# HIGH-SPEED MOTOR DESIGN FOR GAS COMPRESSOR APPLICATIONS

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## ABSTRACT

Past industrial gas compressor applications have utilized existing technology to achieve high rotational shaft speeds. Direct drive high-speed gas turbines or a slow-speed electric motor coupled with a speed increasing gearbox have typically generated the necessary shaft speeds for gas compression. But advances in high-speed motor technology, along with improvements in the cost and performance of variable frequency electronic drives (VFDs), permits an alternative approach. By directly coupling a high-speed motor to a gas compressor, the inherent benefits of such an arrangement can be realized. Primarily, allowing the development of an integrated motor-compressor system can eliminate the need for ancillary support systems, including the gearbox, the lube-oil system, and, in some cases, the dry gas seals.

This tutorial is presented to help the gas compression industry better understand motor electrical design, the components that constitute a motor, challenges in taking motors to high speeds, and potential application issues. In this way, a less cautious approach may be taken in implementing new technology.

## INTRODUCTION

Conventional motor designs have typically been limited to 3600 rpm, based on the availability of a 60 Hz line frequency for supply power. If these motors were to be used for gas compressors, a speed-increasing gearbox would be required to dive shaft speeds in the required range of 5000 to 20,000 rpm. Implementing a high-speed motor directly to the compressor eliminates this issue, while maintaining the environmental benefits of an electric driven system. However, implementing this arrangement will have an impact on motor construction. This topic is the purpose of this tutorial. The information presented herein should give the reader an appreciation for general design considerations when configuring a motor for high-speed applications.

Table of Contents

## ELECTRIC MOTOR FUNDAMENTALS

Since the electromagnetic equations that govern motor design are largely independent of the mechanical shaft speed, the primary consideration for high-speed motor design comes in the motor construction itself. Depending on the type of motor, various techniques and features must be incorporated into the design to accommodate the operating requirements. To understand the details of construction, a brief discussion on the relevant motor types is warranted.

### *Motor Types*

Almost all industrial electric motors in use today can be classified as alternating current (AC) radial field motors. This arrangement consists of a rotating cylindrical magnetic structure (the rotor) that is supported concentrically by bearings within a stationary annular magnetic structure (the stator) as shown in the exploded view of Figure 1.

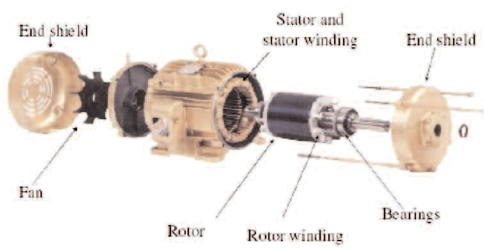


*Figure 1. Typical AC Radial Field Motor Components.*

Shaft torque is generated when the magnetic field pattern produced by the rotor lags behind the complementary rotating magnetic field pattern produced by AC electrical currents established in the armature windings of the stator. This motor type gets its name from the radial orientation of the magnetic field across the rotor-stator gap (the air gap), and from the use of three-phase AC current within a special polyphase stator winding arrangement to produce the rotating magnetic field that drives (or drags) the rotor.

The simplest AC radial field motor configuration is the permanent magnet motor shown in Figure 2. In this design, the magnetic field of the rotor is produced by powerful magnets built into the structure, and arranged to drive flux across the air gap in alternating directions into and out of the rotor surface. The resulting alternating poles must occur in pairs to achieve a symmetrical pattern around the rotor. Although a multitude of pole pair combinations is possible, practical and physical limitations are such that motors having greater than eight poles are uncommon in all but the very largest variable speed machines.

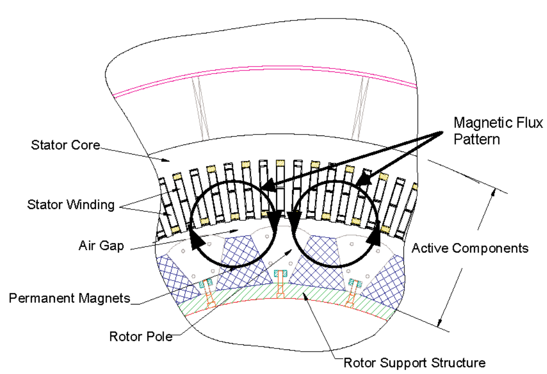


*Figure 2. Typical PM Motor Cross Section.*

Constant torque is produced only when the pattern of flux on the rotor revolves in perfect synchrony with the rotating field produced by the stator. The speed of rotation of the stator magnetic field is known as the synchronous speed (N) and is defined as:

$$N = 120 f / p \quad \textbf{(1)}$$

where $N$ is expressed in rpm, $f$ is the electrical frequency of the supply current, and $p$ is the number of magnetic poles. Motors of this type are often generically referred to as permanent magnet AC synchronous motors.

The alternating pattern of magnetic fields produced by the permanent magnets of Figure 2 can also be produced by an arrangement of rotor field coils that are excited by DC electrical currents. In essence, the permanent magnets are replaced by electromagnets. This arrangement results in a “wound field” AC synchronous motor. Low-speed wound field motors are typically produced as “salient pole motors,” where the field coils are wound around individual pole pieces that project from the rotor shaft. High-speed wound field motors, on the other hand, have field coils wound into slots cut into a solid rotor forging. Such a configuration is called a “round rotor” AC synchronous motor. The wound field rotor suffers in comparison with its permanent magnet cousin by its need for a continuous source of direct current (DC) excitation current, via “slip rings” or a “brushless exciter,” and its constant dissipation of electrical power in the field windings, with attendant cooling requirements.

