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Application Guide for AC Adjustable Speed Drive Systems

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Foreword

This guide was developed by the Motor and Generator Section and the Industrial Automation Control Products and Systems Section and approved for publication as an application guide of the National Electrical Manufacturers Association. This guide is intended to assist users in the proper selection and application of AC adjustable speed drive systems. The guide is revised periodically to provide for changes in user needs, advances in technology, and changing economic trends. All persons having experience in the selection, use, or manufacture of electric motors and adjustable speed drives are encouraged to submit recommendations that will improve the usefulness of this guide. Inquiries, comments, and proposed or recommended revisions should be submitted to the Motor and Generator Section and the Industrial Automation Control Products and Systems Section by contacting:

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The best judgment of the Motor and Generator Section and the Industrial Automation Control Products and Systems Section on the performance and construction of adjustable speed drive systems is represented in this guide. The guide is based upon sound engineering principles, research, and records of test and field experience. Also involved is an appreciation of the problems of manufacture, installation, and use derived from consultation with and information obtained from manufacturers, users, inspection authorities, and others having specialized experience. For systems intended for general applications, the individual companies through normal commercial contact determined information as to user requirements. Practical information concerning performance, safety, test, construction, and manufacture of adjustable speed drive systems is provided in this guide.

In the preparation and revision of these standards, consideration has been given to the work of other organizations whose standards are in any way related to adjustable speed drive systems. Credit is hereby given to all whose standards may have been helpful in the preparation of this volume.

This application guide was developed jointly by the Industrial Automation Control Products and Systems Section and the Motor and Generator Section. Section approval of the guide does not necessarily imply that all section members voted for its approval or participated in its development. At the time this guide was approved, the Industrial Automation Control Products and Systems Section was composed of the following members:

ABB Control, Inc.—Wichita Falls, TX
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Reliance Controls Corporation—Racine, WI
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The Motor and Generator Section was composed of the following members:

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The Imperial Electric Company—Akron, OH
Toshiba International Corporation—Houston, TX
WEG Electric Motor Corp.—Suwanee, GA

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Section 1
SCOPE

This guide covers AC electrical drive systems, rated 600 volts or 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.

Section 2
REFERENCED STANDARDS

2.1 REFERENCED NEMA STANDARDS

The following normative documents contain provisions, which through reference in this text constitute provisions of this standards publication. By reference herein these publications are adopted, in whole or in part as indicated, in this standards publication.

2.1.1 MG1-2011 Motors and Generators

Part 30 *Application Considerations For Constant Speed Motors Used On A Sinusoidal Bus With Harmonic Content And General Purpose Motors Used With Adjustable—Voltage Or Adjustable—Frequency Controls Or Both* provides information for NEMA Design A and B motors that are covered in MG1 Part 12 *Test and Performance—AC and DC Motors*, when used with adjustable voltage or frequency controls, as indicated in the Scope of Part 30. It also defines terms, performance considerations, and sets limits for which these general-purpose motors are suitable for operation.

Part 31 *Definite-Purpose Inverter-Fed Motors* defines a definite-purpose motor specifically designed for operation with adjustable frequency controls. Part 31 gives the minimum performance standards that apply to this type of motor.

2.1.2 ICS 1-2000 Industrial Control and Systems: General Requirements

NEMA Standards Publication ICS 1 provides practical general information concerning ratings, construction, testing, performance, and manufacture of industrial control and systems equipment and terminal blocks.

2.1.3 ICS 7-2006 Industrial Control and Systems Adjustable-Speed Drives

NEMA Standards Publication ICS 7 provides practical information concerning ratings, construction, test, performance and manufacture of industrial control equipment. These standards are used by the electrical industry to provide guidelines for the manufacture and proper application of reliable products and equipment and to promote the benefits of repetitive manufacturing and widespread product availability.

2.1.4 ICS 7.1-2006 Safety Standards for Construction and Guide for Selection, Installation, and Operation of Adjustable Speed Drive Systems

NEMA Standards Publication ICS 7.1 defines the construction and test requirements for adjustable-speed drive systems. It also provides recommendations for their selection, installation, and operation in such a manner as to provide for the practical safeguarding of persons.

2.1.5 NEMA 250-2008 Enclosures for Electrical Equipment (1,000 Volts Maximum)

NEMA Standards Publication 250 covers enclosures for electrical equipment rated not more than 1,000 volts. It provides descriptions, features, and test criteria for hazardous (classified) locations and nonhazardous location enclosures.

2.2 OTHER REFERENCED STANDARDS

ANSI/NFPA 70-2014 *National Electrical Code®*

ANSI/IEEE 112-2004 *Standard Test Procedure for Polyphase Induction Motors and Generators*

UL 2111-1997 *Overheating Protection for Motors*

IEEE 100-2000 *Authoritative Dictionary of IEEE Standards Terms*

IEEE 519-1992 *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*

UL 508C-2002 *Power Conversion Equipment*

UL 1569-1999 *Metal-Clad Cables*

CISPR11, EN55011 *Industrial, Scientific and Medical (ISM) Radio-Frequency Equipment Electromagnetic Disturbance Characteristics—Limits and Methods of Measurement*

IEC 60034-18-41 *Rotating electrical machines—Part 18-41: Qualification and type tests for Type I electrical insulation systems used in rotating electrical machines fed from voltage converters*

IEC 61800-2 *General Requirements—Rating Specifications for Low Voltage Adjustable Frequency A.C. Power Drive Systems*

IEC 61800-3 *EMC Product Standard Including Specific Test Methods*

FCC Rules and Regulations, Volume II, Part 15, Subpart J, Class A

Section 3
DEFINITIONS

The following definitions apply for use in this Guide.

adjustable speed drive (ASD): See Drive.

adjustable speed drive system: See Drive System.

base rating point: Base rating point for motors defines a reference operating point at a specified speed, fundamental voltage, and torque or horsepower.

base frequency: Base frequency of an adjustable frequency drive system is the lowest frequency at which it is capable of delivering maximum output power.

base speed: Motor full-load speed at base frequency.

braking, regenerative: A form of dynamic braking in which the kinetic energy of the motor and driven machinery is returned to the power supply system.

breakaway torque (motor): The torque that a motor produces at zero speed when operating on a control.

breakdown torque (motor): The breakdown torque of a motor is the maximum torque that it will develop with rated voltage applied at rated frequency on sinewave power, without an abrupt drop in speed.

center winder (unwinder): A winder in which the roll of material is driven (or held back in the case of an unwinder) through the reel on which the material is wound (see Figure 3-2).

control: The term “control” used in this application guide applies to devices that are also called inverters and converters. They are electronic devices that convert input AC or DC power into a controlled output AC voltage or current.

dancer control: A form of loop control in which the feedback signal is derived from a transducer which responds to the position of a roll (dancer) which rides in the loop of the material.

displacement power factor: The cosine of the phase displacement angle between the fundamental component of the voltage and current.

drive: The equipment used for converting available electrical power into mechanical power suitable for the operation of a machine. A drive is a combination of a power converter (control), motor, and any motor-mounted auxiliary devices. Examples of motor-mounted auxiliary devices are encoders, tachometers, thermal switches and detectors, air blowers, heaters, and vibration sensors.

drive system: An interconnected combination of equipment that provides a means of adjusting the speed of a mechanical load coupled to a motor. A drive system typically consists of a drive and auxiliary electrical apparatus.

efficiency (control): The ratio of the power delivered by the converter (control) to the total power drawn from the plant electrical power system. Efficiency is usually expressed in percentage.

efficiency (drive system): The efficiency of the drive system is the ratio of the power delivered by the machine shaft to the total power drawn from the plant electrical power system, and it is usually expressed in percentage. The input power includes that for the auxiliary functions, such as switching equipment, overload protection, and fans.

frequency, carrier: See switching frequency.

frequency, switching: Switching frequency refers to the switching rate of an inverter phase pole and is synonymous with carrier frequency when a pulse-width modulation (PWM) strategy is employed. The rate of switching events, when observed from line-to-line, is equal to twice the switching (carrier) frequency.

Switching period, T_s, is the time interval between consecutive turn-on events of an inverter output-switching device. Switching frequency, f_s, is the inverse of T_s,

$$f_s = \frac{1}{T_s}$$

inverter: A machine, device, or system that changes direct-current power to alternating-current power.

line speed: The rate of linear travel of material being conveyed or processed. Line speed is expressed in linear units, such as feet or meters per minute.

line speed range: The maximum and minimum line speeds between which the system is designed to operate.

The drive system must remain within specified deviation bands throughout this range. (This requirement does not normally include thread speed operation.)

loop control: The effect of a control function or a device to maintain a specified loop of material between two machine sections by automatically adjusting the speed of at least one of the driven sections.

maximum loop travel: The maximum permissible movement of the bottom of the loop during any operation, including transients. See Figure 3-1.

maximum roll build-up: The build-up from the empty reel diameter to the full roll diameter.

maximum roll build-up ratio: The ratio of the maximum roll diameter to the empty reel diameter.

open-circuit ac time constant: When a polyphase induction motor is open-circuited while running at rated speed, the rotor flux-linkages generate a voltage in the stator winding. The decay of the open-circuit terminal voltage is determined as follows:

$$T''_{do} = \frac{X_M + X_2}{2\pi f r_2} \text{ (seconds)}$$

Where:

a) r_2 = Rotor resistance per phase at rated speed and operating temperature referred to stator
b) X_2 = Rotor leakage reactance per phase at rated speed and rated current referred to stator
c) X_M = Magnetizing reactance per phase
d) f = Rated frequency, Hz

operating loop travel: The maximum movement of the bottom of the loop during steady-state operation. See Figure 3-1.

operating storage: The change in the length of material in the loop as the result of the operating loop travel.

operating storage time: The operating storage divided by the maximum rated line speed, expressed in seconds.

overload torque: The maximum load beyond rated that a motor can carry for a specified period of time without permanent damage or significant performance deterioration.

pulse-width modulated (PWM) control: A control where the frequency and magnitude of the output voltage or current are accomplished by pulse modulation in which the duration of the pulses is varied.

rated flux: Rated flux is the value of flux which exists at the base rating point when rated voltage, frequency, and load are applied.

rectifier: A device for converting alternating current (AC) to direct current (DC).

reel: A core, with or without flanges, upon which the material is wound.

regeneration: An operation where the drive system converts mechanical power from the motor shaft into electrical power for the supply system.

rise time (voltage): The time required for the voltage to make the change from 10 percent of the steady-state value to 90 percent of the steady-state value, either before of a peak voltage or in the absence of a peak voltage.

roll; coil: The material wound upon the reel.

roll build-up (build-down): The change in roll diameter while winding (unwinding).

roll build-up ratio: The ratio of the roll diameter to the empty reel diameter.

running tension control: A control function which maintains tension in the material at operating speeds.

service factor (motor): Service factor is defined as a multiplier that, when applied to the rated power, indicates the permissible power loading that may be carried continuously without exceeding a defined temperature rise in the motor.

slip: The difference between synchronous speed and operating speed, at the same frequency, expressed in rpm or in percent or ratio of synchronous speed.

speed-range: All the speeds that can be obtained over a defined operating region for a defined load. The speed range is generally expressed as the ratio of the maximum to the minimum rated speed.

stalled tension control: A control function which maintains tension in the material at zero speed.

surface winder: A winder in which the roll of material is driven by friction rolls or belts in contact with the outer surface of the roll (see Figure 3-3).

taper tension: Provision for varying tension with build-up, or line speed, or both, as opposed to constant tension.

tension: The total force in pounds or newtons acting on the cross section and tending to cause extension of the material being processed.

total power factor: The ratio of the total power input in watts to the total volt-ampere input at the point of connection to the power supply system. Total power factor includes the effect of harmonic components of current and voltage and the effect of phase displacement between current and voltage.

total storage: The change in the length of material in the loop as the result of maximum loop travel.

total storage time: The total storage divided by the maximum rated line speed, expressed in seconds.

voltage boost: An additional amount of control output voltage, above the value based on constant volts per Hz, applied at any frequency. It is generally applied at lower frequencies to compensate for the voltage drop in the stator winding.

volts/Hz ratio: The volts/Hz (volts per Hz) ratio is the ratio of fundamental voltage to frequency.

voltage source inverter: For the purpose of this guide, a voltage source inverter produces variable frequency AC from a constant voltage DC bus.

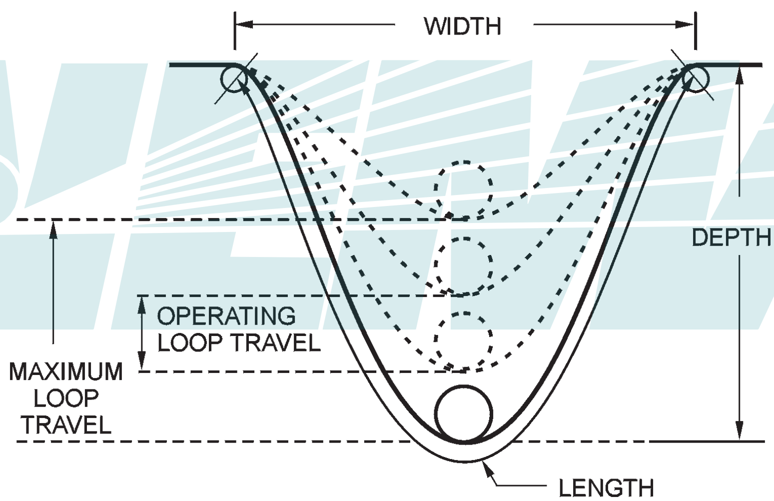


Figure 3-1
OPERATING LOOP TRAVEL

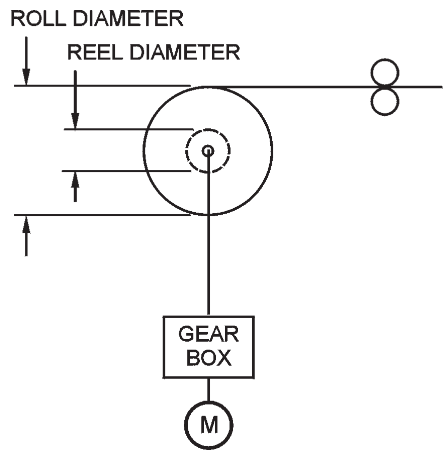


Figure 3-2
CENTER WINDER (UNWINDER)

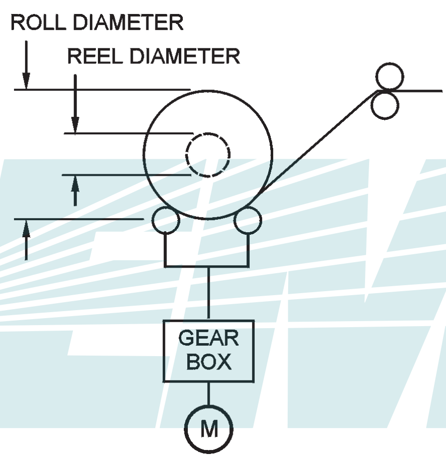


Figure 3-3
SURFACE WINDER

Section 4
DESCRIPTION OF SYSTEM COMPONENTS

4.1 LOAD TYPES

In most processes the load varies with speed as described using one of the following terms: variable torque loads, constant torque loads, and constant horsepower loads. When applying a control and motor to a process, it is important to determine how the load is related with speed.

4.1.1 Variable Torque

Variable torque loads are good candidates to apply ASDs for energy savings. Typical examples of such loads are centrifugal pumps, centrifugal fans, centrifugal blowers, and centrifugal compressors.

4.1.1.1 Squared Torque Variation

A variable torque load having a squared relationship means that the torque varies at a rate proportional to the square of the speed and horsepower varies as the cube of the speed, reaching 100 percent load torque and horsepower at a defined speed. (See Figure 4-1.)

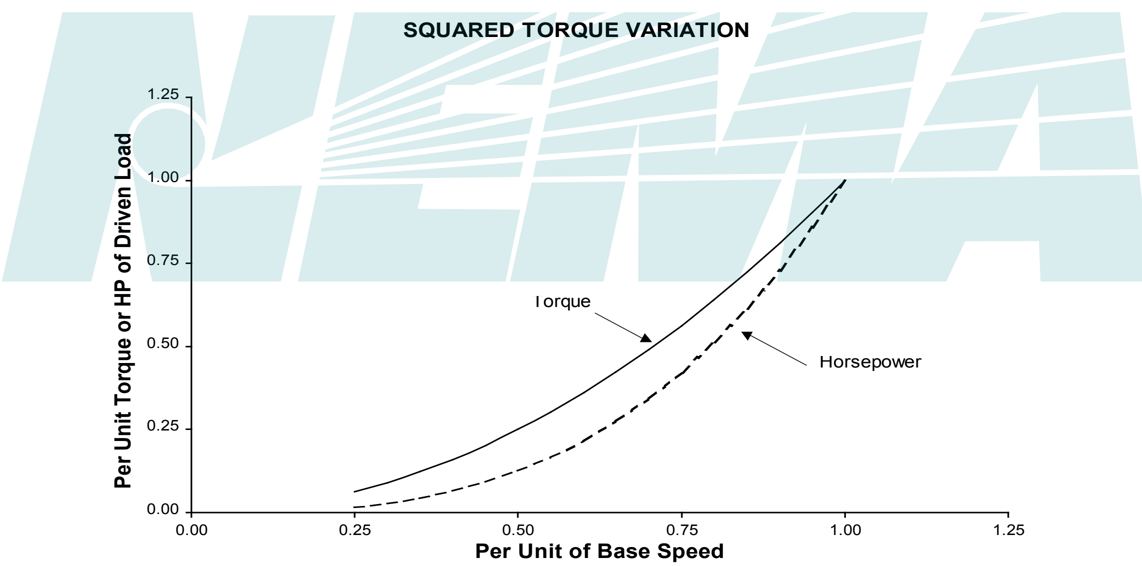


Figure 4-1
SQUARED TORQUE VARIATION

4.1.1.2 Linear Torque Variation

A variable torque load having a linear relationship means that the torque varies linearly with speed and horsepower varies as the square of the speed, reaching 100 percent load torque and horsepower at a defined speed. (See Figure 4-2.)

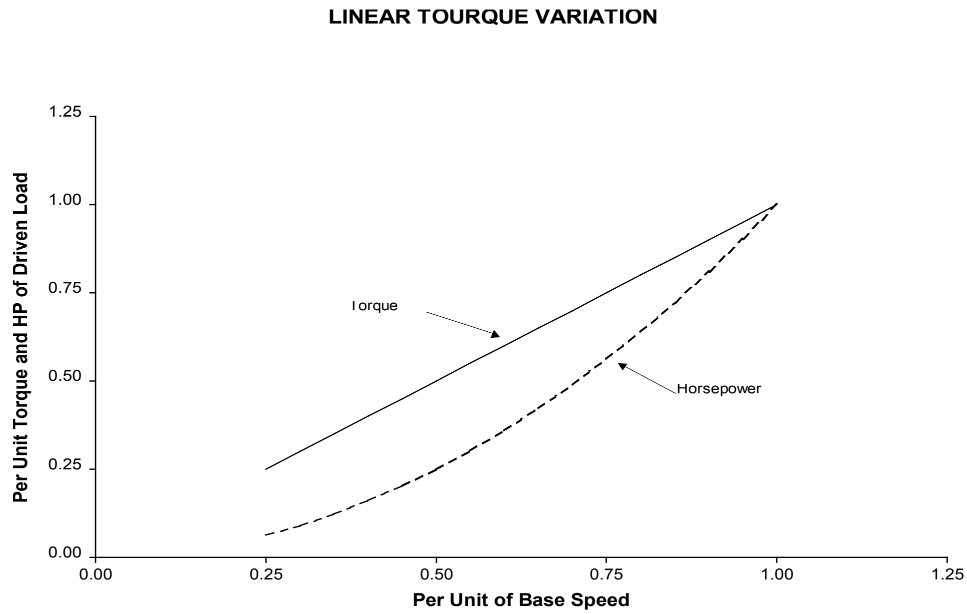


Figure 4-2
LINEAR TORQUE VARIATION

4.1.2 Constant Torque

For constant torque loads, the load torque remains constant throughout the speed range, as shown in Figure 4-3. The horsepower changes linearly with speed for these loads.

Machines that are high-impact loads or duty-cycle loads typically fall into the constant torque classification. Conveyors, process lines (strip, web, and sheet), augers, positive displacement pumps, extruders, crushers, screw compressors, reciprocating compressors, and ball mills are examples of constant torque loads.

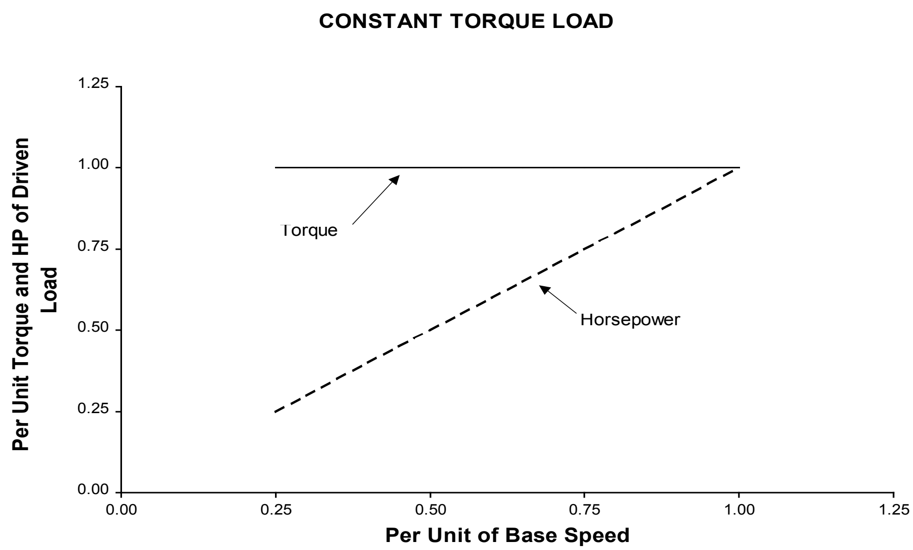


Figure 4-3
CONSTANT TORQUE LOAD

4.1.2.1 Duty Cycle

A duty cycle consists of discrete loads applied for defined periods of time repeated periodically. The discreet loads may be at changing or constant speeds. (See Figure 4-4.) A typical duty cycle definition consists of speed and load versus time. An example would be a material handling conveyor system.

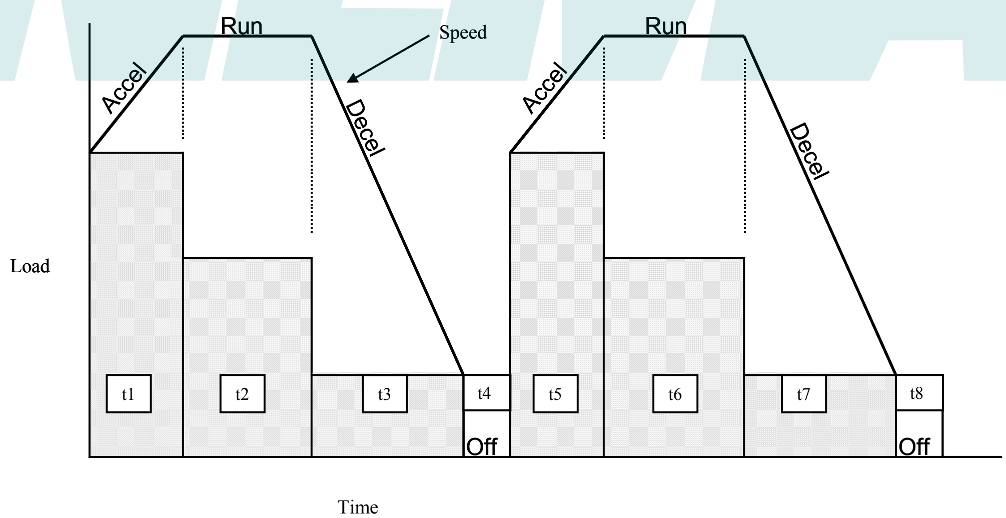


Figure 4-4
DUTY CYCLES

4.1.2.2 High Impact Load

With an impact load, the torque loading is intermittent and is not a function of speed. Impact loads are exhibited by a punch press, which uses a large flywheel to deliver the energy needed for the load. It is also characteristic of loads that are driven through a clutch, which is cycled during the process operation. Press applications require that the motor and control combination produce sufficient accelerating torque to return the flywheel to the required speed prior to the beginning of the next work stroke. (See Figure 4-5.)

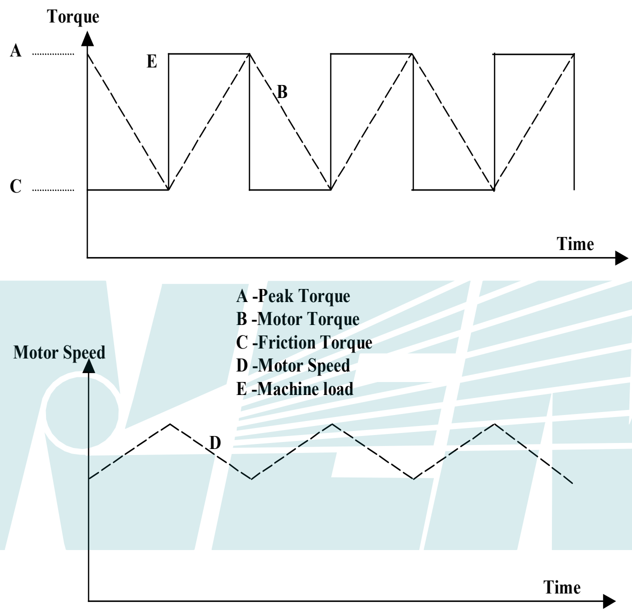


Figure 4-5
IMPACT LOAD

4.1.3 Constant Horsepower

For constant horsepower loads, the load torque drops as speed increases resulting in constant horsepower throughout the speed range, as shown in Figure 4-6.

Center driven winders and machine tools (where heavier cuts are taken at lower speeds and lighter cuts at higher speeds) are examples of constant horsepower loads.

CONSTANT HORSEPOWER LOAD

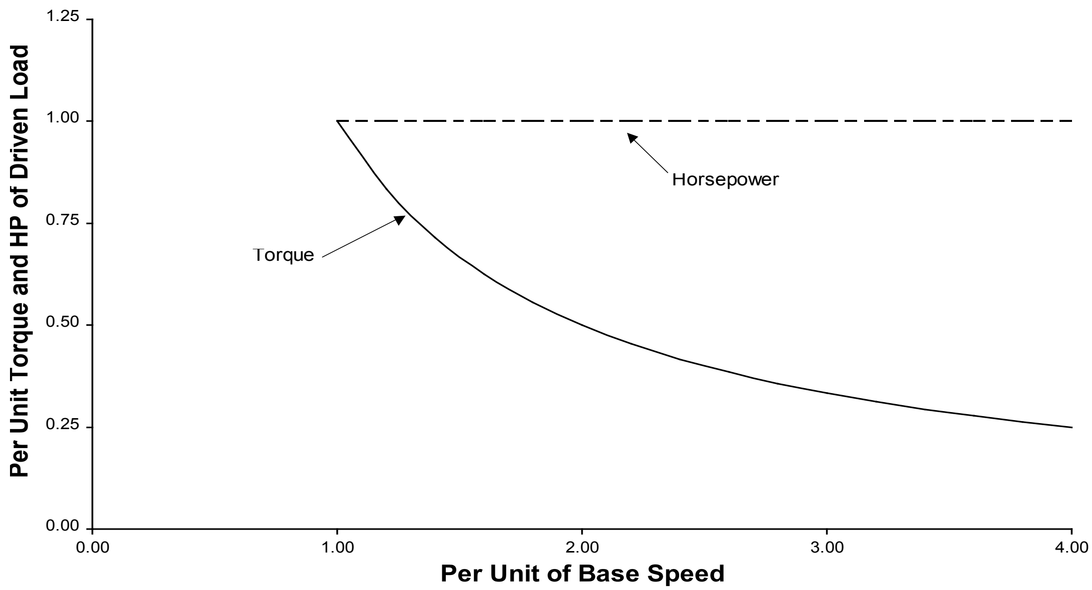


Figure 4-6
CONSTANT HORSEPOWER LOAD

4.2 MOTOR TYPES

4.2.1 General

Performance requirements for various types of induction motors for use on standard sinewave power supplies are identified in NEMA MG1. Some of these types of motors are suitable for use in variable speed applications, dependent on the type of application. Performance requirements are also identified for motors for specific use in variable speed applications. The purpose of this section is to provide guidance on the selection of one or more of the types of motors identified in NEMA MG1 that may be appropriate for the particular variable speed application under consideration. See Figure 4-7.

