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Fields and Forces in Flywheel Energy Storage with High-Temperature Superconducting Bearings

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Abstract--**The development of low-loss bearings employing high-temperature superconductors has brought closer the advent of practical flywheel energy storage systems. These systems require magnetic fields and forces for levitation, stabilization, and energy transfer. This paper describes the status of experiments on flywheel energy storage at Argonne National Laboratory and computations in support of that project, in particular computations for the permanent-magnet rotor of the motor-generator that transfers energy to and from the flywheel, for other energy-transfer systems under consideration, and for the levitation and stabilization subsystem.**

I. Introduction

A small permanent magnet (PM) passively levitated above a body of high-temperature superconductor (HTS) is now a common sight. This phenomenon has led to the development of low-loss bearings, at Argonne National Laboratory (ANL) and elsewhere. Efforts are now underway to develop a flywheel energy storage (FES) system employing these bearings [1].

Availability of FES would reduce the costs that electrical utilities incur in adjusting their powerplant output. At present, demand for electrical power can vary as much as 30% over a 12-h period. FES with HTS bearings, operating at diurnal storage efficiencies of 90% or more, could compensate for load swings and level out the diurnal variations of load on transmission lines. They also could be coupled with wind and photovoltaic power generation to compensate for the variability of those sources.

A major difficulty in using FES for diurnal leveling of power generation and transmission is power loss in the bearings. HTS bearings should be able to reduce the losses from about 1%/h to about 0.1%/h.

To be specific, I will focus attention on FES development at ANL. Early ANL experiments used a PM rotor of mass less than a kilogram spinning above an HTS stator cooled by liquid nitrogen. The apparatus operated within the vacuum of a bell-jar, as seen in Fig. 1. In the experiments, both a nitrogen gas jet and an induction motor were used for rotor spin-up. The experiments gave information about how the coefficient of friction varied with rotor velocity and with the height of the permanent-magnet rotor above the HTS stator.

Later experiments used a 2.5-kg PM rotor, with and without an additional 10-kg graphite/epoxy flywheel ring, see Fig. 2. Since these experiments were reported in Ref. 1, work on FES has continued.

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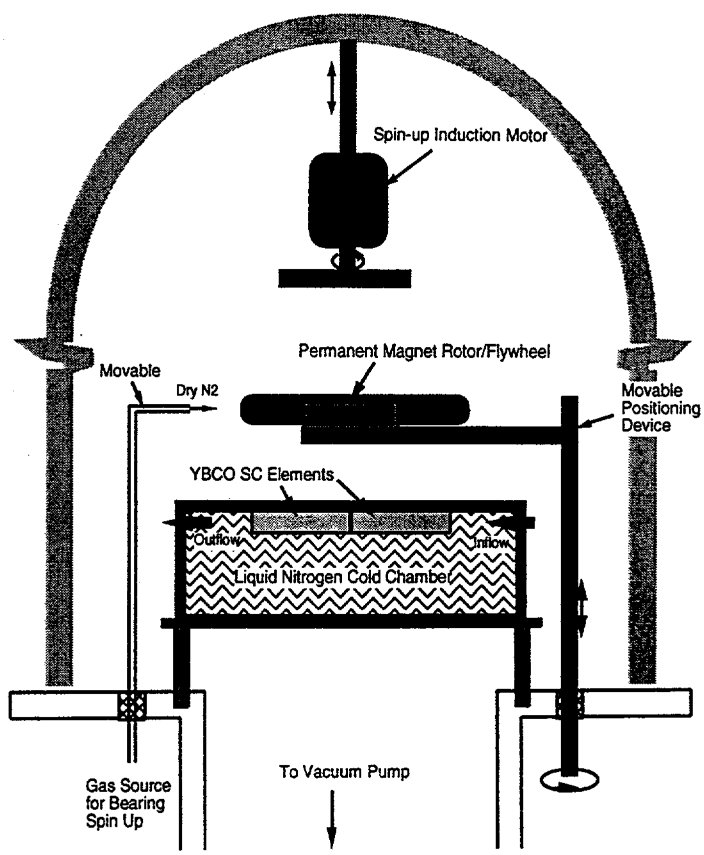

Fig. 1. Schematic representation of belljar spin-down vacuum chamber

Developing such a flywheel system requires the analysis of several subsystems made up of permanent magnets, magnetic iron, and/or HTS materials

