NEMA Application Guide for AC Adjustable Speed Drive Systems

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Paper No. PCIC-2001-7

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Abstract - The application of AC adjustable speed drive systems has presented many unique challenges not only to electrical equipment manufacturers, but also to electrical equipment end users as well. In an effort to aid the user in proper selection and application of AC adjustable speed drive systems, the National Electrical Manufacturers Association (NEMA), through combined efforts of its Motor and Generator Section and its Industrial Control Products and Systems Section, has recently published an Application Guide for AC Adjustable Speed Drive Systems. This paper summarizes key topics addressed by the guide that will enable the user to avoid common application pitfalls and assist the user in clearly communicating critical application information and requirements to the electrical equipment manufacturer.

I. INTRODUCTION

A three-phase AC induction motor has for over 100 years proven to be an extremely reliable electromechanical conversion device. For the vast majority of that time period it has evolved as a constant speed device that operates from a constant frequency, constant voltage sinusoidal utility power source. Its characteristics have been well defined and standardized by the National Electrical Manufacturers Association (NEMA).

In industrial processes there has always been a need for speed variation to meet the needs of flow or torque control. However, flow control has historically been handled mechanically by throttles, valves, and dampers. In some instances, variable speed was handled electrically with DC equipment, multi-speed induction motors, or with single speed motors used in conjunction with slip producing devices. In others it was accomplished with mechanical drivers such as turbines or gas engines. Except for the use of DC equipment, all of these other methodologies incurred a severe penalty in system efficiency.

Advances in power electronics over the last couple of decades have enabled a change in the approach to process control. Speed and/or torque control are now commonly accomplished by supplying variable voltage and frequency via an adjustable frequency control (AFC) to an induction motor. This change in approach has enabled the elimination of gears, clutches, valves, throttles, dampers, and other equipment from industrial systems.

These changes have largely been implemented very successfully and have had a very positive impact on costs and efficiencies in the process industries. On the other hand, the electromechanical industry has endured many growing pains throughout the maturation and application of new and constantly improving AFC technologies. A plethora of excellent papers and publications over the last several years have very well documented many of the now well known challenges and pitfalls that may be encountered.

Proliferation of this technology is only expected to accelerate. It is expected to find its way into many yet to be considered applications in the future. Because of this, NEMA formed a committee of industry experts from both its Motor and Generator section and its Industrial Control Products and Systems Section. The committee has undertaken the task of assembling into a single document information and industry accepted approaches necessary for problem free implementation of an adjustable speed drive (ASD) system.

The guide covers AC electrical drive systems, rated 600 volts of less, consisting of three-phase induction motors, voltage source pulse width modulated adjustable frequency controls, and associated components. The guide addresses common issues that should be considered in the selection of drive system components and the installation and application of the drive system. Its text exceeds 75 pages, so it is therefore an impossible task to reasonably summarize its sections here in this short paper. Instead, the authors have attempted to select common issues that may be helpful to the application engineer in communicating with his system components suppliers. All tables and figures were taken from the NEMA documents listed in the references.

II. MOTOR SELECTION

The proper selection and installation of the drive motor is absolutely essential to the successful operation of any variable frequency drive system. For this reason, various motor parameters, such as horsepower and torque requirements, the speed range of the motor, the acceleration and deceleration requirements, and duty cycle should be acquired and specified during the initial planning phases of the ASD application.

A. *Motor Enclosures*

One of the fundamental specifications of an AC induction motor includes the type of enclosure. The environment in which the motor may operate and the risk of the motor's internal components being exposed to airborne particles often dictates the type of enclosure required. Examples of enclosures for non-hazardous locations include open drip proof, totally enclosed fan cooled, totally enclosed non-ventilated, totally enclosed blower ventilated, and open blower-ventilated. Each of these enclosures provides varying degrees of protection and should be carefully evaluated based on the motor's operating environment. Motors used in Division I (hazardous) locations should be certified for these environments and clearly identified as such on the motor nameplate. Before using a motor in a Division II location, the motor manufacturer should be notified.

B. *Interaction between Motor & Load*

A second important consideration in the proper selection of a drive motor is the characteristic of the driven load. The loads of many applications can be defined by one of three primary types: variable torque, constant torque, and constant horsepower. The first load type, variable torque, is typical for processes such as centrifugal pumps, centrifugal fans, centrifugal blowers, and centrifugal compressors. The torque load in these applications usually varies linearly with speed or with the square of the speed as illustrated in Fig. 1 below.

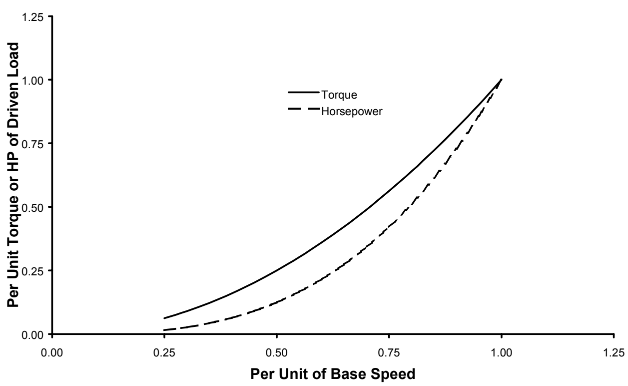

Fig. 1. Variable Torque Load Curve

The second typical motor load type is constant torque, in which the load torque remains constant over a given speed range (See Fig. 2). This loading is typically representative of applications with high impact loads or duty cycles. Examples include conveyors, augers, reciprocating compressors, crushers and positive placement pumps.

