The Impact That Voltage Variations Have on AC Induction Motor Performance

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ABSTRACT

Operation of AC Induction motors at voltage and frequencies other than the nominal value can affect significant changes in the motor operating costs, performance characteristics and life expectancy. This paper explores these changes using the NEMA Motor-Generator standard as the benchmark for acceptable performance and variations.

Introduction

Motor reliability, performance and life cycle cost are key elements of a successful motor application when viewed from the user's perspective. To be more specific, industrial motor specifications, such as IEEE 841, address bearing life, vibration, geometry and efficiency with considerable detail to achieve desired results.

When the power supply is defined, the nominal voltage is stated with the understanding that NEMA MG-1 will apply. This standard allows for variations in voltage and frequency, along with voltage unbalance.

The part of this standard that is not fully understood is that when allowing these variations, the motor performance and life are usually adversely effected. The purpose of this paper is to review these NEMA MG-1 standards and the impact they have on motor performance and life. The amazing thing is that the standard does an excellent job of pointing these issues out but they usually go unnoticed, partly due to the very limited distribution of MG-1.

Voltage Conditions

The following voltages are defined as standard in accordance with MG-1-10.30

Table 1. Nominal Three Phase Voltages

Nominal Voltages		
Voltage	60 HZ	50 HZ
200	√	—
220	—	√
230	√	—
380	—	√
460	√	—
575	√	—
2300	√	—
4000	√	—
4600	√	—
6600	√	—

This paper is limited to motors operating on sinusoidal power and does not consider the impact of adjustable speed drives. However, NEMA MG-1 Part 30 and Part 31 do cover this condition.

Variations From Rated Voltage and Rated Frequency (NEMA 12.44)

"Alternating-current motors shall operate successfully under running conditions at rated load with a variation in the voltage or the frequency up to the following:

- Plus or minus 10 percent of rated voltage, with rated frequency for induction motors.
- Plus or minus 5 percent of rated frequency, with rated voltage.
- A combined variation in voltage and frequency of 10 percent (sum of absolute values) of the rated values, provided the frequency variation does not exceed plus or minus 5 percent of rated frequency. . . .

Performance within these voltage and frequency variations will not necessarily be in accordance with the standards established for operation at rated voltage and frequency. In fact, they could reduce the motor life significantly."

Effect of Variation of Voltage and Frequency Upon the Performance of Induction Motors (NEMA 14.30)

"Induction motors are at times operated on circuits of voltage or frequency other than those for which the motors are rated. Under such conditions, the performance of the motor will vary from the rating. The following are some of the operating results caused by small variations of voltage and frequency and are indicative of the general character of changes produced by such variation in operating conditions.

14.30.1. With a 10 percent increase or decrease in voltage from that given on the nameplate, the heating at rated horsepower load may increase. Such operation for extended periods of time may accelerate the deterioration of the insulation system.

14.30.2. In a motor of normal characteristic at full rated horsepower load, a 10 percent increase of voltage above that given on the nameplate would usually result in a decided lowering in power factor. A 10 percent decrease of voltage below that given on the nameplate would usually give an increase in power factor.

14.30.3. The locked-rotor and breakdown torque will be proportional to the square of the voltage applied.

14.30.4. An increase of 10 percent in voltage will result in a decrease of slip of about 17 percent, while a reduction of 10 percent will result in an increase slip amount of about 21 percent. Thus, if the slip at rated voltage were 5 percent, it would be increased to 6.05 percent if the voltage were reduced 10 percent."

14.30.5. "A frequency higher than the rated frequency usually improves the power factor but decreases load rotor torque and increases the speed and friction and windage loss. At a frequency lower than the rated frequency, the speed is decreased, locked-rotor torque is increased and power factor is decreased. For certain kinds of motor loads, such as, textile mills, close frequency regulation is essential.

14.30.6. If variations in both voltage and frequency occur simultaneously, the effect will be superimposed. Thus, if the voltage is high and the frequency low, the locked-rotor torque will be very greatly increased, but the power factor will be decreased and the temperature rise increased with normal load.

14.30.7. The foregoing facts apply particularly to general-purpose motors. This may not always be true in connection with special-purpose motors, built for a particular purpose, or for very small motors."

An Industrial Study on Voltage Variation

In 1995, Dr. P. Pillay conducted a study to determine the amount of voltage variation experienced in a typical petro-chemical application and its impact on motor performance. Figures 1, 2, 3 and 4 illustrate the amount of variation experienced over a relative short period of time. Although the extremes are within the NEMA standards they will definitely affect the motor performance and life.

