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High temperature active magnetic bearings in industrial steam turbines

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Abstract

After 8 years of industrial research and development between industry and Zittau/Görlitz University, the prototype of a feed water power turbine (SPAT) with active magnetic bearings was successfully taken in operation at the Jänschwalde power plant in 2015.

Due to extended conditions of use (particularly high process and environmental temperatures) the active magnetic bearings in the turbo machines must be cooled elaborately. In conventionally supported turbo machines the lubricant in the friction bearings additionally does the cooling. Parts of the heat flux are dissipated from the bearing by the bearing oil. In terms of turbo machines with magnetic bearings lubricant is not used. This leads to significantly higher temperatures in the area of rotor lamination and its sleeves. Particularly demanding is the cooling of the sleeves which is currently very demanding – compressors are necessary. The tube cooling applied reduces the efficiency of the magnetic bearing which is high compared with hydrostatic friction bearing. Moreover, the additional peripheral effort has a negative effect for investment and maintenance in cost accounting.

This paper shows the stages in developing High Temperature Magnetic Bearings (HTAMB). First approaches of suitable HTAMB concepts are depicted. Within the next 3 years shall on the basis of theoretical and experimental investigations be determined which state of the art materials and construction principles must be used and applied. The focus within that topic is the use of temperature resistant materials for the lamination of active radial magnetic bearings with respect to elimination of high manufacturing effort of sleeve cooling.

For this reason the essential tests of magnetic and catcher bearing components shall be realized at the test rig for magnetic and catcher bearings MFLP. Single effects and long-term strain will be analyzed under scaled power plant conditions. The test field is introduced by representing its main parameters.

Key words : High temperature active magnetic bearing, HTAMB, turbomachine, industrial steam turbine, optimization

1. Introduction

Active magnetic bearings (AMB) are an essential key technology in modern power plant concepts. The application of AMB in turbo machines (steam turbines, cooling pumps and compressors) is characterized by extreme process and environmental conditions like high temperatures, corrosive fluids and gases. Especially the use of organic materials limits the insulation level of electromagnetic actuators. Currently the allowed maximum continuous temperature is 180 °C for coils and laminated cores. Known solutions like ceramic insulation systems allow actuator temperatures up to 450 °C. But their production is complex and the specific actuator size increases compared to conventional insulated actuators.

The development of new surface technologies and advances in material science allow new basic approaches for insulations and thereby for High Temperature Active Magnetic Bearings. For instance the use of the physical vapor deposition technology (PVD) allows low cost coatings with thicknesses of only a few micrometers. Furthermore, the fusion of AMB with catcher bearings (CB) to an integrated unit is advantageous for a compact machine design. It is one objective to place the bearing units close to the process section, if appropriate into the process section. So the CB also have to fulfill their functions under extreme conditions.

For the use of the AMB in the industrial steam turbine Siemens SST-600 (shaft power approximately 10 MW, rotor mass approximately 2 500 kg, nominal speed 4 500 rpm to 5 400 rpm, steam parameters 540 °C/3.6 MPa) it was necessary to investigate the technological feasibility.

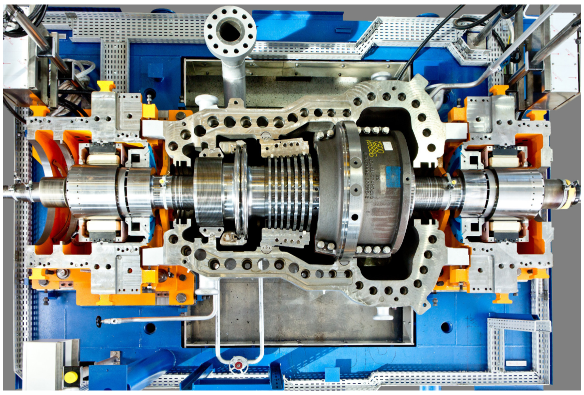

Fig. 1 Siemens steam turbine SST-600 with active magnetic bearings [1]

Therefore, especially thermal effects were analysed in the test field SFDT (Fig. 2). Additionally, the contactless bearings were qualified together with the Siemens AG.

