

The Motor Designer's Viewpoint of an Adjustable Speed Drive Specification

Lester B. Manz

Historically, AC motors have been installed on fixed voltage/frequency power supplies. When motors were specified for these power supplies, it was adequate to specify a few things like voltage, frequency, horsepower, service factor, enclosure, NEMA design, and so on. As demands to reduce energy consumption surfaced, some new features began to be specified, including efficiency and power factor.

With the advent of the adjustable speed drive (ASD) and its adjustable voltage/frequency power, new features were again added to those specified—type of load, speed range, and ASD type, to name a few.

When specifying a motor for use on an ASD, it is not enough to think about what additional features are required. We must also look at relaxing some of the requirements historically specified. Cost is added and benefits are sacrificed if some of these features are specified when not necessary.

I will base my comments on my own experience, which has been with NEMA frame sizes 182 through 5011—though some of what I say here may be applicable for motors in frame sizes outside this scope.

Application Strategy

Users of integral horsepower motors in these frame sizes have differing thoughts as to whether to use custom-designed ASD duty (NEMA calls these motors Definite Purpose designs) or standard motors in various places in their mills. Their choice is

This article appeared in its original form in the conference record of the 1993 Annual Pulp and Paper Industry Technical Conference, June 21-25, 1993. The author, an IEEE and IAS member, is manager of adjustable speed engineering at GE Motors in Fort Wayne, Ind.

influenced by various factors, including price and availability.

I will not try to convince the user of electric motors to use standard or custom motors. Instead, I will try to offer guidance in specifying one or the other.

When applying ASDs to standard motors, it is necessary to determine how much derating (if any) is required on the specific motor/ASD combination in order to prevent premature failures from overheating the motor's windings or bearings. Derating may be required because of the additional losses introduced by the harmonics in the ASD's power and because of the reduced speed of the motor's cooling fan.

The amount of derating a specific motor/ASD combination requires depends on the motor design and the ASD design. In order to decide upon the proper amount of derating, it's necessary to know both the specific motor and ASD designs being used.

To help simplify the mating of motor and ASD, some motor manufacturers have derating curves available. A curve is provided for each specific motor/ASD combination. (Consult the motor manufacturer if the curves are unavailable or do not cover the design in question.) A representative capability curve is shown in Fig. 1. To use the curve, compare the load curve to the motor's capability.

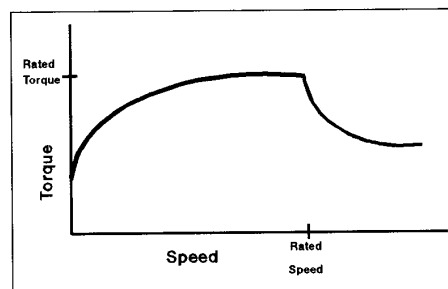


Fig. 1.

Ordinarily a curve will include specifics as to the ASD type and the motor. I have omitted these here in order to prevent improper use of this curve.

If the capability curves indicate that the next higher horsepower standard design is needed, an alternative is to order a custom-designed ASD duty motor. I believe the system integrator should use the derating curves or consult the motor manufacturer when matching motors to ASDs, and should not substitute existing "rules of thumb."

One popular rule of thumb, often quoted by both motor and ASD sales representatives, is built into some specifications and causes confusion in determining what is desired: "Buy a Class B rise motor with 1.15 Service Factor (SF) on sine wave power and derate it to 1.0 SF on the ASD. When this is done the motor can be run constant torque down to 25% speed."

When a custom motor design is required, options such as special rotor slots, special stator windings, and auxiliary cooling may allow the user to avoid the larger frame of the next higher HP standard design. (Most of the following sections discuss the decisions required when specifying a custom design.)

To evaluate the derating required on a standard design, or the design requirements of a custom design, most motor manufacturers will request an ASD/Load Requirement information sheet be supplied. An example appears in the sidebar, "ASD/Load Requirement Data Sheet."

Service Factor and Temperature Rise Ratings

Better information in this area helps avoid confusion and misapplication of the motor/ASD combination.

