EXPERIENCE WITH HIGH SPEED INDUCTION MOTORS FOR DIRECT DRIVING OF COMPRESSORS

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ABSTRACT

This paper presents the high speed, high power induction motor as a viable alternative for direct driving of compressors. A comparison is made between the existing different mechanical and electrical solutions, and the advantages of the induction motor are emphasized. The design of such motors is described with special attention to mechanical problems, bearing possibilities, and cooling solutions. The field experience is described and the solution to the encountered problems is presented. Finally, the speed-power capability curve of this type of motor is discussed.

INTRODUCTION

Mechanical solutions like gas turbines, steam turbines, or reciprocating engines have been widely used for driving high power compressors in pipelines and industry. Since the early 1980s, with the progress made in frequency converters, high speed electrical motor solutions have been used. At first, the load commutated synchronous inverter was the only acceptable solution and, during the 1980s, the synchronous motor, most of the time an extrapolation of the turbogenerator technology, was the only existing high speed electrical motor. Very powerful units have been installed, for instance 20 MW at 5400 rpm, 35 MW at 4500 rpm, or 41 MW at 3600 rpm. But the high power synchronous motor is limited by construction to 7000 rpm.

This means that the direct electrical driving of compressors may not completely be solved by the synchronous solution. From this, ALSTOM ACEC Energie, in 1987, started to develop a concept of high speed, high power induction motor based on a classical laminated rotor, with complete squirrel cage and a special bar to end-rings connection system. The first development has been an integrated motor pipeline compressor (MOPICO) (Gilon, 1991) for gas pipeline transportation, jointly developed with Sulzer Turbo, followed by a more general concept of high speed, high power stand-alone induction motor (Marriott and Gilon, 1993).

WHY ELECTRICAL SOLUTIONS FOR DRIVING COMPRESSORS?

The existing different solutions for driving compressors in pipelines and industry may be classified in two categories: the mechanical solutions (gas turbines, steam turbines, or gas engines) and the electrical solutions (conventional or high speed, synchronous or induction, etc.).

The comparison between mechanical and electrical solutions has been made in the literature (Oliver and Poteet, 1995; Rama and Gieseck, 1995). Without going into detail, it can be said that the four major advantages of the electrical solutions are:

- Lower maintenance costs
- Improved efficiency
- Lower emissions
- Increased possibility for unmanned operation

Lower maintenance costs of the electrical solutions are due to the relative simplicity of the electrical motor and drive with respect to all the mechanical solutions. Also of importance is the small number of wearing parts in both electrical motors and drives. The estimated ratio between mechanical and electrical solutions maintenance costs are values from three to 10.

Efficiencies must be compared in terms of global efficiencies, which means that the electrical solution efficiency must be calculated from the natural gas electric utility power station to the electrical motor. On this basis, it is often announced that the electrical solution has an advantage of four to five percent, with respect to mechanical solutions based on turbines, and even more with respect to gas engines.

The electrical solutions are clearly better than the mechanical solutions in terms of local emissions. It may be argued that the problems are transposed in the electric power station, but the high power turbine units in a power station may clearly be more effectively and economically adapted for low emission criteria than the small local units on the compression sites. Noise may also be included in the environmental concerns, especially for units operating in areas of high population density; here also, the electrical solutions are more advantageous than the mechanical ones.

Unmanned operation may be facilitated with electrical equipment because the electrical drive may be designed with a high level of automation and remote control. The motor itself does not require any presence onsite and the main parameters may be controlled through a very simple control system, which may be easily included in the variable frequency drive system.

It is important to point out that the possible solution with magnetic bearings instead of the conventional lubricated bearings has a positive impact on the four already mentioned advantages:

- Maintenance costs are reduced, due to the absence of wearing parts in the bearings, and mean time to repair is very short with the existing self diagnosis procedure for electronic failures.
- Efficiencies are usually 0.5 percent higher with magnetic bearings.
- A magnetic bearing solution is a completely oil free solution.
- The automation and remote control opportunities are further increased when the motor is equipped with magnetic bearings.

