Abstract—This paper presents a magnetic bearing set developed to work in a flywheel energy storage system. The bearing set is composed of a Permanent Magnetic Bearing (PMB) and a Superconducting Magnetic Bearing (SMB). A new configuration of a PMB having Nd-Fe-B magnets rings and a back yoke is proposed and compared with an existing one. Finite Element Method (FEM) simulations were used to design two different PMB configurations. Measurements results of axial and radial forces were carried out in Zero Field Cooling (ZFC) and Field Cooling (FC) processes. These measured force results are presented and discussed in order to discover which configuration is more promising for the proposed application.

Index Terms—Permanent Magnetic Bearing, Superconductor Magnetic Bearing, Flywheel.

I. INTRODUCTION

A flywheel energy storage system (FESS) has been developed at the Laboratory for Applied Superconductivity of the Federal University of Rio de Janeiro, Brazil. In order to improve the performance of the FESS, a passive magnetic bearing system was designed. The system provides radial and axial stability to the flywheel. The whole passive bearing system is composed of a Permanent Magnetic Bearing (PMB) and a Superconducting Magnetic Bearing (SMB). This PMB presents an attractive force that is responsible for providing radial stiffness and also reducing the total load above the SMB. The use of a PMB allows for cost reduction with superconductors and refrigeration, but has as a drawback a limited stability region. This paper presents a magnetic bearing set developed to work in a flywheel energy storage system [1][2][3]. The bearing set is composed of a Permanent Magnetic Bearing (PMB) and a Superconducting Magnetic Bearing (SMB), Fig. 1. SMBs are useful for high-speed rotating devices because of their low energy losses at high speed and their self-stability [4], but their cost is still high and they need refrigeration. On the other hand, PMBs have low cost, but are not able to produce completely stable levitation, as predicted by Earnshaw’s theorem [5]. One possibility for optimizing the whole bearing system benefit-cost is the use of a PMB working as an auxiliary bearing of a SMB. In this case, the whole system is able to produce stable levitation, reducing the cost with refrigeration and superconductors blocks. In an attempt to optimize the PMB, a new configuration is presented in this paper and it is compared with a conventional PMB [6][7] (both having the same permanent magnet volume). The new PMB presents higher levitation force and stiffness than the previous configuration.

The thrust SMBs studied here are composed basically of rare earth permanent magnets rotors and YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) superconducting stators refrigerated by liquid nitrogen (LN$_2$). They are able to reach self stability due to the flux pinned inside the superconductors in a Field Cooling (FC) process. When the superconductors are cooled without the field of permanent magnets, Zero Field Cooling (ZFC) process, a larger levitation force is reached, but the bearing stiffness is too small [4]. For this work two SMBs prototypes were built and the analysis is developed considering the following parameters: the mapped magnetic flux density, the levitation force for ZFC and FC processes and the bearing’s stiffness for different cooling gaps. The SMB prototypes tested are: a Flux Shaper (FS) topology [1][8][9] and an Axially Magnetized Ring (AMR) [10][11], both having the same dimensions and permanent magnet volume. The main difference between these SMB prototypes is the direction of magnetization of the permanent magnets. A previous work [12] presented a preliminary comparative analyses of these SMB topologies, and more concluding results will be presented here. The measurements show that the FS configuration presents a larger levitation force for ZFC. However, in FC process both configurations present very similar levitation force, even for various initials gaps tested. After FC process, when the gap is decreased, the AMR presents a slightly higher levitation force.

II. PERMANENT MAGNETIC BEARING

Due to the higher magnetic flux density reached by Nd-Fe-B magnets and their low cost, applications with permanent magnetic bearings have become attractive, in spite of being very unstable. Therefore, PMB can be used as an auxiliary bearing for a SMB to reduce the load weight of the rotor and the flywheel and to increase the stiffness of the whole bearing system. It makes possible to reduce significantly the quantity of superconductor blocks in the SMB, bringing down
the overall cost. Previous work [7][8] showed a PMB topology using 2 rings configuration presenting good results. In the present paper a new PMB configuration is proposed using the same permanent magnet volume, but with 4 rings and a back yoke that has the function of reducing stray magnetic flux. Fig. 2 shows the two topologies of PMB that will be compared here. The Nd-Fe-B rings are made with N35 material, whose coercivity force and remanent field are -918kA/m and 1.198T, respectively. In order to provide a damping mechanism due to induced current by inhomogeneity field, 3 small aluminium rings are introduced between the rings magnets in the 4 rings topology, as shown in Fig. 2(b).

To develop the analysis comparing these 2 PMB configurations, 2D and 3D Finite Element Method (FEM) simulations were carried out. In these simulations the magnetic forces are calculated during the postprocessing stage applying the virtual work method. Attractive force results for different disc axial levels are presented in Fig. 3, and it shows that the new configuration (4 rings and a back yoke) presents an increase of over 73% in the force for a gap of 5mm. This result can be attributed to the reluctance reduction in this PMB magnetic circuit.

Other function of the PMB is the system radially positioning. The restoring force is important to help to bring back the operational position of the flywheel when the shaft is displaced radially. The maximum radial displacement is limited by the air gap length of the electrical machine used in the flywheel system. A switched reluctance machine is used in this work, and it has an air gap of 2.5 mm. The restoring radial force for a lateral displacement is presented in Fig. 4. The 2 rings PMB topology has a stiffness of 19.4N/mm, whilst the 4 rings and back yoke PMB present stiffness of 30.4N/mm, for a 5mm gap. Axial and radial forces results indicate that the 4 rings and back yoke topology must be considered as good option to work together with others stable bearings.

