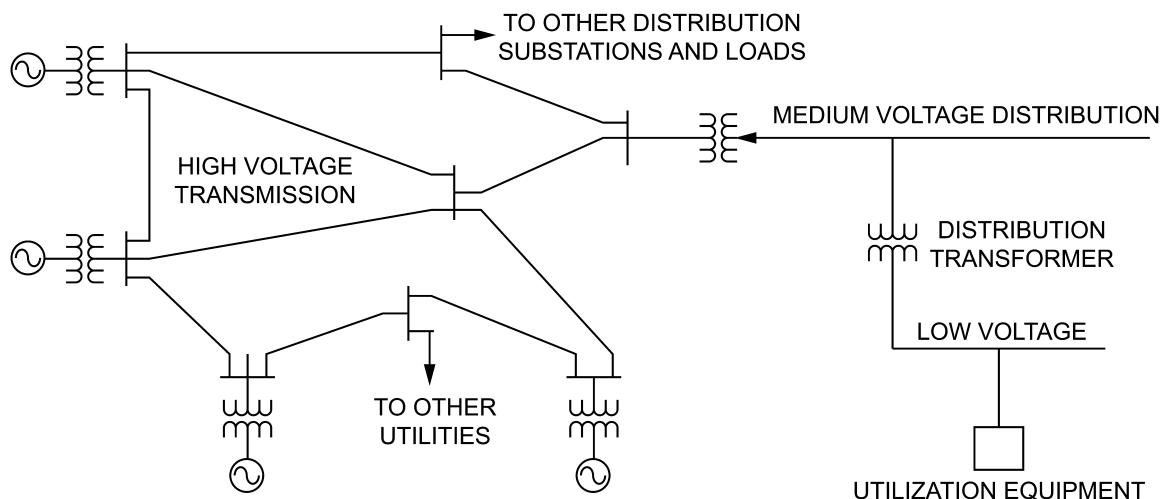


Figure 3—Typical utility generation, transmission, and distribution system

The occurrence of ferroresonance at medium voltage becomes more likely when delta-connected transformer primaries are switched by non-ganged operated switches (e.g., pole-mounted fuse cutout switches).

Voltage control is applied, when necessary, for the purpose of supplying satisfactory voltage to the terminals of utilization equipment. The transformers used to step the transmission voltage down to the primary distribution voltage are generally equipped with automatic tap-changing under-load equipment, which changes the turns ratio of the transformer while under load. This regulates primary distribution voltage within a specific range of values regardless of fluctuations in the transmission voltage or load. Separate step or induction regulators may also be used.

If the load is remote from the primary distribution substation, the regulator controls are equipped with compensators that raise the voltage as the load increases and lower the voltage as the load decreases to compensate for the voltage excursions in the primary distribution system that extends radially from the substation. This prevents the voltage from rising to excessive values during light load conditions when the voltage drop along the primary distribution system is low. This effectively regulates the voltage at a point of the primary distribution system some distance from the substation. This is illustrated in Figure 4. Note that facilities or buildings close to the distribution substation will receive voltages that, on average, will be higher than those received by facilities or buildings at a distance from the distribution substation. See 5.9 on the use of distribution transformer taps. Switched or fixed-shunt capacitors are also used by utility distribution companies to improve the voltage on primary feeders.

The primary distribution system supplies distribution transformers that step the primary distribution voltage down to utilization voltages, generally in the range of 120 V to 600 V, to directly supply individual services or to supply a secondary distribution system to which utilization equipment is connected. Distribution transformers generally do not have any automatic means for regulating the utilization voltage. Small transformers used to step a higher utilization voltage down to a lower utilization voltage, such as 480 V to 280Y/120 V, are considered part of the secondary distribution system.

The supply voltages available to an industrial plant or commercial building depend on whether the point of interconnection between the utility and the customer distribution system is at the distribution transformer, the primary distribution system, or the transmission system that, in turn, depends on the electric power requirements of the facility.

Small facilities with loads up to several hundred kilovolt-amperes of load and all facilities supplied from low-voltage secondary networks have a utility-interconnections point supplied from the distribution transformer. The utility secondary distribution system consists of the connections from the distribution transformer to the facility service and wiring.