Another type of AC radial field motor exploits the principal of electromagnetic induction to produce the rotor field. Motors of this type utilize a pattern of axial “bars” lying in grooves uniformly spaced about the rotor periphery, and connected at both ends of the rotor by “connection rings” to form a “squirrel cage.” Hence this motor, which is properly known as an “AC induction motor,” is also universally known as a “squirrel cage motor.” The great majority of medium power industrial motors are of this type.

In the AC induction motor, the stator winding generates a rotating magnetic field. This field cuts through the rotor bars positioned on the outside diameter of the rotor shaft. A voltage is subsequently induced, causing current to flow in the bars. The interaction of the magnetic flux from the stator and the current in the bars produces a torque causing the rotor to turn. The physics involved requires that the magnetic field of the stator be moving relative to the rotor shaft. This difference in speed between the rotating stator magnetic field and the rotor shaft is defined as slip and is normally expressed as a fraction of synchronous speed. Quantitatively, slip is defined as:

$$S = \left(N_s - N\right) / N_s \quad \textbf{(2)}$$

Where $N_s$ is the speed of rotation of the stator field (the synchronous speed per Equation [1]) and $N$ is the speed of rotation of the rotor conductors. Induction motors are also referred to as asynchronous motors, owing to the lack of synchronism between the rotation of the rotor and the stator field.

### *Motor Torque and Power*

Within each of the motor types described, and electric motors in general, the torque producing forces may be defined by the Lorentz force law. This law describes the force (F) acting on a current carrying conductor located within a magnetic field as:

$$F = J \times B \quad \textbf{(3)}$$

where $J$ is the current density, or current per unit cross sectional area, and $B$ is the strength of the magnetic field. As both $J$ and $B$ are vector quantities, the cross product notation is used to indicate the force acts in a direction that is perpendicular to both the orientation of the magnetic field and the direction of the flow of current as shown in Figure 3.

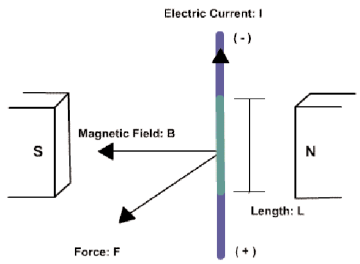


*Figure 3. Relationship Between F, J, and B.*

It is useful to relate the parameters of the Lorentz force equation to a cylindrical surface passing through the mean radius of the rotor-stator gap, at diameter D. We can define the force resulting F in the tangential direction, stator electrical loading (current flow) A in the axial direction, and magnetic loading (mean air gap flux density) B in the radial direction. Quick review with the right-hand-rule verifies this definition. For a current flow A and air gap flux density B that are considered effective over the nominal air gap length L of an electric machine, the resulting force F acts at rotor diameter as shown in Figure 4 to produce the "air gap torque" T.

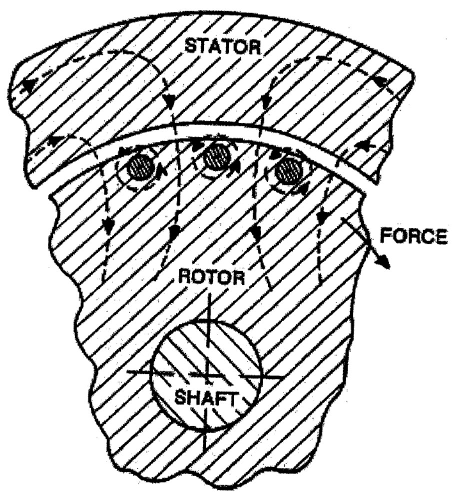


*Figure 4. Motor Shaft Torque Production.*

In terms of these parameters, the Lorentz force equation can be used to derive the air gap torque equation:

$$T = cABD^2 L \quad \textbf{(4)}$$

where $c$ is a constant. Similarly, with shaft rotation occurring at speed N, the air gap power P may be written as:

$$P = kABD^2 LN \quad \textbf{(5)}$$

where $k$ is another constant. The stator electrical loading A, with units of amperes per inch, defines the peak current density of the virtual rotating sinusoidal current sheet at mid gap that is produced by the stator armature winding when excited with three-phase AC current. The magnetic loading B is the net magnetic flux density in the air gap that is produced by vector summation of rotor and stator magnetic fields, and limited by the permeability of the magnetic path through rotor and stator steel and across the air gap.

The electrical power required to supply the load is the product of the supply current (I) and supply voltage (V):

$$P = IV \quad \textbf{(6)}$$

With a purely resistive load, the current and voltage waveforms are exactly in phase, and the power supplied is identical to the power available to perform useful work. This is known as real power ($P_r$). Electric motors however present reactive loads, or loads containing energy storing (inductive) elements that result in a phase shift between the supplied voltage and resultant current. This energy storage, which requires current flow from power source, does not contribute to the production of useful power by the motor. In a reactive circuit, the product of supply voltage and supply current is known as the apparent power ($P_a$) and is measured in volt-amps (VA). The ratio of real power to the apparent power is known as the power factor:

$$PF = P_r \,/\, P_a \quad \textbf{(7)}$$

Typical induction motors have power factors in the range of 0.80 to 0.90. Permanent magnet motors can be operated up to unity power factor.

*Motor Losses and Efficiency*

The real power, although available for work is not an indication of available motor shaft power. Losses, such as windage, bearing friction, ohmic losses, and hysteresis losses must all be supplied. Hence, the actual power available at the motor shaft is a portion of the real power supplied. The ratio of shaft power to real power supplied is known as the motor efficiency:

$$\eta = \textit{shaft power / real power supplied} \quad \textbf{(8)}$$

Electric motor losses are generally classed based upon the physical origin of the loss within the machine. For example, stator losses are subdivided between copper loss (winding) and iron loss (core). In a well-designed winding, the majority of the copper loss is the ohmic or $I^2R$ loss resulting from the main stator winding current. Circulating currents induced by the time varying magnetic field produces additional winding ohmic losses. These circulating, or eddy current losses vary in proportion with the strength of the magnetic field and the square of its frequency.

