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COST EFFICIENT ELECTRIC HIGH-SPEED DRIVES WITH MAGNETIC BEARINGS FOR THE COG MARKET

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ABSTRACT
Electric high-speed drives with magnetic bearings offer significant technical and economic advantages for gas compression and pipeline operation. Compressors with magnetic bearings and dry gas seals have been successfully used for more than a decade. These installations have demonstrated that the elimination of the compressor lube oil system results in increased availability and is economically viable. Nevertheless, as long as a lube oil system is still necessary for the driver or for a gearbox the benefits of an oil-free operation such as increased safety and increased availability cannot be fully exploited. Electric high-speed drives do not require a gearbox. In combination with the use of magnetic bearings such drives allow the elimination of the entire lube oil system resulting in a dry rotor string. The elimination of the gearbox and of the drive lube oil system results in increased efficiency and increased availability. This leads to reduced operation and maintenance cost. Furthermore, such electric high-speed drives can easily be adjusted to specific requirements, allow a wide operating range and thus the pipeline operation can be optimized. High efficiency, oil-free operation and no emissions make electric high-speed drives the most environmental friendly compressor drive.

INTRODUCTION
Gas compression is needed at many places in the chemical, oil and gas (COG) industry, mainly for gathering (i.e. moving gas from the wells on- or off-shore upstream to the processing plants), gas transmission from the terminals to the downstream and chemical industries and for gas re-injection into storage facilities for use in peak hours. In specific applications processing the gas downstream (hydrocarbon processing industries and chemical industries) and gas distribution to the end-user needs compression as well. The demand for natural gas can be expected to increase over the next years due to increasing demand from households as well as from gas fired power plants.

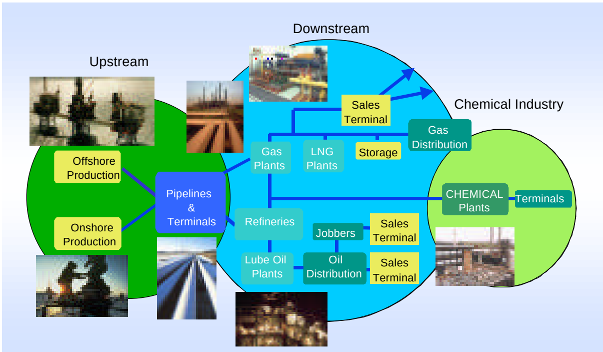

FIGURE 1: COG market

The natural gas industry recognizes the importance of efficient, flexible compression equipment for the transmission of gas. In the beginning, the gas industry met its compression objectives with many small reciprocating compressor units. As competition increased, gas companies began employing more cost efficient larger units and eventually gas turbines became the prime mover of choice. While gas fired engine driven compressors are convenient for gas companies they are becoming increasingly difficult to install. Environmental restrictions have tightened making permitting difficult. The larger gas turbine units seemed a solution because they were the low capital cost prime mover and allowed relatively clean burning. However, gas turbines have not yet achieved the high degree of flexibility and fuel efficiency gas transporters hoped.

Flexibility has become an increasingly important issue because of the new “peaking power plants” that are coming on-line. Gas companies are trying to solve the problem of low cost, low maintenance compression that can be quickly ramped up to meet peak demands. The idea of using electric motors to drive compressors to minimize the environmental, regulatory and maintenance issues is not new but progress in the area of power electronics and magnetic bearings have made them attractive.

ADVANTAGES OF ELECTRIC HIGH-SPEED DRIVES AGAINST GAS TURBINES

The development of cost efficient power converters for high power did not only lead to an increase of the adjustable speed market (new installations as well as retro-fits) but opens the market for high-speed drives. The on-going progress in the area of power electronics helps to realize power converters for higher frequencies at lower cost than in the past.

Higher efficiency

The efficiency of an electric high-speed drive is above 94 percent with efficiencies above 96.5 percent for the motor, 98.5 percent for the power converter and 99 percent for the transformer. Thus, the total efficiency of an electric high-speed drive is in the range of 40 to 50 percent when centralized power generation is considered and transmission and distribution losses are taken into account. This is much higher than the efficiency of a modern industrial gas turbine with an efficiency of about 30 to 35 percent.