"Motors are designed to operate off 460 volts, measurements in the petro-chemical industry have revealed that the actual operating voltages can be somewhat higher as shown in Figure 1, 2, 3, and 4 for a 50 hp motor driving a pump, a 200 hp motor driving a pump, a 100 hp motor driving a fan, and a 30 hp motor driving an agitator. The corresponding loadings are shown in Figures 5 and 6. These graphs show both the motor control center voltage as well as the actual motor terminal voltage obtained by subtracting off the line impedance drop. Coincidence of the two voltages indicated periods of no load or complete shut down." [5]

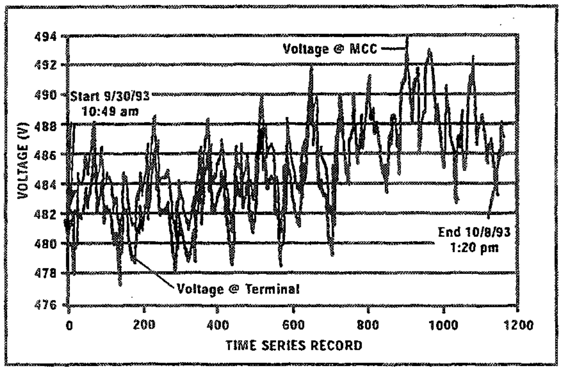


Figure 1. 200 Hp Motor Driving a Pump

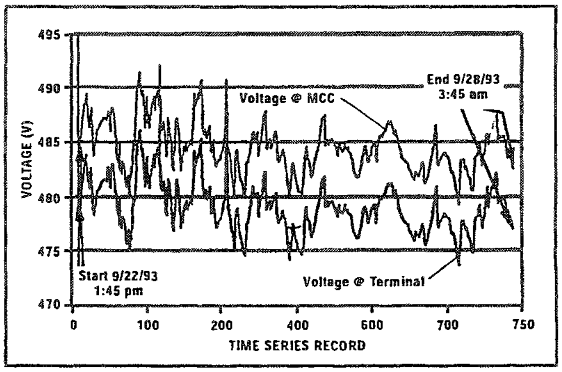


Figure 2. 100 Hp Motor Driving a Fan

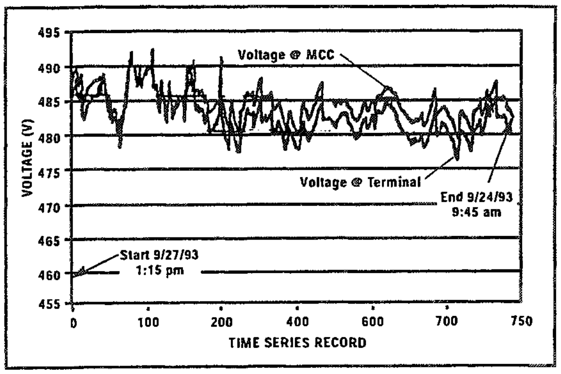


Figure 3. 50 Hp Motor Driving a Pump

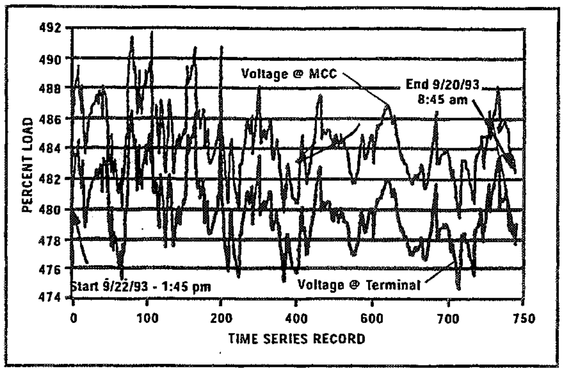


Figure 4. 30 Hp Motor Driving an Agitator

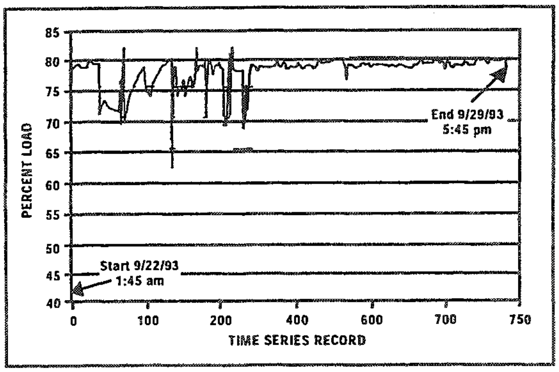


Figure 5. % Load - 100 Hp Motor Driving a Fan

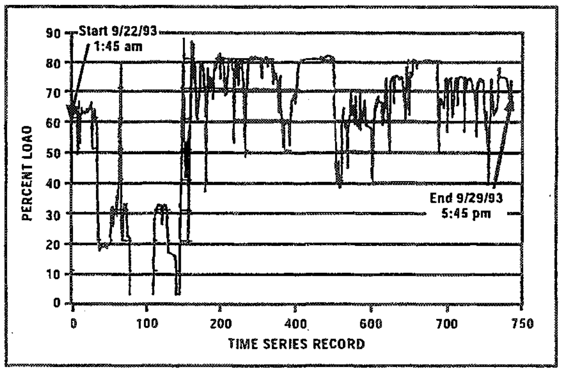


Figure 6. % Load - 50 Hp Motor Driving a Pump

Speed-Torque Starting Characteristics

Variations in the voltage will have a significant impact on the motor starting torque since it will vary as the square of the flux density.

