First Heavy Load Bearing for Industrial Application with Shaft Loads up to 10 kN

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Abstract. We report on design, construction and testing of a heavy load HTS bearing for a 4 MVA HTS generator. According to the requirement profile of Siemens the bearing was designed for a shaft weight of 1000 kg. To meet these specifications, Nexans has designed and manufactured a HTS bearing fully encapsulated in a stainless steel cryostat with an operation temperature of \(-240 \, ^\circ\text{C}\). The working elements of the bearing are single-domain YBCO monoliths fabricated by a top-seeded-melt-growth process, optimized for large batches with 64 pieces per batch. The monoliths exhibit trapped magnetic fields up to 1.4 T and self-field critical current densities at 77 K up to \(1.3 \times 10^5 \, \text{Acm}^{-2}\). The stator of the bearing comprises 270 such monoliths, which were arranged in nine rings. The levitation properties of the complete system, comprising the HTS stator and a permanent magnet rotor, were recently successfully tested. The system is the largest bearing manufactured worldwide and one of the first to be tested for industrial applications.

1. Introduction:
Recent developments in Y-Ba-Cu-O (YBCO) melt-texturing techniques enable the production of high quality single-domain bulk parts in larger batches. In particular, monoliths produced by the Top-Seeded-Melt-Growth (TSMG) process exhibit high values of remanant induction and associated levitation force. Thus the material is an excellent candidate for the potential application in HTS magnets, frictionless magnetic bearings, hysteresis motors and flywheel energy-storage systems \[1,2,3\]. Superconducting magnetic bearings (SMB) for fast rotating machines like turbines, flywheels, motors and generators are one of the most promising applications for TSMG YBCO bulk materials.

The SMB can be used for suspending and nearly frictionless operation of shafts rotating with high circumferential speeds. During operation, the activation of the superconductors by permanent magnets occurs via the field cooled (FC) mode, which provides a high stiffness and passive stability in all directions. This paper presents a novel design of an HTS bearing with an activation mode called operational field cooling with offset (OFCo) \[4\]. The major feature of our design is the subdivision of
the cylindrical HTS stator into two half shells. The lower half shell can be traversed in vertical
direction, which enables the centered activation of the rotor related to the bore of the stator.
The complete bearing system was fabricated as a plug-in system according to the specifications of
the Siemens AG, (Corporate Technology, Power Components & Superconductivity, Erlangen,
Germany) as a customer related project.

2. HTS sample processing
The stator of the bearing (figure 1) comprises 270 YBCO monoliths fabricated by a standard TSMG
process at Nexans SuperConductors GmbH [3,5]. The required precursor powder was produced in
house in batches up to 100 kg with a nominal purity of 99.96%. The square shaped green bodies
used for the melt texturing were pressed, using an automated uniaxial press. SmBaCuO seed crystals,
cleaved from melt textured pellets, were placed on top of each YBCO precursor pellet. The TSMG
production was performed as a batch process with a production rate of 64 mono domain samples per
batch. All textured samples were cut to trapezoidal tiles with dimensions of 33 × 35 × 10 mm³.

3. Bearing design
Calculations for the SMB design were carried out at the Institute of Electrical Machines, Traction and
Drives (IMAB) of the Technical University of Braunschweig (IMAB). The stator and rotor were
designed and assembled at Nexans SuperConductors GmbH, Huerth (NSC). Design, construction and
assembling of the cryostat system for the bearing were performed at Nexans Deutschland Industries,
Hannover (NDI).

The stator was designed as a Cu cylinder subdivided into two half shells, in which several YBCO
rings were stacked together (figure 1). The stator is covered by a stainless steel cryo-housing with a
warm bore of ∅ 321 mm. To enable continuous operation of the heavy-load SMB, a coldhead
“Coolpower 140T” (Leybold Vakuum GmbH) is used for cryogen free stator cooling.

![Figure 1](image1.png)
1) Stator Cu half shells with HTS monoliths

![Figure 2](image2.png)
2) Rotor of the SMB assembled from NdFeB ring segments, stabilized with CFR

![Figure 3](image3.png)
3) Cryo-housing with cold-head and activation device, yet without rotor

The inner bore of the stator, i.e. the cylindrical surface of the superconductor, is 325 mm in
diameter and 305 mm long. The insulation gap between HTS surface and the outer 1-mm thick
stainless steel wall of the warm bore is 1 mm. The outer diameter of the cylindrical rotor based on
permanent magnets (the exciter system) is 319 mm (figure 2). The working gap between the exciter
system and the HTS surface is thus only 3 mm. Figure 3 shows the assembled cryostat of the SMB.
The warm bore is eccentric due to mounting flange.

