Considerations for the Use of AC Induction Motors on Variable Frequency Controllers in High Performance Applications

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ABSTRACT

Until recently the majority of AC variable speed drives have been applied to variable torque, pump and fan applications. Advances in drive technology have led to the use of induction motors in high performance applications that exceed the capability of motors designed for operation on sine wave power. These applications, which have traditionally been served by DC systems, have created the need for definite purpose AC induction motors designed specifically for operation on adjustable frequency controllers. This paper will discuss many of the considerations for a successful application and will highlight the limitations of standard motor designs.

INTRODUCTION

The reasons for operating industrial motors over a range of speeds are as varied as the industries served. The need for variable speed prime movers is widespread - energy savings on fan drives, constant surface speed cutting on machine tool spindles, wind and unwind operations of a bridle drive, etc. Improved performance of these variable-speed drive systems has always been a key means for achieving increased factory productivity. While various methods have historically been used to achieve these speed ranges, advances in technology are making one of the options more attractive than ever.

The low cost and ruggedness of the AC squirrel cage induction motor are benefits which have increased the desire to use it as the electromechanical energy conversion means. Today's control schemes are obtaining higher levels of performance from these AC motors as well. However, a common limiting characteristic of AC induction motors' performance (on adjustable frequency controls) has not been a technological limitation. Rather, it has been a limitation imposed by the nature of the standardization of industrial AC motors for general-purpose, constant-frequency use. Throughout this highly refined standardization process there has been little consideration for operation on variable frequency power.

Until recently the majority of high performance industrial applications have been satisfied using DC motors and controls. This technology has well defined standards and has been dominated by a limited number of manufacturers where the control supplier assumes responsibility for the performance of the control/motor system.

The rapid development of adjustable frequency AC technology has encouraged a large number of new control manufacturers to enter the market. As would be expected, their primary experience is in electronics and not variable speed system application. Also few of these control manufacturers produce motors. The majority of AC motor manufacturers have limited variable speed experience as their products have traditionally operated at a fixed frequency and speed. Due to the large number of possible control and motor design combinations in the market place, it is impractical to assume all combinations have been tested extensively. In this environment the machine builder and user accept greater responsibility for the total system's performance and greater knowledge of the components design considerations and limits is needed.

HIGH PERFORMANCE DRIVES

When the "drive" (motor and control) performance requirements are minimal, a standard industrial AC induction motor can often be successfully applied to adjustable-frequency power, variable-speed applications. Indeed, some applications can be converted from constant speed to variable speed while utilizing an existing induction motor. However, when the performance level required is more demanding, a definite-purpose motor design is appropriate. This is usually the case when maximum process productivity is the goal.

While the definition of a high performance application is not precise, these applications will typically have one or more of the following characteristics:

- Continuous constant torque required below 50% of base speed
- Continuous constant horsepower required above 150% of base speed
- High starting loads or overloads
- High dynamic performance
- A process (driven machine) that cannot be started or run without a variable speed control

The vast majority of adjustable frequency AC controls applied to date have been on low performance applications such as pumps, fans and mixers. Only recently have significant numbers been applied to applications such as extruders, winders and coordinated web processes that meet the criteria above. As improvements in control technology make these applications commonplace there is a need for definite purpose motors designed specifically to optimize the performance of the drive.

DEFINITE PURPOSE MOTORS FOR HIGH PERFORMRNCE DRIVES GENERAL CONSIDERATIONS

The first task is to design a basic motor configuration which is matched to the general needs of adjustable frequency power and variable speed operation. Second, the design must be adaptable to match the specific needs of many different drive applications. Third, by relaxing inappropriate constraints associated with fixed frequency, fixed voltage, fixed speed applications the design can be tailored to meet the performance objectives by making typical design trade-offs as outlined in Table 1. Also, when the controller design is known, more subtle techniques which include the controller can be used. An example is the use of a lower than usual voltage at the low speed end of a region of constant horsepower, so that the flux level (hence, peak load capability) at the highest speeds can be maximized to produce sufficient torque without having to oversize the motor. Of course, this must be weighed against the increased current required of the controller at the low speed.

