High Power Density Superconducting Motor For Control Applications

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Abstract. A high dynamics superconducting low power motor for control applications has been considered for design. The rotor is cylindrical with machined bulks that generate the field by trapping flux in a four poles configuration. The toothless iron armature is wound by copper, acting iron only as magnetic screen. Details of the magnetic assembling, cryogenics and electrical supply conditioning will be reported. Improvements due to the use of a superconducting set are compared with performances of equivalent conventional motors.

1. Introduction

Since the discover of the high temperature superconductors (HTS), more people hope that electrical machines, as motors and generators, will take more profit by using this elements in your composition. In the last two decades, the substitution of HTS instead of copper or magnets in electrical machines has being progressive, but slowly. Actually, the great percentage of motors doesn’t use still superconductors materials.

Initial superconductors wires needed liquid helium as cooler. His cryogenic system was complex and very expensive. For that, only in cases of high power machines, special machines or medicine applications (image), the change of materials from copper or magnets to superconductors is accepted.

The development of HTS bulks, of YBaCuO family, make easily the construction of some types of motors or generators [1], more of them with axial magnetic flux, that have a well power-volume ratio. The mechanics characteristics of YBaCuO bulks isn’t ideal to apply to radial magnetic flux machines,
but a few prototypes have being constructed demonstrating that HTS are adapted it to radial flux machines too.

The cryogenic system for HTS superconductors is less complicated and cheaper than for low temperature superconductors. Furthermore the cryogenic advances are a big help to construct superconducting machines. Some important industries at the world have constructed different motors or generators with superconductors, usually very high power machines (hundreds megawatts or more) as naval propulsion [2].

Other area when superconductors machines have applications are wherever the traditional systems don’t let to achieve where we need (CERN, Limodraw [3]). But ever have a common denominator; they are a high (even more high) or medium power machines.

The present work wont to explore other type of electric machines: low power machine for a specific or particularly application. We present a design of a little radial trapped flux machine with four poles configuration.

2. Motor description.

The motor designed is a four poles three-phase motor for a control application. The physical restrictions are a cylindrical form with 60 mm diameter and 100 ~ 120 mm long. The machine is a toothless motor without iron to avoid the not desirable cogging effect. In this conditions the motor can have high magnetization, upper than 1.7 T.

The cylindrical rotor will be made by YBCO HTS superconductors and the stator windings are made by copper conductors. Iron is only in the exterior and acts as a magnetic screen. The fluid cooler selected is hydrogen gas working around 50 K temperature. Only the rotor is cooled, the stator works at environment temperature.

Between the stator (at high temperature) and the rotor (low temperature) we purpose a thin vacuum layer to reduce the thermal influence from stator to rotor.

3. Motor structure and magnetization propose.

The dimensions of the motor are shown in figure 1.

![figure 1]
From the outer to inner, the different layers are: iron, copper, a thin sheet steel, vacuum isolation, a second thin sheet steel, a very narrow layer for the cooler fluid, the superconducting pellets, the support of the pellets and finally the shaft.

In the construction of the machine, we can define the diameter of copper wires of stator’s winding and the distribution of each phase in the motor see figure 2.

The machine is a radial trapped flux motor, and the magnetization of the superconductors will be produced by the stator windings making a current pulse (or successive pulses) in a ZFC process [4][5][6][7]. To have an optimum magnetization process, we use the three phases at the same time, but emulating the currents in a three-phase system. If we choose the instant time when the phase T has the maximum current and R and S phases have a half value, the magnetic field generated on the superconductors will be:

\[ B_{\text{total}} = B_T + B_R \cdot \cos \delta + B_S \cdot \cos \delta \]

\[ B_{\text{total}} = B_T + (B_R + B_S) \cdot \cos \delta \]

We can make an approximation than the magnetic field generated by each phase is a magnetic field generated by N straight wires couples L length. The wires are separated a distance D (phase winding wide, 22 mm from the center). The field value at the center of the wires is:

\[ B = N \cdot 2 \cdot \frac{\mu_0 \cdot I}{4 \cdot \pi \cdot D} \cdot \frac{\text{sen} \varphi}{2} = \frac{2 \cdot N \cdot \mu_0 \cdot I}{\sqrt{2} \cdot \pi \cdot R} \cdot \frac{\text{sen} \varphi}{2} \]

\[ \text{sen} \varphi = \frac{L/2}{\sqrt{(D/2)^2 + (L/2)^2}} = 0.955 \]

and

\[ B_{\text{total}} = \frac{2 \cdot N \cdot \mu_0}{\sqrt{2} \cdot \pi \cdot R} \cdot \text{sen} \varphi \left[ I_T + (I_R + I_S) \cdot \cos \delta \right] \]

