UNDERSTANDING LOW VOLTAGE SQUIRREL CAGE INDUCTION MOTORS

The intent of this paper is to examine the design features and performance characteristics of polyphase low voltage (<750 volts) squirrel cage induction motors ("LVM"), in order to provide a more detailed understanding of the characteristics of these machines, and to aid in the specification and technical evaluation of such equipment.

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TOSHIBA INTERNATIONAL CORPORATION

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1.0 NEMA/EEMAC

The National Electrical Manufacturers Association (NEMA) is a nonprofit U.S. organization consisting of members from the manufacturing sector. One of the stated purposes of NEMA is "to promote the standardization of electrical apparatus and supplies". The NEMA working document for LVM is Standard MG 1, "for Motors And Generators". NEMA standards "are intended to assist users in the proper selection and application of motors". The Electrical and Electronic Manufacturers Association of Canada (EEMAC) uses MG 1 with some modifications.

2.0 FRAME SIZES

In North America, the "T" frame is the modern NEMA motor frame designation (replacing the older "U" frame standard), and is applicable up to the 680 frame. Motors in frame sizes up to 44 7T are completely interchangeable, with specific frame assignments for each horsepower/rpm combination, while mounting dimensions on frames larger than 44 7T are not necessarily interchangeable. Not all motor dimensions are designated by NEMA, and the end user must take care to ensure that critical dimensions have been considered. NEMA does define certain critical dimensions for T-frame motors, however, including foot mounting dimensions, shaft height, etc.. NEMA defines 'Small' machines as those rated at <1 hp. For small machines in two digit frame sizes, the frame number is the "D" dimension in inches, multiplied by 16. (The "D" dimension is the distance from the centerline of the shaft to the bottom of the feet.) For 'Medium' machines (1 - 500hp), the first two digits of the frame number are equal to the "D" dimension in 1/4 inches, and the third digit (and fourth digit when required) establishes the distance between the centerlines of the mounting holes of the feet or base (side view). This provides for a high degree of interchangeability between offerings of various manufacturers (hence the tendency to view the LVM as a commodity), and minimizes motor spare requirements.

An "S" suffix denotes a motor with a short shaft, and ball type drive end bearing, suitable for direct coupling. A "Z" suffix denotes a shaft extension modification (usually a longer shaft, with a roller bearing on the drive end, suitable for belt coupled applications). A "C" suffix denotes a C-face flange. No suffix indicates a motor with ball bearings and a standard shaft, suitable for direct coupling, and which may also be suitable for belt coupled applications. The manufacturer should be consulted prior to using a standard shaft motor on a belt coupled application.

Motor frames may be of cast iron, or rolled steel or rolled aluminum. Cast iron is generally considered to be the most suitable frame material for industrial use, due to its high resistance to corrosion, extreme rigidity, etc..

3.0 NAMEPLATE DATA

NEMA specifies that certain information be present on the motor nameplate, including: manufacturer's type and frame designation, horsepower output, time rating, maximum ambient temperature for which the motor is designed, insulation system designation, full load rpm, frequency, number of phases, voltage, full load amps, and code. For medium size motors (1.5 to 500 hp), the following information is also required to be shown on the nameplate: design letter, nominal efficiency, and service factor (if other than 1.0 S.F.).

4.0 ENCLOSURE TYPES

NEMA designates certain enclosure types, and the degree of protection against environmental intrusion that each affords. The more common of these enclosure types are Open machines: Drip-Proof (ODP), and Weather Protected (WPI/WPII); Totally Enclosed machines: Fan Cooled (TEFC), Pipe-Ventilated (TEPV), Air Over (TEAO), Non-Ventilated (TENV), Air to Air (TEAAC), Water to Air (TEWAC), and Explosion-proof (XP); and those with encapsulated or sealed windings. Explosion-proof motors are intended for use in hazardous locations, which are classified according to the nature of the hazard. The CLASS designation indicates the type of combustible to be expected: Class I indicates combustible gases or vapors; Class II indicates combustible or electrically conductive dusts; and Class III indicates easily ignitable fibers or flyings. Class I and II locations are further divided into two DIVISIONS, with the Division designation indicating the frequency and duration of the presence of the combustible gas or dust. A Division 1 location is one in which the hazardous gas or dust is expected to be present under normal operating conditions or may exist frequently, while a Division 2 location is one in which combustibles are not normally expected to be present, but which, under certain (usually failure mode) conditions, may be present in hazardous concentrations. Atmospheric GROUP ratings are used to indicate the gas grouping. However, the Canadian Electrical Code and NFPA should be consulted for specific gas characteristics.

Motors used in Class I and II hazardous locations must bear markings to indicate the Class and Group locations for which they have been approved. Further, motors may be marked with the maximum external temperature, or the TEMPERATURE CODE, which indicates the maximum skin temperature of the motor under normal full load operating conditions. This gives an indication of the suitability of the motor given the ignition temperature of a specific combustible. The Canadian Electric Code (CEC) indicates that in Class I, Division 2 areas, motors that do not incorporate arcing or sparking producing components or integral resistance devices may be of the non explosion-proof type. However, as each province may have its own amendments to the CEC, and local inspection authorities may also have specific requirements for hazardous locations, the end user must take care to ensure that the equipment selected meets the requirements of these inspection and regulatory bodies.

