Use of superconductors in the magnetic circuit of electric generators adapted to renewable energy sources

Hugo M. B. Serieiro

Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

Abstract — This work presents a study of the internal behavior of high temperatures superconductor (HTS) bulks of YBCO and GdBCO. With the objective of future implementation of HTS bulks on the magnetic circuit of electric generators, magnetization and temperature tests were performed. These tests consist in exposing constant and pulse magnetic fields to the HTS bulks. The same bulks were also exposed to room temperature, when previously magnetized. Electromagnetic and thermal models were used for the construction of a computational simulation that recreates the laboratory experiments. These models depend on parameters, to simulate the behavior of the HTS. Those parameters were adjusted from the experimental data to guarantee the best fit possible of the simulation. A comparison between the YBCO and GdBCO was also performed, demonstrating that the GdBCO can expel magnetic fields much better than the YBCO, hence not being so easily magnetized. Using magnetic pulses it was possible to achieve magnetizations of 0.45 T for the YBCO and 0.34 T for the GdBCO. When at ambient temperature, the GdBCO takes almost twice the time to lose its superconducting state compared to the YBCO. Experimental data shows that the initial magnetization of the sample influences the demagnetization rate when heating up.

Index Terms—High temperature superconductors, PMF, HTS bulks, YBCO, GdBCO, electromagnetic and thermal models.

I. INTRODUCTION

High temperature superconductors have been used in several applications in the last years including levitations systems, flywheels, power transmission cables and electric machines. High temperature bulk superconductors exhibit a high critical current density $J_c$ and are able to expel magnetic field to which they are exposed. They have, also, the ability to trap high magnetic fields. Those properties make HTS bulks great candidates to be used on electric machinery. Recently it was possible to trap fields up to 17 T on an HTS cooled at 29K, this is more than ten times the magnetic field originated from the strongest permanent magnets to date [1]. Many electric machines have been built with the use of superconducting materials. The first approach was to use superconducting coils instead of the traditional ones, but later HTS bulks started to be used in the composition of the rotor of synchronous machines and reluctance machines. The principal reasons to superconducting machines starting to emerge, are the high power density, reduced mass and increased efficiency.

This paper focuses on the study of HTS bulks of YBCO and GdBCO and in the validity of the current electromagnetic and thermal models [2][3][4]. The validity of these models depends on the ability to fit to the experimental data. The approach used to validate the electromagnetic model was by exposing both, the YBCO and GdBCO bulks, to time varying magnetic fields in the laboratory. The objective is to measure the electromagnetic forces generated in the process (Meissner effect). Another approach was to analyze the HTS bulks magnetization when exposed to magnetic pulses (PMF).

To validate thermal model, it was performed a heating of the HTS bulks in exposition to room temperature. Both HTS were previously magnetized in a process called field cooling (FC).

The electromagnetic and thermal models depend on specific parameters that allow the fit to different HTS materials. These parameters are adjusted, for each superconductor, so the model can fit the experimental results. A comparison was made between the two types of HTS, from the results obtained in each experiment.

II. SUPERCONDUCTIVITY

The superconducting state is a state that some metals obtain when cooled down below a certain temperature called the critical temperature $T_c$. There are 33 metals that have the capacity of becoming superconductors, besides hundreds of compounds and alloys [5]. There are two types of superconductors, type 1 and type 2. The main difference between them is their critical temperature, which varies according to the material. Type 1 superconductors have usually a critical temperature lower than 10K, while the critical temperature on type 2 superconductors is around 100K [6].

The state of superconductivity is, mainly, characterized by a vanishing of electrical resistance and diamagnetism.

A. Vanishing of electrical resistance

When it is cooled below the critical temperature, the material exhibits an abrupt drop in electrical resistance, becoming near zero. However, this almost null resistivity it’s only valid to DC currents, in AC currents there is a critical frequency that once it’s exceeded the resistance increases.
B. Diamagnetism

The superconductors have the ability of repelling magnetic field that are exposed to them, however this diamagnetism is not ideal. In the presence of low magnetic fields there is total cancelation of the external magnetic field, although when magnetic fields are higher there is a superficial penetration on the material. The penetration depth is called London penetration. The superconductor when exposed to an external magnetic field generates internal currents that create a symmetrical field, cancelling the first. That property is known as Meissner effect.