Compared with low-speed drives high-speed drives with magnetic bearings offer an additional efficiency gain due to reduced bearing losses and the elimination of the gearbox losses. The efficiency of a gearbox is typically in the range of 98 to 98.5 percent. Together with reduced losses for magnetic bearings compared with oil bearings, the efficiency of an electric high-speed drive is about 1.5 to 2 percent higher than for an electric low-speed drive with gearbox.

Lower capital cost

Capital cost for electric drives is significantly lower than for gas turbines. As long as electricity is available or can be made available without extraordinary effort and thus cost for electrification, the investment for electric drives will be the lowest possible.

Lower weight and foot-print

When gas turbines with all auxiliary systems are compared with electric drives, i.e. motor, power converter and transformer, then weight and size, i.e. foot-print, of electric drives are smaller.

Higher reliability and availability

The reliability and availability of electric adjustable speed drives is dominated by the power electronics. Today’s power converters achieve a mean time between failure (MTBF) of 6 years and more. Typically, the mean time to repair (MTTR) is less than 4 hours. These values have been proven with several hundred installations of adjustable speed drives over the last years [9]. Thus, electric drives achieve an availability as high as 99 percent and above. This is much higher than typical figures for gas turbines where reliability is about 99 percent and availability is in the range of 96 to 98 percent.

Lower maintenance cost

It is obvious that an electric drive with its relatively simple design requires less maintenance than gas turbines and gas engines that have many hot gas parts and wearing parts.

Electric high-speed drives require even less maintenance than electric low-speed drives with gearbox. The elimination of the gearbox and of the lube oil system makes the drive simpler and more reliable. The two parts of an electric motor that need most service and maintenance are obsolete with high-speed drives. It is estimated that maintenance cost for high-speed drives is only half of the cost for low-speed drives with gearbox.

Safety and environmental aspects

Electric drives have no emissions on-site and total emissions are reduced as well. The lower noise levels compared with gas turbines make electric drives very attractive for urban areas. Furthermore, they are much better suited for remote control and unmanned operation.

For electric high-speed drives the elimination of the gearbox and the entire lube oil system and the necessary auxiliary systems does not only increase efficiency and availability but increases safety. No oil leakage and no fires are possible. Furthermore, with the elimination of the gearbox one noise source is eliminated.

Increased flexibility

Compressor drives need to have a certain speed range capability in order allow a variation of the transported gas flow. Gas turbines usually have a limited speed range whereas adjustable speed drives offer more flexibility because power and rotational speed can easily be adjusted with the power converter. Furthermore, variable speed operation allows higher part load compressor efficiency and reduced emissions. Moreover, compressors need to be quickly ramped up to cover peak demands. Electric drives are much easier to start and can be ramped up to full speed within seconds. With electric drives the operating speed can be controlled more accurately than with gas turbines. The flexibility allows optimization of the pipeline operation whereas accurate speed control is more important for process control.

Conclusions

Electric high-speed drives have higher efficiency, higher availability and lower maintenance cost. If high-speed drives have a capital cost comparable with low-speed drives, it is obvious that such high-speed drives would out-perform low-speed drives with a gearbox both technically and commercially. Such competitive capital cost must be achieved not only for one optimized drive design or one application but for a range of drives which allows the necessary flexibility for different applications and customer needs.

SPEED-POWER RANGE OF ELECTRIC DRIVES

The power of an electric drive is proportional to the torque and the rotational speed. The torque depends on the volume of the active part of an electric motor and is limited by maximum voltage and maximum current of the power converter. It is therefore possible to cover a large speed-power range with one basic motor design. On the other hand certain speed-power combinations can be achieved with different basic motor designs (see figure 2).