Stator iron losses include eddy current losses that are analogous to the winding eddy current loss, varying in proportion to the square of the frequency and in proportion to the strength of the magnetic field. An additional iron loss, known as hysteresis loss, is caused by the cyclic magnetization and demagnetization of the iron. A quantity of energy is dissipated in the iron in each electrical cycle, which grows in a highly nonlinear fraction with the strength of the local magnetic field, and depends on the detailed magnetic characteristics of the core material. Because the loss occurs at each cycle, the rate of loss is proportional to the electrical frequency.

Similar ohmic, eddy current, and hysteresis losses exist within the rotor iron and conductors, and also in permanent magnets if present.

High-speed motor applications have large eddy current and hysteresis losses due to high electrical frequency. Careful design is

Table of Contents



necessary to minimize losses and ensure acceptable motor operating temperatures. Features such as laminated rotor poles, complex stator coil transposition schemes, and use of unusually thin electrical steels and thin conductor strands to minimize eddy current loss should all be considered.

Heat removal provisions must be provided to ensure acceptable motor operating temperatures in the presence of these losses. When losses are relatively small, modest amounts of air directed through the rotor-stator gap are sufficient. As electrical and magnetic loading increases, demands on the cooling system likewise increase, and additional complexity is required in rotor and stator cooling features. High-pressure gas cooling or even liquid cooling may be required to achieve the very highest electrical and magnetic loading.

Friction and windage losses include the power required to turn the rotor at operating speed. The friction component refers to bearing friction, while the windage component refers to the sum of fluid drag losses on exposed rotor surfaces, power to drive attached fans, and to self-pump fluid through rotor cooling channels. Bearing friction loss can be very significant with the use of typical fluid film bearings, or relatively insignificant if magnetic bearings are employed. Windage loss can be a major loss source for high-speed motors used in gas pumping, because the loss is proportional to gas density, and increases nearly with the cube of shaft speed. Motor cooling systems must be well designed to minimize fluid drag and unnecessary coolant flow and pumping loss. With high-speed motors, it is possible that the energy required to circulate coolant will exceed the energy that the coolant is intended to remove.

## DIRECT DRIVE MOTORS FOR GAS COMPRESSION

There are many motor types, all of which exploit the fundamental relationships described above to produce torque. Selection of the most appropriate motor type for a given application is made only after giving due consideration to the attributes such as cost, efficiency, reliability, availability, and maintainability among others. The direct drive compressor application requires power levels in excess of existing high-speed motors. Based on their application, the development of these high-power, high-speed motors must ensure high reliability, but with an emphasis on low first time and life cycle costs. These requirements are best met with the simple, yet proven, robust configurations of the induction type and permanent magnet synchronous type AC machines.

## MOTOR CONSTRUCTION—BASIC COMPONENTS

Both induction and permanent magnet motors comprise the same basic components, as shown in Figure 5.

- *Stator*—Stationary member with polyphase armature windings that utilize electrical supply power to produce a rotating magnetic field in the rotor-stator gap, and thereby transfer drive power to the rotor.

- *Rotor*—The rotating member whose magnetic fields couple with the rotating magnetic fields of the stator to produce mechanical torque and drive the load.

- *Bearings*—Support the rotating shaft within the stationary motor housing.

- *Terminal box*—Housing for the connections between the power supply and motor

- *Frame*—Structure that supports the functional components of the motor and provides enclosure of the motor environment. The frame attaches to the foundation, supplying support and reaction to drive torques.

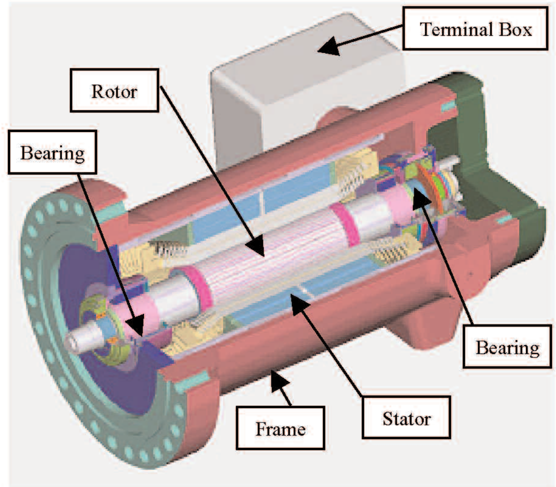


*Figure 5. Motor Components.*

### *Rotor Design Details*

For the two motor architectures targeted for high-speed applications, the rotor arrangement and associated materials will vary the most.

### *Induction Motors Rotors*

The rotor shaft is typically a single continuous member that spans between the bearings at each end of the stator, supporting the magnetically active rotor body and extending to a drive flange for connection to the load equipment. The rotor body can be an integral part of the shaft, or it may comprise a stack of thin insulated laminations shrunk onto the shaft, with stack plates at each end to maintain a high interlaminar pressure; providing a tight, well-integrated stack.

The squirrel cage winding surrounds the rotor body. Conducting bars, usually of copper alloy, run down the length of the rotor body either parallel to the axis of rotation, or with a uniform skew. All of the rotor bars are shorted together at each end of the main rotor body by full circular conducting rings called connection rings. The bar-to-connection ring joints are normally accomplished by brazing. In applications where the relatively low-strength copper of the connection ring cannot sustain the hoop stresses imposed at speed, or the joints cannot accommodate the resulting radial displacements, a high-strength retaining ring is added to provide the necessary support and rigidity. A rotor end turn design that incorporates these features is shown in Figure 6.