"Severe Duty" is a term that is rather abused when used in reference to LVM. To each manufacturer and each customer it can mean something different, since there is no general consensus of just what does constitute a severe duty motor. A severe duty motor offered by some manufacturers may often be nothing more than a standard cast iron frame motor, to which has been added a cast iron terminal box and/or cast iron fan cover. However, the IEEE (Institute of Electrical and Electronic Engineers), with the cooperation of API (American Petroleum Institute), have developed a recommended standard for LV motors intended for use in hostile environments and severe service applications. This standard is IEEE RP841, and addresses such factors as corrosion protection, winding insulation temperature rise, bearing temperature rise, bearing regreaseability, vibration, internal ventilation and drainage, audible noise, number of leads, etc.. Premium efficiency motors meeting IEEE RP 841 are currently available on the market.

5.0 SEALS AND SLINGERS

Various types of seals are employed to prevent moisture from entering the interior of the motor along the shaft - they are especially required for outdoor, shaft up, mounting configurations. These seals include "shaft slingers" (or "flingers"), more sophisticated types of motor seal designs, and "Inpro" seals.

"Slingers" operate by centrifugally flinging moisture away to prevent it from progressing along the motor shaft and into the bearing housing. The disadvantage of most slingers is that they only offer protection when the motor is running (i.e.: while the shaft is turning). Once the motor is stopped, moisture that runs down the end bell or shaft and encounters the slinger may then make its way behind the slinger and into the bearing housing.

On shaft up motor mounting configurations of horizontal motors, slingers are more effective, but still do not totally prevent moisture from entering the bearing housing when the motor is at standstill. Sometimes, conical shaped disks are mounted on the motor shaft so that, at standstill, moisture that runs down the shaft drips over the edges of the disk, and away from the shaft. More sophisticated slingers have recently been developed to prevent water from entering the motor along the shaft when the motor is running or at standstill. These new designs are gaining rapid acceptance as a very effective and economical method of preventing moisture ingress along the motor shaft. These slingers operate as follows: at standstill, the inner portion of the slinger presses snugly against the motor end bell, thus preventing moisture from entering the bearing housing. When the motor is running and the shaft is turning, the inner portion of the slinger pulls away slightly from the end bell (by centrifugal action, thus preventing undue wear of the slinger), and operates as a conventional slinger. When the motors stops, the slinger once again seals against the bearing housing.

An "Inpro" seal is a two part seal that is installed around the shaft on the drive-end bearing bracket. The bearing bracket is machined to accept the Inpro seal, part of which is mounted on the inside of the bracket, and part of which is mounted on the outside of the bracket, resulting in a very effective seal against moisture. The only minor disadvantage of the Inpro seal (apart from the initial cost) is a slight reduction in usable shaft extension, due to the thickness of the seal on the outer portion of the bearing bracket. Inpro seals are generally not available as standard options due to limited end bell material and clearances on many motor designs.

6.0 DRAIN AND BREATHER PLUGS

LVM generally come standard with one or more drain holes located in the lowest part(s) of the motor frame, where moisture is most likely to collect . Optionally, one or more 'drain and breather plugs' may be threaded into tapped drain holes. Drain and breather plugs are designed to permit moisture to leave the motor enclosure, while at the same time preventing contaminants from entering the motor enclosure. If used, they should be checked regularly to ensure their proper operation.

7.0 BEARING CONSTRUCTION/LUBRICATION/TEMPERATURE RISE

It has been estimated that roughly 70-80% of all LVM failures are bearing related. Consequently, bearing design is a major factor in influencing motor life. The selection of bearing types is influenced by a number of factors, including motor hp, speed, as well as environment, lubrication practices, and other factors. Anti friction bearings (ball and roller) are most common in lower hp ratings, with sleeve bearings used generally only for higher hp, higher speed, applications. Anti friction bearings may be of the shielded, sealed for life (i.e.: double sealed, with no lubrication required), regreaseable, or oil mist lubricated types.

There are relative advantages and disadvantages of each type of lubrication method. For smaller hp motors, double sealed (greased for life) bearings are often preferred, due to the long life of grease in smaller bearings. This also avoids the inconvenience and cost of greasing smaller motors. In larger hp ratings, regreaseable bearings are more commonly used. This permits an open bearing construction, which helps to limit bearing temperature rises.

A well-accepted rule of thumb is that for every 15 deg. C. that the lubrication temperature rating is exceeded, the life of the grease is halved. IEEE RP841 recommends that the maximum bearing temperature rise be limited to 45 deg. C. (based upon an assumed ambient of 40 deg. C.).

