Design of a Multidisk Axially Excited low power class Superconducting Motor for industrial application

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Abstract. In this work we present the design of a multidisk bulk based superconducting low power motor for control application. The motor consists of a set of disks shaped rotor with superconducting blocks in a four pair of poles configuration. The bulks act as field generators in a trapped flux way by interacting with conventional copper coils which are responsible of both running and magnetizing functions. Details of the magnetic assembling, cryogenics and electrical supply conditioning will be reported.

1. Introduction
High temperature superconducting power applications are highly efficient and environmentally friendly. Considering the electrical current density and high magnetic density that can be reached, superconductor materials allow a wide range of applications. Several applications of low power motors are related with high acceleration capacity achieved by high torque, a lower cogging torque and low inertia moment, where control system has a special relevance. It is of interest to study the application of bulk materials on this field due to its remnant magnetization characteristics and convenient geometry where superconducting conductors can not achieve. In this paper it is presented the design of a low power motor using superconducting bulk materials which act as magnetic elements by working on a trapped flux regime. It will be compared in terms of technical standards by a commercial top brushless electrical motor (CTBEM).

1.1. Aims and procedure
The aim of this paper is to design a low power motor using YBa₂Cu₃O₇ Melt Textured Growth (MTG YBCO) samples and compare their characteristics with a conventional low power motor designed for high acceleration and precision requirements. The design will be called axial flux superconductor machine (AFSCM). The design is planned taking in account as conventional reference the dimensional, nominal and limit characteristics of the CTBEM shown on table 1.1.
A way to adapt the bulk superconductors to electrical motors is by using an axial flux design. Axial flux allows working with the magnetic best faces of the bulk materials, using YBCO pellets directly obtained by a melt textured growth (MTG) after cutting the adequate slides and milling the surfaces to achieve plane faces.

In order to trap a flux density of 2 T on each YBCO bulk sample a temperature of 60 K has been chosen [1].

The motor allows holding different number of rotors and stators as a modular set. Figure 1 shows a schematic design of the axial flux motor. Design consists of seven three phase cooper armatures and six HTS rotors between them. Each rotor cooled by coolant flowing through conduit and is thermally isolated by a vacuum system covering the whole set.

### Table 1. Technical parameters of CTBEM

| Parameter                  | Unit | Value     |
|----------------------------|------|-----------|
| Dimensions                 |      |           |
| Outer armature length      | mm   | 107       |
| Outer armature diameter    | mm   | 80        |
| Characteristics            |      |           |
| Stall armature current     | A    | 2.74      |
| Stall torque               | N·m  | 1.7       |
| Armature inductance        | mH   | 3.2       |
| Armature resistance        | Ω    | 8.5       |
| Electrical time constant   | ms   | 0.307     |
| Mechanical time constant   | ms   | 5.246     |
| Inertia moment             | Kg·m²·10⁻³ | 0.137    |
| Mass                       | Kg   | 1.9       |
| Limits                     |      |           |
| Speed limit                | rpm  | 12000     |

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### Figure 1.- Schematics of the design of an axial flux electrical motor applying HTS bulk elements.

2. Magnetization considerations for armature design

The armature windings are used for produce both, the magnetizing field and also the tracking field of the motor. For this reason the armature winding is designed taking in account the field needed to magnetize YBa$_2$Cu$_3$O$_7$ bulk samples up to 2 T [2,3,4,5].

The procedure of this paper will start with the design of the different parts of the motor considering the principal technical standards and compare them front the CTBEM.

It has been decided to make a three phase motor to obtain an equilibrated rotating magnetic field from stator. The angular distribution of the windings has been designed to obtain an eight poles magnetic field.
The cooper section area has been designed considering the electrical field and the high current required to magnetize every superconductor with a remnant field up to 2 T by applying high current pulses. To achieve a remnant magnetic field of 2 T on the HTS bulks it will be used a Zero Field Process (ZFC) applying magnetic field pulse. Although DC ZFC full magnetization could be accomplished by applying an external field of 4 T according to the Bean model [6], the pulsed system should include a series of pulses achieving values higher than in DC magnetization. We expect to accomplish our goal by adjusting the temperature and the peak value of the pulse after the construction and testing them. An approach of the magnetization field could be obtained by assuming:

- Conductors of different phases are held parallel and the whole set are joined on an average angular position.
- It is supposed that the whole magnetic flux generated by the armature arrives at the top face of YBa$_2$Cu$_3$O$_7$ bulk material samples.
- It is considered the electromagnetic torque that the conductors can produce in an average stator diameter.

To obtain a field applied of 4T it is required a current per phase of 10 kA·turn applying a single pulse. A thermal calculation on copper wires shows that the maximum time applying this current cannot be longer than 10 ms. Also it is known that remnant field depends on the magnitude of the applied pulse, raise time, fall time and the number of field pulses [5]. It is desired to design a ZFC process capable to fully magnetize the samples taking in account the dielectric winding properties, winding parameters and mechanical strength. For these reasons, several pulses are required to fully magnetize the samples. Table 1.1 shows the winding principal parameters calculated.