NEMA 12.44.2. "Medium motors shall start and accelerate to running speed a load which has a torque characteristic and an inertia value not exceeding that listed in MG-1-12.54 with the voltage and frequency variations specified in 12.44.1.

The limiting values of voltage and frequency under which a motor will successfully start and accelerate to running speed depends on the margin between the speed-torque curve of the motor at rated voltage and frequency and the speed-torque curve of the load under starting conditions. Since the torque developed by the motor at any speed is approximately proportional to the square of the voltage and inversely proportional to the square of the frequency, it is generally desirable to determine what voltage and frequency variations will actually occur at each installation, taking into account any voltage drop resulting from the starting current drawn by the motor. This information and the torque requirements of the driven machine define the motor-speed-torque curve, at rated voltage and frequency, which is adequate for the application."

The following curves illustrate the impact of voltage variation on the speed-torque characteristics.

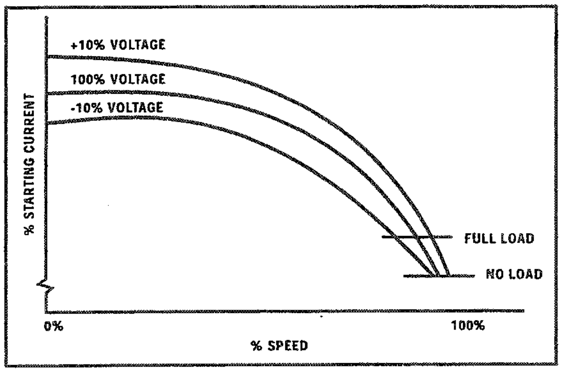


Figure 7. Starting Current vs. Speed

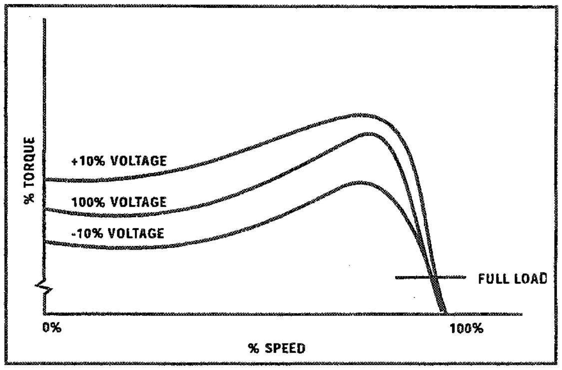


Figure 8. Torque vs. Speed

Motor Insulation Life as Affected by Temperature

Figure 9 provides a means to estimate the impact voltage/frequency variation have on the winding insulation life once the temperature change is determined. As shown in Figure 9, for every 10°C increase in winding temperature, the expected thermal life of the winding is reduced by half. There may also be a notable decrease in bearing lubricant life as the operating temperature of the motor increases.

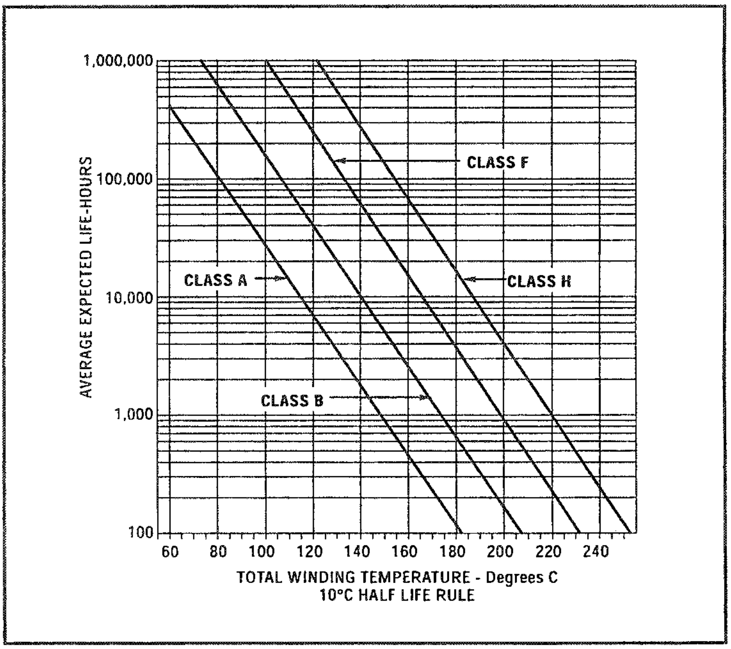


Figure 9. Temperature vs. Life Curves for Insulation Systems (per IEEE 117 & 101)

Summary of Effects of Voltage Change

There are numerous tables available that indicate the effects of voltage variation on motor performance. The following table is typical for energy efficient motors.