Table 1. Changing Motor Parameters to Meet Performance Objectives

Objective	Parameter Change
Wide Constant HP Speed Range	Increase peak torque at base speed
Higher Peak Torque	Oversize motor Decrease stator and rotor inductance Decrease stator resistance
Lower Primary Time Constant	Increase stator resistance Decrease inductances
Higher Stator Resistance	Increase stator coil turns Decrease stator wire/slot size
Lower Inductances	Decrease stator coil turns Increase flux densities Change slot shapes
Lower Flux Density	Increase volume of core Increase stator coil turns
Lower Magnetic Noise	Decrease slot size Decrease flux density Alter shape/volume of material
Higher Efficiency	Decrease stator resistance Decrease rotor resistance Reduce flux density

As can be seen from Table 1, there are many design compromises that can be made within the motor to provide optimum performance for a given application. The following paragraphs will discuss issues that are commonly raised in discussions of variable frequency applications.

STARTING CHARACTERISTICS

Figure 1. Fixed Voltage and Frequency Speed Torque Curve

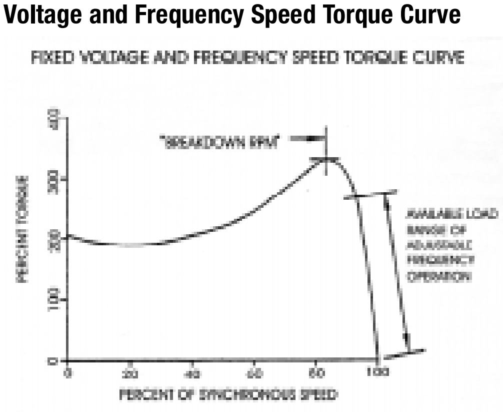
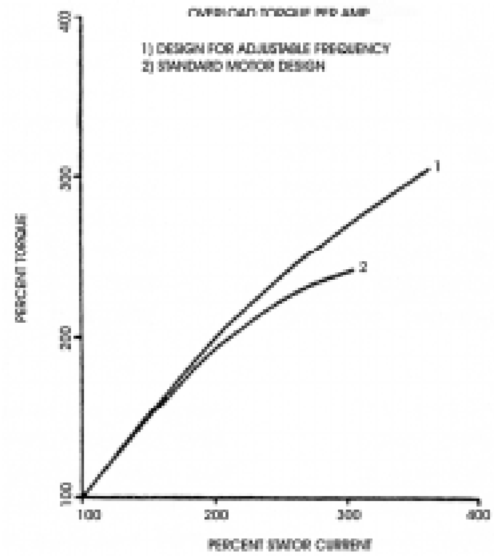


Figure 2.

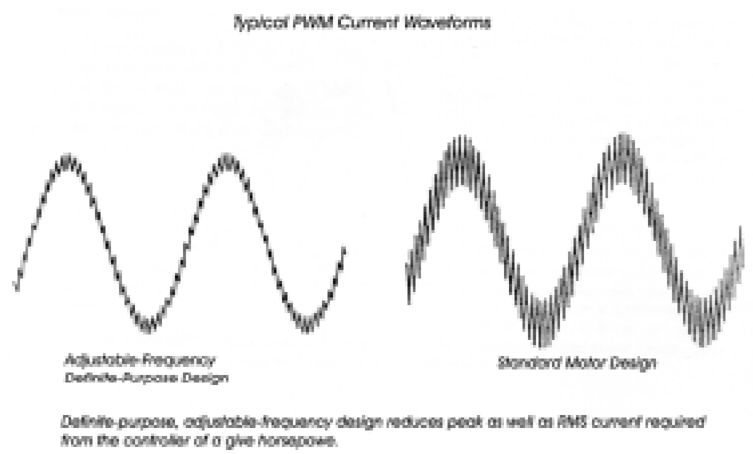


Since adjustable frequency controllers typically accelerate a motor and load by slewing the motor voltage and frequency in such a way as to remain in a region of operation above “breakdown RPM” (as illustrated in Figure 1), the usual constraints of fixed voltage, fixed frequency starting and acceleration do not apply. Starting torque and current are no longer functions of the 1.0 per unit slip characteristics of the motor but are limited by the overload capability of the control. Thus, the controller can be matched to the motor in such a manner as to produce the appropriate starting torque based on a torque/amp ratio equal to that under full load conditions. By evaluating the drive as a motor and control “package”, the motor designer can take advantage of this to enhance the level of starting torque as well as overload torque per amp as shown in Figure 2.

