Baldor Motor Basics: Electric Motors and Power Systems and Electric Motors and Voltage

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Motors and Power Systems

There seems to be a lot of confusion about the voltage standards for motors and why they are structured the way they are. There are, of course, two broad categories of motors, AC and DC. The voltage standards for these two decidedly different motors are much different from each other. It will be the goal of this paper to try to reduce some of the confusion that exists in the AC motor voltage standards.

AC power systems. To understand how voltage standards for motors are set it is important to know the basics of the power systems they operate on. In general, utilities that supply power in the USA, and most other 60 cycle countries, are required to provide power to the incoming point of a facility in multiples of 120 volts. Thus incoming equipment, such as circuit breaker panels, are rated in multiples of 120 volts. The common voltages are 120, 240, 480, and 600.

In addition, utilities are obligated by the regional governing authorities (usually called Public Utility Commissions) to regulate the voltage within a fairly narrow range such as plus-or-minus %.

For example, in most single-phase residential systems the voltage is 120/240. It is brought to the building with 3 wires, one being a neutral and the other two having voltages 120 volts different from the neutral wire. The voltage difference between the two "hot" wires is 240 volts.

In 3-phase systems the situation is a bit different. There are 3-phase, 3-wire, ungrounded systems where the voltage between the three wires is 240 volts. The big brother of that system is the ungrounded 3-phase, 3-wire 480-volt system. Ungrounded systems are usually found in older facilities.

In newer installations the two most popular systems are called 4-wire "grounded wye" systems. The low-voltage version is represented by a 120/208-volt system. The higher-voltage version is a 277/480-volt system. On both of these grounded wye systems, the low-voltage portion (120 or 277 volts) is only available as single-phase. The high-voltage (208 or 480 volts) is available as either single-phase or 3-phase. It should be noted that in the 4-wire grounded wye systems the high-voltage is 1.73 times (the square root of 3) higher than the low voltage. These grounded wye systems are generally felt to be safer and more flexible than the older ungrounded systems. The flexibility comes from the ability to handle single-phase lighting circuits that operate at 120 volts or 277 volts, from the same system that feeds the 3-phase circuits for motors, equipment for heating, air conditioning, elevators, and industrial machinery.

Motors. Now to discuss motors that operate on these 60-cycle power systems. In the case of "utilization equipment," such as motors, the voltage standards have been selected in multiples of 115 volts; for example, 115, 230, 460 and 575 volts. The standards for the "utilization equipment" have been deliberately picked to be slightly less than the utility delivery voltages because in an industrial plant, or large

Table 1 Summarizes this information to show the power system voltage and description along with the motor voltage rating for single- and 3-phase 60-Hertz motors

Supply Voltage	Commercial And Industrial System Configuration*	Typical 60 Hz Power System Voltages – Utilization Equipment Voltage Ratings		Classification
		Single Phase	3 Phase	
120/208	3 Phase 4 Wire Grounded Wye (A)	115 208 - 230	200 208 - 230	Low Voltage
240	3 Phase 3 Wire Delta Connected (B) (Normally Ungrounded) (1)	230 208 - 230	230 208 - 230	
120/240/240	3 Phase 4 Wire Tapped Delta (C) Neutral Grounded	115 230 208 - 230	230 208 - 230	
277/480	3 Phase 4 Wire Grounded Wye (A)	277 265 (2)	460	
480	3 Phase 3 Wire Delta Connected (B) (Normally Ungrounded) (1)	460	460	
600	3 Phase 3 Wire Delta Connected (B) (Normally Ungrounded) (1)	575	575	
2400	3 Phase 3 Wire Delta Connected (B)	2300	2300 2300/4160	Medium Voltage
4160	3 Phase 4 Wire Grounded Wye (A)	2300 4000 4160	4000 2300/4160	

(1) On some systems grounding of one leg may be utilized.
(2) Some Single Phase equipment may be rated for 265 Volts.

commercial building, there may be several hundred feet between the incoming service point and the equipment. The distances involved will always lead to some voltage loss (or drop) through the wiring. On short runs this loss might be very small, even less than a volt, but on long heavily loaded runs it might be as much as 3 or 4% of the operating voltage. So choosing the utilization voltage to be different — and less than — the utility service voltage makes good sense.