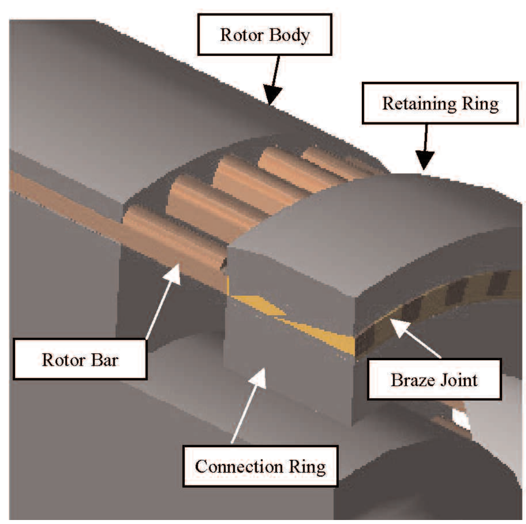


*Figure 6. Rotor End Turn Section.*

Material considerations for each component in the induction rotor are as follows:

• *Shaft*—High-strength steel with good fatigue characteristics is typically required, especially for high-speed applications. For integral rotor bodies, good magnetic permeability is required, and accurate characterization of the material's magnetic properties is necessary for faithful prediction of machine reactance. Electrical resistance as a function of temperature is needed to quantify losses.

• *Laminations*—If used for the rotor body, laminations must be magnetic with adequate load carrying capability. An insulation coating, applied to prevent induction of axial currents, keeps rotor body losses to a minimum. Typical low-speed motors utilize electrical steels such as ASTM-A-677. For higher speed machines, the strength requirements often exceed the properties of available electrical grade steels, and higher strength alloy steels, with generally poorer permeability and loss properties, must be substituted.

• *Rotor bars*—Copper and copper alloys with low electrical resistance are most often used. The soft start capabilities of variable frequency drives limit concern for torque at low speeds, so rotor bar shape and bar resistance can be optimized to minimize losses at operating speed.

• *Connection ring*—Comparable to the rotor bars, the connection ring requires low electrical resistance to minimize losses. Depending on operating speed, higher strength copper alloys can be used, provided the strength capability can be maintained through the metal joining process.

• *Retaining ring*—Typically required only in higher speed applications, the retaining ring comprises high-strength alloy steel with good fatigue characteristics. To reduce induced losses, the retaining ring should be nonmagnetic.

*Permanent Magnet Motor Rotors*

In this motor type, an array of permanent magnets is mounted to the outer diameter of the rotor body. Rare earth magnets with strong magnetic fields are installed either on the surface, with the flux oriented radially, or embedded between magnetic poles, with flux oriented circumferentially. Choice of the surface mount or embedded configuration depends on the desired pole count and the magnetic saturation characteristics of the materials.

Various approaches have been used to retain the magnets to the rotor outer diameter. Bolted retainers, as shown in Figure 7, have been employed on embedded magnet designs. Strength limitations for the bolted joint, however, relegate this arrangement to either slower speed or lower power applications. Higher speed applications can be satisfied by substitution of dovetail type joints for the bolted connections.

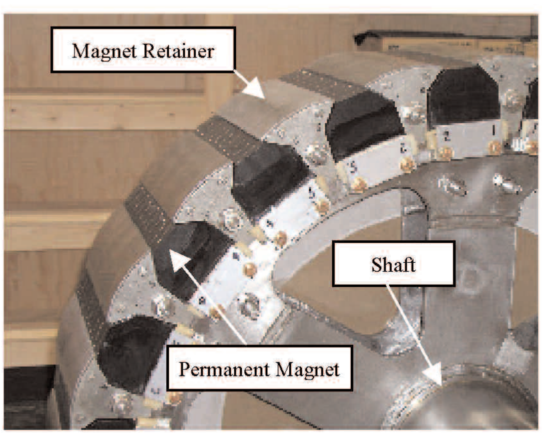


*Figure 7. Embedded Magnets with Retainers.*

Still higher rotor tip speeds can be achieved for a broad range of power applications by applying banding around the rotor outer diameter. High-strength nonmetallic banding can enable tip speeds up to 250 m/s while carrying the full load of the magnets at speed. Required banding preload can be obtained either by direct tension winding in place on the rotor, or by press fit of prefabricated composite rings over appropriately tapered rotor sections. Figure 8 shows a typical cross section of composite banding on a permanent magnet (PM) rotor.

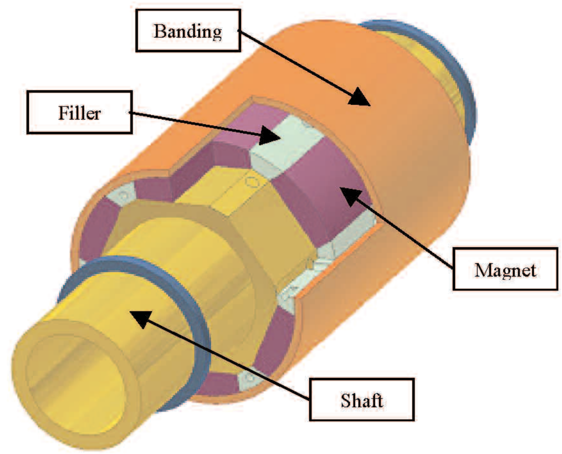


*Figure 8. Surface Mount Magnets with Banding.*

Typical materials for the permanent magnet motor application include:

• *Magnets*—Based on the magnetic strength per unit volume capability, leading material candidates for permanent magnet applications include samarium cobalt and neodymium boron iron. Other rare earth magnet materials exist and can also be employed. Each material has inherent mechanical strength and temperature characteristics that must be matched to suit the operating environment.