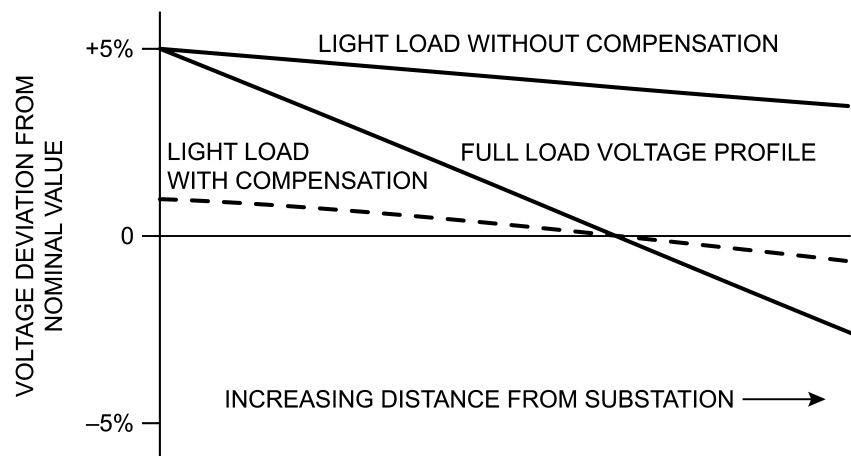


Figure 4—Effect of regulator compensation on primary distribution system voltage

Medium-sized facilities and multiple-building complexes with loads of a few thousand kilovolt-amperes are generally connected to the utility at their primary distribution system, and the facility owner provides the portion of the primary distribution system within the facility, the distribution transformers, and the secondary distribution system.

Large facilities and multiple-building complexes with loads of more than a few thousand kilovolt-amperes may use the utility transmission system as a service point, and the facility owner provides the primary distribution system, the distribution transformers, and the secondary distribution system. The owner might also provide the primary distribution substation.

Details of the connection between the utility system and the facility system will depend on the policy of the supplying utility. Refer to IEEE Std 3001.2 for more detailed information about utility interface considerations.

If power is supplied by local generation at the building, the generators will replace the primary distribution system up to the distribution transformer where the generation voltage is over 600 V and will also replace the distribution transformer where the generation is 600 V or below.

5.2 System voltage tolerance limits

ANSI C84.1 specifies the preferred nominal voltages and operating voltage ranges for utilization and distribution equipment operating from 120 V to 34 500 V in the United States (refer to Table 1). It specifies voltages for two critical points on the distribution system: the point of delivery by the supplying utility and the point of connection to utilization equipment. The voltage tolerance limits at the point of delivery by the supplying utility provide the voltage limits within which the supplying utility should maintain the supply voltage in order to provide satisfactory operation of the user's utilization equipment. The voltage tolerance limits at the point of connection of utilization equipment provide the voltage limits within which the utilization equipment manufacturer should design the utilization equipment for it to operate satisfactorily.

Table 1 lists two voltage ranges to provide a practical application of voltage tolerance limits to distribution systems. The tolerance limits for the service voltage provide guidance to the supplying utility for the design and operation of its distribution system. The service voltage is the voltage at the point where the utility conductors connect to the user conductors. It is generally measured at the service switch for services of 600 V and below and at the billing meter voltage (potential) transformers for services over 600 V. The tolerance limits for the voltage at the point of connection of utilization equipment provide guidance to the user for the design and operation of the user distribution system and to utilization equipment manufacturers for the design of utilization equipment. Electric supply systems are to be designed and operated so that most service voltages fall within Range A limits. User systems are to be designed and operated so that when the service voltages are within Range A, the utilization voltages are within Range A. Utilization equipment is to be designed and rated to give fully satisfactory performance within the Range A limits for utilization voltages.

Range B allows limited excursions of voltage outside the Range A limits that necessarily result from practical design and operating conditions. When voltages are outside Range A and inside Range B, corrective action should be taken within a reasonable time to restore service voltages to Range A limits. Insofar as practicable, utilization equipment may be expected to give acceptable performance at voltages outside Range A but within Range B. When voltages occur outside the limits of Range B, prompt corrective action should be taken. Responsibility for corrective action depends on where the voltage is out of Range A compared to the limits specified for each location identified in ANSI C84.1.

The actual voltage measured at any point on the system will depend on the location of the point of measurement and the system load at the time the measurement is made. Fixed voltage changes take place in transformers in accordance with the transformer ratio. Voltage variations occur from the operation of voltage control equipment, changes in voltage drop due to changes in load current, and other reasons. It

should be recognized that because of conditions beyond the control of the supplier or user, or both, there will be infrequent and limited periods when sustained voltages outside Range B limits can occur.

For transmission voltages over 34 500 V, ANSI C84.1 only specifies the nominal and maximum voltage because these voltages are normally unregulated and only a maximum voltage is required to establish the design insulation level for the line and associated apparatus.

5.3 Development of the voltage tolerance limits for ANSI C84.1

The voltage tolerance limits in ANSI C84.1 are based on NEMA MG 1, which established the voltage tolerance limits of the standard induction motor at $\pm 10\%$ of nameplate ratings of 230 V and 460 V. Since motors represent the major component of utilization equipment, they were given primary consideration in the establishment of the voltage standard.

One convenient way to show the voltages in an electric power distribution system is in terms of a 120 V base. This cancels the transformation ratios between systems so that the actual voltages vary solely on the basis of the voltage drops in the system. Any voltage may be converted to a 120 V base by dividing the actual voltage by the ratio of transformation to the 120 V base. For example, the ratio of transformation for the 480 V system is 480/120 or 4, so 460 V in a 480 V system would be 460/4 or 115 V on a 120 V base.