4.2.2 Design A

NEMA MG1 does not impose any limits on the magnitude of the locked-rotor current on Design A motors, other than that the locked-rotor current is greater than the upper limit for Design B motors. They are usually used in situations where higher locked-rotor current is used for the purpose of obtaining higher running efficiency and higher breakdown torque. Such motors typically require the use of reduced-voltage starting techniques for starting across the standard utility power source. However, normal adjustable frequency control function limits motor operation to the portion of its torque speed characteristic that lies between no-load and breakdown, even during starting. Because of this, the higher locked-rotor current of Design A motors is generally of little concern, and the motors are well suited for variable speed operation, exhibiting low slip and high efficiency. The potentially higher breakdown torque of a Design A motor will extend its constant horsepower speed range beyond that achievable by a Design B motor. However, caution should be used when applying Design A motors in by-pass operation, as their high locked-rotor current can increase starter, thermal overload, and short circuit protection device sizing. Design A motors may also suffer greater thermal and mechanical stress than other designs when started across-the-line. Design A motors with very low slip may also exhibit instability under lightly loaded conditions.

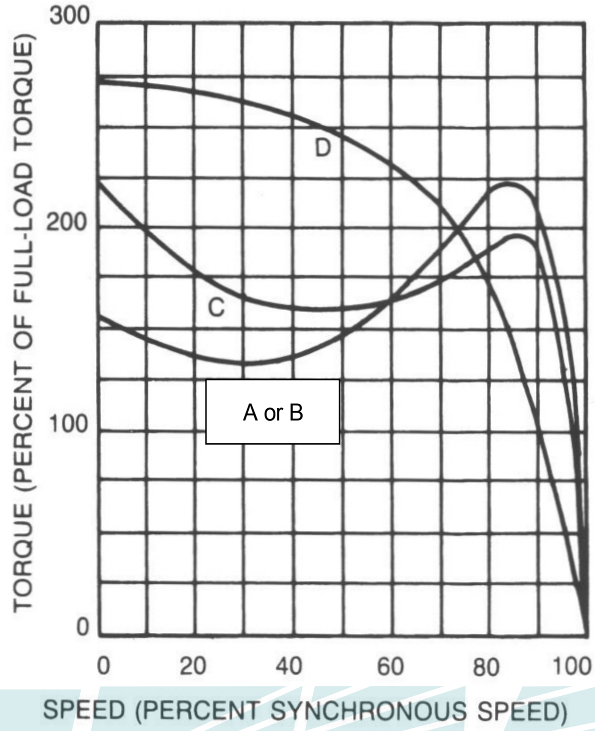


Figure 4-7
TYPICAL MOTOR SPEED TORQUE CURVES

4.2.3 Design B

Design B motors are applied in variable torque, constant torque, and constant horsepower applications. Adjustable frequency control algorithms are generally optimized to the speed-torque-current characteristics of Design B motors. They exhibit good efficiency and low slip, and are suitable for across-the-line starting in bypass mode. Design B motors with very low slip may also exhibit instability under lightly loaded conditions.

4.2.4 Design C

Design C motor speed-torque-current characteristics were defined to address across-the-line applications requiring high starting (locked-rotor) torque while generally maintaining Design B locked-rotor current but slightly higher slip. Since a Design B motor operated from an adjustable frequency control can provide the same breakaway torque as a Design C motor operated from a control, it is usually preferred because of its industry-standard availability and higher running efficiency. Also, since an adjustable frequency control driven motor normally operates at speeds above the breakdown speed, the high locked-rotor and pull-up torque of a Design C motor serves no benefit in most adjustable speed drive applications. Because Design C motors usually achieve high starting torque with a double or pseudo-double cage rotor slot, they may exhibit higher rotor losses if the control output current waveform has significant low order harmonic content. This can result in additional heating in Design C motors over that in Design B and a corresponding greater decrease in system efficiency. Design B motors may not be suitable for bypass operation in an application that normally requires use of a Design C motor for fixed frequency application.

4.2.5 Design D

Design D motors were developed specifically for high-impact, high-starting torque, or high-inertia loads. They exhibit very high locked-rotor torque but suffer in running efficiency due to their high slip characteristic. By employing negative slip compensation with an adjustable frequency control, a Design A, B or C motor can be made to emulate the speed-torque characteristic of a Design D motor while providing higher running efficiency. As a result, Design D motors are seldom used in general ASD applications. Design A, B, or C motors cannot be used for bypass operation on an application that normally requires a Design D motor for fixed frequency application.

4.2.6 Definite-Purpose Inverter-Fed

NEMA has recognized the elevated stresses imposed on induction motors by adjustable frequency controls and has developed a performance standard for motors that are specifically identified as “inverter duty” or “inverter rated.” Part 31 of NEMA MG1 addresses issues of particular concern to adjustable frequency control-fed motors such as basis of rating over a speed range, thermal aging of insulation for operation at different loads and speeds, minimum breakaway and breakdown torque requirements, overload and overspeed capabilities, voltage spikes, and vibration, among others. Of unique pertinence to such definite-purpose motors is their ability to better withstand the repetitive voltage spikes that are characteristic of modern, fast-switching devices used in adjustable frequency controls. (See 5.2.9.1.2.)

Definite-purpose inverter-fed AC induction motors are rated based on identification of the applicable load points selected from the four load points shown in and defined in Figure 4-8. The base rating is defined coincident with point (3) in Figure 4-8 by specifying the motor voltage, speed, and horsepower or torque at that point.

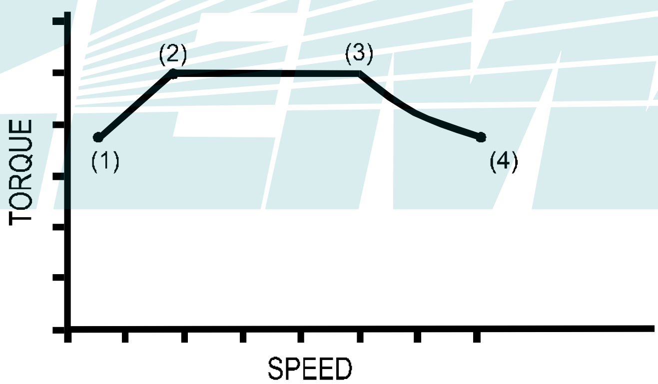


Figure 4-8
BASIS OF RATING

NOTES—

1 = Torque at minimum speed based on temperature considerations and voltage boost
2 = Lowest speed of the constant torque range based on temperature considerations
3 = Base rating point at upper end of constant torque range
4 = Maximum operating speed based on constant horsepower and any limitation on rotational speed

When the voltage ratings at reference points 3 and 4 are different, then, unless otherwise specified, the voltage is assumed to reach the maximum value at a frequency between points 3 and 4 per a constant volts-to-hertz relationship equal to the voltage at point 3 divided by the frequency at point 3.

4.2.6.1 Variable Speed Duty

A definite-purpose inverter-fed motor designated for variable speed duty is intended for varied operation over the defined speed range marked on the motor, and is not intended for continuous operation at a single or limited number of speeds. The motor design takes advantage of the fact that it will operate at a lower temperature at the load levels for some speeds than at others over the duty cycle. (See 5.2.1.7.2.)

4.2.6.2 Continuous Duty

A definite-purpose inverter-fed motor designated for continuous speed duty can be operated continuously at any speed within the defined speed range. The motor is designed on the principle that it may be operated at its rated load level at the speed which results in the highest temperature rise for an indefinite period of time. (See 5.2.1.7.2.)

4.3 CONTROL TYPES

4.3.1 Typical Power Ratings

4.3.1.1 General

Controls are rated to provide a defined amount of current for continuous operation at a defined maximum ambient temperature. While controls may be marked with a horsepower rating, it should be used for reference purposes only. Controls are generally identified as one of two basic types, distinguished by short-time overload current capabilities.

4.3.1.2 Variable Torque

A variable torque control is rated with a one-minute overload capability of typically 110 percent to 125 percent of nameplate continuous rated current which is typically sufficient for variable torque loads. However, a variable torque control is not limited to variable torque load applications.

4.3.1.3 Constant Torque

A constant torque control is typically rated with a one-minute overload capability of 150 percent of the nameplate continuous rated current.

4.3.2 Control Methods

4.3.2.1 Volts per Hertz

In V/Hz control the volts to hertz ratio is maintained at a user programmable value over the operating frequency range. It is generally applied where fast response to torque and speed commands is not required. For motors rated 460 volts, 60 Hz the volts per Hz ratio will be 7.67 (460/60), while for a motor rated 230 volts, 60 Hz the volts per Hz ratio will be 3.83. Once established, this ratio of voltage to frequency does not change with load unless trimmed using voltage boost or IR compensation.

Voltage boost is a fixed voltage that is added but has more effect at low speeds when the applied motor voltage is low. Using too much voltage boost can saturate the motor if it is operated at light loads. A technique to circumvent this limitation is to use IR compensation in place of voltage boost.

When IR compensation is used the amount of voltage available to boost the voltage ratio is proportional to the amount of current in the motor. Therefore at light loads, a voltage that is high enough to saturate the motor cannot be applied to the motor.

A control using the V/Hz technique is particularly useful where multiple motors are connected to a single control.

4.3.2.2 Vector Control

4.3.2.2.1 General

A squirrel-cage motor is a singly excited machine fed by connection to its stator windings, unlike a DC motor that is doubly excited through its armature and field windings. An AC vector control essentially decouples the magnetizing flux producing current and the torque producing current to control them separately. This gives the ASD excellent steady state and dynamic performance. Very accurate speed and torque control can both be achieved.

4.3.2.2.2 Direct

A direct field-oriented control scheme is one that directly regulates the motor flux vector in order to produce controllable motor torque. Such a scheme could employ the use of Hall effect transducers or-air gap flux-sensing windings for the measurement of the motor-air-gap-flux with the necessary modifications to approximate the rotor flux. The rotor flux would then be used as the feedback in the direct vector control regulator.

4.3.2.2.3 Indirect

An indirect field-oriented control scheme is one that interprets the motor flux vector from other parameters, such as speed or current. The two types of indirect vector drive control schemes used today are closed-loop or feedback vector control (which requires a speed feedback sensor to provide rotor position feedback) and open loop or sensorless vector (SV) control (monitors motor current instead of using a speed feedback sensor). A closed-loop vector drive can provide precise speed control and maximum torque from zero speed to base speed. An open-loop vector drive does not have as wide a speed range as a closed-loop vector drive and cannot produce holding torque at zero speed.

4.3.3 PWM Techniques

4.3.3.1 Sine-Triangular Modulation

The sine-triangular modulation technique is normally referred to as sine-coded PWM output of a control. This modulation technique uses a symmetrical triangular carrier wave of a higher frequency that is compared with a sinusoidal reference wave of the desired output frequency. The resultant of these two signals is a sine-coded PWM signal from an analog comparator circuit within the control.

4.3.3.2 Space Vector Modulation (SVM)

This modulation technique is well-suited to digital implementation and produces similar PWM waveforms to those of the sine-triangular method with third harmonic injection. The main advantages of the SVM technique are:

a) Simple digital calculation of the switching times.
b) A 15% increase in DC link voltage utilization compared with simple sine-triangular techniques.
c) Possible lower harmonic content at high modulation indices, compared with simple sine-triangular techniques.

The SVM technique does not offer any improved motor torque performance, however, the PWM control algorithms are much simpler to implement in digital PWM type controls.

Section 5

Section 5
DESCRIPTION OF COMPONENT INTERACTIONS

5.1 INTERACTION BETWEEN LOAD AND MOTOR

5.1.1 Service Factor

General-purpose motors with a service factor greater than 1.0 may be capable of operating on a control over a slightly wider constant torque speed range, at rated torque, than motors with a 1.0 service factor. However, service factor is not related to breakdown torque of a motor, and therefore has no effect on the constant horsepower speed range.

5.1.2 Maximum Safe Operating Speed

Mechanical considerations limit the maximum speed at which a general-purpose Design A or B motor can safely operate (see 5.2.3). Also, above approximately 90 Hz in the constant horsepower operating region, such motors operating with constant voltage above 60 Hz may not provide sufficient torque to support a constant horsepower load. The maximum continuous operating speed of a direct-coupled Design A or B general-purpose motor operated in a 0°C to 40°C ambient temperature should not exceed the values given in Table 5-1. Consult the motor manufacturer for operation at speeds greater than those values and ratings not covered by Table 5-1.

5.1.3 Overspeed Capability

5.1.3.1 General-Purpose Motor

The permissible overspeed (not to exceed two minutes duration) is 10 percent above the value in Table 5-1, except where the maximum safe operating speed is the same as the synchronous speed for 60 Hz operation. For those motors for which the speed in Table 5-1 is equal to the synchronous speed at 60 Hz the permissible overspeed (not to exceed two minutes duration) in Table 5-2 applies.

Table 5-1

MAXIMUM SAFE OPERATING SPEED FOR STANDARD DESIGN A AND B DIRECT DRIVE (TS SHAFT FOR MOTORS ABOVE THE 250 FRAME) SQUIRREL-CAGE INDUCTION MOTORS

	Totally Enclosed Fan-cooled			**Open Drip Proof**		
	Synchronous Speed at 60 Hz					
	3,600	**1,800**	**1,200**	**3,600**	**1,800**	**1,200**
Horsepower	**Minimum Design Speed**					
1/4	7,200	3,600	2,400	7,200	3,600	2,400
1/3	7,200	3,600	2,400	7,200	3,600	2,400
1/2	7,200	3,600	2,400	7,200	3,600	2,400
3/4	7,200	3,600	2,400	7,200	3,600	2,400
1	7,200	3,600	2,400	7,200	3,600	2,400
1.5	7,200 7,200	3,600	2,400	7,200	3,600	2,400
2	7,200	3,600	2,400	7,200	3,600	2,400
3	7,200	3,600	2,400	7,200	3,600	2,400
5	7,200	3,600	2,400	7,200	3,600	2,400
7.5	5,400	3,600	2,400	7,200	3,600	2,400
10	5,400	3,600	2,400	5,400	3,600	2,400
15	5,400	3,600	2,400	5,400	3,600	2,400
20	5,400	3,600	2,400	5,400	3,600	2,400
25	5,400	2,700	2,400	5,400	2,700	2,400
30	5,400	2,700	2,400	5,400	2,700	2,400
40	4,500	2,700	2,400	5,400	2,700	2,400
50	4,500	2,700	2,400	4,500	2,700	2,400
60	3,600	2,700	2,400	4,500	2,700	2,400
75	3,600	2,700	2,400	3,600	2,700	2,400
100	3,600	2,700	1,800	3,600	2,700	1,800
125	3,600	2,700	1,800	3,600	2,700	1,800
150	3,600	2,700	1,800	3,600	2,700	1,800
200	3,600	2,300	1,800	3,600	2,700	1,800
250	3,600	2,300	1,800	3,600	2,300	1,800
300	3,600	2,300	1,800	3,600	2,300	1,800
350	3,600	1,800	1,800	3,600	1,800	1,800
400	3,600	1,800	-	3,600	1,800	-
450	3,600	1,800	-	3,600	1,800	-
500	3,600	1,800	-	3,600	1,800	-

Table 5-2
OVERSPEED CAPABILITY OF GENERAL-PURPOSE MOTORS

Hp	Synchronous Speed, Rpm	Overspeed, Percent of Synchronous Speed
200 and smaller	1,801 and over	25
	1,201 to 1,800	25
	1,200 and below	50
250-500, incl.	1,801 and over	20
	1,800 and below	25

5.1.3.2 Definite-Purpose, Inverter-Fed Motors

Definite-purpose, inverter-fed motors are constructed so that in an emergency not to exceed two minutes they will withstand overspeed above the maximum operating speed given on the nameplate. The percent overspeed these motors can withstand without mechanical damage is given in Table 5-3.

Table 5-3
OVERSPEED CAPABILITY OF DEFINITE-PURPOSE INVERTER-FED MOTORS

Maximum Operating Speed, RPM	Overspeed, Percent of Maximum Operating Speed
3,601 and over	15
1,801 – 3,600	20
1,800 and under	25

5.1.4 Direction of Rotation

5.1.4.1 General-Purpose Polyphase Induction Motors

A standard direction of rotation has not been established for general-purpose polyphase induction motors. Such motors may be constructed such that the position of the drive end of the motor relative to the conduit box can be easily changed between F1 and F2 configurations. This reverses the direction of rotation of the shaft relative to the lead terminal markings and phase sequence.

WARNING—DIRECTION OF ROTATION SHOULD BE CHECKED BY MOMENTARY APPLICATION OF VOLTAGE BEFORE CONNECTING THE MOTOR TO THE DRIVEN EQUIPMENT.

5.1.4.2 Definite-Purpose Inverter-Fed Polyphase Induction Motors

5.1.4.2.1 F1 or F2 Arrangement, Foot Mounted

The standard direction of rotation for definite-purpose inverter-fed motors having an F1 or F2 arrangement and foot mounting is counter-clockwise when phase sequence 1, 2, and 3 are applied to terminals T1, T2, and T3, respectively, when facing the end of the motor for which the conduit box is on the right and the feet are down.

WARNING—DIRECTION OF ROTATION SHOULD BE CHECKED BY MOMENTARY APPLICATION OF VOLTAGE BEFORE CONNECTING THE MOTOR TO THE DRIVEN EQUIPMENT.

5.1.4.2.2 Other Arrangements

The standard direction of rotation for definite-purpose inverter-fed motors having arrangements other than F1 or F2 is counter-clockwise when phase sequence 1, 2, and 3 are applied to terminals T1, T2, and T3, respectively, when facing the opposite drive end.

WARNING—DIRECTION OF ROTATION SHOULD BE CHECKED BY MOMENTARY APPLICATION OF VOLTAGE BEFORE CONNECTING THE MOTOR TO THE DRIVEN EQUIPMENT.

5.1.4.3 Phase Sequence of the Adjustable Frequency Control

WARNING—THE PHASE SEQUENCE OF THE OUTPUT POWER FROM THE ADJUSTABLE FREQUENCY CONTROL MAY NOT BE THE SAME AS THE PHASE SEQUENCE OF THE POWER INTO THE CONTROL. DIRECTION OF ROTATION SHOULD BE CHECKED BY MOMENTARY APPLICATION OF VOLTAGE TO THE MOTOR BEFORE CONNECTING THE MOTOR TO THE DRIVEN EQUIPMENT.

5.2 INTERACTION BETWEEN MOTOR AND CONTROL

5.2.1 Thermal Considerations

5.2.1.1 Inverter Losses

Inverter losses are composed of two components: conduction losses and switching losses. Conduction losses are the product of the voltage drop across and the current through the device while the device is conducting current. Conduction losses do not vary with switching frequency. Switching losses are the product of the voltage across the device and current through the device during turn on and turn off. Switching losses increase proportionally to switching frequency. This results in higher operating temperatures, reduced efficiency of the control, and the possible need to derate maximum continuous horsepower at higher switching frequencies (see control installation manual). Higher horsepower controls typically use lower switching frequencies.

5.2.1.2 Non-Fundamental Currents

Distortion of the motor currents varies inversely with switching frequency because of the low pass filtering effect of the leakage inductances of the motor windings. The higher the switching frequency, the lower the total distortion and the better the current waveform, up to a point. As switching frequency is increased higher and higher, distortion of the motor currents about their zero crossings caused by the switch deadband (intentionally built-in time delay between upper- and lower-switch conduction) becomes significant. Usually, however, tradeoffs between current distortion and switching loss are such that little is to be gained above approximately 5 kHz.

Motor temperature is a function of both cooling and the magnitude of heat producing losses in the motor. These losses are increased, when compared to operation on line power, because of the current distortion. The non-fundamental currents contribute very little to useful torque, but do increase several components of motor losses. Core losses are increased due to eddy currents and hysteresis. Rotor conductor losses are increased due to high frequency surface losses. The high frequency component also adds to the total rms current and thus the I^2R loss in the stator conductors. The magnitude of this increase in losses depends on the switching frequency of the control and the motor design characteristics.

5.2.1.3 Reduced Speed

There are two general methods of motor cooling or ventilation: 1) speed dependent, 2) speed independent. These methods may be affected by operation on variable frequency.

In the case of speed dependent ventilation (totally-enclosed fan-cooled or open drip-proof motors) where the rotation of the cooling fan is supplied by the motor, cooling depends on motor speed. Therefore, cooling will decrease as motor speed decreases. The magnitude of the decrease depends on the speed range. The rate of decrease depends on motor construction. Motors in this group may have only 20 to 50 percent of base speed cooling at very low speeds. Care should be taken to be certain that unidirectional motors are operated only in the intended direction of rotation.

In the case of speed independent ventilated motors (totally-enclosed non-ventilated, totally-enclosed air-over, blower-cooled, etc.), cooling variation with speed is minimal, effectively staying constant. As a result, motors of this type are better suited for operation at very low speeds or for wide constant horsepower speed ranges.

5.2.1.4 Voltage Boost

Voltage boost is often used on volts per Hz controls at frequencies below 20 Hz for the purpose of obtaining sufficient breakaway torque or running torque without requiring excessive current. At very low frequencies, such as 6 Hz or lower, this voltage boost may be as great as 100 percent of the prescribed voltage at that frequency based on a constant volts per Hz relationship. At rated torque, this additional voltage compensates for the voltage drop across the stator winding impedance when rated current flows in the motor. However, when the load is removed from the motor operating at such low speeds, the load current is reduced and the higher (boosted) voltage may then result in operation of the motor in a highly saturated condition. This can result in overheating of the motor. It is recommended that, when necessary to provide breakaway torque in excess of 140 percent of rated torque, the motor should not be operated at no-load under a fixed voltage boost condition at frequencies less than 10Hz for more than one minute without careful observation of motor temperature or consulting with the motor manufacturer. When extended operation at no-load is required, a control providing compensation in relation to the IR drop should be used.

5.2.1.5 Motor Thermal Protection

Since the operating conditions of a motor used on a control vary across wide speed and torque ranges, motors often use some type of thermal protection.

Thermal protection devices built into the motor come in either line interrupting or pilot devices. Line interrupting devices open the power supply circuit when the motor overheats. They are protectors that sense both motor temperature and current and offer inherent protection against all abnormal stalled and running conditions. They are supplied with the motor and may be either automatic or manual reset. These protectors are typically only available with motors under five HP.

CAUTION—BECAUSE THESE PROTECTORS ARE CURRENT SENSITIVE AND MAY BE SENSITIVE TO AIRFLOW, EXTREME CAUTION SHOULD BE USED IN APPLYING A MOTOR WITH THIS TYPE OF PROTECTION ON A CONTROL. UNDERWRITERS LABORATORIES (UL) RECOGNIZED PROTECTOR/MOTOR COMBINATIONS ARE TRADITIONALLY SELECTED BASED ON SINEWAVE POWER AT THE RATED LINE FREQUENCY SUCH AS 60 OR 50 HERTZ. THE CHANGE IN THE HEATING RATE IN THE PROTECTOR AS A RESULT OF ADDITIONAL HARMONIC CURRENTS OR VARIABLE FREQUENCY OPERATION WHEN A MOTOR IS OPERATED ON A CONTROL MAY RESULT IN IMPROPER PROTECTOR OPERATION.

Pilot devices open the holding coil of a magnetic switch to take the motor offline, or energize alarm bells or warning lights. Motors taken offline by pilot devices typically cannot be restarted until an operator re-closes the magnetic starting switch. Typical examples include thermostats, thermistors, and resistance temperature devices (RTDs). When pilot motor thermal protection is supplied, it is ineffective as a motor trip device unless the pilot leads are wired into the control logic circuit.

CAUTION—CONNECTING THE PILOT DEVICES INTO THE CONTROL LOGIC CIRCUIT IS MANDATORY IN HAZARDOUS LOCATION APPLICATIONS. IN THESE APPLICATIONS, THE AGENCY LISTING MAY HAVE BEEN OBTAINED ASSUMING THE PILOT PROTECTORS WILL CAUSE THE MOTOR TO BE DISCONNECTED FROM THE LINE WHEN THE PROTECTORS TRIP. IN THESE CASES, NOT CONNECTING THE PILOT DEVICES FOR THEIR INTENDED PURPOSES MAY INVALIDATE THE AGENCY LISTING IN ADDITION TO THE HAZARD OF CAUSING DAMAGE TO EQUIPMENT AND PERSONNEL.

Most adjustable frequency controls have overload protection built into them that will shut off the motor if the current versus time profile built into them is activated in software. Care should be taken, when using this feature, to assure that the current setpoint is based on the motor nameplate current and not the default current programmed into the control software.

5.2.1.6 Voltage

AC motors are rated by NEMA standards to operate at 100 percent output torque when the voltage applied to the motor terminals is within ±10 percent of the rated voltage. Although some control designs may operate when the supply voltage is beyond these limits, their output voltage may vary more than ±10 percent under these conditions and could result in damage to the motor.

5.2.1.7 Allowable Temperature Rise

5.2.1.7.1 General-Purpose Motors—Designs A, B, C, and D

General-purpose motors are designed such that the temperature rise when operating under sinewave power at the nameplate rating is within the limits given in Table 5-4. Some derating of the motor may be required when used with a control in order for the temperature rise to remain within these limits.

Table 5-4
TEMPERATURE RISE FOR GENERAL-PURPOSE MOTORS—DESIGNS A, B, C, AND D

Class of Insulation System	A	B	F	H
Time Rating (continuous or any short-time rating) Temperature Rise (based on a maximum ambient temperature of 40°C), Degrees C Windings, by resistance method				
1. Motors with 1.0 service factor other than those given in items a.3 and a.4	60	80	105	125
2. All motors with 1.15 or higher service factor	70	90	115	...
3. Totally-enclosed non-ventilated motors with 1.0 service factor	65	85	110	130
4. Motors with encapsulated windings and with 1.0 service factor, all enclosures	65	85	110	...

NOTES—

1. Abnormal deterioration of insulation may be expected if the ambient temperature of 40°C is exceeded in regular operation. See 5.2.1.7.3.
2. The foregoing values of temperature rise are based upon operation at altitudes of 3,300 feet (1,000 meters) or less. For temperature rises for motors intended for operation at altitudes above 3,300 feet (1,000 meters), see 5.2.1.7.4.

5.2.1.7.2 Definite-Purpose Inverter-Fed Motors

5.2.1.7.2.1 Maximum Temperature Rise for Continuous Duty-Rated Motors

The maximum temperature rise of the windings, above the temperature of the cooling medium, does not exceed the values given in Table 5-5.

Table 5-5
TEMPERATURE RISE FOR CONTINUOUS DUTY DEFINITE-PURPOSE INVERTER-FED MOTORS

	Maximum Temperature Rise Degrees C Method of Temperature Determination	
Insulation Class	Resistance	Embedded Detector
A	60	70
B	80	90
F	105	115
H	125	140

5.2.1.7.2.2 Maximum Temperature Rise for Variable Speed Duty-Rated Motors

The maximum intermittent temperature rise of the windings, above the temperature of the cooling medium, does not exceed the values given in Table 5-6 when tested at any rated load within the rated speed range with the identified control. All temperature rises in the table are based on a maximum ambient temperature of 40°C.

