Test Field for Magnetic Bearing Applications under Extreme Conditions

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***Abstract*—Active magnetic bearings (AMB) are an essential key technology in modern power plant concepts. The application of AMBs 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 of coils and laminated cores is 160 °C. 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 (HTAMBs). 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 AMBs 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 CBs also have to fulfil their functions under extreme conditions.

I. Introduction

In November 2011 the University Zittau/Goerlitz received funding for three projects placed in the research field of energy and environment with a volume of 5.75 million euros. Taking the required equity into consideration the total volume is 6.35 million euros. The project is financed within the "program of energy efficiency, renewable energies" by the European Regional Development Fund (ERDF) and the Saxon State Ministry for Economic Affairs, Labour and Transport (SMWA).

The aim within the three scientific projects is to develop and optimize technologies, which can increase the efficiency of energy systems. It will be shown how energy can optimally be used and transformed in subsystems of large and small power plants. This allows to conserve the natural resources. The three projects are:

- Increase in the energy efficiency of turbo machines in power plants through innovative bearing concepts (MFLP)
- Energy efficiency in thermal power plants, thermal energy storage system (THERESA)
- Thermochemical energy storage system (TCV)

Therefore it is planned to construct and build three separate test fields within a new university power plant laboratory called "Zittauer Kraftwerkslabor".

For simulating scaled process conditions – like in power plants – THERESA will provide superheated steam for the MFLP with a maximum controlled flow rate of $0.1\,\mathrm{kg\,s^{-1}}$ and with a maximum controlled temperature of 250 °C.

The steam is necessary for studying the AMB and CB behaviour concerning temperature and corrosive influences. Alternatively the interaction between the two test fields can be used for the simulation of different operation points in a turbomachine. Concerning the steam process this would be startup, shutdown and emergency shutdown. Here the question is how the thermohydraulic process can follow. Another question is for example whether it is possible to store the steam fast enough in a thermal energy storage system.

The demand for

- electric power of 680 kVA,
- steam with a maximum mass flow of $5\,\mathrm{kg\,s^{-1}}$ and with a maximum temperature of 220 °C,
- an area with $300\,\mathrm{m^2}$

requires the reconstruction and expansion of a machine hall in the area of the public utilities company "Stadtwerke Zittau GmbH" (SWZ).

II. Test field MFLP

The main objective within the project "Increase in the energy efficiency of turbo machines in power plants through innovative bearing concepts" is to develop, construct and build a complete test field for longterm tests of AMBs and CBs under extreme process and environmental conditions.

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.

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 1 shows an overview of the recipient with the components installed (Table I). During the design of the test rig one aim was to get a high modularity and an easy access for assembly and disassembly. As Figure 1 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.

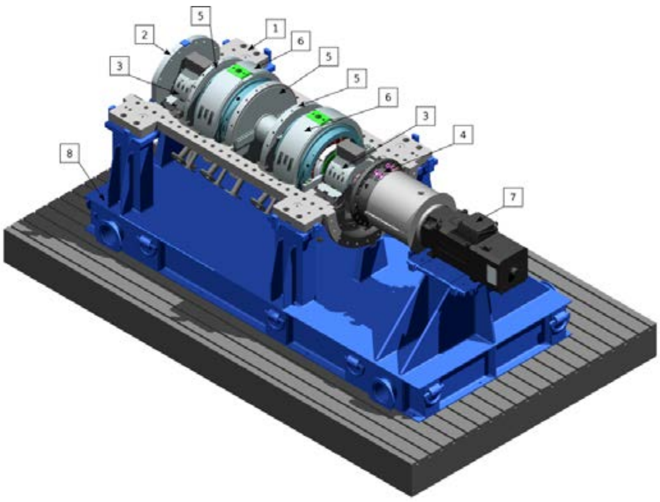

Figure 1. Test rig with installed components

Table I
COMPONENTS OF TEST RIG MFLP

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 II.

Table II
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 (Figure 2) will be increased up to maximum rotation 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).

Figure 2. 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 (Figure 3). 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.