When a motor specification reads "Class B temperature rise, 1.15 SF, suitable for use on an ASD," the motor supplier does not know whether the B rise and the 1.15 SF are to be met on the ASD or on sine wave power. If the specification is read as written, the B rise and the 1.15 SF would be required on the ASD. However, the widespread use of the above faulty rule of thumb would indicate that the 1.15 SF and Class B rise are designed on sine wave power. It is my experience that most often the B rise and 1.15 SF are indeed intended to be met only on sine wave power. Class F rise at 1.0 SF is satisfactory for the motor on the ASD.

To make sure that there is good understanding of what is being requested, clearly state on what type of power the Service Factor and the temperature rise requirements should be met. (See sidebar, "Suggested Specification for Some Relevant Sections.")

In addition to causing confusion, the faulty rule of thumb can lead to overheated motors. Lowery and Petro [1] detailed test results in their paper showing that a 10 HP motor they tested on a PWM ASD overheated at 25% speed, while a 50 HP

When a custom motor design is required, options such as special rotor slots, special stator windings, and auxiliary cooling may allow the user to avoid the larger frame of the next higher HP standard design.

motor they tested on a PWM ASD overheated at 50% speed. Yet the rule of thumb indicates they both are acceptable down to 25% speed!

On variable torque loads, the hottest condition is typically the fastest speed the motor is allowed to run. (By the affinity laws, the HP drops as the cube of the speed. Therefore, the watts required to be dissipated fall off faster than the airflow of the cooling fan.) Does a 1.15 SF motor assure acceptability then on a variable torque load at 1.0 SF?

Assuming current is linear with torque, and watts lost are proportional to current squared, a 1.15 SF machine has the ability to dissipate $1.15 \times 1.15 = 1.32$ times the watts lost of a 1.0 SF machine. From this one can determine that when the temperature rise of a motor on an ASD is less than 32% higher than on sine wave power, a 1.15 SF motor could be derated to 1.0 SF for a variable torque load. This is not always the case.

ASD/Load Requirement Data Sheet

Variable Frequency Operation:

Design point: HP @ rpm

Range (min-max): - rpm

Type of load: ☐ constant torque ☐ variable torque

(Above design rpm: ☐ constant HP ☐ constant torque ☐ variable torque)

ASD type: ☐ PWM ☐ VSI ☐ CSI

Make Model #

Fill out only the applicable requirements below:

Service factor: sine wave ASD

Temperature rise: sine wave ASD

Overload (150% for one minute standard):

Starting torque (140% rated torque with 150% rated current standard):

Is NEMA A design acceptable if required to keep in NEMA frame? (Will have higher inrush. May be undesirable if inverter bypass is required.)

Both of the motors Lowery and Petro tested would have been acceptable on variable torque loads on the ASD. (At rated speed, the 10 HP motor temperature on PWM power was 8% hotter than on sine wave power, while the 50 HP motor was 18% hotter.) However, I have tested motors where the temperature rise on a PWM ASD went up as much as 65% over the sine wave power temperature rise at rated speed conditions! The design with 65% extra ASD losses would need derating even on a variable torque load.

The results of this testing indicate that the rule of thumb should no longer be used in either constant torque or variable torque applications when matching motors and ASDs.

When ordering a special-purpose motor, it's best to determine first whether NEMA B is necessary (line bypass, ripple current). If it is not, allow the option of a NEMA A design.

Should NEMA A or NEMA B Designs be Used?

Examination shows that the only difference between the NEMA A and NEMA B design [2] is that the inrush currents of a NEMA A design are not limited by the values of MG 1-12.35. Should one be concerned with 60 Hz inrush on a motor that goes on an ASD and is not started on 60 Hz? A couple of detriments to specifying NEMA B for ASD use bear considering:

- Limiting inrush current has the side effect of also limiting the breakdown torque of AC induction motor. Limited breakdown torque means limited overload capability (typically 150% for a NEMA B design) when this motor is powered by an ASD. A NEMA A design is usually required to achieve greater than 150% overload.
- What is done to obtain the lower inrush currents of a NEMA B design, especially on motors in the larger NEMA frames (NEMA 400 and higher), results in a high resistance to high-frequency currents (skin effect). The inverter adds a high-frequency voltage component to the input wave. The current at the high frequency is determined almost exclusively by the leakage reactance. So the watts that produce heat in the harmonics are determined by the harmonic I^2R . With a NEMA A design in larger NEMA frames, we can sometimes greatly reduce the harmonic losses by reducing the harmonic resistance.