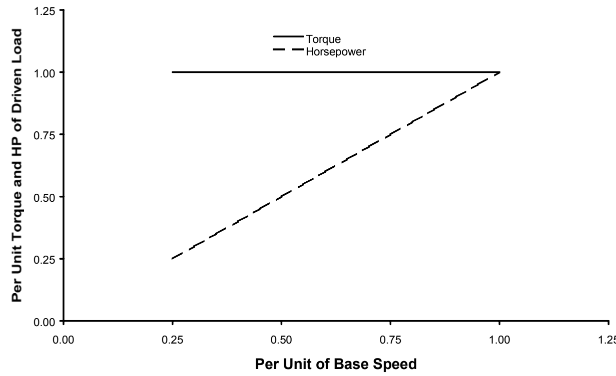

Fig. 2. Constant Torque Load Curve

The third load type, constant horsepower, is shown below in Fig. 3. Center driven winders and machine tools normally exhibit this type of load. These applications maintain a constant horsepower or a given speed, while the torques vary with the inverse of the speed.

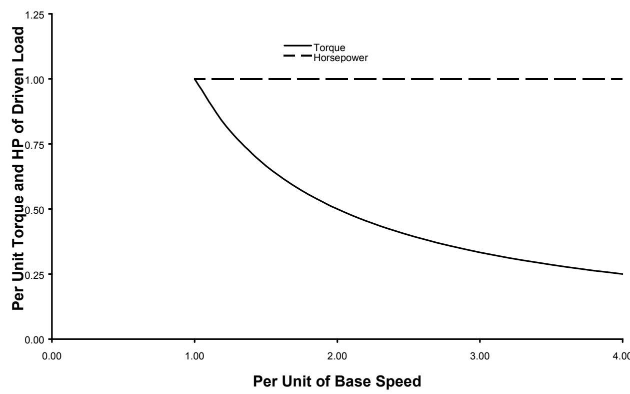

Fig. 3. Constant Horsepower Load Curve

In addition to the load variation of a machine with respect to speed, some applications experience transient loads, or changes in load over time. The first type of transient loading, duty cycle, refers to applications where a machine may experience periodic, discrete load changes over a certain interval of time. A duty cycle load may or may not be dependent on speed. (Fig. 4) A second type of transient load, impact loading, usually involves sharp, abrupt changes in load which are not dependent on speed. Impact loads may be non-cyclic in nature. When a motor operates under these variable loads, three important issues may need to be considered.

1) Will the motor be shut down during certain portions of the duty cycle? Motors with shaft-mounted fans have greater cooling potential at increased speeds. During periods of brief shutdown, the heat from the motor operation may take time to dissipate.

2) Does the duty cycle or impact loading require torques above the rated motor full load torque? Increased torques may heat the motor beyond its designed limits and may require a higher class of insulation. Momentary loads that require torque greater than 140 percent of the motor full load torque at base speed or below should be stated in the motor specification.

Additionally, for periodic torque loads greater than 110% of the rated torque at the maximum speed, consult the motor manufacturer. NOTE: Torque overloads may also be needed to accelerate a given inertia over a small period of time.

3) Will regenerative braking be required to stop or slow the motor during the duty cycle? Regenerative braking causes increased motor heating, which cannot be neglected when selecting the motor for the application.

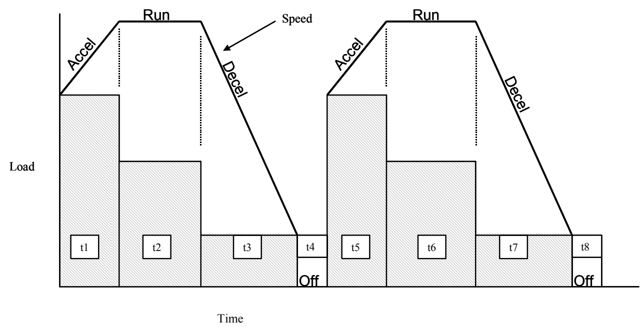

Fig. 4. Duty Cycle

The various torque capabilities of standard induction motors, denoted by Designs A, B, C, and D in NEMA MG1, were originally developed for motors driven by sinewave power but can be applied to motors operating on variable frequency drives. Fig. 5 below illustrates the torque speed relationship between the various motor designs.

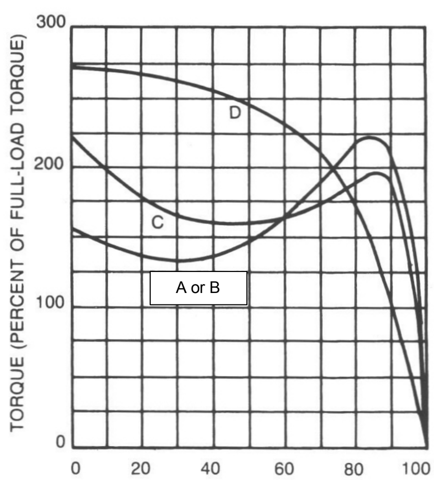

Fig. 5. NEMA MG1 Load Designs for Induction Motors Operating on Sine wave power

Design A motors generally have low slip and high efficiencies, but may not be the best choice for applications requiring bypass or across the line starting. Design B motors are generally characterized by their high efficiencies and low slip. These types of motors are typically used in variable torque, constant torque and constant horsepower applications. Design C motors were originally designed to accommodate the high starting torque requirements of across the line starting. These motors typically exhibit higher motor losses and lower efficiency than design B motors. Design D motors are generally used in applications that require high starting torque or high inertia loads. Additional characteristics include high slip and lower efficiencies.