The tolerance limits of the 460 V motor in terms of the 120 V base become 115 V plus 10%, or 126.5 V, and 115 V minus 10%, or 103.5 V. The problem is to decide how this tolerance range of 23 V should be divided between the primary distribution system, the distribution transformer, and the secondary distribution system, which make up the regulated distribution system. The solution adopted by ANSI Accredited Committee C84 is shown in Table 4.

The range B tolerance limits raised the standard motor tolerance on the 120 V base 0.5 V to 127 V maximum and 104 V minimum to eliminate the fractional volt. These values became the tolerance limits for Range B in the standard. An allowance of 13 V was allotted for the voltage drop in the primary distribution system. Deducting this voltage drop from 127 V establishes a minimum of 114 V for utility services supplied from the primary distribution system. An allowance of 4 V was provided for the voltage drop in the distribution transformer and the connections to the facility wiring. Deducting this voltage drop from the minimum primary distribution voltage of 114 V provides a minimum of 110 V for utility secondary services from 120 V to 600 V. An allowance of 6 V, or 5%, for the voltage drop in the facility wiring, as provided in ANSI/NFPA 70 Articles 210.19(A) and 215.2(A), provides the minimum utilization voltage of 104 V.

**Table 4—Standard voltage profile for
low-voltage regulated power distribution system, 120 V base**

	Range A (V)	Range B (V)
Maximum allowable voltage	126 (125 ^a)	127
Voltage drop allowance for primary distribution line	9	13
Minimum primary service voltage	117	114
Voltage drop allowance for distribution transformer	3	4
Minimum secondary service voltage	114	110
Voltage drop allowance for facility wiring	6 (4 ^b)	6 (4 ^b)
Minimum utilization voltage	108 (110 ^b)	104 (106 ^b)

^aFor utilization voltage of 120 V to 600 V.

^bFor building wiring circuits supplying lighting equipment.

The range A limits for the standard were established by reducing the maximum tolerance limits from 127 V to 126 V and increasing the minimum tolerance limits from 104 V to 108 V. The spread band of 18 V was then allotted as follows: 9 V for the voltage drop in the primary distribution system to provide a minimum primary service voltage of 117 V; 3 V for the voltage drop in the distribution transformer and secondary connections to provide a minimum secondary service voltage of 114 V; and 6 V for the voltage drop in the facility low-voltage wiring to provide a minimum utilization voltage of 108 V.

Four additional modifications were made in this basic plan to establish ANSI C84.1. The maximum utilization voltage in range A was reduced from 126 V to 125 V for low-voltage systems in the range from 120 V to 600 V because there should be sufficient load on the distribution system to provide at least 1 V drop on the 120 V base under most operating conditions. This maximum voltage of 125 V is also a practical limit for lighting equipment because the life of the 120 V incandescent lamp is reduced by 42% when operated at 125 V (see 9.4, Table 12). The voltage drop allowance of 6 V on the 120 V base for the drop in the facility wiring was reduced to 4 V for circuits supplying lighting equipment. This raised the minimum voltage limit for utilization equipment to 106 V in Range B and 110 V in Range A because the minimum limits for motors of 104 V in Range B and 108 V in Range A were considered too low for satisfactory operation of lighting equipment. The utilization voltages for the 6900 V and 13 800 V systems in Range B were adjusted to coincide with the tolerance limits of $\pm 10\%$ of the nameplate rating of the 6600 V and 13 200 V motors used on these respective systems.