PEAK CURRENTS

In addition to the RMS current level, an important rating point for a transistor (typically used in adjustable frequency controllers) is the peak current capability. The high frequency transient current which results from the electronic switching of the control output voltage is inversely proportional to the leakage inductance of the motor. As noted in Table 1 the leakage inductances can be increased by altering the design of the windings and the magnetic cores in the motor. The use of an electromagnetic design specifically for adjustable frequency power can significantly reduce the peak current required for a given level of power output (see Figure 3). This will not only improve the reliability of the drive, but often can prevent costly over sizing of the AC controller and provide the most cost effective solution.

Figure 3. Typical PWM Current Waveforms

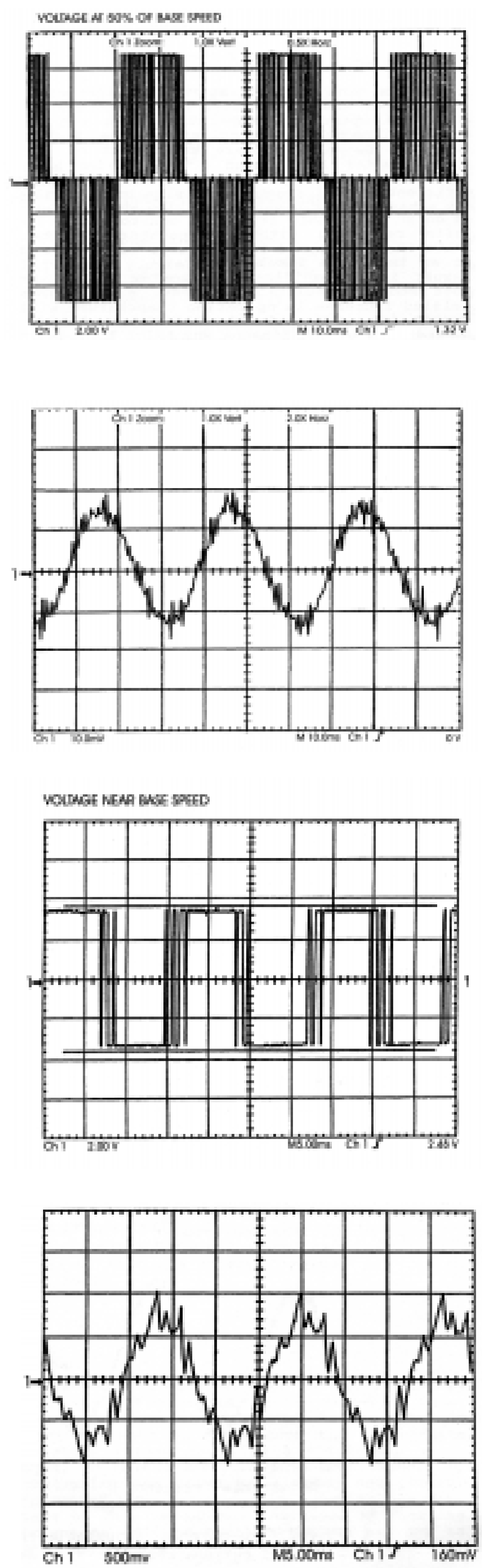


MOTOR HEATING

One of the more obvious sources of increased stress on an induction motor insulation system is higher operating temperature when run on variable frequency controllers. The higher operating temperatures are the result of increased motor losses and often reduced heat transfer as well. As a result, many standard efficient, fixed frequency design motors will not achieve their nameplate rating when operated on an adjustable frequency control at 60 Hz while remaining within temperature limits. While these elevated temperatures may not lead to an immediate insulation failure they will result in a significantly shorter life. In most modern insulation systems, a 10 degree Celsius increase in operating temperature will result in a 50% reduction in expected life. This is one of the reasons why “High Efficient” designs, which have inherently greater thermal reserves, are often recommended for operation on adjustable frequency controls.