C. Interaction between Motor & Control:

Safe operating speeds are usually pre-defined in the ratings of inverter fed motors. When operating a general-purpose motor on an adjustable frequency drive, however, several motor and control speed characteristics need to be considered.

1) *Continuous Maximum Motor Speed:* A motor's speed capability is most often limited by the mechanical stress limits of the rotating structure. For continuous operation, motors operating above 90 Hz with constant voltage above 60 Hz may not have the required torque to sustain a constant horsepower load. Maximum, safe operating speeds for Design A and B motors are given in NEMA MG 1, Part 30. The control's maximum speed should be set such that the motor is not unintentionally operated beyond the recommended speeds. If a continuous speed greater than the operating speed listed in NEMA MG 1 is required, the motor manufacturer should be consulted.

2) Maximum Motor Overspeed: Motors typically may be required to operate for a short period of time beyond the maximum speeds listed in NEMA MG 1. A motor with a maximum speed greater than its rated synchronous speed can typically be over-speed 10% beyond its maximum speed for a period of two minutes. Motors with maximum speeds equal to their synchronous speeds should follow the guidelines listed in table 1 for general-purpose motors and table 2 for inverter fed motors.

Hp	Synchronous Speed, RPM	Overspeed Percent of Synchronous Speed
200 & Smaller	1801 and over	25
	1201 to 1800	25
	1200 and below	50
250-500, incl.	1801 and over	20
	1800 and below	25

Table 1. Over-speed Capability of General-Purpose Motors

Maximum Operating Speed, RPM	Overspeed, Percent of Maximum Operating Speed
3601 and over	15
1801 to 3600	20
1800 and under	25

Table 2. Over-speed Capability of Definite Purpose Inverter-Fed Motors

3) *Operating Speed Range:* Motor and drive applications typically operate on a wide variety of speed ranges. Examples of typical speed ratios for constant and variable torque applications are listed below in table 3. Speed ratios for constant and variable torque motors are expressed in terms of motor base speed to motor minimum speed. Applications that require extremely slow (below 6 Hz) or extremely high speeds may require a custom motor design.

(Base Speed = 2500 RPM)		
Minimum Speed (RPM)	% Motor Base Speed	Speed Range Ratio
1250	50	2:1
625	25	4:1
250	10	10:1
125	5	20:1
25	1	100:1

Table 3. Constant and Variable Torque Speed Range Examples

Typical speed ranges for constant horsepower motors are listed in table 4 below. Speed ranges for these applications are expressed as motor maximum speed to motor base speed.

(Base Speed = 2500 RPM)		
Maximum Speed (RPM)	% Motor Base Speed	Speed Range Ratio
3750	150	1.5:1
5000	200	2:1
7500	300	3:1

Table 4. Constant Horsepower Speed Range Examples

4) Acceleration: Several items need to be considered when using an adjustable frequency drive to accelerate a load. The amount of torque and therefore current required to accelerate a given load increases as the acceleration time is reduced. The total amount of necessary accelerating torque is the sum of two components: the torque required by the load plus the torque required to overcome the inertia of the rotating assembly. This total torque requirement can be calculated by the following equation:

$$T_{required} = \frac{Wk^2 \times \Delta RPM}{308 \times t} + T_{load}$$

Where:

$T_{required}$ = Torque to accelerate load (lb-ft)

T_{load} = Load torque during acceleration. Use average torque for variable torque loads.

WK^2 = Inertia of the load reflected to the motor plus the inertia of the motor (lb-ft^2)

Δ RPM = Change in motor speed desired

t = Time (seconds) required to accelerate motor

Applications requiring greater acceleration times may require an oversize control to meet the increased current demands. If a motor is required to produce more than 140% of the motor full load torque during acceleration, the motor manufacturer should be consulted.

5) *Deceleration and Braking:* Deceleration is often used to save production time, prevent damage to the attached equipment, or meet specific duty cycle requirements. Because of the friction and windage of the rotor assembly, deceleration time is at least equal to or less than the acceleration time. For duty cycles that require significant deceleration over a short period of time, dynamic or regenerative braking may be required. Dynamic braking is typically used on applications with high inertia loads; however, dynamic braking cannot produce holding torque at zero speed. In this instance a mechanical brake is required. When using dynamic braking, the following equation can be used to estimate the rotating inertia of a medium ac induction motor:

$$Wk^2 = \left[0.02 \text{ x } 2^{\left[\frac{\text{Poles}}{2}\right]} \text{ x } HP^{\left[1.35 - 0.05 \text{ x } \frac{\text{Poles}}{2}\right]} \right]$$

Regenerative brakes return some of the energy generated from the braking process to the motor and control power source. However, like dynamic braking, regenerative braking also does not posses holding torque capability.

6) *Starting Requirements:* For applications with high starting torques, it is important that the motor has enough breakaway torque to start the load. Applications with static starting torques that are 140% above the motor full load torque may require an oversized control and a motor with a large torque capacity. Voltage boosts may also be used to obtain high starting torques and low frequency operation (below 20 Hz) without the associated effects of high starting current. When using voltage boosts, care should be taken to ensure that the motor does not operate at no-load conditions below 10 Hz for more than one minute.