• *Shaft*—Magnet orientation (surface mount or embedded) dictates that the shaft be either magnetic or nonmagnetic. For surface mount designs, the same shaft materials employed in typical synchronous motor and generator designs are applicable. The magnetic nature of the material can carry the radial flux of the surface mount design through the body of the rotor. For embedded magnet designs, nonmagnetic stainless and alloy steels are required to direct the circumferential flux of the embedded magnets into the air gap. Materials are selected based on the strength and fatigue characteristics required for the specific application.

• *Banding*—Typical banding is a nonmetallic composite material incorporating high-strength fibers in a polymer matrix. Maximizing the strength to weight ratio of the banding minimizes self-induced banding inertial loads while maintaining its load carrying capability. Materials such as carbon fibers exhibit superb strength-to-weight ratios.

## STATOR DESIGN DETAILS

Whether the motor architecture is induction or permanent magnet, the stator configuration will be very similar for each. Typical stators comprise laminated steel with uniform slotting around the inner diameter. Copper coils, insulated for the appropriate voltage level are wound into the slots to deliver the supply power in the correct spatial and phase orientation. The ends of the stator iron are capped with fingerplates to distribute compressive loads and maintain adequate interlaminar pressure. Figure 9 illustrates the primary components of stator core construction.

Table of Contents



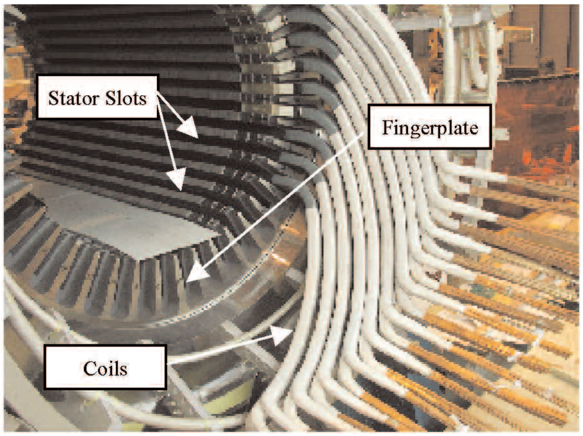


*Figure 9. Stator Core Construction.*

Stator coil construction is complex and must take into consideration numerous factors. The voltage class of the machine dictates coil insulation design. High voltage machines must account for any location on the coil that can experience a sufficient voltage potential to cause dielectric breakdown of the local insulating materials. An electrical discharge that only partially bridges the insulation between conductors is called a partial discharge (PD). PD causes progressive damage to many insulating materials and is a primary contributor to the electrical degradation to motor windings. Areas especially susceptible to PD damage include the interface between coil insulation and stator core iron, the region where coils exit core slots, and regions where different phases are in close proximity. PD measurement techniques are described in IEEE 1434 (2000). Another test that is used to evaluate insulation condition is the power factor tip-up test described in IEEE 286 (2000).

Coil ohmic losses must be effectively transferred through the groundwall insulation to the adjacent stator core material, so maximum coil temperature can be maintained within the safe operating range for the insulation materials used. The National Electrical Manufacturers Association (NEMA) prescribes the safe operating temperature limits for various insulation systems by categorizing insulation materials by temperature index, and insulation systems by temperature class. Motor specifications and operating experience generally dictate that the maximum winding surface temperature, or MWST, that the insulation systems should experience must be conservative with respect to the NEMA ratings if long operating life is to be expected. For instance, large electric generator specifications often limit winding temperatures to Class B insulation temperature limits where the actual insulation is rated Class F. Insulation thickness reduces the ability to get the heat from the copper (the source of the losses) to the cooling medium. In general, higher voltage class machines use thicker insulation with higher thermal resistance, so the current carrying capacity of the windings is reduced.

## BEARING DESIGN

Bearings used for high-speed motors will typically be hydrodynamic oil-film bearings or magnetic bearings. Oil-film bearings are a low risk solution for supporting the rotor during operation. Although numerous configurations exist for fluid film bearings, high-speed operation often dictates a tilt-pad journal bearing be used to eliminate rotor instabilities in the form of oil whip. In addition, oil film bearings provide excellent damping for rotor vibration, reducing the impact of any resonant conditions experienced during variable speed startup or coastdown operation. Figure 10 shows a typical tilt-pad journal bearing used for a hydrodynamic bearing application.


*Figure 10. Hydrodynamic Oil-Film Bearing.*

Advancements in magnetic bearing technology have made this option more attractive for high-speed applications. Low losses, oil-free operation, and the ability to be incorporated into a hermetically sealed design have given magnetic bearings preferred status in high-speed gas compression applications. The benefits of the magnetic bearing must be weighed against higher upfront costs, as magnetic bearings and their associated controller are typically more expensive than oil bearings with supporting oil supply systems.

## FRAME DESIGN DETAILS

Motor frames serve multiple functions. First and foremost, the motor frame supports the rotor and stator during operation. Careful attention must be given during frame design to understand and account for resonances and dynamic performance in the operating speed range. Poorly structured frames can lead to accelerated machine degradation with amplified vibration on the rotor and stator. In addition, excessive vibration of the frame structure itself can cause high levels of acoustic noise and create an environmental issue for operators.

