**TRAPPED-FLUX INTERNAL-DIPOLE SUPERCONDUCTING
MOTOR/GENERATOR***

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Submitted to 1998 Applied Superconductivity Conference, Sept. 13-18, 1998, Palm Desert, CA.

*Work supported by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, as part of a program to develop electric power technology, under Contract W-31-109-Eng-38.

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Trapped-Flux Internal-Dipole Superconducting Motor/Generator

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Abstract—A new class of motor/generator (M/G) utilizes the magnetic flux trapping capability of high-temperature superconductors (HTSs). The rotor, consists of a cylindrical shell composed of HTS segments. These segments act as trapped-field magnets, magnetized in such a way that a dipole magnetic field is produced in the interior of the shell. A stator coil assembly is placed in the interior of the shell and current passing through the conductors of the coil produce a rotational torque, either as a hysteresis motor or as a synchronous motor. The coil may be either conventional, with copper wires and an iron core, or composed of superconductors and can be used to establish the trapped fields in the HTSs.

I. INTRODUCTION

The use of bulk HTSs in rotors of brushless motors has been investigated by several researchers [1]-[4]. Interest in such motors increased with the development of melt-textured Y-Ba-Cu-O, which is presently available with engineering critical current densities of up to 4×10^8 A/m² at liquid-nitrogen temperatures. The two most common designs are to operate as a hysteresis motor, with the magnetic field from the stator coils rotating faster than the rotor, or as a synchronous motor, with substantial magnetic flux trapped in the HTS.

The major advantage of superconducting motors is that the ability to produce high magnetic fields results in a high specific torque, i.e., a smaller sized motor can

produce a given amount of torque. An advantage of brushless types of superconducting motors over other superconducting motors is that no attachments need be made to the rotating part.

Bulk HTSs differ fundamentally from permanent magnets (PMs), which are the major alternative for rotors of brushless motors. PMs have a magnetization which is uniform throughout the volume of the material, with NdFeB PMs commercially available with remanent magnetizations approaching 1.5 T. A constant volume magnetization can be modeled with a fictitious Amperian current shell at the magnet's perimeter. Further, the coercive field of the PM is high, so that the magnetization remains relatively constant in an opposing magnetic field. On the other hand, an HTS will demagnetize slightly in an opposing magnetic field. Also, an HTS has a magnetization produced by real currents, and approximately uniform current density throughout the HTS. The advantage for single-grained HTS is that the magnetization is proportional to the product of current density and grain radius. In principle, HTSs with large radii can have magnetizations larger than the PM. However, for cylinders field-cooled in high magnetizing fields, the resultant magnetization is conical, starting from zero at the cylinder edge and peaking in the center. The average magnetization over the HTS volume is $1/3$ that of the peak value. Thus, HTSs must obtain peak magnetizations of 4.5 T in order to have the same volume energy product as the best PM. At 77 K, peak magnetic fields at the surface of an HTS of over 1.0 T have been obtained in Y-Ba-Cu-O in unirradiated samples and up to 8.5 T at 50 K [5]-[7]. As in PMs, magnetizations in the interior of the HTS are higher than the fields measured at the surface and depend on the aspect ratio of the sample. Usually, the figure of merit for a PM application is the energy product, which is the largest rectangular area that can be inscribed in the second quadrant of the B vs. H curve for the material. The translation of HTS

surface field measurements into an equivalent energy product has, to the authors' knowledge, yet to be found in the literature.

One of the concepts under development for brushless PM motors involves Halbach arrays that act as the rotating element in a motor/generator (M/G) [8]-[11]. The concept in the Halbach array is that by arranging uniformly magnetized PM segments in a circle, so that the magnetizations of each segment rotate around the perimeter of the circle, maximum effectiveness of the magnetizations can be made, with less leakage flux and higher fields in the air gap than what can typically be achieved in PM designs with only radial magnetizations. The Halbach array has a further advantage that the self demagnetization field is less than for conventional designs. The Halbach array can be used to produce external poles [9], or internal poles [10], [11], and the internal dipole concept is the subject of the present paper. Such an arrangement is shown as the cross section of a cylinder in Fig. 1, in which the heavy arrows represent the direction of magnetization of the permanent magnet segments, and the light arrows represent the direction of the magnetic field inside the cylinder. A stator coil is placed inside the PM array to act as a M/G. With the Halbach array shown in Fig. 1, the dipole magnetic field is very uniform. If the stator coil has no iron, the motor is essentially a pure-torque machine, with no sideways forces to a first approximation. Many experimental models of this type of magnet have been built, and it has been used successfully as a M/G in an experimental flywheel with HTS bearings [11].