Table 5-6
TEMPERATURE RISE FOR DEFINITE-PURPOSE INVERTER-FED MOTORS

	Maximum Intermittent Winding Temperature Rise Degrees C		Relative Equivalent Temperature Rise (T_E) Degrees C	
	Method of Temperature Determination		Method of Temperature Determination	
Insulation Class	Resistance	Embedded Detector	Resistance	Embedded Detector
A	70	80	60	70
B	100	110	80	90
F	130	140	105	115
H	155	170	125	140

5.2.1.7.2.3 Relative Equivalent Temperature Rise for Variable Speed Duty

The relative equivalent temperature rise T_E for a defined load/speed cycle as determined below does not exceed the values given in Table 5-6.

The load cycle of the definite-purpose inverter-fed motor may be comprised of varying load conditions at varying speeds within the defined speed range. The minimum load within a load cycle may have the value zero.

The reference to a load cycle, given in this guide, is to be considered as integral figures over a long period of time such that thermal equilibrium is reached. It is not necessary that each cycle be exactly the same as another (which would be periodic duty, which implies times too short for thermal equilibrium to be reached). They will be similar and can be integrated to give a nominal pattern with the same thermal life expectancy. An example of a load cycle based on temperature and time of operation is shown in Figure 5-1.

The rate of thermal aging of the insulation system will be dependent on the value of the temperature and the duration of operation at the different loads and speeds within the load cycle. A thermal life expectancy of the motor operating over the load cycle can be derived in relation to that for the motor operating continuously at a temperature equal to that for the temperature classification of the insulation system. This relative thermal life expectancy can be calculated by the following equation.

$$\frac{1}{TL} = \Delta t_1 \times 2^{\frac{\Delta T_1}{K}} + \Delta t_2 \times 2^{\frac{\Delta T_2}{K}} + \ldots + \Delta t_n \times 2^{\frac{\Delta T_n}{K}}$$

Where:

TL = relative thermal life expectancy for the load cycle related to the thermal life expectancy for continuous operation at the temperature rating of the insulation class

$\Delta T_1 \ldots \Delta T_n$ = difference between the temperature rise of the winding at each of the various loads within the load cycle and the permissible temperature rise for the insulation class

$\Delta t_1 \ldots \Delta t_n$ = period of time for operation at the various loads expressed as a per unit value of the total time for the load cycle

k = 10°C = difference in temperature rise which results in a shortening of the thermal life expectancy of the insulation system by 50%

A relative equivalent temperature rise based on continuous operation at that temperature rise for the load cycle time and resulting in the same level of relative thermal life expectancy for the defined load cycle can be determined as follows:

$$T_E = k \times LOG_2\left(\frac{1}{TL}\right) + T_R$$

Where:

T_E = relative equivalent temperature rise
T_R = permissible temperature rise for insulation class (Figure 5-1; for example see Table 5-4)

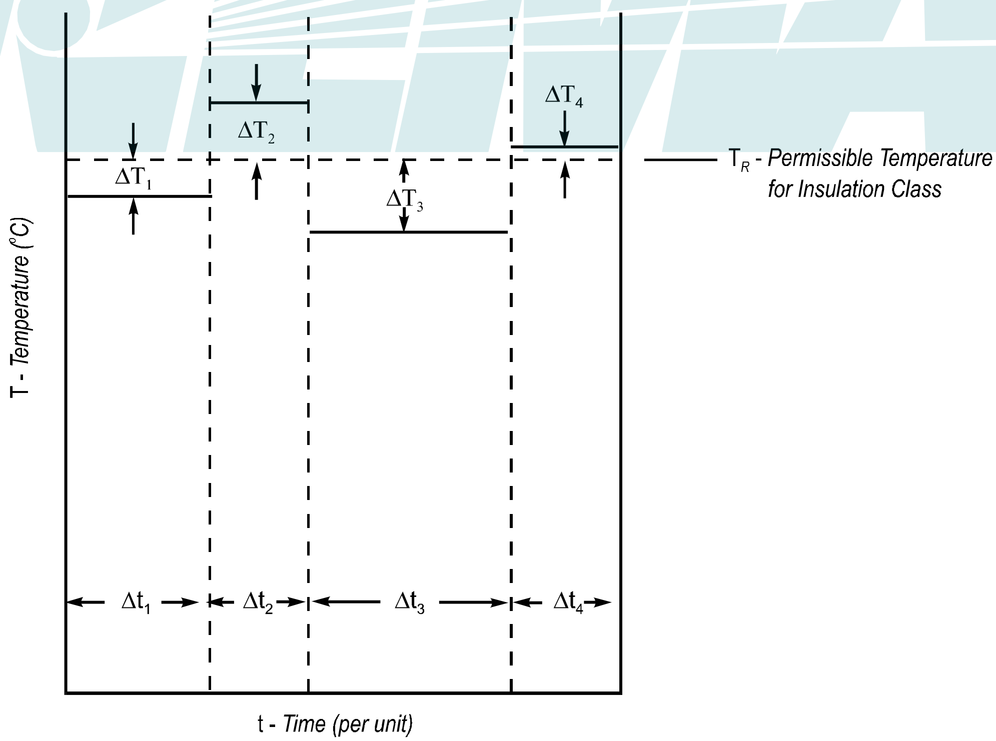


Figure 5-1
LOAD CYCLE BASED ON TEMPERATURE AND TIME OF OPERATION

5.2.1.7.3 Temperature Rise for Ambients Higher Than 40°C

The temperature rises given in Tables 5-4, 5-5, and 5-6 are based upon a reference ambient temperature of 40°C. However, it is recognized that induction machines may be required to operate in an ambient temperature higher than 40°C. For successful operation of induction machines in ambient temperatures higher than 40°C, the temperature rises of the machines given in the foregoing tables are reduced by the number of degrees that the ambient temperature exceeds 40°C. When a higher ambient temperature than 40°C is required, preferred values of ambient temperatures are 50°C, 65°C, 90°C, and 115°C.

5.2.1.7.4 Temperature Rise at Altitudes Above 3,300 feet (1,000 meters)

The temperature rises given for machines noted above are based upon operation at altitudes of 3,300 feet (1,000 meters) or less and a maximum ambient temperature of 40°C. It is also recognized as good practice to apply machines as indicated in the following paragraphs at altitudes greater than 3,300 feet (1,000 meters).

5.2.1.7.4.1 Ambient Temperature at Altitudes for Rated Temperature Rise

Machines having temperature rises in accordance with Tables 5-4, 5-5, and 5-6 will operate satisfactorily at altitudes above 3,300 feet (1,000 meters) in those locations where the decrease in ambient temperature compensates for the increase in temperature rise, in Table 5-7.

Table 5-7

AMBIENT TEMPERATURE AT ALTITUDES FOR RATED TEMPERATURE RISE

Maximum Altitude, Feet (Meters)	Ambient Temperature, Degrees C
3,300 (1,000)	40
6,600 (2,000)	30
9,900 (3,000)	20

5.2.1.7.4.2 Temperature Rise at Sea Level

Machines which are intended for use at altitudes above 3,300 feet (1,000 meters) at an ambient temperature of 40°C should have temperature rises at sea level not exceeding the values calculated from the following formula:

When altitude in feet:

$$T_{RSL} = T_{RA}\left[1 - \frac{(Alt - 3{,}300)}{33{,}000}\right]$$

When altitude in meters:

$$T_{RSL} = T_{RA}\left[1 - \frac{(Alt - 1{,}000)}{10{,}000}\right]$$

Where:

T_{RSL} = test temperature rise in degrees C at sea level
T_{RA} = temperature rise in degrees C from the appropriate Table 5-4, 5-5, or 5-6
Alt = altitude above sea level in feet (meters) at which machine is to be operated

5.2.1.7.4.3 Preferred Values of Altitude for Rating Motors

Preferred values of altitude are 3,300 feet (1,000 meters), 6,600 feet (2,000 meters), 9,900 feet (3,000 meters), and 13,200 feet (4,000 meters).

5.2.2 Power Factor Correction and Surge Protection

CAUTION—THE USE OF POWER CAPACITORS FOR POWER FACTOR CORRECTION AND/OR THE USE OF SURGE PROTECTION CAPACITORS ON THE LOAD SIDE OF AN ELECTRONIC CONTROL CONNECTED TO AN INDUCTION MOTOR IS NOT RECOMMENDED; DAMAGE TO THE CONTROL MAY OCCUR. CONTACT THE CONTROL VENDOR FOR SUITABILITY.

5.2.3 Speed Range

The speed range of a definite-purpose inverter-fed motor is defined as a part of its rating. This is not typically true for general-purpose motors. This section is a discussion of principles of operation and concerns when operating general-purpose motors across a speed range.

An adjustable frequency control will allow the motor to be operated over a wide range of speed. There are several issues that must be addressed for reliable operation:

a) Operation below the base speed of the motor is subject to potential thermal problems depending on the rating and design of the motor and the profile of the load. See 5.2.1.3 for additional information.
b) The maximum safe operating speed (see 5.1.3) of the motor or driven equipment should not be exceeded. The control's maximum frequency should be set at or below the maximum safe operating speed so that an operator cannot unintentionally overspeed the system.
c) As the speed is increased more power may be required, possibly exceeding the control or motor rating. The control and motor should be sized to supply the power required by the load for the highest load condition that the equipment will see in the installation.
d) The speed range may include speeds that are resonant with the motor itself or with the driven load. Some controls have the ability to skip over the resonant frequency. However, even when the resonant frequency is skipped, the load will be accelerated through that speed if the motor is set to run at any speed above this resonant speed. Decreasing the acceleration time can help minimize the time spent in resonance.
e) The fundamental component of motor input voltage remains constant above base speed. As shown in Figure 5-2 as frequency increases above base-speed frequency, the motor delivers constant horsepower across some frequency range. The corresponding torque varies inversely with the speed. The motor breakdown torque varies at a rate inversely proportional to the square of the change in speed. At some value of frequency—typically at 150 to 200 percent of base frequency—the maximum (breakdown) torque capability of the motor will limit the motor torque output. Above that frequency, the horsepower is reduced. For general-purpose motors, the maximum frequency of 90 Hz (1.5 pu speed) is established based on the approximate peak torque capability of greater than 175 percent for NEMA Design A and B motors assuming operation at a constant level of voltage equal to rated voltage from 60 to 90 Hz. For the capability of motors for which the minimum breakdown torque is less than 175 percent, consult the motor manufacturer. For operation above 90 Hz at a required horsepower level, it may be necessary to utilize a motor with a greater horsepower rating at 60 Hz if constant horsepower is required.
f) If the fundamental component of motor input voltage continues to increase above base speed to reach its final maximum value at a speed above base speed, then the breakdown torque available over that speed range will remain constant. The breakdown torque capability of the motor will then begin to decrease when the voltage remains constant for further increases in speed. The maximum speed at which the motor can carry constant horsepower will increase

to the speed at which the motor breakdown torque again approaches the load torque for the constant horsepower.

g) At top speed, some margin between motor breakdown torque and the load constant horsepower torque should be considered to allow for temporary overload, motor temperature limitations, and system stability.

For further guidance contact the motor manufacturer.

5.2.4 Acceleration Time

An adjustable frequency control can be used to control the acceleration time of a motor. More torque is required to accelerate in a short time, so the motor will require higher current during acceleration. The current required for acceleration may be beyond the control's rating which may cause the control to trip. Simply setting the control for a slower acceleration will lower the required current and may prevent the trip. Controls are also designed not to trip if current limit is reached during acceleration. Instead it will stop accelerating until the current is below the limit and then resume accelerating. This feature establishes the minimum possible acceleration time without tripping the control. The torque and current required for acceleration must be considered when selecting the size of the motor and control. The rotational inertia, load torque, and time to accelerate are needed to calculate the additional acceleration torque. This subject is discussed in more detail in 6.3.7.

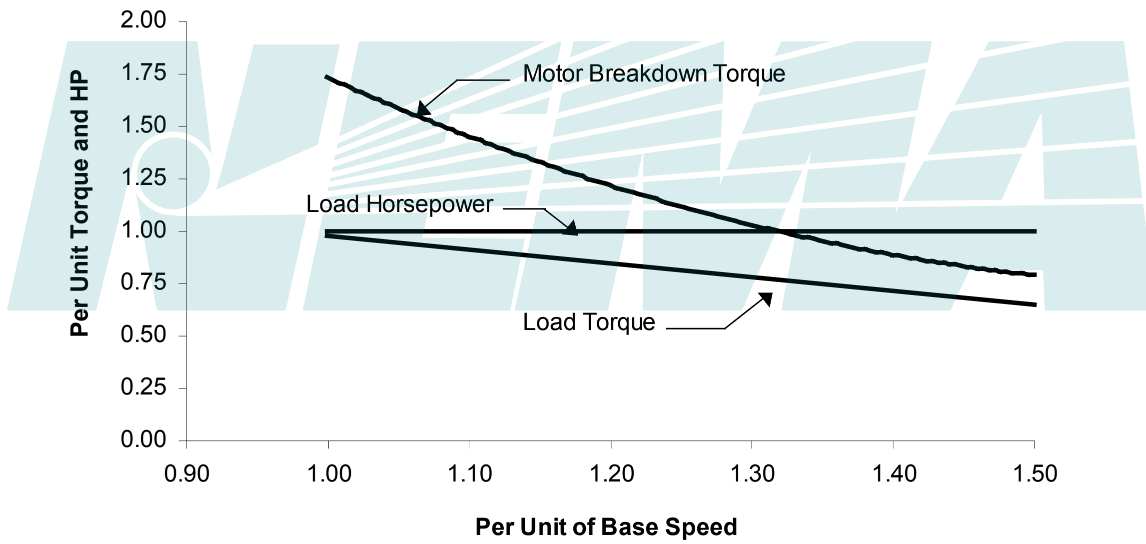


Figure 5-2
CONSTANT HORSEPOWER LOAD

5.2.5 Deceleration Time/Internal Motor Braking

Deceleration time of the motor load combination can be a concern in some cases since most standard adjustable frequency control units are equipped with limited braking capability. In addition, some loads are sensitive to an application of a retarding torque; therefore the deceleration time may need to be extended. The following comments can be made concerning the various modes of operation in which the unit does decelerate. Be sure to check with the particular control manufacturer as to availability of these modes where needed.

When no controlled deceleration is required power is removed from the motor and the motor coasts to a stop in a manner determined by the characteristic of the load.

When a controlled deceleration is desired, the load decelerates within the programmed deceleration time of the control. Many loads, such as pumps, have low inertia and the programmed deceleration rate is followed. In some controls, the deceleration time of the unit is automatically adjusted to bring the load to a stop in the shortest time without tripping the control. In this instance, the deceleration time is slightly shorter than a coast stop because the losses in the system help to dissipate the energy left in the inertia of the system. If it is required to stop a load in even less time, one of the following methods may be used:

a) Dynamic braking may be used in applications where a shorter deceleration time is occasionally required. (See 6.3.8.3.)
b) Common DC bus tie braking may be used as an alternative to dissipating the energy by a resistor when several controls are being used in a process. In a DC bus tie control, the DC buses of the controls are tied in parallel. During braking, energy is returned to the common DC bus tie. A control with DC bus tie braking is generally used where a short deceleration time is needed, a high inertia is present and a recovery of energy can be economically justified.
c) Regenerative braking is generally used where a short deceleration time is needed, a high inertia is present and a recovery of energy can be economically justified. (See 6.3.8.4.)

5.2.5.1 DC Injection Braking

In some cases an injection of DC into the stator windings will create a retarding torque to bring the motor to a stop. This is most effective when the motor speed corresponds to a speed lower than a 10 Hz output of the control. If full-load current is applied in DC injection braking, the time should be limited to five minutes per hour without consulting the motor manufacturer. It is recommended that the motor have overtemperature protection.

5.2.6 Reversal

The control is capable of electronically reversing the direction of rotation of the motor. On an AC line fed motor, reversal is achieved by simply reversing two phases. Reversing two phases of the input to a control has no effect on the direction of rotation of the motor because the gating sequence of the output power devices determines the direction of rotation.

Changes in direction of rotation can be dynamic or static. In static reversal, the drive is capable of operating in either direction, however the direction selection must be made from a stopped condition. In dynamic reversal, the drive is capable of changing direction during normal operation from either direction of rotation. The drive will decelerate to zero speed, change the gating sequence of the control, and accelerate to the set speed in the commanded direction.

5.2.6.1 Bypass Considerations

In cases where a control is supplied with bypass, care should be taken to be sure that any direction change occurs in both the control and the bypass modes of operation.

5.2.6.2 Direction Sensitive Motors and Loads

In some cases, motors, loads, or both, are unidirectional. For instance, many centrifugal pumps have impellers on threaded shafts and a reversal operation could potentially unscrew the impeller. Reversal features should not be used in such applications.

5.2.6 Stability

V/Hz controls are widely used in adjustable speed applications, and have advantages of simplicity over controls using current, speed feedback, or field orientation. However, open loop V/Hz controls are often subject to sustained speed oscillations under light load conditions at low frequencies. This stability problem becomes worse for low slip motors and multiple motors on a single control. This instability phenomenon is understood to be the direct result of uncontrolled energy swapping between the control's DC link capacitors, the motor's magnetic field, and rotor and load inertias.

5.2.8 Bypass

Contactors can be provided to bypass and isolate a control, and connect a motor directly to the main power lines (mains). Several issues must be addressed for this arrangement to work properly:

a) The motor must be of a type that is suitable for across-the-line starting (see 4.2).
b) The motor must be suitable for across-the-line operation. For example, because of its maximum speed rating point, some types of definite-purpose inverter-fed motors may not be capable of being operated across-the-line. Also, the motor may not be rated to operate at the power system voltage and frequency.
c) The direction of rotation of the motor's shaft should be checked to ensure that it is the same on the control as on the mains. This should be verified during installation.
d) The motor may run faster on bypass than when on the control if the control has been set to limit the operating speed to a lower value. The load should be checked to ensure that it will not exceed the motor's rating when operated at the bypass speed. Particular care should be taken with fan loads.
e) To avoid damaging the motor during transfer from the control to line power, a delay of one and one-half open circuit AC time constants should be used between the time of disconnecting the control and connecting to line power to allow the motor residual terminal voltage to decay to less than 25 percent of the initial value.
f) Transients can occur during bypassing which can damage the drive. To avoid damage to the control, the motor field should be allowed to decay for a minimum of three open-circuit AC time constants after disconnecting from line power and before connecting to the control.
g) Ensure the control has the capability of restarting a coasting motor before switching from line power back to control power while the motor is still rotating.

5.2.9 Motor Terminal Voltage Transients

Modern controls use power transistors that switch at very high rates. To achieve this, the devices have very fast turn-on times that result in voltage pulses with high dv/dt. When such a control is used with a squirrel cage induction motor, the pulses, in combination with the cable and motor impedance, generate high peak voltages at the motor terminals. These peak voltages are repetitive. They occur continuously and can reduce motor insulation system life.

Due to space and surface charge creation within the insulation components, the electric stress is not only defined by the instantaneous voltage itself but also by the peak voltages that have been stressing the insulation previously. Generally, it has been shown by experience that, within certain limits valid for drive systems, the stressing parameter is the peak/peak voltage. A dc overlapping voltage within these limits does not contribute to the field stress. This is also the reason why a unipolar voltage produces the same stress as a bi-polar voltage with a peak/peak voltage of the same value as the unipolar amplitude. (Above paragraph is section 4.4 from IEC 60034-18-41.)

In order to guarantee a normal service life, one must be sure that these peak voltages do not exceed the maximum repetitive voltage rating of the motor.

A PWM motor control rectifies the sinusoidal main supply into a DC voltage, and then generates rectangular pulses of fixed amplitude voltage that have varying width and frequency. The output pulse amplitude is normally not above the peak of the sinusoidal main supply (1.414 times the rms). The interaction with the cable and motor, however, causes the peak voltage at the motor's terminals, such as that illustrated in Figure 5-3.

The cable and motor can be considered an RLC resonant circuit. The rectangular pulses from the control excite this circuit. The response to this excitation is a peak voltage when the values of R, L, and C are such that the peak voltage rings above the source voltage. The value of peak voltage has a typical maximum of twice the source voltage pulses when the pulses are far enough apart to allow the ringing to decay. However, in certain cases, this value can be higher if the pulses are too close together, if the pulse duration is too short, or if cable lengths are very long.

5.2.9.1 Peak Repetitive Voltage Rating

5.2.9.1.1 General Purpose Motors

General purpose induction motors are not designed with a continuous repetitive peak voltage rating much beyond the peak of the rated rms voltage. NEMA MG1 Part 30 states that a general purpose motor is capable of withstanding a repetitive peak voltage of 1,000 volts. In general, 230 volts systems will not generate repetitive peak voltages above 1,000 volts; 460 volt and 575 volt systems can easily generate repetitive peak voltages above 1,000 volts. It may be possible to use filters or reactors placed between the control and the motor to reduce the peak voltage to a level more acceptable to a general purpose motor. For such applications the manufacturer should be consulted.

5.2.9.1.2 Definite-Purpose Inverter Fed Motors

Per NEMA MG1 Part 31, definite-purpose, inverter-fed motors are designed to withstand maximum repetitive voltage peaks at the motor terminals equal to 3.1 times the motor's rated rms voltage with a rise time not less than 0.1 μs. These motors can be used on a control without additional filters or reactors provided the particular combination of control and cable does not generate peak voltages which exceed this requirement at the motor terminals.

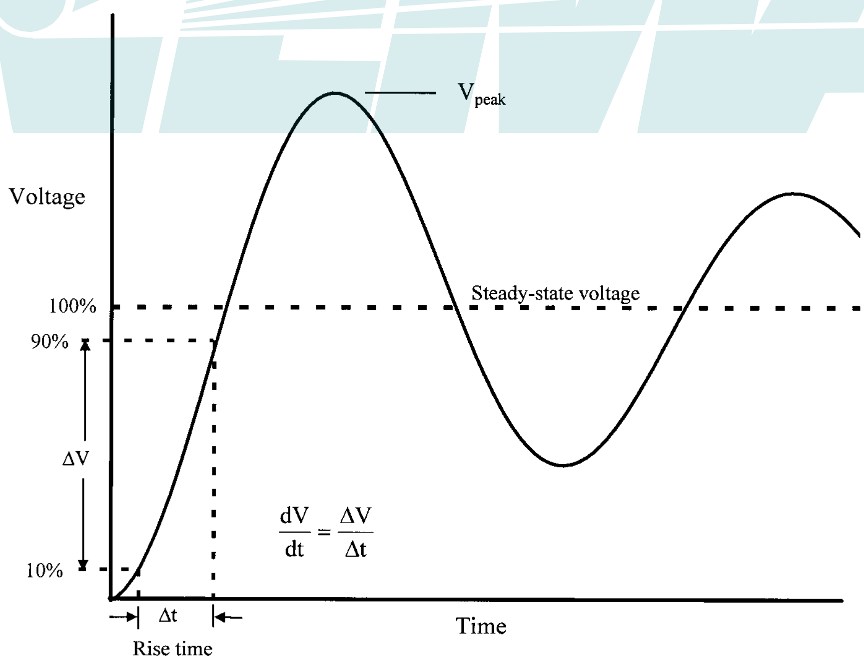


Figure 5-3
TYPICAL VOLTAGE RESPONSE AT MOTOR TERMINALS

5.2.9.2 Fundamental Contributors to Peak Voltages

It is difficult to determine if a particular control and cable will cause peak voltages in excess of the motor's insulation capability. There are six fundamental issues that determine the amount of peak voltage that will exist at the motor's terminals: pulse rise time, cable length, minimum time between pulses, minimum pulse duration, transition type (single or double), and the use of multiple motors.

5.2.9.2.1 Pulse Rise Time

A certain amount of time is required for the voltage at the control's terminals to transition from low to high. This is called the rise time. A shorter rise time will cause the peak voltage at the motor's terminals to reach a higher value for a given cable length between the motor and the control.

5.2.9.2.2 Cable Length

In general, longer cable will increase the value of the peak voltage at the motor's terminals. With modern insulated-gate bipolar transistor controls, the peak voltage begins to occur with a cable length of a few feet and can reach two times the control DC bus voltage at a length less than 50 feet. In some cases, however, very long cables (in excess of 400 feet, for example) can result in a situation where the peak voltage does not decay quickly enough. In this case the peak can ring up well beyond two times the control DC bus voltage.

5.2.9.2.3 Minimum Time between Pulses and Minimum Pulse Duration

An adjustable frequency control creates average voltage changes by varying the width of the pulses it outputs and the time between them. The peak voltage is potentially at its worst when time between pulses is at the minimum for the control and the length of the pulse duration is at the minimum. The minimum time between pulses is most likely to occur at high peak or high output voltages and during transient conditions, such as acceleration and deceleration. Minimum pulse width is most likely to occur at low output voltages. If the time between pulses or the minimum pulse duration is less than three times the resonant period of the cable (0.2 to 2 μs for industrial cable), higher peak voltages will occur. The only way to be sure this condition does not exist in any particular control is by measuring the pulses directly or by contacting the manufacturer of the control.

5.2.9.2.4 Transition Type

Each of a control's three output phases is capable of being switched. Generally, only one of the three phases is switched at any given instant. This situation is called a single transition. Some controls will switch two phases simultaneously. This is referred to as a double transition. The result is a line-to-line polarity reversal with twice the voltage excursion as that of a single transition. This causes higher peak voltages at the motor's terminals. Some controls perform double transitions only during transient conditions such as acceleration or deceleration. Double transitions are generally found in older controls and are not widely used today. The only way to be sure a control does not perform double transitions is by measuring the pulses directly or by contacting the manufacturer of the control.

5.2.9.2.5 Multiple Motors

If more than one motor is connected to a control, there can be higher peak voltages due to reflections from each motor. The situation is made worse when there is a long length of lead between the control and the common connection of motors. This length of lead acts to decouple the motor from the control. As a result, reflections which would normally be absorbed by the control's low impedance can be carried to another motor and add to the peak voltage at its terminals.

5.2.9.3 Switching Frequency

The output sine coded waveform applied to the motor terminals of an ASD is composed of a fundamental frequency and other frequencies. This pattern is generated in many cases by electronically comparing a “fixed” high frequency triangular waveform to a sinusoidal reference. The resulting switching frequency generated in each of the output power devices is the same as the “fixed” high frequency triangular waveform, traditionally called the carrier frequency. Thus, the measured switching frequency of any one of the output power devices would be the same as the carrier frequency while the measured switching frequency of the line to line output waveform (in a 6-switch output) would be twice the carrier frequency. In a multilevel ASD unit, where the output waveform is composed of series connected switches, the measured line-to-line switching frequency is substantially higher than the carrier frequency. In addition, some ASD units do not utilize a “fixed” high frequency carrier to generate the PWM pattern and these are generally characterized as “carrierless” PWM units.

Many PWM controls provide for convenient user adjustment of the switching frequency. This frequency can be adjusted over a range as broad as 500 Hz to 20 kHz. The choice of switching frequency is significant because it defines the number of peak voltages that will be occurring at the motor in a certain amount of time. The higher the switching frequency, the greater the number of peak voltages and their magnitude (see 5.2.9.2.3) that will be stressing the motor’s insulation system. If the motor’s peak voltage rating is higher than the level of the peak voltage applied to the motor, high switching frequency should not be a problem. If, however, the peak voltage levels are higher than the peak voltage rating of the motor, the use of a lower switching frequency may reduce the peak voltage levels below the peak voltage rating of the motor.