7) Bypass (Across the Line Starting): Applications that require bypass or across the line starting may need special consideration. Firstly, the motor must be capable of both across the line starting and across the line operation. Some inverter fed motors are designed specifically for connection to a control and are incapable of across the line starting. Secondly, the motor wiring must be sized for both AFD and bypass starting. Thirdly, the control may be set to limit the maximum speed of the motor. On bypass power, the motor could exceed the maximum speed recommendations. Fourthly, in order to avoid damage to the motor during power transfer, a time delay of one and one half AC time constants should be observed before switching from control to line power, while a time delay of three AC time constants is necessary for the reverse procedure. Lastly, a special control may be needed if it is necessary to switch from line power to control power while the motor is rotating.

8) *Motor Terminal Voltage Transients:* High switching rates of the transistors in today's controls can cause voltage overshoots at the motor terminals of squirrel cage AC induction motors. These overshoots are illustrated in Fig. 6 below. Significant damage to the motor insulation can occur if these overshoots are greater than the maximum rated voltage of the motor. As defined by NEMA MG1, Part 30, general-purpose motors should be limited to voltage overshoots of less than 1000 volts. General-purpose motors that operate at less than 460 volts generally due not produce overshoots of this magnitude. Motors with voltages of 460 or greater may require filters or reactors to reduce the amount of overshoot to an acceptable level. According to NEMA MG1, Part 31, inverter fed motors are designed to withstand "3.1 times the motor's rms voltage with a rise of not less than 0.1 µs" without filters or reactors. There are five primary factors that cause increased voltage overshoots.

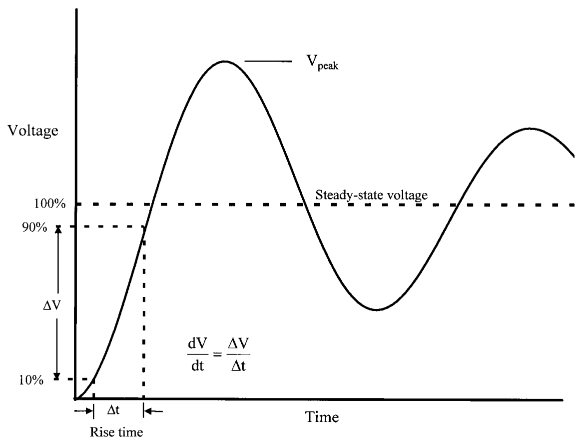

Fig. 6. Voltage Overshoots

These include:

a) Short rise times in the transition of high to low voltage at the motor terminals.
b) Long motor leads between the motor and control.
c) Small time periods between ASD voltage pulses.
d) Double transition conditions where the control switches two phases simultaneously.
e) Voltage reflections due to multiple motors connected to the same control.

In order to avoid voltage overshoots, the following precautions should be implemented as required.

a) Use an inverter fed motor with a voltage of 230 or less when possible.
b) Use the lowest carrier frequency that satisfies the motor requirements. A lower switching frequency results in less overshoots per second.
c) Avoid connecting multiple motors in parallel to the same control.
d) If the peak voltage is over the recommended limit, use a filter or reactor between the control and motor.

9) *Shaft Voltages and Bearing Currents:* In many motors operating on adjustable frequency drives, shaft currents have been found to discharge through the motor bearings, breaking down the bearing grease and causing a severe wear pattern in the bearing called "fluting." If allowed to continue, these shaft currents will lead to high motor vibration levels and eventual bearing failure. Fig. 7 illustrates the detrimental effects of a continuous flow of shaft currents through an anti-friction bearing. There are four primary causes of bearing currents, each of which may create voltages high enough to discharge through the bearings:

a) An unbalanced magnetic circuit can cause current to flow in a closed loop through the shaft, bearings, end brackets, and the motor frame.
b) Applications such as paper rollers may emit an electrostatic charge due to the friction between the motor shaft and the driven load.

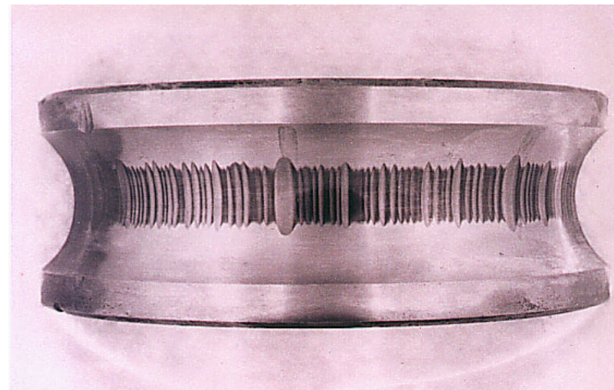
Fig. 7. Anti-Friction Bearing Inner Race With Severe Fluting

c) Common mode voltages or voltage fluctuations resulting from the switching frequency of the control may cause unwanted bearing currents.
d) Common mode voltages may also cause a capacitive coupling between the stator and rotor, creating a path to ground between the above mentioned capacitance, shaft, bearings, and grounded end bracket. See Fig. 8 below.