Careful attention should be paid to the path that the grease must take as it travels from the grease inlet, to the relief (since the grease cannot do its work if it cannot make its way into the bearing). It is very common to find bearing lubrication designs where the grease need not necessarily enter into the bearing, but rather can simply pass along the face of the bearing to the relief. This can result in older grease being trapped in the bearing, where it eventually loses its ability to lubricate. Preferred designs are those in which new grease is forced through the bearing on its way to the grease relief. This can be achieved by porting new grease in behind the bearing so that, in order to get to the relief, it must travel through the bearing.

Grease is comprised of two main components - a thickener and an oil - while additives such as anti-oxidants or anti-rust agents, etc. may also be included. The thickener acts like a sponge, to hold the oil within the grease until it is released by heat and mechanical action. Thickeners may be of soap, clay, or polyurea base. The oil in grease is one of two major types - mineral oil, or synthetic oil. Mineral oil is by far the most common in use. Synthetic oils perform well in extreme temperatures, but are more expensive. Oil mist lubrication systems require an oil pump and filter, which adds to the initial capital cost of the system. However, in severe environments, where a number of motors are located in the same proximity, this can be a practical alternative.

8.0 BALANCING/VIBRATION

NEMA has established standards for maximum allowable unbalance for LVM. The allowable unbalance is a function of motor speed, and is expressed in mils (1/1000 inches) displacement at the bearing housing, with the motor operating at no load, and with one half of a standard key in the key seat. The maximum allowable unbalance for 2, 4, 6, and 8 pole motors is 1.0, 1.5, 2.0, and 2.5 mils peak to peak, respectively. These values should be considered worst case values, since, in practice, much lower values of unbalance are economically achievable . (NEMA balancing/vibration standards are currently under review, and are expected to be revised in the next year. It is anticipated that present displacement limits will be replaced by velocity limits.)

Motor life is influenced to a large degree by the performance of the bearings, and the advantages of good mechanical balance cannot be overstated. Better balance provides for: lower bearing wear, lower bearing temperature rise (which in turn extends grease life), increased mechanical life of all parts, and smoother and quieter operation. Secondary benefits of better balance are: lower transmitted losses to driven equipment, better electrical balance, higher efficiency, higher and smoother torque output, higher power factor (from a more uniform air gap), longer regreasing intervals, longer bearing life, and higher overspeed capabilities.

9.0 NOISE

NEMA recommends that audible noise by a motor be measured in accordance with IEEE Standard 85, "Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery". Motor sound tests are measured at no load. Higher speed motors (especially 2 pole machines) are generally noisier due to the higher windage (i.e.: fan) noise. While the "85" of IEEE 85 is intended to denote a recommended upper limit of motor noise, NEMA does not specify limits for motor noise. Practical limits for noise levels are influenced by such factors as motor location, proximity to residential areas, background noise levels, etc..

10.0 SERVICE FACTOR

The service factor is a measure of the overload capability of a motor. Essentially, it is a factor by which the motor nameplate horsepower may be multiplied, to obtain the rating at which the motor can be operated continuously, when supplied by rated voltage and frequency. A service factor of 1.15 is common for most NEMA frame ratings these days. That is, a 1.15 S.F., 100 hp motor could deliver 115 hp continuously, without exceeding its design temperature rise, with rated voltage and frequency applied. It is important to note that, per NEMA, "When operated at the service factor, the efficiency, power factor, and speed may be different from those at rated load, but the locked-rotor torque and current and breakdown torque will remain unchanged."

It is important to understand that when an older motor is rewound with a higher insulation class to increase horsepower output (by permitting more current and higher temperature rise), the performance characteristics such as full load current, efficiency, power factor, etc. may be affected. Bearing temperature rise should also be considered. A service factor is particularly useful in ASD applications, where the harmonics in the ASD output wave form cause extra rotor heating, and would otherwise result in the motor being derated to something less than nameplate hp.

11.0 WINDING INSULATION RATING AND MOTOR TEMPERATURE RISE

Winding insulation temperature rating, and motor operating temperature, should be considered together when specifying motors. Ideally, a motor should have a relatively high insulation temperature rating, and a relatively low operating temperature. This provides for thermal margin in the event of motor overload, or severe starting duty or running conditions. (A well-accepted rule of thumb is that for every 10 deg. C. that the motor temperature exceeds its rated insulation temperature, the insulation life is reduced by half.)

NEMA specifies letter designations for motor insulation temperature ratings. These insulation temperature ratings are denoted as: Classes A, B, F, and H, and are rated at 105, 130, 155, and 180 deg. C., respectively. Further, NEMA specifies allowable temperature rises for motors at full load (and at service factor, if applicable). These allowable temperature rises are based upon a reference ambient temperature of 40 deg. C., and are determined by the "resistance method", in which the resistance of the windings is measured with a bridge after the motor has achieved thermal equilibrium under load. The resistance of the winding is a function of temperature of the winding. NEMA allowable temperature rises (at full load) for a 1.0 S.F. motor are 60, 80, 105, and 125 deg. C, for Classes A, B, F, and H insulation, respectively. NEMA allowable temperature rises (at service factor) for a 1.15 S.F. motor are 70, 90, and 115 deg. C, for Classes A, B, and F insulation, respectively.