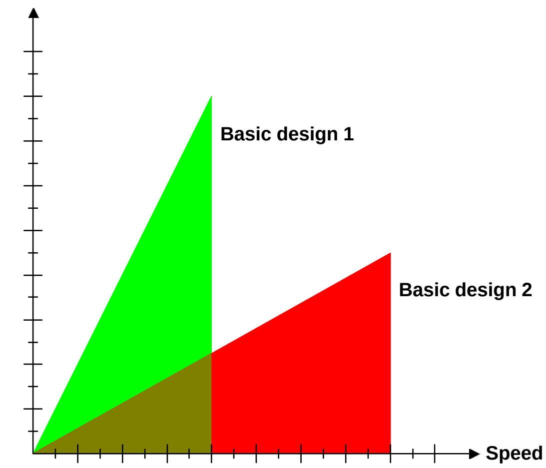

FIGURE 2: Speed-power range that can be covered with basic motor designs

When a few basic motor designs are used then it is easily possible to cover the whole necessary speed-power range and to adjust each motor to specific customer needs. With a modular converter concept the drive system can be chosen according to the requirements. A consequence of this approach is that there are a large number of different motors with different rotordynamic behavior. This requires that the magnetic bearing design needs to be checked and optimized for the entire speed-power range. In addition, in the overlapping areas different design options exist and the optimum solution needs to be found. The speed-power range of ABB's high-speed drives is shown in the figure 3. This range covers the needs for existing compressors as well as for foreseeable developments.

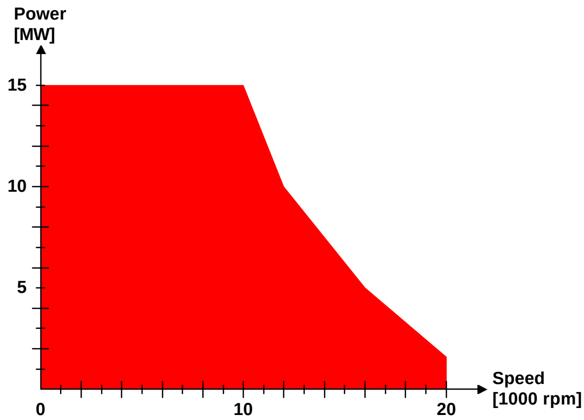

FIGURE 3: Speed-power range of ABB's high-speed drives

The main disadvantage so far has been that electric high-speed drives and especially magnetic bearings needed high engineering effort resulting in high cost. Usually magnetic bearings need to be designed to a specific application because the hardware design, the location of sensors, bearings and auxiliary bearings as well as the controller design depend on the design of the motor. The concept developed by ABB overcomes these problems with a modular approach for the motor and the drive as well as for the magnetic bearings. In addition, the magnetic bearing design concept has been integrated into the development of the high-speed drive range. The goal has not only been to achieve a cost efficient magnetic bearing solution by modular design but to realize a solution that is robust to design modifications of the motor. This concept enables a large range of speed and power requirements to be covered, fulfills specific customer requirements and allows the drive system to be adjusted according to the compressor needs. The motor and the power converter designs are matched in a way that optimization of the system to the customer needs can easily be met.

MODULAR COST EFFICIENT HIGH-SPEED DRIVE DESIGN

Over the last years a few electric high-speed drives have been developed for special applications. The main disadvantage of electric high-speed drives so far is high cost compared with electric low-speed drives. The main reasons for high cost are special motor designs, prototype development instead of a range development, complex cooling systems and very high cost for magnetic bearings. Thus, such high-speed drives have not been overly successful and have been used for special applications and in niche markets.

ABB's high-speed drives are designed to cover a large speed-power range and can be adjusted to customer needs. Such an electric high-speed drive system consists of a motor, a power converter and a transformer. In order to achieve the necessary flexibility for customer needs while avoiding extensive engineering effort and thus high cost for each application, the drive design has to be pre-engineered. This cost efficient solution has required a new, modular concept for the motor and the power converter. With a system approach the high-speed drive has been optimized technically and cost-wise. The main data of the high-speed drive is given in table 1.

TABLE 1: Main data of ABB's high-speed drive

Motor type	Induction
Motor efficiency	> 96.5 %
Power converter type	ACS 6000 TWIN
Power converter efficiency	> 98.5 %
Electric drive efficiency[1]	> 94 %
Power	From 2 to 15 MW
Speed	Up to 20000 rpm
Bearings	Magnetic bearings
Cooling	IC616, IC86W
Speed range	50 to 105 %
Availability	> 99 %
Delivery time	6 months

Power converter

The power converters for the high-speed drives are based on ABB's pre-engineered medium voltage ACS 6000 drives family. The high-speed power converters use optimized control software for high frequencies and are used in a new, twin configuration. Two standard IGCT 3-level inverter units from the ACS 6000 drives family feed the two terminals of the induction motor with open three phase windings. This configuration has the big advantage that it leads to excellent voltage and current waveforms and hence to very low torque pulsation. The converter system is tailored for high-speed motor applications with its optimized voltage waveform. It combines low harmonics for minimized motor losses and excellent motor efficiency with low inverter switching frequency demand, which also leads to smallest inverter losses and high component utilization.