Fig. 2 Test rig SFDT

Table 1 Main parameters of the test rig SFDT

Rotor	
Mass	2 500 kg
Length	3 800 mm
Maximal speed	5 760 rpm
Magnetic bearings	
Axial force	25/50 kN
Nominal airgap, axial	800 µm
Radial force	25 kN
Nominal airgap, radial	800 µm
Catcher bearings	
Nominal airgap	300 µm

Design of AMB in high temperature environment

The machine design of the Siemens SST-600 (Fig. 1) considers the cooling concept [2] which was developed and tested on the SFDT. The magnetic bearings are water and air-cooled. On the one hand the air flow cools the airgap between stator and rotor (airgap cooling) of the electromagnetic actuator. On the other hand the rotor itself is cooled (bushing cooling) by air. So the bearings are protected by limiting the heat flows which are caused by the process environment.

The air cooling requires complex peripherals including a compressor. The overall efficiency of the AMB is reduced accordingly by the active cooling.

Strategies for the development of high temperature bearing concepts

Further tests and studies show that the cooling effort of the electromagnetic actuator can be reduced or even eliminated. Within a feasibility study (performed by the Hochschule Zittau/Görlitz – Institute of Process Technology, Process Automation and Measuring Technology) the basics are shown for the design process of a HTAMB. Furthermore, in this study are presented the research results of marketable materials and their (temperature depended) properties.

Within the next 3 years a holistic approach will be developed for designing and integrating of HTAMB in turbomachines. This approach includes the design, modeling and dynamic simulation of active magnetic and backup bearings. The research will consider the non-linearity and temperature dependence in the material parameters. Furthermore, the reliability of the magnetic bearing shall be determined. The theoretical investigations shall be validated by experiments on the test rig MFLP (chapter 3).

2. Strategies for the development of high temperature bearing concepts

2.1. Objective

With respect to typically used standard materials the application of active magnetic bearings at steam turbines, for example, is in electrical machine engineering subjected to essential limitations relating to upper operation temperatures. Amongst others, main criteria for that are temperature limits for insulation of magnetic bearing windings and sheet insulation for rotor and stator laminations. The heat input into the bearing areas of turbomachines often happens through the rotor. This is why the biggest temperature problems occur in the rotor part of the bearing.

In magnetic bearings heat dissipation is restrained by the bearing air gap which, however, is essential for operation. Therefore, cooling of the bearings is necessary. On the one hand the cooling reduces possible improvement of efficiency in application of magnetic bearings in comparison with friction bearings, on the other hand it causes additional effort to provide and pipe the cooling medium.

While the stator can relatively simple be cooled by a water cycle, the cooling of the rotor lamination is much more difficult. Because of the lubricant-free magnetic bearings there is no cooling effect by the lubricant just like in oil-lubricated friction bearings. The required air-gap in magnetic bearings which is necessary for their function also acts as thermal insulation. The absence of this cooling and the fact that coils and sensors are located in direct process environment lead to heavy heat strain of the magnetic bearings and require the use of demanding cooling concepts. Because of constructional reasons, only gasses can be used as a cooling medium for rotor lamination.

The essential additional effort for cooling can be described as follows:

- Specific calculation and optimization of cooling
- Additional subcomponents like pumps, compressors, heat exchangers, pipelines are required
- Additional energy effort
- Leakages
- Energetic losses in the cooling system
- Increased maintenance effort

An alternative to bearing cooling are concepts aiming for higher insulation temperature limitations of the bearing coils and sheets achieved by more temperature resisting insulation materials and coatings.

The goal pursued is to get along without additional cooling measures for active magnetic bearings as they are for example applied at the SFDT and the magnetically supported prototype feed water power turbine. On the basis of theoretical and experimental investigations shall be determined, which state-of-the-art materials and construction principles must be used and applied. The focus within that topic is the use of temperature resistant materials for the lamination of active radial magnetic bearings with respect to elimination of high manufacturing effort of sleeve cooling.

2.2. Preliminary considerations on high temperature effects on construction and design of active magnetic bearings

The specific properties of materials used for active magnetic bearings are temperature dependent. This applies both for electrical and magnetical properties relevant for magnetic bearings and also for mechanical and chemical properties.

Electrical properties -– The materials copper and aluminium used for the windings are thermistors with positive temperature coefficient for electrical resistance, i. e. an increasing temperature also leads to increasing resistance. Accordingly, winding losses rise, which again leads to a rise of temperature up to thermal equilibrium. The ferromagnetic materials used for the magnetic cycle consist of iron alloy with additives containing silicium or aluminium to increase the specific electrical resistance. At increasing temperature the ohmic resistance rises which leads to further reduction of eddy current losses.