II. The Rotor Bearings

FES designs by various investigators have considered different geometries of HTS, PM, and magnetic steel, and different approaches to bulk material and banding selection to maintain the mechanical integrity of the rotor and prevent

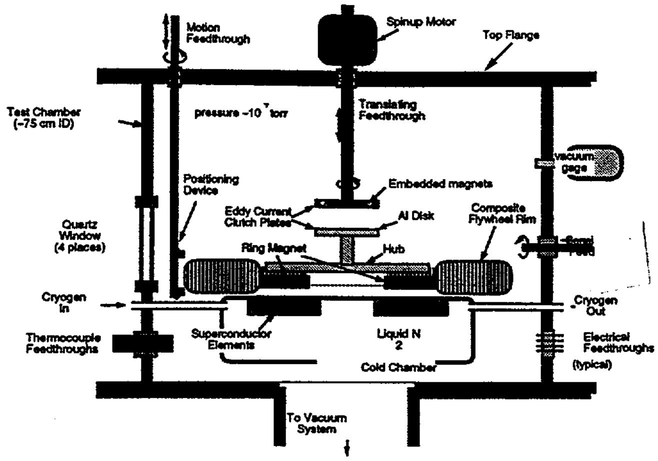

Fig. 2. Schematic diagram of spin-down vacuum chamber

motion of the PM material. They have also considered different choices of single or multiple bearings to provide levitation and radial and axial stabilization. But at ANL, most experiments to date have been carried out with a high-speed, multipiece rotor (Rotor B) that has one HTS bearing. It has been found to have low energy losses, within one order of magnitude of those needed to make long-term FES economically viable [2].

The rotor's HTS bearing uses only one double-ring PM assembly incorporated in a hoop-wound fiber-composite disk

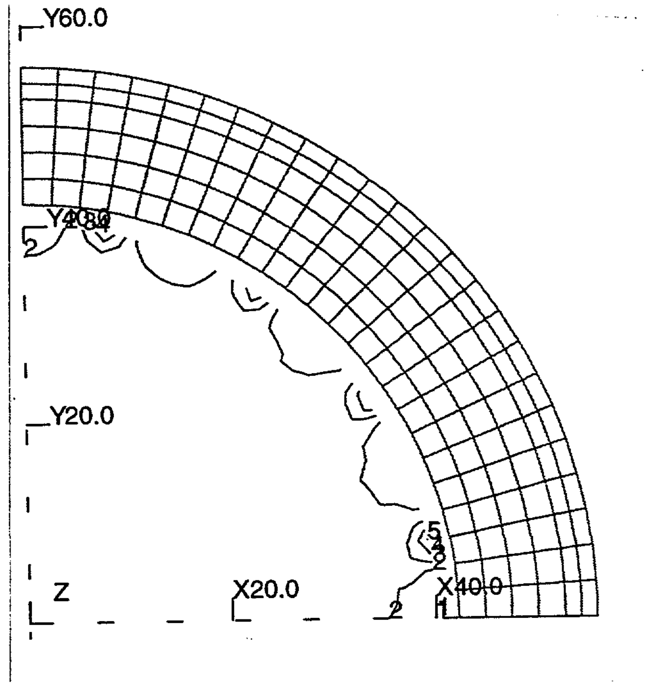

Fig. 4. Contour plot of field component B_y in the 16-magnet Halbach array. 2-D Computation with 3-D code. Minimum 0.2 T, Maximum 0.4 T, spacing 0.04 T

rotor spinning about a vertical axis. With this concept, the rotor position is passively stabilized due to pinning of the