5.2.9.4 Description of Installation Categories

5.2.9.4.1 General

The six factors affecting peak voltage as described in 5.2.9.2 can be used to determine two installation categories.

5.2.9.4.2 Category I

In a Category I installation, there is low probability that the peak voltage at the motor’s terminals exceeds 3.1 times the motor’s rated rms voltage. This is true as long as the control uses single transitions and if a favorable combination of lead length, rise time, minimum time between pulses and minimum pulse duration exists. In this case, a motor rated for the NEMA MG1 Part 31 peak voltage limits will provide a normal service life. Figure 5-4 and Figure 5-5 show the combination of factors which will likely result in peak voltages below the 3.1 times limit. Figure 5-4 and Figure 5-5 apply to THHN cable in steel conduit; other cable arrangements may be slightly different. Category I is that region for which the lead length is less than the value indicated by the curve for a specified minimum time between pulses.

5.2.9.4.3 Category II

Category II is that region in Figure 5-4 and Figure 5-5 for which the lead length is greater than the value indicated by the curve for a specified minimum time between pulses. In a Category II installation, there is a high probability that the peak voltage at the motor will exceed 3.1 times the rated rms voltage of the motor. This condition exists when the control has double transitions, the lead length is beyond Category I, or the necessary parameters to use Figure 5-4 or Figure 5-5 are not known.

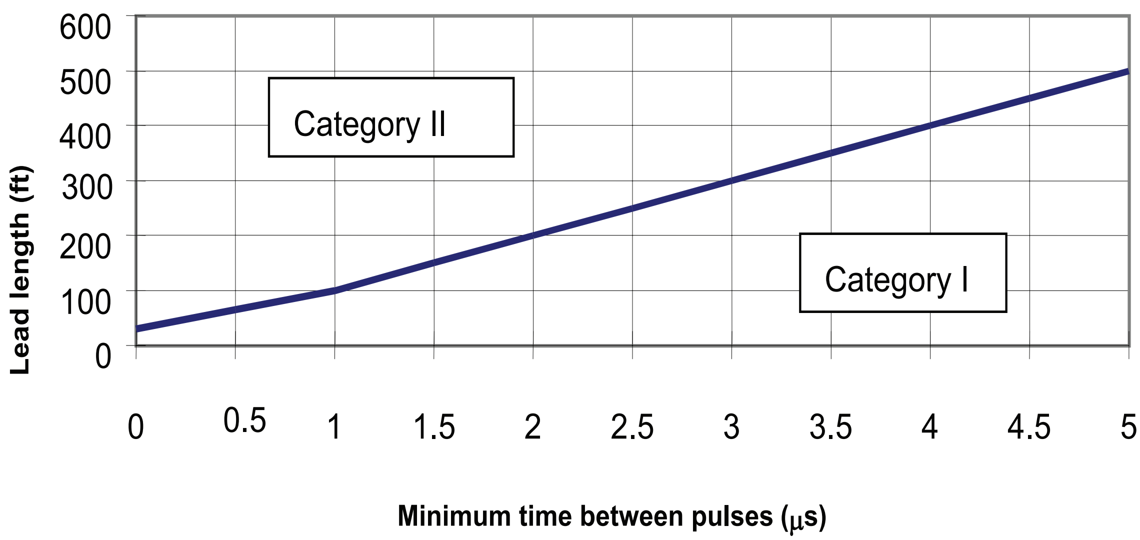


Figure 5-4
PEAK VOLTAGE CATEGORIES WHEN USING 65NS RISE TIME PULSE

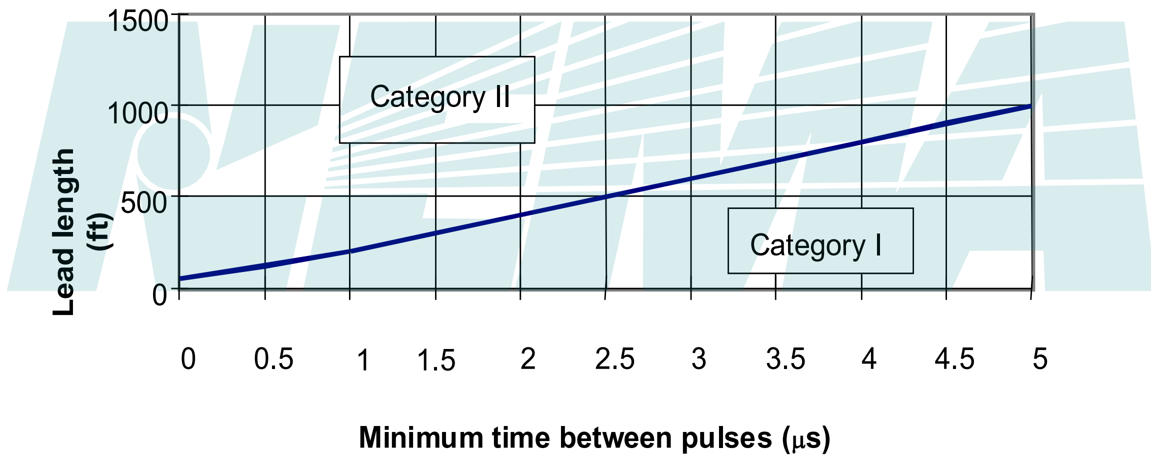


Figure 5-5
PEAK VOLTAGE CATEGORIES WHEN USING 160NS RISE TIME PULSE

5.2.9.5 Recommendations to Avoid Detrimental Effects of Peak Voltages

a) When possible, use a definite-purpose, inverter-fed motor per MG1 Part 31, or a general purpose motor that has an insulation system rated for the Part 31 voltage limits.

b) When possible, use a lower voltage supply (for example, 230 volts instead of 460 volts) and the appropriately rated motor and control.

c) Run the control at the lowest carrier frequency that satisfies any audible noise and temperature requirements.

d) Avoid running multiple motors in parallel from one control. If multiple motors are necessary, connect each directly to the control's terminals or as close to the control's terminals as possible instead of "daisy chaining" the motors to each other.

Note—Occasionally it may be necessary to parallel multiple motors from a common connection point. An example is a motor control center where a cable is run from the control to individual motor starters and individual cables are run to each motor from its starter. The goal, in this case, should be to keep the distance from each motor to its starter significantly larger than the distance from the starter to the control to minimize the possibility of voltage reflections in excess of doubling.

e) Determine the probable lead length, rise time, minimum time between pulses of the control, minimum pulse duration, and whether the control uses single transitions. Using this information, determine whether the particular application is Category I or Category II.

f) If the situation is Category I, a motor designed for a peak voltage of 3.1 times rated rms voltage per MG1 Part 31 should provide normal service life.

g) If the situation is Category II, do one or both of the following:

   1. Use a reactor or filter between the control and the motor. Follow the control manufacturer's recommendations concerning its installation.

   2. Use a motor with a peak voltage rating that exceeds the voltage level of the installation.

h) Measure the peak voltage at the motor's terminals. If the terminal voltage is greater than the motor's peak voltage rating, use a filter or reactor between the motor and control.

5.2.9.6 Peak Voltage Test Results

Figure 5-6 illustrates the peak voltage which was measured on a five horsepower, 460-volt motor as a function of the lead length between the motor and control for some typical controls. The controls had the characteristics in Table 5-8.

Table 5-8
CHARACTERISTICS OF THE THREE CONTROLS

Control	Default Switching Frequency (kHz)	Rise Time (ns)
A	4.5	458
B	4.8	130
C	15	35

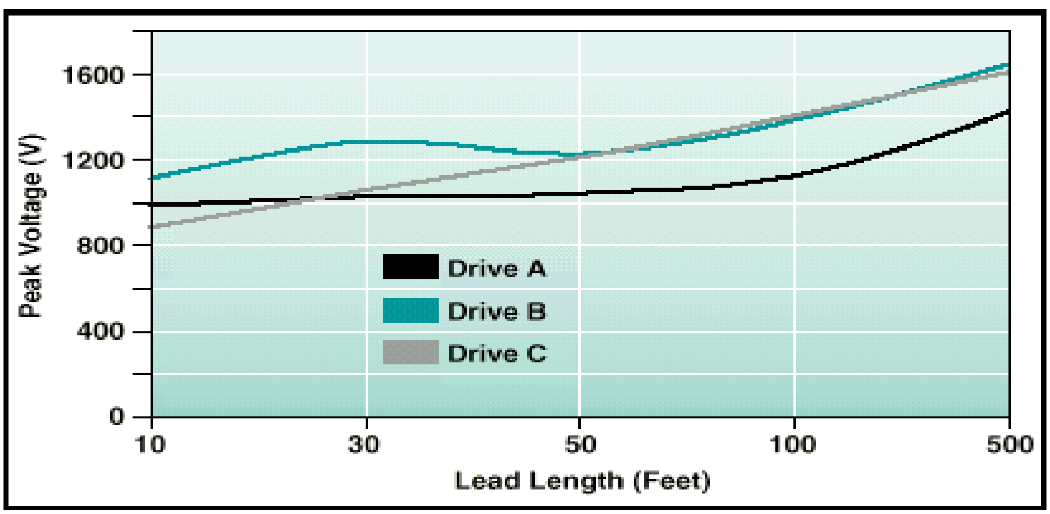


Figure 4. Peak Motor Voltage Based Upon Lead Length

Figure 5-6
TEST RESULTS OF PEAK MOTOR VOLTAGE BASED UPON LEAD LENGTH FOR A FIVE-HORSEPOWER MOTOR

Figure 5-7 illustrates the results on the same controls and motor with a fixed cable length of 100 feet and varying carrier frequencies.

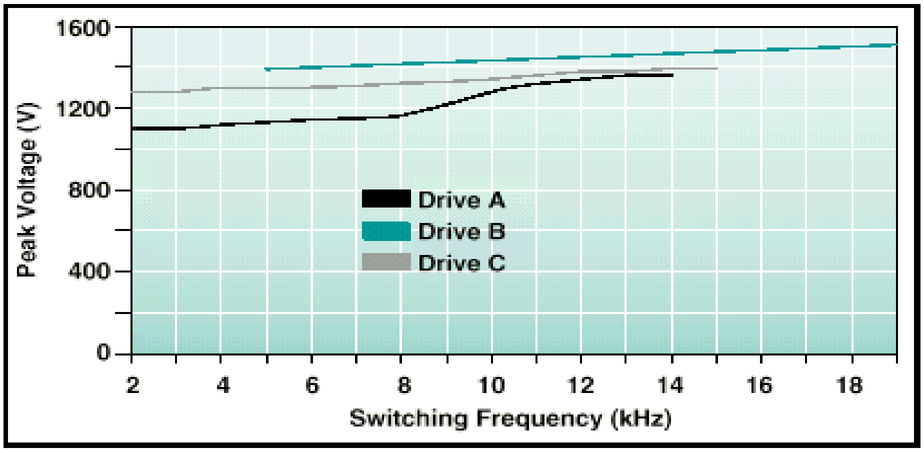


Figure 5. Peak Motor Voltage Based Upon Switching Frequency (Lead Length of 100 Feet)

Figure 5-7
TEST RESULTS OF PEAK MOTOR VOLTAGE BASED UPON SWITCHING FREQUENCY FOR A FIVE-HORSEPOWER MOTOR (LEAD LENGTH OF 100 FEET)

5.2.10 Shaft Voltage and Bearing Currents

5.2.10.1 Recommendations to Avoid Detrimental Effects of Shaft Voltages and Bearing Currents

In some applications, controls have been found to produce currents in the bearings of motors they control. At this point, there has been no conclusive study that has served to quantify the type of application most prone to bearing currents. In general, these guidelines can minimize the potentially detrimental effects of shaft voltages and bearing currents:

a) Use a lower voltage supply (for example, 230 volts instead of 460 volts) and the appropriately rated motor and control.
b) Run the control at the lowest carrier frequency that satisfies any audible noise and temperature requirements.
c) Add a shaft-grounding device to the motor. Some devices have a brush that rides on the motor shaft. Current does not go through the bearing, but is instead conducted directly to ground through the brush. These brushes are especially selected to tolerate misalignment and maintain rotating contact throughout the brush's life when properly maintained.
d) Use a motor with both bearings insulated. This approach will avoid damage to the motor's bearings.

   CAUTION—OTHER NON-INSULATED BEARINGS CONNECTED TO THE SHAFT WITH A CONDUCTIVE COUPLING (SUCH AS TACHOMETERS OR GEARBOXES) MAY BE DAMAGED BY THE SHAFT VOLTAGE.

   CAUTION—INSULATION FOR BEARINGS MUST PROVIDE A HIGH IMPEDANCE TO HIGH FREQUENCY SIGNALS IN ORDER TO BE EFFECTIVE AGAINST COMMON MODE VOLTAGE INDUCED BEARING CURRENTS.

e) Use non-conductive couplings for loads or devices which may be damaged by bearing currents.

f) Ensure that the control and motor are grounded per the manufacturers' instructions.
g) Use a filter that reduces common mode voltage.

5.2.10.2 Examples of Bearing Current Damage

Figure 5-8 shows the inner race of a bearing from a 20-horsepower motor operated on a control. The serration pattern is called "fluting." The flutes are the source of audible bearing noise and reduced bearing service life.

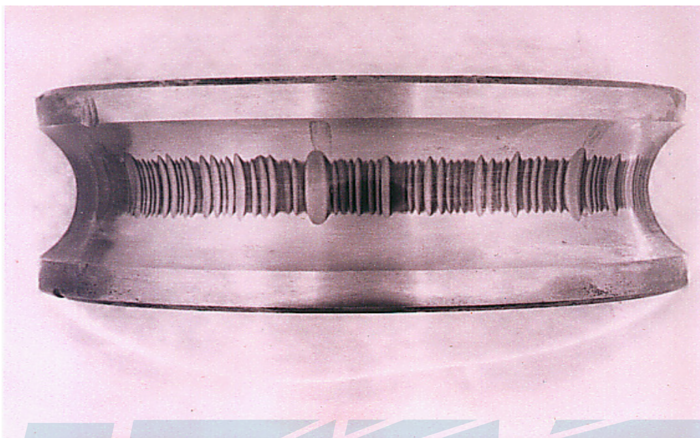


Figure 5-8
FLUTED BEARING DAMAGE CAUSED BY ELECTRICAL CURRENT FLOW

The image from a scanning electron microscope, Figure 5-9, shows a one-micron diameter pit in the fluted area of the bearing. It is caused by current flowing during a single discharge. As electrical discharges continue to occur the pits begin to overlap each other. Ultimately, if the bearing operates with current long enough, the groove like configurations called flutes will form.

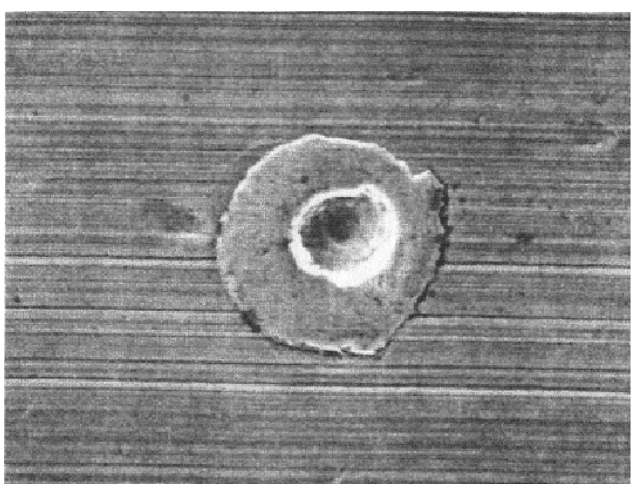


Figure 5-9
ELECTRICAL ARC PIT LOCATED ON THE INNER RACEWAY OF BEARING

5.2.10.3 Sources of Bearing Current

Bearing current will flow when voltage is developed across the bearing sufficient to break down the insulating capacity of the grease. There are several sources of this voltage:

a) Dissymetery in the magnetic circuit of a motor creates a situation that causes bearing currents. This is more common in motors greater than 75 HP. The unbalanced magnetic circuit results in unwanted time-varying circumferential flux in the motor that inducesAC voltage along the length of the motor shaft. The shaft, bearings, end brackets, and outer shell form a closed circuit which may allow current to flow. If the induced voltage is sufficient to break down the grease, current will flow through the bearing.

b) A voltage can also be caused by an electrostatic build up on the shaft due to friction with the driven load (such as paper on rollers). This situation does not normally lead to fluting.

c) A voltage across the bearings can also be the result of common mode voltage created through the application of the control generated voltage to the motor.

d) The common mode voltage also causes current to flow from the stator winding to ground via parasitic capacitances between the winding and ground. These currents generate a radial time-varying magnetic flux which links the shaft and induces voltage along its length end-to-end. Although this voltage is rooted in a different source than that caused by magnetic dissymmetries described in item a), the resulting current path is the same. In contrast to the phenomenon described in item a), these circulating currents may cause bearing problems in frame sizes smaller than 500 frame (most likely in the 400 and larger frames).

5.2.10.4 Common Mode Voltages

Controls produce adjustable frequency by switching their three outputs alternately from the positive to the negative potential rails of a DC voltage bus. The switching occurs at a high rate on modern controls, typically 1 kHz to 20 kHz. Since there are an odd number of outputs, there can be only four possible control output states: 1) two high and one low, 2) two low and one high, 3) all high, and 4) all low. Note that none of these states is balanced, resulting in a fluctuation of the motor neutral voltage with respect to ground. This voltage fluctuation is typically referred to as common mode voltage.

Unwanted current pulses are driven by fast-rising common mode voltages through unintentional (parasitic) capacitance that exists from the lead to ground. Parasitic capacitance exists between the leads and the metal conduit, for example, and between the motor’s windings and its frame. Since the common mode voltage contains high frequency AC components, a current will flow into the lead and to ground through these capacitances.

5.2.10.5 Shaft Voltage and Bearing Current

A primary cause of bearing currents in motors driven by controls is common mode voltage. A capacitive coupling exists between the stator winding and the rotor surface, Figure 5-10. High frequency common mode voltage, produced by the control, forces current to ground through a circuit path consisting of this capacitance, the rotor, the shaft, the bearings, and the grounded end bracket.

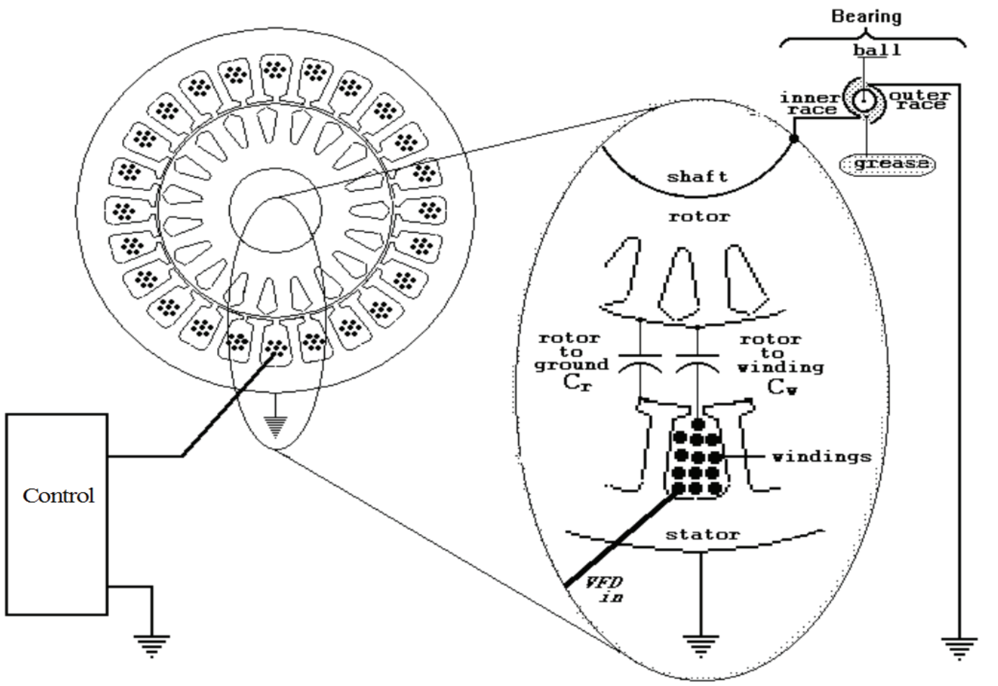


Figure 5-10
ELECTRIC MACHINE SHOWING PARASITIC COUPLINGS

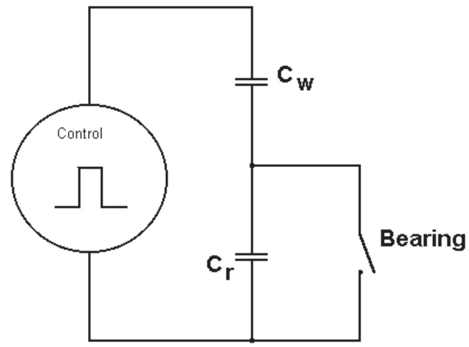
5.2.10.6 The Common Mode Circuit

The control forces current through the capacitor divider formed by the winding-to-rotor capacitance (C_w) and the rotor-to-ground capacitance (C_r). The result is an AC voltage on the rotor and shaft, with respect to ground. The amplitude of this voltage is proportional to the source common mode voltage at the motor terminals and the ratio of C_w to (C_r + C_w). (See Figure 5-10). C_w is normally much smaller than C_r, so the shaft voltage is lower than the applied common mode voltage. The shaft voltages can reach 25 volts when the control is fed with 460 volts.

The balls, races, and grease film in the bearing form a “switch” across C_r, capable of discharging it. If the shaft voltage reaches a high enough level, the bearing will conduct and C_r will discharge through the ball and races.

The rotor is supported by bearings with a grease film that is not normally conductive. At high speeds, an even distribution of the grease film exists, and the rotor is not in contact with the outer (grounded) bearing race. The rotor voltage is free to oscillate with respect to ground. The voltage that the grease film can support is constantly changing due to thickness, surface roughness, load, temperature, etc. When the shaft voltage reaches a level capable of breaking down the grease film, electrical conduction occurs and C_r discharges through the bearing.

The entire circuit can be simplified as shown in Figure 5-11.



Common Mode Basic Circuit

Figure 5-11
COMMON MODE BASIC CIRCUIT

5.2.10.7 Experimental Evidence

Figure 5-12 is an oscillograph of the shaft voltage on a 20 HP 6-pole induction motor excited by a control. Note the shaft voltage is an AC voltage and continues to vary in amplitude while no current flows through the bearings.

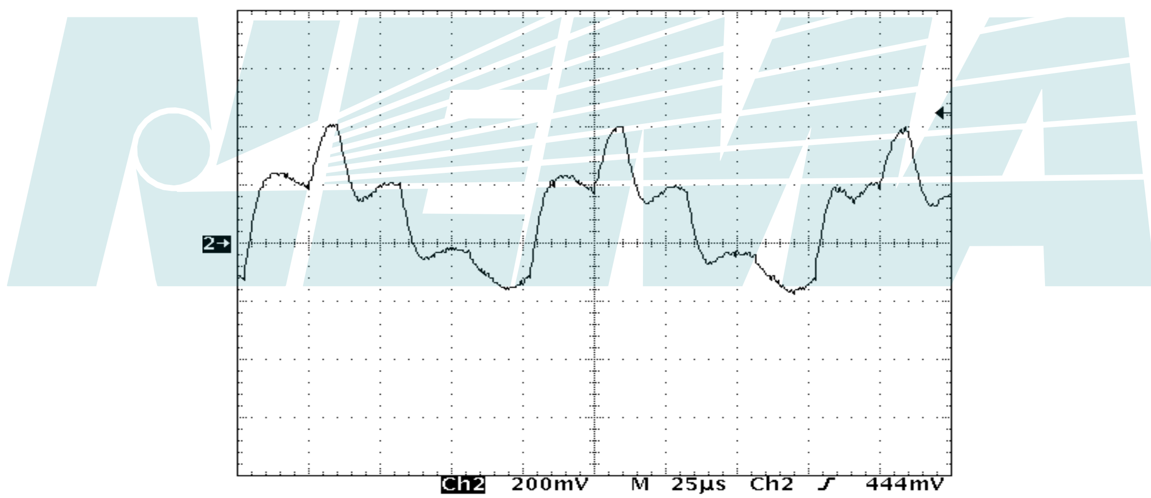


Figure 5-12
SHAFT VOLTAGE WITHOUT BEARING CURRENT 10V/DIV 25µS/DIV

Eventually the voltage exceeds the value that the grease can support and it breaks down. Then the bearing conducts and the rotor and shaft are discharged. The oscillograph in Figure 5-13 shows such a discharge. Note that the shaft voltage collapses at the instant of discharge. Such a discharge can cause a pit such as the one shown in Figure 5-9.

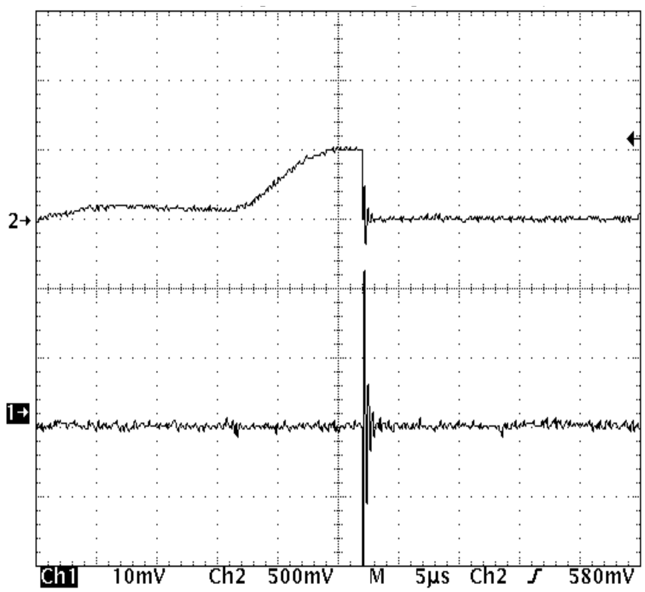


Figure 5-13
SHAFT VOLTAGE TOP 25V/DIV 5µS/DIV AND BEARING CURRENT BOTTOM 500mA/DIV 5µS/DIV

5.2.10.8 Shaft Mounted Accessories

Once there is voltage on the shaft, a current may flow in any bearing electrically connected to the shaft system, such as the bearing in a tachometer, encoder, or gearbox. Care should be taken to ensure that possible flow of bearing currents through those devices is prevented or at least minimized.

5.2.11 Load Reactors and Filters

It is possible to reduce the peak voltage at the motor's terminals by using a filter or reactor connected between the control and the motor. Successful operation depends on selecting the correct size and the high frequency performance of the device. The manufacturer should be consulted for the proper application of such filters. This may require measurements of the peak voltage at the motor terminals both before and after installation of a filter.

Such filters and reactors may have an effect on reducing common mode voltage.

5.2.12 Multiple Motors

5.2.12.1 Starting

Motors are not typically line-started when used with a control; the control and motor are usually started together. When started in this manner, the motor is not subjected to the inrush current associated with an across-the-line start. When more than one motor is used with a control there may be a requirement to connect additional motors while the control is operating. Under this condition of starting a motor while the control is operating other motors, the control must provide the inrush current associated with the motor being connected. Under this condition, the control may need to be oversized to provide the required starting current of the motor being started when the control is already operating.

5.2.12.2 Protection

Most controls are designed to provide overload protection to individual motors. These controls have built-in circuitry to sense the total current supplied by the control to the motor. If more than one motor is connected to a single control, there is a requirement to individually protect each motor.