Adding the NEMA allowable temperature rise of 105 deg. C (for a Class F insulated, 1.0 S.F. motor), to the reference ambient temperature of 40 deg. C, results in a total operating temperature for the motor of (105+40)=145 deg. C. The 10 deg. C. temperature differential between the Class F insulation maximum temperature rating (155 deg. C) and the allowable maximum temperature (145 deg. C.) provides an allowance for the "hotspot" temperature of the interior of the winding, which cannot be measured directly, - the overall winding resistance is the sum of the resistance of the cooler end turns, and the warmer (hot spot) windings embedded in the stator slots.

Although NEMA does not specify temperature rises by letter designation, it has become common practice in industry to refer to the allowable temperature rise for a given class of insulation, as a temperature rise letter classification. For example, an 80 deg. C rise is often referred to as a 'Class B' temperature rise, since 80 deg. C is the maximum allowable temperature rise for a 1.0 S.F. motor insulated with Class B insulation. Thus, a motor with Class F insulation and an 80 deg. C rise is commonly referred to as an 'F/B' motor.

Many improvements have been made in motor insulation in the past couple of decades, such that a Class F (or better) insulation system is common for motor winding insulation. With conservative motor design, a 'Class B' temperature rise is quite achievable. For a 1.15 S.F. motor wound with Class F insulation, a Class B temperature rise at full load translates to a thermal margin of 155-(40+90)=25 deg. C. that, in turn, translates to an expected insulation life of approximately 5 to 6 times that which would be expected with a motor operating at its rated insulation temperature (i.e.: the 10 deg. C - one half insulation life rule applied to a temperature rise that is lower than the rated insulation temperature). It follows, then, that a 1.15 S.F. motor with a Class B rise at the service factor has more thermal margin than a 1.15 S.F. motor with an equivalent temperature rise at full load. The former rating provides additional safety factor for higher ambient temperatures, unbalanced voltage supply, ASD duty, etc..

12.0 STATOR CORE AND STATOR WINDING CONSTRUCTION

In the assembly of a motor stator core, individual stator laminations are stacked up, and then banded or welded together while being compressed under several tons of pressure. This yields a tightly packed lamination stack, which results in reduced magnetic losses by virtually eliminating any air gaps between the laminations. The laminations are of high grade electrical steel to reduce magnetic losses (i.e.: hysteresis), and are insulated from one another to reduce eddy current losses.

The stator core is then wound with insulated (preferably Class H, 200 deg. C) magnet wire (preferably copper). Individual phases should be separated and insulated from each other with phase paper (preferably Class H), and the end turns should be laced or stitched to ensure a tight assembly. Any wedges used to secure the windings in the slots should similarly be of Class H material.

The wound core is then passed through a number of "dip and bake" cycles, wherein it is preheated in an oven, and then repeatedly dipped in a high dielectric varnish, and baked in an oven for curing. This process effectively bonds the individual windings and the stator together into a rigid mass, which is then very resistant to movement due to the strong magnetic forces acting within the motor. Because movement is resisted, the insulation on the motor windings tends to remain intact, without cracking, resulting in extended insulation life. The more dip and bake cycles, the more solid will be the assembly. This is particularly important on high inrush or frequent starting duty applications. The dip and bake process also increases the heat transfer rate from the windings to the stator iron, due to the tighter bond between these constituent components, thus increasing the thermal capability of the machine.

The stator winding of a LVM is typically "random", or "mush wound", wherein a fixed number of turns of a specific wire diameter are wound into a coil of a specific diameter, which is then inserted into the stator winding slots. This type of winding is referred to as random, since there is no particular orientation of the turns relative to one another - that is, the first turn could be next to the second turn, the third turn, or any other turn.

Alternately, the coil may be "form wound", a design in which prefabricated wire bar is formed into a coil in which each successive turn is located next to the previous turn. This winding type is usually reserved for medium and high voltage motors, to control the turn to turn voltage. This reduces the likelihood of insulation failure due to voltage stress. This winding type is sometimes used in LVM applications to lessen the impact of the high voltage transients that can occur when the motor is controlled by an adjustable speed drive. Whereas a random (mush) winding is typically dipped and baked, a form wound winding is usually vacuum pressure impregnated (VPI). In this process, the wound stator is placed in a VPI tank, from which much of the air is then evacuated, to achieve a high degree of vacuum (to remove the air from the winding voids). A resin (usually epoxy) is then introduced into the tank, under high pressure. The high pressure forces the epoxy into the voids in the winding, thus reducing the possibility of air pockets in the winding, and likelihood of failure due to voltage breakdown.

A "trickle epoxy" process has recently been introduced, in which liquid epoxy is poured over the end turns, and which subsequently bonds the windings tightly together. This one part epoxy system (no hardener) has good environmental and temperature characteristics.