The frame structure will also serve as the interface between the outside world and the motor interior. NEMA categorizes motors as either open or totally enclosed machines, depending on the method of cooling employed to remove motor losses. Open machines will use the surrounding ambient to cool the motor, while totally enclosed machines will circulate their own internal medium. In some cases, the internal cooling medium of a totally enclosed machine is pressurized to enhance its cooling capability. In these instances, the frame must take into consideration this added requirement and be designed accordingly.

Hazardous location requirements will influence the design of the frame as well. National Electric Code (NEC) requirements must be adhered to for motors employed in environments that can pose safety concerns during operation.

## HIGH-SPEED MOTOR DESIGN ISSUES

When designing the major components of a motor for high-speed operation, several issues arise that must be thoroughly addressed to ensure success. The most obvious concern is the rotational speed of the rotor. As noted previously, the power output of a motor is controlled by the following equation:

$$Power \propto D^2 \times Length \times RPM \qquad \textbf{(9)}$$

For a given speed of a motor, the power of the machine is greatly affected by the size of the rotor diameter. But there are practical limitations to this dimension. Dependent on the structural load carrying capability of the rotor design, the diameter of motor will be set at a maximum. Typically, conventional designs have yielded diameters that run at tip-speeds approximately equal to 150 to 200 m/s. Further advancements in materials and their applications will continue to raise this bar.

Referencing the power equation (10), for a fixed diameter based on maximum allowable tip speed at a given RPM, an option for increasing power of a motor is to increase the length. As was the case for diameter, however, this length variable has practical limitations as well.

The combination of high power requirements and high shaft speed inherently leads to a long flexible shaft with small diameter. If the rotor design is to be subcritical, with the first bending mode well above operating speed, the rotor body length is limited. It is also possible to build supercritical rotor designs, where one or more rotor bending modes exist below the rotor operating speed. This means that the rotor must operate at least briefly at these speeds during startup and shutdown of the motor, and that the steady-state operating speed range must be carefully placed to avoid resonant frequencies. Experience shows that this can be accomplished and lead to predictable behavior over the life of the machine, but at the cost of significant added attention to rotor balance and the stability and damping characteristics of the bearings.

*Motor Cooling*

Recall Equation (5), which equated motor power to the product of variables A, B, D, L, and N. Since the motor rotor diameter (D) is fixed based on an allowable tip speed and the length (L) of the shaft is limited by subcritical rotordynamics performance, than allowable variations in A and B must be sought to increase power for a given speed (N). B, the net magnetic flux density in the air gap is limited by the permeability of the magnetic path through rotor and stator steel and across the air gap. Some exotic materials can be employed to allow an increase in flux through the machine, but typically at a cost of strength and capability. The benefits are somewhat limited and are usually not worth the cost required to implement. A larger benefit can be gained by increasing stator current loading (A).

The obvious limitation to increasing stator current loading is thermal. Adequate cooling must exist to maintain temperatures congruent with the insulation capability. Cooling effectivity is dependent on what cooling medium is used and how it is directed through the machine.

Although there are a multitude of choices for the cooling medium of an electric machine, careful attention must be made to the impacts each has on the design, efficiency, and support system cost of the motor. Historical gas cooling options have typically utilized air or hydrogen. Some new motor technologies for the gas compression industry have even used methane, or the process gas, as the motor cooling medium. Reference Table 1 for a tabulation of the relevant gas properties for these selected options.

*Table 1. Gas Properties at Atmospheric Conditions.*

| Gas | Specific Heat (kJ/kg*K) | Viscosity (kg/s*m) | Thermal Conductivity (W/m*K) |
|---|---|---|---|
| Hydrogen | 14.3 | 89.6 | 183 |
| Methane | 2.2 | 112.0 | 34 |
| Air | 1.0 | 184.6 | 26 |

The specific heat of gas, or how much energy per unit mass a gas can carry, dictates how much flow is required through the machine to remove the generated loss from the motor. The viscosity influences the quantity of windage losses that are generated by the surface of the rotor, and is of particular importance at high speeds. The thermal conductivity determines how effectively a gas can draw heat from the surface of a body.

A motor design that required the stator to be more thermally taxed would implement a cooling gas that is more efficient. As can be seen, the best selection for gas cooling of these three choices is hydrogen. It requires less flow through the motor, generates less loss, and is the best at pulling heat from the motor. Air, on the other hand, requires high flow rates, generates more loss, and has poor cooling effectiveness.

Since each option has its own pros and cons for implementing, the final cooling selection will depend on what impact the gas has on the overall system. For example, although methane is readily available in the gas stream, will its chemical composition and contaminants, required routine maintenance, and potential motor fouling justify its use? Similarly, will the reduced power capability and lower efficiency of an air-cooled motor justify its potential lower initial costs? Ultimately, as is the case with many aspects of motor design, a tradeoff must be made in the final cooling scenario.

Liquid mediums, in place of a cooling gas, have also been employed in cooling electric machines. Water or oil has typically been used for this purpose. As is the case with gases, utilizing this cooling medium must be factored into the power gain one can achieve versus the increased complexity imposed on the design.

*Cooling Paths*

In addition to the selected cooling medium, the path of the coolant through the machine has significant impact on the motor power capability. Cooling can be simple, such as indirect stator cooling, in which the cooling gas is passed across the outside surface of the coil (Figure 11).