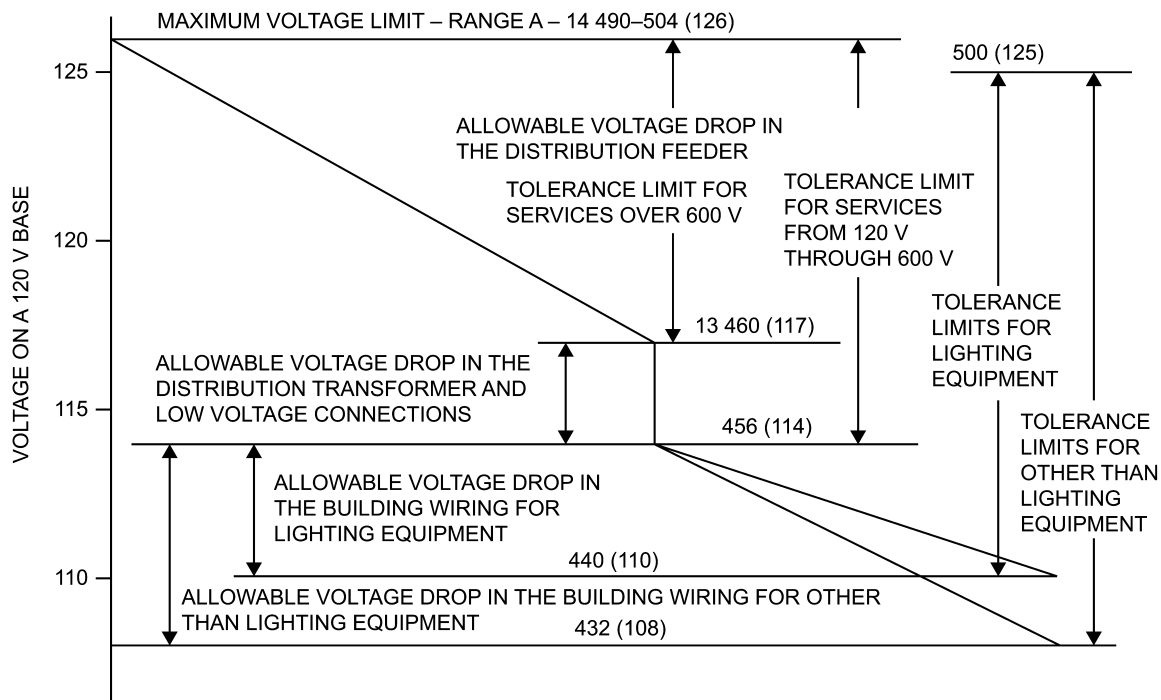
To convert the 120 V base voltage to equivalent voltages in other systems, the voltage on the 120 V base is multiplied by the ratio of the transformer that would be used to connect the other system to a 120 V system. In general, distribution transformers for systems below 15 000 V have nameplate ratings that are the same as the standard system nominal voltages; so, the ratio of the standard nominal voltages may be used to make the conversion. However, for primary distribution voltages over 15 000 V, the primary nameplate rating of distribution transformers is not the same as the standard system nominal voltages. Also, most distribution transformers are equipped with taps that can be used to change the ratio of transformation. So, if the primary distribution voltage is over 15 000 V, or taps have been used to change the transformer ratio, then use the actual transformer ratio to convert the base voltage to another system.

For example, the maximum tolerance limit of 127 V on the 120 V base for the service voltage in Range B is equivalent, on the 4160 V system, to $4160 \div 120 \times 127 = 4400$ V to the nearest 10 V. However, if the 4160 V to 120 V transformer is set on the +2.5% tap, the voltage ratio would be $4160 + (4160 \times 0.025) = 4160 + 104 = 4264$ to 120. The voltage on the primary system equivalent to 127 V on the secondary system would be $4264 \div 120 \times 127 = 35.53 \times 127 = 4510$ V to the nearest 10 V. If the maximum primary distribution voltage of 4400 V is applied to the 4264 V to 120 V transformer, the secondary voltage would be $4400 \div 4264 \times 120 = 124$ V.

5.4 Voltage profile limits for a regulated distribution system

Figure 5 shows the voltage profile of a regulated power distribution system using the limits of Range A in Table 1. Assuming a nominal primary distribution voltage of 13 800 V, Range A in Table 1 shows that this voltage should be maintained by the supplying utility between a maximum of 126 V and a minimum of 117 V on a 120 V base. Since the base multiplier for converting from the 120 V system to the 13 800 V system is $13\,800/120$ or 115, the actual voltage limits for the 13 800 V system are 115×126 or 14 490 V maximum and 115×117 or 13 460 V minimum.

If a distribution transformer with a ratio of 13 800 V to 480 V is connected to the 13 800 V distribution feeder, Range A of Table 1 requires that the nominal 480 V secondary service be maintained by the supplying utility between a maximum of 126 V and a minimum of 114 V on the 120 V base. Since the base multiplier for the 480 V system is $480/120$ or 4, the actual values are 4×126 or 504 V maximum and 4×114 or 456 V minimum.



NOTE—Limits provided by ANSI C84.1 see Table 1.

Figure 5—Range A voltage profile limits

Range A of Table 1, as modified for utilization equipment of 120 V to 600 V, provides for a maximum utilization voltage of 125 V and a minimum of 110 V for lighting equipment and 108 V for other than lighting equipment on the 120 V base. Using the base multiplier of 4 for the 480 V system, the maximum utilization voltage would be 4×125 V or 500 V, and the minimum for other than lighting equipment would be 4×108 V or 432 V. For lighting equipment connected phase to neutral, the maximum voltage would be 500 V divided by the square root of 3 or 289 V and the minimum voltage would be 4×110 V or 440 V divided by the square root of 3 or 254 V.

5.5 Conservation voltage reduction

Conservation voltage reduction (CVR) is defined by McNamara et al. [B88] as the “intentional operation of the transmission and distribution system to provide customer voltages in the lower end of the acceptable range, with the goal of achieving energy and demand reductions for customers. When utilities manage and optimize voltage and reactive power simultaneously (combining the voltage management associated with CVR with reactive power management), it is referred to as Volt/VAR optimization (VVO). VVO focuses on circuit-level operations and reduces energy losses by reducing reactive power flow along the distribution circuit.”