The magnet wire used in forming the random wound coils is usually insulated with a Class H (200 deg. C) varnish. Typically, a double application, or "double-build" varnish is standard. (The more applications of varnish, the greater is the thickness of the varnish, and the greater is the voltage withstand capability of the insulation.) For adjustable speed drive (ASD) applications, a third layer of varnish (or "triple-build" magnet wire) may be specified. This is intended to reduce the likelihood of turn to turn, or turn to ground failure due to voltage stress. Phase paper (which is not used by all motor manufacturers) further reduces the likelihood of phase-to-phase failure due to voltage stress, particularly on ASD applications.

13.0 ROTOR CONSTRUCTION

For many years, rotors for LVM were fabricated bar designs of copper or aluminum, and their alloys. Modern LVM rotors are of die-cast aluminum design. In this process, rotor laminations are punched out of sheets of rolled steel via stamping machines - rotor bar slots are punched into the circumference of the laminations. A number of laminations are then stacked together and placed in a casting machine. The lamination stack is then compressed under several tons of pressure, and liquid aluminum is forced up through the slots to form the rotor bars. The end rings are also formed at the same time, resulting in an integral casting of laminations, rotor bars, and end rings. Depending upon the design, cooling fins may also be cast on the end rings. This entire casting process takes only seconds to complete. After casting, the rotor is fitted with a shaft, machined to smooth the rotor circumference, and then balanced. Concerns may be raised regarding the possibility of voids in the castings, which would result in electrical and mechanical unbalances. Quality motor manufacturers will establish a maximum residual unbalance for cast rotors, so that those with too large an unbalance will be rejected at the time of balancing (a large residual unbalance is indicative of a void in the casting). While a rotor with voids could be balanced mechanically, it would still be electrically unbalanced, as voids represent high electrical impedances that would result in electrical hotspots within the rotor. The presence of a small amount of balance weights on the motor does not mean that a bad rotor (i.e.: one that has voids within the rotor) has been mechanically balanced. Rather, reputable motor manufacturers often balance acceptable rotors to better than NEMA standards.

14.0 SAFE STALL TIME

The safe stall time of a motor is a measure of its thermal capability, and is the period of time for which the motor can safely be held in a stalled, or locked rotor condition, without incurring thermal damage. Stall times may be given for a motor in a hot or cold condition.

Typically, smaller motors are stator limited, while larger motors are rotor limited. Therefore, care needs to taken when applying motor protection relays (MPR's) on larger motors, since monitoring the stator current and temperature alone may not adequately protect the rotor. Consequently, more "intelligent" MPR's have been developed which employ sophisticated microprocessor-based algorithms to emulate rotor heating based upon stator current values.

15.0 NUMBER OF STARTS

Specifications often dictate that a motor be capable of 'x' number of starts per hour, "per NEMA standards". NEMA MG-1 requires that a motor be capable of "two starts in succession (coasting to rest between starts) with the motor initially at the ambient temperature, or one start with the motor initially at a temperature not exceeding its rated load operating temperature" - effectively, 2 Cold/1 Hot starts. A "cold" start is a start of the motor from ambient temperature while a "hot" start is a start of the motor at some higher temperature, not exceeding its rated operating temperature. The actual number of starts possible from a motor, without incurring thermal damage, is a function of the acceleration time, relative to the safe stall time. (For example, a motor and its driven load have an acceleration time of, say, 5 seconds, while the motor has a safe stall time of 20 seconds. In this case, 4 starts would be permissible.) The acceleration time is a function of motor torque, the load torque, the load inertia, and the power supply characteristics). NEMA MG10 provides further guidance for motors subjected to repetitive start-run-stop-rest cycles, and indicates maximum number of starts per hour based upon variable torque loads, and NEMA rated WK^2 values.

16.0 POWER FACTOR

The power factor of a motor is typically given at 100%, 75%, and 50% full load, and is a measure of the amount of magnetizing current required by the motor. The power factor is the ratio the motor kW/kVA.

The current to a motor is comprised of two components: the real, or working current, which is in-phase with the voltage and is a measure of the power input to the machine (i.e.: kW or HP); and the magnetizing current, which lags the voltage by 90 degrees, and is responsible for setting up the magnetic field in the motor stator, air gap, and rotor. The vector sum of these two components is the total current drawn by the motor. The power factor is also the cosine of the angle between the voltage and the resultant current.

A higher power factor (i.e.: closer to unity) therefore means that less magnetizing current is required to be supplied by the power system, with subsequent lower demand charge or power factor penalty being imposed by the utility. A higher power factor is therefore desirable.

The power factor of a motor is primarily influenced by the rotor/stator air gap, and the reluctance (grade of steel) of the stator core and rotor core material, with the air gap being the dominant factor. Motor manufacturers will often sacrifice power factor in favour of higher efficiency, since power factor is relatively inexpensive to correct later, which low efficiency can never be corrected after manufacturing.

