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Industrial Design Aspects of High-Speed Electrical Machines among Active Magnetic Bearings designed for Compressor Applications

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ABSTRACT
These paper present Two-stage oil-free centrifugal air compressors can convey noteworthy advantages and open new market opportunities for compressor manufacturers. One of the core technologies following this compressor type is the high-speed electrical machine sustain beside active magnetic bearings. In this paper, the desires set through the compressor on the electrical machine design are existing. The design solutions aimed to satisfy these requirements are discussed in industrial application. Two case studies demonstrate probable design approaches for the target relevance through examples of a 120-kW, 60 000-r/min induction machine with a solid rotor and a 225-kW, 50 000-r/min permanent-magnet synchronous machine (PMSM) with a full cylindrical magnet. The organization design and simulation results are established next to measurements of a PMSM prototype.

Keywords: Compression, AMB, HS, Induction Motor

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I. INTRODUCTION

Compressed air is worn in many industrial applications, such as pneumatic actuators, sandblasting, machining, fermentation, instrumentation, air polishing, and numerous others. Rotary screw compressors have usually been used as the foremostresource of compressed air. Conversely the moderndevelopment toward oil-free air is preventive theirindustrial application, and centrifugal compressors are used as a substitute [2]. With centrifugal compressors, the required pressure ratio can be achieved by using several compressor stages. To decrease piping and the numeral of components, it is favourable to trim down the number of stages. The generallycompressedresolution is achieved all the way through two stages on the equivalent shaft. This approachnevertheless requires a noteworthy power density and high speed (HS), which poses confront to the design of an electrical machine for such an appliance. The power density of an electrical machine increases by way of the speed [2], [3]. HS machines make available a small footprint and are characterized by high Competence [4]. by means of variable frequency drives, it is possible to operate at the desired operating point exclusive of a gearbox [5]In many HS machines, ordinary ball bearings or high-precision ceramic ballbearings are replaced with active Magnetic bearings (AMBs) [4], [7]. The AMBskeep the rotor in the air with magnetic forces and without any contact. Furthermore, friction of thesebearings is low. Thus, no lubricant is necessary anddesires on sanitation can be met. Consequently, throughthis equipment, the Class 0 oil-free Compressor certification can be achieved according to ISO 8573-1 [8]. The other imperative advantage is the capability to obtain programmable stiffness and rotor dynamics monitoring [9], [2]. The above-mentioned benefits of an HS machine with magnetic bearings make it an ideal candidate for a two-stage turbo compressor [11].The benefits approach with the charge of a importantattempt required for the system growth The design of an HS electrical machine is a complex and multidisciplinary task [2], [3]. In general, one machine cannot be intended universally appropriate as each application imposes limitations of its own [4].The induction machine (IM) and the permanent magnet synchronous machine (PMSM) are two HS machine topologies that are frequently selected for a compressor application. The HS PMSM provides a higher efficiency, power factor, and power density than the HS IM [5], [6]. However, the HS IM does not have permanent magnets (PM), which allows it to function at higher temperatures and higher rotational speeds thereby extending the power and speed boundaries [7]. The selection of the machine topology is case explicit for the air compressor application.

A preliminary feasibility study must be conducted to select between the IM and the PMSM based on the requirements, boundaries, and preference. This paper considers common limitations and needs of the two-stage compressor set on the electrical machine through AMBs. The study covers examples of a 120-kW, 60 000-r/min IM with a solid rotor and a 225-kW, 50 000-r/min PMSM with a full cylindrical magnet. The main involvement of this paper is the swot up of the HS IM and HS PMSM drive trainintend aspects, in order to address the limitations forcedbeside the Class 0 oil-free two-stage air compressor. The design decisions are confirmed through HS PMSM prototype quantity

II. DESIGN PROCEDURE

The design of an HS machine consists of several iterative steps [8] . The design development is based on a list of needs, and in the case of two-stage boundary conditions, which are discussed added in this paper. Foremostfeasibilitylearns is made to confirm the concept. The main needs are specified in terms of power, speed, and minimum motor effectiveness required in the operating variety to achieve the optimum compression ratio and air volume flow. This makes available the initial point for the electrical machine design. Subsequently, based on the rotor weight and rotational speed, the bearing type is selected. At this stage, the machine topology and the location of the impellers are distinct Then, a detailed and iterative breakdown of the electrical machine, the AMB design, and the rotor dynamics is carry out.themajor aspects that link all the design steps jointly are the thermal stability of the organization and the dynamics of the rotor. These two characteristics are firmly related to all geometrical dimensions. at length the calculation results are compared with means of the needs

III. BOUNDARIES AND REQUIREMENTS

Fig. 1 shows two alternatives to place the impellers on the shaft. The first option is to mount both impellers at one end of the electrical machine. This arrangement is implemented, for example, in the 500 000 r/min two-stage compressor for the Solar Impulse airplane [1]. In the second option, the impellers are located at both ends of the electrical machine. In [20], this building type is executedesigned for a 300-kW, 60 000-r/min compressor.