Table 2. Effect of Voltage Change on a Motor. (P. Pillay, 1995)

Operating Characteristic	Effect Of Voltage Change 90% Voltage	 110% Voltage	 120% Voltage
Starting and Max. Running Torque	Decr. 19%	Incr. 21%	Incr. 44%
Synchronous Spd.	No Change	No Change	No Change
Percent Slip	Incr. 23%	Decr. 17%	Decr. 30%
Full Load Speed	Decr. 1-1/2%	Incr. 1^1/2%	Incr. 1^1/2%
Efficiency			
Full Load - High Eff.	Decr. 1-2 pts.	Incr. ^{1}/2-1 pt.	Small Incr.
T-Line	Incr. ^{1}/2-1 pt.	Decr. 1-4 pts.	Decr. 7-10 pts.
3/4 Load - High Eff.	Pract. No Chg.	Pract. No Chg.	Decr. ^{1}/2-2 pts.
T-Line	Incr. 1-2 pts.	Decr. 2-5 pts.	Decr. 9-12 pts.
1/2 Load - High Eff.	Incr. 1-2 pts.	Decr. 1-2 pts.	Decr. 7-20 pts.
T-Line	Incr. 2-4 pts.	Decr.4-7 pts.	Decr. 14-16 pts.
Power Factor			
Full Load - High Eff.	Incr. 1 pt.	Decr. 3 pts.	Decr. 5-15 pts.
T-Line	Incr. 9-10 pts.	Decr. 10-15 pts.	Decr. 10-30 pts.
3/4 Load - High Eff.	Incr. 2-3 pts.	Decr. 4 pts.	Decr. 10-30 pts.
T-Line	Incr. 10-12 pts.	Decr. 10-15 pts.	Decr. 10-30 pts.
1/2 Load - High Eff.	Incr. 4-5 pts.	Decr. 5-6 pts.	Decr. 15-40 pts.
T-Line	Incr. 10-15 pts.	Decr. 10-15 pts.	Decr. 10-30 pts.
Full Load Current			
High Eff.	Incr. 11%	Decr. 7%	Decr. 11%
T-Line	Incr. 3-6%	Incr. 2-11%	Incr. 15-35%
Starting Current	Decr. 10-12%	Incr. 10-12%	Incr. 25%
Temperature Rise			
Full Load - High Eff.	Incr. 23%	Decr. 14%	Decr. 21%
T-Line	Incr. 6-12%	Incr. 4-23%	Incr. 30-80%
Magnetic Noise, Any Load	Decr. Slightly	Incr. Slightly	Noticeable Incr.

Unbalanced Voltage

Far too many assumptions are made when dealing with the symmetry of a voltage supply. In order to accurately assess the quality of the voltage supply, it is necessary to verify it at a number of places within the service and over a reasonable period of time and seasons. NEMA offers the following explanation of the effects of unbalanced voltage along with a load derating curve.

Effects of Unbalanced Voltages on the Performance of Polyphase Induction Motors. (NEMA 14.35).

NEMA states "When the line voltages applied to a polyphase induction motor are not equal, unbalanced currents in the stator windings will result. A small percentage voltage unbalance will result in a much larger percentage current unbalance. Consequently, the temperature rise of the motor operating at a particular load and percentage voltage unbalance will be greater than for the motor operating under the same conditions with balanced voltages.

The voltage should be evenly balanced as closely as can be read on a voltmeter. Should voltages be unbalanced, the rated horsepower of the motor should be multiplied by the factor shown in Figure 10 to reduce the possibility of damage to the motor. Operation of the motor above a 5 percent voltage unbalance condition is not recommended.

When the derating curve of Figure 10 is applied for operation on unbalanced voltages, the selection and setting of the overload device should take into account the combination of the derating factor applied to the motor and increase in current resulting from the unbalanced voltages. This is a complex problem involving the variation in motor current as a function of load and voltage unbalanced in addition to the characteristics for the overload device relative to $I_{maximum}$ or $I_{average}$. In the absence of specific information, it is recommended that overload devices be selected or adjusted, or both, at the minimum value that does not result in tripping from the derating factor and voltage unbalance that applies. When unbalanced voltages are anticipated, it is recommended that the overload devices be selected so as to be responsive to $I_{maximum}$ in preference to overload devices responsive to $I_{average}$."