There is also another factor that should be mentioned. The design standards for utilization equipment are set so the equipment is able to handle a voltage variation of plus or minus 10% of the nameplate rating. Thus a motor nameplated at 460 volts should be able to be operate successfully up to 460 plus 10% (506 volts) and down to 460 minus 10% (414 volts). If everything is right with the voltage of the system being in multiples of 120 plus or minus 5%, and the equipment voltage being multiples of 115, plus or minus 10%, then everything fits together like a neat jigsaw puzzle.

There is one oddity in the mix. That is 3-phase motors for the 120/208-volt power systems. For example, if the power system were to be 208 volts minus 5% (approximately 198 volts), and you were using a 230-volt motor, then the 230-volt motor could only go down to 207 volts (–10%) without being in trouble. There would be a discrepancy between the 198-volt low range of the system voltage and the 207 lowest operating voltage of a 230-volt motor; this could spell trouble. So — how to address it?

There are two ways that motor manufacturers have faced up to the problem. The first is to provide motors rated for 200 volts that can operate successfully down to 180 volts, or up to 220 volts. This is an adequate margin to cover the normal range of voltages that could be expected on a 120/208-volt system. But using this approach exclusively would mean that the complete inventory of motors in all sizes, enclosures, mechanical configurations, etc. would have to be duplicated to handle the motor requirements for the 120/208-volt power systems. This would be very expensive and cumbersome — especially with the wide variety of small motors (under 10 HP) that exist.

Most motor manufacturers have therefore taken a different approach to handling these smaller motors. This approach entails using a somewhat more conservative design on the 230-volt motors, by which it is possible to create a 3-phase, tri-voltage motor with voltage ratings of 208-230/460. With this approach the 230-volt winding (and connection diagram) is used on the 208-volt power system. When this approach is taken, the motor manufacturer is essentially saying that this motor can be successfully operated on voltages as low as 208 minus 10% or 187 volts. This approach usually works very well since 208-volt power systems are normally used in small buildings with relatively short distances between the incoming power service and the utilization equipment. These short runs tend to make 208-volt power systems quite stable so that the limit of the motor's low-voltage capability is seldom tested.

On motors larger than 10 HP the 200-volt motor is generally the best choice; but in many situations 230-volt motors are frequently and successfully applied on the 208-volt systems. In some cases a derate table is provided for the "low-voltage" situation. In other cases the motor service factor may be reduced from 1.15 down to 1.0 when it is applied to a 208-volt power system. Table 1 summarizes this information to show the power system voltage and description along with the motor voltage rating for single and 3-phase 60 Hertz motors.

50-hertz power systems. There seems to be an endless array of possible combinations, but most of them do make sense. In 50-hertz areas virtually all power systems are of the 4-wire, grounded wye type. A typical arrangement would be a 220/380-volt power system. In this case, as in the case of a 120/208-volt 60-hertz system, the (low voltage) 220-volt power is only available as single-phase and the 380-volt power is available as either single- or three-phase.

As a result of the voltage being described as 220/380, we frequently see specifications indicating that 3-phase motors be wound for 220/380. Although feasible to do this, it is unnecessary because the 3-phase motors will only be operated on 380-volt, 3-phase power.

Some of the most popular voltages are 220/380 and 240/415. Recently, European countries have recognized the problem of trying to provide equipment for these two different voltage standards and have come up with a standard that splits the difference. The new standard is 230/400. What this means is that if the motor has an adequate amount of tolerance, it can run on either a 380-volt system or a 415-volt system without being damaged. Also in most 50-hertz systems — unlike the domestic systems — the equipment voltage rating tends to be the same as the supply voltage. In other words, 380-volt motors are used on 380-volt systems — as opposed to situations in this country where the equipment utilization voltage is deliberately set lower than the supply voltage. Table 2 shows some typical supply voltages and the appropriate equipment standards for 50 cycle power systems.