When an induction motor is run with voltage and current wave forms as seen in Figures 4a through 4d, the deviation form the ideal sinusodial waveshapes create additional losses without contributing to steady state torque production. The higher frequency components in the voltage waveform do not increase the fundamental air gap flux rotating at synchronous speed. They do, however, create secondary “hysteresis loops” in the magnetic steel, which along with high frequency eddy currents produce additional core losses and raise the effective saturation level in the lamination material. As another consequence of these higher frequency flux variations there are higher frequency currents induced in the rotor bars which generate additional losses. Appropriate electromagnetic design, including rotor bar shape can minimize these added losses.

Figure 4. Typical Waveforms From Adjustable Frequency Controllers

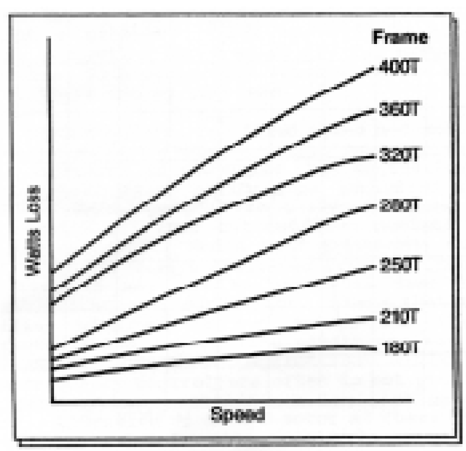


The higher frequency components of the current waveform also do not contribute to the steady state torque. They do, however, increase the total RMS current resulting in added I R losses in the stator winding. In addition to higher frequency current components there can also be low frequency “instabilities” in the currents seen by the AC motors on variable frequency controllers. These asynchronous components of current again cause added losses without contributing to the steady state torque production. Motor designs which help minimize harmonic currents lead to lower I R losses.

MOTOR COOLING

As has been well documented in the literature, when AC motors are run across a wide speed range their heat transfer effectiveness will vary a great deal. Cooling fans whose rotation is directly supplied by the motor are subject to high windage losses and noise at high speeds. Modern AC controllers are capable of operating across a very wide frequency range, often up to several hundred hertz. While this provides great flexibility in the control, it places the motor cooling fan well above its fixed frequency design operating point which often leads to inefficient air flow and objectionable noise. In low speed operation the fan’s effectiveness falls off with the motor’s speed. Figure 5 shows typical cooling curves for a family of totally enclosed fan cooled motors. In variable torque applications this reduction in cooling air often stays in balance with the reduction in motor losses as the load is reduced with speed. However, in constant torque applications the motor’s temperature limits will likely be exceeded. An independently powered blower can provide an essentially constant heat transfer rate. Although not a standard fixed frequency motor feature, depending on the load/speed profile required by the application, this can be a very effective choice and is often specified for high performance applications.

Figure 5.



In addition to fan speed, the operating temperature of the motor is determined by how effectively the heat generated in the motor can be conducted to surfaces which are in contact with the cooling medium (generally air) and the ability to transfer this heat via convection to the cooling medium. In a conventional totally enclosed fan cooled motor the heat must be transferred from the laminated steel stator core to the cast iron frame and finally to the air. Since the fan is located opposite the drive end of the motor, there is generally greater air flow and heat transfer at one end of the motor than the other. Square laminated frame AC motors have been offered by a variety of manufacturers as a method to improve heat transfer. The laminated frame design eliminates the stator-to-frame interface and provides a more direct and effective heat transfer path to the cooling air while integral cooling ducts trap the air in contact with the frame along the motor's length. This laminated frame construction has been common in variable speed DC motors for over twenty years.

An offshoot of motor cooling is the need to protect the motor should the motor cooling system fail. While thermostats and thermistors are not common in fixed frequency AC motors they should be required for variable speed applications. A standard AC motor operates at a fixed speed on a well-defined power supply which allows the shaft driven fan to provide adequate cooling air in all normal circumstances. By design a variable frequency control will allow the motor to operate at very low speeds where little or no cooling is provided. This might occur during maintenance, jog, or threading operation for example. On the other hand, if a separately powered blower is provided the drive motor must be protected from a potential blower failure. As is the case with DC motors, over temperature protection is recommended.