Certain applications call for the use of one large control for multiple motors rather than driving each motor separately. In such applications, all the multiple motors on the common bus have the same voltage and frequency applied and will consequently speed up or slow down together. A typical application is a modular condenser coil system, with multiple modules, as part of a commercial duty ventilating or air conditioning system. With such a system, cooling capacity (and therefore condenser fan speed) is modulated to meet the demand of the proportional-integral temperature control loop.

Several issues should be considered regarding the protection of multiple motors on a single control:

a) Each motor should have its own independent thermal protection device scheme that disconnects it from the control or shuts off the control in the event of a thermal overload.
b) Protection schemes that use automatic reset protectors for each motor can impose locked-rotor current demand for an individual motor on the control. This requires that the control be adequately sized to handle the peak demand of line starting an individual motor, while supplying running current to the other motors, if nuisance control overcurrent trips are to be avoided.
c) Thermostats may be used for overheating protection by suitable connection to the control circuit.
d) Other requirements of NFPA 70 Article 430-53 may apply.

5.2.12.2 Peak Voltages

The use of multiple motors with a single control can result in a higher probability of having problems with repetitive high peak voltages at the motors' terminals. See 5.2.9.5(d) for additional information.

5.2.13 Pole Count

In the past, the required speed of a three-phase induction motor application defined the number of poles that the motor needed to operate successfully. With the advent of adjustable frequency controls this is no longer the case and the possibility of using a variety of motor pole options now exists. For example, an application requiring a motor speed of 3,600 RPM could use either a 2-pole motor being fed with 60Hz power or a 4-pole motor being fed with 120 Hz power.

In many cases, there are advantages to using a different pole count than one that might have been selected in the past. For example, using a 4-pole motor in many applications that typically use a 6-pole design can frequently result in higher operating efficiency and improved power factor. Many times, however, the need to maintain bypass ability limits the number of pole choices that are available to a particular application.

These issues should be considered before specifying in too much detail the pole count of the motors needed for an application. If bypass operation is not required, significant benefits may be gained through the optimization of motor pole count. By simply specifying the speed and torque requirements, in many cases, the motor and control designers can assist in choosing the optimum arrangement for the application in question.

5.2.14 Connecting High Voltage to the Low Voltage Connection of a Dual Voltage General-Purpose Motor

For general-purpose motors it is possible in some instances to extend the top speed for constant torque operation above the base operating speed by utilizing the low voltage connection of the motor. As an example, the base volts per Hz ratio of a 60 Hz motor, connected for 230 volt operation is 3.83. If the system voltage is 460 volts this allows for constant volts/Hz and therefore constant torque operation may be possible up to 120 Hz (3.83 x 120 = 460 volts). However, there are other issues that must be considered before implementing this type of arrangement.

a) Care must be taken to assure that a motor is not operated above its maximum safe operating speed, in order to avoid potential damage to equipment and personnel. Maximum safe operating speed information can be found in 5.1.2 and 5.1.3.
b) Operation at increased speed at constant torque increases the motor losses and consequently additional heat must be dissipated to prevent the motor from overheating. In many cases, increased airflow produced by the faster-running fan, when present, is enough to remove the increased losses, but this is not always the case. Consult the motor manufacturer to determine if cooling is sufficient at speeds above name plate full-load RPM.
c) At increased speeds, the windage noise produced by the fan increases approximately by the fan law: $db = db_{base} + 50\log_{10}(RPM/RPM_{base})$. As an example, a motor operated with a shaft-mounted fan at twice its base operating RPM, the noise level may increase by approximately 15 db.
d) The low voltage connection, especially on larger NEMA frame size motors, may utilize a large number of parallel circuits. Because the winding is split into smaller sections to accommodate a large number of parallel circuits, full line voltage ends up being applied across these smaller sections and the voltage stresses within the winding increase. Therefore, a possible negative consequence of using the low voltage connection to extend the constant torque range is that a motor manufacturer’s intended turn to turn and coil-to-coil voltage stress levels may be exceeded.

Consult the motor manufacturer to determine the suitability of operating a motor at high voltage on the low voltage connection.

5.3 INTERACTION BETWEEN CONTROL AND AC POWER LINE

The performance or protection of an adjustable frequency control can be affected by the power distribution system (utility/generator power source) characteristics. These interactions are reviewed in the following paragraphs.

5.3.1 Source Impedance/Short-circuit Ampere Interrupting Capacity (AIC) Ratings

The source impedance or available short-circuit current rating of the AC power source that an adjustable frequency control is connected to should be reviewed for proper operation and protection of the equipment.

UL 508C provides guidelines on the minimum AIC ratings of adjustable frequency controls indicated in Table 5-9.

Table 5-9
MINIMUM AIC RATINGS

Horsepower	AIC Ratings
1.5 – 50	5000
51 – 200	10,000
201- 400	18,000
401 – 600	30,000
601 – 900	42,000

The maximum short-circuit AIC rating is usually designated on the control’s nameplate. When a control is connected to a high-capacity power source (high available short-circuit current), the control AIC rating should exceed the short-circuit current available from the power source. When this is not the case, AC input current limiting fuses and line reactors can be used to provide protection.

5.3.2 Line Variations

5.3.2.1 Voltage Amplitude

Most adjustable frequency controls will operate over a wide range of input voltage variations; many allow a ±15 percent voltage variation range without tripping. However, when other electro-mechanical devices (bypass, line, output contactors, etc.) are used in the same motor circuit, the overall voltage variation of the adjustable speed drive system will be limited to the lowest device voltage variation rating. Typically electro-mechanical contactor devices have a nameplate rating of ±10 percent voltage variation.

AC motors are designed to operate at 100 percent output torque with ±10 percent of the nameplate rated voltage applied to the motor terminals. Although many controls can operate at an input voltage of ±15 percent of the control rating, the maximum output voltage may be reduced under these conditions that could reduce the motor's output torque performance.

The applied line voltage at the input terminals to a control should be confirmed to be within the nameplate voltage rating.

5.3.2.2 Voltage Unbalance

A voltage unbalance results in a current unbalance. If this current unbalance results in a phase current exceeding the input power device current rating, damage to the control may occur. Adjustable frequency controls can operate on power systems with a voltage unbalance not exceeding three percent.

5.3.2.3 Single-Phase Input for Three-Phase Drives

Some three-phase adjustable frequency controls are rated for operation with a single-phase input. In these instances, the control is typically derated or qualified at a reduction from its nameplate rating based on manufacturer's recommendations.

Those three-phase controls that have been designed for installations where only 115 volt, single-phase power is available may utilize an internal voltage step up circuit to provide a 230 volt three-phase output. These controls are typically available in ratings one horsepower and less.

Some of the side effects of single-phase operation include, but are not limited to, higher input ACrms currents, higher zero-sequence harmonic currents on the distribution system, and reduced output voltages.

Care should be exercised when single-phase input operation is being proposed to ensure that the control, the input power wiring, and the upstream protective components are being operated within their ratings and as recommended by the control manufacturer.

5.3.2.3 Frequency

Typically, an adjustable frequency control can operate satisfactorily with an input frequency variation of ±3 percent.

5.3.3 AC Line Power Factor

5.3.3.1 General

Inductive loads like AC motors operating across-the-line will cause a lagging displacement power factor, thus causing non-power producing or reactive current to flow in the power distribution system. This reactive current will not be observed in the AC line when the motor is operated from an adjustable frequency control. Because of the rectifier design, a voltage source PWM control will typically operate with a displacement power factor of .95 or greater, and it remains essentially constant at all operating speeds. Hence, the need or desire for power factor correction is eliminated.

Distortion or harmonic power factor is a result of harmonic currents flowing and exists for all adjustable frequency controls operating from an AC power source. Since the distortion component of the total power factor is determined by line impedance for a specific installation, it is impractical to define a total line power factor value for adjustable frequency controls. For this reason, most manufacturers provide only the displacement power factor.

5.3.3.2 Power Factor Correction/Precautions

The installation of any power factor correction capacitors on the input to the control, if applied, should be carefully analyzed to avoid harmonic frequency resonance conditions. A harmonic study of the power distribution system should be conducted to determine the harmonic resonance frequencies.

The effect of distortion or harmonic power factor cannot be corrected with power factor correction capacitors, but may be improved by adding AC line inductance (line reactors), multi-pulse front ends (12, 18, 24, 36 pulse), or broad band filters. A harmonic study of the power distribution system must be conducted to determine the effect of the distortion power factor improvement.

Random switching of power factor correction capacitors may cause voltage transients on the AC line that could cause nuisance overvoltage control tripping. When this condition occurs a line reactor may be installed in front of the control to reduce the magnitude of the line transients, thus preventing overvoltage control tripping.

5.3.4 Line Harmonic Currents—Adjustable Frequency Control Created

Nonlinear loads like adjustable frequency controls create line harmonics when connected to the AC power distribution system. These harmonic currents are a result of non-sinusoidal current, which is a characteristic of all adjustable frequency controls using diodes or silicon controlled rectifiers (SCRs) on the input. The control's input current is composed of the fundamental sinusoidal current (50 or 60 Hz) and currents at frequencies higher than the fundamental frequency. These harmonic currents do not aid in the transmission of power to the connected load, but contribute to the volt-ampere losses in the power distribution system.

Some of the negative effects of AC line harmonics if not properly addressed are:

a) Possible interference with communication equipment.
b) Possible overheating of transformers and other branch circuit equipment.
c) Possible increased heating in motors connected across-the-line due to copper and iron losses.
d) Possible resonance with power factor capacitors.

The AC input line harmonic current magnitudes may vary with control designs. The power distribution system impedance at the installation and the control's input design determines the actual magnitude of line harmonic currents. Because of these variables, it is difficult to suggest general guidelines to predict the magnitude of the line harmonic currents. When the actual harmonic current values are required, the control manufacturer should be consulted.

When AC line harmonic currents exist in a power distribution system, the harmonic currents may be amplified through frequency resonance of power factor correction capacitors with transformer inductance to cause equipment failures.

Harmonic distortion levels as stated in IEEE 519 are intended to be applied at the Point of Common Coupling (PCC) between the utility system and multiple users. Harmonic distortion levels can be measured or predicted through modeling techniques of the power distribution system and the total connected adjustable speed drive system.

The harmonic voltage and current distortion values at the PCC may be reduced through several abatement methods that include:

a) Design Techniques
   1. Power system design—decreasing the drive system load, as a percentage of the total power distribution network load will improve harmonic voltage distortion conditions.
   2. DC Link choke/inductor—an inherent design feature within some controls, provides a minimum level of harmonic reduction by changing the rate of rise of the input current.

b) Line Impedance
   1. AC line reactor—based upon the percent of line impedance, provides a lower amplitude of harmonic currents by slowing down the rate of rise of input current pulses, similar to DC link choke.
   2. Drive Isolation Transformer—provides similar performance to an AC line reactor with the additional power quality benefit of being able to adjust the voltage magnitude.

c) Multi-Pulse Methods/Converter Design Topologies
   1. Phase multiplication—involves the use of a phase-shifting transformer for feeding multi-pulse control inputs. By properly shifting the phase relationship to various six-pulse controls, the net effect in the power system is to create a twelve-pulse circuit with cancellation of the fifth and seventh characteristic harmonics. However, this method is most effective when the motor loads are of equal size and load.
   2. Twelve-pulse rectifier—a control that utilizes a dual six-pulse rectifier network with a phase shifting transformer for proper commutation of the dual bridges. Similar to phase multiplication, the net effect is cancellation of the fifth, seventh, seventeenth, and nineteenth characteristic harmonics.
   3. Eighteen-pulse rectifier—a control that utilizes three six-pulse rectifier networks with phase shifting transformers for proper commutation. This results in an improved waveform, cancellation of lower order fifth, seventh, eleventh, thirteenth, twenty-third, twenty-fifth, twenty-ninth, and thirty-first characteristic harmonics.
   4. Active rectifier input—a control that incorporates gate controlled power semi-conductors in the input rectifier stage to shape the input current waveform, to a sinusoidal current waveform symmetrical to the voltage. This method of harmonic abatement is the most complex. A microprocessor controller is required for gate control of the input power semi-conductors.

d) Harmonic Filters
   1. Shunt filters—passive filters that are properly designed and for the fifth, seventh, and thirteenth harmonics can effectively reduce the harmonic currents in a power distribution system. Each filter consists of a series LC circuit, tuned to resonate at a specific harmonic frequency acting as a low-impedance path, shunting the source of harmonics. Specific site application considerations apply since the filter cannot distinguish between the harmonics from the control equipment, other external power system harmonics, or additional installed control equipment.
   2. Series filters—these filters consist of a parallel LC circuit tuned to resonate at a specific frequency, similar to a shunt filter. The series reactor acts to de-tune other power distribution system harmonics from being trapped by the passive filter.
   3. Harmonic injection—adaptive compensators are designed to constantly monitor the AC line input current to the control by injecting a current equal in frequency/magnitude and 180° out phase to the distorted current. This action will cause cancellation of the line harmonic currents.
   4. Active filters—designed primarily for multiple non-linear harmonic loads, monitoring dynamic load conditions and switching necessary VAR compensation.

5.3.5 Control Protection

5.3.5.1 General

When a control is used to adjust motor speed, the utility power source is isolated from the motor; therefore the control becomes the motor power source. This control, which is limited in ampere capacity as compared to the utility power source, is then sized to the motor nameplate electrical rating. Due to its limited capacity, protection circuits must be used to prevent control failures when certain fault conditions occur.

5.3.5.2 Short Circuit Protection

The short circuit withstand rating of the control should be greater than the available short circuit capacity of the connected AC line. AC input fusing can help protect the control from input power short circuit conditions. Refer to 5.3.1 for additional information. In general, branch circuit breakers or disconnect switches do not provide the same level of current limiting protection for control components.

It is the responsibility of the user to provide proper branch-current protection according to the *National Electrical Code®* (*NEC*) and local codes.

5.3.5.3 Transient Voltage Protection

Transient voltages occurring in AC power circuits can originate from lightning effects or system switching transients such as capacitor switching. Voltage transients can cause overvoltage tripping or damage to control components.

A control can be very sensitive to transient voltages when compared to other loads, such as motors. Metal oxide varistors are commonly used for transient voltage protection. When the varistor is exposed to a high voltage transient, its impedance changes from infinity to a low value. The varistor can clamp the transient voltage to a safe level and absorb the transient voltage energy. When the varistors fail during a transient, a short circuit occurs, which could result in a fuse operation and tripping of the control.

5.3.5.4 Overvoltage Protection

An overvoltage condition may be the result of high line voltage, line voltage transients or regenerative power (overhauling load) from the AC motor/load. During overvoltage conditions, protection circuits are used to protect the control from component failure. The control overvoltage trip value is not adjustable. The actual trip value is per the manufacturer’s specifications. Line reactors or isolation transformers may be used to protect against line voltage transients. Dynamic braking resistors may be used in some instances to dissipate the regenerative power from overhauling loads.

When the control senses an overvoltage condition (transient or regenerative) an overvoltage protective fault will occur, causing a trip event. Many controls may be configured to auto re-start under these conditions, however persistent tripping will require corrective action.

The major causes of control overvoltage tripping are the switching of power factor capacitors, lightning storms, regenerative loads, and poor grounding techniques. When experiencing overvoltage conditions, each cause must be investigated. A solution should then be applied per the manufacturer’s recommendation.

5.3.5.5 Undervoltage Protection

An undervoltage condition may be the result of low line voltage or momentary power interruption. The control undervoltage trip value is per the manufacturer’s specifications. During undervoltage conditions, the voltage output of the control may be reduced. This may result in decreased motor-output torque, therefore affecting system performance.

The control may include a re-start or ride-through function to minimize the effects of undervoltage events. A ride-through function allows the control to maintain control of the motor during an undervoltage transient condition. The ability of ride-through to maintain control of the connected motor is dependent on duration of the undervoltage disturbance, amount of stored energy available from the control and the demands of the connected motor load.

Many controls may be configured to increase their ride-through capability by using the regenerative energy from the reflected motor/load inertia to maintain the control's DC bus voltage.

5.3.5.6 Single Phase Input Protection

Single-phase operation will result in a significant increase in input rms currents, additional heating in the DC bus capacitors, and higher harmonic currents in the power distribution system. Most controls are equipped with single-phase protection to either reduce the load on the equipment or shutoff the unit. Consult the manufacturer for proper guidelines and ratings.

5.3.5.7 Ground Fault Protection

A ground fault condition may be the result of motor phase to ground short, parasitic capacitance coupling to ground (long or motor cables in water) or motor cables shorted phase to ground. During output ground fault conditions, the control protects against component failure. The control's ground fault ampere trip value is not adjustable. The actual trip value is specified by the manufacturer.

The parasitic capacitance coupling to ground may be cancelled with the use of a reactor or LC filter between the control and motor.

5.4 DRIVE SYSTEM INTERACTIONS

5.4.1 Efficiency

The overall efficiency of an ASD is based on the total losses of the control, the motor, and any auxiliary equipment. The control efficiency is typically very high (98 percent or higher) for most control sizes. The motor efficiency varies, depending on motor size and speed, from the 60-70 percent range for small motors to the upper 90 percent range for larger motors when operated from a sinewave source. Motor efficiency also changes as the load changes, typically decreasing below 75 percent of rated torque. The motor efficiency when operated on a control is slightly less than when operated on sinewave power.

Overall system efficiency is often increased when using an ASD. Traditional methods of changing speed such as gears or belts introduce additional losses which reduce efficiency. Methods of adjusting load such as closing dampers or valves either unload the motor, reducing efficiency, or bypass part of the output also reducing efficiency. Improvements in system efficiency when using an ASD come from the fact that the motor can be operated over a range of voltage and frequency to meet speed and load requirements.

The extent to which efficiency is increased using an ASD depends on the type of application or load. The greatest benefit will be on variable torque loads where the torque demand on the drive reduces with speed. Motor voltage from the control can then be reduced to compensate for the decrease in motor efficiency that would normally result from reduced load. This is in addition to the gain in efficiency that may result if dampers, valves, or other external devices are no longer needed to reduce flow.

System efficiency improvement for constant torque or constant horsepower loads is primarily due to the ability to change speeds rather than relying on multi-speed motors, with a fixed number of speeds, or mechanical means of changing speed.

5.4.2 Sound, Vibration, Resonance

5.4.2.1 General

The motor and the driven equipment have natural resonant frequencies in the lateral, axial, and torsional modes. When a control is used with a motor, the motor is excited by a spectrum of harmonics originating from the control. This excitation can affect the sound level, vibration level, and torsional response of the entire system by corresponding to the natural resonant frequencies of the motor or the driven equipment. In some cases, the switching frequency may be adjusted to avoid objectionable frequencies. Additionally, some drives can be programmed to exclude or skip frequency bands that cause objectionable mechanical resonances.

5.4.2.1 Sound and Vibration

Sound and vibration levels of the drive system are influenced by the following parameters:

a) electromagnetic design of the motor
b) control type
c) resonance of the motor’s frame structure and enclosure
d) integrity, mass, and configuration of the motor’s base mounting structure
e) sound and vibration originating at the coupling between the motor’s shaft and the driven load
f) windage

It should be noted that since many of these influencing factors are outside of the motor, it is not possible to address all sound and vibration concerns through the design of the motor alone.

5.4.2.3 Torsional Considerations

When an induction motor is operated from an adjustable frequency control, harmonics in the control output waveforms may generate torque ripple over the operating speed range. Consideration should be given to the frequency and amplitude of such torque ripple and to the potentially harmful effect of torque ripple on the motor and the driven equipment. It is of particular importance that the equipment not be operated other than momentarily at any speed where a resonant condition exists. Such resonance points correspond to the mechanical natural frequencies of the load or support structure. For example, if the control operates in a six-step mode, a sixth harmonic torque ripple is generated, varying from 36 to 360 Hz when the motor is operated over the frequency range of 6 to 60 Hz. If the mechanical system has a natural frequency between 36 and 360 Hz, continuous operation at this point must be avoided.

At low speeds, torque ripple may be apparent as observable oscillations of shaft speed or as torque and speed pulsations, usually termed “cogging.” The lower the switching frequency, the greater the current ripple and the more pronounced the effect. Typically, because of the high rotor and load inertias, these effects are minor and are neglected for PWM controls operating at 2.5 kHz and higher. Only for special cases of very sensitive loads and low inertia rotors or very low speeds does torque ripple become a factor.

5.4.3 Grounding

5.4.3.1 Grounding of Control

AC power system grounding is a critical consideration. The control must be solidly grounded to the main distribution system ground.

A ground common with electrical welding equipment or large current electrical equipment (5x rating of the control) should not be used. If either of these two conditions exists, use an isolation transformer sized for the installed control with a wye secondary neutral solidly grounded.

Where more than one control is used, ground each directly to the system ground terminal, do not loop ground or install them in series.

Always follow the *NEC* local codes, and the manufacturer's recommendation when installing control ground wiring.

5.4.3.2 Grounding of Motor

The output ground conductor may be run in the same conduit as the AC motor power leads. This wire should be used as an equipment ground for the motor and not as the fourth current carrying wire of a "wye" motor circuit. The grounded metal conduit carrying the output power conductors can provide EMI shielding, but it does not provide an adequate ground for the motor; a separate ground conductor should be used.

5.4.3.3 Bonding of Motor

Consideration should also be given to bonding the motor to the coupled equipment to prevent shaft extension currents.

5.4.4 Power Cable Selection

5.4.4.1 Sizing

A control may have two current ratings listed on its nameplate, an input and an output current rating. The input current rating may be higher than the output current rating due to harmonic currents associated with low impedance distribution systems. The input feeder conductors must be sized per Article 430-2 of the *NEC* using the control nameplate listed input current rating.

The output conductors must be sized per Article 430-2 of the *NEC* using the motor nameplate current.

5.4.4.2 Differential Mode Considerations

When considering the relationship of motor-cable type to motor-terminal voltage transients, the effect of the voltage transients upon the motor cable must be considered as well as the impact of cable choice upon the magnitude of the transients.

Motor cable selection has been found to have only modest impact upon voltage transients. The use of shielded, armored motor cable may reduce the transient magnitude by 50 volt to 100 volt for 460 volt to 575 volt systems experiencing peak voltage above 1,000volt when compared to unshielded cable.

The impact of motor terminal voltage transients upon motor cable insulation systems must also be considered. As illustrated below, the voltage capability of standard cable types is sufficient for most dry applications. Applications in wet conditions, however, may require different cable.

5.4.4.2.1 Partial Discharge Inception Voltage (PDIV)

Standard cable insulation voltage ratings are 600 Vrms (850 Vpeak), 2,000 Vrms and 5,000 Vrms, with 10,000 Vrms available on a limited basis. Reflected wave stress of 2 pu to 2.4 pu on 480 volt systems is 1,300 to 1560 Vpeak while 575 volt systems result in 1620 to 1945 Vpeak stress. Although peak reflected wave duration is less than 1 μs, it occurs at the carrier frequency rate, which is typically 3 to 12 kHz for drives up to 20 horsepower and 1.5 to 3 kHz for larger drives. Thus, there is a concern whether a satisfactory service life for 600 Vrms rated cable is achievable with 2 to 2.4 pu peak repetitive reflected wave stress.

The dielectric failure mechanism most likely to reduce cable life is if the insulation is susceptible to corona at the 2 to 2.4 pu peak transient voltage. Partial Discharge Inception Voltage (PDIV) is the minimum applied voltage at which partial discharges occur, that is, the lowest applied voltage that causes electrical breakdown of the air around the cable or in air voids. No degradation in sinewave rated cable life is expected if the measured PDIV peak voltage is higher than the 2 to 2.4 pu reflected wave peak voltage. As a guideline, this section presents UL dielectric test requirements for type MC cables and also provides some PDIV test results to determine if the cable is susceptible to corona from reflected wave voltages.

Table 5-10 contains 60 Hz sinewave rms dielectric test voltages specified in UL 1569 Type MC 600V cable using both XLPE and PVC insulation as wire AWG is increased. Test results show the PDIV of XLPE under dry atmospheric conditions is within five percent to 17 percent of UL 1569 specified dielectric potentials, while the PDIV of PVC is within four percent to 27 percent of UL specified peak dielectric voltage required. Tested PDIV values of 2723 Vpeak for PVC (at 15 mils) and 4942 Vpeak for XLPE (at 30 mils) are still greater than applied peak reflected wave voltage of 1924 Vpeak (for a 575 volt system). Thus, both 600 volt rated insulations should achieve rated life under dry conditions. However, because XLPE insulated cables have a higher PDIV compared to PVC cables with the same insulation thickness, they should achieve even a longer life relative to reflected wave voltage spikes.

PDIV tests performed on 600 volt rated 30 mil XLPE and 15 mil THHN PVC insulation under wet conditions of 90 percent relative humidity for 48 hours show the PDIV of XLPE decreased only 5 percent, while PVC had a 50 percent reduction in PDIV level. Thus, 600 volt XLPE will retain higher PDIV levels than PVC in the presence of moisture. There is concern for 15 mil thickness PVC wire used in moisture laden applications and which contain nicks in the insulation induced by the wire pulling process. This combination may reduce the dry 2,723 Vpeak PVC 15 mil wire PDIV level by 50 percent to 1,361 Vpeak and into the peak reflected wave voltage range of 1,300–1,560 Vpeak and 1,620–1,945 Vpeak that occur in 480 volt and 575 volt applications, respectively.

Peak reflected wave voltage is not of concern when using PVC insulation thickness of 30 mils or greater because the PDIV level Table I in greater than the system peak reflected wave voltage. Thus, 600 volt rated XLPE and 600 volt PVC cables of phase insulation thickness ≥30 mils are adequate to handle the 2 pu reflected wave transient, while 15 mil PVC cables should be restricted to dry environments to prevent cable insulation failure.

Load filters (see 5.2.11) will further reduce the reflected wave amplitude seen on the cable, increase cable life, and eliminate wire voltage concerns, even for 15 mil PVC wire. These additional reflected wave solutions will insure cable service life similar to that when operating on the 60 Hz sinewave utility line.

Table 5-10
60 HZ SINEWAVE DIELECTRIC TEST VOLTAGE SPECIFIED IN UL 1569 600V TYPE MC CABLE VS.
CORONA INCEPTION VOLTAGE TEST RESULTS AT 25°C

Drive HP		XLPE Insulation Type XHHW					PVC Insulation Type THHN				
		Insulation Thickness (mils)	Specified Voltage			CIV Test	Insulation Thickness (mils)	Specified Voltage			CIV Test
	Possible AWG used		(V_{rms})	(V_{pk})	(V_{pk})	Δ = CIV– UL		(V_{rms})	(V_{pk})	(V_{pk})	Δ = CIV– UL
250 to 500	500 MCM to 250 MCM	65	5,000	7,071	6,749	-5%	60	3,000	4,242	4,793	12%
		65	5,000				60	3,000			
125	1– 2/0	55	4,000	5,656	6,309	12%	50	2,500	3,535	4,450	25%
	2	45	3,500	4,949	5,819	17%	40	2,000	2,828	4,063	43%
50	4	45	3,500				40				
	6	45	3,500				30	2,000	2,828	3,613	27%
	8	45	3,500				30				
30	10	30	3,000	4,242	4,942	15%	20	2,000	2,828	3,062	8%
7.5– 20	12–14	30	3,000				15				
0.5– 5	12–14	30	3,000				15	2,000	2,828	2,723	-4%

5.4.4.3 Common Mode Considerations

As described in more detail below, common mode voltages are a result of either the PWM modulation scheme or cable and grounding dissymmetries. Selection of the proper cable helps to mitigate these voltages and resultant currents. While many installations perform successfully with standard cable, to assure that this issue is minimized, continuous welded aluminum armor cable from Figure 5-13 may be required.