II. HTS HALBACH

The concept in the present paper is to replace the PMs in the Halbach array with HTSs, each HTS with its c-axis oriented along the direction of magnetization shown in Fig. 1 [12]. When experiencing an external magnetic field, each HTS segment will tend to magnetize in the direction of the c-axis, i.e., in the direction of the heavy

arrows in Fig. 1. The resulting internal-dipole field should be similar in form to that of the PM Halbach. One of the advantages with this design is that the trapped-field geometry has low self-demagnetization tendency and should result in a higher magnetization than radially magnetized HTSs.

The HTS material is preferably melt-textured Y-Ba-Cu-O, due to its high irreversibility field, but any superconducting material capable of trapping a magnetic field is possible to use. There is a soft-magnetic, high-mechanical-strength shell around the HTS segments. This shell, typically made of low-carbon steel, helps to confine the magnetic flux and acts as a mechanical band to contain the relatively low-strength and brittle HTS members when the cylinder is rotating. Clearly, the stator can consist of one, two, three, or any number of phases.

The HTS shell shown in Fig. 1 consists of eight segments. A sixteen segment shell, with the rotation of magnetization between adjacent segments of 45 degrees is also possible. In this case the dipole field is retained and is more uniform. A larger number of segments may also be used. If desired, the magnetizations can be configured so that the magnetic field is that of a quadrupole, as opposed to a dipole. Higher order poles are also possible.

The stator coils could be composed of superconductors, preferably HTS wires, as this would ultimately provide the largest specific torque for the M/G. However, the stator sees a rotating magnetic field, and with present HTS wire technology, the ac losses may be too high. A more conventional arrangement would have the coils embedded in an iron yoke that acts as a low-reluctance magnetic flux path. The conductors in this case could be either superconductors or normal conductors, such as copper wire. The iron core would typically be made of laminations. The iron core does create a much larger lateral force between the coil and the shell, and this force must be accommodated by the bearings.

III. ROTOR SIZE OPTIMIZATION

One of the interesting features of the Halbach internal-dipole configuration is that the dipole field can be much larger than the magnetization of the segments. For a PM array, the magnetic field B is [8]

$$B = M_0 K \ln(R_0/R_i) , \quad (1)$$

where M_0 is the magnetization of the segments, R_0 is the outer radius and R_i is the inner radius of the array, and $K = \sin(2\pi/N)/(2\pi/N)$, where N is the number of segments. For large ratios of R_0/R_i , B can exceed M_0 by severalfold, a feature that may be of interest to nonmotor applications.

We consider a unit length of arc segment $d\theta$ of conductor, extending from $r = R_c$ to $r = R_i - \delta$, where δ is the air gap between the stator conductor and the array. The maximum torque τ per unit length of this conductor is

$$\tau = A \ln(R_0/R_i) [(R_i - \delta)^3 - R_c^3] \quad (2)$$

where $A = d\theta j M_0 K$, where j is the current density. Fig. 2 shows torque as a function of R_i/R_0 for several values of δ/R_0 and $R_c = 0$. We note that torque decreases with increasing R_c , but the optimal value for R_i/R_0 does not change. From Fig. 2 we see that the optimal value of R_i/R_0 is weakly dependent on the air gap and is in the range of 0.7 to 0.75. The extent of $d\theta$ or the number of phases in the stator will affect the torque, but they do not affect the R_i/R_0 optimization.

IV. PRACTICAL CONSIDERATIONS

In Fig. 1, the HTS segments are shown cut as arc segments. This makes best use of the internal volume for the stator coil. With PMs, it is possible to cut or grind segments to this geometry. The manufacture of HTS segments is more problematic, as melt-textured HTSs have low mechanical strength and are brittle. Further, one must consider the need for the current to flow in the *ab* plane of the HTS. The arrangement of the *c*-axis makes the effective grain radius inherently vary from piece to piece, depending on the inside to outside ratio of the array, however, the pieces must be constructed to avoid tendencies of current to flow in the *c*-axis, if possible. Thus, it is prudent to construct the segments as trapezoids, so that the segments take the form of an octagon, with little sacrifice in the quality of the dipole field. It is known that the use of trapezoids does not impair the field homogeneity [8]. In this case the inside surface of the banding steel shell would be machined to accommodate the flat surfaces of the HTSs.