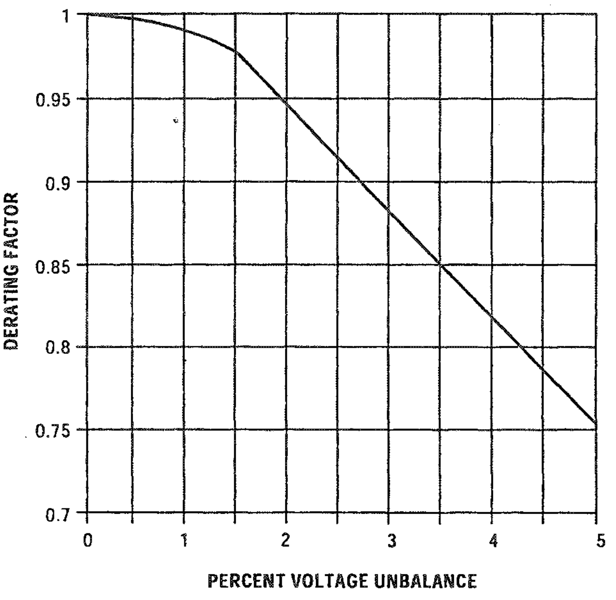


Figure 10. Medium Motor Derating Factor Due to Unbalanced Voltage (NEMA, Figure 14.1)

Effect on Performance - General (NEMA 14.35.1)

NEMA states "The effect of unbalanced voltages on polyphase induction motors is equivalent to the introduction of a "negative sequence voltage" having a rotation opposite to that occurring with balanced voltages. This negative sequence voltage produces in the air gap a flux rotating against the rotation of the rotor, tending to produce high currents. A small negative-sequence voltage may produce in the windings currents considerably in excess of those present under balanced voltage conditions".

Unbalance Defined (NEMA 14.35.2)

The voltage unbalanced in percent may be defined as follows:

$$\textbf{percent voltage unbalance} = 100 \times \frac{\textbf{Maximum voltage deviation from average voltage}}{\textbf{Average voltage}}$$

Example: With voltages of 460, 467, and 450, the average is 459, the maximum deviation from average is 9, and the percent unbalanced (Vu) equals:

$$Vu = \frac{100}{459} \times 9 = 1.96 \text{ percent}$$

Torques (NEMA 14.35.3)

NEMA states "The locked-rotor torque and breakdown torque are decreased when the voltage is unbalanced. If the voltage unbalance should be extremely severe, the torques might not be adequate for the application.

The torque may still be adequate on variable torque applications, such as pumps and fans. However, on constant torque applications, such as conveyers, there can be acceleration or stall problems."

Full-Load Speed (NEMA 14.35.4)

The full-load speed is reduced slightly when the motor operates at unbalanced voltages.

Currents (NEMA 14.35.5)

The locked-rotor current will be unbalanced to the same degree that the voltages are unbalanced, but the locked-rotor kVA will increase only slightly.

The currents at normal operating speed with unbalanced voltages will be greatly unbalanced in the order of approximately 6 to 10 times the voltage unbalance."

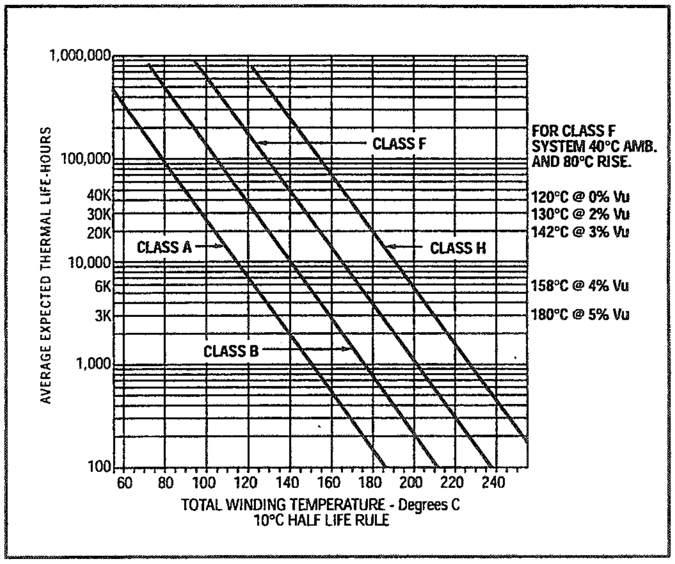
Impact on Winding Temperatures [4]

A good assumption for the impact of unbalanced voltage on the winding temperature rise is that the rise equals two times the percent voltage unbalance squared.

Increased Temp. Rise (Δ°C) = 2 x $(\% \text{ V unbalanced})^2$

Figure 11 shows the drastic impact voltage unbalance has on temperature rise and the winding insulation life.

Increased Temp. Rise = 2 x (% V unbalance)^2



Vu @ 0% = 0% Δt = 120°C Vu @ 4% = 32% Δt = 158°C
Vu @ 2% = 8% Δt = 130°C Vu @ 5% = 50% Δt = 180°C
Vu @ 3% = 18% Δt = 142°C

Assume 40°C ambient, normal temperature rise 80°C @ zero voltage unbalance and a total temperature of 120°C.

Figure 11. Impact of Voltage Unbalance

Test Results

The following study was conducted at the Emerson Motor Technology Center in St. Louis, Missouri to compare the standard efficiency motor to a premium efficient motor under unbalanced voltage conditions.