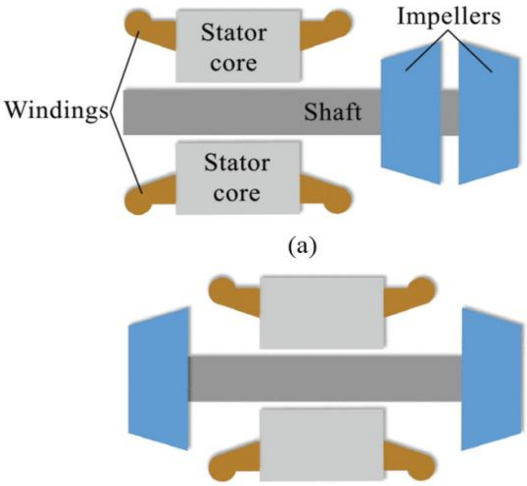

Fig.1impeller arrangement of a two-stage compressor: (a) two impellers are mounted at one end of the machine and (b) impellers are mounted at both ends of the machine.

IV. HS MACHINE DESIGN

When the arrangementorganization has been definite and the machine category chosen, it is achievable to commence the detailed electrical machine design. It starts through the selection of the rotor outer diameter and length. The resulting rotor volume ought to provide the required torque. In all-purpose a larger rotor diameter increases the peripheral speed, which leads to two major problems. First, a higher rotor peripheral speed increases the rotor stresses and sets more stringent needs for the components to preserve the rotor integrity. Instant it increases wind age losses, which can be overriding at high rotational speeds. Amongst a long and thin rotor, there is a risk of andisapproving system. In this case, the nominal functioning point is above the first critical frequency of the rotor, which causes supplementary control problems. Consequently, the selection of the length/diameter ratio not only plays a critical role in the machine design excludingmoreover affects the entire compressor get-together. The initial length/diameter ratio can be calculated by means of the equations for the IM, χIM, and the synchronous machine, χSM, correspondingly [2],

$$\chi_{\mathrm{IM}} \approx \frac{\pi}{2p}\sqrt[3]{p}$$

$$\chi_{\mathrm{SM}} \approx \begin{cases} \frac{\pi}{4p}\sqrt{p} - & \text{if } p > 1, \\ 1-3 - & \text{if } p = 1 \end{cases}$$

Where p is the number of pole pairs. In addition, the length/diameter ratio can be personalized to address the aforementioned exertion, the electromagnetic design of an HS machine ought to address several critical issues, including additional copper losses since of the skin effect and circulating currents, high core losses at high frequencies, and rotor eddy-current losses since of the air gap flux density harmonics. For example, to avoid losses caused with the skin effect, each individual conductor diameter must be smaller than the penetration depth. Anadditional detailed analysis of the parasitic effects caused by the circulating currents and the traditions to conquer them can be found in [3].And the backup bearings constitute the input information required for this step. After that, the detailed AMB design can be performed.The machine cooling can be calculated after the frame has been designed. The most common cooling method for a two-stage air compressor is forced air cooling, sometimes combined with stator water jacket cooling. A two-stage compressor has to have a short axial length to avoid problems associated with rotordynamics. This can be achieved through a high integration level of the system and a high machine power density. However, a high integration level leads to a high loss density and can cause overheating of the critical parts and a machine breakdown. Therefore, the cooling design and machine temperature calculations must take account of the impellers, which act as heat sources, and which are thus extremely important in a compact two-stage compressor with a high power density.