III. SUPERCONDUCTOR MAGNETIC BEARING

In this section two kind of thrust superconductor magnetic bearings will be compared: FS [1][8][9] and AMR [10][11] configurations. The FS and AMR topologies were build having the same Nd-Fe-B (N35) volume, and the main difference between them is the permanent magnet magnetization orientation. Both configuration are made with steel SAE-1020, aluminium and Nd-Fe-B permanent magnets, as shown in Fig. 5. In the FS topology, the magnetic flux density is concentrated in an intermediary ring steel by two opposite polarities radially magnetized Nd-Fe-B discs. To obtain the rings magnetized radially, it was necessary to use small rings segment. As shown in Fig. 5, FS uses an aluminium cover that has a function of supporting the system. In the AMR topology the Nd-Fe-B rings are magnetized axially, and a back yoke is introduced to reduce the reluctance. The advantages of FS are: it is lighter (FS and AMR mass are, respectively 1.84kg and 2.43kg) and it has steel between consecutive magnets (eliminating irregularity in B). AMR advantages are: it can be constructed much more easily (it does not need glue) and auto stability among their rings magnets in the base because of the magnetic poles attraction due to the back yoke (while in FS disc theirs permanent magnets have a potential energy stored because of magnetic poles repulsion). The AMR configuration has a diameter of 130mm, while the FS one has 140mm (because it’s aluminium encapsulation). The height of permanent magnets rings for both topologies is 10mm.
A. Magnetic Induction

This section discusses the magnetic arrangement of FS and AMR topologies, induction configuration of both topologies. Some Finite Elements Method (FEM) simulations were performed by 2D Axisymmetric static magnetic analysis. The first simulation results presented in Fig. 6 show flux lines for both SMB stators discs and magnetic induction vectors (B in radial and axial direction) in some specific positions. From Fig. 6, it is possible to see that magnetic induction for FS and AMR are dual. It means that the profile of axial component of B of FS rotor is approximately the radial component of AMR rotor and vice-versa, as confirmed by Fig. 7. Fig. 7 shows FEM B results simulations (for radial and axial components), and magnetic induction measurements for both stators discs in the axial direction. Another important result shown by Fig. 7 is a good agreement among axial component of magnetic induction measurements and calculations made by FEM. These results are still important to find maximum B gradient and determine where the YBCO cylinders must be placed.

B. Levitation Force for Zero Field Cooling

The YBCO blocks, with 28 mm diameter and 10 mm height, were mounted in a region under the higher rotor field (centered in radius of 45mm). This arrangement of superconductor were chosen taking in consideration the size of the YBCO discs, the number of available superconductor and the maximum B gradient region presented in Fig. 7.

In the ZFC measurements the YBCO was cooled at a distance of 45mm from the permanent magnet rotor (where its magnetic field is negligible). After the YBCO is cooled the permanent magnetic disk was approximated to the YBCO stator at a speed of 0.75mm/s. When a gap of 3.5mm was reached the moving direction was reversed, and it was returned immediately with the same speed. During all this process the levitation force is measured and synchronized with the position data. The result for the ZFC process described above is presented on Fig. 8. As may be seen on this figure, the FS configuration presents a larger levitation force than the AMR. This result should be attributed to the fact that FS configuration has a greater peak-to-peak value of magnetic induction in the axial direction (see Fig. 7) than the AMR, associated with very low penetration flux into the YBCO superconductor.

C. Levitation Force for Field Cooling

For FC refrigeration process the YBCO was cooled when the magnets disc was in an initial distance from it. The measurements were made for the followings initials gaps: 3mm, 5mm and 7mm. Then the disk was vertically elevated 45mm at 0.75mm/s. Finally, the disk was brought back to a vertical distance of 1mm above the superconductor. Measurements for
Superconductor Magnetic Bearing were analyzed: a Flux
radial forces. In the second part, two configurations of thrust
was proposed and allowed significant increase in levitation and
flywheel system. Initially, two Permanent Magnetic Bearing
topologies were evaluated for the tested gaps (3mm, 5mm and 7mm).
As may be seen in Fig. 11, the radial displacement force has
is decreased, which makes the radial restoring force decrease.

Gap is increased the pinned flux inside the superconductors
is decreased. This can be attributed to the greater trapped flux
attraction force is higher, and the capability to support loads
is decreased. These results indicate that the trapped magnetic field in both bearing
configurations should be of the same intensity and profile.

D. Radial restoring Force for Field Cooling

The radial restoring force is important to bring back the
shaft to its working position when a disturbance occur in
the system. Fig. 11 shows the radial displacement force
for both SMB topologies for different FC gaps. As the cooling
gap is increased the pinned flux inside the superconductors
is decreased, which makes the radial restoring force decrease.
As may be seen in Fig. 11, the radial displacement force has
the same magnitude for both SMB topologies investigated for
the tested gaps (3mm, 5mm and 7mm).

IV. CONCLUSION

This paper presented a magnetic bearing set to work in a
flywheel system. Initially, two Permanent Magnetic Bearing
topologies were compared and a new magnetic arrangement
was proposed and allowed significant increase in levitation and
radial forces. In the second part, two configurations of thrust
Superconductor Magnetic Bearing were analyzed: a Flux
Shaper and an Axially Magnetized Ring having dual magnetic
induction topologies and the same Nd-Fe-B volume. Initial
Zero Field Cooling tests indicated that the AMR presents
lower levitation force than the FS. However, these vertical
levitation forces are similar when Field Cooling process are
adopted, even for various tested initial gaps. Finally, the
restoring force for a radial displacement indicated the same
magnitude force for both topologies. These results indicate that
the AMR topology seems to be the better SMB configuration
for the proposed flywheel prototype.

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