DISADVANTAGES OF OVERSIZING (DERATING) MOTORS

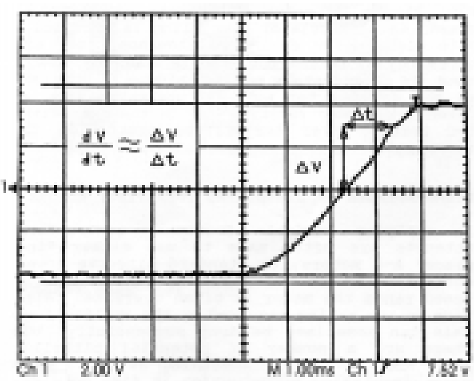
In applying variable frequency controllers attempts are often made to use either “inplace” AC motors, or standard sinewave power designs. To do this, and operate across a speed range the motor is often oversized relative to the rating required by the application. This can sometimes be done successfully, but there are a number of potential pitfalls. These can range from something as basic as a motor insulation system which is fine on sinewave power, but inadequate for the voltage and current waveshapes on the controller, to drive system instability due to a lack of damping. The oversized motor will have correspondingly higher rotor inertia, which could lengthen acceleration and deceleration times and reduce process productivity. Also, since no load current tends to be a fairly constant percentage of full load current within a motor product line, the higher no load current of a derated motor could result in lower power factor and higher current at the load point required by the application. This current may exceed the capability of the variable frequency controller requiring a costly oversizing of the controller as well. A derated motor will have a lower nominal slip at the application load than a matched motor, which can cause problems either with load sharing in the case of multi-motor drives, or with IET trips whenever the load changes quickly. While it often appears to be economic to oversize a standard motor to achieve a greater speed range, this course of action should be approached cautiously while weighing all factors of the desired performance of the drive.

THE EFFECT OF FAST POWER TRANSISTORS

As power transistor technology has evolved, there has been a proliferation of variable frequency controllers operating at an AC input voltage of 460 V, using these transistors as the power-switching device. As the transistor manufacturers have continued to push toward devices with lower losses and the capability of the higher switching rates, a result has been very rapid transition times between the “off” and “on” states. This is the case for both bipolar (BJT) as well as insulated gate (IGBT) transistors.

The combination of fast transitions (turn-on time) and the DC bus voltages of 460 VAC (input) controllers results in the high “dV/dt” levels as seen in Figure 6. What is typically referred to as dV/dt is the time derivative of the voltage, or the slope of the voltage versus time curve.

Figure 6. Typical Transistor Transition Voltage



Increasing the dV/dt levels at the variable frequency controller output (and motor input) can have effects which need to be considered in the design of motors for such applications. The significance of these effects can be shown by the following equation:

I = C x dV/dt

As can be seen from this equation, as dV/dt increases, the capacitively coupled current increases linearly with it. While items such a lead wires and motors are not usually thought of in terms of capacitance, three phase AC motor windings have a capacitance to ground as well as between phases. The leads between the controller and motor also exhibit similar effects. While these capacitance values are normally considered negligible, given enough dV/dt, it does not take much “IC” to get quite a bit of “I”.

A second way of viewing the high dV/dt levels is to use transmission line theory to compute the voltage distribution due to the propagation of the steep wavefront. This involves careful modeling of the leads and motor windings as well as transition points such as conduit box connections. Reflected as well as incident wavefronts must be computed and combined. This type of analysis will not be described in this paper. Analyses done by this methodology are susceptible to errors due to many things including the choice of appropriate complex impedance models for circuit components. Generally, the results of this type of analysis have indicated that the first length of wire in a motor will see higher voltages than will subsequent parts of the winding. This type of modeling is typically used for the analysis of high voltage surges incident on the terminals of very large machinery.

Another result of the very fast transition time of today's transistors is that the voltage at the inverter output and the motor terminals is not the same. The voltage waveshapes in Figures 7 and 8 demonstrate typical differences. Using the transmission line model mentioned above, the two major differences in these waveshapes can be explained as follows. The impedance of the leads results in the voltage wavefront being distributed to some extent across those leads, softening the wavefront to a lower dV/dt level at the motor terminals. Secondly, the termination of the transmission line (leads) at the motor results in a reflected wave, producing the overshoot and dampened oscillation seen in Figure 8. This waveform could also be modeled as the response of an L, R, C, circuit to an impulse input.