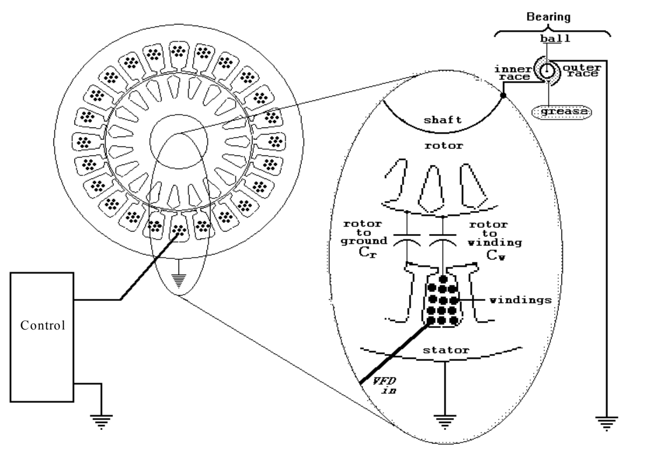

Fig. 8. Path of Common Mode Voltage the Stator Windings to Ground

Several safeguards against the detrimental effects of shaft currents include the following:

a) Use an inverter fed motor with a voltage of 230 or less when possible.
b) Use the lowest carrier frequency that satisfies the motor requirements.
c) Install a shaft grounding brush to the motor, which will offer an alternative, less restrictive current path around the ball bearings.
d) Insulate the bearings on both ends of the motor.
e) Use a non-conductive coupling.
f) Ground the motor and control as required by the manufacturer.
g) Reduce common mode voltage at the control by installing a drive filter.

10) Sound & Vibration Considerations: The motor and control system may posses several natural frequencies that may be excited by the control when operating within a particular frequency range. These natural frequencies may exist in the horizontal, vertical, axial, or torsional directions and are affected by factors such as the mass and stiffness of the motor base, the type of control, the natural frequencies on the motor structure, the electromagnetic design of the motor, coupling vibration, and air flow. Once these natural frequencies have been identified, the control should be programmed to avoid prolonged operation at these speeds.

11) *Thermal Considerations:* Unlike motors operating on an AC power supply, motor and drive systems have several sources of heat generation resulting from the interaction between the motor and control. In certain instances these thermal effects may be high enough to justify derating or over sizing of a motor or control.

a) Inverter losses are a combination of both the control switching frequency losses and the conduction losses due to the voltage gradient across the device. The switching losses increase with higher frequencies, forcing most of the higher horsepower controls to use lower switching frequencies.
b) Current distortion is another source of control related heat generation and is inversely proportional to switching frequency. The motor losses decrease with increasing switching frequency up to the point where switch dead band becomes significant.
c) For motors with shaft mounted fans (speed dependent), the amount of cooling decreases at slower speeds. For variable torque applications, where the load also decreases with speed, a speed dependent motor may be adequate. Applications that require high torque at low frequencies may require a motor with an auxiliary blower (speed independent) to provide constant cooling at all speeds.
d) General-purpose motors have published maximum allowable temperature rises for operation on continuous sine wave power. When using these motors on an ASD, the motor may need to be derated to meet these requirements. Other factors affecting temperature rise, such as duty cycle, high ambient temperatures, and high altitude operation may also influence the decision to derate the motor.

III. CONTROL SELECTION

A. Control Types

Adjustable frequency controls are typically rated by the amount of output current that they can supply on a continuous basis for a defined maximum ambient temperature. Their nameplates may be marked with a horsepower, but this should be used for reference purposes only. For example, a control that is capable of supplying a 10 horsepower 2 pole motor may not be capable of supplying a 10 horsepower 24 pole motor because of its significantly lower power factor, the efficiency of the slower speed motor, and its correspondingly higher full load current requirement. Controls are generally identified as two basic types as distinguished by their short-time overload current capabilities.

1) Variable Torque: A variable torque control is typically capable of a 110 percent to 125 percent over current relative to its nameplate rating for 1 minute. This overload capability is normally sufficient for variable torque loads. It should be noted, however, that a variable torque control is not limited to variable torque applications.

2) Constant torque: A constant torque control is typically capable of a 150 percent over current relative to its nameplate rating for 1 minute.

B. *Control Techniques*

There are many types of controls and control techniques available in the marketplace today. However, the only control techniques that are applicable to three phase AC induction motors within the scope of the NEMA Application Guide are volts/Hertz control and vector control, which can be subdivided into two schemes: sensorless vector and feedback vector control.

1) *Volts per Hertz Control:* A volts per hertz control maintains a fixed volts to hertz ratio over its prescribed operating range. Motors with respective base ratings of 230 volts or 460 volts 60 Hz have volts per hertz ratios of 3.83 (230/60) and 7.67 (460/60). Once established by the control set up, the voltage supplied to the motor by the control at various operating frequencies is strictly governed by this ratio unless voltage boost or IR compensation is activated, or the frequency is increased beyond a value for which system voltage is sufficient to maintain it. Voltage boost is a fixed voltage that is added to the voltage prescribed by the volts per hertz ratio. Voltage boost has much more effect at lower frequencies where the prescribed voltage is low. Voltage boost has the disadvantage that it may cause saturation and overheating of a motor that is lightly loaded at low speeds. With IR compensation, the amount of boost applied is proportional to the amount of current drawn by the motor. Consequently, at light loads, a voltage that is high enough to saturate the motor will not be applied. The operating region where the frequency increases beyond the point at which the available system voltage can maintain the voltage prescribed by the volts per hertz ratio is known as the field-weakening region. It is referred to as the field-weakening region because the motor magnetic flux is decreased in proportion to the volts per hertz ratio. Load torque must be reduced in this area of operation because motor torque decreases with this decrease in motor flux.