[1] Includes motor, power converter and transformer.

Motor rotor design

A key decision for the design of high-speed motors is whether lamination sheets should be used as for low-speed motors or whether a solid rotor design should be used. Lamination sheet materials have limited strength and for high-speed motors the most usual motor design, i.e. shrink-fit of the laminations onto a solid carbon steel shaft, is not possible due to very high stress in the shrink-fit region. An alternative is to use lamination sheets without a central shaft. Such a design leads to challenges for the rotordynamic behavior and the manufacturing process. It needs to be guaranteed that the rotor is stiff enough even without a central solid shaft, has acceptable unbalance and does not significantly change the balancing state during operation. Manufacturing and assembly must take care of the fact that thousands of thin lamination sheets need to be staggered to form a uniform lamination stack. Tolerances need to be small to achieve the necessary accuracy. This makes it obvious that a solid rotor design is highly preferable for high-speed motors. Mechanical strength is less problematic, rotordynamic stiffness is much better and manufacturing and assembly is easier, more repeatable and better predictable. Usually solid rotor designs are assumed to have lower efficiency and higher machining cost. These two problems have been overcome with a proper electric design (see next section) and a design for manufacturing. ABB's high-speed motors use solid rotor disks that are bolted together. This concept is similar to many aeroderivative gas turbine designs and combines the advantages of a solid rotor with a high degree of modularity and reduced manufacturing cost. Delivery time is rather short due to the modular concept and the similar manufacturing process for different motors.

Electric design

Electric high-speed motors need to be electrically designed carefully. The high frequencies lead to higher losses and a different loss distribution in the rotor and the stator compared with low-speed motors. Therefore, the electric design needs to be done together with the cooling design in order to avoid overheating. With a proper design and a system optimization, i.e. power converter waveform, motor design and cooling design, high-speed motors achieve high efficiencies above 96.5 percent even for solid rotor designs. The difference in efficiency between a solid rotor design and a laminated rotor design is rather small (less than 0.3 percent) because the dominating losses are caused by the high frequencies in the stator core and by windage.

Cooling

Cooling of electric high-speed motors is more difficult than for low-speed motors due to higher power density and higher circumferential speeds. Cooling can be increased by using pressurized gas and/or by using gas with lower friction losses and increased heat transfer rate (e.g. helium). Nevertheless, such solutions appear not to be very attractive due to high maintenance cost. ABB's high-speed motors use therefore air cooling at ambient pressure, a simple, reliable and cost efficient solution. This is possible because of a concept that has both, efficient rotor and stator cooling. The airflow is split up into two parallel paths, one for the rotor and one for the stator (see figure 4). This way heat can be removed efficiently from the heat sources, i.e. the locations where electrical losses occur. Furthermore, any transmission of air from the rotor into the stator or vice versa and thus entrance losses are avoided.

Although the losses of the magnetic bearings are relatively low, the bearings need to be cooled to avoid overheating. In figure 4 it can be seen that a small amount of the cooling air is fed through the magnetic bearings integrating them into the cooling concept of the motor.