V. AMB DESIGN

The common trend for AMBs is to minimize their dimensions, especially the axial dimension, and to minimize the power losses. The first target is important in order to increase the frequency of the rotor flexible modes to achieve subcritical operation, or at least to reduce the number of modes crossed during a run-up. The second target is to mitigate the cooling problems and increase the overall efficiency of the system.For machines with high rotational speeds approximately above 30 000 r/min, the eddy currents in the rotor lamination stack should be considered. The field provided with the bearings is not rotating with the machine, and thus, the rotor faces significant flux changes. In traditional heteropolar magnetic bearings, this strength lead to a reduced load capacity above a certain speed level and coupling between the axes [26] . Both of these effects are undesirable. To overcome the issue, a homopolar type of bearing is applied. In that case, the flux travels all the way through the rotor surface only in one direction, thus reducing the eddy currents and increasing the bandwidth.A compact homopolar solution is a hybrid bearing with PM biasing. The magnet provides an initial flux density, which is later adjusted in the desired direction with control coils. In that way, both control coils can be completed smaller, the total current in the windings is reduced, and thus, resistive losses are minimized [6]. A schematic of heteropolar and homopolar bearings is offered in Fig. 2 . The heteropolar bearing has eight poles, and the flux bias is provided by the bias current. In that case, the flux travels from one pole to another through the rotor surface in the radial direction. The homopolar bearing uses the PM to provide the initial bias flux, and the control coils can revolutionize the flux balance. The flux passes throughout the rotor in an axial plane and flows addicted to the poles with the same direction pointing from the inside of the rotor to the outer surface. In Fig. 2, the hybrid constitution that combines the axial and radial bearings is demonstrated. In the axial part, the flux is controlled with an axial coil that defines from side to side which leg the flux will flow. consequently, it determines the direction of the axial force. If an axial bearing is not needed, it is replaced witha solid steel part, which is typically referred to as a “dead leg.”

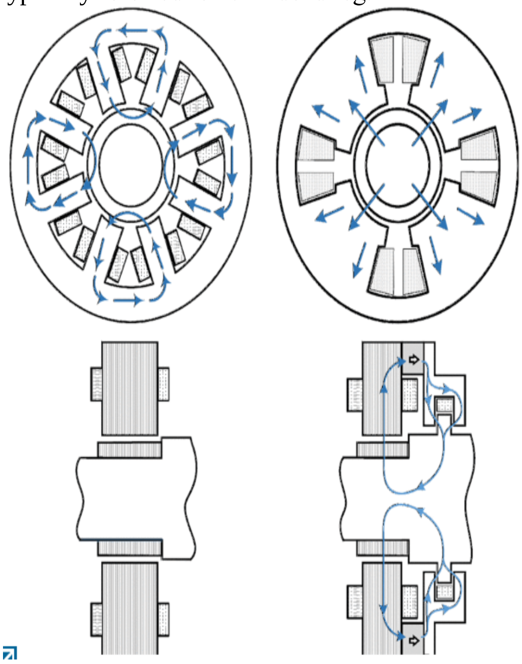

Fig.2 Radial and axial cross sections of magnetic bearings. On the left, there is a typical heteropolar bearing with current biasing and eight poles. On the right, there is a hybrid combined axial and radial bearing with PM biasing. The blue lines indicate the flux path.

VI. INDUCTION MACHINE

The first case study is a 120-kW, 60 000-r/min IM with hybrid AMBs. The machine has an axially slitted solid rotor with conducting end rings at both rotor ends. The conducting end rings appreciably enhance the effectiveness and power factor of the solid rotor IM. The machine is a 2-pole organization and has 24 stator slots. The key design parameters of this machine are illustrating in Table I. The rotational speed of 60 000 r/min and the rotor outer diameter of 76 mm lead to the rotor peripheral speed of 239 m/s, which sets strict desires on the mechanical inflexibility of the rotor. The rotor structure is shown in Fig. 3.

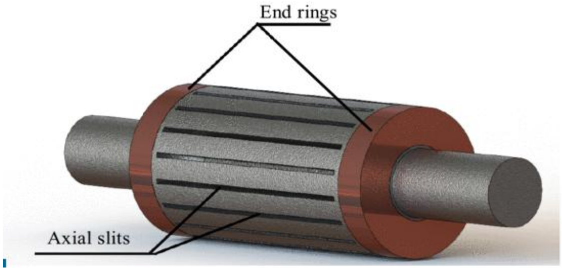

Fig.33-D model of the solid rotor with axial slits and conducting end rings.

Table I Key Parameters of 3d Induction Motor

Parameter	Value
Rated speed, rpm	50 000
Rated power, kW	225
Pole pairs	1
Rated voltage, V	380 (Star)
Maximum current, A	570
Number of stator slots	36
Stack length, mm	88.5
Rotor outer diameter, mm	70.2
Physical air gap length, mm	1.2
Stator outer diameter, mm	192
Stator core material	25PN1500
Magnet material	NdFeB
Rotor sleeve material	Inconel 718