2) *Vector Control:* A vector control decouples the magnetizing flux producing and torque producing currents supplied to a motor and controls them separately. An ASD that utilizes this control technique exhibits very good steady state and dynamic performance and very accurate speed and torque control, comparable performance to that obtainable from a DC motor. As mentioned earlier, vector control can be subdivided into two different schemes as identified below.

a) *Direct vector control:* A direct field orientated control scheme makes use of Hall effect transducers or air gap flux-sensing windings to measure the air gap flux with the intent of regulating it in order to produce controllable motor torque.

b) *Indirect vector control:* Indirect field orientated control interprets the motor flux from parameters such as speed or current. A closed loop vector control makes use of a speed feedback sensor and can provide precise speed control and maximum torque throughout a speed range that extends anywhere from zero speed to base speed. An open loop vector control monitors motor current instead of motor speed and cannot produce holding torque at zero speed. It also has a narrower operating speed range than a closed loop vector control.

To ensure successful operation of an adjustable speed drive system, when selecting the control, each performance consideration must be reviewed. There are specific considerations that point to a given technique. Common performance considerations are given below in table 5.

Performance Consideration	**Feedback Vector**	**Sensorless Vector**	**Volts/Hz**
Speed regulation < 1%	Best	Good	Poor
Low speed torque capability < 6 Hz	Best	Good	Poor
Multi-motor operation	Poor	Poor	Best
Torque regulation	Best	Good	Poor
Speed range >20:1	Best	Good	Poor
High breakaway torque >150%	Best	Good	Poor

Table 5

C. Control Enclosure and Environmental Considerations

The environmental conditions of the control installation are also an important consideration. Based upon these considerations, suitability of the designated NEMA enclosure must be evaluated. Conditions that should receive special attention are ambient temperature, altitude, humidity, outdoor mounting, and shock and vibration conditions.

1) *Ambient Temperature:* Adjustable frequency controls are typically suitable for operation in a temperature range of 0 °C to 40 °C. When ambient temperatures are expected to dip below 0 °C, the enclosure should be fitted with space heaters. Ambient temperatures that exceed 40 °C require derating of the control output per recommendations of the manufacturer.

2) *Altitude:* Beyond 3300 feet above sea level, thinner air negatively impacts the ability of the heat sink to adequately cool the electronic equipment. As a result, the adjustable frequency control must be derated according to the recommendations of the manufacturer.

3) *Humidity:* Adjustable frequency controls are typically rated for 95% humidity, non-condensing. Condensation may occur if the equipment becomes cooler than the surrounding air temperature because of varying ambient temperatures. Provided that the ambient temperature is above 0 °C, leaving the control energized continuously will provide enough heat to minimize condensation. When temperatures are likely to drop below 0 °C, the control enclosure should be fitted for space heaters.

4) *Outdoor Mounting:* An adjustable frequency control may be located outdoors when adequate protection against falling rain, ambient temperature, including the expected sun load, dust and dirt, and the watt-losses dissipated from the control are provided, preventing temperature rise conditions beyond the component specifications. This usually requires a NEMA 4 enclosure with an adequately sized air conditioner mounted on the enclosure to maintain the temperature rise within specifications.

5) *Vibration Conditions:* Most adjustable frequency controls have the ability to operate in an environment of continuous vibration of .3 mm peak from 2 to 9 Hz, or acceleration of 1 m/s^2 from 9 to 200 Hz. If an installation has vibration levels that exceed manufacturer specification, the control must either be located in a lower vibration area or it must be mounted on a vibration absorbing assembly.

The following is a summary of NEMA designated enclosures for electrical equipment. NEMA Standard 250 contains additional information on control enclosure classifications.

NEMA 1 - Designates enclosures that are designed for indoor use. These enclosures protect the components they contain from physical contact with operating and maintenance personnel.

NEMA 3R - Designates enclosures that are designed for outdoor use. These enclosures protect the components they contain from falling rain, sleet and external ice formation.

NEMA 12 - Designates enclosures that are designed for indoor use. These enclosures protect the components they contain from dust and dripping liquids. This includes protection against fibers, flyings, lint, dust, dirt, and non-corrosive dripping liquids.

NEMA 4 - Designates enclosures that are designed for indoor and outdoor use. These enclosures protect the components they contain against dust, dirt, splashing water, falling water, seepage, hose-directed water, and external condensation.

NEMA 4X - Designates enclosures that are designed for indoor and outdoor industrial use. NEMA 4X enclosures protect the components they contain from the same elements as systems designated NEMA 4, but they are also corrosion resistant.

D. *Control Input Voltage*

Typical Control voltage ratings are 200, 208, 230, 460, and 575 volt. Depending upon the magnitude of line voltage transients and the type of control design, surge protection may or may not be required for the control. If line voltage transients are known to be a problem in the installation, a line reactor or isolation transformer may be used for transient attenuation.

E. *Control HP/Current Rating Considerations*

Most controls are horsepower rated based upon full load amperes listed in the National Electric Code Table 430-152. These current ratings are typically for 2 and 4 pole motor designs. The control may need to be oversized to accommodate higher pole count motors. Consequently, when selecting an adjustable frequency control, the output current rating should be based upon the connected motor nameplate rated full load current and not on its horsepower rating. Additionally, the control may need to be oversized to accommodate application requirements such as high breakaway torque, overload, or accelerating torque. Another reason to upsize the control is multi-motor operation.

(Short time over current capability has been addressed in section A, control types.)

F. *Power Cable Selection*

A control nameplate may have two current ratings listed on its nameplate: an input and an output current rating. The input AC current rating may be higher than the output current rating because of current harmonic distortion. Care should be taken to size the input cables according to this current rating. The output cables must be sized according to the motor nameplate current rating. Other considerations include motor terminal voltage transients and common mode voltages and their associated common mode currents.