C. Critical region

Superconductivity is characterized by three critical parameters: the critical temperature \( T_c \), the critical current density \( J_c \) and the critical magnetic field \( B_c \). If in a superconducting material, one or more of these parameters are exceeded the state is lost, Fig. 1. However, the material does not lose all superconductivity at the same time, zones that exceed critical values may exist within the material, leading to a loss of local superconductivity while other zones remain superconductive.

D. Type 2 superconductors

High temperature superconductors as the YBCO and the GdBCO are type 2 superconductors. This type of superconductors is characterized by having two distinct operation zones, the magnetic field being the decisive parameter in which the superconductor operates, Fig. 2. There are two critical magnetic fields, \( B_{c1} \) and \( B_{c2} \), where \( B_{c2} > B_{c1} \). When \( B < B_{c1} \) the superconductor exhibits diamagnetism. If \( B > B_{c2} \) the superconductor loses the state of superconductivity. However, if \( B_{c1} < B < B_{c2} \) the superconductor enters a mixed zone where the magnetic field partially penetrates.

III. ELECTROMAGNETIC AND THERMAL MODELS

A. Electromagnetic model

1) Equations

The model is based on a H-formulation [2][3], so there are three independent variables: \( H_x, H_y \) e \( H_z \). The current and electric fields are also composed of three components: \( J = [J_x, J_y, J_z]^T \) e \( E = [E_x, E_y, E_z]^T \) and their computation can be taken directly from the Maxwell equations:

\[
\begin{align*}
J &= \nabla \times H \\
E &= \frac{\partial H}{\partial t} - \mu_0 \mu_r \nabla \times E
\end{align*}
\]  \( \text{Eq. 1} \)

Considering that there is no significant variation of the electric field:

\[
\begin{align*}
\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial z} &= -\mu_0 \mu_r \frac{\partial H_z}{\partial t} \\
\frac{\partial E_z}{\partial z} - \frac{\partial E_z}{\partial x} &= -\mu_0 \mu_r \frac{\partial H_y}{\partial t} \\
\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} &= -\mu_0 \mu_r \frac{\partial H_x}{\partial t}
\end{align*}
\]  \( \text{Eq. 2} \)

Type 2 HTS are characterized by a non-linearity between electric current and voltage, however they can be characterized by a relation between electric field \( E \) and the current density \( J \):

\[
E = E_0 \left( \frac{J}{J_c(B)} \right)^n
\]  \( \text{Eq. 3} \)

\( E_0 \) and \( n \) are HTS electromagnetic parameters.
$J_c$ is the critical current density and can be given by eq. (4):

$$J_c(B) = \frac{J_{c0}B_0}{B_0 + B}$$

(4)

The external magnetic field $B$ is given by eq. (5):

$$B = ||\mathbf{B}|| = \mu_0 \mu_r H_x^2 + H_y^2 + H_z^2$$

(5)

Finally, the electric field $\mathbf{E}$ is given by eq. (6):

$$\begin{align*}
E_x &= E_0 \left( \frac{\partial H_x - \partial H_y}{J_c(B)} \right)^n \\
E_y &= E_0 \left( \frac{\partial H_x - \partial H_z}{J_c(B)} \right)^n \\
E_z &= E_0 \left( \frac{\partial H_y - \partial H_z}{J_c(B)} \right)^n
\end{align*}$$

(6)

2) Electromagnetic parameters

The parameter $n$ represents the precision of the relationship between the magnetic field-electric current, which dictates the possible conductivity states of the superconductor. The parameter $E_0$ represents the value of the critical electric field, not varying much for different HTS materials. The parameter $J_{c0}$ represents the critical electric current density when the applied external magnetic field $B$ is zero. The default values for this parameter are the most variable among all parameters. The parameter $B_0$ represents the magnetic field value which reduces by half the critical electric current density $J_c: J_c(B_0) = J_{c0}/2$. In Table 1 are summarized the typical electromagnetic parameters in superconductors of the YBCO and GdBCO family (Rare Element Barium Copper Oxide - (RE)BCO).

Table 1 Typical electromagnetic parameter for HTS superconductors of (RE)BCO.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>(RE)BCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$</td>
<td>$1 \times 10^6$ V. m$^{-1}$ [2]</td>
</tr>
<tr>
<td>$J_{c0}$</td>
<td>$10^7$[2] – $10^8$ A/m$^2$ [7]</td>
</tr>
<tr>
<td>$B_0$</td>
<td>0.1[2] – 1 T [8]</td>
</tr>
</tbody>
</table>

B. Thermal model

It is expected that the superconductor has a uniform internal temperature once it is cooled, however after the application of magnetic fields or electric currents, there is an internal heating from the Joule effect.