ADVANTAGES OF THE HIGH SPEED INDUCTION MOTOR

If we focus on the possible electrical solutions for driving compressors, a first classification is to be made between fixed speed and variable speed operations. Fixed speed operation is, by far, less costly and the variable speed option is clearly decided based on the interest for the global efficiency of the process itself.

The two other characteristics of the electrical solutions are the speed and the type of motor. The first possible solution for the speed is the conventional speed—up to 3600 rpm. This also means that a conventional low cost motor may be used, with or without a variable speed system. The consequence for the turbocompressors and most of the pumps application is also that a gearbox is required, with negative consequences on global efficiency, required space, complexity of the installation, and costs.

Increasing the speed of the motor above 3600 rpm may be an interesting solution when variable speed operation is applied to the process. In that case, one could say that the faster, the better, mostly because it helps to reduce the space required and the weight of the equipment, and that it allows for a better optimization of the compressor. Assuming a direct drive of the compressor by the motor, the efficiency of the compressor will be significantly better if the speed is higher. If we assume a nondirect drive of the compressor, i.e., a high speed motor and a gearbox, we lose one of the highest advantages of the high speed solution.

Concerning the type of motor, the two most common solutions are the synchronous brushless motor and the induction motor. DC motors are not suitable for high speed and high power duties, and homopolar machines have proved to have very poor performances. Permanent magnet motors and reluctance motors may be promising solutions, but there are no high speed, high power references.

The synchronous brushless motor is, by construction, limited to about 7000 rpm in high power applications. The difficulty is related to the necessity of providing electrical power on the rotor and to the natural complexity of this rotor (insulated conductors, slot wedges, etc.). The induction motor has a very simple and robust rotor, and it is possible with this technology to cover the speed/power capability curve of most of the existing compressors. This rotor simplicity is the major reason for the lower maintenance costs and better reliability of the high speed induction motors, with respect to synchronous motors.

The induction motor may be designed with solid or laminated rotors. In a first approach, the solid rotor solution looks to be attractive for a good mechanical performance at high speed. In practice, the simple solid rotor solution is nearly unacceptable on the electrical performance point of view, like power factor and magnetic losses. Grooves on the rotor surface to reduce losses, and a rotor cage and end-rings to improve performance are usually mandatory. The more classical laminated rotor with a complete squirrel cage is more "challenging" on the mechanical point of view, but is a guarantee to obtain very good electrical characteristics.

DESIGN OF A HIGH SPEED INDUCTION MOTOR

Rotor

The most critical part of a high speed motor is obviously the rotor. It has been observed that the good electrical performance (power factor, efficiency) of the motor was obtained by using a laminated rotor with a complete squirrel cage. The mechanical performance of a high speed electrical motor is mostly related to:

- The ability of the laminations and the end-rings to withstand the high stresses induced by the centrifugal forces.
- The ability of the rotor to stay balanced, even with the different thermal expansion of the various rotor components.

The first problems have been solved by using high strength materials and by making a very detailed finite element analysis of the rotor cross-section. The most advanced rotor technology developed is now able to achieve circumferential surface speed of about 300 m/sec (984 ft/sec).

To minimize unbalance problems, a special bar to end-rings connection system has been developed. This system provides a good electrical contact, even at low speed, and is insensitive to the thermal growth of the rotor bars.