5.4.4.3.1 Common Mode Considerations Background

When considering the motor cable type relative to common-mode performance, the cause and effects of common mode voltage and currents should be evaluated. Common mode voltage is a natural result of PWM techniques used in the typical adjustable frequency control. This common mode voltage, in conjunction with the existence of a common mode impedance (all of the stray capacitance and inductance throughout the system), will produce one component of a common mode current. A second component of the common mode current is caused by the asymmetries of an inadequately designed cabling system. In theory, a three-phase power system has zero summed current (the summation of the currents in each of the phases, frequently referred to as “zero sequence”). This is because the load is equal for all 3 phases, and the wires, which make up the phase conductors in the cable, are oriented in a symmetric fashion. This provides equal capacitances and inductances. In this situation, there will be no contribution to a common mode current. When the single wire for the safety ground is added, the symmetry is disturbed, and both the capacitance and inductance balance is upset, and a current is induced into the safety wire which becomes an added common mode component.

To reduce the generation of the second component of the common mode current, an obvious approach is to use a symmetric safety ground within the cable structure by incorporating three wires for safety distributed within the interstices formed by the phase conductors, as shown in the continuous welded aluminum armor example in Figure 5-14. The total current carrying capacity of these three wires must be equivalent to the single wire normally used for safety as well as the current circulating in each of the wires due to coupling from the phase conductors (the sum of the current is zero but there is a finite circulating current in each one). The total reduction of the second component of common mode current cannot be realized because of the reality of cable manufacturing is not precise, and true symmetry cannot be maintained. Therefore, some common mode current will tend to flow.

To reduce the impact of common mode current, whether caused by the asymmetry of the cabling system itself or from the modulation technique, a low impedance return path must be provided for the current. Keep in mind that the common mode current is trying to return to the drive source and not to the earth ground. The lowest inductive path is the one which forms the minimum area around the phase conductors and is symmetric relative to them. This basically describes the sheath/armor or conduit around the cable. The low inductance can be obtained through the use of a continuous-corrugated-aluminum sheath/armor or some other low resistance material. The selection of a continuous-corrugated material was chosen over an over-lapping or interlocked configuration (as seen in Figure 5-14) because the later geometric structure permits oxidation/corrosion to occur which increases both the resistance and inductance of the sheath. This increased impedance will force the current to seek an alternate, lower impedance path. This alternate path back to the control could be through the motor bearings or even the customer’s equipment, earth ground and/or the building structure and the stray impedances within the control. This metal clad cable can also serve as a conduit as it is totally sealed and normally covered with a PVC material to prevent inadvertent contact with other metal to minimize potential unwanted ground loops. This cable construction is also very beneficial for the reduction of radiated emissions as long as the ends are terminated properly with a 360-degree connector (one which makes an unbroken circumferential contact with the sheath, no pigtails).

Rigid conduit, in theory, will accomplish the same as the above cable; but, in practice, it does not work because it is normally thought of providing mechanical protection of cables. Practical problems can develop causing discontinuities and a poor high frequency ground. Motor cables may start out from the control in conduit but may have a discontinuity caused by transitioning to a cable tray, going to an interlocked flexible conduit (same problems as above) or going through a “pull-box” which could add impedance at input and output connections. Quite often the conduit is never terminated in the control or possibly the motor. Conduit can only be used for the common mode current path if it ensures a continuous connection from the motor frame all the way to the control cabinet with 360-degree connections at both ends.

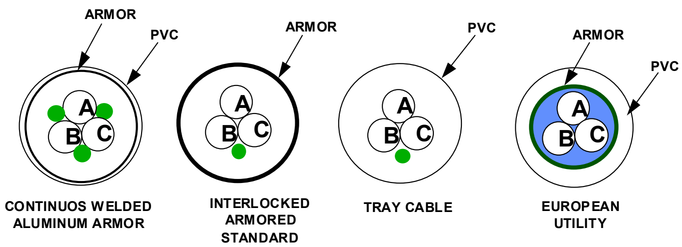


Figure 5-14
TYPES OF DRIVE POWER CABLES

5.4.5 Electromagnetic Compatibility (EMC)

Electromagnetic Interference (EMI), sometimes referred to as Radio Frequency Interference (RFI), may be an application consideration, primarily in installation areas of sensitive radio frequency receiving equipment or where controls are fed from a residential power source.

Adjustable frequency controls use microprocessors for their control. As part of the operation of microprocessors, clocks are required. Not only does the frequency of these clocks operate in the MHz range, the clock frequency is increasing as more demands are being made of these circuits. As the frequency of operation increases, the wavelength decreases. It is these short wavelengths that become a factor in the physical layout and operation of the circuit.

The four basic aspects of electromagnetic compatibility (EMC) issues are:

a) Radiated emissions
b) Radiated susceptibility
c) Conducted emissions
d) Conducted susceptibility

Radiated emission is EMI energy coming out of the unit. The unit itself is the source of the radiated energy. The antenna on a radio is an example of a source of radiated emissions. In the case of the radio, this energy is necessary to the operation of the device, however, many times this radiant energy is not desired. Radiated susceptibility refers to the likelihood of undesired EMI energy negatively affecting the unit. In this case, external radio waves might be interfering with the operation of a piece of equipment. Radiated energy is controlled by shielding the control and the power leads. This shielding must be metallic, and all shields must be connected together (common). These shields become a barrier to EMI, and thereby assist in diminishing the effects of both radiated emissions and susceptibility. Metallic conduit and shielded wire are examples of EMI shields. Plastic conduit, while providing mechanical protection, does not shield EMI. To be most effective, shielding must completely enclose the equipment in question.

Conducted emission is EMI energy that is being conducted out of the unit through the wires connecting it. Conducted susceptibility refers to the likelihood of undesired EMI energy coming into the unit on the wires connecting it to the power source. Techniques for dealing with conducted energy primarily consist of using filters on the wires, which block the EMI energy. In some cases, filters need to be used on both the incoming AC power lines, and the control’s output power conductors.

Many adjustable frequency controls today carry the CE mark according to the electromagnetic compatibility, (EMC) directive. Susceptibility and emission requirements which satisfy the EMC directive for AC adjustable speed drive systems are found in EN 61800-3. The CE mark is a requirement for all controls installed in European installations. Optional filter equipment may be needed to ensure full compliance with the EMC directives.

FCC CFR Title 47 Section 15.101-15.109 addresses Radio Frequency Interference in the USA. This FCC document list limits for both conducted and radiated emissions at various frequencies. Some controls comply with these regulations, but this does not necessarily prevent problems from occurring in the field.

EMI interference is minimized when the control is installed in a properly grounded sheet metal enclosure, with the input/output feeder conductors installed in separate metallic conduits. The control manufacturer should be consulted for recommended field wiring practices of the equipment.

Where EMI interference problems exist, an input or output filter may be installed to attenuate the conducted EMI signal levels. Installing EMI filters without analyzing the probable cause is typically not recommended since fortunately EMI interference is an exception, rather than the rule for most control installations.

Section 6
SELECTION OF MOTOR AND CONTROL BY APPLICATION

Important factors to consider in the selection and application of an ASD are outlined below. Although the steps in selecting the proper ASD components are similar for any application, the various selections are greatly influenced by the type of application. In this section these steps are described, bringing in information from other parts of this guide to aid in the selection process. Then the unique effects of various application load types are discussed.

6.1 APPLICATION INFORMATION

Complete application information is critical to the proper selection and installation of an ASD system. Creation of an initial specification that considers the driven load, motor, control, and utility power supply is the best way to achieve a successful installation.

In general this specification should include:

a) The horsepower or torque requirements at various speeds.
b) The desired speed range of the load and motor.
c) The acceleration and deceleration rate requirements of the process being controlled.
d) Starting requirements including the frequency of starting and a description of the load (the inertia reflected at the motor, load torque during starting).
e) Whether the application is a continuous process or a duty cycle of starts, stops, and speed changes.
f) A general description of the type of application including the environment in which the ASD system components must operate.
g) A description of additional functionality that may not be met with the motor and control only (motor temperature monitoring, ability to bypass the control if necessary, special sequencing circuits or analog input speed reference signals to control the ASD system).
h) A description of the available electrical supply power and wiring. The final configuration may be affected by the requirements of the system selected.

See Section 8 for an example of an ASD Application Data Form.

6.2 MOTOR SELECTION

6.2.3 Determine Motor Enclosure Requirements

Most often the environment dictates the motor enclosure selection. However, in the case of all ventilated motors, care must be taken to provide space for adequate ventilation. Some examples of commonly available enclosures for non-hazardous locations are:

a) Self-ventilated open dripproof (ODP) motors are not suited for environments containing significant amounts of airborne materials that could accumulate in the motor or chemicals that could damage motor internal parts and insulation.
b) Totally enclosed fan cooled (TEFC) motors, with external self-ventilation, are suited for most environments.
c) Totally enclosed non-ventilated (TENV) motors do not use forced air for ventilation but rely on radiation and convection to the surrounding air. When available, they are suited for most environments except where significant amounts of airborne materials are present that could

accumulate on the motor and insulate it.

d) Totally-enclosed blower-ventilated motors are similar to TEFC except with a separate motor driving the cooling fan and can be used in similar environments.

e) Open blower-ventilated motors are similar to ODP except with a separate motor driving the cooling fan and can be used in similar environments.

6.2.1.1 Hazardous Locations

WARNING—MOTORS OPERATED FROM ADJUSTABLE FREQUENCY CONTROLS SHOULD NOT BE USED IN ANY DIVISION 1 HAZARDOUS (CLASSIFIED) LOCATION UNLESS THE MOTOR IS IDENTIFIED ON THE NAMEPLATE AS ACCEPTABLE FOR ADJUSTABLE FREQUENCY OPERATION WHEN USED IN DIVISION 1 HAZARDOUS (CLASSIFIED) LOCATIONS. FOR MOTORS TO BE USED IN ANY DIVISION 2 HAZARDOUS (CLASSIFIED) LOCATIONS, THE MOTOR MANUFACTURER SHOULD BE CONSULTED.

Failure to comply with this warning could result in an unsafe installation that could cause damage to property or serious injury or death to personnel, or both.

6.2.2 Determine Motor Torque and Speed Requirements

6.2.2.1 Operating Speed Range

The desired speed range may be difficult to achieve depending on the type of application. In general, depending on motor size and load type, very wide ranges may require a special motor. Operation at very low speeds, requiring the motor to run at very low frequency (below approximately 6 Hz) or very high speeds requiring the motor to run at very high frequencies (above 90 Hz) may require a special motor.

Motor synchronous speed varies directly with the control output frequency. Therefore, the frequency required to achieve a desired application speed can be approximated by dividing the desired speed by the motor rated speed and then multiplying by the rated frequency of the motor. If the minimum or maximum frequencies are near or outside the limits mentioned above then the motor manufacturer should be consulted before proceeding. See 5.2.3 for additional information.

Examples of speed ranges are listed in Table 6-1 and 6-2, expressed as a ratio of the motor base speed to a minimum speed.

Table 6-1

**CONSTANT AND VARIABLE TORQUE SPEED RANGE EXAMPLES
(BASE SPEED = 2,500 RPM)**

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

Constant horsepower applications have a speed range where the base speed is the lowest speed, not the top speed.

Table 6-2

**CONSTANT HORSEPOWER SPEED RANGE EXAMPLES
(BASE SPEED = 2,500 RPM)**

Maximum Speed (RPM)	% Motor Base Speed	Speed Range Ratio
3,750	150	1.5:1
5,000	200	2:1
7,500	300	3:1

NOTE—These speed range examples are for illustration purposes only. Not all motors will be capable of operating within these ranges.

6.2.2.2 Breakaway Torque

The motor must have enough breakaway torque to start the load. This is not related to the motor locked rotor or starting torque published for across-the-line starting. Breakaway torque is limited by the motor, the available current from the control, and by the setup of the control. If the static torque required to start the load moving is above 140 percent of motor full-load torque, an oversized control and a motor with sufficient torque capability may be required.

There are several techniques that can be used to achieve the required torque, within the capability of the components used. These techniques should be discussed with the motor manufacturer to achieve the optimum configuration.

6.2.3 Determine Accelerating and Decelerating Requirements (Time and Load)

Once the load starts to move it must be accelerated to the desired operating speed. The motor must supply both the load torque during the acceleration plus enough torque to accelerate the inertia of the load within the desired time.

Motor selection is affected by the amount of torque required to meet the required acceleration time and how often the acceleration must be performed. If the motor is required to produce more than 140 percent of full-load torque during the acceleration, it should be clearly stated in the specification (see 5.2.4 and 6.3.7).

During acceleration, motor temperature increases as it does for any increased load (see 5.2.1.7.2.3).

If acceleration time is an important consideration for an application, the required accelerating torque must be determined, added to the load torque, and compared to the available torque. It may be necessary to oversize the control or motor, to produce enough accelerating torque to meet the specified acceleration time. It is necessary to know the specific acceleration time required, the reflected inertia at the motor shaft, the inertia of the motor, and the torque load on the motor during acceleration. Use the following to calculate the required accelerating torque.

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

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 rotor (lb-ft^2)
Δ RPM = Change in motor speed desired
t = Time (seconds) required to accelerate motor

By knowing the accelerating torque required and how often the acceleration occurs, the proper motor and control can be selected. The motor must be capable of supplying the torque, by way of overload torque (see 6.2.4), and must have the cooling capacity to handle the frequency of these starts or overloads. The control must be capable of supplying the necessary current for the duration and frequency which it occurs (see 6.3.2).

A typical control is capable of providing a deceleration torque equal to 10-15 percent of the acceleration torque. If more torque is required in order to meet a desired deceleration time, then the control will need to provide regenerative or dynamic braking. (See 5.2.5 and 6.3.8.)

The rotor inertia (Wk^2) in lb-ft^2 for the application of medium AC induction motors with dynamic braking equipment may be estimated by the following formula:

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

6.2.4 Overload Capability

Motors operating from adjustable speed controllers have a continuous torque production capability that is a function of the operating speed. Refer to NEMA MG-1 Motors and Generators Part 30.2.2.2 (see Annex A) and Part 31.3.1 (see Annex B) for additional information. Also, motors can produce torque in excess of the continuous torque capability for a short time. The ability to operate at a torque value in excess of the continuous torque capability is known as overload capability and is defined in NEMA MG-1 Motors and Generators Part 30.2.1.12 (see Annex A).

Overload capability may be required to handle peak loads during a cycle of operation, emergency operation, to handle infrequent occurrences, or for load acceleration or speed changes. The effects of overload operation on motors are similar when operated on a control as when operated on utility power. Overload operation increases motor heating. Overload capability, however, often changes at the high or low speed limits for some motors. Overload capability can vary as a function of the motor power rating and no-load magnetizing current (based on the relationship between the motor torque producing current and the maximum control output overload current). Motors with larger power ratings (i.e., 500hp) typically have less overload torque capability than motors of small power rating (i.e., 5hp). For any adjustable speed motor application, overload capability greater than 140 percent of full-load torque at a speed not exceeding base speed or greater than 110 percent of continuous torque capability at maximum speed should be clearly stated in the drive specification.

Overload torque is only available on an occasionally repeated basis (see 6.2.5.2). Unless accompanied by periods of reduced torque, overload can result in motor overheating and possible damage.

6.2.5 Determine Type of Duty

6.2.5.1 Continuous Process

A continuous process is one in which the motor starts and runs for long periods of time at various or a number of fixed speeds. Rapid speed changes, accelerations, or overloads requiring the motor to deliver more than full-load torque are infrequent.

General-purpose motors are designed originally for continuous operation at one frequency, typically 50 or 60 Hz. They also perform well within the manufacturers' recommended speed range when operated on a control. Definite-purpose inverter-fed motors are available for extended speed ranges and more demanding applications. (See 4.2.6–4.2.6.2.)

6.2.5.2 Duty Cycles

Duty cycle applications are those in which motor starts, stops, and transitions between speeds or loads are common and are done frequently. Several aspects of this type of application affect the motor and the control.

a) The motor may also be off for portions of the cycle. Normal cooling on self-ventilated motors is only achieved when the motor is rotating. With significantly less cooling when off, heat built up in the motor during operation will take longer to dissipate. Manufacturer assistance may be required to assure that there is adequate cooling for the desired duty cycle.
b) Torque demands above motor full-load torque may be required. Operation above motor full load may be required to accelerate, handle peak loads, and even decelerate the load. Operation above motor rated current will increase motor heating. This may require a higher temperature class of insulation (see 5.2.1.7.2.2), a motor rated for the overload, or evaluation of the duty cycle to determine if the motor has enough cooling for the application (see 5.2.1.7.2.3).
c) DC injection, dynamic, or regenerative braking may be required to stop the motor. (See 5.2.5 and 5.2.5.1). Regardless of whether the motor is generating torque to drive the application, generating power back to the control due to the motor being driven by the load, or supplying torque during deceleration by applying DC current to the windings, motor heating takes place approximately proportional to the square of the current while applied. This heating must be included in the duty cycle analysis.

6.2.6 Other Considerations

6.2.6.1 Bypass (Across-the-Line Starting)

In applications where across-the-line motor starting (bypassing the control) is required, the motor, contactors, and wiring must be sized properly for both bypass operation and control operation. This is especially true if the motor selected is a motor specifically designed for use with a control because it may not have the same starting characteristics as a general-purpose motor (see 5.2.8).

6.2.6.2 Operating Frequency

Operation at various frequencies can affect the following motor characteristics:

a) Cooling (see 5.2.1.3)
b) Low speed torque which may require voltage boost (see 5.2.1.4)
c) Overload (see 6.2.4)
d) Maximum safe operating speed (see 5.1.2)
e) Thermal considerations (see 5.2.1)
f) Sound and vibration (see 5.4.2)
g) Torsional considerations (see 5.4.2.3)

6.2.6.3 Efficiency

The decision of whether or not to use a high efficiency motor is typically independent of the decision to use a control. (See 5.4.1 for other considerations.)

6.3 CONTROL SELECTION

When selecting an adjustable frequency control, the following items should be considered when they are applicable. This selection process will help ensure reliable operation and maximum performance of the adjustable speed drive system

6.3.1 Control Type Considerations

When selecting an adjustable frequency control, each application performance consideration must be reviewed to ensure successful operation.

There are various types of adjustable frequency controls available today, these include: feedback vector, sensorless vector, switched reluctance, volts/Hertz, current source, and servo type. The scope of this document covers only sensorless vector, feedback vector, and volts/Hertz type controls for use with NEMA rated AC motors. When selecting these control types there are specific performance considerations of each type. These performance considerations are in Table 6-3.

Table 6-3
CONTROL PERFORMANCE CONSIDERATIONS

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
Torque @ zero speed	Best	Poor	N/A
Torque response <1.0ms	Best	Good	Poor

6.3.2 Control and Motor Voltage Considerations

6.3.2.1 Control Input Voltage

An adjustable frequency control must be selected based upon the voltage rating of the connected utility power source. Typical control voltage ratings are 200 volt, 208 volt, 230 volt, 460 volt and 575 volt (see 5.3.2). Line voltage transients may or may not affect the control operation, depending on the magnitude of the transient and the type of control design. If line voltage transients are known to be an issue, a line reactor or isolation transformer feeding the control may be required to attenuate the high magnitude of voltage transients.

6.3.2.2 Motor Voltage

Normally, the control voltage and motor voltage will be the same. However, certain applications using general-purpose motors and requiring constant torque above 60 Hz may be accomplished by connecting the control to a 460 volt supply and connecting the motor for 230 volt at 60 Hz. The control can be adjusted to provide 230 volt out at 60 Hz and 460 volt out at 120 Hz. This provides a constant volt per Hz ratio of 3.83 (230/60 and 460/120) over the entire operating speed range for constant torque applications. When this mode of operation is desired, the control must be selected based on the full-load current rating of the motor at 230 volt at 60 Hz (see 5.2.1.4).

6.3.3 Control HP/Current Rating Considerations

When selecting an adjustable frequency control, the output current rating should be sized based on the nameplate rated full-load current of the connected motor. Most controls are horsepower rated for the *NEC*, Table 430-152 full load amperes. These motors are typically of the 3,600 rpm and 1,800 rpm designs. The control may need to be oversized to accommodate application requirements such as high breakaway, overload, or accelerating torque, multi-motor operation, or higher pole-count motors (typically 1200 rpm or lower).

6.3.3.1 Short-time Overcurrent Rating

The ability of an adjustable frequency control to withstand a transient overcurrent condition above the maximum continuous output current rating, is referred to as the short-time overcurrent (overload capacity) rating. Typically the transient overcurrent is defined as 150 percent for 60 seconds with constant torque rated controls and 110 to 120 percent for 60 seconds with variable torque rated controls. The control continuously monitors its output current through feedback sensors to provide overcurrent protection against damage of the power semiconductors when the rated percentage values are exceeded. These short-time overcurrent ratings are necessary to provide the extra motor current (torque) that is greater than the motor full-load current to accelerate the connected load. The overload capability of the ASD will be limited by either the motor overload torque or the control short-time overcurrent rating.

6.3.4 Control Enclosure Considerations

Verify that the control enclosure is suitable for the installation environment based on NEMA designated enclosures for electrical equipment. Refer to NEMA Standards Publication 250 for additional information on control enclosure classifications.

NOTE—Underwriters Laboratories refers to enclosures as “Type” X, rather than “NEMA” X where “X” is the enclosure number.

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. These enclosures protect the components they contain from the same elements as systems designated NEMA 4, but NEMA 4X enclosures are also corrosion resistant.

6.3.4.1 Environmental Considerations

The surrounding environmental conditions of the control installation are an important consideration. The following are installation conditions that should be evaluated:

a) Ambient temperature range
b) Altitude above sea level
c) Humidity
d) Outdoor mounting
e) Shock and vibration conditions

6.3.4.2 Ambient Temperature

Typically, adjustable frequency controls are rated from 0°C to 40°C (32°F to 104°F). Derating is usually required for ambient temperatures above 40°C. Consult the control manufacturer for temperature derating information. Ambient temperatures below 0°C typically require adequately sized space heaters.

6.3.4.3 Altitude

Most adjustable frequency controls will operate at 3,300 feet (1,000 meters) above sea level without derating. Elevations higher than 3,300 feet typically will require derating of the control; this is a result of thinner air affecting its cooling efficiency. Elevations higher than 6600 feet (2000 meters) typically will require other derating considerations. Consult the control manufacturer for altitude derating information.

6.3.4.4 Humidity

Typically, adjustable frequency controls are rated for 95 percent humidity, non-condensing. Condensation may occur when the equipment is colder than the surrounding air temperature. Leaving the control energized should provide enough heat to minimize condensation, unless the ambient temperature is below 0°C. Use a properly applied enclosure space heater for those applications.

6.3.4.5 Outdoor Mounting

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

6.3.4.6 Vibration Conditions

Most adjustable frequency controls have the ability to operate in an environment of continuous vibration. Typical specifications for vibration, measured at the control, are given in IEC 61800-2:

Resistance to vibrations:
Amplitude: 0.3 mm peak from 2 to 9 Hz

Acceleration: 1 m/s^2 from 9 to 200 Hz
In installations where vibration values exceed manufacturer's specifications, the control should be moved to a location of less vibration or mounted on a vibration absorbing assembly.

6.3.5 Speed Range and Regulation Considerations

6.3.5.1 Speed Range

The control must be capable of providing the frequency range required to cover the speed range for the motor. (See 6.2.2.1.)

6.3.5.2 Speed Regulation

In some process and machine applications speed regulation may be critical; in pump and fan applications speed regulation is usually not a critical consideration. Speed regulation is usually expressed as a percentage of speed variation in full load speed to the no load speed of the motor. A standard NEMA general purpose motor will exhibit approximately one to three percent speed variation from no load synchronous speed to full load rated speed. To improve speed regulation, a low slip motor can be used. Speed variation may also be improved by enabling the slip compensation feature in the adjustable frequency control, by using a speed feedback signal from a motor mounted tachometer, or by using a vector control. The percentage of speed regulation may be determined by the following expression.

$$\%\,Speed\ Regulation = \frac{No\,Load\ RPM - Full\ Load\ RPM}{No\,Load\ RPM}\,x\,100$$

When using a speed of 1,800 RPM to calculate percentage of speed regulation, a one percent speed regulated adjustable speed drive will slow down 18 RPM to 1782 RPM at full load rated torque. When using a low speed, such as 100 RPM, to calculate percentage of speed regulation, a one percent speed regulated adjustable speed drive will slow down 1 RPM to 99 RPM at full load rated torque. Both operating points have the same one percent speed regulation specification, however there is a significant difference in the speed change between full-load and no-load.

6.3.6 Bypass Operation Considerations

The purpose of bypass operation (commonly referred to as isolation and bypass) is to run the motor on the power system in the event of an adjustable frequency control failure or shut down due to a protective fault trip condition. Centrifugal pump and fan applications are considered good candidates for isolation and bypass configurations because many of these applications may operate at the power system frequency.

There are application considerations when applying emergency isolation and bypass configurations. Each pump and fan application should be evaluated to ensure the process can handle the flow or pressure developed with the motor operating at line frequency (see 5.2.8).

In bypass configuration, some motors may require reduced voltage starters to prevent voltage sags on the electrical distribution system.

6.3.7 Acceleration Time Considerations

Acceleration time may be important for several reasons, such as:

a) To save production time by accelerating a load quickly
b) To prevent damage to the load by accelerating a load slowly and gradually
c) To meet system requirements

The sizing of the control should take into account the current required by the motor to deliver the accelerating torque. The motor should be sized per 6.2.3. It may be necessary to oversize the control so that the specified acceleration time can be met.

Example 1: Adjustable Frequency Control oversizing is necessary to meet fast acceleration requirement for a motor loaded 90 percent and accelerating a load as described.

Motor nameplate HP	=	100
HP required by load	=	90
Motor rpm	=	1790
Wk^2	=	100 lb-ft^2
Acceleration time	=	2 seconds required for application
T_{load} (Torque load)	=	5252*HP/RPM = 5252*90/1790 = 264 lb-ft total load torque—constant torque
T_R (Torque rated)	=	5252*HP/RPM = 5252*100/1790 = 293 lb-ft
$T_{150\%}$ (Torque @150%A)	=	293 lb-ft * 1.4 = 410 lb-ft (Assumes motor can deliver 140% of rated torque using the control's 150% overcurrent capability)
T_{Acc} (Torque to accelerate)	=	$\frac{Wk^2 \times \Delta rpm}{308 \times time} = \frac{100 \times 1790}{308 \times 2} = 291\ lb-ft$ acceleration required to accelerate the connected load in 2 seconds

From the equation in 6.2.3

$$T_{required} = T_{acc} + T_{load}$$

$$T_{required} = 264 + 291 = 555\ lb-ft$$

Note that the $T_{required}$ of 555 exceeds the $T_{150\%}$ of 410 by 100% x (555-410)/410 = 34%

To select control size either :

1. Estimate the control size required by assuming the control's rated overcurrent amperes were required at $T_{150\%}$ of 410 lb-ft and go to a control with a 34% higher ampere rating or,
2. Determine the actual control size if the actual current rating of the motor is known at 555 lb-ft by comparing this to the control's overcurrent ampere rating.

Example 2 – Adjustable Frequency Control oversizing is necessary to prevent overload tripping when accelerating a high inertia load with a motor loaded 90 percent.