Electrical isolation -– In electrical isolation there is distinction between insulation of electrical conductors and insulation of sheet metal. The heat resistance of the insulation materials depends on the matter used. Exceedance of the maximum allowed permanent temperatures influences the function and duration of the machine in a negative way and accelerates the chemical aging process.

Magnetic properties -– The magnetic saturation polarization of various ferromagnetic materials nonlinearly depends on temperature in the same manner. Firstly, the saturation polarization decreases slowly in line with rising temperatures and then falls increasingly stronger down to the Curie temperature to the value zero. Above the Curie temperature the ferromagnetic properties get lost – the material shows paramagnetic behavior.

Mechanical properties -– The mechanical properties are mainly determined by temperature dependent specific material parameters like the elastic modulus or the yield strength and indicate the behavior of the material against outer strains. The specific parameters decrease with increasing temperature. Having a ratio of operation temperature and melting temperature higher than 0,4 the material starts to creep. In case of exceeding this ratio the creep strength of the components must be checked and the maximum operation time at corresponding temperatures must be defined.

Thermal expansion -– The thermal expansion of materials at high temperatures cannot be neglected. Different heat expansion coefficients of materials may lead to increased strain which might be inner tensions or increased slackness, for example, which must be considered for the whole range of temperatures during constructive design.

Chemical reactions -– The atmosphere in the operational environment influences the behavior of materials used. Materials corrode because of oxidation at room temperatures already. At high temperatures this process can significantly be accelerated. Besides that, the contact of two materials leads to reactions between them. Many materials show inert behavior at room temperature. At high temperatures, however, they do not so anymore. Thus, the contact of nickel and copper at high temperatures leads to diffusion and thus to lower conductivity of the copper.

2.3. Selection of suitable materials

Magnetic materials -– Magnetic materials must have excellent magnetic, mechanical and electrical properties covering a large range of temperature and time. Investigations on the application of magnetic materials were realized a. o. by order of NASA. Other research programs like AMBIT or MAGFLY pursued similar goals. Here, the suitability of various magnetically soft iron alloys was fundamentally analyzed for HTAMB. The works focused on the behavior of saturation induction over temperature, aging behavior, electrical and magnetic properties and losses over frequency at various temperatures. Because of their very high saturation polarization and Curie temperatures various cobalt-iron alloys like AFK 502, VACOFLUX, VACODUR or HIPERCO have been identified as particularly suitable.

Insulation material -– For wire insulation at temperatures over 180 °C it is not possible to use insulation varnish anymore. Inorganic materials like glass fibers, mica, ceramic materials (Fig. 3) or asbest are used instead. Wire insulations should be resistant to high temperatures, compact and flexible and have good electrical insulation properties and good heat conductivity. These requirements are partly hard to reach. Available wire insulation materials are e. g. cercal, alcal, samico or ceramic braid. Several manufacturers provide insulation materials for electric sheets made of inorganic pigments containing organic sinthetic resins which are resistant against permanent temperatures up to 300 °C, Suralac 7000 or Remisol 5620, for example. Blued electric strip can be used without any temperature limitation.

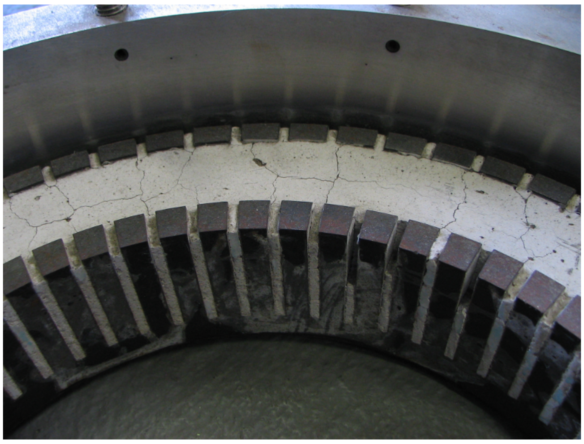

Fig. 3 Sensor of an axial high temperature active magnetic bearing

3. Test field for high temperature magnetic bearings

The test field consists of a test rig for magnetic and catcher bearings which is called MFLP and also of different peripheral subsystems. These include energy distribution, electric drive, process control, uninterruptible power supply and steam pipes.