CVR or voltage reduction has been used by many electrical utilities and their associated grid management authorities for decades to reduce energy and peak demand. This leads to a decrease in energy consumption, lower demand charges, and consequently, a potential reduction in greenhouse gas emissions. While CVR is difficult to implement in industrial or commercial facilities due to limited control of their voltage source(s), its use in smart microgrids is feasible during islanded operational modes. CVR may help moderate risks associated with power-flow dynamics in microgrid systems using distributed generation such as wind and solar. Decreases in demand will depend on whether loads exhibit a positive voltage sensitivity (CVR factor), meaning they consume less energy when lowering the voltage. Examples may include loads such as pumps/motors, power electronics, and resistive loads. A detailed analysis is required to determine the overall system efficiency and energy consumption with variations in voltage. The modeling techniques

used for industrial and commercial power systems are not the same as those used for utility systems and some energy savings might not be apparent using the techniques used for industrial and commercial power systems. The models used—which include constant power, constant impedance, and constant current—do not capture the effects of cabling that is used, the use of thermostatically controlled loads, or the loads that draw a constant amount of current over different time periods. For more information on this, refer to PNNL-19596 [B97]. CVR practices can raise operational concerns and/or influence equipment life expectancy because customer equipment is designed to operate within a prescribed voltage range around the nominal voltage. Operation of equipment at voltages that are greater or lower than the prescribed voltage range may expose the equipment to several issues, including inefficiency, mis-operation, damage, or reduced life expectancy. Moreover, reducing the system voltages may increase the susceptibility of the customer's equipment to intermittent trips and unplanned interruptions because it is forced to operate closer to its lower viable threshold. Subsequently, what once may have been a subtle voltage sag event (either originating on the utility system or within the customer system) could now have more severe consequences (ANSI/ASHRAE 90.1 [B6]).

As noted in Annex B of ANSI C84.1-2018, “CVR is sometimes used for energy and or demand reduction. Determination of the value of CVR is beyond the scope of this standard. However, it is recommended that the application of CVR should be limited to voltages in Range A of Figure 6 for normal operation. Range B of Figure 6 should be reserved for emergency, infrequent operation. CVR systems should not be designed to operate below Range B for any condition.”

5.6 System voltage nomenclature

The nominal system voltages in Table 1 are designated in the same way as on the nameplate of the transformer for the winding or windings supplying the system.

- a) Single-phase systems
 - 1) 120: Indicates a single-phase, two-wire system in which the nominal voltage between the two wires is 120 V.
 - 2) 120/240: Indicates a single-phase, three-wire system in which the nominal voltage between the two phase conductors is 240 V, and from each phase conductor to the neutral it is 120 V.
- b) Three-phase systems
 - 1) 240/120: Indicates a three-phase, four-wire system supplied from a delta-connected transformer. The midtap of one winding is connected to a neutral. The three-phase conductors provide a nominal 240 V three-phase system, and the neutral and the two adjacent phase conductors provide a nominal 120/240 V single-phase system.
 - 2) 480: Indicates a three-phase, three-wire system in which the number designates the nominal voltage between phases.
 - 3) 480Y/277: Indicates a three-phase, four-wire system from a wye-connected transformer in which the first number indicates the nominal phase-to-phase voltage and the second number indicates the nominal phase-to-neutral voltage.

NOTE 1—All single-phase systems and all three-phase, four-wire systems are suitable for the connection of phase-to-neutral load.

NOTE 2—See IEEE Std 3003.1™ [B69] for methods of system grounding.

NOTE 3—Figure 6 gives an overview of voltage relationships for 480 V three-phase systems and 120/240 V single- and three-phase systems.