Table 1.1. Technical parameters of AFSCM armature

| Parameter            | Unit  | Value |
|----------------------|-------|-------|
| Maximum current density | A/mm$^2$ | 6     |
| Conductor diameter   | mm    | 0.75  |
| Windings             | turns | 25    |
| Resistance           | mΩ    | 37    |
| Total mass           | Kg    | 0.5   |

Windings are specially designed to be held in the armature containing the maximum amount of copper. It is needed to leave enough space for the winding heads on the inner and outer armature diameter parts. Also it is designed a ferromagnetic yoke at the end of series of stators to shield the magnetic field on the motor edges.

3. Superconductor bulk rotor design
Disks of 60 mm. outer diameter should be made by Fibre Glass Reinforced Epoxy as a support. A copper refrigeration base is in contact with eight YBCO samples symmetrically distributed covering an angle of 41º each. The remaining angle will be used as a mechanical support and for the refrigeration channels. To obtain room enough on the inner part to hold the winding ends, the rotor thickness is reduced as it is shown on Figure 3. Properties of the rotor are shown on table 3. The thickness required of the rotor, will depend on the thickness of YBCO bulk material needed to obtain a remnant field of 2 T.
The density of YBCO is about 5-6 gr/cm$^3$, lower compared than a typical permanent magnet as NdFeB that has 7.4 gr/cm$^3$ providing a low mass so obtaining a low inertia moment and consequently improving the rotor acceleration capacities.

![Figure 3. Design of the rotor](image)

### Table 3. Technical parameters of AFSCM rotor

| Parameter                  | Unit   | Value  |
|----------------------------|--------|--------|
| Magnetic remanence [B$_R$] | T      | 2      |
| Mass [M]                   | Kg     | 0.35   |
| Inertia moment [J]         | Kg·m$^2$·10$^{-3}$ | 0.25   |

4. **Motor output parameters**

Having obtained the principal design parameters of the motor parts, the technical parameters have been calculated in order to compare nominal and dynamic characteristics between AFSCM and CTBEM motors.

It has been calculated the electromagnetic torque with the hypothesis that the maximum remnant flux of YBCO bulk material is disposed over the whole armature conductors of each phase.

$$ F_{pole\_phase} = \left| \bar{I} \times \bar{B} \right| = 2 \cdot N_{c\_phase} \cdot I_a \cdot l_c \cdot B_R = 2.25 \cdot 2.74 \left( \phi_{in} - \phi_{out} \right) / 2 = 5.05N $$

(1)

Where the number of conductors per phase is $N_{c\_phase}$, $I_a$ is the nominal current of the armature, $l_c$ is the length of each conductor and $B_R$ is the rotor remnant magnetic field. Taking in account the number of poles and the number of armatures of the motor it has been calculated a force of 0.28 kN for the whole motor. For an average armature radius of 20.75 mm, it is obtained an electromagnetic torque of 5.9 N·m.

On variable torque applications, where a reduced acceleration and deceleration time is required to achieve a desired speed, electromagnetic torque, mechanical and electrical time constants are highly important.

The mechanical time constant defines the time required to reach 63.2% of its steady state [7] value when a step input voltage is applied. For a sinus-trapezoidal wave in eight poles:

$$ \tau_{mech} = 0.9549 \frac{R \cdot J}{K_e \cdot K_T} = 0.22ms $$

(2)

Table 4 compares the principal parameters of the AFSCM designed and those of the CTBEM. Taking in account the same volume and approximately the equal total mass of both motors, a higher electromagnetic torque is achieved due to the high remnant field trapped by YBCO material.
It is worth to remark the low inductance of the AFSCM design and consequently a lower electrical time constant. That is achieved by the absence of ferromagnetic materials on the armature. Also mechanical time constant has a lower value due to its lower armature resistance and high torque constant.

| Parameter               | Unit | SC | Convert |
|------------------------|------|----|---------|
| Nominal current        | A    | 2.74 | 2.74   |
| Electromagnetic torque | N·m  | 5.9  | 1.7     |
| Total mass             | Kg   | 1.85 | 1.9     |
| Resistance             | mΩ   | 37   | 8.5     |
| Inertia moment         | Kg·m²·10⁻³ | 0.25 | 0.137   |
| Mechanical time constant | ms | 0.22 | 5.246   |

5. Conclusions
Comparative on high dynamics between a CTBEM motor and AFSCM has been done. Results indicate high improvements on electromagnetic torque of AFSCM. Also, due to the lower mechanical and electrical time constant, it is possible to work on highly variable torque applications where the acceleration and deceleration are key points to decrease the time cycles and making it more efficient. Thinking on the motor and the driver as a set, the driver will work with a lower current range thus reducing the conduction losses in the driver and allowing a higher efficiency and a reduction of volume.

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