VII. PERMANENT-MAGNET SYNCHRONOUS MACHINE

The second case is a 225-kW, 50 000-r/min PMSM. This machine is designed for a two-stage turbo compressor shown in Fig. 7 [33]. It consists of upper and lower impellers, a rotor shaft, magnetic bearings, and an electrical machine. A detailed analysis of the designed AMBs is presented in [32] and [34]. The rotor shaft is a shrink-fitted assembly of a full cylindrical magnet, SUS 304 shaft studs, and an Inconel 718 sleeve. Because of the high thermal resistance of the carbon fiber sleeve, it could not be applied in the machine under study. The compressor housing has a water cooling channel to cool the motor stator, and the inlet and the outlet are designed to supply cooling air

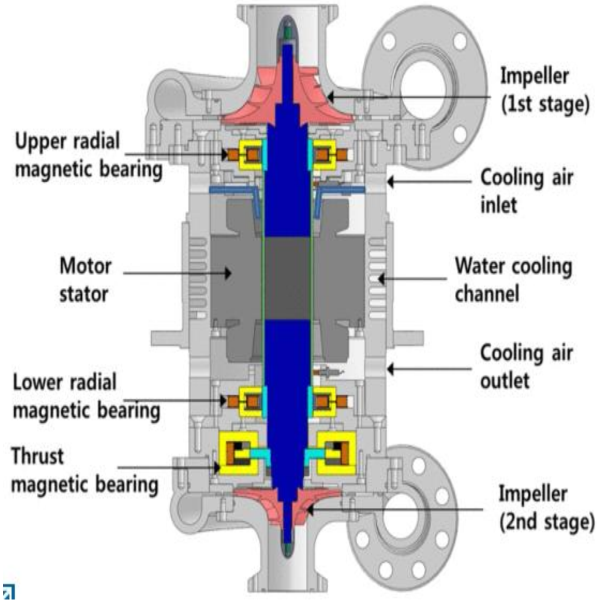

Fig.3Configuration of the 225-kW, 50 000-r/min turbo compressor.

Both to the rotor and motor stator. The machine has a two-pole design and 36 stator slots. The key design parameters of this machine are illustrated in Table III. The PM material selected for the machine is NdFeB, the tensile strength of which is only 80 MPa, making it the weakest part of the rotor. Therefore, an appropriate sleeve thickness and a suitable shrink fit of the sleeve around the magnet should be found to protect the magnet against centrifugal forces at 50 000 r/min. Fig. 8 shows the stress analysis results over the magnet and the sleeve for the sleeve thickness of 3.1 mm and the diametric interference of 200μm at the rotational speed of 52 000 r/min. The maximum stress is around 58 MPa at the centre of the magnet, which leads to a safety factor of 1.38. The thickness of the sleeve is selected conservatively to reach the safety margin of 2.0 in order to ensure a mechanical design that withstands operational loads in the prototype testing process.In this paper, the main design aspects of an HS electrical machine supported by AMBs for an air compressor were demonstrated. The key limitations of the selected application were described. This paper showed how the system configuration including the impeller location, the horizontal or vertical shaft positioning, and the electrical machine type affects the limitations. The main design challenges for electrical machine and AMB designers from electromagnetic, mechanical, thermal, and control viewpoints were listed. The advantages of the hybrid AMBs for the two-stage compressor were described.
The two case studies illustrated how the design challenges are addressed in the case of an IM and a PMSM supported by AMBs. The key mechanical limitations of both topologies are related to the

specific rotor construction and must be assessed considering an overspeed operation and a temperature rise. A PMSM can provide a significantly more compact solution compared with the IM if a proper cooling of the system can be arranged. In the machines under study, it leads to overcritical IM and under critical PMSM operation. Mechanical losses and extra electromagnetic losses caused by the high frequency in the windings and in the stator must be accurately calculated to define the output compressor power and ensure sufficient cooling. Because of the high integration level, a feasible HS drive train design for a two-stage oil-free air compressor is possible only with a systematic approach when the mutual influence of the components is taken into account.

Table IIKey PMSM Parameters

Parameter	Value
Rated speed, rpm	60 000
Rated power, kW	120
Pole pairs	1
Rated voltage, V	400 (Star)
Rated current, A	267
Number of stator slots	24
Stack length, mm	120
Rotor outer diameter, mm	76
Stator outer diameter, mm	184
Stator core material	M250-35A
Rotor core material	Imacro M
End ring material	Glidcop 15

VIII. PROTOTYPE TEST RESULTS

The constructed stator and the assembled compressor, which does not have impellers for a no-load test. First, the motoring test was performed in the no-load condition to evaluate the structural strength of the shaft. The rotational speed of the shaft can be stably increased up to 51 000 r/min, which verifies that the shaft has a sufficient structural strength. Fig. 11 shows the back EMFs of the three phases, which were measured at 20 000 r/min during spin-down. The peak value of the measured back EMF is 102 V, and the error is 2.5% compared with the predicted value based on the results calculated using the back EMF constant. The calculated and measured phase resistances at the rated temperature are 2mΩ and 2.1mΩ, correspondingly.