17.0 TORQUE

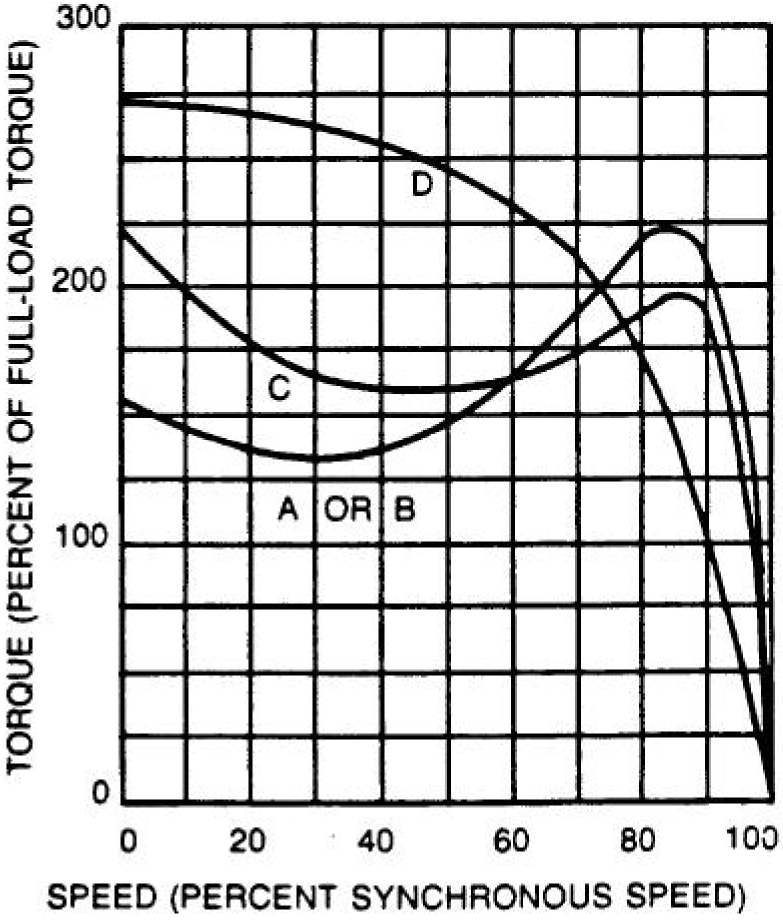
Torque refers to the turning effort exerted by the motor shaft. NEMA defines various torque characteristics for motors, which are designated as Designs A,B,C, and D. with Design B being by far the most common design used in industry. For each design classification, NEMA specifies performance parameters such as locked rotor torque, pull-up torque, breakdown torque (except for Design D), inrush current, and slip. The NEMA required minimum values are dependent upon the motor size and speed. Three values of torque are generally of particular interest, and are as follows:

(i) Locked Rotor Torque (LRT) - the torque developed by the motor at standstill, also know as starting torque.

(ii) Pull-up Torque (PUT) - the minimum torque developed by the motor as it accelerates from zero speed to the speed at which breakdown torque occurs.

(iii) Breakdown Torque (BDT) - the maximum torque that the motor is capable of developing.

The following chart indicates typical torque vs speed curves for typical NEMA Design A, B, C, & D motors.



GENERAL SHAPE OF SPEED-TORQUE
CURVES FOR MOTOR WITH
NEMA DESIGN A, B, C, AND D

Motor torque at any given speed is proportional to the square of the applied voltage. Thus, a 10% voltage dip during starting would result in $(0.9)^2$=0.81% available torque. "Accelerating torque" is the difference between the motor torque and the load torque. Load torque is the torque required to drive the load, and includes the friction, windage, etc. of the load. In order to determine the acceleration time of a motor driving a particular load, the torque vs. speed curves of both the motor and load must be provided, in addition to the load inertia and the power system information.

The torque-speed curve for a given load is a function of the specific nature of the load. For instance, centrifugal loads such as centrifugal pumps and fans follow a square law relationship of torque vs. speed. That is, at zero speed, virtually zero torque is required, but the torque requirement increases as the square of the speed (to 100% torque at rated speed) as the load accelerates. Loads of this nature are generally referred to as "Variable Torque" (V.T.). Loads such as conveyors, screw pumps, etc. are generally referred to as "Constant Torque" (C.T.) loads, as they can require 100% torque (current) at any or all speeds. V.T. loads are therefore less demanding on motor starting performance, from the standpoints of torque and motor heating at less than full load speed.

LRT and BDT are interdependent - each can be increased, but at the expense of the other. It is relatively easy to design a motor for a particularly high LRT, or a high BDT, but this would be at the sacrifice of the other. A thorough design should attempt to optimize both the LRT and BDT, and both should be considered when comparing torque.

18.0 LOCKED ROTOR CURRENT

NEMA designates (by the Design type) the maximum allowable locked rotor current (LRC), or starting current. The LRC influences the size of starter and overload protection required, as well as the system voltage drop on starting. Ideally, low inrush current and high torque are desired in many industrial applications.