Table 2 Typical supply voltages and the appropriate equipment standards for 50-cycle power systems

Supply Voltage	Typical 50 Hz Commercial and Industrial Power: System Configuration*	System Voltages: Utilization Equipment Voltage Ratings: Single Phase	3 Phase
115/200	3 Phase 4 Wire Grounded Wye (A)	115 200	200
127/220	3 Phase 4 Wire Grounded Wye (A)	127 220	220
220/380	3 Phase 4 Wire Grounded Wye (A)	220 380	380 400 (1)
230/400	3 Phase 4 Wire Grounded Wye (A)	230 400	400
240/415	3 Phase 4 Wire Grounded Wye (A)	240 415	415 400 (1)
250/440	3 Phase 4 Wire Grounded Wye	250 440	440
220	3 Phase 3 Wire Delta Connected	220	220
440	3 Phase 3 Wire Delta Connected (B)	440	440

(1) Alternate Rating

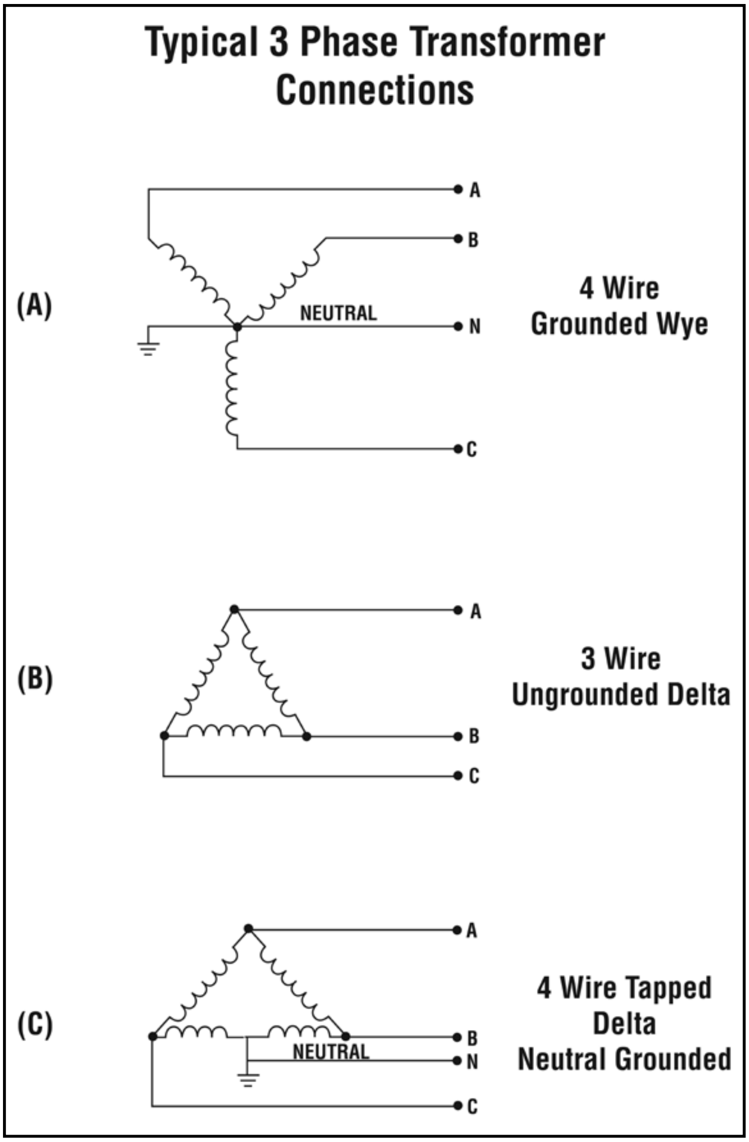

Figure 1 Typical 3-phase transformer connections.

When dealing with foreign voltage requirements, it is always desirable to check the specified voltage against the listing of available voltages indicated in a U. S. Department of Commerce booklet, *Electric Current Abroad*. If the specified voltage and frequency do not match the voltages shown in the booklet for the country and city involved, it should be a red flag that would suggest that the customer be contacted and the voltage confirmed for accuracy. Mistakes can be very costly!!

Summary

Matching motors to the power system voltages can be fairly simple if the basics of the system are understood. See Figure 1 for typical transformer connections.