Motor nameplate horsepower	=	100
HP required by load	=	90
Motor rpm	=	1790
Wk^2	=	2500 lb-ft^2
Acceleration time	=	60 seconds required for application
T_{load} (Torque load)	=	5252*HP/RPM = 5252*90/1790 = 264 lb-ft total load torque – constant torque
T_R (Torque rated)	=	5252*HP/RPM = 5252*100/1790 = 293 lb-ft
$T_{150\%}$ (Torque @150%A)	=	293 lb-ft * 1.4 = 410 lb-ft (Assumes motor can deliver 140% of rated torque using the control's 150% overcurrent capability)
T_{Acc} (Torque to accelerate)	=	$\frac{Wk^2 \times \Delta rpm}{308 \times time} = \frac{2500 \times 1790}{308 \times 60} = 242\ \text{lb-ft}$ acceleration required to accelerate the connected load in 60 seconds
From the equation in 6.2.3		
$T_{required}$	=	$T_{acc} + T_{load}$
$T_{required}$	=	264 + 242 = 506 lb – ft

Note that the $T_{required}$ of 506 exceeds the $T_{150\%}$ of 410 by 100% x (506-410)/410 = 23%

To select the control size either:

1. Estimate the control size required by assuming the control's rated overcurrent amperes were required at $T_{150\%}$ of 410 lb-ft and go to a control with a 23% higher ampere rating or,
2. Determine the actual control size if the actual current rating of the motor is known at 506 lb-ft by comparing this to the control's overcurrent ampere rating.

6.3.8 Deceleration and Braking

6.3.8 Deceleration Time Considerations

Deceleration time may be important to a process/machine application for several reasons:

a) To save production time by decelerating the motor load quickly
b) To avoid a long coasting time of the motor load
c) To prevent damage to the process/machine by decelerating the load slowly
d) To meet system specification requirements

The sizing of the control should take into account the current required by the motor to deliver the decelerating torque. The motor should be sized per 6.2.3. It may be necessary to either oversize the control or provide braking provisions so that the specified deceleration time can be met.

6.3.8.2 Load Inertia Considerations

If the process/machine application has a large flywheel or possesses a large weight that must have controlled deceleration, load inertia may be an application consideration. It may be necessary to apply a dynamic braking or regenerative braking option to permit the motor to decelerate the load without tripping the adjustable frequency control on DC bus overvoltage.

6.3.8.3 Dynamic Braking

An ASD system without external dynamic braking will produce 10 to 15 percent of motor full-load torque as dynamic braking retarding torque due to the DC bus capacitors ability to absorb energy and associated motor losses. This method of deceleration is adequate for most applications. External dynamic braking is used if a motor must be decelerated in a shorter time than the inherent dynamic braking and the load friction can provide. ASD dynamic braking systems designed to meet NEMA ICS 61800-2-2005 are capable of decelerating six times the motor inertia with no more than 150 percent of rated current with the motor at its base speed. Applications with high-inertia loads are typical candidates for dynamic braking. (See 5.2.5.)

Because dynamic braking cannot provide holding torque, a mechanical brake should be used when the application requires holding torque. The power source for the brake may need to be separate from the power source for the motor, with adequate interlock features.

6.3.8.4 Regenerative Braking

Regenerative braking returns some of the braking energy from the motor to the AC power distribution system. Because energy is returned to the AC line and not dissipated as heat in resistors, the use of regenerative braking is preferred to the dynamic braking method for applications where large amounts of energy losses are undesirable. Because regenerative braking cannot provide holding torque, a mechanical brake should be used when the application requires holding torque. (See 5.2.5.)

6.3.9 Line Harmonic Voltage and Current Considerations

The suggested guidelines for voltage and current distortion are addressed in IEEE Standard 519. See 5.3.4 for further information on line harmonic voltage and current considerations.

6.4 VARIABLE TORQUE APPLICATION

6.4.1 Motor Selection

All general methods for determining application parameters outlined in 6.2 apply to variable torque applications, with the following additional considerations.

6.4.1.1 Operating Speed Range

Because of the very low torque requirement at low speed (see 4.1.1 and 4.1.1.1), low speed operation is not normally an important consideration with variable torque applications. Motor load decreases, which offsets the effects of reduced cooling. During running, the highest motor load, and therefore operating temperature, occurs at the highest operating speed because the load increases with speed for variable torque loads. The horsepower requirement of the load continues to increase above base speed yet the motor torque (see 5.2.3) may be decreasing if control voltage is being held constant. For operation above motor base speed the motor's capability must exceed the load requirements.

6.4.1.2 Determine Accelerating and Decelerating Requirements (Time and Load)

Although the load inertia for some variable torque applications (see 4.1.1) such as large fans can be high, rapid acceleration is typically not required. As a result, the load can usually be accelerated without exceeding motor rated torque.

6.4.1.3 Overload

Overloads are not normal for typical variable torque applications.

6.4.1.4 Bypass

Bypass is most common in variable torque applications.

6.4.2 Control Selection

All general methods for determining application parameters outlined in 6.3 apply to variable torque applications, with the following additional considerations. (See 4.3.1.2)

6.4.2.1 Control Type

Volts per hertz controls typically meet the requirements for variable torque loads.

6.4.2.2 Speed Range

Typically the control operating output frequency range is 2 to 1 for variable torque type loads. The 2 to 1 speed range is not a consideration issue with the control, because all adjustable frequency controls operate over a minimum of 6 to 1 output frequency range.

6.4.2.3 Bypass

Bypass is most common in variable torque applications.

6.5 CONSTANT TORQUE APPLICATION

6.5.1 Motor Selection

All general methods for determining application parameters outlined in 6.2 apply to constant torque applications, with the following additional considerations.

6.5.1.1 Operating Speed Range

Motor cooling and available motor torque at low speeds are special considerations of constant torque applications.

6.5.1.2 Breakaway torque

Breakaway torque can be an important consideration for constant torque applications, such as loaded conveyers, mixers, augers, and traction applications (cranes).

6.5.1.3 Determine Accelerating and Decelerating Requirements (Time and Load)

Acceleration and deceleration requirements are typically important in constant torque applications.

6.5.1.4 Overload

Overload capability is a common requirement of constant torque applications.

6.5.1.5 Duty cycles

6.5.1.5.1 General

Duty cycles are common in constant torque applications. General guidelines for duty-cycle applications should be followed. (See 6.2.5.2)

6.5.1.5.2 High Impact

High-impact loads are a special case of duty cycle applications and are encountered in certain constant torque applications. In these applications load is applied or removed from the motor very quickly. It is also possible for this load torque to be positive (against the direction of rotation of the motor) or negative (in the same direction as motor rotation).

Available current from the control limits available motor torque. Therefore it is not likely that the impact load will be high enough to damage the motor mechanically because ASD overload protection should protect the motor. However this should be discussed with the motor manufacturer especially if an oversized control is used to support impact loading.

The impact load will result in a rapid increase or decrease in current demand (from the control). If the torque is negative the motor may generate current back into the control. These transient currents create stresses in the stator winding. The magnitude of these transient currents is a function of the size of the control. This should be discussed with the motor manufacturer especially when using an oversized control for the application. (Also see 6.5.2.3)

6.5.2 Control Selection

All general methods for determining application parameters outlined in 6.3 apply to constant torque applications, with the following additional considerations. (See 4.3.1.3)

6.5.2.1 Control Type

Two types of controls could be used for a constant torque application. The first is a V/Hz control and the second is a vector control. A V/Hz control is typically used when the minimum frequency is greater than the motor's slip frequency (the difference between synchronous speed and operating speed multiplied by the ratio of operating frequency to synchronous speed) and the low frequency overload requirements are low (typically less than 120 percent of motor torque).

A vector control may be required if one or more of the following are needed:

a) Operation below slip frequency
b) Operation at zero speed
c) Precise torque control
d) High peak torque at low speed

6.5.2.2 Control HP/Current Sizing Considerations

In constant torque applications, low frequency operation and momentary overload requirements must be considered.

6.5.2.3 Duty Cycle

6.5.2.3.1 General

The basic horsepower/current rating of a control, as shown on the nameplate, is the continuously rated duty. For duty cycle loads (see Figure 4-4) an equivalent rms current must be calculated. For example, a duty cycle load of 150 percent of full load rated current for 30 seconds, 90 percent for 30 seconds and 40 percent for 45 seconds, will yield an equivalent rms value of 97.1 percent of rated full load current. This duty cycle load does not exceed the continuous rated full load current of the control.

$$Equivalent\ rms = \sqrt{\frac{(150^2\ x\ 30) + (90^2\ x\ 30) + (40^2\ x\ 45)}{30 + 30 + 45}}$$ Equivalent rms value = 97.1%

6.5.2.3.2 High Impact

Impact type loads as described in 4.1.2.2 present application considerations that affect the control selection. These considerations are:

a) Speed Droop: If the impact-load torque is high enough to overload the motor beyond its rated slip speed, the control will automatically reduce its output voltage and frequency (current limiting effect) to limit the peak ampere load of the motor. When this occurs, the motor speed will droop as a result of the reduced control output frequency. If the speed droop cannot be tolerated due to the product production process, then the control must be oversized to prevent the current limiting effects.
b) Acceleration Torque: Some impact loads use a flywheel to provide stored energy for the production process. In this application it is critical that the motor and control combination produce sufficient accelerating torque to return the flywheel to its rated speed prior to the beginning of the next work cycle. The control must be sized to provide enough output current that will allow the motor to produce sufficient overload torque.
c) Overcurrent Tripping: Some impact loads may be so severe the general purpose control, current limiting sensing circuits are not fast enough to prevent instantaneous overcurrent tripping. When this occurs, the control must be oversized to prevent tripping from peak overcurrent conditions.
d) Regeneration: Some impact loads will exhibit an overhauling (overspeed) condition during its normal operating cycle. If this condition occurs, then the control must handle the regenerative energy from the motor during this time. This regenerative energy can cause the control to trip on DC bus overvoltage if greater than 15 percent of the control full load power rating. When greater than 15 percent, dynamic braking, regenerative control, or sharing of a common DC bus from other controls must be used to manage the motor regenerative energy due to an overhauling condition.

6.5.2.4 Speed Range and Regulation Considerations

Typically the speed range for a constant torque application is wider than that of a variable torque application. Speed (and torque) regulation requirements are typical in constant torque applications.

6.6 CONSTANT HORSEPOWER APPLICATION

6.6.1 Motor Selection

All general methods for determining application parameters outlined in 6.2 apply to constant horsepower applications, with the following additional considerations.

6.6.1.1 Determine Motor Torque and Speed Requirements

Constant horsepower applications fall into two general categories—narrow range and wide range. Motors suitable for other applications (variable and constant torque), are capable of a narrow range of constant horsepower operation. This range starts at a base frequency and extends to a maximum frequency (typically 150 percent of base frequency). Control voltage reaches rated value at base frequency. (See Figure 6-1) The output torque capability of the motor, when operated at rated constant voltage throughout this range, determines the exact range for a particular motor. (See 5.2.3(e))

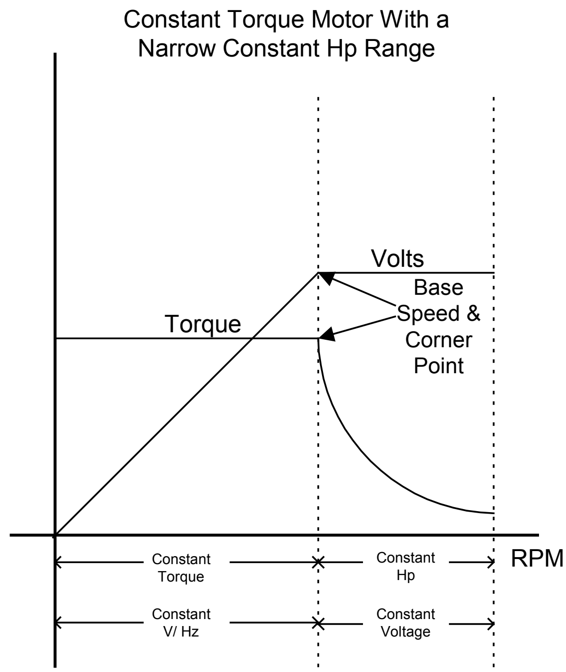


Figure 6-1
A MOTOR DESIGN WHERE THE VOLTAGE AND TORQUE CORNER POINTS ARE THE SAME

Some applications require constant horsepower over a wider speed range. To accomplish this, the motor is designed based on the principle that the voltage reaches rated voltage at a frequency above base frequency. (See Figure 6-2) The width of the constant horsepower speed range and the base frequency influence the size and number of poles of the motor. (See 5.2.3(f))

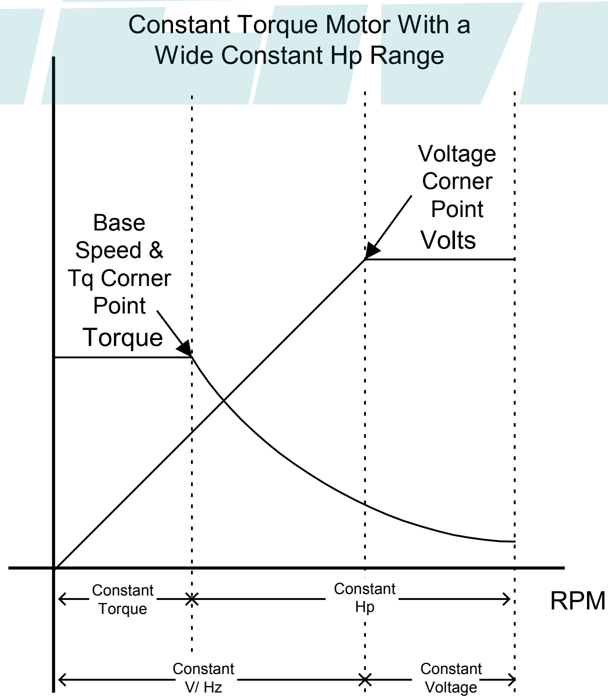


Figure 6-2
A MOTOR DESIGN WHERE THE TORQUE CORNER POINT IS AT A LOWER RPM THAN THE VOLTAGE CORNER POINT. BASE SPEED IS AT THE TORQUE CORNER POINT

The speed and torque capability depend on the motor selected but are also affected by the control. Since there may be more than one combination of motor and control that can meet the requirements of the load, it is best to discuss the alternatives with the manufacturers to determine the correct combination for a particular application.

6.6.1.2 Operating Speed Range

For narrow speed range constant horsepower applications the speed range is typically 1.5:1 to 2:1. For wide speed range constant horsepower applications the speed range is typically 3:1 or 4:1.

6.6.1.3 Overload

The amount of overload required at maximum operating speed in the constant horsepower speed range can affect the size of the motor. In the portion of the speed range where the voltage is constant the motor breakdown torque decreases at a rate proportional to the square of the change in frequency. However, the load torque requirement decreases at a rate inversely proportional to frequency. Therefore, the maximum possible speed at which the motor can continue to provide overload capability is determined by the speed at which the motor breakdown torque equals the sum of the constant horsepower load torque, the overload required, and any additional margin required for stability considerations. If the final maximum operating speed is insufficient for the application, a larger motor may be required.

6.6.2 Control Selection

All general methods for determining application parameters outlined in 6.3 apply to constant horsepower applications, with the following additional considerations.

6.6.2.1 Control Types

The types of controls used in constant torque applications are typically used in constant horsepower applications and may be either V/Hz or vector control.

6.6.2.2 Control HP/Current Sizing Considerations

It is common for motors designed for constant horsepower applications to 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.

6.6.2.3 Speed Regulation Considerations

Speed (and torque) regulation requirements are typical in constant horsepower applications.

6.7 LOOP POSITION AND TENSION CONTROL SYSTEMS

6.7.1 General

The guidance in this clause applies to processing systems whose object is to control the loop position, or tension, or both, of a material in such forms as strip, web, rod, or wire. Unwind and rewind reel systems are not included. See Clause 6.8.

6.7.2 Characteristics and Ratings

6.7.2.1 Torque Control Systems (With Motor Armature Current Feedback)

6.7.2.1.1 Torque Control Operation

Motor armature quadrature current is maintained at a desired value by the regulating action of a converter provided with motor armature current feedback field orientation algorithm. Substantially constant motor direct axis current (field flux) is assumed. In some cases, it is necessary to regulate direct axis (field) current field flux. (Although compensation is not made for machinery and motor losses, sufficient control of tension is established for many applications.) See Figure 6-3.

The tension deviation will exceed the motor torque deviation because of variations in the losses in the driven machine. This is an important consideration when systems are operated at tension values where the torque necessary for tension is of a magnitude comparable to or lower than that required to overcome the losses in the driven machine.

Table 6-4
TORQUE CONTROL OPERATING VARIABLES AND DEVIATION BANDS

Directly controlled variable	Motor quadrature current
Indirectly controlled variable	Motor torque
Principal operating variable	Line or motor speed
Range of principal operating variable	10-100 percent of rated value
Operating deviation bands (see ICS 61800-1, 61800-2, or 61800-4)	20, 10 and 5 percent of rated motor torque
Service deviation bands	See ICS 61800-1, 61800-2, or 61800-4 definition of “service deviation band”

Other operating deviation bands, if required, shall be selected from the appropriate tables in ICS 61800-1, 61800-2, or 61800-4.

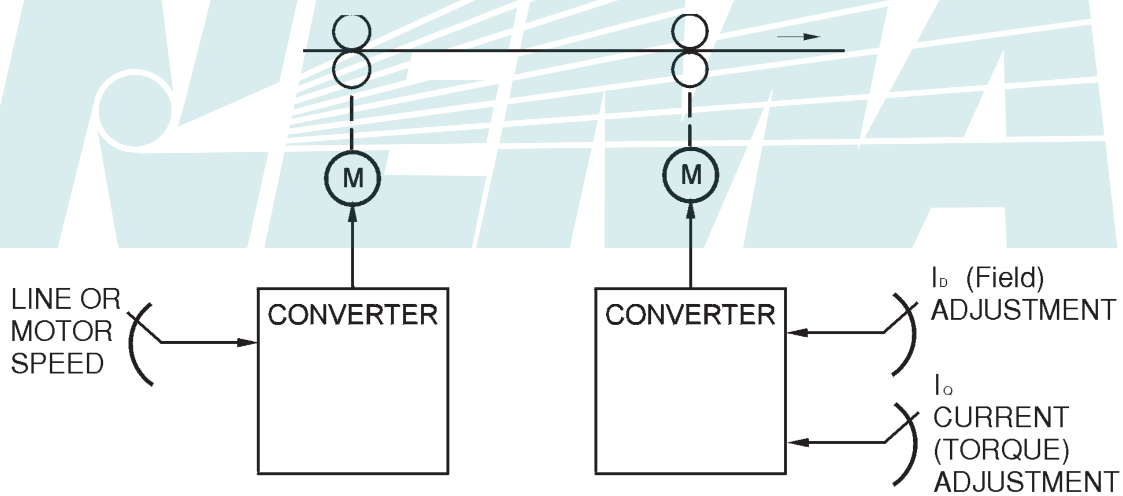


Figure 6-3
TORQUE CONTROL SYSTEMS

6.7.2.2 Constant Force Loop Position Control Systems

6.7.2.2.1 Constant Force Operation

Tension is set and maintained by a constant force on a loop in the material, the force being provided by pneumatic or hydraulic cylinder, gravity, or a spring with substantially constant force over its operating range. The action of the converter is to maintain the loop position within prescribed limits. The steady state tension is substantially constant provided the sides of the loop are parallel. See Figure 6-4.

In those cases where the design is such that the changing force characteristics of the spring are used to change the strip tension as a function of position, the characteristics of the tension feedback control system apply.

Table 6-5
CONSTANT-FORCE LOOP POSITION OPERATING VARIABLES AND DEVIATION BAND

Directly controlled variable	Loop position
Principal operating variable	Line or motor speed
Range of principal operating variable	10-100 percent of rated value
Operating storage time, including service deviation	0.1, 0.2, 0.5 and 1.0 seconds

Systems which require regulation at zero speed require reversible drives.

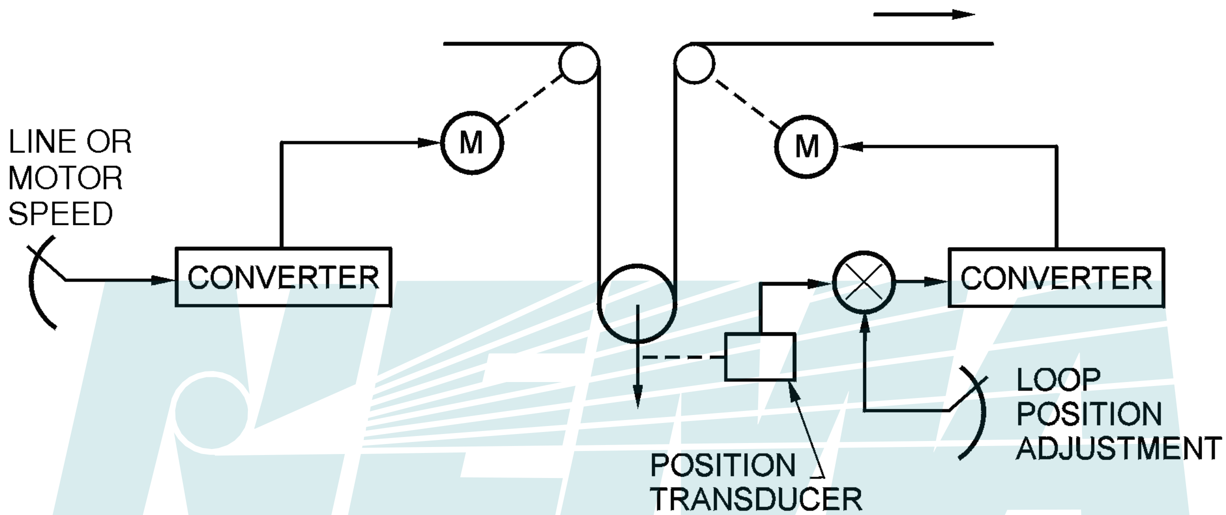


Figure 6-4
CONSTANT FORCE LOADED LOOP—POSITION CONTROL SYSTEM

6.7.2.3 Hanging and Storage Loop Position Control

6.7.2.3.1 Hanging and Storage Loop-Position Operation

Loop operation hanging and storage loops are used in process systems to provide storage or tension isolation, or both, between sections of the system. These are position control systems with position feedback from such devices as photoelectric cells, proximity detectors, or lightly loaded dancers. Where the primary purpose of the loop is storage, the total storage time is usually large relative to the operating storage time. See Figure 6-5.

When the operating storage time is to be very small, the manufacturer should be consulted.

Table 6-6
LOOP OPERATION OPERATING VARIABLES AND DEVIATION BANDS

Directly controlled variable	Loop position
Principal operating variable	Line or motor speed
Range of principal operating variable	10-100 percent of rated value
Operating storage time, including service deviation	0.1, 0.2, 0.5 and 1.0 seconds

Systems which require regulation at zero speed require reversible drives.

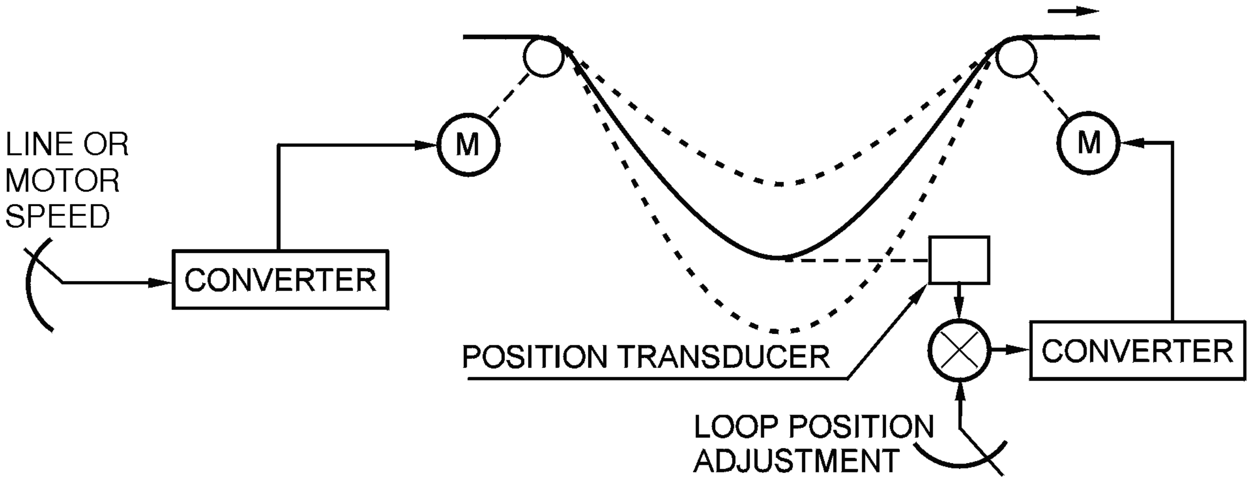


Figure 6-5
HANGING AND STORAGE LOOP CONTROL SYSTEM

6.7.2.4 Tension Feedback Control System

6.7.2.4.1 Description of Tension Operation

Tension is controlled in response to a signal from a tension sensing transducer. See Figure 6-6.

Table 6-7
TENSION CONTROL OPERATING VARIABLES AND DEVIATION BANDS

Directly controlled variable	Tension (range specified)
Principal operating variable	Line or motor speed
Range of principal operating variable	10-100 percent of rated value
Operating deviation bands (see ICS 61800-1, 61800-2, or 61800-4)	20, 10, 5 and 2 percent of rated motor torque
Service deviation bands	See ICS 61800-1, 61800-2, or 61800-4 definition of “service deviation band”

Other operating deviation bands, if required, shall be selected from the appropriate tables of ICS 61800-1, 61800-2, or 61800-4.

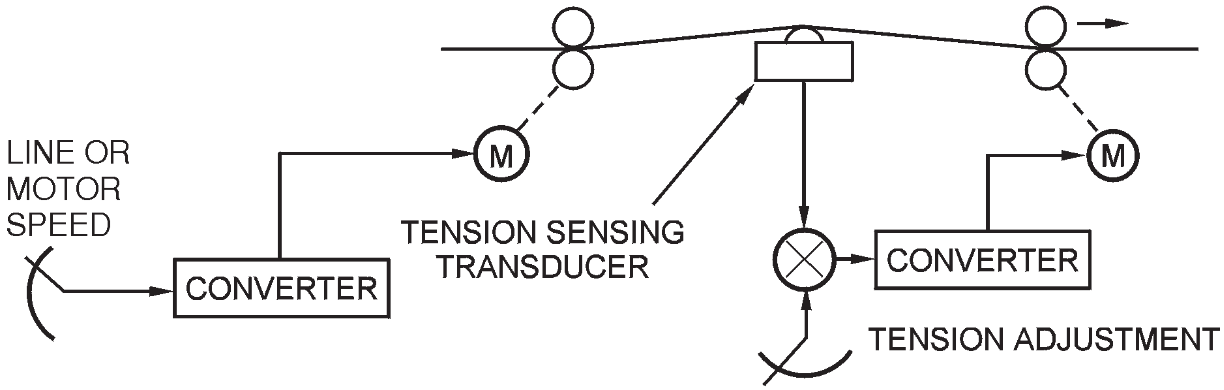


Figure 6-6
TENSION FEEDBACK CONTROL SYSTEM

6.7.3 Application

The following information should be furnished by the user or equipment builder:

1. System Arrangement—A flow diagram including the relative position of mechanical features such as rolls, gearing, motors, looping pits, and reels.
2. Driven System Inertia—The total inertia of each section of the driven equipment, referred to a single shaft (such as the motor shaft). Include inertia of driven and idler rolls and gearing. System inertia affects system stability and performance during normal running as well as during acceleration and deceleration. Where the control supplier does not supply motors, the motor inertia data should be provided as separate items.
3. Driven Roll Diameter and Gear Ratio
4. Required Acceleration and Deceleration Rates
5. Low–Speed Operation—Means of threading and requirements for stalled and start up tension. Limitations on tension variation values and the speed ranges involved must be included.
6. Broken Material Considerations—Maximum permissible speed and requirements for automatic shutdown when material breaks.
7. Steady–State Tension Range—To be specified in pounds force or newtons. The material to be processed will have a range of normal operating tensions. The specific running tension desired will vary with the cross section and yield strength of the material being run.
8. Transient Limitations—Limitations on permissible torque, tension, or position deviations during starting, stopping, acceleration, and deceleration. Factors such as breakaway friction, operation of mechanical brakes, electrical braking, windage, and overcoming inertia may cause the operating loop travel or the operating deviation band to be exceeded. Expected line speed transients should be identified.
9. Line–Speed Feedback—In order to limit deviations in loop height during acceleration and deceleration the rate of change of line speed should be available as feedback for the regulator.
10. Driven System Losses—The total losses of the drive equipment, referred to a single shaft (such as the motor shaft). Consideration should be given to losses which may be a function of speed.
11. Speed Range—To be specified in terms of the linear velocity of the material. The operating speed range may differ from the total speed range. The operating speed range pertains only to that range wherein the limits of deviation bands apply. Both the operating range and the total

range should be specified in such cases. The motor may be of such a size that it cannot provide maximum tension at all line speeds. A schedule of tensions and line speeds should be provided to permit choosing the optimum size of the drive equipment.