Construction of HTS segments to form a prism with octahedral cross section and the desired *c*-axis orientation is shown in Fig. 3. We have fabricated an octahedral ring of melt-textured Y-Ba-Cu-O in this method, and it will be tested in the near future. The motor is constructed from 32 rectangular parallel pipeds of YBCO of dimension 32 x 32 x 13 mm, with the *c*-axis in the short dimension. Each block is cut in half along one of the lengths and the bottom part removed to bring to its final height. Parts (a) in Fig. 3 are composed of two HTS blocks that are 32 x 12 x 6.4 mm; parts (b) by three blocks that are 32 x 12 x 7.9 mm; and parts (c) by four blocks that are 32 x 12 x 6.4 mm. The blocks are glued together and then machined to shape by a diamond saw. The set of 8 blocks are assembled together in an octagonal cross section and bonded with alumina-doped epoxy. Two disks of G-10 fiberglass/epoxy composite are used on the top and bottom of the array to hold it together.

The present concept for the M/G is that the rotor could be constructed from a stack of the arrays described above.

There are many methods to cool the motor. For example, one could run the entire motor in a bath of liquid nitrogen. One preferred possibility is to embed the stator coils in a structure that is thermally attached to a cryogenic refrigerator that conductively cools the coil. Then, either by convection of the gas between the coil assembly and the shell, the shell is also cooled. Alternatively, cold nitrogen gas could be fed into the space.

The motor could be run at high speed if the space around the shell were evacuated. The shell could be suspended with magnetic bearings and torque coupling to the external world would be accomplished by a magnetic clutch. In this case, the shell would be cooled by radiative exchange between the coil assembly and the shell.

V. FIELD UNIFORMITY

Because of the nonuniform magnetization of the HTS segments, the dipole field of the HTS array is likely to be less uniform than its PM counterpart. A 2-d mathematical model of each segment was constructed that considered wire segments of square cross section with uniform current density. The total current in each segment was equal to zero with wires orientation divided along a line parallel to the c-axis of the segment. The wire size was reduced by successive factors of 2 until the maximum percentage variation in magnetic field at any point in the interior was less than 1% from the preceeding calculation. The result is shown in Fig. 4. The dipole field is slightly distorted compared to literature values of PM Halbach arrays constructed from arc segments, however, it is probably good enough for practical purposes, and actual field profiles will be strongly affected by practical

considerations, such as variation in properties from one segment to the next, as well as the geometry used to initially magnetize the array.

VI. MAGNETIZATION

One method to magnetize the array is to cool the HTSs to their superconducting state in the absence of a magnetic field and with no current in the stator coil. The array is held fixed and current is passed in a pulse through one of the phases in the coil. These conductors form a magnetic field that is an approximation to the dipole field, and this field will be impressed upon the HTSs, magnetizing them. The surrounding iron shell helps to shape the field through the HTSs. Typically, the magnetization would occur with a very large current of very short duration.

Alternatively, if the coils are very good superconductors, it may be possible to have the stator coil cooled into the superconducting state, activate one of the phases in dc mode, and then cool the HTSs in the shell into their superconducting state, and deactivate the coil. A fraction of the original impressed field will remain in the HTSs. External coils may also be used to help achieve the original magnetization.

VII. CONCLUSIONS

A concept for a superconducting motor using bulk HTS segments in the form of a Halbach array for the rotor has been introduced. A prototype array of YBCO has been fabricated and the magnetic field from the array has been predicted.

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FIGURE CAPTIONS

Fig. 1. Halbach-array internal-dipole magnet.

Fig. 2. Calculated dimensionless torque as a function of inner to outer array radius for several values of air gap.

Fig. 3. Construction of HTS segments for internal-dipole array of octahedral cross section.

Fig. 4. Calculated flux lines for infinitely long prism of HTS array.

Fig. 1

Fig. 2

(a)

(b)

(c)

Fig. 3

Fig. 4