1) Equations

The internal heating is characterized by the heat diffusion equation, eq. (7):

$$\nabla \cdot (\lambda(T)\nabla T) - \rho_m C_p(T) \frac{\partial T}{\partial t} + p_q = 0$$

(7)

$\lambda, \rho_m, C_p$ and $p_q$ are thermic parameters of the HTS material. In the analysis of the electromagnetic model of the superconductor (section III.A), the dependence of the electric current density $J_c$ by the magnetic field $B$ was demonstrated, however the temperature was not taken into consideration. Considering the temperature, $J_c$ is directly influenced by the temperature $T$ of the HTS [4]:

$$J_{c0}(T, T_c) = \alpha \left( 1 - \left( \frac{T}{T_c} \right)^2 \right)^{3/2}$$

(8)

In eq.(8), $\alpha$ represents the critical current density at 0K with no applied external magnetic field. Replacing eq.(8) in eq.(4) results on the $J_c$ final equation, eq. (9):

$$J_c(B, T) = \alpha \left( 1 - \left( \frac{T}{T_c} \right)^2 \right)^{3/2} \left[ \frac{B_0}{B_0 + B} \right]$$

(9)

2) Thermal parameters

The parameter $\lambda$ is the thermal conductivity, $\rho_m$ is the mass density, $C_p$ is the specific heat capacity and the variable $p_q$ is a volumetric power loss which represents the heat source.

Table 2 summarizes the typical thermic parameters in (RE)BCO HTS, in a temperature range from 69 to 150 K.

Table 2 Typical thermic parameter for HTS superconductors of (RE)BCO.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>(RE)BCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (W(m . K))</td>
<td>2 – 20 [8]</td>
</tr>
<tr>
<td>Specific heat (J/(Kg .K))</td>
<td>100-200 [9]</td>
</tr>
<tr>
<td>Mass density (Kg/m$^3$)</td>
<td>$5.9 \times 10^3$ [10]</td>
</tr>
<tr>
<td>Critical temperature (K)</td>
<td>$\sim 92$ [2]</td>
</tr>
</tbody>
</table>

IV. METHODS AND PROCEDURES

In order to validate the electromagnetic and thermal models for HTS, the execution of laboratory experiments was carried out, and its comparison with results from the computational simulation of the models.

A. HTS bulks

In the laboratory experiments, two superconducting bulks of different materials were used: the YBCO (Fig. 4) and the GdBCO (Fig. 3). Both superconductors are type 2. The YBCO was the first discovered superconductor with a critical temperature above the boiling point of liquid nitrogen (77 K), which allowed it to be studied and used globally, without the need for liquid helium.
The Table 3 shows the geometric parameters and the weight of the superconducting samples used in the laboratory experiments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GdBCO</th>
<th>YBCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Cylindrical</td>
<td>Parallelepiped</td>
</tr>
<tr>
<td>Weight (g)</td>
<td>175.8</td>
<td>64.7</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Diameter (cm)</td>
<td>4</td>
<td>1.4</td>
</tr>
<tr>
<td>length / width (cm)</td>
<td>-</td>
<td>3.2</td>
</tr>
</tbody>
</table>

B. Electromagnetic model validation

For the validation of the electromagnetic model, is necessary experimental data on the superconducting electric currents in the bulks. In addition to the difficulties associated with the low temperature measurement of superconducting bulks, the bulks format also prevents a direct measurement of the magnitude of the values of induced currents or electrical resistivity.

One of the ways to prove the electromagnetic model was by comparing electromagnetic repulsion forces, between the results of the computational simulation and the laboratorial experiments. Due to the Meissner effect, an expulsion of the magnetic field exposed to the HTS occurs when the HTS is cooled, without an external magnetic field applied. This field expulsion, originated from the currents on the surface of HTS, generates an electromagnetic repulsion force. By varying the intensity of the magnetic field to which the HTS is exposed, it is possible to trace its relation with the generated electromagnetic force.