Figure 7. Voltage Wavefront An Inverter Output

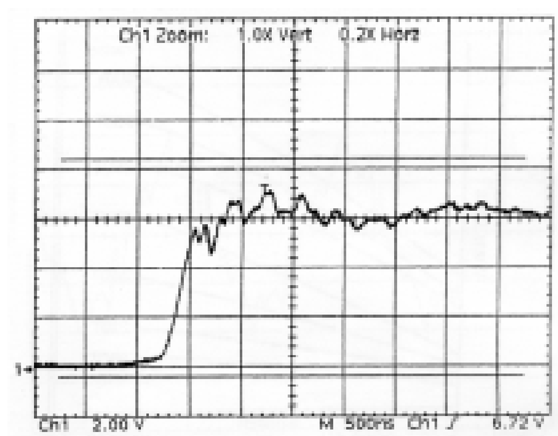
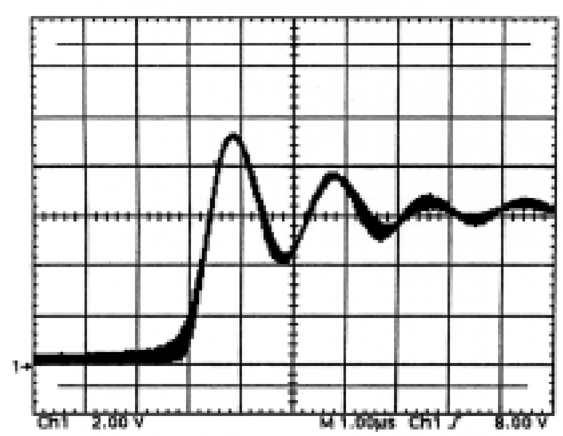


Figure 8.



The end result of these waveshapes being applied to the motor terminals is increased stress on the insulation system. Since these waveshapes do not exist in sinewave applications it is clear that their effect has not been considered in standard AC motor insulation systems. The motor insulation system must be capable of withstanding both the increased thermal stress as well as the capacitively coupled currents and voltage stresses. Appropriate selection of individual materials, properly integrated into a motor insulation system is needed to withstand the demands of operation on variable frequency controllers.

MOTOR FLUX LEVEL

The fundamental frequency component of the voltage output of a variable frequency controller can be as high as the AC input to the controller. However, this is often not achieved. In order to maintain PWM modulation for example, the output voltage may be limited to 90-95% of the incoming AC voltage. As long as this situation is recognized, and appropriate design choices made, it does not usually present a problem. When an existing motor design (expecting 460 V at 60 Hz, for example) is applied to a controller which delivers only 420 V, there can be problems.

While NEMA standards for fixed speed AC motors allow for a 10% voltage variation from nominal, it is important to recognize that at 10% lower than nominal flux, performance including the nominal HP rating will vary. For example, it may require 10% more current than nominal to deliver rated HP. While this additional current is almost always available from the incoming line it may not be available from the variable frequency controller. Users that are familiar with static DC drives and their characteristics in low line conditions may be unpleasantly surprised to find that AC variable frequency controllers often do not provide the same rating capability at low line conditions. Operation of an AC motor at lower than nominal flux levels will result in increased slip and rotor heating which is self compounding and may lead to a thermal runaway condition. High efficiency AC motors designed for sinewave operation are often particularly susceptible to poor performance when the controller output voltage is low, since they usually employ low flux density designs at nominal terminal conditions.

MEASUREMENTS IN A PWM ENVIRONMENT

Another effect of the rapid-rise-time pulses which today's variable frequency controllers can apply to motors is to challenge existing measurement tools and techniques. The high dV/dt voltage pulses are themselves not trivial to measure. Typically, an oscilloscope with a single shot bandwidth greater than 10 MHz, plus a high voltage probe with high frequency capability (carefully impedance matched) is required. Since voltage isolators typically cannot faithfully reproduce these waveshapes, the scope must be "floated" unless the variable frequency controller is operating on a floating power system. This then requires appropriate care to avoid electrical shock to the operator.