Figure 3. 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 4 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 (Figure 5).

Figure 4. Massive grounding

Figure 5. 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.

III. Objectives of planned experiments and tests

Model validation – Design, modelling and simulation of magnetic bearings and catcher bearings form the basis of the experimental work executed at test rig MFLP. Existing algorithms for the design of magnetic bearings and sub-models for simulation of bearing dynamics are applied. The model must be extended to be applicable for new bearing concepts and for investigations on reliability of bearing components under extreme environmental conditions. Thus, non-linearities or temperature-depending drift-offs must be considered more strongly.

Based on the experimental results the methods will be validated with this new test facility.

Testing new catcher bearing concepts – Another focus is to experimentally investigate radial plain catcher bearings. At present, mainly ball CBs are used in large-scale machines. They allow the control of dynamics during contact of rotor and catcher bearing to the greatest possible extent. Extensive operating experience is available that allows industrial application. The constructive design consisting of inner ring, ball element, outer ring and rotor sleeve is more complex in comparison with the plain bearing. It consists only of 2 wearing components – Stator sleeve and rotor sleeve. Enhancing magnetic bearings for use in turbo machines requires departing from traditional construction already in the design process. The increase of operation temperatures allows placing the bearing components in the vicinity of or directly in the process room. This also applies for catcher bearings.

Catcher bearings fulfill safety requirements. The influence of steam or aqueous solutions leads to premature aging of bearing components. Dispersion grease in ball bearings is rinsed out or burned and steel alloy corrodes. Thus, the temperature range for operation is from the start limited in a higher degree than for plain bearings. In switched-off mode the named impacts cause damage. This will cause malfunction and failure particularly for ball bearings.

Derived from the construction principle of hydraulic bearings, the application of split plain bearings is interesting. Figure 6 shows a plain CB with horizontal split. The bearing components (Table III) were designed and constructed in the course of the project.

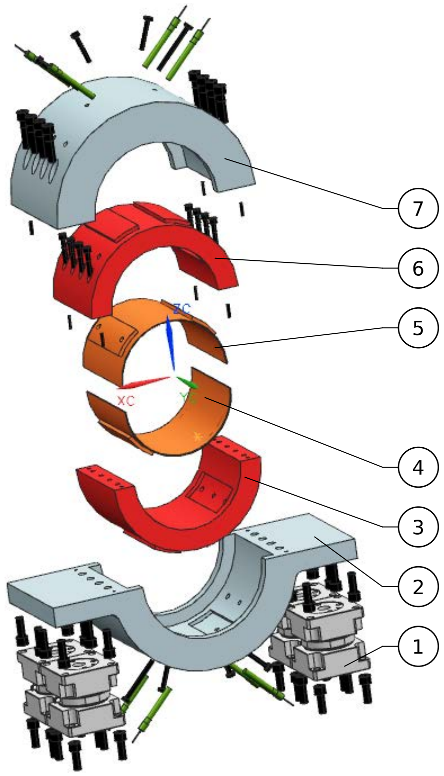

Figure 6. Radial plain CB with horizontal split

Table III
COMPONENTS OF RADIAL PLAIN CB

No.	
1	Load measurement device
2	Bearing housing, lower part
3	Bearing stator, lower part
4	Lower bearing shell
5	Upper bearing shell
6	Bearing stator, upper part
7	Bearing housing, upper part

Subsequently, the bearing construction as a result of strength analysis was evaluated (Finite Element Method) at various load situations. Figure 7 shows an example for mechanical total deformation of the lower bearing shell. Assuming the line compression and a force of 180 kN, the bearing shell will deform max. 85 µm.

This novel construction of plain catcher bearings is intended to be tested in follow-up projects under normal and extreme process conditions. The results of numerical simulation will be validated within this framework as well. Moreover, optimizations in terms of geometry and material selection will be derived on the basis of results and operational experiences.