The other key point of the design, to minimize vibration problems, is a stiff shaft arrangement. With this design, the motor is always running below its first shaft bending mode, with a safety margin with respect to the maximum continuous speed of 25 percent minimum. This means that, even at the highest values of the speed range, there is no possibility of exciting any lateral resonances due to the proximity of the first bending modes. The ability to run at low speed will be determined by the proximity of the bearing modes. If we suppose that any bearing mode must be at least 25 percent below the minimum speed, the calculations show that on oil bearings, the minimum speed may be as low as 50 to 60 percent of the nominal speed, depending on the size of the motor. On magnetic bearings, this lower limit goes down to 35 to 50 percent. The stiff shaft design of the high speed induction motor is, therefore, a good solution for obtaining a very broad speed range (typically 50 to 105 percent) free of all bearing or shaft bending modes. The undamped critical speed map for an integrated motor on magnetic bearings is shown in Figure 1. And, last but not least, to avoid excessive pulsating or transient torques associated with torsional natural frequencies, torsional analysis is performed.

Stator

The stator of the high speed induction motor is much more conventional than the rotor. The most important problem here is to minimize the losses due to the high frequency supply.

The solutions used are well-known solutions already used in high power turbogenerators or hydrogenerators, for instance:

- Nonmagnetic or conducting shields to protect the massive magnetic parts (casing, stator end plates, etc.)
- End-winding transpositions to minimize the circulating currents between the different strips of the stator conductors.

In addition to that, high quality laminations are used, once again in order to minimize the high frequency losses.

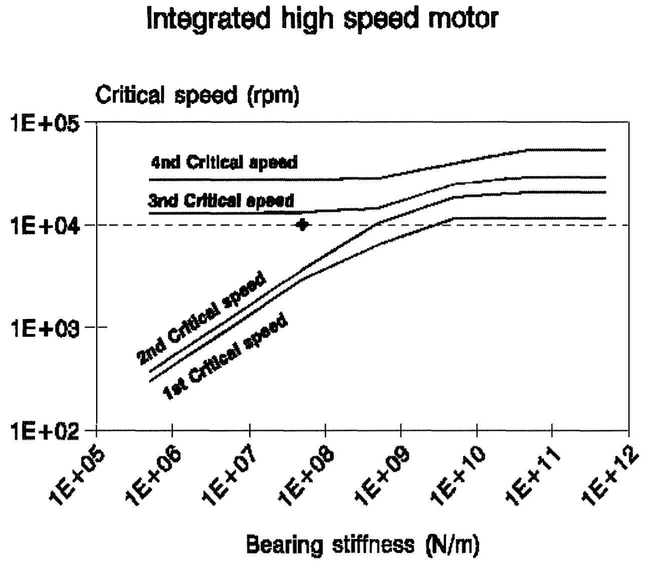

Figure 1. Lateral Analysis Undamped Critical Map.

Bearings

Two types of bearings have been used on high speed induction motors: magnetic and lubricated tilting pad bearings. Magnetic bearings have been used in most of the cases, especially in all the pipeline applications where the motor and the compressor are integrated and the motor is consequently running in the high pressure process gas. This arrangement is schematically represented in Figure 2.

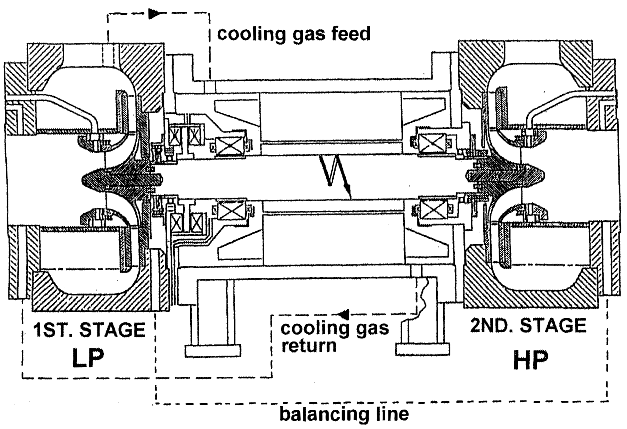

Figure 2. Arrangement of the Integrated Motor Compressor.