The increase in winding temperature causes additional I^2R losses. The rotor losses also increase because of the impact the "Negative Sequence Component" has on the rotor. Therefore, as shown in Figure 12, there is a significant drop in motor efficiency.

Table 3. Motors Design Data

Description	Prem. Eff.	Std. Eff.
Model No.	7965	E398
Type	TCE	CT
HP Rating	5	5
Voltage/Freq.	230/60	230/60
No. of Poles	4	4
Syn. Speed	1800	1800
Connections	Wye	Wye
Full Load Performance:		
Amps	12.56	13.47
RPM	1750	1738
Slip P.U.	0.0280	0.0344
Losses (Watts)	445	611
Efficiency %	89.3	85.9
Power Factor %	83.4	80.9
Flux Density: Kl/in^2		
Stator Core	107	110
Stator Teeth	114	120
Airgap	.0325”	.0359”
Rotor Core	43	51
Rotor Teeth	116	116

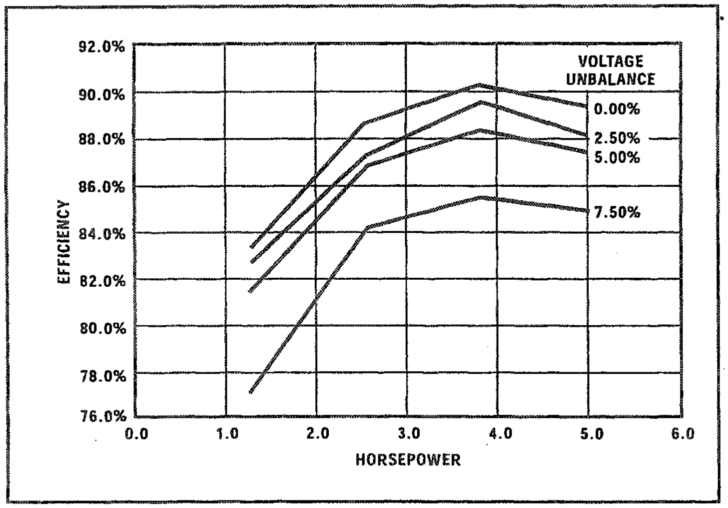


Figure 12. Efficiency Variation vs. HP

Table 4 shows the impact on current and power for 0%, 2%, and 4% unbalance. The difference do not appear to be significant. However, the motor heating will be significantly more on the standard motor.

Table 4. Unbalanced Voltage Operation (Premium Efficiency vs. Standard Motor) At Full Load

		Ratio of Unbalanced Balanced Values		
Machine Type	**Parameter**	**0% Unbal.**	**2% Unbal.**	**4% Unbal.**
Prem. Eff. Motor	Line Amps			
	1	1.009	0.949	0.895
	2	0.991	1.171	1.325
	3	0.999	0.935	0.904
	Line Power			
	1	1.011	0.014	0.988
	2	0.999	1.187	1.365
	3	0.991	0.863	0.728
	Av. Amps Ln.	1.000	0.0205	1.0462
	Av. Power Ln.	1.000	0.0239	1.0399
	Av. P.F.	1.000	1.0006	0.9874
Standard Motor Eff.	Line Amps			
	1	0.973	0.901	0.832
	2	1.021	1.129	1.277
	3	1.006	0.962	0.958
	Line Power			
	1	0.968	0.941	0.903
	2	1.010	1.167	1.354
	3	1.023	0.881	0.779
	Av. Amps Ln.	1.000	0.9971	1.0222
	Av. Power Ln.	1.000	0.9964	1.0120
	Av. P.F.	1.000	0.9967	0.9836

NOTE: Ratios are with respect to average line values under balanced operation.

Vibration and Noise

Figures 13 and 14 illustrates the relationship between voltage unbalance and vibration noise. Note that in both cases there is a significant impact on motor performance as it relates to acceptable vibration levels and sound power levels.

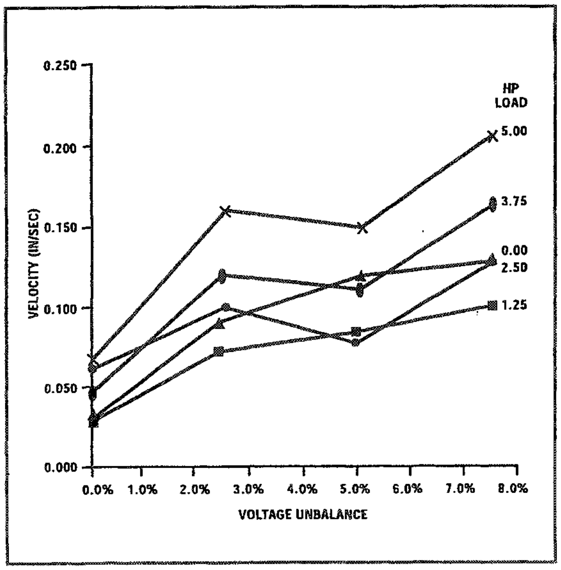


Figure 13. Vibration vs. Voltage Unbalance (Drive End Bracket)