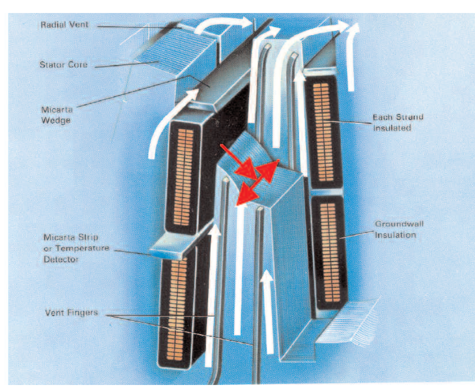


*Figure 11. Indirect Stator Cooling.*

Cooling can also be more direct, running through tubes internal to the coil (Figure 12). This arrangement, although more complicated for coil manufacturing, greatly enhances the cooling

Table of Contents



efficiency by placing the gas internal to the coil, thereb eliminating the thermal drop across the groundwall insulation.

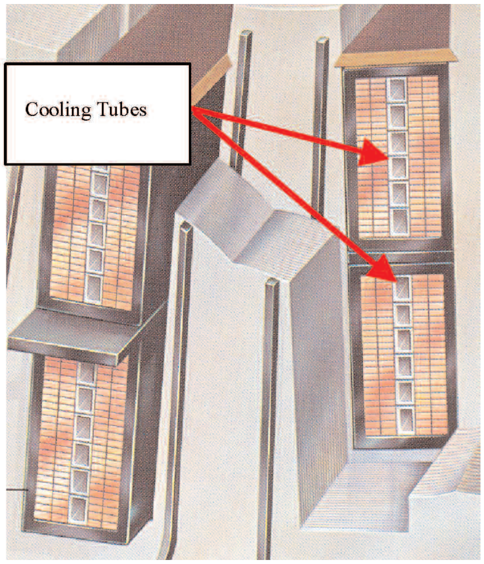


*Figure 12. Direct Stator Cooling.*

Liquid cooled options can go one step further. Liquid can be sent through hollow conductors in the coil cross section. This adds even further complexity in overall design, but is offset by the superior heat transfer characteristics of intimate contact between the coolant and the conducting copper itself (Figure 13).

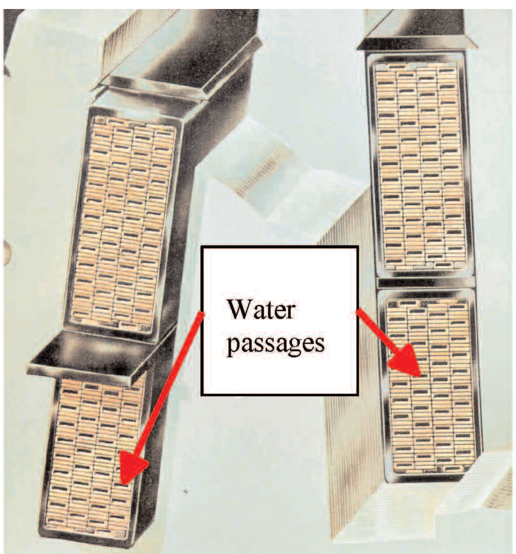


*Figure 13. Liquid Cooled Coil.*

## APPLICATION SPECIFIC ISSUES

Gas compressors are currently utilized in a wide variety of applications to suit a broad range of natural gas processing and refinery needs. Ideally, high-speed, direct-coupled motors could be adapted to all of the current applications. In some cases, such as subsea compression, high-speed motors may actually be an enabling technology.

The primary benefit of the direct-coupled motor is that it eliminates the need for a gearbox between the motor and compressor, reducing system size, weight, complexity, and maintenance. Further reductions in system complexity can be achieved if the shaft seal system between the motor and compressor can be eliminated, allowing the process gas to flood the interior spaces of the motor. Allowing gas into the motor has significant implications and potential benefits.

The primary concern with introduction of the process gas into the motor is degradation of the motor's component materials due to the contents of the process gas and the potential for deposition of contaminants on the motor surfaces. Long-term experience in a variety of gas streams is required to fully understand and appreciate the feasibility of arrangement.

The contents of the process gas vary dramatically across the range of applications. Some applications in the distribution and refinery segment are relatively clean, with contaminant levels that are very modest and pose little concern. Other applications, such as reinjection at the well, involve gas with a significant level of fluids, contaminants, and fairly aggressive chemical agents.

Adapting a reliable motor design to process gas cooling is a multistep task. Component materials can be adjusted to maintain suitability for a particular environment. An example of this is a change in the rotor steel from chrome moly nickel alloy (4340) to ferritic stainless steel (410) to improve corrosion resistance. Coatings can be applied to components to protect against particular process gas constituents. An example of this is the addition of ultraviolet (UV) curable overspray to the stator windings. A more general protective step is the introduction of stator and rotor cans to the motor. A can is a thin membrane, of either metallic or nonmetallic material, applied to the rotor or stator that forms a barrier between the process gas and the component.

When process gas is introduced into the motor interior, all power and instrumentation leads from the motor must go through hermetic connectors in the pressure housing. The commercial connector marketplace has developed these for low-level voltage and power levels, and high voltage and power levels up to 7000 V and 1200 amps. Some development is required for higher power applications, but the notional designs will not change dramatically.

Demand for natural gas has been increasing steadily for the last decade. Only recently has the balance between supply and demand caused natural gas prices to increase dramatically, providing incentive to the gas industry to increase production. The industry has responded by actively seeking gas in new locations, some of which are located offshore. Subsea compression is a technology development needed to maximize the production and economic return from these wells.

The subsea compression application involves placement of the motor and compressor on the seabed, in close proximity to the wellhead. A directly coupled motor-compressor utilizing magnetic bearings is ideal for this application, as it can operate remotely with minimal intervention. However, subsea compressor applications have not been demonstrated and require specific areas of technology development. Table 2 lists the motor related technology issues and resolution plans.