1) *Motor Terminal Voltage Transients:* The impact of motor terminal voltage transients due to reflections in the cables between the motor and control must be considered. A definite purpose inverter rated motor as defined by NEMA MG 1, Part 31 must be able to withstand terminal voltage transients of $V_{peak} = 3.1xV_{rated}$. That means that terminal voltages can range from 1488 – 1860 volts for motors rated 480 – 600 volts. Although the peak transient voltage duration is less than 1 μs, the transients occur at the control output device carrier frequency rate, which is typically 3 to 13 kHz for drives to 20 Hp and 1.5 to 3 kHz for larger drives. Thus, there is concern that satisfactory life may not be achievable for 600 Vrms cable.

The most likely cable insulation failure mechanism to occur would be degradation due to corona. Corona inception voltage (CIV) is the minimum applied voltage between cables that will result in partial discharges in the air spaces between cables. No degradation of service life can be expected if the CIV measured peak voltage is higher than the peak transient voltages that are expected in service. The NEMA Application Guide offers test results for XHHW XLPE and THHN PVC insulated wire. Excerpts from that table are offered here in table 6. The test results show that both insulation types should achieve rated life under dry conditions. Because XLPE had higher CIV than PVC for the same thickness of insulation, XLPE should have a longer life relative to reflected wave voltage spikes.

Further tests were performed on 30 mil XLPE and 15-mil PVC wire under wet conditions of 90 percent relative humidity for 48 hours. The tests showed that under these conditions the CIV of XLPE only decreased by 5 percent while the CIV for the PVC decreased by 50 percent. Looking at table 6, it is obvious that PVC wire with insulation thickness 20 mils or less is of concern when used in moisture-laden environments. It is clear from the data that 600 volt XLPE and 600 volt PVC of thickness 30 mils are adequate for applications whose terminal voltage conditions are within the guidelines prescribed by NEMA MG 1, part 31. PVC wire of 15 and 20 mils should be restricted to dry environments.

CIV TEST RESULTS AT 25 °C					
Drive HP	Possible AWG used	XLPE Type XHHW		PVC Type THHN	
		Insula-tion Thick-ness		Insula-tion Thick-ness	
		(mils)	(V_{PK})	(mils)	(V_{PK})
250 to	500 MCM to	65	6749	60	4793
500	250 MCM	65		60	
125	1 thru 2/0	55	6309	50	4450
	2	45	5819	40	4063
50	4	45		40	
	6	45		30	3613
	8	45		30	
30	10	30	4942	20	3062
7.5- 20	12 thru 14	30		15	
0.5- 5	12 thru 14	30		15	2723

Table 6

2) *Common Mode Considerations:* Common mode voltages are a natural result of either the PWM modulation scheme or various cable and grounding dissymmetries. Proper selection of cable helps to mitigate these voltages and their resultant currents. While many installations perform successfully with standard cable, to assure that this issue is minimized, continuous welded aluminum armor cable may be required.

G. *Interaction Between Control and Power Supply*

The performance or protection of an adjustable frequency control can be affected by the power distribution system. These issues and interactions are reviewed in the following sections.

1) *Source Impedance/Short-circuit Ampere Interrupting Capacity (AIC) Ratings:* In order to assure proper operation and protection of the equipment, the system impedance and AIC rating of the power source that an adjustable frequency control is connected to must be reviewed. The AIC rating is typically listed on the control nameplate. The control AIC rating should exceed the available short circuit current from the power source. When this is not the case, current-limiting fuses and line reactors should be used to provide protection. Additionally, source impedance should be reviewed in the event that bypass operation is desired. It must be low enough to assure that voltage does not sag excessively at the motor terminals during across the line starting.

2) *Line Voltage Variations:* Most adjustable frequency controls will operate satisfactorily with a +/- 15 percent variation in voltage. However, the other electromechanical devices associated with the ASD including the motor are limited to a +/- 10 percent voltage variation.

3) *Line Voltage Phase Unbalance:* Phase voltage unbalance results in a phase current unbalance. If this current unbalance results in phase current that exceeds the rectifier device rating, damage to the control may occur. Adjustable frequency controls will typically tolerate a maximum of 3 percent input voltage phase unbalance.

H. *Control Protection*

Due to its limited capacity, protection circuits must be utilized to prevent control failures under certain fault conditions.

1) *Short Circuit Protection:* It is the responsibility of the user to provide branch circuit protection according to the National Electrical Code. For additional information, see part 1 of section G.

2) *Transient Voltage Protection:* Transient voltages occurring on AC power systems likely originate from lightning, system switching transients, and capacitor switching. A control may be very sensitive to voltage transients compared to other equipment connected to the power system. Metal oxide varistors are commonly used for transient voltage protection. When a varistor is exposed to a voltage transient, its impedance changes from near infinity to nearly zero in order to clamp the transient voltage to a safe value. When the varistors act, a short circuit occurs which could result in a fuse operation and tripping of the control.

3) *Overvoltage Protection:* The major causes of control overvoltage tripping are power system transients, lightning, regenerative loads, and poor grounding techniques. When the control senses an overvoltage condition, an overvoltage protective fault will occur. The control overvoltage trip is not adjustable and is used to protect the control from component failure. Persistent tripping requires corrective action. Line reactors or isolation transformers may be used to protect against line voltage transients. Dynamic braking resistors may be useful for dissipating the regenerative energy from regenerative or overhauling loads.