In these conditions, the use of magnetic bearings is very interesting, because it completely eliminates the need for any type of sealing and the unit is completely nonpolluting. But magnetic bearings may also be used in high speed stand-alone motors as in Figure 3. In that case the advantages are:

- Elimination of the lube-oil system
- Low maintenance costs
- Possibility of remote control and unmanned operation
- Low losses

Some of our applications have been made on tilting pad lubricated bearings and, with this solution, speeds of up to 16,000 rpm have been industrially achieved. The tilting pad bearing is effective when a low initial equipment cost is required or when the motor is used to retrofit the existing drive, without changing the existing compressor and lube-oil system.

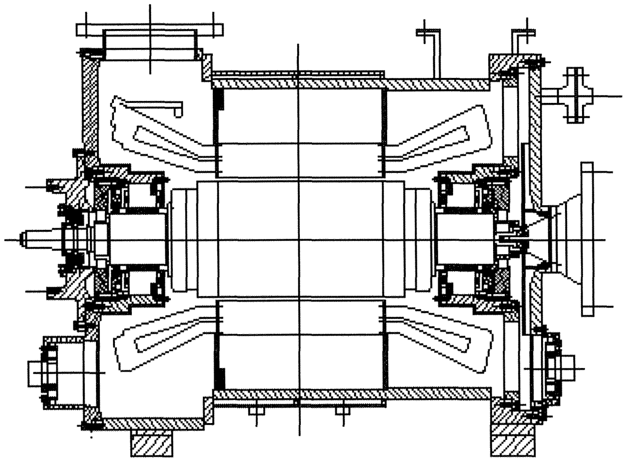

Figure 3. Internal Arrangement of a Stand-Alone High Speed Motor.

Cooling

Cooling a high speed electrical motor is a challenging matter (Gilon, 1994): the higher the speed, the smaller the motor is for a given power, but as the losses are not reduced in the same proportion as the size, the losses to evacuate per volume or surface unit are increased. The only solution is to then increase the effectiveness of the cooling circuit or the effectiveness of the exchange coefficients. Basically, three different options have been used up to now.

First, in the pipeline integrated motor compressor, the cooling of the motor is accomplished by the high pressure process gas itself. A small percentage of the outlet flow of the compressor is diverted through the motor and goes back to the compressor inlet. This cooling solution is very efficient as there is a high flow available, a high pressure allowing for very high thermal exchange coefficients, and a high thermal capacity cooling agent. The efficiency is affected by this closed loop cooling gas, but, in a more classical solution, the efficiency is also affected by the cooling fans and/or water cooling pumps that do not exist here.

The second cooling option, used in the stand-alone motors, is that used in the standard motor: air-to-air or air-to-water heat exchanger or pipe ventilated motors, with a pressurization system maintaining a small overpressure in the unit to allow its use in a hazardous area.

The third cooling option is a mix of the first two: the arrangement is classical, with an air-to-air or air-to-water heat exchanger, but the pressurization system maintains a pressure of two to five bars (18 to 70 psi). With this medium pressure, the effectiveness of the cooling is increased and the same machine is able to produce more torque. In the last two options, the air in the internal closed loop circuit may be moved either by an independent motor-fan unit or by a fan directly mounted on the shaft as in Figure 3.

Power Limit

Figure 4 illustrates how the different design problems described above contribute to the limit in speed and power of high speed induction motors. Assuming a need to deliver a power at a defined speed, this speed will immediately fix the maximum acceptable rotor diameter, taking into account the stresses in the rotor laminations. This rotor diameter will fix the stiffness of the rotor and the critical speed calculation will determine the maximum length of the rotor, assuming the required safety margin of 25 percent between maximum continuous speed and first bending mode. The maximum rotor volume is then known. The torque developed by a motor is proportional to the rotor volume for a given cooling solution. The maximum power is consequently also determined. If this maximum power must be increased, the only possibility is to improve the efficiency of the cooling system.