Not only is measuring the voltage pulses difficult, all other measurements on the equipment are exposed to this high dV/dt environment. This requires the use of equipment which has high noise immunity and excellent rejection of common mode voltages. Common devices such as thermocouple and tachometer readouts often “misbehave” and provide unreliable readings if they are not capable of faithful operation in these high dV/dt conditions. This effect makes activities such as drive start-up and troubleshooting difficult as specialized equipment is required to take even basic measurements.

NOISE

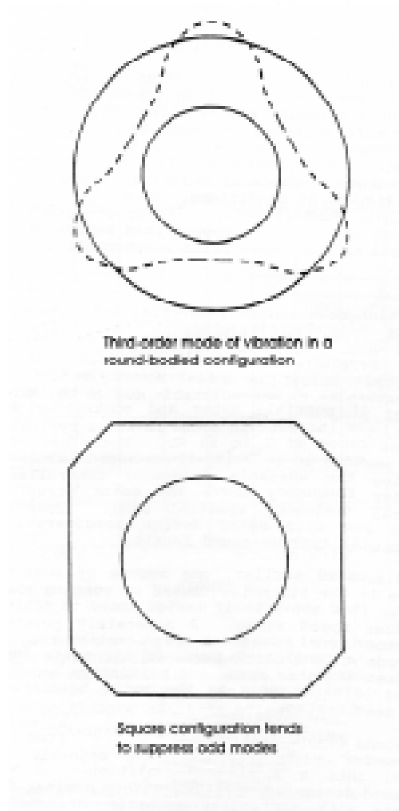
Operation of standard industrial AC induction motors on adjustable frequency power over a speed range often results in unacceptable sound power levels as well as an annoying tonal quality. While the actual sound power level has proven to be unpredictable due to the large number of possible motor and controller designs, the increase in sound level is typically in the range of 7 to 10 db. There has been some success in reducing these sound levels by pushing the variable frequency controller’s carrier frequency above the motor structure natural frequency spectral band. However, there are also motor design considerations which will improve sound levels.

As discussed earlier, one source of acoustic noise is the air noise caused by running shaft driven fans above their design speed to achieve a wider speed range. A separately powered, unidirectional, constant speed cooling fan will provide a consistent level of air noise independent of motor speed and eliminates annoying sound level changes as the motor accelerates and decelerates.

A second source is the magnetic noise from flux harmonics which are driving the magnetic core steel into a saturated condition. A well planned design will use lower than nominal flux levels with particular emphasis on avoiding localized regions of higher flux density or “pinch points”. Air gap length and rotor slot bridge thickness, which reduce saturation in localized areas are two contributing areas where additional reductions in sound power level can be achieved.

Electro-magnetic-mechanical noise from parasitic forces which are caused by flux and current harmonic interactions produce mechanical vibrations within the motor and contribute to an overall increase in sound power levels. This mechanism will usually become a problem when amplified by mechanical resonances in the motor or driven machine. To offset this source rotor and stator slots can be designed to reduce haromonic flux that contributes to parasitic torques. Also, the use of a laminated frame construction eliminates a separate frame and stator structure which simplifies the mechanical system and reduces the richness of possible noise producing natural frequencies and modes of vibration. If a square frame configuration is used it will tend to suppress odd ordered modes of vibration which are present round bodied configurations. This is illustrated in Figure 9.

Figure 9.



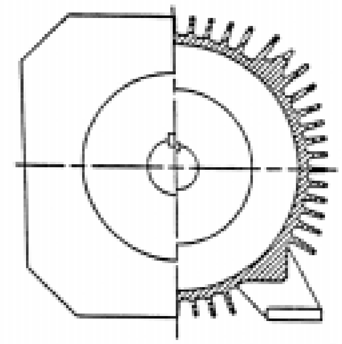
In summary, there are many factors that combine and ultimately result in noise at the motor. The motor and controller must be considered as a system to insure the desired results.