The HTS is placed on the bottom of a vertically positioned rail, where it is still. The rail and the HTS assembly are submerged in liquid nitrogen within a styrofoam structure, and the superconductor is cooled (without exposure to external magnetic fields). When the HTS is in a superconducting state, a permanent magnet (PM) is placed, in the rail, above the HTS. Next, a platform is place on the magnet where it is possible to place different weights. Placing these weights allows the distance between the magnet and the superconductor to be reduced, Fig. 5.

C. Thermic model validation

A possible approach to the validation of the thermal model is an analysis of the behavior of the superconductor in heating process. With the laboratory experiments, it’s analyzed the evolution of the superconductor magnetization and the evolution of its temperature over time, when exposed to room temperature. The process of magnetization occurs with the imposition of a constant magnetic field during the cooling of the HTS. The magnetic field originates from a PM previously cooled, Fig. 6.

One of the objectives of this experiment is the analysis of the influence of magnetization on superconductor heating. A set of experiments were carried out with different distances between the PM and the HTS, leading to the variation of magnetic fields exposed to HTS. The distance variation was obtained by including pieces of plastic of different thicknesses between the magnet and the HTS sample during the cooling process.
The spacing distances were as follows: \( d_1 = 1.25 \text{ cm}, d_2 = 0.9 \text{ cm} \) and \( d_3 = 0.5 \text{ cm} \). The smaller the distance the greater the magnetic field exposure to the superconductor. Once the sample is cooled, the outer magnetic field is slowly withdrawn (the PM is withdrawn), resulting in the sample being magnetized. The sample is then withdrawn from the nitrogen container, and exposed to room temperature. The Fig. 7 represents the how the magnetization and temperatures data were obtained from the HTS bulks.

![Fig. 7 Illustration of the coupling of the thermal and Hall effect probes to the YBCO superconductor.](image)

**D. PFM**

As a complement to the laboratory experiments described in (section IV.B), the samples were magnetized using magnetic pulses. Pulsed magnetization makes it possible to reach magnetic field magnitudes several times higher than the magnetization resulting from FC, with a magnet. The objective of this experiment is to analyze the distribution of the magnetic field trapped in the superconductor, the maximum magnetization reached and the comparison of the magnetizations between the two superconductors (YBCO and GdBCO).

For the creation of the magnetic pulses, an "E" magnetic circuit with a winding of 400 turns is used. The superconducting bulks are placed in alignment with the central leg of the magnetic circuit and then cooled by total submersion in liquid nitrogen, while the winding is only partially submerged, Fig. 8. During cooling, there was no exposure to external magnetic fields (ZFC). The HTS bulks are exposed to magnetic pulses after they enter into the superconducting state. The pulses are generated by the discharge of a capacitor in an RLC circuit. Pulses with different magnitudes are generated.

![Fig. 8 Illustration of magnetic circuit with superconducting bulk.](image)

After the magnetic pulse is generated, the magnetic circuit and the HTS bulk are removed from the liquid nitrogen and the magnetic field is measured along the HTS surface. The probe is driven by a rail, where a hall effect sensor and a position sensor are installed, Fig. 9.

![Fig. 9 Side view of the configuration of the Hall effect probe and the position probe coupled to the rail.](image)

The probe is moved with the aid of a DC electric motor in constant speed and in rectilinear motion. The magnetic field is measured along the length of the superconducting bulk as shown in Fig. 10.

![Fig. 10 Path covered by the Hall effect probe on the superconductor when placed in the rail.](image)

Once the magnetization of the superconductor is recorded, the HTS is exposed to room temperature for the purpose of losing the state of superconductivity, thus losing its magnetization. The process is repeated for each magnetic pulse.
V. EXPERIMENTAL RESULTS

A series of experiments were performed following the procedures mentioned in section IV. The results are presented for the YBCO and GdBCO bulks. A comparison is made between the HTS bulks.

A. Electromagnetic forces

To register the electromagnetic forces originated by the Meissner effect, the HTS was exposed to different magnetic fields. Five weighing cycles were performed in each HTS bulk.

In the YBCO bulk, in the first cycle, when the first weight (30 g) was placed, the recorded distance was 2.86 cm, the highest value of all measurements. At the end of this same cycle, with the initial weight placed again, the distance was 2.26 cm, which indicates that the repulsion force decreased. The results are shown in Fig. 11.

Similar results were obtained for the GdBCO bulk (Fig. 12), but the largest distance recorded was 3.11 cm, corresponding to the application of the smallest weight. At the end of the first cycle, this distance decreased to 2.79 cm.