Electric Motors and Voltage

The effect of low voltage on electric motors is pretty widely known and understood, but the effect of high voltage on motors is frequently misunderstood. This presentation will try to describe the effects of both low and high voltage, and to describe the related performance changes that can be expected when voltages other than nameplate voltages are utilized.

Low voltage. When electric motors are subjected to voltages below the nameplate rating, some of the characteristics will change slightly and others will change more dramatically. A basic point: to drive a fixed mechanical load connected to the shaft, a motor must draw a fixed amount of power from the power line. The amount of power the motor draws is roughly related to the voltage times current (amps). Thus when voltage gets low, the current must get higher to provide the same amount of power. The fact that current gets higher is not alarming unless it exceeds the nameplate current rating of the motor. When amps go above the nameplate rating it is safe to assume that the buildup of heat within the motor will become damaging if it is left unchecked. If a motor is lightly loaded and the voltage drops, the current will increase in roughly the same proportion that the voltage decreases.

For example, a 10% voltage decrease would cause a 10% amperage increase. This would not be damaging if the motor current stays below the nameplate value. However, if a motor is heavily loaded and a voltage reduction occurs, the current would go up from a fairly high value to a new value which might be in excess of the full load rated amps. This could be damaging. It can be safely said that low voltage in itself is not a problem — unless the motor amperage is pushed beyond the nameplate rating.

Aside from the possibility of over-temperature and shortened life created by low voltage, some other important items need to be understood. The first is that the starting torque, pull-up torque and pull-out torque of induction motors all change based on the applied voltage squared. Thus a 10% reduction from nameplate voltage (100% to 90%, 230 volts to 207 volts) would reduce the starting torque, pull-up torque, and pull-out torque by a factor of $.9 \times .9$. The resulting values would be 81% of the full voltage values. At 80% voltage the result would be $.8 \times .8$, or a value of 64% of the full voltage value.

In this case it is easy to see why it would be difficult to start "hard-to-start" loads if the voltage happens to be low. Similarly, the motor's pull-out torque would be much lower than it would be under normal voltage conditions.

To summarize the situation, low voltage can cause high currents and overheating which will subsequently shorten motor life. Low voltage can also reduce the motor's ability to get started and its values of pull-up and pull-out torque. On lightly loaded motors with easy-to-start loads, reducing the voltage will not have any appreciable effect except that it might help reduce the light-load losses and improve efficiency under this condition. This is the principle that is used in the so-called Nola devices that have been sold as efficiency-improving, add-on equipment to motors.

Effects of high voltage. One thing that people assume is, since low voltage increases the amperage draw on motors, then by the same reasoning, high voltage would tend to reduce the amperage draw and heating of the motor. This is not the case. High voltage on a motor tends to push the magnetic portion of the motor into saturation. This causes the motor to draw excessive current in an effort to magnetize the iron beyond the point to which it can easily be magnetized. This generally means that the motors will tolerate a certain change in voltage above the design voltage, but extremes above the designed voltage will cause the amperage to go up with a corresponding increase in heating and a shortening of motor life. For example, older motors were rated at 220/440 and had a tolerance band of plus/minus 10%. Thus the voltage range that they can tolerate on the high-voltage connections would be 396 to 484. Even though this is the so-called tolerance band, the best performance would occur at the rated voltage. The extreme ends, either high or low, would be putting unnecessary stress on the motor.

Generally speaking, these tolerance bands are in existence not to set a standard that can be used all the time but rather to set a range that can be used to accommodate the normal hour-to-hour swings in plant voltage. Operation on a continuous basis at either the high extreme or the low extreme will shorten the life of the motor.