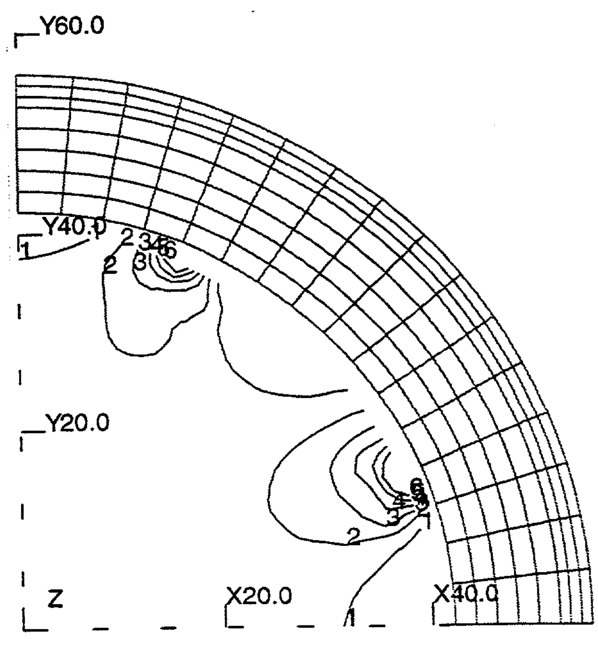

Fig. 3. Contour plot of field component B_y in the 8-magnet Halbach array. 2-D Computation with 3-D code. Minimum 0.2 T, Maximum 0.4 T, spacing 0.04 T

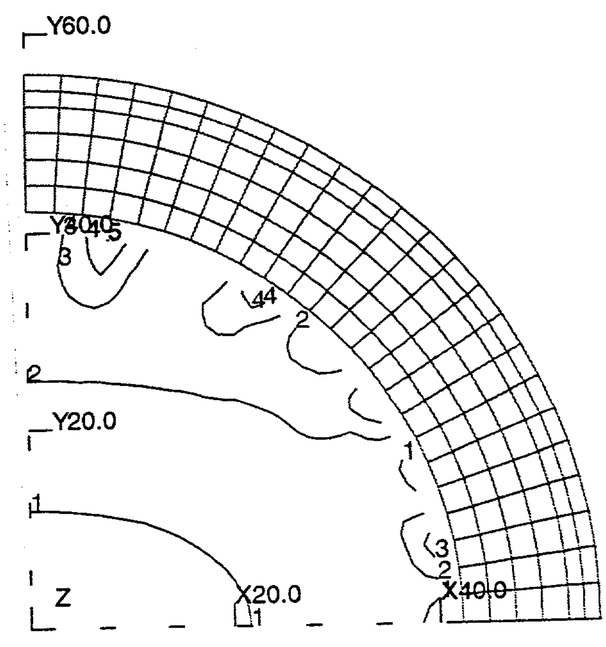

Fig. 5. Contour plot of field component B_y in the 16-magnet Halbach array. 3-D Computation with 3-D code. Minimum 0.2 T, Maximum 0.4 T, spacing 0.04 T. Field in midplane.

magnet flux by the HTS of the stator. Using two concentric ring PMs of opposite polarity and equal volume results in large gradients in the fields from the PM, and thus larger levitation forces (under the assumption of constant magnetization density in the HTS) [3].

For an auxiliary levitation scheme using PM and magnetic iron, the two-dimensional (2-D) code OPERA-D [4] was used in its axisymmetric mode. How the levitation force and axial stabilization varied with axial gap between the PM and iron was studied via the method of virtual work. That is, computations were carried out for different axial gaps, and the stored energy was computed for each position. From the energy differences and the gap differences, the force and the axial gradient of the force could be determined. Radial stabilization was studied in the same way using the 3-D code TOSCA [4] to compute the stored energy for different radial displacements. The contour of the iron face was varied as a possible way to optimize the radial stabilization.

Because of concerns about stresses in the PM material at high rotational speeds, additional computations were carried out for magnets with alternating layers of PM material and high-strength banding material. These computations showed that the field strength of the magnets decreased proportionally as the fraction of banding material increased.

III. Energy Transfer with a Halbach PM Dipole Array

With an FES system such as discussed here, some displacement of the rotating components is expected during operation. Consequently the motor-generator that feeds energy into and out of the flywheel system cannot have the close tolerances characteristic of conventional rotating machinery. In the case considered here, the motor-generator consists of a many-turn wire armature as stator, surrounded by a rotor made up of an array of permanent magnets providing a dipole magnet field.

The magnet array consists of several wedge-shaped blocks whose directions of magnetization are chosen to give a nearly uniform dipole field, as described by Halbach [5]. A steel ring constrains the blocks and helps reduce the external field, but does not contribute to the field inside. In the initial implementation of this approach, eight permanent magnets made up a cylinder 50.8 mm long with inner diameter 40.8 mm and outer diameter 105.8 mm. The iron ring is 3.17 mm thick.