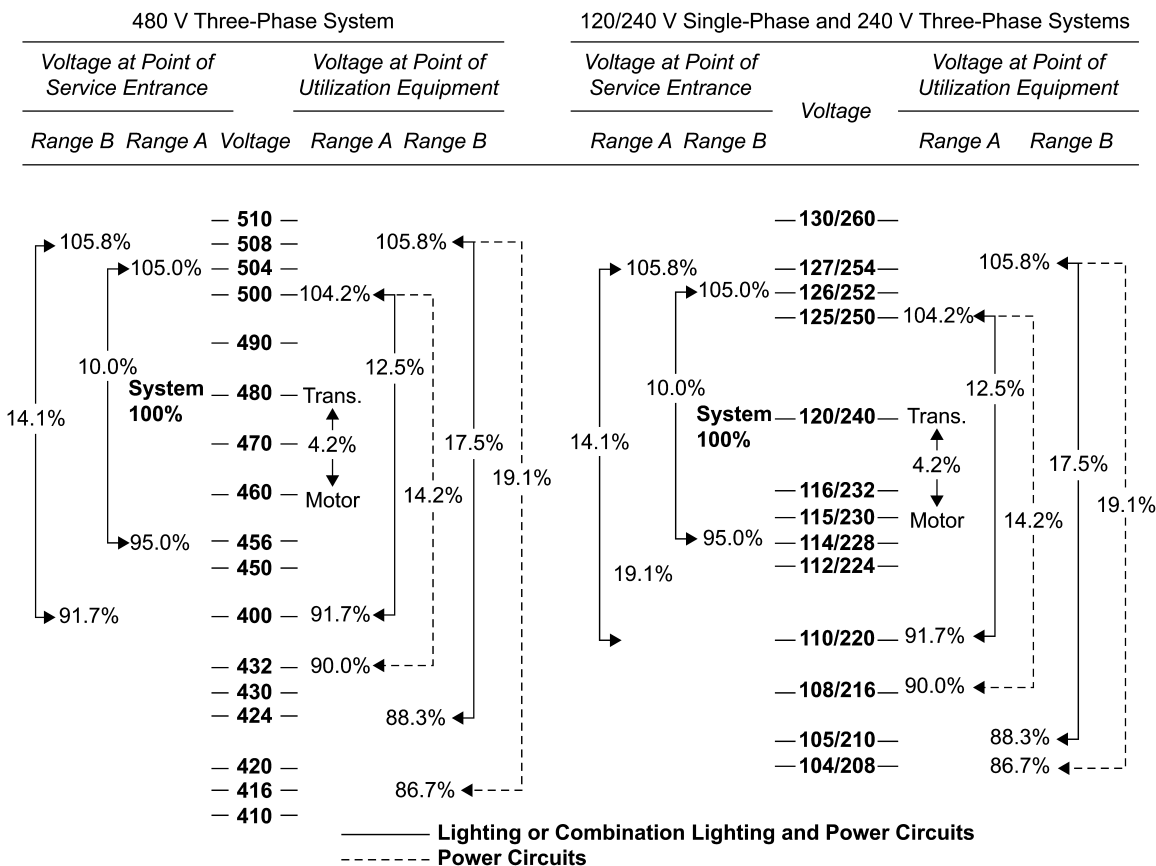


Figure 6—Voltage relationships based on voltage ranges in ANSI C84.1

5.7 Nonstandard nominal system voltages

Since ANSI C84.1 lists only the standard nominal system voltages in common use in the United States, system voltages will frequently be encountered that differ from the standard list. A few of these may be so widely different as to constitute separate systems in too limited use to be considered standard. However, in most cases, the nominal system voltages will differ by only a few percent as shown in Table 5. A closer examination of the table shows that these differences are due mainly to the fact that some voltages are multiples of 110 V, others are multiples of 115 V, some are multiples of 120 V, and a few are multiples of 125 V.

The reasons for these differences go back to the original development of electric power distribution systems. The first utilization voltage was 100 V. However, the supply voltage had to be raised to 110 V to compensate for the voltage drop in the distribution system. This led to overvoltage on equipment connected close to the supply, so the utilization equipment rating was also raised to 110 V. As generator sizes increased and distribution and transmission systems developed, an effort to keep transformer ratios in round numbers led to a series of utilization voltages of 110 V, 220 V, 440 V, and 550 V, a series of primary distribution voltages of 2200 V, 4400 V, 6600 V, and 13 200 V, and a series of transmission voltages of 22 000 V, 33 000 V, 44 000 V, 66 000 V, 110 000 V, 132 000 V, and 220 000 V.

As a result of the effort to maintain the supply voltage slightly above the utilization voltage, the supply voltages were raised again to multiples of 115 V, which resulted in a new series of utilization voltages of 115 V, 230 V, 460 V, and 575 V, a new series of primary distribution voltages of 2300 V, 4600 V, 6900 V, and 13 800 V, and a new series of transmission voltages of 23 000 V, 34 500 V, 46 000 V, 69 000 V, 115 000 V, 138 000 V, and 230 000 V.

As a result of continued problems with the operation of voltage-sensitive lighting equipment and voltage-insensitive motors on the same system, and the development of the 208Y/120 V network system, the supply voltages were raised again to multiples of 120 V. This resulted in a new series of utilization voltages of 120 V, 208Y/120 V, 240 V, 480 V, and 600 V, and a new series of primary distribution voltages of 2400 V, 4160Y/2400 V, 4800 V, 12 000 V, and 12 470Y/7200 V. However, most of the existing primary distribution voltages continued in use and no 120 V multiple voltages developed at the transmission level.

Table 5—Nominal system voltages

Standard nominal system voltages	Associated nonstandard nominal system voltages
Low voltages	
120	110, 115, 125
120/240	110/220, 115/230, 125/250
208Y/120	216Y/125
240/120	
240	230, 250
480Y/277	460Y/265
480	440
600	550, 575
Medium voltages	
2400	2200, 2300
4160Y/2400	
4160	4000
4800	4600
6900	6600, 7200
8320Y/4800	11 000, 11 500
12 000Y/6930	
12 470Y/7200	
13 200Y/7620	
13 200	
13 800Y/7970	14 400
13 800	
20 780Y/12 000	
22 860Y/13 200	
23 000	
24 940Y/14 400	
34 500Y/19 920	
34 500	33 000
46 000	44 000
69 000	66 000
High voltages	
115 000	110 000, 120 000
138 000	132 000
161 000	154 000
230 000	220 000
Extra-high voltages	
345 000	
500 000	
765 000	

5.8 Standard nominal system voltages in the United States

The nominal system voltages listed in the left-hand column of Table 5 are designated as standard nominal system voltages in the United States by ANSI C84.1. In addition, those shown in boldface type in Table 1 are designated as preferred standards to provide a long-range plan for reducing the multiplicity of voltages.