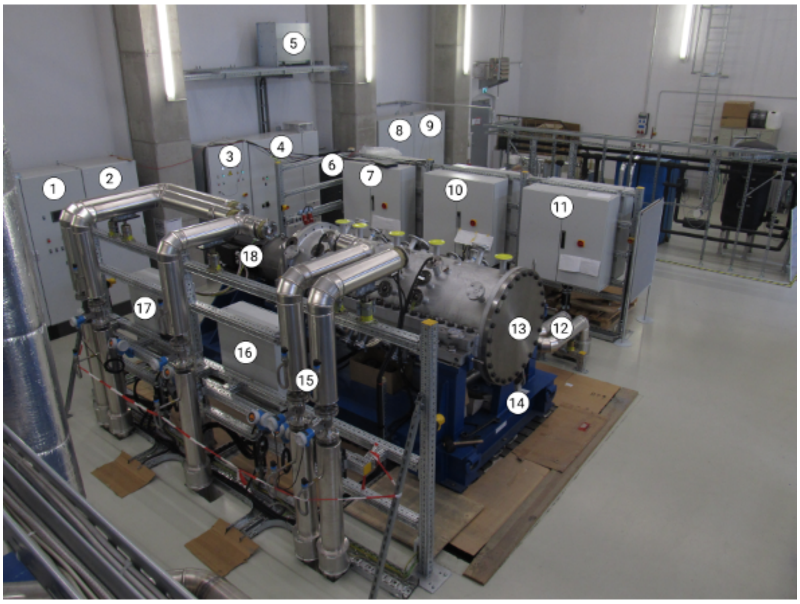

Fig. 4 Test field for high temperature magnetic bearings

Table 2 Test field components

No.	
1	Process control system (master)
2	Process control system (slave)
3	Magnetic bearing control cabinet
4	Drive control cabinet
5	Braking resistor of electric drive
6	Uninterruptible power supply (UPS)
7	Sensor boxes
8	Electric sub-distribution 2.1
9	Electric sub-distribution 2.2
10	Sensor boxes
11	Sensor boxes
12	Exhaust steam pipes
13	Vessel
14	Base frame
15	Live steam pipes
16	Sensor box
17	Sensor box
18	Electric drive

The target within the development process is to achieve a test station providing the possibility to investigate several configurations of AMBs and CBs.

Therefore the following requirements must be fulfilled:

- application of steam specifically to the CBs and separately from the AMBs
- minimum effort for assembly and disassembly
- emergency CBs for testing the regular CBs up to the design limit
- modular setup of the housing to allow installation of several types of bearings.

Test rig – The MFLP is a horizontal machine. Figure 5 shows an overview of the recipient with the components installed (Table 3). During the design of the test rig one aim was to get a high modularity and an easy access for assembly and disassembly. As Fig. 5 shows the recipient can be divided horizontally. Each component has its own case and can be separated from the recipient with the help of a crane.

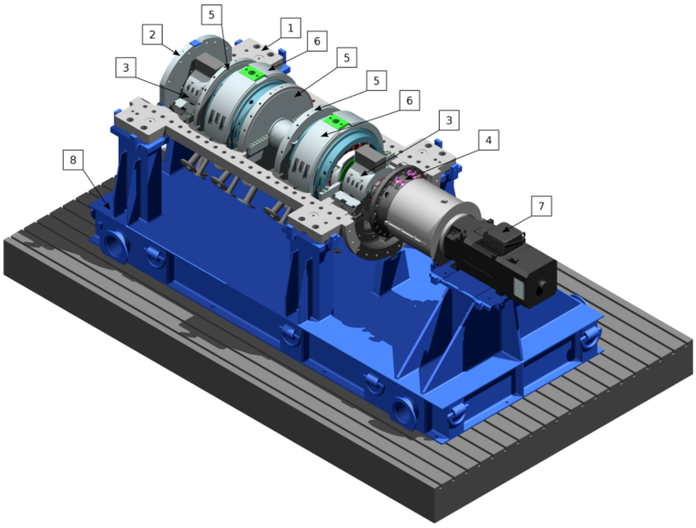

Fig. 5 Test rig with installed components

Table 3 Test rig components

No.	
1	Recipient
2	Emergency CB
3	Radial CB
4	Axial CB
5	Seal
6	AMB
7	Drive
8	Mounting base

The main part of the test rig is a magnetically levitated rotor having a mass of approximately 1 300 kg. On drive end (DE) as well as on non-drive end (NDE) combined axial and radial active magnetic bearings are installed. They are identical. This guarantees optimum position of the center of gravity point. In cases of deactivation or malfunction of AMBs catcher bearings guarantee the rotor stability. On the DE and NDE side it is possible to install ball or plain bearings as radial CBs. Furthermore, on the DE side an axial plain bearing is installed.