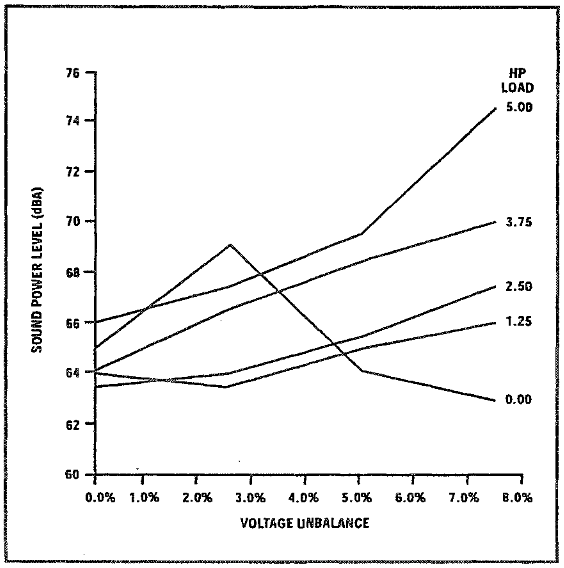


Figure 14. Noise - Outlet Box Side

Appendix I

System Nominal Voltage

There continues to be some confusion between the system or service voltage and utilization or equipment voltage. Table 5 provides these relationships for the normal range "A" and for range "B" when the voltage moves outside of the normal voltage range.

NOTE: That the four wire systems have a center or neutral tap that provides a lower voltage with the ratio of the √3. (i.e. for a 4160 V system the neutral voltage is 4000/√3 or 2300 volts.)

Application of Voltage Ranges

Range "A" - Service Voltage (ANSI C84.1.2.4.1). Electric supply systems shall be so designed and operated that most service voltages will be within the limits specified for Range "A". The occurrence of service voltages outside of these limits should be infrequent.

Table 5. Standard Nominal System Voltages and Voltage Ranges [ANSI C84.1-1995]

Nominal System Voltage		Voltage Range "A"			Voltage Range "B"		
		Minimum		Maximum	Minimum		Maximum
Three-wire	Four-wire	Utilization Voltage	Service Voltage	Utilization and Service Voltage	Utilization Voltage	Service Voltage	Utilization and Service Voltage
Single-Phase Systems							
		110	114	126	106	110	127
120/240	—	110/120	114/228	126/252	106/212	110/220	127/254
Three-Phase Systems							
	208Y/120	191Y/110	197Y/114	218Y/126	184Y/106	191Y/110	220Y/127
	240/120	220/110	228/114	252/126	(Note d) 212/106	(Note d) 220/110	220/127
240		220	228	252	212	220	254
	480Y/277	440Y/254	456Y/263	504Y/291	424Y/245	440Y/254	508Y/293
480		440	456	504	424	440	508
600		550	570	630	530	550	635
2400		2160	2340	2520	2080	2280	2540
	4160Y/2400	3740Y/2160	4050Y/2340	4370Y/2520	3600Y/2080	3950Y/2280	4400Y/2540
4160		3740	4050	4370	3600	3950	4400
4800		4320	4680	5040	4160	4560	5080
6900		6210	6730	7240	5940	6560	7260
	8320Y/4800		8110Y/4680	8730Y/5040		7900Y/4560	8800Y/5080
	12000Y/6930		11700Y/6760	12600Y/7270		11400Y/6580	12700Y/7330

Range "A" - Utilization Voltage (ANSI C84.1.2.4.2). User systems shall be so designed and operated that with service voltages within Range "A" limits, most utilization voltages will be within the limits specified for this range.

Utilization equipment shall be designed and rated to give fully satisfactory performance throughout this range.

Range "B" - Service and Utilization Voltages (ANSI C84.1.2.4.3). Range "B" includes voltages above and below Range "A" limits that necessarily result from practical design and operating conditions on supply or user systems, or both. Although such conditions are a part of practical operations, they shall be limited in extent, frequency, and duration. When they occur, corrective measures shall be undertaken within a reasonable time to improve voltages to meet Range "A" requirements.

Insofar as practicable, utilization equipment shall be designed to give acceptable performance in the extremes of this range of utilization voltages, although not necessarily as good performance as in Range "A".

It must 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 of Range "B" limits will occur. Utilization equipment may not operate satisfactorily under these conditions, and protective devices may operate to protect the equipment. When voltage occur outside the limits of Range "B", prompt corrective action is recommended. The urgency for such action will depend upon many factors, such as location and nature of load or circuits involved, and magnitude and nature of the deviation beyond Range "B" limits.