Both the HTS bulks diminished their electromagnetic force of repulsion. The reason of this decrease of force is due to bulk magnetization. In the end of the experiment, a measurement of the magnetic fields was performed on the surface of the HTS. The maximum trapped field recorded are shown in Table 4.

Table 4 Maximum trapped magnetic fields, at the end of the 5 cycles.

<table>
<thead>
<tr>
<th></th>
<th>YBCO</th>
<th>GdBCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_{max} (T)</td>
<td>0.036</td>
<td>0.016</td>
</tr>
</tbody>
</table>

The YBCO bulk has a higher magnetization than the GdBCO bulk. The average value of the electromagnetic forces in the 5 cycles (in the two HTS) reinforces the fact that YBCO is easily magnetizable than the GdBCO, Fig. 13.

A new experiment was carried out in order to observe better the magnetizations in the HTS bulks, Fig. 14. The experiment consisted in applying, in both samples, a weight of 30 g followed by one of 3 kg. The process was repeated 12 times.

In the first application of the weight of 30 g, both HTS bulks repel the magnetic field exposed to them, obtaining similar results, however, after the first application of the weight of 3kg the greater expulsion of field by the GdBCO begins to be noticeable. The YBCO does not have the ability to repel the entire magnetic field exposed to it, so when the light weight is replaced, the distance is on average 55% of the pre-magnetization distance. The GdBCO returns to a state closer to the initial state, returning to a distance of 86% of the pre-magnetization distance.

B. Heating at room temperature

In this section are presented the results of the laboratory experiment described in section IV.C, where temperatures and magnetic fields are measured during the heating of the superconducting bulks. The HTS were magnetized by exposure to the magnetic field (FC) of a permanent magnet placed at different distances during cooling: d_1 = 1.25 cm, d_2 = 0.9 cm and d_3 = 0.5 cm. In the Fig. 15 is shown how the sensors were placed to measure the temperature and magnetic fields of the HTS bulks in the process of heating up.
After cooling in FC, the magnetization evolution of the YBCO and GdBCO bulks was measured during its heating at room temperature. The air temperature at the time of the experiment was around 295.15K (22°C). The results of the evolution of the magnetic filed in the HTS bulks are shown in Fig. 16.

The GdBCO has a field conservation superior to the YBCO, with a demagnetization time of around 80 seconds compared to the YBCO demagnetization time of about 40 seconds. The reason for this difference is the values of the electromagnetic and thermal parameters characteristic of each material. It is also possible to notice the effect of the internal heating from the superconducting currents that support the magnetic field, although this effect it’s much more noticeable in the GdBCO. The evolution of the temperatures is shown in Fig. 17.

In the YBCO bulk the internal heating is more evident than in the GdBCO bulk. In the case of higher magnetizations, the YBCO underwent a sudden heating at 7 seconds. In the case of the smallest initial magnetization, this heating only occurred after 20 seconds. The GdBCO presents an initial temperature variation similar in the two initial magnetizations. However, after the initial temperature variation, both the YBCO and the GdBCO present a higher temperature in situations of higher initial magnetization. This is due to the internal currents of the superconductor, that cause internal heating.

C. PFM

In this section are presented the results of the experiment mentioned in section IV.D, where the magnetization of the samples, from exposure to magnetic pulses, was measured. Magnetizing by magnetic pulses complements previous experiments, as it is possible to obtain higher magnetizations than with FC. In Fig. 18 is shown the magnetization measurement.

Pulses of 50 V, 75 V, 200 V, 300 V and 400 V were generated. Each magnetic pulse generated is succeeded by the measurement of the magnetic field "trapped" along the HTS length. The magnetizations originated by the magnetic pulses in the YBCO bulk are shown in Fig. 19.

The intensity of the pulse directly influences the magnetization of the YBCO, which increases with the increase of the magnitude of the magnetic pulses. When exposed to small pulses (50 V and 75 V), the superconductor can repel much of the magnetic field, presenting a low and almost uniform magnetic distribution. However, for higher magnetic pulses the magnetization is high and has no uniformity.
The magnetic pulses exposed to the GdBCO are the same. Each magnetic pulse was exposed when the superconducting bulk was already in the superconducting state. The magnetizations originated by the magnetic pulses are shown in Fig. 20. The magnetization in the bulk increases directly with the increase of the exposed magnetic pulses. The magnetization is not uniform, presenting higher trap magnetic fields in the extremities, leaving the center practically demagnetized.