If the windings in the motor isn’t overlapped, \( \delta = 30^\circ \) is the angle between phases (see figure 4) and \( I_T = 2 \cdot I_R = 2 \cdot I_S \):

\[ B_{\text{total}} = \frac{2 \cdot N \cdot \mu_0}{\sqrt{2} \cdot \pi \cdot R} \cdot \text{sen} \varphi \left[ 1 + \cos \delta \right] = \frac{2 \cdot N \cdot \mu_0}{\sqrt{2} \cdot \pi \cdot R} \cdot \text{sen} \varphi \left[ 1 + \frac{\sqrt{3}}{2} \right] \]

\[ B_{\text{total}} = \frac{\mu_0}{\pi \cdot R} \left( \frac{2 + \sqrt{3}}{\sqrt{2}} \right) \cdot \text{sen} \varphi \]

If we wish than \( H^* \) in the pellets be 1.7 T, in theory, we need to apply a 2 \( H^* \) (3.4 T)
The number of wires in each winding is determined by the little space to accommodate the windings. If the windings are collocated at 22 mm from the axis of the motor in a little space of 5.0 mm wide along an arc of 30º, the surface occupied by the winding is:

\[ S_{\text{max}} = \frac{\pi}{2} \left( \pi \cdot (25 \text{ mm})^2 - \pi \cdot (20 \text{ mm})^2 \right) = 58.9 \text{ mm}^2 \]

If we select the diameter of the copper wires \( \phi = 1.0 \text{ mm} \), and suppose a factor \( k = 0.75 \) of packed, the number of conductors in each wire is:

\[ N = \frac{S_{\text{max}}}{\pi \left( \frac{\phi}{2} \right)^2} = 56 \]

The current necessary in each wire of a winding is:

\[ I_r = \frac{3.4 \cdot \pi \cdot R}{N \cdot \mu_0 \cdot \text{sen} \phi} \left( \frac{\sqrt{2}}{2 + \sqrt{3}} \right) = 1322 \text{ A}, \text{ and } 74 \text{ kA} \text{ is the current necessary to a winding.} \]

The resistance and inductance of one of this winding are \( R = 1.24 \Omega \), and \( L = 1.0 \text{ mH} \).

The voltage necessary to achieve this peak current is 1639 V. This voltage value is inappropriate, for as we associate the 56 wires in a different form; the coil winding should be an association of eight wires in parallel that make 7 turns to the motor.

In this new condition, the new winding resistance is \( R = 19 \text{ m}\Omega \), and the necessary voltage decrease to 207 V.

When we need the peak current in one phase will be double than other two, is possible to obtain connecting one phase with the parallel between the other two. The set resistance is \( R' = 29 \text{ m}\Omega \), and the voltage necessary is \( V' = 310 \text{ V} \). This voltage can be obtained from the grid in three-phase connection. For that, we can be a peak current with a half grid period (\( \Delta t = 10 \text{ ms} \))

The maximum energy that, in last conditions, copper conductors can dissipate is:

\[ E = R \cdot I^2 \cdot \Delta t = 1.24 \Omega \cdot \left( \frac{1322}{\sqrt{2}} \text{ A} \right)^2 \cdot 10^{-3} = 12.7 \cdot 10^3 J \]

The phase winding have a mass of 0.413 kg. The increase of temperature in the coil is:

\[ \Delta T = \frac{E}{m \cdot c} = \frac{12.7 \text{ kJ}}{0.41 \text{ kg} \cdot 390 \text{ J/kg} \cdot \text{K}} = 79 \text{ K} \]
This increase of temperature is high enough, for that, we think is necessary to cool, with water, the windings too.