While Design A and Design B motors have very similar torque characteristics, Design A motors have substantially higher inrush currents than do Design B motors (typically, 800% for Design A, vs 650% for Design B). This high inrush current can result in nuisance tripping of motor circuit protector breakers on starting, even when the trip levels of the breakers are set to the maximum (1300%) value permitted by the Canadian Electrical Code. Premium efficiency motors may also have higher than normal inrush currents, due to reduced motor resistance (for reduction of I^2R losses). It is not uncommon for inrush currents on premium efficiency motors to be as high as 1700 to 1800%. Changes to the NEC and CEC present limitations of 1300% x FLC settings for motor circuit protector breakers are now being considered, to eliminate nuisance tripping on starting.

19.0 LOAD INERTIA

NEMA specifies the minimum load inertia (WK^2, expressed in lb-ft^2) which a motor of a specific rating must be capable of accelerating. These values are based upon a variable torque load characteristic. The load inertia is in addition to the motor rotor/shaft inertia. It is important to consider the load inertia when calculating motor sizing (in addition to the torque, brake horsepower, and power system characteristics, etc.), especially on those types of loads that tend to have high inertias (i.e.: fans, centrifuges, flywheels, etc.).

20.0 VOLTAGE UNBALANCE

A small percentage of voltage unbalance (unequal line voltages) results in a much larger percentage of current unbalance (approximately 6-10 times the voltage unbalance), which results in higher operating temperature of the motor. As a result, NEMA recommends that the motor horsepower be derated, depending upon the percentage of voltage unbalance, to reduce the possibility of damage to the motor. NEMA does not recommend the operation of a motor when the amount of voltage unbalance exceeds 5%.

Voltage unbalance (in percent) is defined as:

$$\%V_{\text{UNBALANCE}} = 100\% \times \frac{\text{Maximum Voltage deviation from } V_{\text{AVERAGE}}}{V_{\text{AVERAGE}}}$$

Voltage unbalance also causes reduced torque ,and reduced full load speed.

21.0 EFFICIENCY

Recently introduced utility high efficiency motor rebate programs have sometimes resulted in efficiency values being considered the single-most important criterion for motor selection. While efficiency is most certainly important, overall motor performance cannot be forsaken in favour of compelling efficiency numbers. For example, careful attention should be paid to such factors as temperature rise, torque, etc.. It is very easy to increase the efficiency of a motor simply by trimming the cooling fan slightly, thus resulting in reduced windage losses. The motor will then run more efficiently for the entire duration of its significantly shortened life, due to the lack of cooling air and resultant higher temperature rise on the motor rotor and windings and bearings. Tradeoffs are also made in motor design with respect to torque, for example.

Generally, the more skew and slip a rotor has, the greater its torque will be, and the higher its losses. However, there is little energy savings to be had if a larger hp motor must be selected due to a lack of starting torque! Larger bearings provide for higher load rating capabilities, and better maintain rotor balance, but also have higher losses due to their larger running surface area. Larger bearings are often selected, though, because these advantages are perceived to outweigh the slight extra losses. It is common for manufacturers of high efficiency motors to reduce the size of the air gap between the rotor and stator, in an effort to reduce the reluctance in the magnetic path, and subsequent magnetizing losses. However, the closer proximity of the rotor and stator also increases the amount of harmonics induced into the rotor, resulting in higher rotor losses. When a motor is to be supplied to a non-sinusoidal power source (i.e.: an adjustable speed drive), this closer proximity of the rotor and stator can result in significantly higher overall losses, as the increased harmonic heating of the rotor far outweighs the reduced magnetizing losses. It may therefore make more sense to increase the air gap in light of this fact. A thorough review of all motor performance characteristics, including efficiency, will result in a motor selection that is an optimization of all performance features.

A number of terms are used to describe motor efficiency. These include "nominal", "minimum guaranteed", and "quoted" efficiencies. "Nominal" efficiency is the average efficiency of a large number of motors of a given rating, within the limits of the NEMA allowable 20% loss tolerance. "Minimum guaranteed" efficiency is, as the description implies, the minimum efficiency value that any motor of a given rating would ever produce under test. "Quoted" efficiency is the average efficiency value of a large number of motors of a given rating, when tested to the tolerances of the CSA-C390 efficiency test method.

As alluded to above, there is more than one method used in the determination of motor efficiency. The primary difference in these methods are the manner is which stray load losses are treated, and the reference temperatures used during testing. Stray load losses are those losses that are not accounted for by the sum of stator and rotor I^2R losses, windage and friction, and core losses. NEMA recommends that efficiency measurements be determined in accordance with IEEE - 112, Method B (dynamometer method). CSA has a similar test standard, CSA-C390-M1985, which accounts for stray load losses and measures them indirectly based upon the IEEE method. Utilities generally accept efficiency data based upon either method.