The benefit of going to a NEMA A design in the first item above is more momentary overload capability. The benefit in the second item is the possibility of a design in a lower frame size. Putting a design in a lower frame size has the potential benefits of lower cost, lower rotor inertia, lower motor weight, higher reed critical frequency on a vertical motor, and so on.

The detriments of going to a NEMA A design are higher inrush on sine wave power (inconsequential if the motor is not started at 60 Hz power) and lower leakage reactance. The lower leakage reactance will allow higher ripple (harmonic) currents. The higher ripple currents could cause the user to go to a larger ASD rating, but since the ASD ratings are in discrete steps, and the differential in ripple currents is relatively small compared to the fundamental, the current rating of the ASD would need to be close to the current rating of the motor for a larger ASD to be required.

Therefore, when ordering a special-purpose motor, it's best to determine first whether NEMA B is necessary (line bypass, ripple current). If it is not, allow the option of a NEMA A design. (See sidebar, "Suggested Specification for Some Relevant Sections.")

When Should NEMA C and D Designs Be Specified on an ASD?

The definition of a NEMA C designs differ from that of a NEMA B design in starting torque only. A NEMA C design has the same starting current as a NEMA B design but higher starting torque on across-the-line starts. Since the ASD starts the motor at reduced voltage and frequency, torque at starting on an ASD is limited by the amperage the ASD will supply to the motor, not by the motor's 60 Hz inrush. Also, since the rotor design for a NEMA C motor could cause higher heating on an ASD, I believe that a NEMA C design motor would only be specified when high starting torque is required and there is provision for bypassing the ASD.

A NEMA D design has considerably higher starting torque than a NEMA B design and considerably higher slip. A NEMA D design might be specified on an ASD specifically because of its higher slip. Examples include load sharing where multiple motors are used with a single ASD. There is not enough room here to cover the use of the NEMA D design. Suffice it to say that if a NEMA D design is being specified on across-the-line starts solely for higher locked rotor torques, a NEMA A or B design is a good substitute on ASD power.

Speed Range

When a motor needs to be controlled by an ASD across a wide speed range in constant torque applications, the size (and cost) of the motor is determined by the bottom speed requirement. On

variable torque loads, the top speed condition determines motor size. Motor manufacturers have developed lines of motors for given load and speed ranges. For example, a motor manufacturer may have a line of 4:1 (from rated speed to 25% of rated speed) constant torque speed range designs, and a

line of 10:1 constant torque speed range designs. He may also have a line for use on variable torque loads. When the motors are designed to run across a given speed range, the designer assumes that the motor will be run continuously at the worst case in the speed range and at the maximum ambient

Suggested Specification for Some Relevant Sections

A. SCOPE

These motors are to be specifically designed for operation with a variable-voltage, variable-frequency adjustable speed drive (ASD) as the power supply to the motor. (When known, brand name, model number, and type—PWM, VSI, or CSI—should be included.)

B. SPEED

Motors shall be designed to operate with constant torque (or variable torque, or constant HP) across a speed range of ____:1 (rated speed down to ____% of rated speed). Motors shall operate above base speed at constant horsepower to ____ rpm. Motors shall be designed to operate continuously at any point in the speed range.

C. ELECTRICAL REQUIREMENTS

1. Voltage and Frequency

a. Motors shall have a base speed rating at ____ volts. Motors will be rated for operation on three-phase power with a base frequency rating of 60 Hz.

b. Motors shall operate on an ASD power supply. The design voltage and frequency for the lowest speed are to be stated on the nameplate.

c. Voltage variations shall not exceed $\pm 10\%$ from the voltages specified on the nameplate at the frequencies associated with those voltages.

d. Motors shall operate successfully under running conditions at rated load and frequency when the voltage unbalance at the motor terminals does not exceed one percent.

2. Operating Conditions—On the ASD

Motors shall be designed with an emphasis on performance on the ASD power supply. Therefore this emphasis may dictate that the motor be designed as a NEMA A design.