Activation principle
The conventional force activation (operational field cooled mode OFC) of a cylindrically shaped
SMB is illustrated in figure 4(left). During cooling, the exciter is lifted by external actuators closest
into a pre-defined position towards the inner surface of the HTS-cylinder. After unlocking the lift-
actuator, the rotor-shaft sinks down into an equilibrium position (the repulsive force of the SMB
equals the rotor weight). A proper design guarantees that SMB and rotor are coaxial.
In this work, we used a patented activation principle in which one of the half shells of the stator is fixed, while the other one can move (see figure 4 mid). In the first test series performed at IMAB with a model bearing, the radial forces exerted on the rotor, have been measured as function of the displacement of the lower HTSC half-shell from its operating (aligned) position \( \delta_{\text{op}} \) (see figure 4). The measured forces for three different activation positions are displayed in figure 5. In comparison to the conventional setup with a undivided HTSC-stator tube and a reduced activation gap, the restoring forces can be increased by a factor of 3.7 depending on the displacement of the lower half shell.

4. Assembly and qualification test
Assembly of the SMB’s components, first cool down, and load capacity measurements were performed at NSC’s test facility in Huert. In these tests a working temperature of 28 K at the stator of the bearing was reached. In cool down experiments with different activation distances and shaft positions a maximum load capacity of 6900 N was measured. Specified values for this SMB were 65 K working temperature and 5000 N load capacity. After the first successful characterization for the proof of concept in view of the SMB’s technical performance, the system has been supplied to the Siemens test site in Erlangen.

5. Characterization
An extensive characterization of the SMB designated to the Siemens 4MVA HTS generator[7] is currently performed at the Siemens test facility in Erlangen[8]. A commercial tensile testing machine (Instron) has been equipped with a special test frame to perform dynamic and static characterization of the SMB outside the HTS generator. To approximate working conditions, measurements were performed when the shaft rotated at a speed of up to 3600 rpm by a 3 kW drive which could be engaged by an electromagnetic clutch. Details of the test facilities setup are published elsewhere [8].

Cooling down the SMB to the working temperature of 28 K takes 32 hours. Maximum temperature difference in the stator (Cu and HTS) was about 3 K as determined by six temperature sensors. The temperature difference between upper and lower YBCO half shells was only circa 1 K. These results confirm the proper design concept of the cryostat and the Cu/HTS-stator.

The force-displacement curve of figure 6 was measured under OFCo conditions with an activation position of the lower Cu half shell of 9.5 mm. The rotor shaft was positioned in the centre of the warm bore. After reaching the working temperature of 28 K, the lower Cu-half shell was lifted 6.5 mm against the upper Cu-half shell to its working position; this resulted in a gap of 3 mm.

Figure 4. Left: SMB displaying the conventional force activation. Activation is done by displacing the shaft while cooling. Mid and right: New concept for SMB with movable HTS half shells, for advanced force activation. The shaft remains in its operational position.

Figure 5. Force displacement curves of a SMB model with advanced force activation prepared with activation traverses of 2, 4 and 6 mm.
between the HTS and permanent magnet. After activation, the rotor was in equilibrium with the forces of the HTS-stator. The bearing stiffness was estimated from continuous measurements of the radial forces exerted on the shaft while its displacing it by ±0.3 mm around the centre position. The radial bearing capacity under static conditions was measured to be 5 kN, while the bearing stiffness was measured to be 5.1 kN/mm.

![Figure 6. Typical force-displacement curves at a stator temperature of 28 K without rotation of the shaft](image)

![Figure 7. Oscillation of shaft under bearing operation at 3600 rpm (60 Hz) and 28 K](image)

The SMB was successfully operated up to a speed of 4400 rpm. In figure 7, the measured vibrations of the shaft at a rotation speed of 3600 rpm, which is the nominal speed of a 4 MVA HTS generator (60 Hz), are exhibited. The shaft oscillation detected was below 0.01 mm in both horizontal (x) and vertical (y) directions (figure 7). The temperature of the HTS stator during these measurements was approximately 28 K.

6. Conclusions
A high capacity SMB, the worlds largest so far, has been designed, developed and successfully tested. The radial bearing capacity of 5 kN was measured under static and rotating conditions. The vertical bearing stiffness at a stator temperature of 28 K was 5.1 kN/mm. The bearing has a linear force-displacement curve over the ±0.3 mm displacement range studied. Oscillations of the shaft at the nominal operational speed of 3600 rpm and generator test speeds up to 4400 rpm are much smaller. The SMB meets the main requirements of the Siemens 4 MVA HTS generator.

7. References
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