In the case of utilization voltages of 600 V and below, the associated nominal system voltages in the right-hand column of Table 5 are obsolete and should not be used. Manufacturers are encouraged to design utilization equipment to provide acceptable performance within the utilization voltage tolerance limits specified in the standard. Some numbers listed in the right-hand column are used in equipment ratings, but these should not be confused with the numbers designating the nominal system voltage on which the equipment is designed to operate.

In the case of primary distribution voltages, the numbers in the right-hand column may designate an older system in which the voltage tolerance limits are maintained at a different level than the standard nominal system voltage, and special consideration should be given to the distribution transformer ratios, taps, and tap settings.

5.9 Use of distribution transformer taps to shift utilization voltage spread band

Except for small sizes, power and distribution transformers often have five taps on the primary winding in 2.5% steps. These taps are generally +5%, +2.5%, nominal, -2.5%, and -5%. These taps allow users to change the transformer ratio and raise or lower the secondary voltage to provide a closer fit to the tolerance limits of the utilization equipment. There are three situations requiring the use of taps:

- a) Taps are required when the primary voltage has a nominal value that is slightly different from the transformer's primary nameplate rating. For example, if a 13 200 V to 480 V transformer is connected to a nominal 13 800 V system, the nominal secondary voltage would be $(13\,800/13\,200) \times 480 = 502$ V. However, if the 13 800 V system were connected to the +5% tap of the 13 200 V to 480 V transformer at 13 860 V, the nominal secondary voltage would be $(13\,800/13\,860) \times 480 = 478$, which is practically the same as would be obtained from a transformer having the proper ratio of 13 800 V to 480 V.
- b) Taps are required when the primary voltage spread is in the upper or lower portion of the tolerance limits provided in ANSI C84.1. For example, a 13 200 V to 480 V transformer is connected to a 13 200 V primary distribution system close to the substation where the primary voltage spread band stays in the upper half of the tolerance zone for Range A, or 13 200 V to 13 860 V. This would result in a nominal secondary voltage under no-load conditions of 480 V to 504 V. By setting the transformer on the +2.5% tap at 13 530 V, the no-load secondary voltage would be lowered 2.5% to a range of 468 V to 491 V.
- c) Taps are required to adjust the utilization voltage spread band to provide a closer fit to the tolerance limits of the utilization equipment. For example, Table 6 shows the shift in the utilization voltage spread band for the +2.5% and 5% taps as compared to the utilization voltage tolerance limits for Range A of ANSI C84.1 for the 480 V system. Table 7 shows the voltage tolerance limits of standard 460 V and 440 V three-phase induction motors. Table 8 shows the tolerance limits for standard 277 V and 265 V fluorescent lamp ballasts. A study of these three tables shows that a nominal tap setting will provide the best fit with the tolerance limits of the 460 V motor and the 277 V ballast, but a setting on the +5% tap will provide the best fit for the 440 V motor and the 265 V ballast. For buildings having appreciable numbers of both ratings of motors and ballasts, a setting on the +2.5% tap may provide the best compromise.

Table 6—Tolerance limits for lighting circuits from Table 1, Range A, in Volts

Nominal system voltage volts (V)	Transformer tap	Minimum utilization voltage (V)	Maximum utilization voltage (V)
480Y/277	Nominal	440Y/254	500Y/288
468Y/270	+2.5%	429Y/248	488Y/281
456Y/263	+5%	418Y/241	475Y/274

Table 7—Tolerance limits for low-voltage three-phase motors, in Volts

Motor voltage rating (V)	−10%	+10%
460	414	506
440	396	484

Table 8—Tolerance limits for low-voltage standard fluorescent lamp ballasts, in Volts

Ballast voltage rating (V)	Minimum −10%	Maximum +10%
277	254	289
120	110	125

Note that these examples assume that the tolerance limits of the supply and utilization voltages are within the tolerance limits specified in ANSI C84.1. This may not be true, so the actual voltages should be recorded over a time period that provides voltage readings during the night and over weekends when maximum voltages often occur. These actual voltages can then be used to calculate voltage profiles similar to Figure 5 to check the proposed transformer ratios and tap settings. If transformer taps are used to compensate for voltage drop, the voltage profile should be calculated for light-load periods to check for possible overvoltage situations.

Where a facility has not yet been built, the supplying utility should be requested to provide the expected spread band for the supply voltage, preferably supported by seven-day data recordings from the nearest available location. If the facility furnishes the distribution transformers, recommendations should also be obtained from the supplying utility on the transformer ratios, taps, and tap settings. With this information, a voltage profile can be prepared to check the expected voltage spread at the utilization equipment.