12. Pit Dimensions—A sketch should be provided indicating the geometry of the pit, the pass line, and the loop. The sketch should indicate the normal range of position of the loop in the pit during controlled operation.
13. Loop Geometry—For both intrastand and looping pit applications, it is important to know the depth, width, and length of the loop together with a schedule of material cross sectional areas, tension, and modulus of elasticity. For looping pit applications, additional information on the maximum loop travel and operating loop travel should be provided. See Figure 2 2 1.
14. Material—The types of material, including dimensions and characteristics, should be listed, indicating any environmental conditions in the process which will affect these characteristics.
15. Coordination—When the loop or tension control system is supplied separately from the rest of the process control, additional information should be provided as follows: signal isolation, signal level, and ground requirements.

6.8 WIND AND UNWIND DRIVE SYSTEMS

6.8.1 General

The guidance in this clause applies to drive systems whose objective is to control tension, or speed, or both, for the winding, or unwinding, or both, of material in such forms as strip, web, rod, or wire. The machine for performing the function of winding or unwinding is known as a reeler, winder, beamer, coiler, or spooler, depending on the industry or application. In these clauses, the machine will be referred to as a winder or unwinder.

6.8.2 Application

The following information may be required by the electrical equipment supplier and should be furnished by the user or machine builder to the electrical equipment supplier:

1. System Arrangement—A flow diagram and physical layout, including dimensions, of mechanical features such as rolls, transducers, gearing and gear ratios, motors, interstand loop and looping pit (or accumulator), and reels. Limiting dimensions of control panels should be included.
2. Line Speed and Steady-state Tension—A table showing, for each material, line speed range, steady-state tension range with material cross-section and modulus of elasticity, as shown in Table Format for Line Speed and Tension Data.
3. Operating Schedule—Time sequence of operating schedule, including stops for inspection, splicing, reel changes, etc., to enable motor rms loading to be established.
4. Taper Tension—Where it is necessary or permissible to change tension as a function of build-up, a schedule indicating this relationship should be provided.
5. Transient Limitations—Limitations on permissible tension and speed deviations during starting, stopping, acceleration, and deceleration. (Factors such as breakaway friction, operation of mechanical brakes, electrical braking, windage, roll changes, splicing, and overcoming inertia may cause the operating deviation band to be exceeded.)
6. Driven-System Inertia—The total inertia of each section of the driven equipment, complete with empty reel, referred to a single shaft (such as the motor shaft). The inertia of driven and idler rolls and gearing should be included.
7. Acceleration and Deceleration—The required range of controlled acceleration and deceleration rates in feet or meters per minute per second.
8. Driven-Equipment Losses—The total losses of the driven equipment at maximum and minimum line speed.

9. Low-Speed Operation—Means of threading and requirements for stalled and start-up tension. Limitations on tension variation values and the speed ranges involved should be included.
10. Broken Material—Requirements for automatic shutdown when material breaks, including maximum permissible overspeed.
11. Emergency Stop—Detailed requirements for emergency stops, including stopping time or stopping travel, and location and type of equipment for initiating such stops.
12. Steady-State Tension Deviation—Permissible steady-state tension deviation, expressed as a percentage of maximum rated tension. (Equipment complexity increases as a product of line speed range, tension range, and roll build-up ratio. It is important, therefore, to be realistic in specifying steady-state tension deviation.)
13. Coordination—Where the winder control is supplied separately from the rest of the process control, additional information, such as the following, is required:
    a) Signal isolation
    b) Signal level
    c) Grounding requirements

Table 6-8
TABLE FORMAT FOR LINE SPEED AND TENSION DATA

Product description **a. Material Type** **b. Dimensions** **c. Density** **And other pertinent information such as temperature**	**Tension** **Pounds** **(Newtons)**		**Line Speed** **Feet/Minute** **(Meters/Minute)**		**Modulus of Elasticity** **Pounds/Square Inch** **(Newtons/Square meter)**
	Maximum	**Minimum**	**Maximum**	**Minimum**	

Section 7
MEASUREMENTS/INSTRUMENTATION

7.1 GENERAL

The use of adjustable frequency controls result in non-sinusoidal current and voltage on both the input and output. Measurements must be taken with the proper equipment. Many digital meters now available will not read the fundamental component of a PWM waveform but most can read the true rms value. Harmonic measurement instruments are capable of reading rms and fundamental values for voltage, current, and power. In some cases, such as transient peak motor voltage measurements, only an oscilloscope with isolated probes is appropriate.

WARNING—THE MEASUREMENT OF ELECTRICAL QUANTITIES OF EQUIPMENT DESCRIBED IN THIS GUIDE INVOLVES POTENTIALLY LETHAL VOLTAGE AND CURRENT LEVELS. CARE MUST BE TAKEN WHEN OBTAINING MEASUREMENTS. ONLY QUALIFIED INDIVIDUALS, FAMILIAR WITH THE CONSTRUCTION AND OPERATION OF THE EQUIPMENT AND HAZARDS INVOLVED, SHOULD TAKE THESE MEASUREMENTS.

7.2 PARAMETER MEASUREMENTS

The following Table 7-1 describes recommended instrumentation for the measurement of various parameters.

Table 7-1
RECOMMENDED INSTRUMENTATION FOR PARAMETER MEASUREMENT

Parameter	Typical Reading	Instrumentation Required	Reason
Control input voltage	Fundamental	Analog or digital voltmeter	Verify control input voltage
	Transient	20 MHz or higher storage oscilloscope	Capture line voltage variation
Control output voltage or motor input voltage	Fundamental	A meter capable of measuring fundamental of a non-sinusoidal wave form	Verify motor input voltage
	Peak transient and dv/dt	Oscilloscope with a sampling rate of at least 1 Ms/sec	Compare to the motor's peak voltage and rise-time withstand capability
Control input current	True rms	True rms meter	Verify feeder size
Control output current or motor input current	True rms	True rms meter	Estimate overheating
	Fundamental	A meter capable of measuring fundamental of a non-sinusoidal wave form	Estimate torque
Input voltage harmonics	Fundamental plus harmonics	Spectrum analyzer	Ensure compliance with IEEE-519
Input current harmonics	Fundamental plus harmonics	Spectrum analyzer	Ensure compliance with IEEE-519
Drive efficiency	NA	NA	Not practical due to difficulty of accurately measuring motor output in situ

Section 8
SAMPLE ASD APPLICATION DATA FORM

DATE:	
COMPANY NAME:	
ADDRESS:	
CITY:	
STATE:	
ZIP CODE:	
PHONE:	
FAX:	
E-MAIL:	

8.1 APPLICATION

TYPE OF MACHINE AND/OR EQUIPMENT:	

BRAKE HORSEPOWER: ______________BHP AT _________ RPM

LOAD INERTIA REFLECTED TO MOTOR: _________________________ $LB\text{-}FT^2$

TYPE OF LOAD: ☐ VARIABLE TORQUE SPEED RANGE __________________ TO _____________________

☐ CONSTANT TORQUE SPEED RANGE _________________ TO _____________________

☐ CONSTANT HORSEPOWER SPEED RANGE _____________________ TO _____________________

☐ OTHER: ____

LOAD DUTY CYCLE (DESCRIBE): ____

NOTE: IF APPLICABLE, SHOW TIME VS. LOAD GRAPH AS AN ATTACHMENT

IMPACT LOAD (DESCRIBE): ____

NOTE: IF APPLICABLE, SHOW TIME VS. LOAD GRAPH AS AN ATTACHMENT

IS HIGH BREAKAWAY TORQUE REQUIRED (> 150%)? ☐ NO ☐ YES, SPECIFY ___________ %

IS HIGH OVERLOAD TORQUE REQUIRED (> 140%)? ☐ NO ☐ YES, SPECIFY ___________ %

IS SPEED REGULATION REQUIRED (< 1%)? ☐ NO ☐ YES, SPECIFY ___________ % OF BASE SPEED

IS ACCELERATION OR DECELERATION TIME CRITICAL? ☐ NO ☐ YES

ACCELERATION REQUIREMENT: MINIMUM: ______________ SECONDS MAXIMUM: _______ SECONDS

DECELERATION REQUIREMENT: MINIMUM: ________ SECONDS MAXIMUM: _______ SECONDS

8.2 MOTOR

TYPE/DESIGN: ☐ NEMA A ☐ NEMA B ☐ NEMA C ☐ NEMA D DEFINITE-PURPOSE INVERTER-FED

☐ OTHER (DESCRIBE): ____________________

MOTOR INSTALLATION: ☐ NEW OR ☐ EXISTING

IF EXISTING, PLEASE PROVIDE:

MEASURED LOAD RUNNING AMPS: ____________ PEAK LOAD AMPS: ________

HORSEPOWER: ________________ VOLTAGE: ______________ FREQUENCY: ____________________

RPM: ___________ FLA: ___________ LRA: ___________ ENCLOSURE TYPE: ________ FRAME: ________

SERVICE FACTOR: _________ GEAR BOX TYPE (WORM, PLANETARY, ETC): GEAR RATIO: ____________

IS AN ENCODER MOUNTED ON THE MOTOR? (DESCRIBE):____________________

IS THERE A SEPARATELY POWERED BLOWER? (DESCRIBE):____________________

ARE THERE SPACE HEATERS IN THE MOTOR? ☐ NO ☐ YES (DESCRIBE):____________________

ANY TEMPERATURE DETECTION OR TRIP DEVICE? ☐ NO ☐ YES (DESCRIBE):____________________

8.3 CONTROL

TYPE: ☐ V/Hz ☐ SENSORLESS VECTOR ☐ FEEDBACK VECTOR

INDICATE TYPE OF CONTROL SCHEME TO BE UTILIZED:

☐ START / STOP

☐ HAND-AUTO SELECTOR ☐ HAND-OFF-AUTO SELECTOR ☐ RUN-JOG ☐ FORWARD-REVERSE

HAND = SPEED REFERENCE BY MANUAL SPEED POTENTIOMETER

AUTO = SPEED REFERENCE BY ☐ 0-5VDC ☐ 0-10VDC ☐ 4-20MADC ☐ 0-20MADC ☐ 20-4MADC

☐ LOCAL-REMOTE (SPECIFY): ☐ REMOTE CONTROL BY MANUAL SPEED POTENTIOMETER

☐ REMOTE CONTROL FROM REMOTE OPERATOR STATION

☐ REMOTE CONTROL FROM AUTO SPEED REFERENCE INPUT

SERIAL COMMUNICATION: ☐ YES ☐ NO

IF YES, SPECIFY: ☐ DEVICE NET ☐ MODBUS/JBUS ☐ MODBUS+ ☐ LONWORKS

☐ OTHER (SPECIFY): ____________________

8.4 MOTOR ENVIRONMENT

AMBIENT TEMPERATURES: __________ MINIMUM °C (°F) ________ MAXIMUM °C (°F)

ALTITUDE IF GREATER THAN 3,300 FEET ABOVE SEA LEVEL, SPECIFY: ______________________________ FT

ENCLOSURE TYPE: _______________________

SOUND LEVEL REQUIREMENT: ______________________ MAXIMUM DBA

8.5 CONTROL ENVIRONMENT

DISTRIBUTION VOLTAGE: ________ ± _____%, ☐ 1 PHASE OR ☐ 3 PHASE, ☐ 60HZ OR ☐ 50 HZ

DRIVE CONTROLLER ENCLOSURE TYPE: ☐ OPEN ☐ NEMA TYPE 1 ☐ NEMA TYPE 12

☐ OTHER (SPECIFY): ____

AMBIENT TEMPERATURES: __________ MINIMUM °C (°F) ________ MAXIMUM °C (°F)

ALTITUDE IF GREATER THAN 3,300 FEET ABOVE SEA LEVEL, SPECIFY: ______________________________ FT

HUMIDITY? ______________%

SHOCK OR VIBRATION REQUIREMENT? ____

8.6 CONNECTION

TYPE OF CABLE BETWEEN MOTOR AND CONTROL: ______________ LENGTH (IN FEET): ________

INSTALLATION: ☐ METAL CONDUIT

☐ PVC CONDUIT

☐ CABLE TRAY

☐ UNDERGROUND

☐ OTHER: ____

8.7 OTHER

ARE THERE POWER LINE HARMONIC REQUIREMENTS? ☐ YES ☐ NO

IF YES, DESCRIBE: ______________________________

IS THERE A CONTACTOR BETWEEN THE LINE AND THE CONTROL? ☐ YES ☐ NO

IF YES, IS IT TO BE USED TO START AND STOP THE DRIVE? ☐ YES ☐ NO

IS THERE A CONTACTOR BETWEEN THE CONTROL OUTPUT AND THE MOTOR(S)? ☐ YES ☐ NO

IF YES, WILL THE CONTACTOR BE OPERATED WHILE THE DRIVE IS RUNNING? ☐ YES ☐ NO

IS A CONTROL BYPASS CONTACTOR REQUIRED? ☐ YES ☐ NO

IS THERE A MECHANICAL BRAKE ON THE MOTOR? ☐ YES ☐ NO

IF YES, IS THE BRAKE USED FOR ANY OTHER PURPOSE THAN A HOLDING BRAKE WHILE THE MOTOR IS STOPPED? ☐ YES ☐ NO

IF YES, EXPLAIN OPERATION:

IS THERE MORE THAN ONE MOTOR CONNECTED TO THE CONTROL? ☐ YES ☐ NO

A. IF YES, NUMBER OF MOTORS: ____________

B. WILL ANY OF THE MOTORS BE STARTED WHILE OTHERS ARE RUNNING? ☐ YES ☐ NO

NOTE: REFER TO THE *NATIONAL ELECTRICAL CODE®* FOR INDIVIDUAL MOTOR PROTECTION.

ARE THERE ANY OTHER SPECIAL REQUIREMENTS IN THIS APPLICATION? ☐ YES ☐ NO

IF YES, DESCRIBE: ______________________________

____

____

____

____

____

____

____

SIGNATURE ______________________________ DATE: ______________________________

ANNEX A

The material contained in this annex is derived from portions of NEMA MG 1-2011, clauses as noted.

30.2.1.12 Overload Capability (Motor)

The maximum load a motor can carry for a specified period of time without permanent damage or significant performance deterioration.

30.2.2.2 Torque

30.2.2.2.1 Motor Torque During Operation Below Base Speed

To develop constant torque below base speed by maintaining constant air-gap flux the motor input voltage should be varied to maintain approximately rated volts per hertz. At frequencies below approximately 30 hertz, an increase in the volts per hertz ratio (boost voltage) may be required to maintain constant air-gap flux (i.e., constant torque). For applications that require less than rated torque below base speed, system economics may be improved by operation at a reduced volts per hertz ratio.

30.2.2.2.2 Torque Derating Based on Reduction in Cooling

Induction motors to be operated in adjustable-speed drive applications should be derated due to the reduction in cooling resulting from any reduction in operating speed. This derating should be in accordance with Figure 30-2. This derating may be accomplished by or inherent in the load speed-torque characteristics, or may require selection of an oversized motor. The curves are applicable only to the NEMA frame sizes and Design types as indicated, and as noted, additional derating for harmonics may be required. For larger NEMA frames or other Design types consult the motor manufacturer.

The curves in Figure 30-2 represent the thermal capability of Design A and B motors under the conditions noted, and are based on non-injurious heating which may exceed the rated temperature rise for 1.0 service factor motors (see 12.44) for the class of insulation. This is analogous to operation of a 1.15 service factor motor at service factor load (with rated voltage and frequency applied) as evidenced by the 115 percent point at 60 hertz for a 1.15 service factor motor.

30.2.2.2.3 Torque Derating During Control Operation

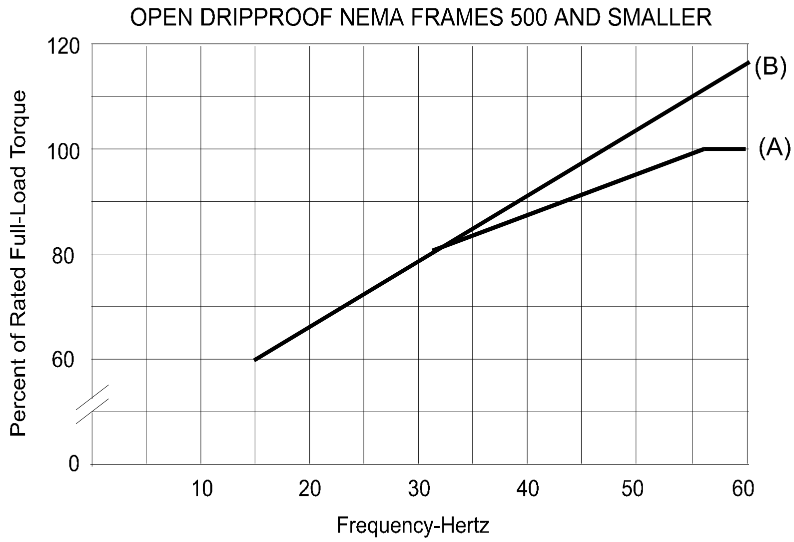
Induction motors to be operated in adjustable-speed drive applications should also be derated as a result of the effect of additional losses introduced by harmonics generated by the control. The torque available from the motor for continuous operation is usually lower than on a sinusoidal voltage source. The reduction results from the additional temperature rise due to harmonic losses and also from the voltage-frequency characteristics of some controls.

The temperature rise at any load-speed point depends on the individual motor design, the type of cooling, the effect of the reduction in speed on the cooling, the voltage applied to the motor, and the characteristics of the control. When determining the derating factor, the thermal reserve of the particular motor is important.

Taking all of these matters into account, the derating factor at rated frequency ranges from zero to 20 percent.

Figure 30-3 shows examples of a derating curve for a typical motor for which the thermal reserve of the motor at rated frequency is less than the additional temperature rise resulting from operation on a control and one for which the thermal reserve is greater. It is not possible to produce a curve which applies to all cases. Other motors with different thermal reserve, different methods of cooling (self-circulation cooling or independent cooling), and used with other types of controls will have different derating curves.

There is no established calculation method for determining the derating curve for a particular motor used with a particular control that can be used by anyone not familiar with all of the details of the motor and control characteristics. The preferred method for determining the derating curve for a class of motors is to test representative samples of the motor design under load while operating from a representative sample of the control design and measure the temperature rise of the winding.



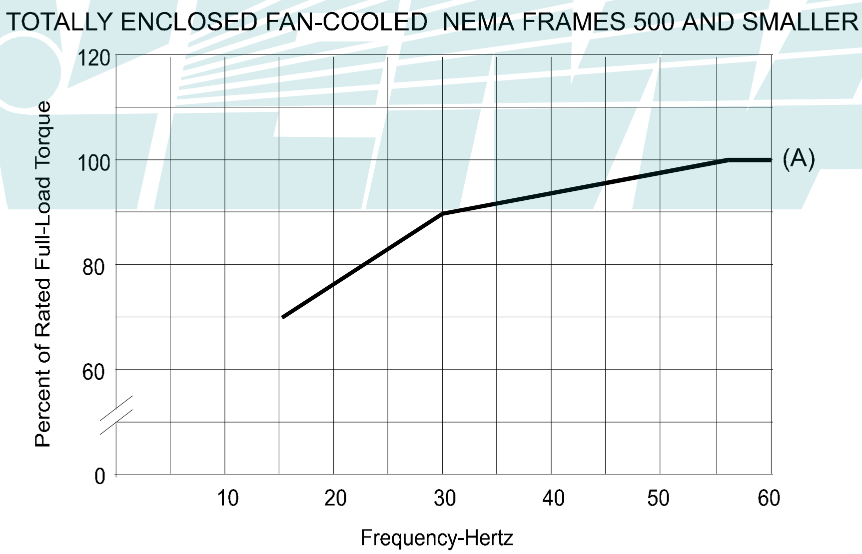


Figure 30-2
THE EFFECT OF REDUCED COOLING ON THE TORQUE CAPABILITY AT REDUCED SPEEDS OF 60 HZ NEMA DESIGN A and B MOTORS

NOTES—
1—Curve identification
a. Limit for Class B 80°C or Class F 105°C rise by resistance, 1.0 service factor.
b. Limit for Class B 90°C or Class F 115°C rise by resistance, 1.15 service factor.
2—All curves are based on a sinusoidal wave shape, rated air-gap flux. Additional derating for harmonic voltages should be applied as a multiplier to the above limits.
3—All curves are based on non-injurious heating which may exceed rated temperature rise.
4—Curves are applicable only to frame sizes and design types indicated. For larger frames or other design types consult the motor manufacturer.

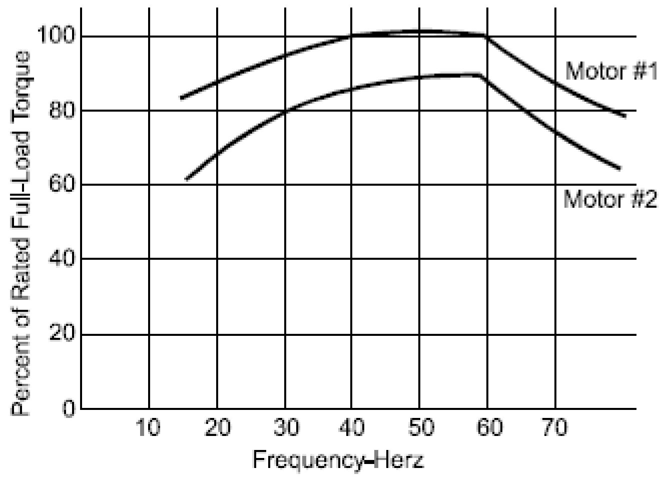


Figure 30-3
EXAMPLES OF TORQUE DERATING OF NEMA MOTORS WHEN USED WITH ADJUSTABLE FREQUENCY CONTROLS

NOTES—
1–Curve identification
a. Motor #1: motor thermal reserve greater than the additional temperature rise resulting from operation on a control
b. Motor #2: motor thermal reserve less than the additional temperature rise resulting from operation on a control

30.2.2.2.4 Motor Torque During Operation Above Base Speed

Above base speed, a motor input voltage having a fundamental component equal to rated motor voltage (which may be limited by the control and its input power) as frequency increases will result in constant horsepower operation (torque reducing with reduced volts per hertz). The maximum (breakdown) torque capability of the motor within this speed range will limit the maximum frequency (and speed) at which constant horsepower operation is possible.

The curves in Figure 30-4 represent the load which the defined motor is capable of carrying above base speed. The curves represent operation at constant horsepower for 1.0 service factor motors and similar performance for 1.15 service factor motors. The maximum frequency of 90 hertz is established based on the approximate peak torque capability of greater than 175 percent for NEMA Design A and B motors assuming operation at a constant level of voltage equal to rated voltage from 60 to 90 hertz. For the capability of motors for which the minimum breakdown torque specified in 12.39.1 or 12.39.3 is less than 175 percent, consult the motor manufacturer.

For operation above 90 hertz at a required horsepower level, it may be necessary to utilize a motor with a greater horsepower rating at 60 hertz.

However, the maximum speed at which a motor can safely operate may be limited to some speed below the maximum speed related to its load carrying capability because of mechanical considerations (see MG1-2006, 30.2.2.3).

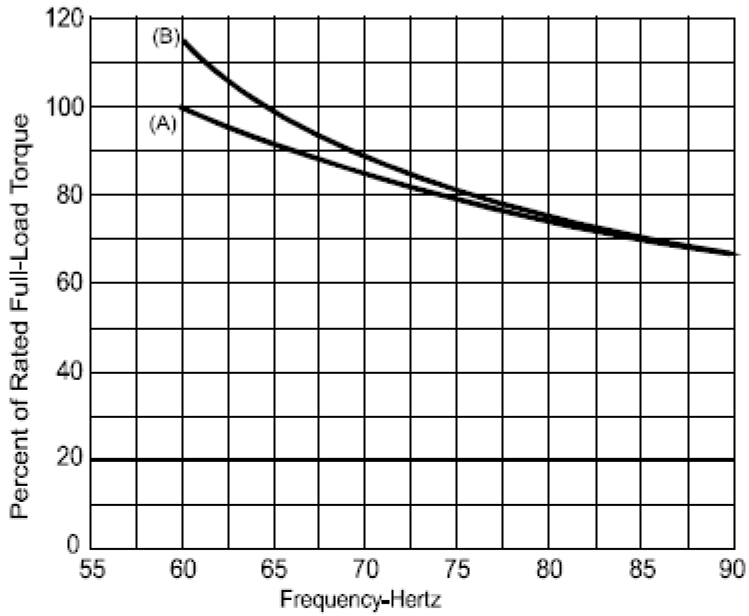


Figure 30-4
TORQUE CAPABILITY ABOVE BASE SPEED

NOTES—
1—Curve identification
a. Limit for Class B 80°C or Class F 105°C rise by resistance, 1.0 service factor.
b. Limit for Class B 90°C or Class F 115°C rise by resistance, 1.15 service factor
2— All curves are based on a sinusoidal wave shape, constant voltage equal to rated voltage. Additional derating for harmonic voltages should be applied as a multiplier to the above limits.
3—All curves are based on non-injurious heating which may exceed rated temperature rise.
4—Curves are applicable to NEMA Design A and B motors having breakdown torques of not less that 175 percent at 60 hertz.
5—See MG 1-2006, 30.2.2.3 for any additional limitations on the maximum operating speed.

ANNEX B

The material contained in this annex is derived from portions of NEMA MG 1-2011, clauses as noted.

31.3.1 Basis of Rating

Definite-purpose inverter-fed AC induction motors covered by this Part shall be rated based on identification of the applicable load points selected from the four load points shown in and defined in Figure 31-1. The base rating shall be defined coincident with point (3) in Figure 31-1 by specifying the motor voltage, speed, and horsepower or torque, at that point.

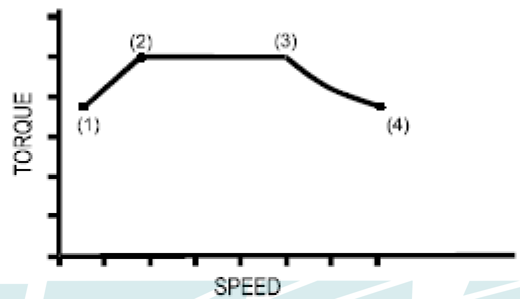


Figure 31-1
BASIS OF RATING

NOTES—
1 = Torque at minimum speed based on temperature considerations and voltage boost
2 = Lowest speed of the constant torque range based on temperature considerations
3 = Base rating point at upper end of constant torque range
4 = Maximum operating speed based on constant horsepower and any limitation on rotational speed

When the voltage ratings at reference points 3 and 4 are different, then, unless otherwise specified, the voltage is assumed to reach the maximum value at a frequency between points 3 and 4 per a constant volts to Hertz relationship equal to the voltage at point 3 divided by the frequency at point 3.

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