4. Motor parameters.

Parameters of the motor:

| Parameter                             | Unit    | Value |
|---------------------------------------|---------|-------|
| Maximum current density               | A/mm²   | 6     |
| Conductor diameter                    | mm      | 1.0   |
| Winding turns per stator and phase    |         | 7     |
| Number of conductors in each turn     |         | 8     |
| Resistance of winding                 | mΩ      | 19    |
| Inductance                            | mH      | 1.1   |
| Total mass                            | Kg      | 1.7   |
| Inertia Moment                        | Kg·m²·10⁻³ | 0.57 |

Electromagnetic parameters of the motors calculated:

a) Torque of the motor

\[
F_{\text{phase}} = 2 \cdot N_{\text{turns}} \left| \mathbf{I} \times \mathbf{B} \right| = 2 \cdot 7 \cdot 21.92 \cdot 0.1 \cdot 1.7 = 52.2 \text{ N}
\]

The total force with the three phases is:

\[
F_{\text{Total}} = F_{\text{Total}} \cdot 3 = 156.6 \text{ N}
\]

If the windings are at 22 millimeters from the axis motor, the final torque is:

\[
\tau_{\text{Total}} = F_{\text{Total}} \cdot d = 156.6 \text{ N} \cdot 0.022 \text{ m} = 3.44 \text{ Nm}
\]

One of the most indicative values in the behaviour motors is the capacity to change and to achieve a desired speed, accelerating or decelerating, this indicators are the electrical and mechanical constants, \( \tau_{\text{elec}} \), \( \tau_{\text{mech}} \) respectively:

\[
\tau_{\text{elec}} = \frac{L}{R} = \frac{1.1 \cdot 10^{-3}}{1.24} \text{ H} = 0.89 \text{ ms}
\]

Where \( L \) is the inductance of the coil and \( R \) is the resistance of the winding if is composed by one conductor that make all of turns.

\[
\tau_{\text{mech}} = \frac{R \cdot J}{K_e \cdot K_f} = \frac{0.019 \Omega \cdot 0.00015 \text{ kg} \cdot \text{m}^2}{(3.44/21.92)^2} = 0.115 \text{ ms} = 115 \mu \text{s}
\]

Where \( J \) is the inertia moment and \( K_e = \tau_{\text{Total}} / I = K_f \)

| Parameter               | Unit     | Value  |
|-------------------------|----------|--------|
| Nominal current         | A        | 21.92  |
| Magnetic rotor field    | T        | 1.7    |
| Electromagnetic torque  | N·m      | 3.44   |
| Resistance winding      | Ω        | 0.019  |
| Inductance              | mH       | 1.1    |
| Inertia moment          | Kg·m²·10⁻³ | 0.15  |
| Mechanical time constant| ms       | 0.115  |
| Electrical time constant| ms       | 0.89   |
If we compare there results with a characteristics of a conventional machine [8], we can show that torque is double, Inductance and electrical constants are equivalents to conventional, but mechanical constant is 50 times lower.

5. Thermal analysis.

The cooler gas selected is hydrogen working at the temperature of 50 K. One of our doubts is if the hydrogen will have cooling power enough to maintain the working temperature. Hydrogen flows into a thin layer of 0.20 mm wide between the YBCO pellets and the isolation vacuum zone.

We want to study the velocity necessary for the hydrogen in the layer, also if it is necessary a big pressure to work, they have a big pressure losses, if the flow regime is laminar or turbulent, and with two different heat sources in the motor (the external power radiation and the internal heat generated in the superconducting pellets) to know if the cooler system is capable to extract this heat from the machine.

Some simulations by finite elements methods have been done by COMSOL®. A symmetrical cylindrical geometry was selected to model a 2D case. A preliminary study shows us that the flow of hydrogen is laminar. The results of simulation are agree with the preliminary study and permit to obtain more detailed results. The most significant results are the temperature and velocity profiles (figure 5), temperature variation and pressure losses in function of inlet velocity (figure 6).

![Figure 5](image.png)

**Figure 5.** Left: Hydrogen velocity profile in different positions along the axis motor. Laminar profile is achieved in a few millimeters. Right: Temperature variation from the pellets surface to vacuum layer for different cross sections along the axis motor.


6. Conclusions

A new low power motor is proposed and their structure and magnetization system is discussed. It can verify that is possible to try the magnetization of the superconducting motors with the coils of the motor and using the grid. The magnetic remanence that would obtained in the pellets is higher than the magnets. The electrics and mechanics parameters of the motor are better than a conventional-commercial motor with the same dimensions and iron volume. The cooler system with hydrogen gas is a good propose for guarantee the cooling of the superconducting rotor.

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