Where the supplying utility offers a voltage over 600 V that differs from the standard nominal voltages listed in ANSI C84.1, the supplying utility should be asked to furnish the expected tolerance limits of the supply voltage, preferably supported by seven or more days of voltage recordings from a nearby location. The supplying utility should also be asked for the recommended distribution transformer ratio and tap settings to obtain a satisfactory utilization voltage range. With this information, a voltage profile for the supply voltage and utilization voltage limits can be constructed for comparison with the tolerance limits of utilization equipment. If the supply voltage offered by the utility is one of the associated nominal system voltages listed in Table 5, the taps on a standard distribution transformer will generally be sufficient to adjust the distribution transformer ratio to provide a satisfactory utilization voltage range.

Taps are on the primary side of transformers. Therefore, raising the tap setting to +2.5% increases the transformer ratio by 2.5% and lowers the secondary voltage spread band by 2.5% minus the voltage drop in the transformer. Taps only serve to move the secondary voltage spread band up or down in the steps of the taps. They cannot correct for excessive spread from the supply voltage or from excessive drop in the facility wiring system. If the voltage spread band at the utilization equipment falls outside the satisfactory operating range of the equipment, then action should be taken to improve voltage conditions by other means (see Clause 11).

In general, transformers should be selected with the same primary nameplate voltage rating as the nominal voltage of the primary supply system, and the same secondary voltage rating as the nominal voltage of the secondary system. Taps should be provided at +2.5% and +5% and at -2.5% and -5% to allow for adjustment in either direction.

5.10 Sheath/shield/screen power cable voltage control

Cross-bonding, single-point bonding, and multiple single-point bonding of the sheaths, shields, and screens of single conductor power cables are common practices. However, if not done correctly, sheath voltages can rise to high levels deleterious to the cables and harmful to workers, especially during transient conditions. There are no industry standards on maximum allowable sheath voltages. A typical power cable carrying 1000 A could have a sheath voltage of 100 V for a length of only 610 m (2000 ft) and much higher under fault conditions, depending on the bonding method and installation. IEEE Std 575™ [B60] instructs how to perform sheath voltage calculations and recommends bonding and installation methods. Figure 7 is an example of multiple single-point bonding incorporating sheath voltage limiters, which are surge protective devices that can limit sheath overvoltages during transient conditions.

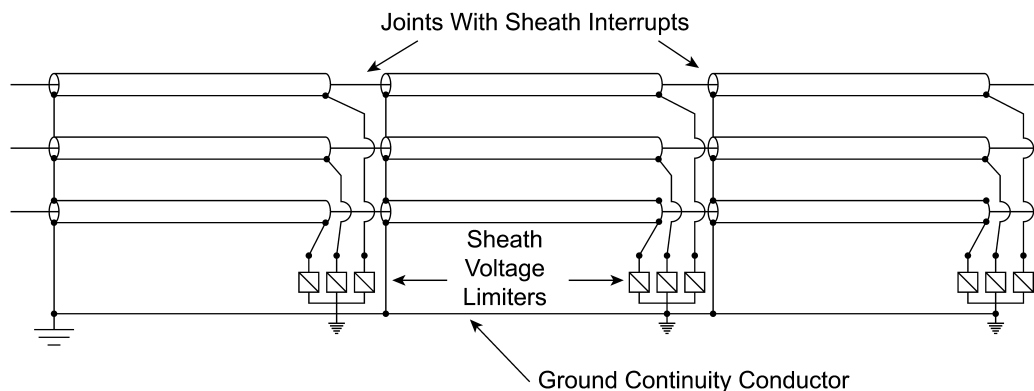


Figure 7—Multiple single-point bonding of cable sheaths using sheath voltage limiters

6. Voltage selection

6.1 Selection of low-voltage utilization voltages

Generally, the preferred utilization voltage for facilities is 480Y/277 V. Three-phase power and other 480 V loads are connected directly to the system at 480 V, and gaseous discharge lighting is connected phase-to-neutral at 277 V. Small dry-type transformers rated 480-208Y/120 V are used to provide 120 V single-phase for convenience outlets and 208 V single-phase and three-phase for small tools and other machinery. Where requirements are limited to 120 V or 240 V single-phase 480-120/240 V single-phase transformers may be used. However, single-phase transformers should be connected in sequence to the individual phases to keep the load on each phase balanced (see Clause 13).

For small facilities supplied at utilization voltage by a single distribution transformer, the choice of voltages is limited to those the utility will supply. However, most utilities will supply most of the standard nominal voltages listed in ANSI C84.1 with the exception of 600 V, although all voltages supplied may not be available at every location. The built-up downtown areas of most large cities are supplied from secondary networks. Originally only 208Y/120 V was available, but most utilities provide spot networks at 480Y/277 V for large installations. For tall buildings, space will be required on the upper floors for transformers and the primary distribution cables supplying the transformers.