For a fixed outer diameter of the array, field strength will increase as the PM inner diameter is decreased. But below a certain inner diameter, the number of turns in the armature must decrease and the average radial position of an armature turn will decrease as well. Consequently, overall torque will decrease despite the increasing field. For this reason, the inner diameter of the array was increased to 84.4 mm.

Both 2-D and 3-D field computations were carried out for the eight-block permanent magnet with the codes OPERA-2D and TOSCA, respectively [4]. The 2-D computations showed the field to be highly uniform (variations of about 0.5%) except near the magnet blocks themselves. When the inner diameter was increased, the number of magnets was increased from 8 to 16 to improve field uniformity near the PM, see Figs. 3 and 4.

Judging the effects of relative motion between the armature and the PM rotor and choosing an armature geometry that minimizes these effects requires knowledge of the spatial derivatives of the magnetic field components. But a finite-element computation does not lend itself to the accurate determination of those derivatives. Consequently, the computed field around a 90° arc fairly near the magnets (radius 37 mm) was fit by harmonic analysis, the significant field harmonics were determined, and the analytical expressions for the harmonics were used to find the field derivatives.

Because the aspect ratio (inside diameter to length) of the PM rotor is more than unity, the 3-D computations revealed considerable inhomogeneity, as seen in Fig 5. Attempts to correct the inhomogeneity with iron shielding have been unsuccessful to date.

IV. Eddy-Current Spin-up and Spin-down

In another concept studied at ANL, four cylindrical permanent magnets rotate above an aluminum or steel disk and transfer energy to and from the disk. It is necessary to know the forces and torques involved, plus any perturbations to the motion caused by misalignment or by irregularities in the magnetization. The four magnets are aligned parallel to the axis of rotation. Magnetization in neighboring magnets may be either parallel or antiparallel.

In the absence of a 3-D code that incorporates the motion of the rotating magnets, the computations are carried out with the 3-D eddy-current code ELEKTRA [4]. The four magnets were modeled by 16 solenoid magnets, with phase adjusted

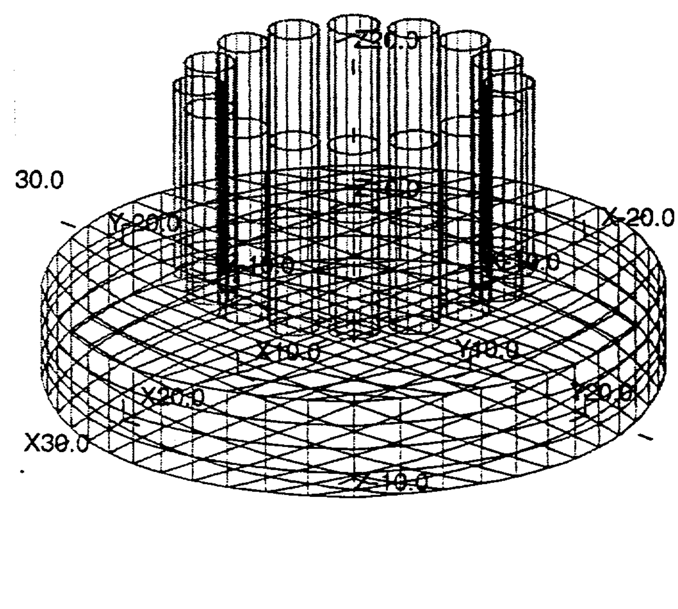

Fig. 6. Four permanent magnets rotating over a conducting disk, modeled by 16 solenoids of varying phase.

to represent the rotation [6], see Fig. 6 If neighboring magnets are antiparallel, the frequency of field oscillation is twice the frequency of rotation, the phase difference between neighboring magnets is 45°, and there is no time-average field. If all magnetizations are parallel, there is an average field, but it produces no eddy currents, no net force, and no net torque, and so can be neglected. The frequency of field oscillation is four times the rotation frequency, and neighboring magnets are 90° apart in phase. In the computations, the disk may or may not be centered on the axis of rotation of the magnets, in order to study possible dynamic effects between the rotating field and the spinning disk.

V. Other Computations

Inhomogenieties in magnetization of the permanent magnets can lead to time-varying magnetic fields, to eddy currents in conducting components, and thus to energy losses. Experimentally, means for eliminating these time variations, such as the placement of shims, have been attempted, with mixed success. An attempt to treat the size and location of shims as an optimization problem has begun, but so far without results that are testable on the actual magnets.

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