MECHANICAL FLEXIBILITY

A motor designed for operation on a high performance variable frequency drive must have considerable flexibility inherent in its construction to accomplish the variety of tasks it will be called upon to perform. A comparison of the standardized NEMA enclosures for fixed frequency AC motors to the wide variety of DC motor constructions available demonstrates the difference in the fundamental design approach. Since high performance variable frequency drives will typically be used in “DC like” applications as opposed to converting fixed frequency AC (pumps and fans, etc.) to variable speed, it can be assumed that more DC like construction will be required in definite purpose AC motors.

One consideration is to achieve the maximum output from the smallest possible motor. High performance adjustable frequency drives are often incorporated as part of specialized machinery or processes where machine realestate is at a premium. The standardization of NEMA fixed frequency dimensions creates unnecessarily large motors and offers few alternatives. The practice of oversizing the rating in order to achieve a speed range aggravates the problem. The replacement of the inactive frame material of conventional AC induction motors with active materials (conductors and magnetic steel) in a laminated frame construction allows a larger air gap diameter and increased power density (Figure 10). Often up to two frame diameters can be reduced by using this technique.

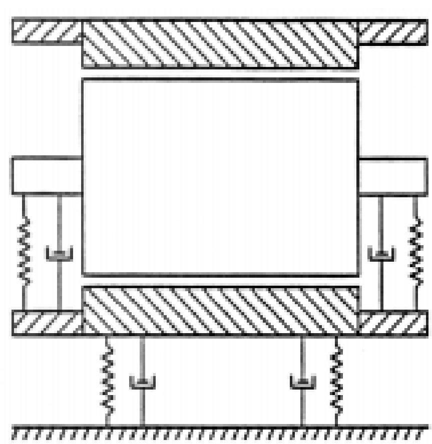
Figure 10.



Standard feetotrame design can result in a two level dynamic system with lower operating sped capability.

Also, to take full advantage of the variable frequency controller the motor must be capable of operating above its fixed frequency design speed at 60 Hz. The standard motor design considers only acceleration up to and operation near its synchronous speed. As a result few of these designs are expected to operate above 3600 RPM. The conventional AC motor rotor support to ground system (via bolted joints to the frame, etc.) can give rise to a low stiff-ness-to-ground and to second order modes of vibration (two level dynamic systems, as shown in Figure 11), which tend to reduce the value of the lowest critical speed. While all elements of a high speed motor system (bearings, rotor balance and strength, etc.) must be evaluated for suitability, the use of integral feet on the end brackets provides increased stiffness to ground by eliminating one of the joints. This can result in increased values of the lowest critical speed and permit operation at higher speeds.

Figure 11.



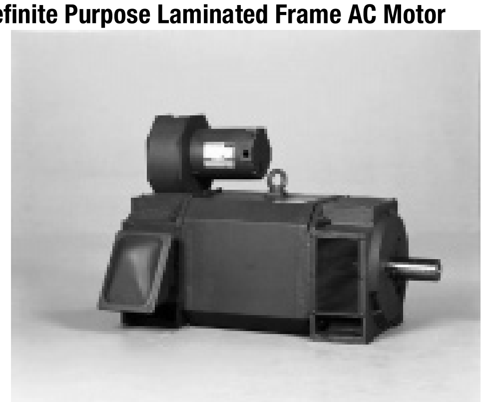
Standard feet-on-frame design can result in a two level dynamic system with lower operating speed capability.

Finally, the motor design must be capable of accepting a variety of accessory devices that are typically mounted on the motor. This includes not only a motor mounting flange but also combinations of brakes, speed feedback devices, and a variety of cooling airflow methods and directions. The design must allow for these devices to be accessed, removed and replaced in service with little difficulty. Providing these features results in a design approach very similar to DC designs and conflicts with much of the standardization in standard AC motors.

CONCLUSIONS

Providing high performance variable speed drives for maximum process productivity has always required complex engineering considerations. Rapid improvements in AC control technology, combined with the ready availability of standard fixed frequency AC motors has increased the number of possible solutions. However, a component approach (control a, motor b) will not lead to an optimal solution in many cases. In order to utilize the present (and next) generation of adjustable frequency controllers to meet application needs equal to or better than DC motors have in the past, a definite purpose AC motor is required. A square laminated-frame configuration with integral feet on the end brackets and adaptable electromagnetic designs is one approach that meets this objective (Figure 12).

Figure 12. A Definite Purpose Laminated Frame AC Motor



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