(Alternatively, one could say simply: NEMA Design B required.)

a. Torque. Motors shall be capable of delivering continuously at any speed within the constant torque speed range a torque that will deliver rated horsepower at rated speed. Motors shall also be capable of delivering continuously at any speed within the constant horsepower speed range a torque that will deliver rated horsepower at that speed.

b. Starting torque. Motors shall be capable of 140% of rated torque while drawing 150% of rated current when started at the proper voltage and frequency on the ASD.

c. Overload Capability. Motors shall be capable of an occasionally repeated overload (of duration less than one minute and not part of a duty cycle) of ____% (typically 150) of rated torque at any speed in the speed range. The overload is available at rated speed and below. (If needed above rated speed, this needs to be specified.)

d. Efficiency. The efficiency, when specified, shall be the efficiency at rated load on sine wave power at the base voltage and frequency rating. The actual efficiency of a given load point on the ASD may well be less than that and depends on the speed and the type of ASD. (For these reasons, a guaranteed minimum efficiency has little meaning and is not applicable.)

e. Power Factor. (See Section XII before specifying.) The power factor stated on the nameplate shall be the power factor at rated load at the base voltage and frequency on sine wave power. The power factor of the motor on the ASD depends on speed and ASD type and is lower on the ASD for a given voltage and frequency than it would be for the same voltage and frequency from a sine wave supply.

f. Temperature Rise. The motor shall be designed for Class F rise on the ASD at the worst-case speed point in the speed range for rated load as specified by service factor.

3. Operating Conditions—On the Sine Wave Power (Reference)

As the reference implies, since these motors shall be designed for ASD duty, the sine wave power ratings should be used as a comparison to standard motors, but are often not very meaningful on the ASD.

a. Motors shall meet or exceed the locked rotor (starting) and minimum breakdown torques specified in NEMA standards for Design B motors for the rating specified at base voltage and frequency.

4. Service Factor and Ambient

a. Motors shall be designed for a 1.0 service factor on ASD power throughout the speed range.

b. Motors shall be designed for operation in a 40C ambient.

c. (Optional) Motor shall be designed for a 1.15 service factor on sine wave power at the base voltage and frequency rating.

D. Frame Size

The frame size shall be determined by the manufacturer. Because of the added losses due to the harmonics of the ASD, and the reduced cooling of the fan when present at reduced speeds, the frame size may be larger than the frame size specified by NEMA for the equivalent HP rating on set voltage and frequency on sine wave power.

temperature condition. If the worst-case condition is short in duration and part of a duty cycle, or always occurs at a lower ambient temperature, a lower-cost design may suffice if the designer knows the operating conditions.

Maximum Required Speed

When a motor is to run at frequencies higher than rated, the overspeed operating conditions need to be known. Definite-purpose ASD motors will have a maximum speed for constant horsepower operation. The reason the motor cannot go higher in speed may be for bearing lubrication, thermal reasons, loss of breakdown torque, mechanical integ-

When a minimum efficiency is specified for a motor designed for use on an ASD, it is important that everyone involved understand under what condition the efficiency is expected.

ity of the parts, or other reasons. When the duty cycle requires some overspeed operation, knowing the conditions of the overspeed operation helps to minimize the cost of the design. An example is a motor with an external blower to achieve cooling at lower speeds. If this motor is run at overspeed, the blower would give the same air at 90 Hz as at 60 Hz. (A shaft-driven fan should have 50% extra cooling air at 90 Hz.) Thermally, this design may not be able to deliver constant HP at 90 Hz continuously and therefore may be rated for 75 Hz maximum constant HP operation. For reduced loads or short times, it will be able to operate at 90 Hz.

Special caution needs to be exercised in running motors with centrifugal loads at overspeed. At first thought, it seems obvious that if the process does not provide enough flow, an ASD can be installed. Note that the HP required by the load increases as the cube of the speed, while the HP deliverable by the motor is constant. As can be seen from Fig. 2, when the constant HP region of the motor (the region above rated speed) is entered, as indicated in the shaded area, the motor's capability and the load's requirement diverge rapidly. For this reason, when the speed range includes speeds above the rated speed of the motor, it is imperative that the motor designer know the HP at the maximum speed.