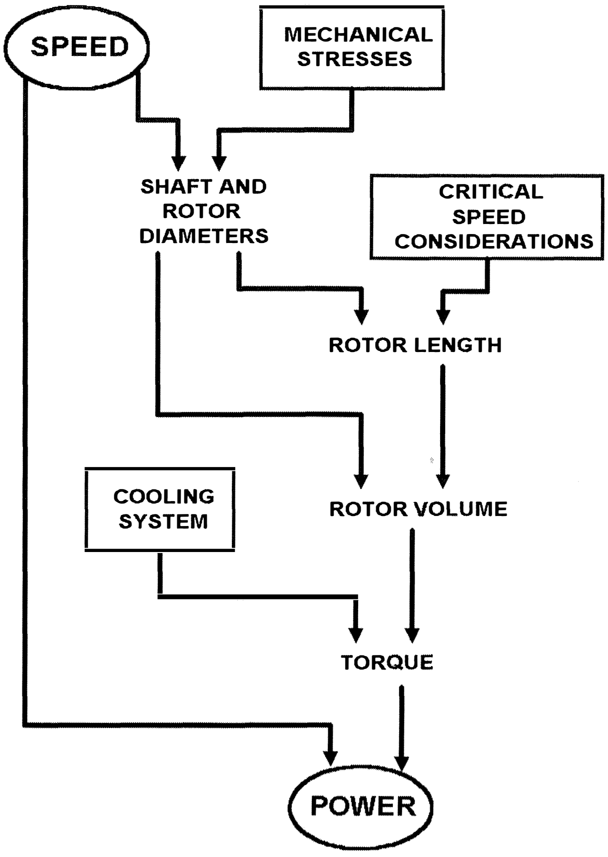

Figure 4. Power-Speed Capability of High Speed Machines.

FIELD EXPERIENCE WITH HIGH SPEED INDUCTION MOTORS

Table 1 summarizes the major characteristics of existing high speed induction motors.

Table 1. List of References of High Speed Induction Motors.

COUNTRY	PROCESS	NUMBER OF UNIT	POWER SPEED		VOLTAGE	BEARINGS	COOLING	COMMISSIONING
			(HP)	(RPM)	(KV)			
U.S.A.	Gas transportation (Pipeline)	1 unit	8000	10000	6	Active Magnetic	Methane 40 barg	07/91
Germany	Salt dome gas storage	1 unit	2700	20000	2.4	Active Magnetic	Helium or air 1.5 barg	05/93
France	Multiphase onshore production	1 unit	710	6800	0.66	Oil sleeve type forced lubrication	Air 0.001 barg	07/93
Germany	Gas transportation (Pipeline)	1 unit	4700	12700	4.16	Active Magnetic	Methane 60 barg	
France	Refinery (Reformer)	2 units	1200	15000	1.3	Oil Tilting pad forced lubrication	Air 0.001 barg	12/93
U.S.A.	Gas transportation (Pipeline)	4 units	4600	10000	4.16	Active Magnetic	Methane 40 barg	01/95
U.K.	Gas transportation (Pipeline)	3 units	10700	10000	6	Active Magnetic	Methane 50 barg	01/98
U.K.	Gas transportation (Pipeline)	1 unit	10700	10000	6	Active Magnetic	Methane 50 barg	10/98
Canada	Gas transportation (Pipeline)	1 unit	9400	10000	6	Active Magnetic	Methane 60 barg	07/98
U.K.	Gas transportation (Pipeline)	1 unit	10700	10000	6	Active Magnetic	Methane 50 barg	01/99
U.S.A.	Gas injection	1 unit	9500	14000	5.7	Active Magnetic	Nirogen 4 barg	06/99

Integrated Motor Compressors

This type of motor dedicated to gas pipeline transportation is the most important part of our reference list. Eight machines are now in operation and one will be commissioned in Canada shortly.