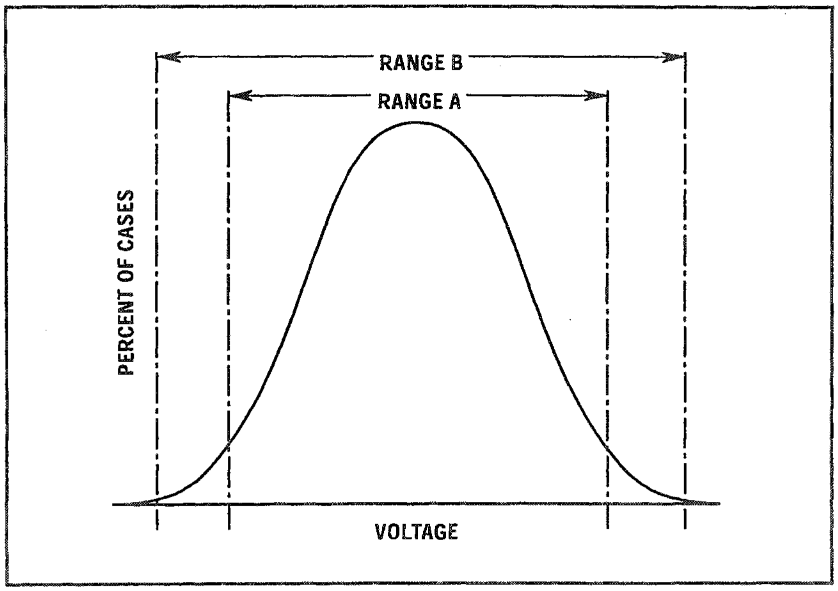


Figure 15. ANSI Voltage Service Ranges

Appendix II

Effects of Voltages Over 600 Volts on the Performance of Low-Voltage Motors. (NEMA 14.32.)

"Polyphase motors are regularly built for voltage ratings of 575 volts or less and are expected to operate satisfactorily with a voltage variation of plus or minus 10 percent. This means that motors of this insulation level may be successfully applied up to an operating voltage of 635 volts.

Based on the motor manufacturer's high-potential test and performance in the field, it has been found that where utilization voltage exceed 635 volts, the safety factor of the insulation has been reduced to a level inconsistent with good engineering procedure.

In view of the foregoing, motors of this insulation level should not be applied to power systems either with or without grounded neutral where the utilization voltage exceeds 635 volts, regardless of the motor connection employed.

However, there are some definite-purpose motors that are intended for operation on a grounded 830 volt system. Such motors are suitable for 460 volt operation when delta connected and for 796 volt operation when wye connected when the neutral of the system is solidly grounded."

Appendix III

Voltage Surges

Most people would not consider voltage surge to be a voltage variation. Yet in reality it is, except of a much higher magnitude and of a much shorter duration. For ease of reference it has been added to this report.

Introduction

Steep-fronted voltage surges have been recorded with values as high as 6 per unit (pu) where the definition of pu is the line voltage times √2/√3 or pu equals $.817V_l$. The two basic causes of these surges are lightning strikes and switching action. The shape of these can vary drastically. For illustration purposes the wave forms can be characterized by stating the crest value and the rise time as shown in Figure 16.

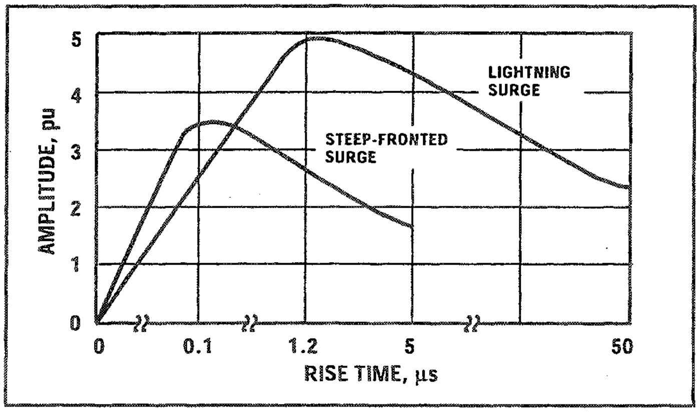


Figure 16. Lightning and Steep-Fronted Surges

The first turn or coils of the stator winding will absorb these surges and place a very high dielectric stress across this part of the winding. In most cases, if a winding fails because of a steep-fronted surge, it will be identified by turn-to-turn shorts in this area and sometimes accompanied by a ground fault in the same area or phase-to-phase fault.

Factors Causing Steep-Fronted Voltages

Line-to-line, line-to-ground, 2 line to ground and 3 phase faults causing over-shoot and line-to-line voltages that will reach 3-1/2 times their normal values during very short time periods.

Other sources include: repetitive restriking, failure of current limiting fuses, rapid bus transfers, opening or closing of circuit breakers, capacitor switching, insulation failure, lightning, variable frequency drive waveforms and standing waves.

References

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