The main parameters of the test rig are summarized in Table 4.

Table 4 Main parameters of test rig MFLP

Parameter	
Rotor	
Mass	1 300 kg
Length	2 653 mm
Maximum speed	3 600 rpm
Recipient	
Mass	4 500 kg
Length	2 700 mm
Diameter	1 700 mm
Magnetic bearings	
Axial force	20 kN
Standard airgap, axial	500 µm
Radial force	35 kN
Standard airgap, radial	800 µm
Catcher bearings	
Standard airgap	300 µm
Standard airgap, emergency	500 µm

Rotor – The speed of the rotor which is mounted horizontally (Fig. 6). The shaft will be increased up to a maximum rotation speed of 4 000 rpm. The rotor mainly consists of

- shaft,
- two tension discs (component of axial magnetic bearing),
- two rotor laminations (component of radial magnetic bearing),
- sleeves (component of operation bearing and emergency catcher bearing) and
- clutch (mechanic connection to the electric drive).

Fig. 6 Pre-assembled rotor

Emergency catcher bearings – The CBs are supposed to be strained up to the design limit. Due to this, a malfunction is possible. Therefore the test rig has special emergency catcher bearings which are designed as plain bearings. They are positioned at the DE and NDE and do have the longest distance to the center of gravity point of the rotor. In case of a malfunction of the radial CBs the emergency CBs prevent the recipient, rotor and the active magnetic bearings from damage.

Recipient – The whole rotor including the bearings will be placed in a pressure-resistant recipient (Fig. 7). It is necessary to simulate different temperature and environmental conditions along the rotor. So the recipient is separated into four sections with a separate steam connection each. The sections are separated by a labyrinth seal system which is typical for turbo machines. In sum there is more than one case to manipulate the conditions. Steam can be applied to the process room, CB or AMB separately. In another case the process room and the CB section can be applied simultaneously for example. In this way several practice-oriented temperature profiles can be adjusted.

Fig. 7 Pressure-resistant recipient with welded flanges

Grounding – The pressure-resistant recipient is mounted on a base frame which is also copied for technical solutions like steam turbines in power plants. The whole machine is connected to a mounting plate on a massive grounding. Massive dynamic forces have to be absorbed by the CBs and therefore also by the basement in case of a rotor touchdown. The grounding has a mass of approximately 132 000 kg.

Figure 8 shows the machine basement. It is a solid grounding having a mass of approximately 120 000 kg. The mounting plate having a mass of 13 000 kg was mounted onto the rotor basement (Fig. 9).

Fig. 8 Massive grounding

Fig. 9 Mounting plate

The resulting machine grounding provides the stiffness, inertia and damping required. This is necessary to deal with the intense reaction forces expected in case of rotor touchdowns.

4. Conclusion

The successful commissioning of the oil-free industrial steam turbine SST-600 was in 2015. The first experiences in the power plant Jänschwalde show a well operating AMB system. Currently a complex cooling system is necessary to limit the bearing temperatures. The cooling solution is the result of extensive investigations on the test rig SFDT. The overall efficiency of the AMB is reduced. So new development approaches are necessary.

Within a market analysis magnetic and insulating materials have been researched, which fulfill the requirements for the use in environment of high temperatures. The search results show that modern design and functional materials are marketable available. However, there are particular insufficient information about the magnetic properties. For example details about frequency dependencies normally are not available in magnetization characteristics. Either the producers of such material cannot measure the characteristic parameters, measure insufficiently or they just don't publish. Similar challenges exist in determining temperature-dependent magnetic properties. In this context, the parameter values must be determined in accordance with test specimens experimentally. This is also the subject of the next 3 years. Furthermore, a prototype of a HTAMB has to be designed and manufactured. Thereby it is also necessary to aply optimization algorithms and methods for actuator and sensor. The prototype shall be tested within the test field MFLP.

The test field MFLP is designed for longterm tests of AMB and CB under extreme process and environment conditions. With the test field it is possible to develop new and innovative bearing concepts. The investigation will be carried out under scaled power plant conditions.

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