Starting Torque

If a load is encountered that requires starting torque that is greater than the running torque, the size of

the ASD may be determined by the current requirement at starting rather than the running current requirement. When this is the case, it is important that the engineer who matches the ASD to the motor understand the short-term current capability of the ASD and the torque capability of the motor. There is a specific starting voltage/frequency combination that gives peak torque per ampere. If this point is used, the starting current requirement for the ASD is minimized. (Since the starting voltage and frequency are dependent on the torque required, these need to be obtained from the supplier of the motor for a given starting torque.)

Overheating on low-speed operation may occur when a scalar control (volts/Hz) scheme is used on an application with a wide speed range and constant torque. Setting the boost voltage high for starting torque also sets a high voltage at the low running frequencies. This high voltage can cause the motor to operate inefficiently and overheat, even if it was designed to run at that speed. NEMA is considering a proposal recommending that voltage and frequency for the low-speed operation appear on the nameplate. If the motor is designed for operation at speeds at 10% of nameplate or lower, get the manufacturer's recommendation for low-frequency voltage.

If the load being accelerated has high starting torque and high inertias, the ASD will be set for long starting cycles with greater than rated amps. The heating effect of long starting cycles needs to be analyzed by the designer.

Efficiency

As discussed earlier, a motor used on an ASD has lower efficiency than the same motor on sine wave power. A motor with higher efficiency on sine wave power usually has higher efficiency on an ASD. It follows that a higher efficiency design on sine wave power should have higher efficiency on ASD power.

When a minimum efficiency is specified for a motor designed for use on an ASD, it is important that everyone involved understand under what condition the efficiency is expected. To date there is no industry standard for measuring efficiency on in-

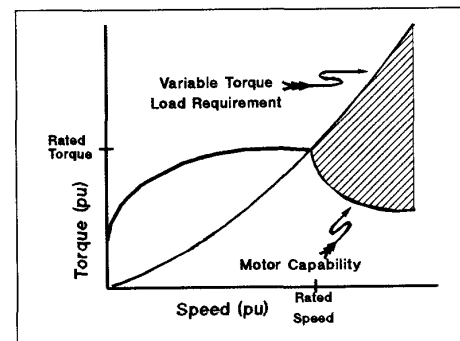


Fig. 2.

verter duty motors. Motor NP efficiencies are at NP conditions (rated volts, frequency, and HP) and on sine wave power. If the efficiency specified is meant to be on ASD power, a test on the desired ASD under the speed conditions desired is the only real way to verify the efficiency.

Overload Capability

AC induction motors are usually rated for 150% momentary overload on ASD power (one minute or less and not part of a duty cycle). The motor's breakdown torque limits its overload capability; overload capability higher than 150% of rated torque will usually require more breakdown torque. (As indicated above, a NEMA A design should then be specified.) For overloads of longer duration, the specifics of the overload should be supplied so heating can be determined.

Power Factor

The power factor of an ASD/motor combination is determined in the rectifier section of the ASD—how the ASD converts AC power to DC power. The power factor the utility company sees looking into an ASD/motor combination is then unaffected by the motor. The output of the ASD is affected by the motor's power factor in this way: low power factor on the motor results in a higher amperage output of the ASD. (In the motor equivalent circuit, rotor resistance changes with slip. Motor reactances change with frequency. Since power factor is a function of both of these variables, it changes with speed and load.)

In my opinion, the critical motor parameter for ASD operation is amperage, not power factor. Maximum ampere rating should be specified instead of minimum power factor. Should one choose

to specify minimum power factor, it should be understood that unless otherwise stated, sine wave power factor is implied. As in the case of efficiency, if power factor on the ASD is being specified, an actual test would need to be ordered on the specific ASD to verify.

Conclusions

Writing a specification for motors intended to be used with ASDs requires that some items be well defined so the user and supplier have a good understanding of what motor is to be supplied. These items include:

- service factor
- temperature rise
- NEMA design
- speed range (and duty cycle if applicable)
- maximum required speed
- starting torque (only if high starting torque is required)
- efficiency
- overload capability (if greater than 150% required)
- power factor
- ASD type

To avoid unnecessary cost, some items, such as the NEMA design, may need to be specified differently than on sine wave power.

Additionally, it may be well to use technical data instead of rules of thumb for applying ASDs to standard motors.

References

- [1] Thomas F. Lowery and David W. Petro, "Application Considerations for PWM Inverter-Fed Low-Voltage Induction Motors," PCIC, September 1992.
- [2] NEMA MG-1.