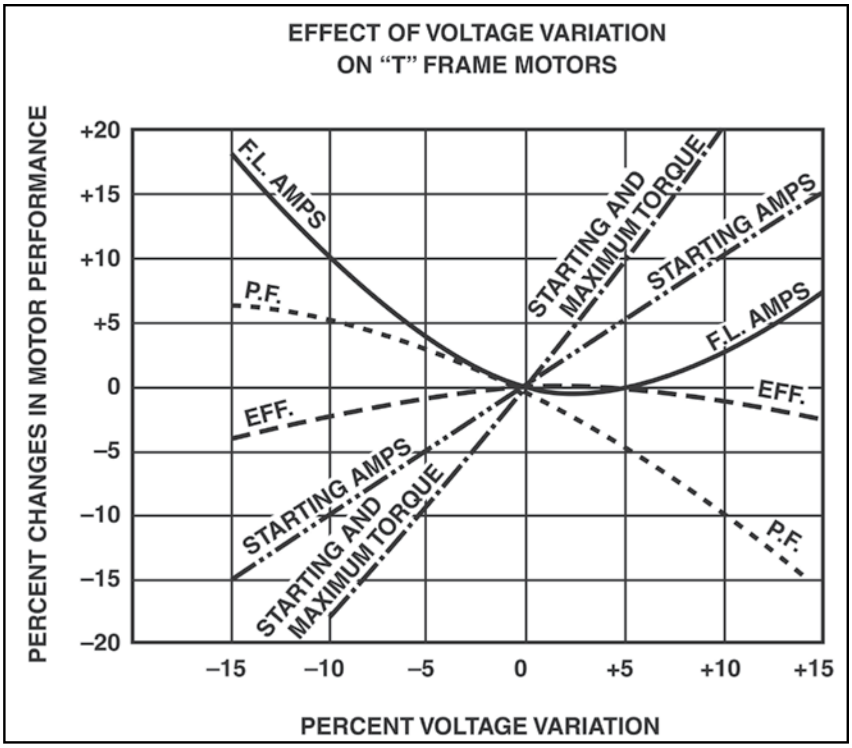

Figure 1 Effect of voltage variation on T-frame motors; percent voltage variation.

Although this presentation covers the effects of high and low voltage on motors, the operation of other magnetic devices are affected in similar ways. For example, solenoids and coils used in relays and starters are punished by high voltage more than they are by low voltage. This is also true of ballasts in fluorescent, mercury, and high-pressure sodium light fixtures. Transformers of all types, including welding transformers, are punished in the same way. Incandescent lights are especially susceptible to high-voltage conditions. A 5% increase in voltage results in a 50% reduction in bulb life. A 10% increase in voltage above the rating reduces incandescent bulb life by 70%.

Overall, it is definitely in the equipment's best interest to have the utility company change the taps on incoming transformers to optimize the voltage on the plant floor to something that is very close to the equipment ratings. In older plants, some compromises may have to be made because of the differences in the standards on old motors (220/440) and the newer "T" frame standards (230/460); but a voltage in the middle of these two voltages, something like 225 or 450 volts, will generally result in the best overall performance. High voltage will always tend to reduce power factor and increase the losses in the system, which results in higher operating costs for the equipment and the system.

The graph shown in Figure 1 is widely used to illustrate the general effects of high and low voltage on the performance of "T" frame motors. It is okay to use the graph to show "general" effects, but bear in mind that it represents only a single motor and there is a great deal of variation from one motor design to the next.

For example, the lowest point on the full-load amp line does not always occur at 2½% above rated voltage. On some motors it might occur at a point below rated voltage. Also, the rise in full-load amps at voltages above rated tends to be steeper for some motor winding designs than others.

Some general guidelines might be useful.

1. Small motors tend to be more sensitive to over-voltage and saturation than large motors.
2. Single-phase motors tend to be more sensitive to over-voltage than three-phase motors.
3. U-frame motors are less sensitive to over-voltage than "T" frames.
4. Premium efficiency Super-E motors are less sensitive to over-voltage than standard efficiency motors.
5. Two-pole and four-pole motors tend to be less sensitive to high voltage than six-pole and eight-pole designs.
6. Over-voltage can drive up amperage and temperature — even on lightly loaded motors. Thus, motor life can be shortened by high voltage.
7. Full-load efficiency drops with either high or low voltage.
8. Power factor improves with lower voltage and drops sharply with high voltage.
9. Inrush current goes up with higher voltage.

Summary

There are very few desirable and many undesirable things that happen to electric motors and other electrical equipment as a result of operating a power system at or near the ends of voltage limits.

The best life and most efficient operation usually occur when motors are operated at voltages close to the nameplate ratings. **PTE**