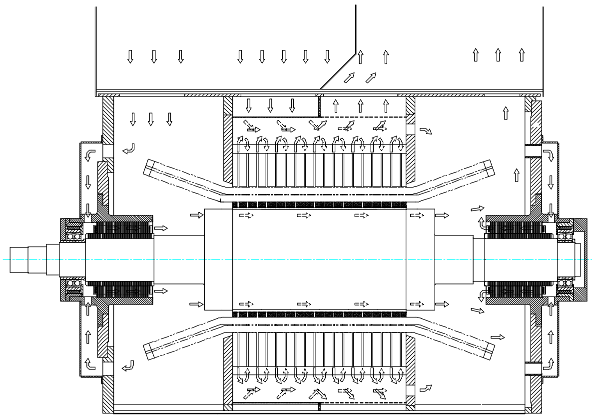

FIGURE 4: Sketch of the motor cooling scheme

Rotordynamics and magnetic bearings

Magnetic bearings offer significant technical advantages and allow an oil-free solution but on the other hand introduce additional cost. Up to now magnetic bearings have only been used for special applications for large turbomachines and thus a typical prototype approach has been used. This leads to special custom-made solutions with a high cost impact. A high-speed motor itself is comparable in material cost with a low-speed motor. As long as no special, expensive cooling systems or extremely expensive materials are used the cost comparison is as follows. The cost for a gearbox, the oil bearings and the lube oil system stand against the cost for magnetic bearings. It needs to be considered that the cost for magnetic bearings does not only include the magnetic bearing hardware but development effort, engineering and commissioning time as well. It is therefore clear that this point needs to be solved in the design process in order to be successful.

Today magnetic bearings follow a typical prototype approach with high engineering effort, long commissioning time, and a lack of standardization as well as of international standards. In order to achieve the cost targets for a cost efficient high-speed drive the magnetic bearing design has been included in the motor design process. The goal has been to optimize the system rather than its components. Magnetic bearings are used in the high-speed motors in a modular way with pre-defined bearing designs and a limited number of sizes. This concept is similar to the use of frame sizes or standard sizes for conventional bearings. This means moving away from an approach for magnetic bearings that tries to optimize the design for each application towards an approach that does not squeeze the bearing design and may lead to over-dimensioning. Such a design may not be optimal for each motor but it appears to be the best and most cost efficient approach for a range of motors. This concept leads to a robust design, reduces the engineering effort for magnetic bearings for different motor designs, and simplifies and standardizes manufacturing processes. As a result, this helps to reduce cost for magnetic bearings and consequently for the drive. This is an important step away from a high-tech product that requires high engineering and deep know-how towards a commodity that is robust and easy to use. The necessary next step for magnetic bearings is a standardization of the bearings and agreed international standards. This will help motor and compressor manufacturers and end-users to design and specify products with magnetic bearings in a better way.

In order to cover the speed-power range shown in figure 3, the most powerful motors need to operate above their first lateral critical speed. The design of the high-speed motors has been done in a way that such an operation does not limit the speed range. According to API 617 this requires an amplification factor of 2.5 or smaller. With magnetic bearings and a proper controller design this can be achieved due to their excellent damping capabilities. As a result, the high-speed motors are capable of operating across the entire speed-power range without any restrictions or large vibrations. During the design process, the rotordynamics of the electric motors and of motor-compressor strings have been analyzed including the influence of the controller design. The goal has been to achieve a robust system design in order to avoid time-consuming controller re-design and tuning for different applications.

Commissioning time will be short due to internal standardization, pre-engineered designs and options and the modular approach. Furthermore, the high-speed drive is designed as a system that can be used for different applications and different compressors where the motor is coupled to the compressor with a flexible coupling. The rotordynamic design as well as the magnetic bearing design is robust against changes from the driven compressor. It is therefore possible to use such a drive with compressors that run on different magnetic bearings or even on oil bearings. This has been validated with extensive rotordynamic analyses for different motor designs and coupled analyses including different compressors. Thus, the high-speed drive can be seen as a stand-alone product that does not need special design and engineering effort in order to be used for different compressor applications.

CONCLUSIONS AND OUTLOOK

It has been shown that electric high-speed drives offer significant advantages for gas compression and pipeline applications. They are favorable from a commercial and a technical point of view. Lower capital cost, lower total cost of operation, higher efficiency, increased availability and lower maintenance are the main advantages. Due to the deregulation of the electricity market and increased importance of environmental aspects electric drives will have a bright future. No emissions on-site, low noise and high efficiency make electric drives the most environmentally friendly solution. Electric high-speed drives with magnetic bearings offer additional advantages such as oil-free operation, increased availability and increased safety.

The main disadvantage of electric high-speed drives and magnetic bearings so far has been that they are rather expensive and thus have only been used in special applications. With the modular concept described in this paper this disadvantage has been overcome and it has been possible to achieve cost efficient electric high-speed drives.

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