The GdBCO has a higher diamagnetism than the YBCO, being less magnetized and conserving magnetic field only in the extremities. YBCO conserves magnetic fields easily, presenting a more uniform distribution compared to the GdBCO. The maximum magnetic field, measure for each HTS, is shown in Fig. 21.

At lower pulses the GdBCO bulk has slightly higher magnetizations, but at higher pulses it’s the opposite, being the YBCO more magnetized. The YBCO bulk cannot create contrary magnetic fields to cancel the one to which it is exposed, having magnetic field penetration throughout its surface. The GdBCO is able to expel most of the field exposed to it, only being penetrated in its periphery (Fig. 20). These differences in magnetization are due to the values of the electromagnetic parameters characteristic of each material. The GdBCO bulk has a higher $J_{c0}$ than YBCO, which means that it generates larger electrical currents, obtaining inferior magnetizations. The higher $n$ value in GdBCO bulk reinforces this since it represents the conductivity of the HTS.

VI. SIMULATION RESULTS

After experiments have been done on the HTS bulks, it’s carried out the simulation of the electromagnetic and thermal models in a finite element software.

A. Electromagnetic model validation

For the electromagnetic model validation, 2D and 3D configurations were constructed. The 3D configuration obtain better overall results, although it takes longer to compute. The simulation performed is a recreation of the laboratory experiment (section V.A), where a variable magnetic field was exposed to the HTS bulks cooled in ZFC. An adjustment of the electromagnetic parameters was made, based on the experimental data and on the typical values for YBCO and GdBCO HTS found in the literature. In Table 5 are shown the electromagnetic parameters that best fit the model.

Table 5 Electromagnetic parameters proposed for the modeling of the YBCO and GdBCO bulks.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>YBCO</th>
<th>GdBCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_{c0}$ (A/m²)</td>
<td>$1.82 \times 10^8$</td>
<td>$4 \times 10^8$</td>
</tr>
<tr>
<td>$B_0$ (T)</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>$n$</td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td>$E_0$ (V/m)</td>
<td>$1 \times 10^{-4}$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

1) Electromagnetic forces

The Fig. 22 shows the experimental and simulated force-distance curves of the YBCO bulk. Were used the estimated parameters presented in Table 5.

Fig. 22 Comparison between the experimental and simulated electromagnetic forces curve in the YBCO.

The Fig. 23 shows the experimental and simulated force-distance curves obtained from GdBCO bulk.

Fig. 23 Comparison between the experimental and simulated electromagnetic forces curve in the GdBCO.

There is a close proximity between the experimental and simulated results, which indicates that the model accurately reproduces the behavior of both HTS (YBCO and GdBCO) when exposed to external magnetic fields.
2) **HTS Magnetization**

At the end of the simulation, the magnetic field distribution was recorded in the YBCO sample, Fig. 24. With the exception of isolated points and the limits of the superconducting bulk, the whole superconductor shows magnetization signals.

![Final magnetization in the YBCO after removal of the external magnetic field.](image)

Fig. 24 Final magnetization in the YBCO after removal of the external magnetic field.

The magnetization distribution of the GdBCO is presented in the Fig. 25.

![Final magnetization in the GdBCO after removal of the external magnetic field.](image)

Fig. 25 Final magnetization in the GdBCO after removal of the external magnetic field.

The GdBCO was only magnetized at the periphery. The magnetic field recorded at the center of the superconductor is negligible. The similarities between the magnetization obtained in simulation and the magnetizations obtained by exposure to magnetic pulses, Fig. 20, are notorious. The maximum recorded magnetic fields obtained in the simulation are compared to the experimental ones in Table 6.

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>YBCO</strong></td>
<td>0.036 T</td>
<td>0.031 T</td>
</tr>
<tr>
<td><strong>GdBCO</strong></td>
<td>0.016 T</td>
<td>0.017 T</td>
</tr>
</tbody>
</table>

**B. Thermal model validation**

The thermal parameters depend on the constitution of the HTS, so it’s necessary to carry out an adjustment of the thermal parameters to approximate the results of the simulation to the experimental ones, Table 7.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>YBCO</th>
<th>GdBCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (W/(m·K))</td>
<td>0.8</td>
<td>0.25</td>
</tr>
<tr>
<td>Specific heat (J/(Kg·K))</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Critical temperature (K)</td>
<td>93</td>
<td>94.5</td>
</tr>
</tbody>
</table>

The Fig. 26 shows the simulated and experimental magnetization evolution in the YBCO, when exposed to room temperature (295.15K).