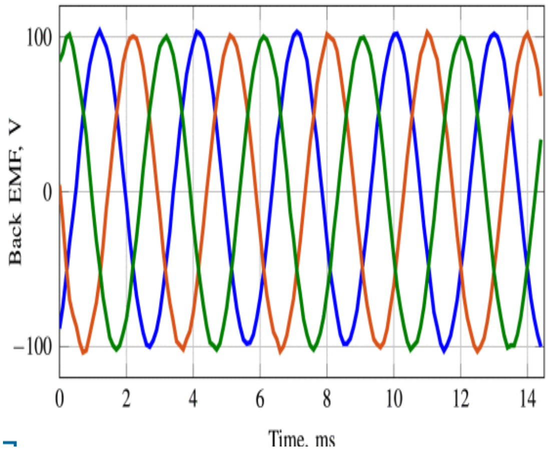

Fig.4 Constructed stator and assembled compressor housing for the no-load PMSM test.

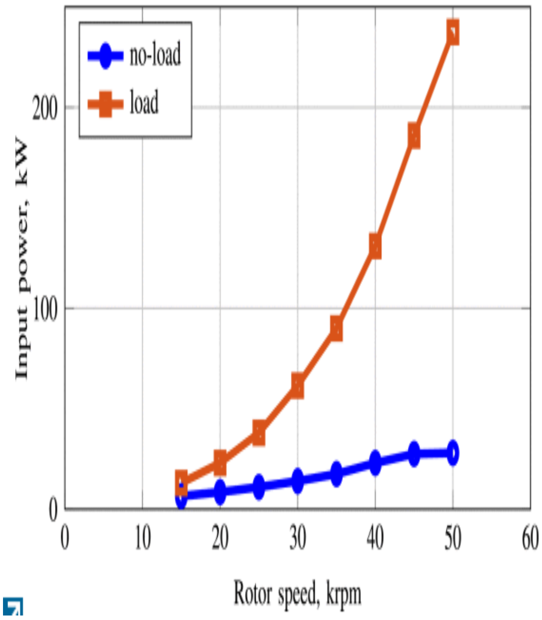

Fig.5 Measured motor input power with a varying rotor speed for the 225-kW PMSM no-load and load tests. Measured back EMF of the three phases at 20 000 r/min for the PMSM prototype.

Since the electromagnetic losses in the rated operation in Table III are significantly lower compared with the input power for the no-load test, we may conclude that there are high mechanical losses, such as windage losses. Another reason for the high measured losses is related to the converter supply and the absence of filters between the converter and the machine. The measured THD value for the phase current in the prototype was 34% at 30 000 r/min. In addition, extra copper and core losses compared with the simulated values are possible in the prototype because of the high supply frequency. Therefore, about 30 kW of electromagnetic and mechanical losses should be considered when determining the output power of the compressor.

The bearing losses were estimated with measuring the input current and voltage of the dc power supply with a power meter. This method gives the full power expenditure of the magnetic bearings and the power electronics. The voltage is 150 V, and the current is 1.5 A, resulting in 225 W losses.

Table III Electromagnetic Loss Distribution in the PMSM

Loss Location	Losses, W	Loss Share, %
Copper	958	37
Rotor	827	31
Core	834	32
Total	2619	100

IX. CONCLUSION

In this paper, the major design aspects of industrial application so that HS electrical machine supported by AMBs for an air compressor were demonstrated. The key limitations of the meticulous application were described. This paper showed how the system construction including the impeller location, the horizontal or vertical shaft situation and the electrical machine type affects the limitations. The main design confront for electrical machine and AMB designers from electromagnetic, mechanical, thermal, and control viewpoints were listed. The compensation of the hybrid AMBs for the two-stage compressor were illustrate

The two case studies illustrated how the design challenges are addressed in the case of an IM and a PMSM supported with AMBs. The key mechanical boundaries of mutually topologies are related to the specific rotor construction and must be assessed considering an over speed operation and a temperature rise. A PMSM can make availableappreciably more condensed solution compared through the IM if a appropriate cooling of the organization can be arranged. In the machines under study, Because of the high integration level, a feasible HS drive train design designed for a two-stage oil-free air compressor is possible only by means of a systematic approach when the mutual influence of the components is occupied into account

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