Section 4: System Voltage Considerations

Bill Brown, P.E., Square D Engineering Services

Basic Principles

The selection of system voltages is crucial to successful power system design. Reference [1] lists the standard voltages for the United States and their ranges. The nominal voltages from [1] are given in table 4-1.

As can be seen, ANSI C84.1-1989 divides system voltages into “voltage classes.” Voltages 600 V and below are referred to as “low voltage,” voltages from 600 V-69 kV are referred to as “medium voltage,” voltages from 69 kV-230 kV are referred to as “high voltage” and voltages 230 kV-1,100 kV are referred to as “extra high voltage,” with 1,100 kV also referred to as “ultra high voltage.” The emphasis of this guide is on low and medium voltage distribution systems.

Table 4-1: Standard nominal three-phase system voltages per ANSI C84.1-1989

Voltage Class	Three-wire	Four-wire
Low Voltage		208 Y/120
	240	240/120
	480	480 Y/277
	600	
Medium Voltage	2,400	
	4,160	4,160 Y/2400
	4,800	
	6,900	
		8,320 Y/4800
		12,000 Y/6,930
		12,470 Y/7,200
		13,200 Y/7,620
	13,800	13,800 Y/7,970
		20,780 Y/12,000
		22,860 Y/13,200
	23,000	
		24,940 Y/14,400
	34,500	34,500 Y/19,920
	46,000	
	69,000	
High Voltage	115,000	
	138,000	
	161,000	
	230,000	
Extra-High Voltage	345,000	
	500,000	
	765,000	
Ultra-High Voltage	1,100,000	

The choice of service voltage is limited to those voltages which the serving utility provides. In most cases only one choice of electrical utility is available, and thus only one choice of service voltage. As the power requirements increase, so too does the likelihood that the utility will require a higher service voltage for a given installation. In some cases a choice may be given by the utility as to the service voltage desired, in which case an analysis of the various options would be required to arrive at the correct choice. In general, the higher the service voltage the more expensive the equipment required to accommodate it will be. Maintenance and installation costs also increase with increasing service voltage. However, equipment such as large motors may require a service voltage of 4160 V or higher, and, further, service reliability tends to increase at higher service voltages.

Another factor to consider regarding service voltage is the voltage regulation of the utility system. Voltages defined by the utility as "distribution" should, in most cases, have adequate voltage regulation for the loads served. Voltages defined as "subtransmission" or "transmission", however, often require the use of voltage regulators or load-tap changing transformers at the service equipment to give adequate voltage regulation. This situation typically only occurs for service voltages above 34.5 kV, however it can occur on voltages between 20 kV and 34.5 kV. When in doubt the serving utility should be consulted.

The utilization voltage is determined by the requirements of the served loads. For most industrial and commercial facilities this will be 480 Y/277 V, although 208 Y/120 V is also required for convenience receptacles and small machinery. Large motors may require 4160 V or higher. Distribution within a facility may be 480 Y/277 V or, for large distribution systems, medium voltage distribution may be required. Medium voltage distribution implies a medium voltage (or higher) service voltage, and will result in higher costs of equipment, installation, and maintenance than low voltage distribution. However, this must be considered along with the fact that medium voltage distribution will generally result in smaller conductor sizes and will make control of voltage drop easier.

Power equipment ampacity limitations impose practical limits upon the available service voltage to serve a given load requirement for a single service, as shown in table 4-2.

Voltage drop considerations

Because all conductors exhibit an impedance to the flow of electric current, the voltage will not be constant throughout the system, but will tend to drop as one moves closer to the load. Ohm's Law, expressed in phasor form for AC circuits, gives the basic relationship for voltage drop vs. the load current:

$$\overline{V}_{drop} = \overline{I}_{l} \times \overline{Z}_{cond} \qquad (4\text{-}1)$$

where

$\overline{V}_{drop}$ is the voltage drop along a length of conductor or across a piece of equipment in volts

$\overline{I}_{l}$ is the load current in amperes

Z_{cond} is the conductor or equipment impedance, in ohms

Thus, the larger the load current and larger the conductor impedance, the larger the voltage drop. Unbalanced loads will, of course, give an unbalanced voltage drop, which will lead to an unbalanced voltage at the utilization equipment.

A voltage drop of 5% or less from the utility service to the most remotely-located load is recommended by NEC article 210.19(A)(1), FPN No. 4. Because this is a note only, it is not a requirement per se but is the commonly accepted guideline.

Table 4-2: Power equipment design limits to service voltage vs. load requirements, for a single service

Voltage (V)	Equipment Type	Maximum Equipment Ampacity (A)	Maximum Load (kVA)
208 480 600	Switchboard or Low Voltage Power Switchgear	5000	1,800 4,157 5,196
2,400 4,160 4,800	Metal-Enclosed Switchgear, w/Fuses 69,000	1080	4,489 7,782 8,979
6,900 8,320 12,000 12,470 13,200 13,800	Metal-Enclosed Switchgear, w/Fuses	720	8,605 10,376 14,965 15,551 16,461 17,210
20,780 22,860 23,000 24,940	Metal-Enclosed Switchgear, w/Fuses	175	6,299 6,929 6,972 7,560
34,500	Metal-Enclosed Switchgear, w/Fuses	115	6,872
2,400 4,160 4,800 6,900 8,320 12,000 12,470 13,200 13,800	Metal-Clad Switchgear	3000	12,471 21,616 24,942 38,853 43,232 62,354 64,796 68,589 71,707
20,780 22,860 23,000 24,940	Metal-Clad Switchgear	2000	71,984 79,189 79,674 86,395

Because conductor impedance increases with the length of the conductor, it can be seen that unless the power source is close to the center of the load the voltage will vary across the system, and, further, it can be more costly to maintain the maximum voltage drop across the system to within 5% of the service voltage since larger conductors must be used to offset longer conductor lengths.

Also from equation (4-1) it can be seen that as load changes, so does the voltage drop. For a given maximum load, a measure of this change at a given point is the voltage regulation, defined as

$$\text{Voltage Regulation} = \frac{\left|\overline{V}_{\text{no load}}\right| - \left|\overline{V}_{\text{load}}\right|}{\left|\overline{V}_{\text{load}}\right|} \times 100\% \qquad (4\text{-}2)$$

where

$V_{no\ load}$ is the voltage, at a given point in the system, with no load current flowing from that point to the load.

V_{load} is the voltage, at the same point in the system, with full load current flowing from that point to the load.

Another source of concern when planning for voltage drop is the use of power-factor correction capacitors. Because these serve to reduce the reactive component of the load current they will also reduce the voltage drop per equation (4-1).

Both low and high voltage conditions, and voltage imbalance, have an adverse effect on utilization equipment (see [2] for additional information). Voltage drop must therefore be taken into account during power system design to avoid future problems.

References

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

[2] IEEE Recommended Practice for Electric Power Distribution for Industrial Plants, IEEE Standard 141-1993, December 1993.