The first unit of this type (Gilon, 1991) was commissioned in 1991 and has approximately 40,000 hours of operation. Some problems have appeared on this machine, related to the dirtiness of the gas compressed and used to cool the motor. The first problem occurred on the magnetic bearings wiring, mostly on the various sensors. This problem has been solved by a better protection of the magnetic bearing against the humidity, a kind of "waterproof" design. The second problem occurred on the rotor itself, and was due to the corrosion of the rotor bars by the impurities of the natural gas. The solution has been to develop a special coating system for both rotor bars and end-rings. These solutions were implemented on this unit in 1994 and, since that time, the unit has run satisfactorily.

The following units have been built with the same improvements and the problems experienced on the first unit did not reappear, with the exception of a problem on some PT100 probes of the magnetic bearings. A new type of PT100 probe, more resistant to gas pollution and pressure, should fix that problem.

The most powerful unit of this type of motor is an 8 MW, 10,000 rpm machine. The other machines are running at the same maximum speed, with power between 3.4 and 6 MW. Another machine running at 12,700 rpm and developing 3.5 MW has been fully tested on a closed loop system.

Stand-Alone Motors

Stand-alone motors have been built with either magnetic bearings or lubricated tilting pad bearings. The stand-alone motor with magnetic bearings is a 2 MW motor running at a maximum continuous speed of 20,000 rpm (Marriott and Gilon, 1993). This motor is used to drive a compressor for a gas storage application. It has more than 8000 hours of operation. With the exception of a failure of the bearing during the commissioning, due to a bad starting sequence not detected by the bearing supervision system, this motor has been running quite satisfactorily.

Two units, in a refinery reformer process, of 900 kW at 15,000 rpm were built with lubricated tilting pad bearings and have been running without any problem since the end of 1993.

To summarize, the problems encountered, up to now, on the different units were never related to the high speed operation itself. Most of them were related to the operation in the gas process and have now been fixed.

SPEED-POWER CAPABILITY CURVE

The capability curve given in Figure 5 is related to stand-alone machines. According to our standardization, four different rotor diameters have been selected. Each of them corresponds to a maximum continuous speed represented by the vertical lines. Starting from the top of this vertical line, which corresponds to the longest and the more powerful motor running at that speed, we consider that this motor is at least able to produce a constant torque, at reduced speed. This determines the possible operating envelope for every size of rotor and, considering the four different rotor diameters, the diagram in Figure 5 is obtained. Typical power factors are between 0.75 and 0.85. Efficiencies are about 96 to 97.5 percent on lubricated bearings, and may be as high as 98 percent on magnetic bearings.

CONCLUSIONS

An always growing field experience proves that the high speed induction motor with laminated rotor is an attractive option for the direct drive of compressors. Low maintenance costs, high efficiency, low emissions, small foot print and weight, simplicity, and reliability are the major advantages of this solution. The capability of these motors, in terms of power versus speed, covers most of the existing compressor applications.

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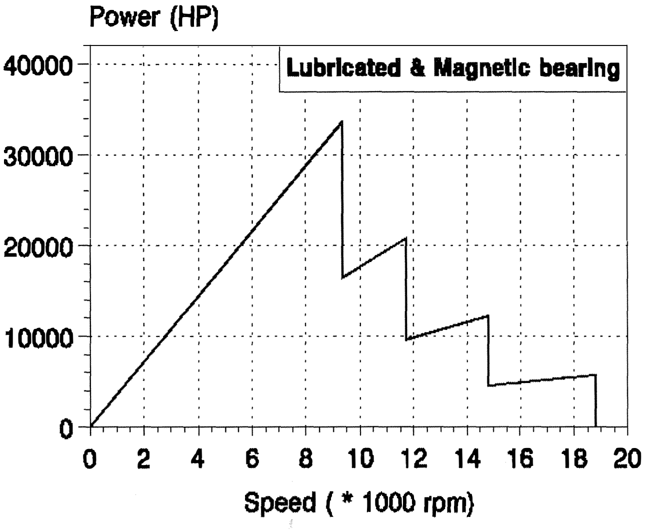

Figure 5. High Speed Induction Motor Capability Curve.

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