![Comparison between experimental results and simulation results of the magnetization for the YBCO in the exposure to room temperature.](image)

Fig. 26 Comparison between experimental results and simulation results of the magnetization for the YBCO in the exposure to room temperature.

The simulation presents a good approximation to the experimental results, however the thermal conductivity used is not a standard value for YBCO samples. The Fig. 27 shows the evolution of the simulated and experimental temperatures at the YBCO periphery. In the simulation results, there were no significant differences in the temperature according to the initial magnetization, contrary to the experimental results. For this reason, simulation results are presented in a single curve.

![Experimental evolution of the temperature in the YBCO sample in comparison to the simulated temperature evolution.](image)

Fig. 27 Experimental evolution of the temperature in the YBCO sample in comparison to the simulated temperature evolution.

The results of the simulation, although presenting a similar evolution to the experimental results, fail to demonstrate the difference in the temperature evolution depending on the initial magnetizations. The Fig. 28 shows the simulated and experimental magnetizations in the GdBCO bulk when exposed to room temperature (295.15K).

![Comparison between experimental results and simulation results of the magnetization for the GdBCO in the exposure to room temperature.](image)

Fig. 28 Comparison between experimental results and simulation results of the magnetization for the GdBCO in the exposure to room temperature.
By adjusting the thermic parameters, it was possible to obtain the same demagnetization time as that obtained in the laboratory experiments (about 80 seconds). However, the laboratory results of the GdBCO exhibit a constant magnetic field for much of the time, until it abruptly loses the superconducting state. The simulations do not recreate this demagnetization, demonstrating a gradual loss of field since the 10 seconds.

The Fig. 29 shows the evolution of the simulated and experimental temperatures at the periphery of the GdBCO. A single temperature-time curve is displayed for the simulation, for the same reason as for the YBCO.

![Fig. 29 Experimental evolution of the temperature in the GdBCO sample in comparison to the simulated temperature evolution.](image)

The results of the thermal simulation, although presenting a similar evolution to the experimental results, fail to demonstrate the difference in temperature evolution from the initial magnetizations.

VII. CONCLUSIONS

The main objectives of this work are an analysis of the behavior of HTS and the experimental validation of the electromagnetic and thermal models that characterize them. For this purpose, the superconductors used, YBCO and GdBCO, were subjected to constant magnetic fields and to magnetic pulses. Both superconductors were also exposed to room temperature when previously magnetized.

The HTS show the ability to expel low magnetic fields, however with increased exposure to upper fields both are partially magnetized. The YBCO is magnetized more easily than GdBCO, not being capable of generating electrical currents large enough to cancel the field to which it is exposed. The results of the magnetization by exposure to magnetic pulses reinforce this fact, the YBCO besides presenting a greater magnetization than the GdBCO, also presents a more uniform field distribution on its surface. The magnetization in the GdBCO’s surface is not uniform. It shows a concentration of magnetic field in its periphery, leaving the center practically demagnetized. The electromagnetic model simulates accurately the magnetization of the HTS bulks, validating the adjusted electromagnetic parameters.

The thermal laboratory experiments revealed that the YBCO, when exposed to room temperature, loses its superconductivity by approximately half the time of the GdBCO. It was possible to observe a more intense heating in situations where the initial magnetization was higher, which led to a faster demagnetization. In the simulation, the temperature-time curves remain practically the same regardless of the initial magnetization. The thermal simulation of the YBCO obtained results closer to the experimental than the GdBCO, nevertheless values were assigned to the thermal conductivity that are not usual in the literature. The configurations used in the thermal simulation were 2D, which may negatively influence the validity of the results, however a 3D simulation presents a higher computational complexity.

In general, GdBCO bulks are a better alternative to use in superconducting machinery since they have a better conservation of their magnetization, both in exposure to external magnetic fields and temperatures. YBCO bulks have the advantage of being magnetized more easily, which is useful when the aim is the generation of constant magnetic fields, although it is more susceptible to external temperatures and magnetic fields.

REFERENCES