Utility rebate programs are generally based upon nominal efficiencies at 75% or 100%, or either. The 20% allowable loss tolerance reflects the fact that the tolerances in manufacturing and raw materials result not in one single efficiency, but rather a band of efficiencies, for a motor of a given rating. That is, a representative sample of motors is tested, and within the limits of a 20% loss tolerance, a nominal (average) efficiency is calculated. A motor having a nominal efficiency of 90%, therefore has losses of 10%, plus or minus 20% (the permissible loss tolerance). [+/- 20% x 10% = +/- 0.2 x 0.1 = +/- 0.02 = +/- 2%.] This means that the actual efficiency of this motor may range anywhere from

90% +/- 2% (i.e.: 88% to 92%). With tighter machining and manufacturing tolerances, it is possible to obtain tighter loss tolerances, which would then result in a motor nameplate efficiency that is closer to the actual motor efficiency. It is anticipated that NEMA will soon adopt a change to reduce the loss tolerance to 10%, in an attempt to give more realistic indication of actual motor efficiency. Some manufacturers already build their motors to the 10% loss tolerance limits, and are able to achieve this due to very accurate machining tolerances made possible by tight quality control manufacturing procedures.

22.0 APPLICATION CONSIDERATIONS FOR LOW VOLTAGE MOTORS ON ADJUSTABLE SPEED DRIVES (ASD's)

When the speed of a LVM is to be controlled by an adjustable speed drive (ASD), there are a number of factors that must be considered. These factors include such things as: voltage, horsepower, line and load side harmonics, load torque and inertia, speed range, speed regulation and accuracy, acceleration/deceleration times, overspeed capability, braking requirements, harmonic considerations, power loss ride-through time, audible noise, length of cable from ASD to LVM), enclosure requirements, area classification, power factor correction, altitude, efficiency, motor insulation life, and many other factors.

NEMA establishes certain parameters (including maximum safe operating speed range) which are applicable to Design A and Design B motors, rated </= 600 Volts, and </= 500 HP.

The torque available from an induction motor that is controlled by an ASD is proportional to the ratio of Volts/Hz. That is, torque is proportional to the magnetic flux in the air gap, which is a function of the ratio of the applied voltage to frequency. At reduced speed (and, therefore, reduced frequency), the effective impedance of the motor is lower, since it is a function of frequency (i.e.: $Z=R+X_L$ where $X_L=2x3.14xf$). Therefore, as the frequency of the voltage applied to the motor is decreased, so too must the voltage be decreased, in order to prevent the current from rising excessively, and saturating the motor iron.

At less than base (nameplate) speed, the ASD/LVM system operates in a constant torque mode. Motor cooling is a function of motor speed, since the motor cooling fan speed is directly proportional to shaft speed. Therefore, at reduced speed motor cooling need be considered. A lack of cooling air from the motor's own fan can be compensated for by providing external cooling, independent of rotor speed, or by upsizing the motor.

Above base speed, the ASD/LVM system operates in a constant HP mode. The motor manufacturer must be consulted if the motor speed is to exceed the safe operating speeds established by NEMA. Torque at overspeed is reduced, and generally falls off at the square of the V/Hz ratio.

Motor efficiency is reduced when controlled by an ASD, due to the harmonic content of the output wave form of the ASD, which results in harmonic heating of the motor stator and rotor. However, depending upon the degree of system voltage unbalance, the introduction of the ASD into the power circuit could result in a higher system efficiency, since the ASD outputs three perfectly balanced voltages to the motor.

A very important consideration in the application of ASD's on LVM is that of voltage stress on motor winding insulation. ASD's manufacture the AC output wave form from a DC source (which has usually been derived from the incoming AC power source). The inversion from DC to AC is generally accomplished by semiconductor switching devices, some of which may have very fast rise times (i.e.: high dV/dt). This high dV/dt stresses motor insulation, and is increased by large amounts of capacitance, such as from long cable lengths between the motor and the drive. It is important that the ASD manufacturer be aware of the consequences of voltage stress on motor insulation life, so that semiconductor rise times, carrier frequencies, cable lengths, filtering, etc. may all be considered in the design of ASD's and motors.

"Inverter duty motors" are motors that are specially designed to withstand the voltage stress of ASD output waveforms. Special measures include: changing motor windings from concentric to lap wind (to improve phase separation), increasing phase insulation thickness for higher dielectric strength, use of "triple-build" magnet wire to improve dielectric withstand capability, multiple dipping and baking (or VPI treatment), and sleeving of the first few turns of the windings to reduce the effects of dV/dt.

Motor audible noise is generally greater when controlled by an ASD. The noise is due to the motor laminations responding to the harmonic frequencies present in the ASD output waveform (much like the hum of a transformer vibrating sympathetically to the 60 Hz input power frequency). This can be a concern when there is a possibility of resonance such as in ventilation ducts.

The use of ASD's on motors for use in classified areas requires special consideration. For instance, the presence of CSA label on an ASD and explosion proof motor does not necessarily mean that the combination of the ASD and the motor together is suitable for use in a hazardous Location (i.e.: a Class I, Division 1 area, for example). The suitability of an explosion proof motor for a given area is, in part, a function of the skin temperature of the motor, which is determined by the application of a sinusoidal voltage. The output of an ASD contains some measure of harmonic content which results in increased motor heating, and higher skin temperature. This higher skin temperature may exceed the maximum temperature for the Group for which the motor is rated on a sinusoidal waveform. Some independent testing and certification agencies, such as Underwriters Laboratories (UL), have certified certain ASD/LVM combinations for use in hazardous locations.