*Table 2. Subsea Motor Application Adaptation.*

| Technology Area | Issue | Resolution Plan |
|---|---|---|
| | | |
| Magnetic Bearing Controller Marinization | Marinized Electronic cabinets not available | Cabinet design employs packaging technology from subsea electronics/controls<br>Prototype environmental tests |
| Magnetic Bearing Instruments | Pressure capability of proximity probes is currently 150 bar | Adapt a proximity probe having sufficient pressure capability |
| Motor Cooling media | Subsea motor cooling methods not demonstrated | Investigate alternative gas and liquid cooling approaches for the motor.<br>Component mockups<br>Prototype Demonstration |
| Motor Power Connectors | Proven subsea connectors not available in high power (>7 kV, 1400A) ratings. | Design connectors<br>Demonstrate performance in mock-up environment |

Table of Contents



The reliability of a high-speed motor system is determined by the reliability of the motor itself, the variable speed drive electronics, and the magnetic bearing system. Electric machinery has been applied in industrial applications for over 100 years, with many examples of machines lasting well over 30 years with minimal maintenance. This level of reliability can be achieved through two approaches:

- Oversize the equipment based on conservative design rules proven by years of experience, or
- Apply a comprehensive analysis-based engineering approach to all critical components to ensure specified performance levels and adequate structural margins.

The high-speed motor technology is typically applied to achieve size and weight reductions. Given the challenging requirements of high-speed, high-power motors in a small package, reliability is best ensured using the comprehensive engineering approach. Typical design and analytical actions needed for a high-speed motor are listed in Table 3. This level of quantified performance simulation allows the designer to predict the reliable life of all components in the motor.

*Table 3. Design Activities for Machine Components.*

| Rotor | Stator |
|---|---|
| **Thermal** | |
| Determine Electrical losses and operating temperatures in all components | Determine Electrical losses and temperatures in all components |
| Determine thermal displacements | Determine thermal displacements |
| | Calculate aging of organic compounds |
| **Structural** | |
| Stress analysis of rotor motor cross section | Stress analysis of stator core with axial compression and thermal boundary conditions |
| Stress analysis of rotor end connection rings, including thermal displacements | Stress analysis of stator winding with imposed thermal displacements |
| Stress analysis of rotor shrink fits under cyclic load | Stress analysis of housing shrink fits |
| **Dynamic** | |
| Rotor dynamic stability analysis | Stator end turn modal behavior and peak responses |
| Rotor balance response | Stator electro-magnetic forces and response displacements |
| | Housing modal behavior, frequencies and displacements |
| **System level** | |
| Ventilation model for entire motor to determine coolant flow, pressure distribution and temperatures | |
| Bearing sizing for internal pressure distributions | |

The reliability of power electronics used for the motor variable frequency drive and magnetic bearing controls can be similarly engineered. Electrical losses are determined throughout the system, and this input is used to determine cooling needs and component temperatures. Thermal displacements are determined from the detailed temperature profiles, and used as input for structural analysis of components throughout the power electronics cabinets. The vibration levels of electromagnetic components must be considered from the perspective of response allowables and stress limits.

Using a comprehensive engineering approach, overall power electronics system reliabilities exceeding 40,000 mean time between failure (MTBF), as is the case with contemporary magnetic bearing systems, are not unusual.

## VARIABLE FREQUENCY DRIVES

The use of high-speed electric motors for direct drive of gas compressors is fully dependent on the availability of appropriate variable speed drives that can convert 60 Hz (or 50 Hz) utility power to the higher frequencies required by the motor per Equation (1). Therefore, discussion of motor application issues should include the availability of VFDs and interface issues.

### *Drive Availability*

Variable frequency drive technology has been evolving rapidly since the inception of reliable solid-state switching devices. Today a large number of drive manufacturers supply products covering a broad range of motor types, ratings, and speeds. Many different drive topologies exist to support this diverse customer base. However, when output requirements move into the high power (>3 MW), medium/high voltage range (>2300 V) with frequency above ~100 Hz the number of drive suppliers is significantly reduced. In many cases a high frequency, high-power drive will require a customized design with considerable consultation between the buyer and one of the top-tier manufacturers.

### *Drive Types*

Currently the majority of medium voltage VFDs change incoming AC line power to DC in a converter section then change it back to a controllable AC output in an inverter section. The DC link between the converter and inverter is either a capacitor for voltage source inverters (VSI) or an inductor for current source inverters (CSI). The switching pattern used by the inverter to control the output is known as pulse width modulation (PWM). A number of different VSI and CSI configurations are available for medium voltage, high frequency applications.

### *Drive Requirements*

Generally, to avoid problems with the motor and driven load system, the VFD should provide output with the following qualities:

- Independently variable voltage and frequency. This allows operation over an extended speed range with constant torque output.
- Voltage and current with good phase balance and minimalDC component. This prevents circulating currents and minimized losses.
- Limited harmonic content (particularly lower order harmonics). This prevents circulating current losses and minimizes torque pulsations.
- Low common-mode voltage. This prevents bearing damage due to shaft currents and minimizes stress on motor insulation.
- Low dV/dt into the motor. This also minimizes stress on the motor insulation.

Not surprisingly, except for the variable frequency capability, these are the same qualities required from standard 60 Hz AC power.

## CONCLUSIONS

An electric motor is a complex piece of equipment, covering many engineering disciplines. As the applications for motors increases to include high-speed compressors, the designs must evolve accordingly. Careful consideration must be given to all aspects of motor design when evaluating the impact of high rotational speeds and increased frequencies. Ultimately, the final design will be a tradeoff between multiple aspects of machine design, including rotor tip speed, rotordynamics, and cooling. The development of a long-term, reliable motor at power levels needed for gas compressor applications will enable the industry and facilitate the simplification of overall compressor systems.

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