4) *Undervoltage Protection:* An undervoltage condition may be the result of low line voltage of momentary power interruption. During undervoltage conditions, the voltage output of the control may be reduced, resulting in decreased motor output torque and system performance. A control may include a re-start or ride-through function to minimize the effects of a momentary power interruption. The ability of ride-through to maintain control of the connected motor through the event is dependent on the duration of the undervoltage, the amount of stored energy available from the control, and the demands of the connected motor load.

5) *Single Phase Input Protection:* Single-phase operation will result in a significant increase in input current in the unaffected phases, causing additional heating in the electronic rectifier devices and additional heating in the DC bus capacitors. Most controls are equipped with single-phase protection that either reduces the load on the equipment or shuts down the control.

6) *Ground Fault Protection:* A ground fault may be the result of a motor phase to ground fault, a motor cable phase shorted to ground, or parasitic capacitive coupling to ground. The control protects itself from component failure in the event of an output ground fault condition. The trip value is specified by the control manufacturer. Ground faults due to parasitic capacitive coupling to ground may be cancelled with the use of a line reactor or an LC filter between the control and motor.

IV. DRIVE SYSTEM SELECTION FOR VARIOUS LOAD APPLICATIONS

Process loads can generally be characterized by three basic categories: variable torque, constant torque, and constant horsepower. In general, most of the considerations covered up to this point apply to all three of these basic load types. However, there are a few application considerations that are unique to each and are identified in this section.

1) *Variable Torque Application:*

a) *Motor:* Because of very low torque requirements of variable torque loads at low speeds, low speed operation is not normally an important consideration in these applications. The load decrease more than offsets the affects of reduced cooling at low speeds. Because the load torque requirement increases with speed in these applications, the greatest load and therefore temperature occurs at the highest operating speed. As a result, the motor must be sized with regard to the load torque at top speed. Additionally, the motor must be oversized if it is intended to be run above the motor base speed, since torque capability declines in the field weakening part of the speed range.

   Although load inertia is quite high for some variable torque applications, rapid acceleration is not normally needed; therefore, these types of loads can normally be accelerated without exceeding the rated torque of the motor. However, bypass is most common in variable torque applications. If bypass is required for high inertia loads, it is important to make certain that the motor is capable of accelerating the load without damage.

b) *Control:* Volts per hertz controls typically meet the requirements of variable torque loads. As mentioned earlier, variable torque controls typically can supply 110 to 125 percent rated current for 1 minute for overload and acceleration. If faster acceleration is required, a constant torque control should be utilized. The typical speed range for variable torque loads is 2:1; however, all adjustable frequency controls operate over a minimum speed range of 6:1.

2) *Constant Torque Application:*

a) *Motor:* Motor cooling and available motor torque at low speeds are special considerations for constant torque applications. In addition, high breakaway torque, stringent acceleration and deceleration requirements, overload, and duty cycles are all common requirements of constant torque loads. All of these requirements must be clearly and completely communicated to the motor manufacturer in order to insure proper motor sizing.

b) *Control:* Both of the control techniques identified earlier in this text may be used for constant torque applications, volts per hertz controls and vector controls. A volts per hertz control is typically used when the minimum frequency in which the system will operate is greater than the slip frequency (the difference between the synchronous speed and operating speed multiplied by the ration of operating frequency to synchronous speed). Further, the low speed overload requirements must be low (typically less than 120 percent of motor torque). A vector control may be needed for operation below slip frequency, operation at zero speed, precise torque control, or high peak torque at low speeds.

The basic horsepower/current rating of a control, as shown on the nameplate, is the continuously rated duty. For duty cycle loads, an equivalent rms current may be calculated for sizing the control, so long as the short term overload requirements do not exceed the 150 percent full load 1 minute rating of the control.

3) *Constant Horsepower Application:*

Motor: The amount of torque required at maximum operating speed in the constant horsepower speed range could affect the size of the motor. In the portion of the speed range where the voltage remains constant, the motor breakdown torque decreases at a rate proportional to the square of the change in frequency (speed). However, the load torque requirement decreases much more slowly at a rate inversely proportional to the change in frequency (speed). Therefore, within the mechanical limitations of the motor, the maximum possible speed at which the motor can carry a constant horsepower load is equal to the speed at which the motor breakdown torque equals the load torque. For reliable performance from the ASD, the motor and control manufacturer should be consulted regarding the margin between load torque and the motor breakdown torque necessary for stability considerations. If short time overload torque is required in addition to the rated load torque, it must also be taken into account.

a) *Control:* It is common for motors designed for constant horsepower applications to also be designed with a lower rated voltage at base speed. This lower voltage design results in higher full-load current. For this reason, the control should be sized to match the motor base speed current. In these cases, it is typical for controls to have horsepower ratings exceeding the motor's horsepower rating.

V. CONCLUSION

This paper touched upon a large number of issues addressed by the NEMA Application Guide for Adjustable Speed Drive Systems that must be considered for successful application of an adjustable speed drive system. Although the limited space here did not allow the authors to do justice to many topics, the material covered here should be helpful to an application engineer attempting to create an initial specification. It is clear that such a specification must consider the driven load, motor, control, and utility power supply. The authors believe that all users of ASD systems would be well served by having a complete copy of the application guide for ready reference when installing a new ASD installation.

VI. REFERENCES

[1] NEMA Publication, Application Guide for AC Adjustable Speed Drive Systems

[2] NEMA Standards Publication No. MG 1-1998 Motors and Generators

VII. VITA

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