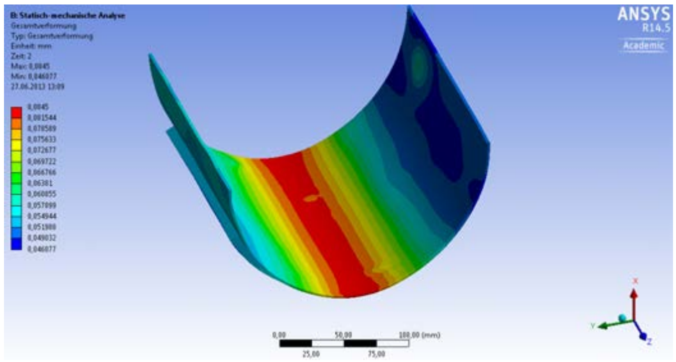

Figure 7. Compression of lines of lower bearing shell

Long-term behavior of magnetic and catcher bearings and its components – Another goal is to extend the range of operation temperature of bearing components. As mentioned before, progress in the field of materials science allows also to increasingly integrate bearings into the process room. Turbo machines can thus be constructed in a more compact way. This leads to considerable improvement of rotor dynamics.

In industrial steam turbines, temperatures of more than 250 °C are expected in the location of bearings. Relating the magnetic bearings, the electrical isolation of lamination and winding limits the operational temperature which is currently at 180 °C. Contrary to hydraulic bearings as they are used in turbo machines, there is no cooling medium in active magnetic bearings. The stator can be cooled effectively with liquid but, the cooling of the rotor lamination, however, can currently be done only with very effortful periphery. The cooling units cause additional effort which is also visible in a reduced degree of efficiency. It is intended to stepwise reduce this cooling demand in future.

The solution is to enhance the electrical isolation. It presently consists of organic materials like varnish and resin. It is intended to use anorganic isolation materials, e.g. ceramic materials in coatings in future. Using state-of-the-art surface technologies (Physical vapor deposition by means of sputtering) it is possible to apply coatings in the µm range.

Besides thermal influence, the long term effect of water vapor and water on the bearing components is going to be investigated. Here, the focus is placed on corrosion susceptibility of ferric and non-ferric metals. The components of magnetic bearing stators and catcher bearing units can be produced of chrome steel either partly or not at all. Here, the lamination and the ball bearing rings can be mentioned in particular. Moreover, also rotor sleeves are susceptible to corrosion. Contrary to that, the ball bearing elements do no further depict a problem. They are made of ceramics.

Long-term investigations will be made to show, how and to which extent it is possible to encapsulate magnetic bearings and catcher bearings in one unit.

IV. Conclusion

The test field is designed for long-term tests of AMBs and CBs under extreme process and environmental conditions. Therefore a modular case and sub-system concept is used. The paper summarizes the needed strategy concerning the recipient, rotor and bearing design.

To reach the experimental goals a test rig rotor has been completely supported horizontally with active magnetic bearings. It is accelerated with an electrical shaft drive. The maximum number of rotations is 4 000 rpm.

The rotor is surrounded by a pressure vessel. The volume of this container is separated by means of inside radial sealing layers. Due to a connected hydraulic cycle it is possible to apply in sections either vapor or compressed air to the rotor. Thus, it is possible to investigate the thermal and chemical behavior of the rotor and the rotor components. Furthermore, the pressure vessel has also the function of a barrier. During selected damage escalations at the machine, the failure of mechanical structures may occur. This is particularly applicable for the investigations planned on plain and ball CBs. Bursting of components thus leads to detaching of fragments. The pressure vessel avoids them entering the space of the test hall.

The test rig is designed in a modular way. Plain CBs and rolling CBs can optionally be mounted radially and axially in the corresponding space. For this reason sufficiently dimensioned mechanical interfaces are available. A key solution here is the additional grading of the circulating air gap in the radial CB which is a plain bearing. The emergency CBs are designed for one-time contact with rotor catcher bearing. They allow secure shut-down of the test rig even in case of burst catcher bearings.

With this test field it is possible to develop and test new and innovative bearing concepts. The investigation will be carried out under scaled power plant conditions.